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Inclusive Photon And Charged-Particle Production In Proton-Proton And Proton-Lead Collisions At LHC Energies With ALICE

Thesis submitted for the degree of
Doctor of Philosophy (Science)
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by

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Dedicated to my parents

Mrs. Kalpana Modak

&

Mr. Tapas Modak

For their endless support in every aspect of my life

Declaration

I do hereby declare that the thesis entitled “**Inclusive photon and charged-particle production in proton-proton and proton-lead collisions at LHC energies with ALICE**” is based on my research works under the supervision of Dr. Sidharth Kumar Prasad. These works are original and have not been submitted earlier as a whole or in part for a degree/diploma at this or any other Institution/University.

Abhi Modak

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Abstract

One of the primary goals of heavy-ion collision experiments, such as ALICE, is to study and understand the properties of the deconfined state of nuclear matter, commonly known as the quark-gluon plasma (QGP). The first step in characterizing the produced QGP matter is the measurement of global observables, such as the number of produced particles (particle multiplicity) and their distribution in pseudorapidity. These measurements are essential to understand the underlying mechanisms of particle production. Such studies in proton–proton (pp) and proton–lead (p–Pb) collisions are also important as they provide baselines for the interpretation of measurements in heavy-ion collisions. In addition, the study of pp and p–Pb collisions is also interesting on its own right. Recent experimental results in high-multiplicity pp and p–Pb collisions have shown interesting features usually attributed to QGP formation in heavy-ion collisions. The origin of these phenomena still needs to be fully understood, and therefore, it is of great interest to investigate and understand the global properties of such collision systems, which makes measurements of multiplicity distributions invaluable.

This thesis reports: a) the first measurements of multiplicity and pseudorapidity distributions of inclusive photons at forward pseudorapidity ($2.3 < \eta < 3.9$) in pp and p–Pb collisions at the nucleon–nucleon centre-of-mass energy $\sqrt{s_{\text{NN}}} = 5.02$ TeV using the data obtained with Photon Multiplicity Detector of ALICE, and b) the study of multiplicity distributions of primary charged particles in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV over a wide pseudorapidity interval ($-3.4 < \eta < 5.1$) for the

first time at the LHC using the Silicon Pixel Detector and the Forward Multiplicity Detector of ALICE. The multiplicity distributions of both photons and charged particles are parametrized with double negative binomial distributions. The centrality dependence of photon production in p–Pb collisions is studied and compared to that of charged particles at midrapidity. The measurements are compared to predictions from various theoretical models to draw important physics conclusions. This thesis also briefly discusses the fundamentals of elementary particle physics and presents the ALICE detector sub-systems utilized in this work.

List of Research Publications

Thesis is based on the following publications

Peer reviewed Journals

1. “Inclusive photon production at forward rapidities in pp and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”

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2. “Charged-particle multiplicity distributions at wide pseudorapidity coverage in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”

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Chapter 1

Introduction

This chapter presents a general introduction to the field of elementary particle physics. It begins with a brief overview of elementary particles, the Standard Model of particle physics. Subsequently, the theory of Quantum Chromodynamics (QCD) is introduced, followed by a discussion of the QCD phase diagram. The phase diagram describes the different phases of nuclear matter as a function of temperature (T) and baryonic chemical potential (μ_B), showing the transition from hadronic matter to a deconfined state of quarks and gluons known as quark-gluon plasma (QGP) at varying values of T and μ_B . The importance of relativistic collisions of heavy-ions in studying the QGP is then highlighted, and various experimental signatures indicative of the formation of the QGP are discussed. The unique aspects of proton–proton and proton–lead collisions are also discussed in the context of the present thesis work.

1.1 Elementary particles and Standard Model

Elementary particle physics aims to explore and identify the fundamental constituents of matter that make up our universe and to understand their properties and interactions. In the past, people believed that matter was composed of indivisible atoms [1]. Then, in 1897, J. J. Thomson first discovered “electron” using a Cathode Ray Tube experiment [2]. He imagined that electrons are essential constituents of an atom and are embedded in a positively charged “soup” inside the atom, similar to the plums in a pudding. In 1911, this model was, however, proved wrong by Rutherford’s scattering experiment, which showed that the positive charge and the majority of the atomic mass are concentrated in a tiny core (known as a nucleus) at the centre of the atom, and electrons revolve around the nucleus [3]. Subsequently, it was discovered that the nucleus also has a composite structure comprising of protons [4] and neutrons [5]. The efforts were continued, and the Deep-Inelastic Scattering (DIS) experiment [6,7] then showed that protons and neutrons are not fundamental particles and consist of quarks which are held together by the exchange of massless particles, called gluons. Quarks and gluons are collectively called “partons”.

In particle physics, the *Standard Model* (SM), a well-established theoretical framework proposed by Glashow [8], Salam [9], and Weinberg [10] during the mid-1970s, provides a comprehensive description of both the basic structure of matter and its fundamental interactions. This model addresses three (strong, weak, and electromagnetic) of the four fundamental interactions (except gravitational interaction) among the elementary particles. The SM is a theory that includes twelve flavours (six quarks and six leptons) of elementary spin-half particles (fermions) plus their corresponding antiparticles and the particles of integral spin (bosons) that mediate the interactions among the fermions. These twelve fermions are classified into three generations. Each generation contains four particles: two quarks and two leptons, which are shown along with their properties (mass, charge, and spin) in

Fig. 1.1. Apart from that, Fig. 1.1 also shows particles that serve as mediators of different types of forces. Here, photons are carriers of electromagnetic interactions, gluons mediate the strong interactions, and $W^\pm$, and Z^0 bosons are responsible for weak interactions. The SM also includes a spin-0 boson known as Higgs, named after Peter Higgs, who, along with five other scientists, proposed the Higgs mechanism in 1964 [11–14]. Their predictions were validated and found to be successful after the discovery of the Higgs boson in 2012 by both ATLAS and CMS experiments [15, 16] at the LHC, CERN. Peter Higgs and Francois Englert were then awarded the Nobel Prize in 2013 for their groundbreaking theoretical work.

Standard Model of Elementary Particles											
three generations of matter (elementary fermions)						three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)		
I		II		III		I		II		III	
mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 2.2 \text{ MeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$	0 0 0	0 0 1	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0		
	 up	 charm	 top	 antiup	 anticharm	 antitop	 gluon	 higgs			
	 down	 strange	 bottom	 antidown	 antistrange	 antibottom	 photon	GAUGE BOSONS VECTOR BOSONS			
 electron	 muon	 tau	 positron	 antimuon	 antitau	 Z ⁰ boson					
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$	$\approx 0.511 \text{ MeV}/c^2$ 1 $\frac{1}{2}$	$\approx 105.66 \text{ MeV}/c^2$ 1 $\frac{1}{2}$	$\approx 1.7768 \text{ GeV}/c^2$ 1 $\frac{1}{2}$	$\approx 91.19 \text{ GeV}/c^2$ 0 1 1	$\approx 80.360 \text{ GeV}/c^2$ 1 1 1	$\approx 80.360 \text{ GeV}/c^2$ -1 1 1		
	 electron neutrino	 muon neutrino	 tau neutrino	 electron antineutrino	 muon antineutrino	 tau antineutrino	 W ⁺ boson	 W ⁻ boson			
	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$					

Figure 1.1: The classification and basic properties of fundamental particles of the standard model. I, II, and III represent the three generations of fermions. The picture is taken from Ref. [17].

1.2 Quantum Chromodynamics

The strong interaction between quarks and gluons, which bind together to form hadrons, is described by a well-known theory of Quantum Chromodynamics (QCD).

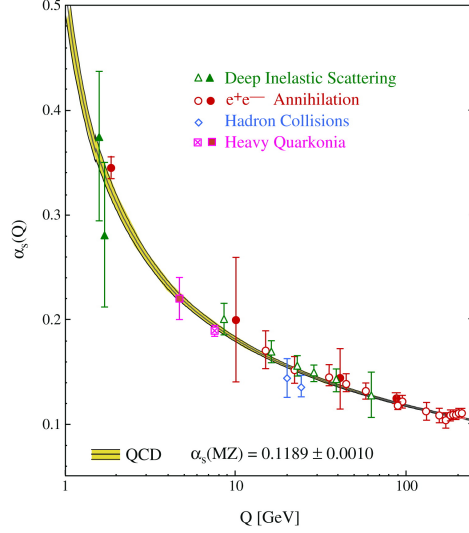


Figure 1.2: Experimental measurements of QCD running coupling constant (α_s) as a function of momentum transfer (Q). Open symbols represent (resummed) NLO, and filled symbols denote NNLO QCD calculations considered in the respective analysis. The curves are the QCD predictions. The figure is taken from Ref. [18].

The term “*chromodynamics*” in QCD comes from the fact that such interactions involve “*colour charges*” associated with quarks and gluons, analogous to Quantum Electrodynamics (QED), where interactions occur between particles carrying an electric charge. Unlike in QED, where photons do not interact with themselves, gluons can interact with other gluons due to their colour charge. *Confinement* and *asymptotic freedom* are the two distinct features of QCD that can be understood from the expression of the strong coupling constant, α_s , which is given by

$$\alpha_s \simeq \frac{12\pi}{(33 - N_f) \ln(Q^2/\Lambda_{\text{QCD}}^2)}$$

where Q^2 is the momentum transfer, N_f denotes the number of colour flavours, and Λ is a scale parameter in QCD calculations, and its value is ≈ 200 MeV [19]. The variation of α_s as a function of Q is presented in Fig. 1.2, which shows that α_s becomes large at small momentum transfers (or large distances), which means the interaction between quarks and gluons becomes stronger, and they can not be

isolated. This property is known as “*Confinement*”. Due to this property, quarks are never found in isolation but rather bound together in groups of three to form baryons (e.g., protons, neutrons) or as quark-antiquark pairs to form mesons. As also seen in Fig. 1.2, for sufficiently large momentum transfers (or short distances), the α_s becomes small, leading to weak coupling between quarks and gluons. As a consequence, quarks and gluons essentially behave as free particles. This property is called “*Asymptotic Freedom*”, discovered by David Gross, Frank Wilczek, and David Politzer in 1973 [20–22]. It was a crucial development in understanding the strong nuclear force. This asymptotic property plays an essential role in exploring the behaviour of QCD matter at extreme temperatures, such as in the early universe or in heavy-ion collisions at particle accelerators.

1.3 Deconfinement and QCD Phase Diagram

After the discovery of “*Asymptotic Freedom*”, J. C. Collins and M. J. Perry argued that at extremely high nuclear density (e.g. the centre of the neutron star), there is a possibility to produce a dense nuclear matter where quarks and gluons are never confined within hadrons but instead behave as nearly free particles [23]. This deconfined state of nuclear matter is called the quark-gluon Plasma (QGP).

Theoretical calculations from lattice QCD also suggested that the nuclear matter undergoes a phase transition from its confined state to a deconfined state of quarks and gluons at a critical temperature of $T_c \sim 170$ MeV and a critical energy density of $\epsilon_c \sim 1$ GeV/fm³ [25, 26]. The current best estimate of T_c and ϵ_c are 156.5 ± 1.5 MeV and 0.42 ± 0.06 respectively [27]. Figure 1.3 shows the temperature (T) variations of thermodynamic quantities (pressure, energy density, and entropy density) obtained from lattice QCD calculations for (2+1) quark flavours at zero baryonic chemical potential (μ_B). Here, the μ_B quantifies how the system’s energy changes due to changes in the number of baryons. There is a sharp rise of energy and entropy

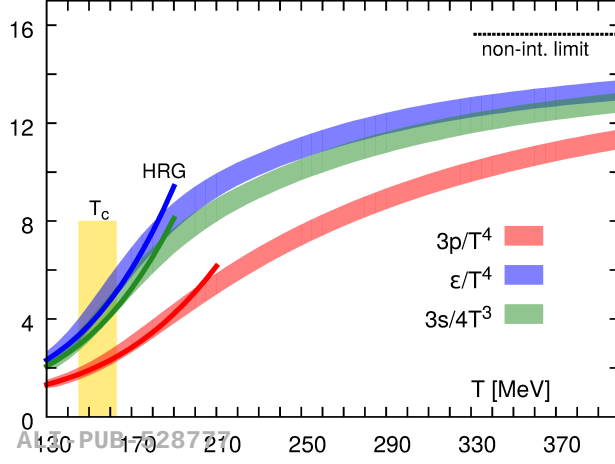


Figure 1.3: Lattice QCD calculations of thermodynamic quantities (pressure, energy and entropy density) as a function of temperature for (2+1) quark flavours at zero baryonic chemical potential ($\mu_B = 0$), as shown by different colour bands. The solid coloured lines correspond to the prediction from the Hadron Resonance Gas model, and the dashed horizontal line represents the ideal gas limit. The cross-over transition region is indicated by the vertical band. The figure is taken from Ref. [24].

density around $T = T_c$, indicating the sudden increase of degrees of freedom in the system, i.e. deconfinement from the hadron to partons. In Fig. 1.3, it is also observed that at high temperatures ($T \sim 400$ MeV), the energy density is lower than the Stefan-Boltzmann limit for ideal gas. This implies that the particles present in the system above the T_c still interact with each other.

Figure 1.4 shows a schematic representation of the phase diagram of QCD matter in terms of T vs μ_B . This diagram is not yet fully established and is under investigation by the scientific community. Lattice QCD predicts a smooth cross-over between hadron and QGP phase at a larger T and low $\mu_B (\sim 0)$ [29,30] whereas various QCD-based model calculations show that the phase transition is to be of the first order at larger μ_B and finite T [31,32]. The point in the phase diagram at which the first-order phase transition ends and the cross-over transition starts is known as the QCD critical point, indicated by a square marker. To explore the QCD phase diagram and to understand the properties of the QGP, one has to create an environment corresponding to high temperature (low μ_B) or large μ_B (smaller T) in the labora-

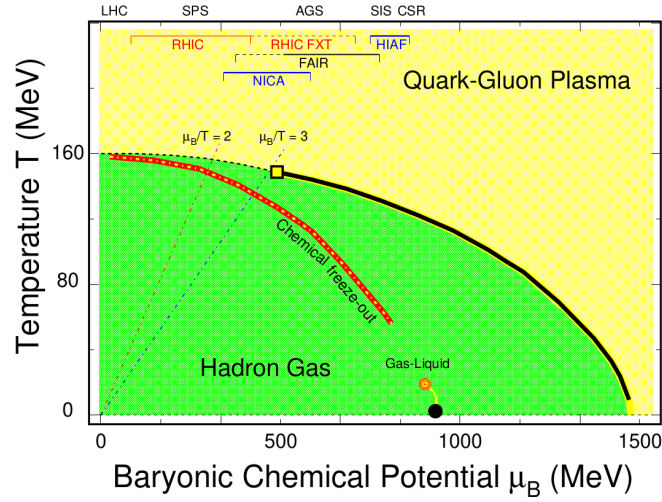


Figure 1.4: Conjectured QCD phase diagram in terms of temperature (T) versus baryonic chemical potential (μ_B). The figure is taken from Ref. [28].

tory. Collisions between different species of nuclei at various relativistic energies (in the order of GeV or TeV) can provide such extreme conditions of temperatures and energy densities and help to probe the QCD matter and its properties.

1.4 Relativistic heavy-ion collisions

As per current understanding, the QGP is believed to have existed shortly after the Big Bang. It can only be recreated at incredibly high temperature and energy densities. Relativistic heavy-ion collision is the only known experimental tool to create such extreme conditions, allowing the formation of QGP in the laboratory. In this context, several heavy-ion accelerators, e.g., Bevalac, AGS (Alternating Gradient Synchrotron), SPS (Super Proton Synchrotron), SIS18 (Schwer Ionen Synchrotron), RHIC (Relativistic Heavy Ion Collider), LHC (Large Hadron Collider), FAIR (Facility for Anti-proton and Ion Research), and NICA (Nuclotron-based Ion Collider Facility) were/are designed to explore the behaviour of the nuclear matter at extreme conditions of temperature and/or pressure. In the following, we briefly discuss the geometrical aspects and space-time evolution of heavy-ion collisions and introduce

the basic kinematic variables used in heavy-ion experiments.

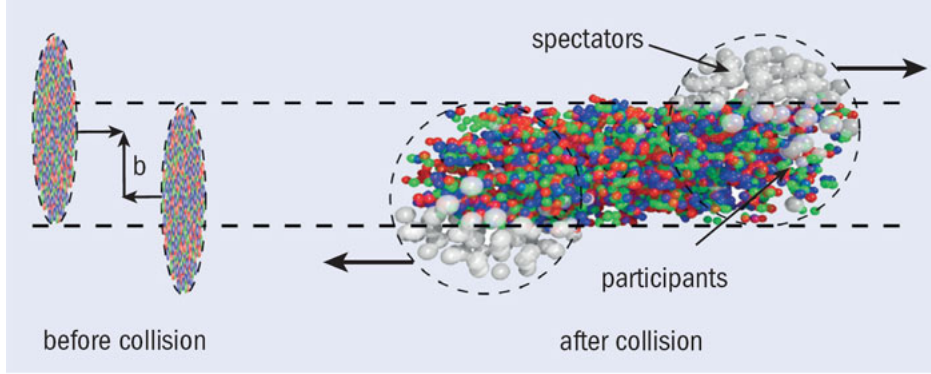


Figure 1.5: A schematic representation of relativistic heavy-ion collision. The figure is taken from Ref. [33].

1.4.1 Geometrical aspects of heavy-ion collisions

Figure 1.5 shows a geometrical representation of a collision between two nuclei at very high energy. Both projectile and target nuclei are accelerated to velocities nearly equal to the speed of light in opposite directions and are then made to collide with each other. As both nuclei travel at relativistic velocities, they become Lorentz contracted along the beam direction (z -axis) and appear as flattened or pancake-like objects. The impact parameter (b) indicates the perpendicular distance between the centre of these two colliding nuclei. The parameter b characterizes the overlap region of collisions and provides information about the centrality of the collision. The value of b can range from 0 fm, corresponding to head-on collisions, to about twice the radius of the nucleus, which corresponds to the most peripheral collisions. Depending on b values, some fractions of nucleons from both nuclei take part in interactions, which are referred to as “*participants*” (N_{part}) while some of nucleons do not participate in the collision, called as “*spectators*” ($N_{\text{spectator}} = 2A - N_{\text{part}}$, A = mass number of nucleus).

to as the QGP. After that, the QGP evolves according to the laws of relativistic hydrodynamics. As the system expands and its temperature drops down to T_c , the hadronization of the QGP medium occurs, and quarks and gluons combine to form hadrons. If the phase transition is of the first order, a mixed phase can occur where quarks, gluons, and hadrons coexist. This phase is likely to have isothermal expansion, and latent heat is used to convert quarks and gluons to hadrons. The expansion continues, and the temperature of the system further decreases, but hadrons still interact with each other both elastically and inelastically. At a temperature T_{ch} , inelastic interactions between hadrons cease, and the relative abundances of different hadron species stop changing. This point is referred to as “chemical freeze-out”. After chemical freeze-out, elastic interactions among hadrons can continue until a temperature T_{kin} , where the distance between two hadrons becomes larger than the mean free path, and hadrons stop interacting elastically. This point is known as “kinetic freeze-out” or “thermal freeze-out”. Afterwards, the particle momenta get fixed, and particles produced in the collision emerge freely from the system and travel towards the detector.

1.4.3 Kinematic variables in heavy-ion experiments

When studying relativistic heavy-ion collisions, it is essential to use kinematic variables that are either invariant under Lorentz transformations or have simple forms that allow for straightforward comparisons between different frames of reference. In the following, we first discuss the natural units used in the context of relativistic heavy-ion collisions, followed by a brief discussion about kinematic variables.

Natural units

In high-energy physics, especially in the context of ultra-relativistic collisions, natural units are often used for simplicity and convenience. In these units, certain fundamental constants, such as the speed of light (c), Planck’s constant ($\hbar$), and

Boltzmann constant (k_B), are set to unity. One can convert a quantity from SI units to natural units using the conversion factor $\hbar c = 0.1975 \text{ GeV}\cdot\text{fm}$. Thus, length and time are expressed in units of inverse energy, typically GeV^{-1} and mass or energy is measured in GeV .

Mandelstam variable

The Mandelstam variables, often denoted as s , t , and u , are fundamental quantities in high-energy particle physics. They are Lorentz-invariant quantities used to describe the kinematics of particle scattering processes.

1. Mandelstam variable s :

s is the square of the centre-of-mass energy of the collision. In other words, it is the square of the invariant mass of the colliding particles. s is a Lorentz scalar and is always positive or zero. For a process with two incoming particles with four-momenta p_1 and p_2 as shown in Fig. 1.7(a), s is given by

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

In collider experiments, both incoming particles are moving with the same velocity (energy) but in opposite directions, which means $\vec{p}_1 = -\vec{p}_2$. Therefore, centre-of-mass energy, $\sqrt{s} = (E_1 + E_2) = 2E$. In the case of fixed-target experiments, one of the incoming particles is at rest. Let us assume particle ‘2’ is at rest, which means $E_2 = m_2$. Thus, $\sqrt{s} = \sqrt{E_1^2 + 2E_1m_2 + m_2^2 - p_1^2} = \sqrt{m_1^2 + m_2^2 + 2E_1m_2}$. Hence, one can achieve more available centre-of-mass energy for new particle production in a collider experiment compared to a fixed-target experiment.

2. Mandelstam variable t :

t is the square of the momentum transfer between the two colliding particles. It is often used in the context of a scattering process. For a process with two

incoming particles with four-momenta p_1 and p_2 and outgoing particles with four-momenta p_3 and p_4 as shown in Fig. 1.7(b), t is given by

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2.$$

t can be positive or negative, depending on the scattering angle and whether momentum is transferred in the forward or backward direction.

3. Mandelstam variable u :

u is another Mandelstam variable that describes the momentum transfer in the scattering process, similar to t , as depicted in Fig. 1.7(c). Mathematically, u is given by

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2.$$

Analogous to t , u can also be positive or negative, depending on the scattering angle and the direction of momentum transfer. The u -channel scattering process is only relevant for identical final-state particles.

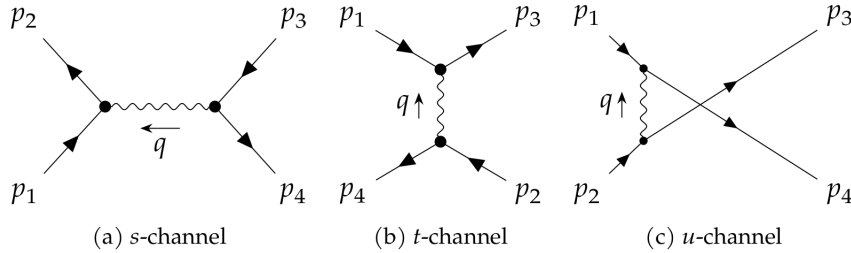


Figure 1.7: Feynman diagrams showing different channels of a $2 \rightarrow 2$ scattering process [34].

The Mandelstam variables also satisfy the relation $s + t + u = \sum m_i^2$, where m_i are the masses of the particles involved in the scattering process.

Transverse Momentum (p_T)

Transverse momentum is the component of a particle's momentum that is perpendicular to the beam axis and is defined as $p_T = \sqrt{p_x^2 + p_y^2}$, where p_x and p_y are the

momentum components in the transverse plane. p_T is a Lorentz-invariant quantity under rotations and boosts along the beam axis.

Rapidity (y)

The rapidity of a particle is defined as

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

where E and p_z are energy and z component of momentum of the particle respectively. In the non-relativistic limit, rapidity represents the velocity of the particle. The advantage of using rapidity in high-energy collisions is because of its linear transformation under Lorentz boosts. This transformation is unlike to that of velocities, which do not transform linearly under Lorentz boosts.

Pseudorapidity (η)

To measure the rapidity of a particle, one should measure two quantities of that particle, such as its energy and z -component of momentum. In many experiments, it is difficult to measure both quantities simultaneously. So, it is convenient to utilize another variable, called pseudorapidity (η), which is defined as

$$\eta = \frac{1}{2} \ln \left(\frac{p + p_z}{p - p_z} \right) = -\ln[\tan(\theta/2)],$$

where θ is the angle between the particle's momentum and beam axis. Hence, in the case of pseudorapidity, one has to measure only one quantity that is more efficient than measuring rapidity. Pseudorapidity also transforms linearly under a Lorentz transformation similar to rapidity. Pseudorapidity and rapidity are equivalent when the particle's kinetic energy is much greater than its rest mass energy.

Azimuthal angle (ϕ)

Azimuthal angle (ϕ) describes the position of a particle in the transverse plane around the beam axis for a fixed θ . Figure 1.8 shows the pictorial representation of

the angle ϕ .

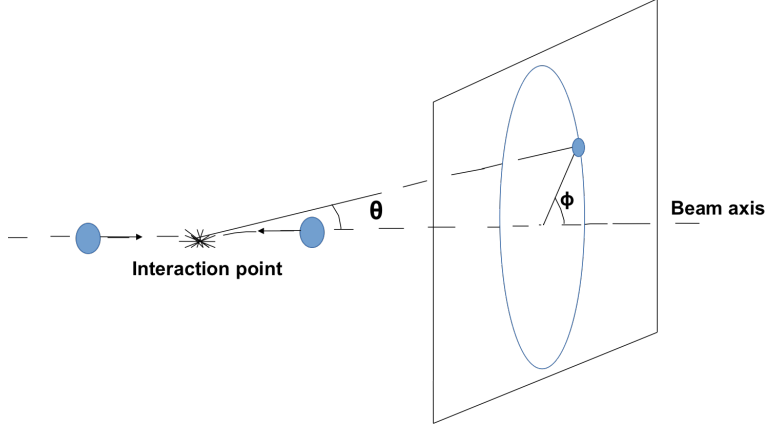


Figure 1.8: Geometry of angle θ and azimuthal angle (ϕ).

1.5 Experimental observables and signatures of QGP

Since the QGP formed in heavy-ion collisions is extremely short-lived (lifetime $\sim 10^{-23}$ s) and exists at extremely high temperature (150-160 MeV), there is no direct way to study and understand this state of matter. However, there are several experimental probes that can be used to explore the QCD matter and its properties. In the following, we briefly discuss about some of the signatures of the QGP.

1.5.1 Charged-particle pseudorapidity density at midrapidity

The formation of QGP in Pb–Pb collisions at the LHC requires certain critical values of energy density and temperature to be achieved. The most recent calculations of Lattice QCD reports $\epsilon_c = 0.42 \pm 0.06$ GeV/fm³ and $T_c = 156.5 \pm 1.5$ MeV [27]. Hence, the initial energy density and temperature are the first two key quantities that should be estimated to characterize the QGP system. First, we concentrate on the estimation of energy density. Once the collision happens, the deposited energy manifests itself in the form of particles streaming out from the collision region. The pseudorapidity density distribution, $dN_{\text{ch}}/d\eta$, of produced charged particles is one

of the basic measurements that allow us to investigate the mechanisms involved in particle production and to estimate the lower bound on the energy density [35].

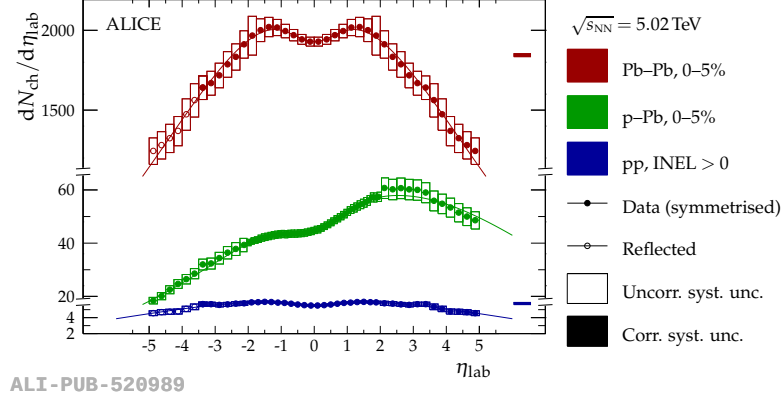


Figure 1.9: Charged-particle pseudorapidity density for minimum bias (INEL>0) pp and for the 5% most central p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The lines show fits to the data using normal distributions [35]. The figure is adapted from Ref. [35].

The energy density can usually be estimated using the conventional approach proposed by Bjorken [36]. According to ‘Bjorken formula’, the energy density can be expressed as

$$\epsilon_{Bj}(\tau) = \frac{1}{S_T \tau} \left\langle \frac{dE_T}{dy} \right\rangle, \quad (1.1)$$

where $E_T = \sqrt{p_T^2 + m^2}$ is the transverse energy, dE_T/dy is transverse energy per unit rapidity, and S_T is the transverse size of the interaction region at proper time τ . This estimate is valid for a system that is free-streaming and experiences boost-invariant longitudinal expansion but not transverse expansion.

By measuring the $dN_{ch}/d\eta$ (see Fig. 1.9) [35] and assuming that the charged-particle rapidity density (dN_{ch}/dy) follows normal distribution [38,39], one can obtain the lower bound of Bjorken energy density (ϵ_{LB}) [35] as

$$\epsilon_{LB} \tau \leq \epsilon_{Bj} \tau = \frac{1}{S_T} \langle m \rangle \sqrt{1 + a^2} \frac{1}{f_{total}} \sqrt{1 + \frac{1}{a^2 \cosh^2 \eta} \frac{dN_{ch}}{d\eta}},$$

where $a = p_T/m$, the effective transverse momentum over mass ratio, $f_{total} = 0.55 \pm 0.01$ is the fraction of charged particles out of all particles and is assumed the

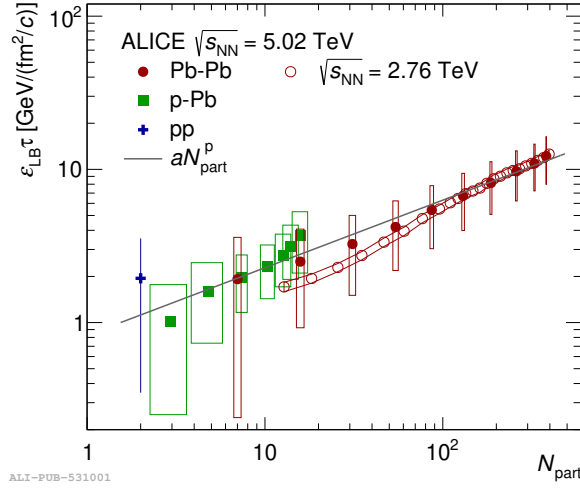


Figure 1.10: Lower bound estimate of Bjorken energy density times τ (solid markers) in pp, p-Pb, and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV as a function of N_{part} [35]. The open markers show the results obtained from direct measurements of E_T in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [37]. The figure is taken from Ref. [24].

same for all colliding systems. The f_{total} is considered to compensate for the non-measured neutral particles in the experiment. Figure 1.10 presents the resulting $\epsilon_{\text{LB}}\tau$ (solid markers) as a function of N_{part} for pp, p-Pb, and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The $\epsilon_{\text{LB}}\tau$ is found to be roughly 1 GeV/fm²c for pp and most-peripheral p-Pb collisions while for most-central Pb-Pb collisions the $\epsilon_{\text{LB}}\tau$ reaches to 10 GeV/fm²c. This value is far greater than the critical energy density predicted by LQCD. The increasing trend of $\epsilon_{\text{LB}}\tau$ is illustrated by a power-law (aN_{part}^p) with the parameter values $a = (0.8 \pm 0.3)$ GeV/fm²c and $p = 0.44 \pm 0.08$. Figure 1.10 also shows the estimate of Bjorken energy density (open markers) from earlier measurements of E_T in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [37]. The data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV have a similar trend to the earlier results.

1.5.2 Direct photon measurements

This subsection describes the estimation of temperature, another key quantity to characterize the QGP system. Experimentally, temperature can be determined by

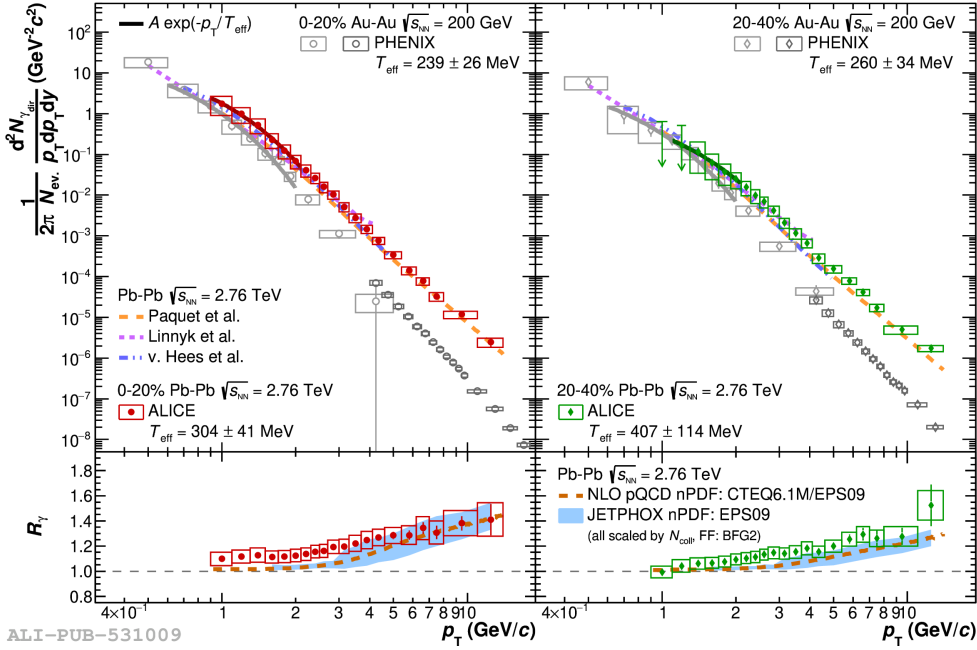


Figure 1.11: Top: direct photon spectra measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for central (left) and semi-central (right) event classes. Bottom: direct photon excess R_γ measured for central (left) and semi-central (right) Pb–Pb collisions. The figure is taken from Ref. [24].

measuring the transverse momentum distributions of direct photons (photons not arising from hadronic decays). Unlike hadrons, direct photons are originated from all stages of the collision and interact with particles only through electromagnetic interactions. Hence, photons are mostly unaffected due to their large mean free path and are expected to deliver information on conditions at the time of their production. *Prompt* direct photons are originated from the initial hard scatterings and provide the information on parton distribution inside the nuclei [40]. *Thermal* direct photons are emitted from the deconfined QGP matter and carry the information of temperature, collective flow and space-time evolution of the medium [41]. Different p_T regions are dominated by photons produced at various stages of the collision. The low- p_T region ($p_T \leq 3$ GeV/c) is dominated by *thermal* photons and exhibits an approximately exponential behaviour, $d^2N_{\gamma_{\text{dir}}}/(p_T dp_T dy) \propto e^{-p_T/T_{\text{eff}}}$, where T_{eff} represents the inverse logarithmic slope and characterizes the effective temperature

of the fireball created in the collision. On the other hand, the high- p_T region ($p_T \geq 5$ GeV/ c) is dominated by *prompt* photons and follows power-law behaviour [42].

Figure 1.11 (top) shows the invariant yield of direct photons measured for central (0–20%) (left) and semi-central (20–40%) (right) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [24, 42]. The results are compared to PHENIX measurements for similar centrality classes in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [43, 44]. The photon p_T -spectra is found to be harder at the LHC energy compared to that measured at the RHIC energy. In the low- p_T region, an exponential fit (shown by solid lines in Fig. 1.11) results to $T_{\text{eff}} = (304 \pm 41)$ MeV for central and $T_{\text{eff}} = (407 \pm 114)$ MeV for semi-central Pb–Pb collisions. The comparison between ALICE and PHENIX data shows that the effective temperature increases from RHIC energy to LHC energy.

Therefore, the energy density (see Sec. 1.5.1) and the temperature reached in heavy-ion collisions at both RHIC and LHC are well above the ϵ_c and T_c predicted by LQCD for the formation of QGP.

1.5.3 Jet quenching

Jets are collimated bunches of hadrons produced from fragmentation and hadronization of hard scattered partons in high energy collision. When these hard scattered partons pass through the QGP medium, they interact strongly with the medium partons due to their colour charges and lose energy through collisions and gluon radiations. This phenomenon of energy loss of the high- p_T partons inside the medium is termed as “*Jet quenching*”. Due to this phenomenon, the jet production in heavy-ion collisions is expected to be suppressed compared to that in pp collisions at the same $\sqrt{s}$, which can be studied in terms of nuclear modification factor (R_{AA}). The R_{AA} is defined as

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{Pb-Pb}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{\text{pp}}}, \quad (1.2)$$

where N_{evt} is the number of Pb–Pb events for a chosen centrality interval, N_{jet} is the jet yield in Pb–Pb collisions, T_{AA} is mean nuclear thickness function, and σ_{jet} is jet cross-section in pp collisions. If the nucleus-nucleus collisions would have been a simple superposition of the pp collisions, the R_{AA} would have been unity. But, in Fig. 1.12, we observe $R_{\text{AA}} < 1$, indicating a clear suppression of jet production in central (0–10%) Pb–Pb collisions relative to that in pp collisions.

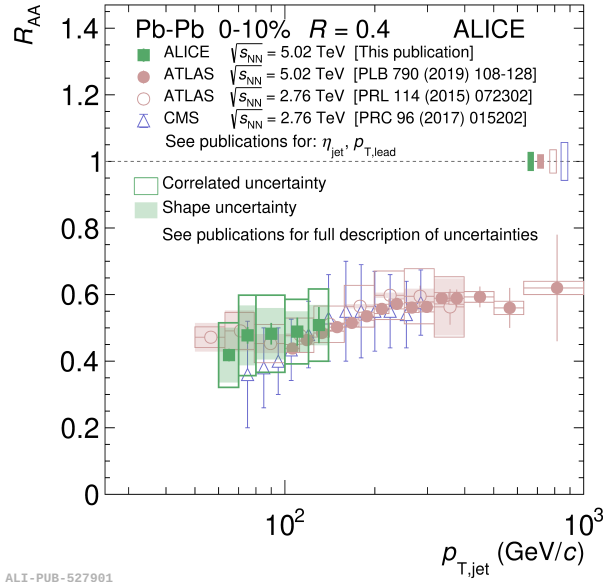


Figure 1.12: Measurements of jet R_{AA} as a function of jet- p_{T} for central (0–10%) Pb–Pb collisions at the LHC energies. The figure is taken from Ref. [45].

1.5.4 Strangeness enhancement

The enhancement of the production of strange hadrons in heavy-ion collisions relative to pp collisions was proposed as one of the signatures of QGP [46]. The strange particle production is of particular interest because strange quarks are not initially present in the colliding nuclei; hence, the formation of strange quarks occurs only as a byproduct of the collisions. Strange quarks are produced through hard scattering processes, which include flavour creation ($q\bar{q} \rightarrow s\bar{s}$, $gg \rightarrow s\bar{s}$), flavour excitation ($qs \rightarrow qs$, $gs \rightarrow gs$), and gluon splittings ($g \rightarrow s\bar{s}$). Due to large gluon density in

the QGP medium, the creation of $s\bar{s}$ pairs from the gluon channel dominates over the annihilation of quark (q) and anti-quark ($\bar{q}$). As a result of the dominance of the gluon channel, strange hadron production is enhanced in the presence of the QGP medium in AA collisions compared to what is observed in pp collisions. Strangeness enhancement was first discovered in 1988 by the CERN fixed-target NA35 experiment [47], subsequently confirmed by CERN SPS [48–53], RHIC [54–56] and later at the LHC [57]. As an example, Fig. 1.13 shows the clear enhancement of strange particle (K^- , ϕ , $\bar{\Lambda}$, Ξ) production in Cu–Cu and Au–Au collisions relative to that in pp collisions [58].

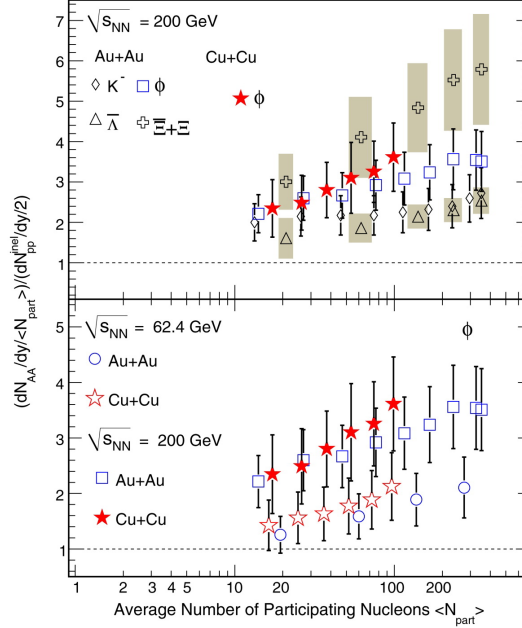


Figure 1.13: Top panel: The ratio of the yields of K^- , ϕ , $\bar{\Lambda}$, and Ξ normalized to $\langle N_{\text{part}} \rangle$ in Cu–Cu and Au–Au collisions to corresponding yields in pp collisions as a function of $\langle N_{\text{part}} \rangle$. Bottom panel: The same ratio only for ϕ mesons in Cu–Cu and Au–Au collisions at $\sqrt{s_{\text{NN}}} = 62.4$ and 200 GeV. The figure is taken from Ref. [58].

1.5.5 J/Ψ suppression

J/Ψ mesons are composed of a charm quark (c) and an anticharm quark ($\bar{c}$). Because charm quarks are relatively heavy, they are produced early in the collisions

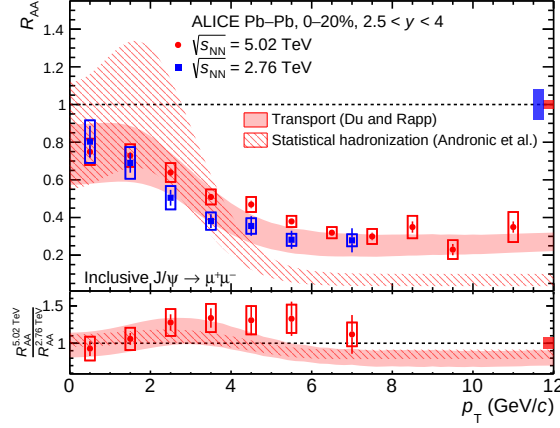


Figure 1.14: Measurements of R_{AA} of J/Ψ as a function of p_T in central (0–20%) Pb–Pb collisions at the LHC energies. The figure is taken from Ref. [59].

through hard scatterings. They can interact with the entire system that is formed in the collision, including the QGP. The potential between the $c\bar{c}$ pair is expected to be modified due to the presence of colour charges in the QGP medium. This modification is analogous to the Debye screening or shielding effect in QED, where the presence of surrounding charges reduces the strength of the potential between charged particles. The modification of the $c\bar{c}$ pair potential can provide insights into the properties of the QGP. In QCD vacuum, the potential between $c\bar{c}$ pair can be expressed as

$$V(r) = \frac{a}{r} + kr, \quad (1.3)$$

where a is the coupling constant for coulombic interaction, k is the string tension, and r is the distance between c and $\bar{c}$. In Eq. 1.3, the second term vanishes for the QGP medium when the temperature of the system reaches T_c . In presence of QGP, the potential between $c\bar{c}$ pair is modified as $V(r) = \frac{a}{r} e^{-\frac{r}{\lambda_D}}$, where λ_D is Debye length which depends on T . In 1986, Matsui and Satz first proposed that the λ_D in the QGP could become smaller than the size of the J/Ψ radius [60]. As a result, the bound state of $c\bar{c}$ can not form, suppressing the J/Ψ production in the presence

of QGP. Experimental observations of J/Ψ suppression were first seen at the CERN SPS [61] and later confirmed at the RHIC [62, 63] and the LHC [59, 64]. As an example, Fig. 1.14 reports the ALICE measurements of R_{AA} of J/Ψ as a function of p_T for central (0–20%) Pb–Pb collisions at the LHC energies [59]. We observe a clear suppression of J/Ψ production in Pb–Pb collisions relative to that in pp collisions.

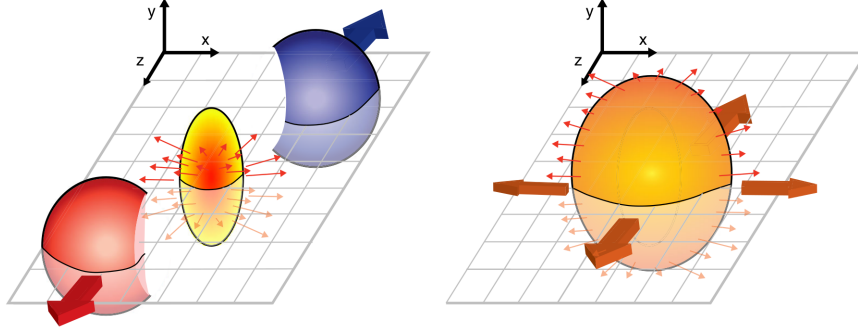


Figure 1.15: Schematic diagrams displaying (left) the initial overlap region and (right) the generated spatial anisotropy due to this overlap region.

1.5.6 Azimuthal anisotropy

In non-central heavy-ion collisions, the overlap region of two incoming nuclei is spatially asymmetric with an almond-like shape as depicted in Fig. 1.15. This asymmetry results in a momentum anisotropy among the final-state hadrons, which means that particles are preferentially emitted in certain directions. This momentum anisotropy then manifests as anisotropy in the azimuthal angle (ϕ) of the produced particles with respect to the reaction plane. The reaction plane is a geometric plane defined by the impact parameters (the relative transverse positions of the colliding nuclei) and the beam direction (the direction of the incoming particles). The angle ϕ measures the angle of emission of a particle in the plane perpendicular to the beam direction. The azimuthal distribution of produced particles can be expressed as [65]

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)] \right), \quad (1.4)$$

where Ψ_r is the reaction plane angle and v_n is the n -th harmonic coefficient. The first coefficient (v_1) is called *directed flow*, the second coefficient (v_2) is called *elliptic flow*, the third coefficient is known as *triangular flow*, and so on. While v_2 is primarily associated with the almond-shaped overlap region of the colliding nuclei, higher order coefficients ($n > 2$) are related to fluctuations in the initial distributions of nucleons within the overlap region, reflecting initial state density fluctuations.

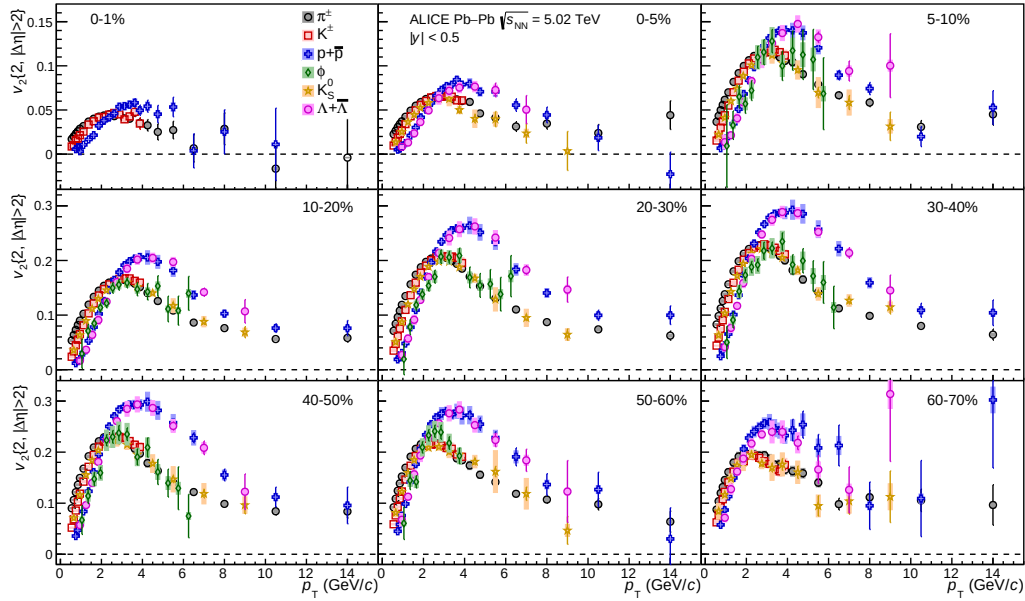


Figure 1.16: Elliptic flow coefficient (v_2) for different hadron species as a function of p_T for various centrality intervals in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [66].

Figure 1.16 shows the measurements of v_2 for charged particles as a function of p_T in various centrality classes of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [66]. As collision centrality decreases, we observe that the magnitude of v_2 increases and reaches the maximum value for 40–50% Pb–Pb collisions. In peripheral collisions (50–60% and 60–70%), v_2 decreases, suggesting that the system in peripheral collisions has a shorter lifetime that cannot generate larger v_2 . In other words, the anisotropy is less pronounced in peripheral collisions.

The v_2 is sensitive to the ratio of shear viscosity to entropy density (η/s) [67–71]. The large value of η/s suppresses the collective flow and reduces the magnitude of

v_2 . By comparing experimental results of v_2 and higher-order flow coefficients with the results of hydrodynamic model calculations, one can estimate the η/s of the medium created in heavy-ion collisions. At the critical temperature, the estimated η/s is found to be compatible with the theoretical lower limit of $1/4\pi$ [72] that suggests that the QGP behaves as a nearly perfect fluid [73].

1.6 Novelty of Proton–Proton and Proton–Lead collisions

Proton–proton (pp) and proton–lead (p–Pb) collisions are primarily studied to provide a crucial reference for interpreting the effects of the QGP formation observed in heavy-ion collisions. However, measurements in pp and p–Pb collisions are also interesting on their own right.

The pp collisions provide a controlled environment to validate and test predictions of the Standard Model of particle physics. This includes studying the interactions of quarks and gluons, electroweak processes, and precise measurements of particle properties, such as masses, lifetimes, and production cross-sections. Historically, pp collisions have played a pivotal role in the discovery of new particles. For instance, W and Z bosons in 1983 [74, 75] and Higgs boson in 2012 [15, 16] were discovered through pp ($p\bar{p}$) collisions. The pp collisions also help to test the perturbative QCD theory by studying processes with high transverse momentum transfer [45, 76–80]. The dead cone effect, one of the fundamental feature of QCD is also experimentally observed for the first time in pp collisions [81].

In p–Pb collisions, protons from one beam collide with lead nuclei from the other. This creates an asymmetric system with higher energy density in the lead nucleus. Studying such asymmetric system helps to understand the interplay between initial-state effects and final-state phenomena. Among initial-state effects, an important role is played by transverse momentum (k_T) broadening of initial- and final-state partons [82], and by the modification of the parton distributions functions (PDFs)

in bound nucleons compared to those of free nucleons, leading in particular to a reduction of parton densities (shadowing) at small parton fractional momentum x [83]. It is harder to study nuclear PDFs than proton PDFs. By itself, it is interesting, and people wish to learn about the nuclear structure. So, the study of p-Pb collisions is important and relevant for our understanding in this context.

Traditional wisdom holds that pp and p-Pb collisions are too dilute to produce a fluid-like state. A larger volume and longer thermalization time are required to form such a state than what a pp or a p-Pb collision can offer. However, in the last decade, experimental measurements [84–95] and theoretical predictions [96–108] at the LHC energies, particularly in high-multiplicity pp and p-Pb collisions, have shown intriguing QGP-like signals (e.g. collective flow, ridge-like structure, and strangeness enhancement) that challenge the conventional understanding. The first surprise was when the CMS Collaboration in September 2010 reported the evidence of long-range near-side correlations in high-multiplicity pp collisions [84]. Thereafter, similar observations were found in p-Pb collisions [87–91].

These novel observations in pp and p-Pb collisions suggest that there is still much to learn about the system which is formed after the collision and the underlying mechanisms of particle production. Multiplicity and pseudorapidity distributions of the produced particles, providing information about the particle production mechanisms, are some of the important global observables to be studied in this context.

1.7 About this thesis work

This thesis reports the study of multiplicity and pseudorapidity distributions of inclusive photons and charged particles in pp and p-Pb collisions utilizing the data recorded by the ALICE experiment. Inclusive photons are measured using the Photon Multiplicity Detector (PMD) at forward rapidity ($2.3 < \eta < 3.9$). On

the other hand, the charged-particle production is studied over a kinematic range $-3.4 < \eta < 5.1$ using the Silicon Pixel Detector (SPD) and the Forward Multiplicity Detector (FMD). The objectives of multiplicity measurements are briefly discussed below.

The multiplicity of the produced particles in an interaction is one of the most fundamental measurements for event characterization and the proper understanding of the physics processes governing particle production. Two important observables related to multiplicity are (a) pseudorapidity distribution ($dN/d\eta$), which gives the average number of particles produced in an interaction per unit pseudorapidity, and (b) multiplicity distribution, which represents the probability distribution $P(N)$ to have an interaction in which N particles are produced. These observables are very sensitive to variables such as colliding species, centre-of-mass energy, initial energy density, and collision centrality. These observables cannot be derived from the QCD Lagrangian since the integrated yield of particle production is mostly dominated by soft QCD interactions, i.e. small momentum transfer (Q^2) processes for which the strong coupling constant is large (see Fig. 1.2). Therefore, perturbative methods are challenging to apply, and instead of that, various phenomenological approaches can be used. Multiplicity measurements are very important since they put constraints on the description of these phenomenological models, which are also the basis of Monte Carlo event generators.

The mechanisms involved in particle production, e.g. in pp collisions, can be categorized as (a) *Elastic*, and (b) *Inelastic (INEL)* processes. In *Elastic* processes, both protons emerge intact after the collisions and no new particles are produced. The *INEL* processes, which are responsible for particle production in pp collisions, can be classified as diffractive and non-diffractive (ND) interactions. The diffractive interactions can be of two types: single-diffractive (SD) and double-diffractive (DD). According to Regge theory [109], diffractive interactions occur via the exchange of Pomerons. In SD processes, the exchanged Pomeron interacts, and one of the

colliding protons breaks up, producing particles at high rapidities while the other colliding proton passes uninfluenced at the beam rapidity. In DD processes, both the colliding protons are excited and break up, producing particles at positive and negative rapidities. In ND processes, parton-parton interactions occur, and more particles are produced. Particles are largely produced at the midrapidity region, falling steeply towards higher rapidities.

However, it is very difficult to distinguish these physics processes experimentally; therefore, the results obtained by the ALICE experiment are reported for two combinations. One is *INEL*, which contains all inelastic processes (SD + DD + ND), and the other one is non-single diffractive (NSD), which contains DD and ND processes.

There are various theoretical models and concepts that have been developed to explain the multiplicity distribution of the final-state particles. The multiplicity distribution is expected to be described by a Poisson distribution if the particle production mechanisms are uncorrelated. However, the multiplicity distribution does not follow such expectation, thus indicating correlations in the production of particles. In 1969, Richard P. Feynman postulated that the mean multiplicity ($\langle N \rangle$) of any kind of particle rises logarithmically with $\sqrt{s}$, i.e., $\langle N \rangle = \ln \sqrt{s}$ [110]. This postulate is known as the Feynman scaling. This postulate led to the idea of KNO (Koba, Nielsen, and Olesen) scaling in 1972 [111] which states that $\langle N \rangle P(N) = \Psi(N/\langle N \rangle)$, where $\Psi(N/\langle N \rangle)$ is an energy independent function. This scaling property indicates that the multiplicity distributions at different energies must fall onto the same curve when plotted as a function of $N/\langle N \rangle$. The experimental measurements in pp ($p\bar{p}$) collisions at the LHC energies [112–119] together with the data at lower energies [120–129] reveal that the mean charged-particle multiplicity at midrapidity ($|\eta| < 0.5$) can be represented by a power law of s , thereby rejecting logarithmic dependence on s as postulated by Feynman. In addition, the KNO scaling is found to be violated for inelastic pp collisions in full phase space. On the other hand, for NSD pp collisions, the scaling is still found to be present in limited central pseudorapidity

intervals; however, it is broken for the measurements in full phase space.

During 1985-86, the UA1 Collaboration reported that the multiplicity distributions of charged particles in pp collisions can be explained by a Negative Binomial Distribution (NBD) [130, 131]. The functional form of NBD is

$$f_{\text{NBD}}(n; \langle n \rangle, k) = \frac{\Gamma(n+k)}{\Gamma(k)\Gamma(n+1)} \frac{(\langle n \rangle/k)^n}{(1 + \langle n \rangle/k)^{n+k}}, \quad (1.5)$$

where $\langle n \rangle$ (the mean multiplicity) and the parameter k (affect the shape of the distribution) are found to increase and decrease with $\sqrt{s}$, respectively. $k = 1$ means a geometric (exponential) distribution and $k^{-1} = 0$ denotes a Poisson distribution. However, the measurements at higher $\sqrt{s}$ and for larger pseudorapidity intervals could not be reproduced with a single NBD [113, 115, 132]. Combinations of two NBDs have provided a better parameterization of the data at the LHC energies [115, 132, 133]. This parameterization assumes that there are two classes of events: events with and without minijets or jets (called semihard and soft, respectively) that are contributing to the particle production. Furthermore, for nucleus–nucleus collisions, the $dN/d\eta$ with collision centrality can be expressed in terms of N_{part} (the number of participating nucleons) and N_{coll} (the number of binary collisions) to shed light on the relative contributions to particle production from hard scatterings and soft processes.

1.7.1 Study of inclusive photon production

In high-energy collisions, photons are produced from all stages of the collisions. They do not undergo strong interactions and, therefore, contain information about the collision history. Since inclusive photons mostly originate from decays of neutral pions, measurement of inclusive photon multiplicity is complementary to charged-particle measurement. A comparative study of charged particles and inclusive photons can reveal possible similarities and differences in the underlying production mechanisms

for charged and neutral particles.

Note that the underlying mechanisms of particle production could be different in different regions of pseudorapidities. At the RHIC energies, it has been observed in Au–Au collisions that the scaling of the produced particles with N_{part} and N_{coll} behave differently at mid and forward pseudorapidities [134–136]. The limiting fragmentation (LF)¹ behaviour of particle production is observed to be centrality and energy independent for photons whereas for charged particles it is found to be energy independent and centrality dependent in Au–Au collisions at forward pseudorapidity at RHIC [135, 136]. Moreover, at the LHC energies, the mean charged-particle multiplicity at midrapidity ($|\eta| < 0.5$) in pp collisions is found to follow a power law dependence on $\sqrt{s}$ [113–115] whereas the mean multiplicity of inclusive photons at forward rapidity ($2.3 < \eta < 3.9$) can be described by both a logarithmic and a power law dependence with $\sqrt{s}$ [137]. The measurement of photon multiplicity, particularly in asymmetric p–Pb collisions, the major part of this thesis work, will extend our understanding in this context.

Measurements in p–Pb collisions are equally important because the particle production could also be different in proton-going and lead-going direction [138–140]. The partons from the proton-going side are expected to undergo multiple scattering while interacting with the Pb-nucleus, whereas those on the Pb-side are likely to be impacted by nuclear effects such as nuclear shadowing. The study of photon production in p–Pb collisions for both proton-going and lead-going directions will shed light on this and provide valuable input for various particle production models to understand photon production mechanisms.

¹According to the hypothesis of LF, the observed pseudorapidity density of particle as a function of $\eta' = \eta - y_{\text{beam}}$ approaches a limiting value in the fragmentation region even if the colliding energy is increased.

1.7.2 Charged-particle multiplicity distributions

At the LHC, charged-particle multiplicity distributions ($P(N_{\text{ch}})$) reported to date are from pp collisions [113–115, 132, 137, 141–146]. There are no experimental measurements (at the LHC) of fully corrected $P(N_{\text{ch}})$ in p–Pb and Pb–Pb collisions. In this thesis, we have attempted for the first time to study $P(N_{\text{ch}})$ not only in p–Pb collisions but also over a wide pseudorapidity range ($-3.4 < \eta < 5.1$), the widest possible among the four large LHC experiments. This analysis is challenging because of the limitations of the unfolding method for the correction of data in a large range of multiplicities. This analysis is the benchmark for the measurement of $P(N_{\text{ch}})$ in Pb–Pb collisions and essential input for tuning theoretical models and Monte Carlo event generators to understand charged-particle production mechanisms.

1.8 Organization of this thesis

This thesis is organized as follows: Chapter 1 introduces theoretical aspects of studying relativistic collisions of proton–proton, proton–lead, and heavy-ions and discusses the motivation of this thesis work. Chapter 2 presents a brief overview of the LHC and the ALICE detector sub-systems. Chapter 3 aims to present and discuss the analysis techniques and methods used to study the production of inclusive photons at forward pseudorapidity in pp and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In this chapter, we report the multiplicity and pseudorapidity distributions of inclusive photons and compare the results with charged-particle measurements and theoretical predictions from Monte Carlo event generators. Chapter 4 describes the measurement of primary charged-particle multiplicity distributions over a wide range of pseudorapidities in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Chapter 5 summarizes the work presented in this thesis.

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Chapter 2

The Experimental Setup

This chapter introduces the facilities and experimental setup used in my research work. My thesis work utilizes the data obtained using the ALICE experimental setup [1, 2] at the Large Hadron Collider (LHC) [3–5] facility at CERN, Geneva. An overview of the collider facility, the LHC and the sub-detector systems of the ALICE experiment is presented in this chapter.

2.1 The Large Hadron Collider (LHC)

The LHC at CERN is a 26.7 km long synchrotron accelerator situated on the border of Switzerland and France in Geneva. It is built in the existing tunnel previously used by the Large Electron-Positron (LEP) collider and positioned between 45 meters and 170 meters below the Earth’s surface. The LHC comprises of two separate rings, each with counter-rotating beams of particles. This “two-in-one” design is achieved through superconducting magnets, enabling the beams to move in opposite directions. To generate the required magnetic fields of 8.33 T, the superconducting magnets are cooled to an extremely low temperature of 1.9 Kelvin using superfluid helium. The LHC can collide protons with protons, reaching energies of up to 7 TeV per beam, resulting in a total collision energy of $\sqrt{s} = 14$ TeV. Additionally, the LHC has the capability to accelerate heavy ions such as lead (Pb). As of the current status, the LHC has reached collision energies of $\sqrt{s} = 13$ TeV for proton–proton (pp) collisions, $\sqrt{s_{\text{NN}}} = 8.16$ TeV for proton–lead (p–Pb) collisions, and $\sqrt{s_{\text{NN}}} = 5.02$ TeV for lead–lead (Pb–Pb) collisions. Protons and heavy ions are accelerated in bunches. For protons, each bunch consists of approximately 10^{11} protons, with a maximum of 2808 bunches per beam. In the case of Pb ions, the number of bunches per beam is 592, and each bunch contains 7×10^7 nuclei [5]. Before reaching the LHC, protons or heavy ions undergo pre-acceleration through several stages. This involves progressively increasing their energy levels to prepare them for injection into the LHC. Figure 2.1 shows the schematic of the LHC accelerator complex [6]. Initially sourced from a bottle of hydrogen gas, protons undergo a process where they are stripped of their electrons. Stripped protons are then injected into the Linear Accelerator (LINAC2), where protons are accelerated to an energy of 50 MeV. The accelerated protons from LINAC2 are further boosted in energy at the Proton Synchrotron Booster (PSB) to reach 1.4 GeV. The protons are then directed to the Proton Synchrotron (PS), where they undergo additional acceleration and

gain an energy of 25 GeV. The accelerated protons are subsequently fed into the Super Proton Synchrotron (SPS), which increases their energy to 450 GeV. The protons, with an energy of 450 GeV, are finally injected into the LHC.

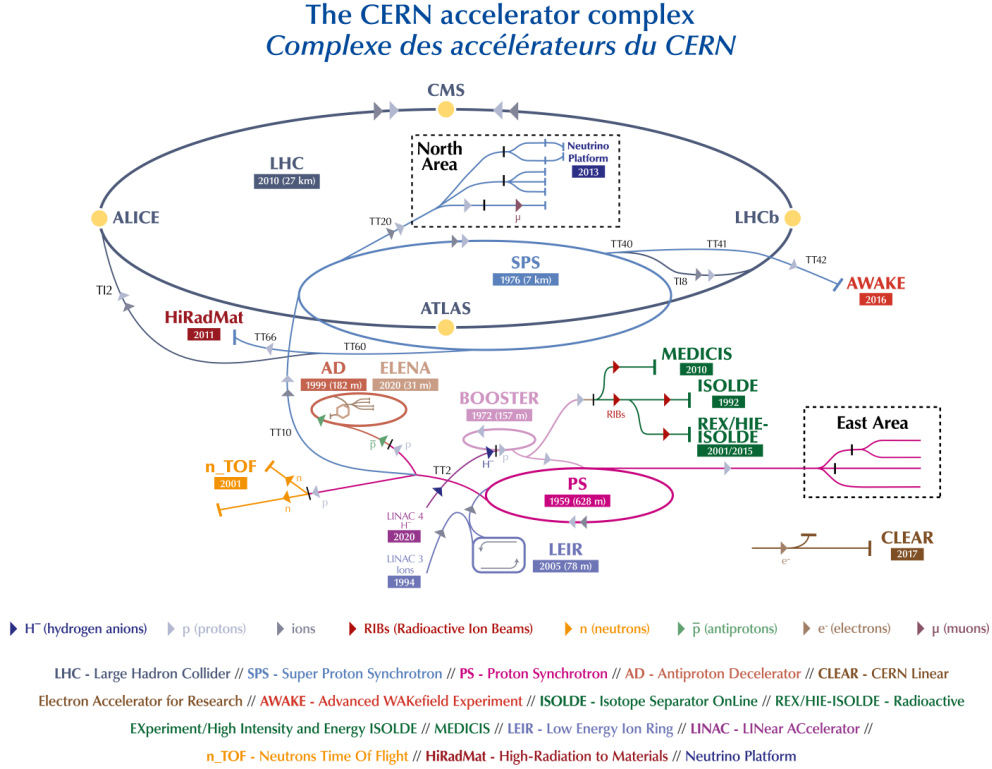


Figure 2.1: Scheme of the CERN accelerator complex [6]. The dark blue line in the scheme represents the LHC. Smaller accelerators, part of the pre-acceleration stages, are used to accelerate ions before they are injected into the LHC. Four major experiments (ALICE, ATLAS, CMS, and LHCb) are located at the interaction points shown by yellow dots.

As shown in Fig. 2.1, the LHC features four interaction points marked by yellow dots. Each of these points is equipped with a large detector system associated with specific experiments: A Large Ion Collider Experiment (ALICE) [1], Compact Muon Solenoid (CMS) [7], A Toroidal LHC ApparatuS (ATLAS) [8], and LHC beauty experiment (LHCb) [9]. ATLAS and CMS are general-purpose detectors and have similar scientific goals. They are designed to investigate various phenomena, from Higgs boson to searches for new particles, supersymmetry, and potential

extra dimensions. The ALICE, on the other hand, is a dedicated experiment for the study of heavy-ion collisions, however, it is also suited for the study of proton–proton and proton–nucleus collisions. The LHCb is specialized in studying rare decays of the beauty quark and the phenomena of charge parity violation. Smaller experiments such as TOTEM (TOTal Elastic and diffractive cross section Measurement) [10], LHC forward (LHCf) [11], and Monopole and Exotics Detector At the LHC (MoEDAL) [12] share the interaction points of ATLAS, CMS, and LHCb, expanding the capabilities of the LHC and covering a broader range of scientific objectives. The data analyzed in this thesis work comes from the ALICE experiment. The following section provides further details on the ALICE experiment and its objectives.

2.2 A Large Ion Collider Experiment (ALICE)

The primary aim of the ALICE experiment is to investigate and understand the properties of quark-gluon plasma (QGP) by studying the collisions of heavy-ions (AA) at ultra-relativistic energies. The QGP is a new state of QCD matter which is believed to have existed microseconds after the big bang. Simultaneously, the ALICE also study the physics of pp and p–Pb collisions. The study of pp and p–Pb collisions is primarily performed to understand the underlying collision dynamics in these colliding systems and to disentangle between initial-state effects and the final-state medium effects observed in AA collisions. In addition, in recent years, the study of pp and p–Pb collisions has acquired importance and interest due to the observed QGP-like effects in these collisions at the LHC energies. The heavy-ion collisions produce a large number of charged particles, which are challenging to track. The ALICE detector is optimized to measure the average charged-particle pseudorapidity density ($\langle dN_{\text{ch}}/d\eta \rangle$) at midrapidity 4000 but tested with simulations up to 8000 [1].

Figure 2.2 shows a schematic of the ALICE detector system. The ALICE, consisting of eighteen sub-detectors, has a dimension of $16 \times 16 \times 26 \text{ m}^3$ and a weight of $\sim 10000 \text{ t}$, similar to the weight of the Eiffel Tower in Paris. The ALICE is capable of measuring a large dynamic momentum range, providing a robust particle identification (PID) from $p_T \sim 0.15 \text{ GeV}/c$ to $p_T \sim 20 \text{ GeV}/c$ [13]. It also has excellent capabilities to reconstruct the primary and secondary vertices, e.g. it achieves a resolution of $\sim 100 \mu\text{m}$ for studying the 2- and 3-prong decays of D mesons. The ALICE detector system can be divided into three categories: central barrel detectors, forward detectors and MUON spectrometer. A brief overview of the different sub-detectors is outlined in the following sections.

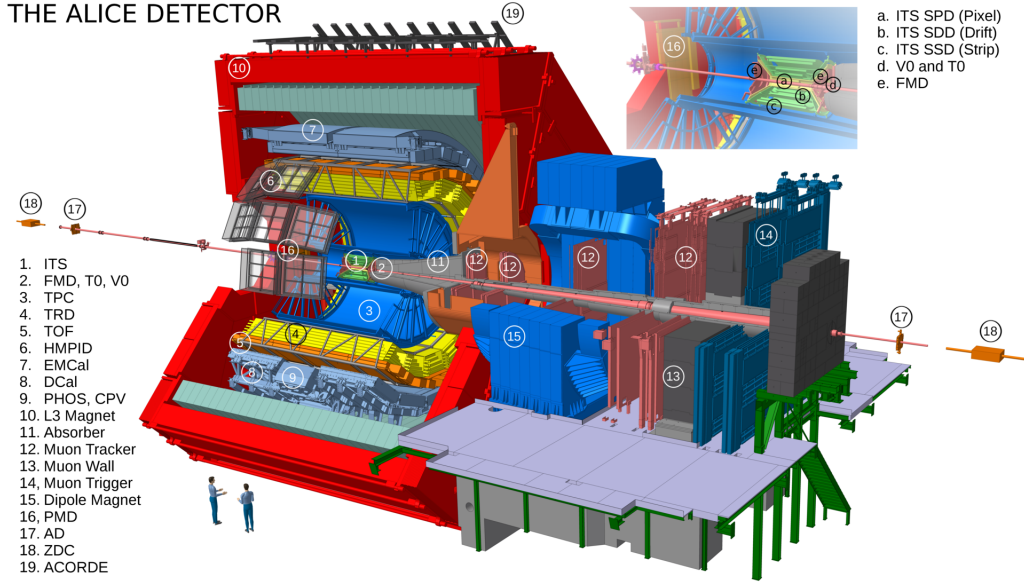


Figure 2.2: The ALICE experiment at the CERN LHC [13].

The ALICE detector system follows a right-handed orthogonal Cartesian system with point of origin $(x, y, z) = (0, 0, 0)$ at the nominal interaction point (IP) [14]. The z axis is directed along the beam line. The positive (negative) z direction corresponds to the forward (backward) direction, also labelled as “A-side” (“C-side”) of the ALICE setup. The x axis is perpendicular to the z axis, aligned with the local horizontal. The positive x axis is from the point of origin toward the centre

of the LHC, and the negative x axis is from the point of origin outward. The y axis is perpendicular to both x and z axes. The positive y axis is pointing upward from the IP, and the negative y axis is directed downward from the IP.

Table 2.1: The acceptance and position of each of the central barrel detectors [2]. Here, r is the transverse coordinate measured with respect to the IP.

Detector	η in polar	ϕ in azimuth	Position (in cm)	Main Purpose
ITS				
SPD	$ \eta < 2.0$	$0^\circ < \phi < 360^\circ$	$r = 3.9$	tracking, vertex
	$ \eta < 1.4$	$0^\circ < \phi < 360^\circ$	$r = 7.6$	tracking, vertex
SDD	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	$r = 15.0$	tracking, PID
	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	$r = 23.9$	tracking, PID
SSD	$ \eta < 1.0$	$0^\circ < \phi < 360^\circ$	$r = 38.0$	tracking, PID
	$ \eta < 1.0$	$0^\circ < \phi < 360^\circ$	$r = 43.0$	tracking, PID
TPC	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	$85 < r < 247$	tracking, PID
TRD	$ \eta < 0.8$	$0^\circ < \phi < 360^\circ$	$290 < r < 368$	tracking, $e^\pm$ id
TOF	$ \eta < 0.9$	$0^\circ < \phi < 360^\circ$	$370 < r < 399$	PID
HMPID	$ \eta < 0.6$	$1^\circ < \phi < 59^\circ$	$r = 490$	PID
PHOS	$ \eta < 0.125$	$220^\circ < \phi < 320^\circ$	$460 < r < 478$	photons
EMCal	$ \eta < 0.7$	$80^\circ < \phi < 187^\circ$	$430 < r < 455$	photons and jets
DCal (6 modules)	$0.22 < \eta < 0.7$	$260^\circ < \phi < 320^\circ$	$430 < r < 455$	photons and jets
DCal (2 modules)	$ \eta < 0.7$	$320^\circ < \phi < 327^\circ$	$430 < r < 455$	photons and jets
ACORDE	$ \eta < 1.3$	$30^\circ < \phi < 150^\circ$	$r = 850$	cosmics

2.3 Central Barrel detectors

The central barrel of ALICE mainly consists of tracking detectors (ITS, TPC, TRD, TOF, and HMPID) and electromagnetic calorimeters (PHOS and EMCal). All these detectors are embedded inside a solenoid magnet. The magnet is named ‘L3’ because it is reused from the L3 experiment at Large Electron Positron Collider (LEP). The magnet provides a magnetic field of 0.5 T that allows to bend the tracks of charged particles, which in turn helps in analyzing and measuring the momentum of these

particles. Apart from that, an array of scintillators (ACORDE) is placed on top of the magnet and used to trigger on cosmic rays. The position, acceptance and purpose of each of the central barrel detectors are summarized in Table 2.1.

2.3.1 Inner Tracking System (ITS)

The Inner Tracking System (ITS) [1, 15] of ALICE is the closest detector to the beam pipe, and its layout is shown in Fig. 2.3. The ITS is composed of six layers of cylindrical silicon detectors: the two innermost layers are Silicon Pixel Detectors (SPD), followed by two layers of Silicon Drift Detectors (SDD), and the two outermost layers are Silicon Strip Detectors (SSD). The SPD is mainly used for trigger selection and determination of the interaction vertex position. Since the SPD is closest to the IP, a high particle density is expected for this detector. Therefore, the sensor matrix of the SPD has the best granularity of 256×160 pixels/cells with a size of $50 \mu\text{m}$ in $r\phi$ and $50 \mu\text{m}$ in z . The first layer of the SPD has an acceptance of $|\eta| < 2.0$ that allows to provide, together with Forward Multiplicity Detector (FMD), a continuous coverage in η ($\sim$ eight units) for the measurement of charged-particle multiplicity. The four outer layers (SDD and SSD) of the ITS are mainly used for PID through the measurement of specific energy loss (dE/dx) of charged particles. Moreover, the ITS improves the angle and momentum resolution of the particles that are reconstructed by the TPC. In this thesis work, the charged-particle multiplicity measured in the outer layer of the SPD is used to determine the centrality classes in p-Pb collisions.

2.3.2 Time Projection Chamber (TPC)

The Time Projection Chamber (TPC) [1, 16, 17] serves as the primary tracking detector for ALICE. Figure 2.4 (left) shows the layout of the TPC. It covers the pseudorapidity region of $|\eta| < 0.9$ with full azimuth for tracks with a full radial track length. For tracks with reduced length (and reduced momentum resolution),

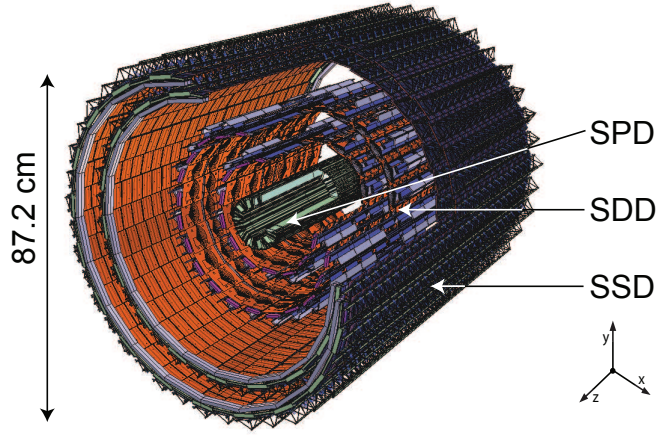


Figure 2.3: Layout of the Inner Tracking System (ITS) detector [15].

an extended acceptance up to about $|\eta| < 1.5$ is accessible. The TPC can cover a large momentum range from 0.1 GeV/ c to 100 GeV/ c and provide good momentum resolution within this wide range. The TPC also has good PID capabilities through dE/dx measurements. The TPC is designed to handle the $dN_{\text{ch}}/d\eta$ up to 8000, which results in $\approx 20,000$ primary and secondary tracks in the acceptance of the TPC. The TPC is cylindrical, with an active volume having an inner radius of 85 cm and an outer radius of 247 cm. The central axis is positioned along the beam direction, and the length of the cylinder is ≈ 500 cm. The active volume is filled with a mixture of Ne + CO₂ + N₂ (90:10:5) gas and divided by a 22 μm thick aluminized mylar foil, acting as the central high voltage (HV) electrode. The endplates are divided into eighteen trapezoidal sectors, each equipped with individual MultiWire Proportional Chambers (MWPC) with cathode pad readout. A voltage of 100 kV is applied between the central HV electrode and the endplates. When charged particles traverse the active volume, they ionize the gas and produce ions and electrons. Due to the electric field, the electrons drift towards the endplates and are then detected by the MWPC. The pads of the MWPC provide the information of x and y coordinates, deposited energy, and drift time. The third coordinate, z , can be calculated from the drift time of the electrons. Thus, the TPC can measure all three coordinates of the

charged tracks, allowing a complete reconstruction of the trajectory of the incident charged particles. In addition, the TPC is operated inside a magnetic field of 0.5 T that helps to measure the momentum of charged particles. For example, Fig. 2.4 (right) illustrates the PID performance of the TPC in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, showing an excellent separation between different species of charged particles [13].

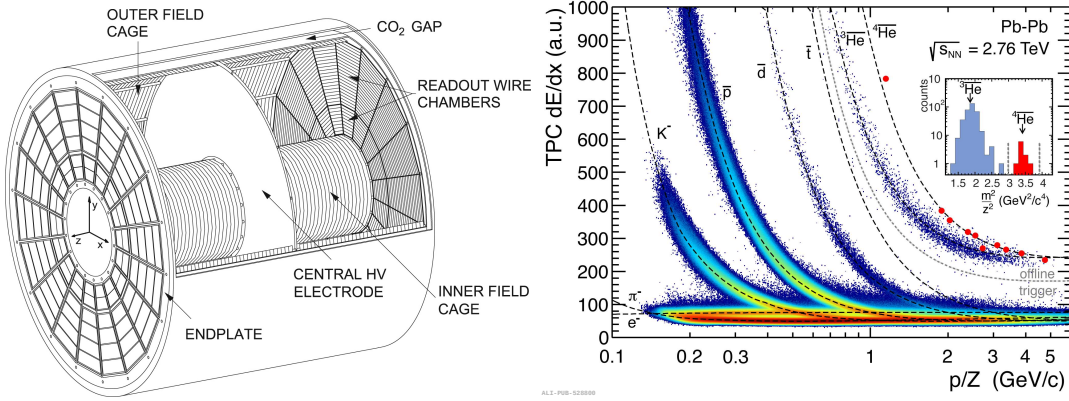


Figure 2.4: (Left) Layout of the Time Projection Chamber (TPC) detector [17]. (Right) Measurements of specific energy loss (dE/dx) for different particles with the TPC [13].

2.3.3 Transition Radiation Detector (TRD)

The Transition Radiation Detector (TRD) [1, 18, 19] of ALICE is cylindrical in shape with an inner radius of 290 cm and an outer radius of 368 cm. A schematic layout of the TRD is shown in Fig. 2.5. The central axis of the cylinder is positioned along the z axis with an active length of ≈ 7 m (entire length is 7.8 m), surrounding the TPC. The TRD comprises of 18 super modules. Each super module contains 30 modules, arranged in six layers in the radial direction and five stacks along the z axis. Each detector module has three components: a 4.8 cm thick carbon fibre laminated Rohacell/polypropylene fibre sandwich radiator, a 3 cm thick drift section, and an MWPC of 0.7 cm thick with pad readout. The cross-sectional view of a TRD module is shown in Fig. 2.6 (left). The primary purpose of the TRD is

to identify electrons with $p_T > 1 \text{ GeV}/c$ because, above this p_T , the pion rejection capability of the TPC is no longer sufficient. Figure 2.6 (left) shows the working principle of the TRD. When particles with very high velocities ($\gamma \approx 1000$) pass through materials with different dielectric constants, the transition radiation (TR) occurs. In the momentum range analyzed with the TRD ($1 < p_T < 10 \text{ GeV}/c$), only electrons can produce the TR. Figure 2.6 (right) presents the average pulse height for pions (triangles) and electrons with (circles) and without (squares) radiator as a function of drift time, showing a clear distinction between electrons and pions for momentum $2 \text{ GeV}/c$.

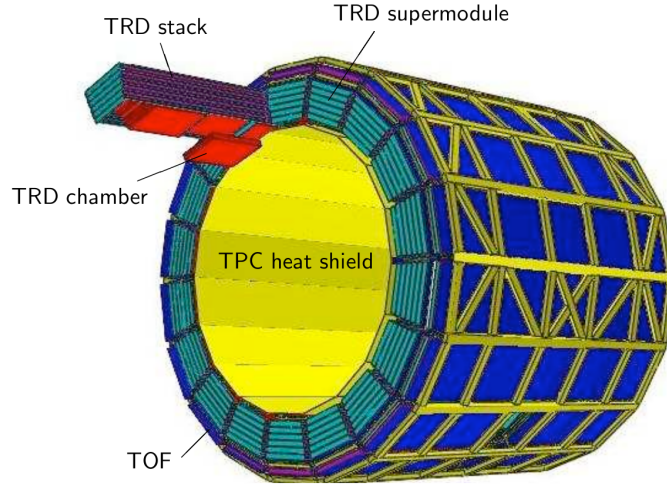


Figure 2.5: Layout of the Transition Radiation Detector (TRD) detector [1].

2.3.4 Time of Flight Detector (TOF)

The Time of Flight Detector (TOF) [1, 20, 21] of ALICE is a large array of Multigap Resistive Plate Chambers (MRPCs), arranged in a cylindrical frame with an inner radius of 370 cm and an outer radius of 399 cm, as shown in Fig. 2.7 (left). The TOF covers the pseudorapidity region of $|\eta| < 0.9$ over full azimuth. The TOF has a modular structure that corresponds to 18 sectors in ϕ and five segments in the direction of the z axis. The primary purpose of the TOF is to identify pions

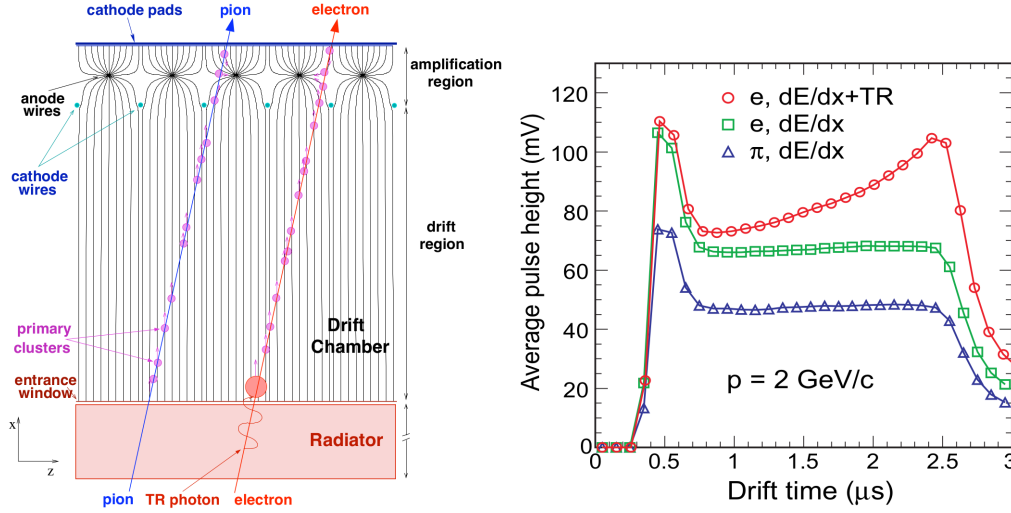


Figure 2.6: (Left) Schematic cross-sectional view of a module of the TRD. (Right) Average pulse height for electrons and pions as a function of drift time [1].

and kaons below 2.5 GeV/c and protons up to 4 GeV/c, complementing the PID capabilities of the ITS and TPC. Figure 2.7 (right) shows the PID performance of the TOF detector in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

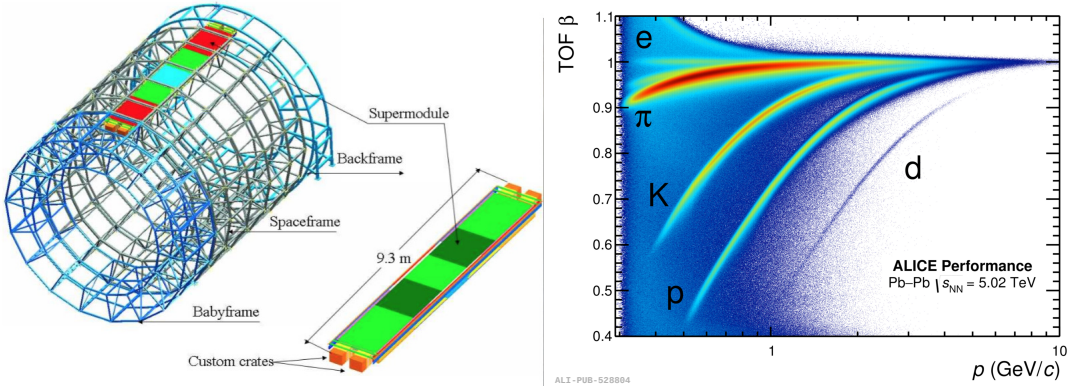


Figure 2.7: (Left) Schematic drawing of one supermodule of the TOF, comprising of 5 modules, in the ALICE spaceframe [1]. (Right) PID performance of TOF detector [13].

2.3.5 High-Momentum Particle Identification Detector (HMPID)

The High-Momentum Particle Identification Detector (HMPID) [1, 23] of ALICE is designed for the inclusive measurements of identified charged hadrons with momen-

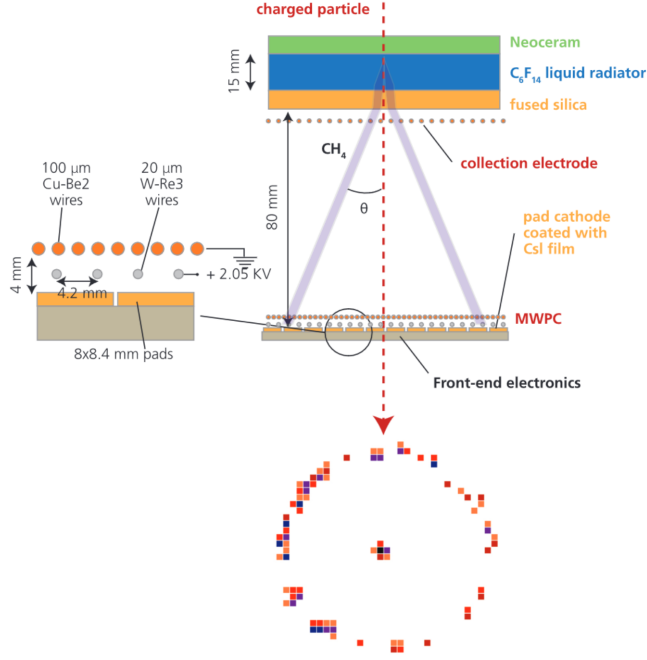


Figure 2.8: Working principle of the HMPID detector [22].

tum above 1 GeV/c. The HMPID consists of 7 modules, each with dimensions of $1.5 \times 1.5 \text{ m}^2$. Each module is based on a proximity-focusing Ring Imaging Cherenkov (RICH) counter. The counter uses a liquid radiator C_6F_{14} (perfluorohexane) and employs CsI thin films deposited onto the cathode plane of a MWPC. The HMPID is placed at $r = 490 \text{ cm}$ and fixed at the two o'clock position, having a pseudo-rapidity coverage of $|\eta| < 0.6$ over an azimuth of $1^\circ < \phi < 59^\circ$. The working principle of HMPID is described in Fig. 2.8. When charged particles pass through the radiator, Cherenkov radiation is generated. The radiation expands in the proximity volume of CH_4 along a cone with the particle's trajectory as an axis and an opening angle θ . The collection cathode close to the radiator prevents the electrons released by ionizing particles in the proximity gap to enter the volume of MWPC. The angle θ is proportional to the velocity (β) of the particle. The MWPC photon detector produces the image of Cherenkov radiation as a ring. One can deduce the angle θ by measuring the ring radius. Hence, the velocity β can be obtained via the well known Cherenkov equation: $\beta = 1/n \cos \theta$ (n = refractive index of C_6F_{14}).

The charge and momentum of the particle can be measured by tracking detectors (ITS, TPC). Therefore, by combining the information from ITS and TPC with the velocity measured by HMPID, one can deduce the mass of the particle and identify it. Figure 2.9 shows the PID performance of HMPID for Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV presented in terms of Cherenkov angle vs momentum [24]. Above momentum 3 GeV/ c , the pion and kaon merge together while the proton remains on a separate band up to 5 GeV/ c .

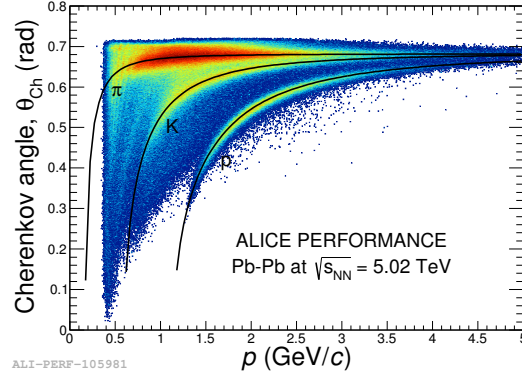


Figure 2.9: Cherenkov angle measured by the HMPID as a function of track momentum [24].

2.3.6 Photon Spectrometer (PHOS)

The PHOton Spectrometer (PHOS) [1, 25, 26] is an electromagnetic calorimeter positioned at $r = 460$ cm in the bottom side of the ALICE setup (see Fig. 2.10). It covers the pseudorapidity $|\eta| < 0.125$ over an azimuth of $220^\circ < \phi < 320^\circ$. The PHOS comprises of four modules: three of them have $56 \text{ rows} \times 64 \text{ columns} = 3584$ detection elements, and the fourth module has $56 \text{ rows} \times 32 \text{ columns} = 1792$ elements. Each detection element or cell consists of a lead tungstate crystal (PbWO_4) of size $22 \times 22 \times 180 \text{ mm}^3$, coupled to an Avalanche Photo-Diode (APD) of size $5 \times 5 \text{ mm}^2$. The signal of APD is processed by a low-noise preamplifier. The crystals are operated at a temperature of -25°C . Operating at this temperature amplifies the

yield of light in the crystals by a factor of three compared to room temperature. Compared to the electromagnetic calorimeters (EMCal and DCal), the acceptance of the PHOS is low; however, the granularity and resolution of the PHOS are significantly better. The main physics objectives of the PHOS are to study the spectra and collective flow of direct photons and to investigate jet quenching via the measurement of high- p_T π^0 and γ -jet correlations.

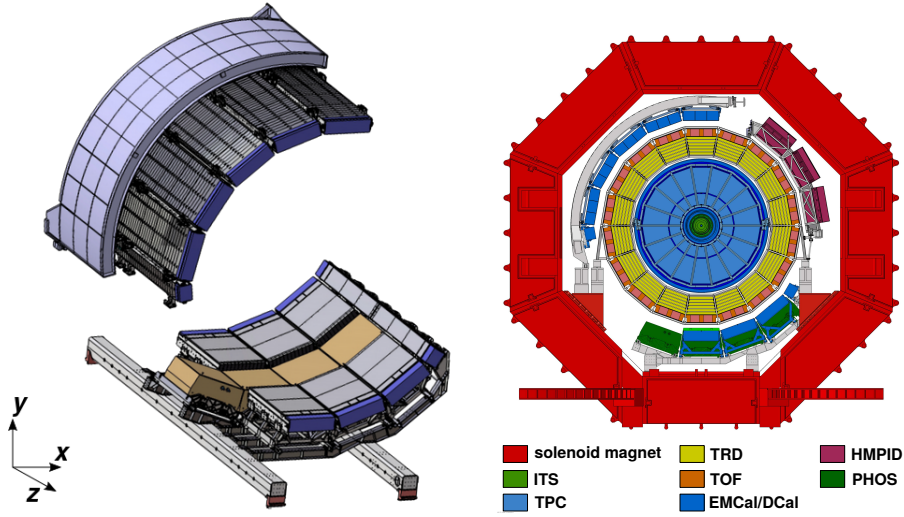


Figure 2.10: (Left) Schematic view of the ElectroMagnetic Calorimeter, showing the positions of the modules on two approximately opposite positions in azimuth. (Right) Cross-sectional view of ALICE Central barrel detectors. The PHOS is inside the DCal and indicated in brown [27].

2.3.7 Electromagnetic calorimeters (EMCal and DCal)

The ElectroMagnetic Calorimeter (EMCal) of ALICE is designed to measure electrons from heavy-flavour hadron decays, the neutral component of jets, and the spectra of direct photons and neutral mesons [27, 28]. The EMCal is placed almost opposite to the PHOS detector (see Fig. 2.10) and covers a pseudorapidity region of $|\eta| < 0.7$ over an azimuth of $80^\circ < \phi < 187^\circ$. Later, the acceptance of the EMCal is extended by installing the Dijet Calorimeter (DCal) [27, 29] which is placed at 180° opposite in ϕ . The design of DCal enables the measurements of back-to-back

hadron-jet and di-jet correlations, which are not possible with the EMCal alone. The EMCal utilizes the Shashlik design that involves 77 alternating layers of lead and plastic scintillators. Incident particles produce showers in the lead absorber layers, and the shower particles then produce light in the scintillator layers. Wavelength shifting (WLS) fibres guide the produced light to the APDs, where the signal is measured. The electromagnetic calorimeters are divided into three different sizes of supermodules (SMs): full-size, 2/3-size, and 1/3-size. Full-size SMs comprises of $12 \times 24 = 288$ modules, 2/3-size SMs have $12 \times 16 = 192$ modules, and 1/3-size SMs consists of $4 \times 24 = 96$ modules. The EMCal is made of ten full-size and two 1/3-size SMs. The DCal is made of six 2/3-size and two 1/3-size SMs. The DCal is split into two separate parts, with the PHOS placed in between them. The acceptance of the DCal is $0.22 < |\eta| < 0.7$, $260^\circ < \phi < 320^\circ$ (for 2/3-size SMs) and $|\eta| < 0.7$, $320^\circ < \phi < 327^\circ$ (for 1/3-size SMs). Figure 2.10 shows a schematic view of the EMCal and DCal. The components of one EMCal module are illustrated in Fig. 2.11.

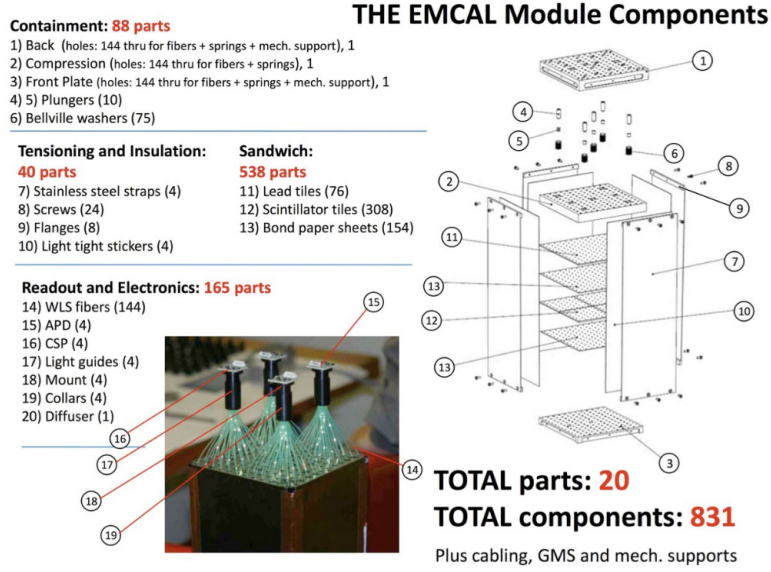


Figure 2.11: Photo and drawing of one EMCal module displaying all components [27].

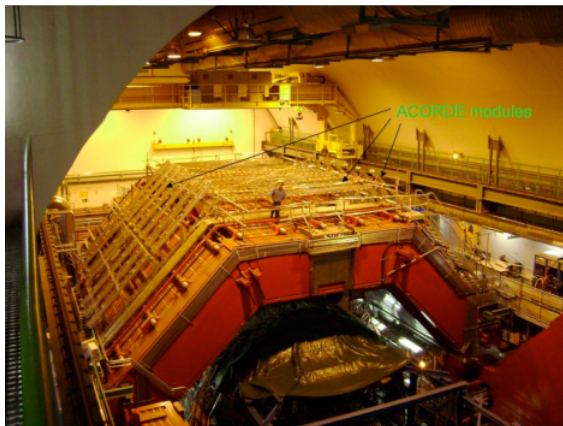


Figure 2.12: Photograph of the ACORDE scintillator array placed on top of the magnet. The figure is adapted from Ref. [30].

2.3.8 ALICE COsmic Ray DETector (ACORDE)

The ALICE COsmic Ray DETector (ACORDE) [1, 30, 31] is an array of plastic scintillator counters positioned on top of the L3 magnet as shown in Fig. 2.12. The ACORDE comprises of 60 scintillator modules in total. Each module has two scintillator counters, each with an effective area of $190 \times 20 \text{ cm}^2$ and a thickness of 10 mm. With this setup, a uniform efficiency higher than 90% is achieved along the entire length of a test module. The ACORDE serves a two-fold role in the ALICE experiment: (i) It provides a fast (Level-0) trigger signal for the commissioning, calibration, and alignment procedures of some ALICE tracking detectors (ITS, TPC, TOF, HMPID). (ii) ACORDE, in combination with the TPC, TRD, and TOF, detects single atmospheric muons and multi-muon events (muon bundles). This allows the study of high-energy cosmic rays in the energy region of the knee in the cosmic ray spectrum [1].

2.4 Forward detectors

The forward detectors [32] of the ALICE consist of V0, T0, Forward Multiplicity Detector (FMD), Photon Multiplicity Detector (PMD) [33, 34], and Zero Degree

Table 2.2: The acceptance and position of each of the central barrel detectors [2]. Here, z is the longitudinal coordinate measured with respect to the IP.

Detector	η in polar	ϕ in azimuth	Position	Main Purpose
V0				
V0A	$2.8 < \eta < 5.1$	$0^\circ < \phi < 360^\circ$	$z = 329 \text{ cm}$	charged particles
V0C	$-3.7 < \eta < -1.7$	$0^\circ < \phi < 360^\circ$	$z = -90 \text{ cm}$	charged particles
T0				
T0A	$4.6 < \eta < 4.9$	$0^\circ < \phi < 360^\circ$	$z = 370 \text{ cm}$	vertex, time
T0C	$-3.3 < \eta < -3.0$	$0^\circ < \phi < 360^\circ$	$z = -70 \text{ cm}$	vertex, time
PMD	$2.3 < \eta < 3.9$	$0^\circ < \phi < 360^\circ$	$z = 367 \text{ cm}$	photons
FMD				
FMD1	$3.6 < \eta < 5.0$	$0^\circ < \phi < 360^\circ$	$z = 320 \text{ cm}$	charged particles
FMD2	$1.7 < \eta < 3.7$	$0^\circ < \phi < 360^\circ$	$z = 80 \text{ cm}$	charged particles
FMD3	$-3.4 < \eta < -1.7$	$0^\circ < \phi < 360^\circ$	$z = -70 \text{ cm}$	charged particles
ZDC				
ZN	$ \eta > 8.8$	$0^\circ < \phi < 360^\circ$	$z = \pm 112.5 \text{ m}$	forward neutrons
ZP	$6.5 < \eta < 7.4$	$ \phi < 10^\circ$	$z = \pm 112.5 \text{ m}$	forward protons
ZEM	$4.8 < \eta < 5.7$	$ 2\phi < 32^\circ$	$z = 7.3 \text{ m}$	photons

Calorimeter (ZDC) [35]. The position, acceptance and purpose of these detectors are summarized in Table 2.2.

2.4.1 The V0 Detector

The V0 detector [32, 36] is made of two arrays of 32 scintillators positioned at $z = 330 \text{ cm}$ (V0A, covering the pseudorapidity interval $2.8 < \eta < 5.1$) and $z = -90 \text{ cm}$ (V0C, covering $-3.7 < \eta < -1.7$). Each of the V0 arrays is segmented into four detector rings in the radial direction. Each ring is subdivided into eight sections in the ϕ direction, as shown in Fig. 2.13. Each detector element is connected with photomultiplier tubes (PMTs) via WLS fibres. Each scintillator can record both the amplitude and the time of the signals produced by charged particles. The V0 detector provides triggers to select minimum bias (MB) events and separates beam-beam interactions from background events such as beam-gas or beam-halo

interactions. Furthermore, the V0 plays a role in determining the centrality of the collision events and participates in luminosity measurements.

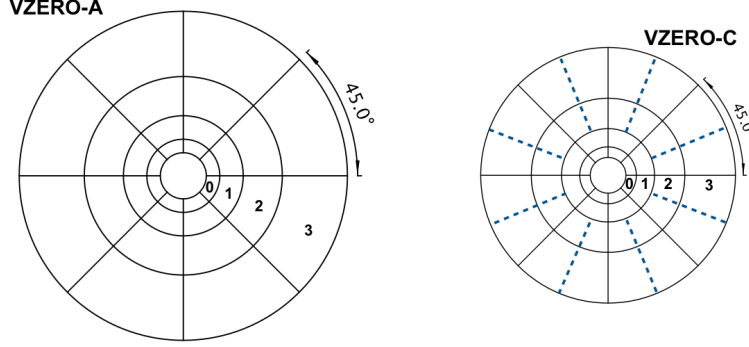


Figure 2.13: Sketches of V0A and V0C arrays displaying their segmentations [36].

2.4.2 The T0 Detector

Analogous to the V0 detector, the T0 [32] comprises of two segments: The T0A and the T0C. Each of them consists of twelve Cherenkov counters based on a fine-mesh PMT coupled to a quartz radiator. The T0A is placed at $z = 370$ cm, covering the pseudorapidity $4.6 < \eta < 4.9$, whereas the T0C is positioned at $z = -70$ cm, covering the pseudorapidity $-3.3 < \eta < -3.0$. The T0 provides the start time for the T0F detector, regardless of the collision vertex. In addition, the T0 detector contributes to the determination of the vertex position, provides Level 0 trigger if the vertex position is within specified boundaries, and participates to discriminate beam-gas interactions.

2.4.3 Forward Multiplicity Detector (FMD)

The Forward Multiplicity Detector (FMD) is a silicon strip detector composed of three sub-detectors placed at $z = 320$ cm (FMD1), 79 cm (FMD2), and -69 cm (FMD3). FMD2 and FMD3 comprise of two rings (inner and outer), while FMD1 contains only an inner ring. The inner ring is divided into 20 azimuthal sectors, and

each sector contains 512 silicon strips with radii from 4.2 to 17.2 cm. On the other hand, the outer ring is segmented into 40 azimuthal sectors, and each sector consists of 256 silicon strips with radii from 15.4 to 28.4 cm. Therefore, each ring (inner or outer) has 10,240 silicon strips, resulting in a total of 51,200 strips. The layout of the FMD detector is shown in Fig. 2.14. The FMD has full azimuthal coverage in the pseudorapidity ranges $-3.4 < \eta < -1.7$ (FMD3) and $1.7 < \eta < 5.1$ (FMD2 and FMD1), which extends the charged-particle detection acceptance beyond the reach of the central detectors in ALICE. The method of determining the charged-particle multiplicity using the FMD is discussed in Sec. 4.1.4 of Chapter 4.

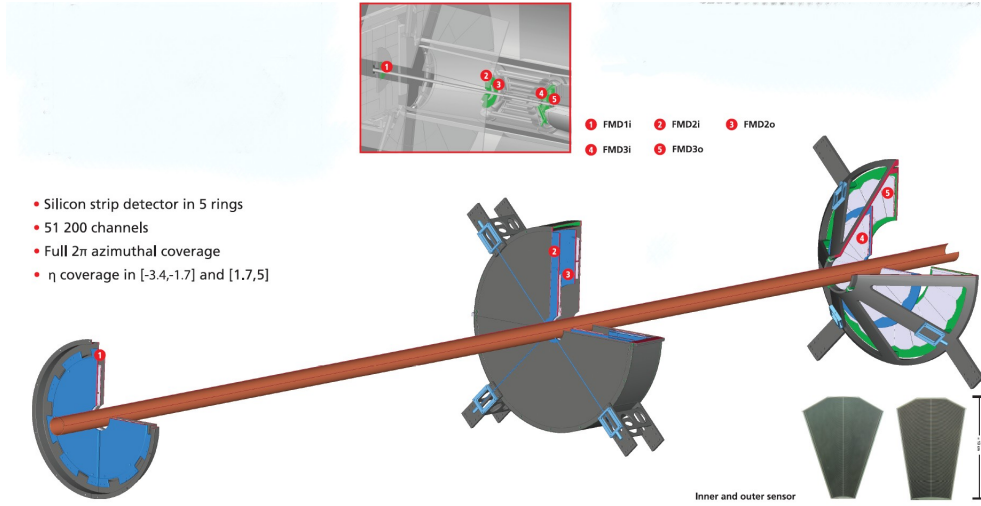


Figure 2.14: Layout and positioning of the FMD detector in the ALICE experiment. The figure is adapted from [WIKIPEDIA](#).

2.4.4 Photon Multiplicity Detector (PMD)

The Photon Multiplicity Detector (PMD) [33,34,37] is a preshower detector to measure inclusive photon multiplicity and its spatial distribution in the forward rapidity region. It is a gaseous detector placed at $z = 367$ cm covering the pseudorapidity region of $2.3 < \eta < 3.9$ with full azimuth coverage. The PMD consists of two fine granular planes: the Charged Particle Veto (CPV) plane and the PREshower (PRE) plane. A lead converter with a thickness equivalent to three radiation lengths ($3X_0$)

is placed between these two planes. The basic building block of the PMD is a hexagonal cell of size 0.22 cm^2 and depth 0.5 cm with a copper honeycomb-shaped cathode extended towards a $20 \mu\text{m}$ thick gold-plated tungsten wire at ground potential at the centre of the cell. Each cell works as a proportional counter. It is filled with a gas mixture of Ar (70%) and CO_2 (30%). The schematic picture of a honeycomb cell is shown in Fig. 2.15 along with a longitudinal cross-section illustrating the use of an extended cathode. The geometry of the extended cathode is considered to have a uniform electric field strength surrounding the anode wire, as shown in Fig. 2.16. For the open geometry, the field varies by a factor of ~ 2 along the length of the anode wire, whereas it is relatively homogeneous for the extended cathode model.

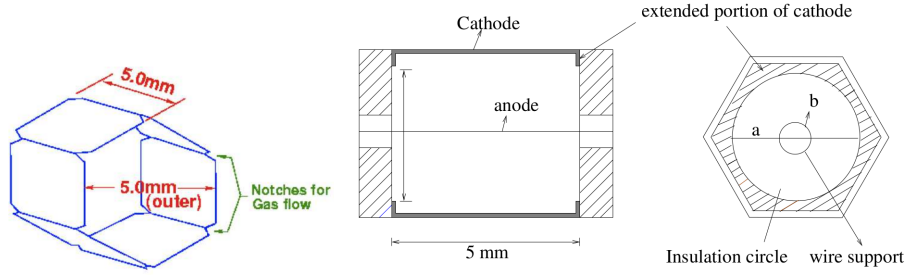


Figure 2.15: A schematic picture of a honeycomb cell of PMD [34].

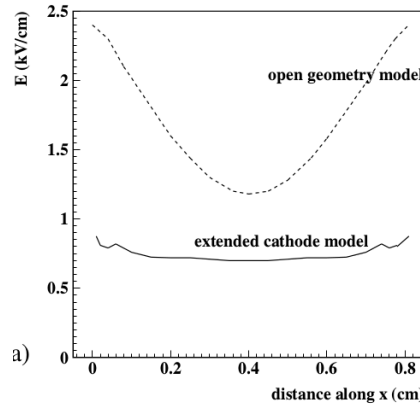


Figure 2.16: Electric field graphs for the open geometry and the model with the extended cathode [33].

An array of 48×96 or 96×48 such hexagonal cells is made using a copper

sheet of thickness 0.2 mm and is known as a honeycomb chamber. The honeycomb chambers are fabricated as modules, which can be handled conveniently. Each PMD plane consists of 20 modules, which are read out by 100 chains. Each chain contains 768 cells, resulting in 76,800 cells in each PMD plane. In Fig. 2.17(a), the gray region shows the active area of the PMD as installed. This configuration provides almost full azimuthal coverage ($> 90\%$) in the pseudorapidity region 2.3 to 3.9, as shown in Fig. 2.17(b).

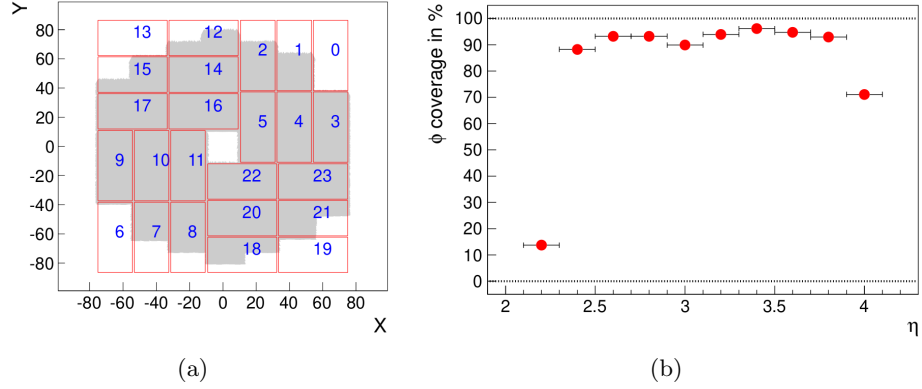


Figure 2.17: (a) Layout of ALICE PMD as installed. There are 20 modules in each plane. (b) Percent azimuthal coverage as a function of pseudorapidity (η) [38].

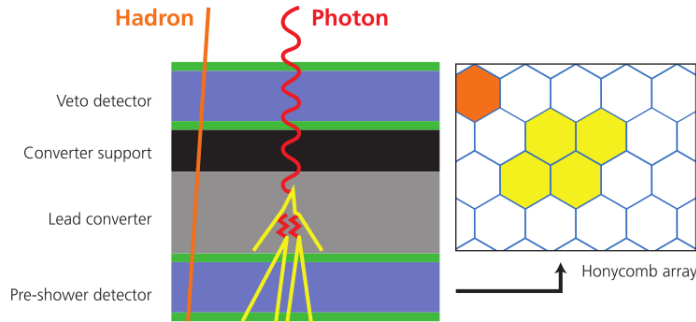


Figure 2.18: Working principle of the PMD. The figure is adapted from Ref. [39].

Figure 2.18 illustrates the working principle of photon detection using the PMD. Due to the presence of the lead converter, the incident photon produces electromagnetic showers by pair production and bremsstrahlung radiation and hits several cells

in the PRE plane. On the other hand, a charged hadron does not produce showers, generally affects one or two cells, and produces a signal typical of a Minimum Ionizing Particle. After receiving signals in the PRE plane, a photon reconstruction algorithm is applied as discussed in detail in Sec. 3.1.6 of Chapter 3, and a photon-rich sample of clusters is obtained by applying suitable rejection criteria to remove clusters from hadrons and secondary particles.

2.4.5 Zero Degree Calorimeter (ZDC)

The Zero Degree Calorimeter (ZDC) [35] is a quartz sampling calorimeter that utilizes Cherenkov radiation generated in a dense absorber. The ZDC consists of two sets of neutron (ZNA and ZNC) and proton (ZPA and ZPC) calorimeters positioned at ± 112.5 m from the IP on both sides. The ZPA and ZPC calorimeters cover the pseudorapidity range $6.5 < |\eta| < 7.4$, while the ZNA and ZNC calorimeters have a geometric coverage $|\eta| > 8.8$. The energy of the spectators (protons or neutrons) detected by the ZDC is used to determine the centrality in heavy-ion collisions. In this thesis work, the energy deposited in the ZNA calorimeter is used to determine the centrality classes in p-Pb collisions.

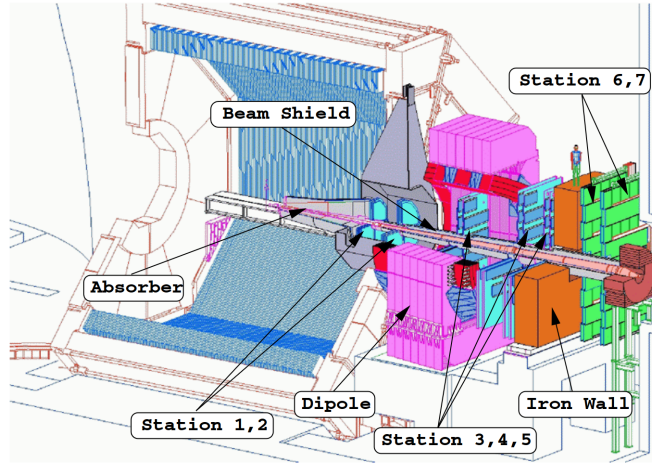


Figure 2.19: Layout of ALICE Muon Spectrometer. The MCH consists of stations 1 to 5, and the MTR comprises of stations 6 and 7 [40].

2.5 Muon Spectrometer (MS)

The Muon Spectrometer (MS) [1, 41, 42] is designed to study the production of heavy flavour mesons, light vector mesons and quarkonium via their $\mu^+\mu^-$ decay channels. The spectrometer is installed in the “C side”, covering the pseudorapidity region of $-4.0 < \eta < -2.5$ over the full azimuthal angle. Table 2.3 summarizes the acceptance, position, and purpose of the Muon spectrometer in the ALICE experiment. The Muon Spectrometer consists of several components: a front absorber to stop most of the hadrons produced in the MS acceptance; a tracking system (Muon CHambers, MCH) composed of five stations (each consisting of two planes: Cathode Pad Chamber and Cathode Strip Chamber); a dipole magnet; a beam shield to reduce the contributions from secondary particles produced at very large rapidities; an iron filter to absorb the residual background of hadrons; and finally the Muon TRigger (MTR) that is made of two stations (each consists of two planes of Resistive Plate Chambers). Figure 2.19 illustrates the layout of the ALICE Muon spectrometer.

Table 2.3: The acceptance and position of Muon Spectrometer [2]. Here, z is the longitudinal coordinate measured with respect to the IP.

Detector	η in polar	ϕ in azimuth	Position (in m)	Main Purpose
Muon Spectrometer				
MCH	$-4.0 < \eta < -2.5$	$0^\circ < \phi < 360^\circ$	$-14.2 < z < -5.4$	muon tracking
MTR	$-4.0 < \eta < -2.5$	$0^\circ < \phi < 360^\circ$	$-17.1 < z < -16.1$	muon trigger

2.6 The ALICE trigger and data acquisition

The different sub-detectors described in Secs. 2.3, 2.4, and 2.5 are read out only after the trigger decision is generated by the Central Trigger Processor (CTP) of

the ALICE [2, 43]. This crucial component, CTP, evaluates signals from various trigger detectors in real time and information about the LHC bunch-filling scheme and bunch crossing to decide whether to record the data from a particular collision. The initial trigger decision, Level 0 (L0), is made $\approx 0.9 \mu\text{s}$ after the collision. This L0 decision is based on the inputs from V0, T0, EMCal, PHOS, and MTR. The accepted events at L0 are further assessed by the Level 1 (L1) trigger algorithm in the CTP. The decision of L1 trigger is made $\approx 6.5 \mu\text{s}$ after the L0 trigger. This delay is due to computation time (TRD and EMCal) and propagation times (ZDC, which is 112.5 m from the IP). The L0 and L1 decisions are then transmitted to the detectors with a latency of ≈ 300 ns in order to trigger the buffering of the event data in the detector front-end electronics. The Level 2 (L2) trigger decision is made after $\approx 100 \mu\text{s}$ that corresponds to the drift time of the TPC. The L2 decision triggers the transmitting of the event data to the Data Acquisition System (DAQ) [44] and simultaneously to the High Level Trigger (HLT) system [45] where event building and data compression are performed. A couple of triggers used in this thesis work can be found in Table 2.4.

Table 2.4: Selection of triggers [2] important to this thesis work.

Trigger name	Different acronyms	Description	Condition
MBor	kINT1	minimum bias trigger to select Inelastic (INEL) events	signals in V0 and SPD
MBand	kINT7/V0AND	minimum bias trigger to select non-single diffractive (NSD) events	signals in V0A and V0C

The ALICE DAQ system is responsible for managing the data flow from the detector to the data storage. Data from the detector are initially sent to front-end machines known as Local Data Concentrators (LDCs). At the LDCs, event fragments are assembled into sub-events. The sub-events are then shipped to a farm

of machines known as Global Data Collectors (GDCs). At the GDCs, the entire event is constructed by combining the sub-events. The DAQ system interfaces with the HLT, which performs a fast reconstruction of each event, making decisions to accept or reject it. The HLT applies compression algorithms to reduce the size of the events without losing essential physics information. This compression is necessary to cope with the DAQ archiving rate, which is around 1 GB/s. Finally, events are stored in the CERN computing centre.

2.7 The ALICE offline framework

The ALICE experiment collects an enormous amount of data that requires a sophisticated infrastructure for processing and analysis. This infrastructure is coordinated by the Worldwide LHC Computing Grid (WLCG) project [46–48], a highly hierarchical computing system with three main levels: (a) the largest computing centre is located at CERN and is known as Tier-0. It serves as a central hub in the WLCG infrastructure. (b) regional computing centres, known as Tier-1, are logically clustered around Tier-0. These Tier-1 centres contribute to the storage of events and are vital for data distribution and accessibility. Tier-1 centres often utilize magnetic tapes for long-term data storage. (c) Tier-2 centres are smaller computing centres that are logically clustered around Tier-1 centres. The WLCG infrastructure is not only limited to data storage but also associated with data processing tasks, which include various steps such as calibration, reconstruction of events, simulation, and analysis. To facilitate collaboration and access to the distributed data on the Grid, the ALICE collaboration has developed a service known as AliEn (ALICE Environment) [49] that makes easier for analyzers and collaborators to interact with and analyze the vast datasets distributed across the WLCG infrastructure.

The data analysis in ALICE is performed using a software environment called AliRoot [50,51]. The AliRoot is based on ROOT [52] framework, which is an object-

oriented data analysis framework written in C++. The AliRoot framework provides various features such as data calibrations, data reconstructions, detector simulations, visualizations, etc., which are required for the data analysis. The framework is also interfaced with various Monte Carlo event generators such as PYTHIA, PHOJET, HIJING, DPMJET, EPOS etc. and different transport codes which simulate the detector response such as GEANT 3 [53, 54], GEANT 4 [55] and FLUKA [56]. The particles produced from event generators are transported through GEANT 3 or GEANT 4 such that the simulated events contain the complete information that is available to real data. The real data and simulated event information are stored in ROOT file formats like Event Summary Data (ESD) and Analysis Object Data (AOD). Finally, various analysis codes are developed and written in the AliRoot framework and kept in a data repository called AliPhysics [57]. These codes are used to access, read, and extract event and particle information from the root files for further physics analysis of interest. My thesis work utilizes ESD file for photon analysis and uses both ESD and AOD files for charged-particle analysis.

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Chapter 3

Inclusive photon production in pp and p–Pb collisions

In this chapter, we report the measurements of multiplicity and pseudorapidity distributions of inclusive photons at forward rapidity for pp, p–Pb, and Pb–p collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. We study the dependence of the inclusive photon production on the centrality of the collision, which is related to the impact parameter of the p–A collision, and its scaling behaviour with the number of participating nucleons (N_{part}) at forward rapidity for the first time in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV at the LHC. This measurement enables an extension of our understanding of particle production at forward rapidity [1, 2].

In this analysis, the Photon Multiplicity Detector (PMD) is used for the detection of inclusive photons at forward rapidity, whereas for the purpose of event selection and centrality determination, the Silicon Pixel Detector (SPD), the V0 detector and the Zero Degree Calorimeter (ZDC) are used.

3.1 Analysis details

The data analysis procedure for measuring the multiplicity and pseudorapidity distributions of inclusive photons consists of several steps, as shown in Fig. 3.1. A brief description of the different steps followed in this analysis procedure is presented in the next subsections.

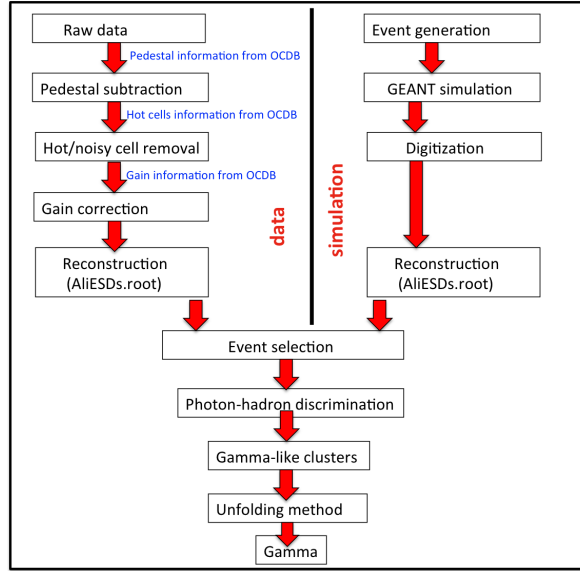


Figure 3.1: The flowchart showing the steps involved in the data analysis and simulation for the measurement of photon multiplicity.

3.1.1 Data sample

This analysis uses p–Pb and pp data samples, which were collected in 2013 during LHC Run 1 and 2015 during LHC Run 2, respectively. The p–Pb collisions were recorded for two beam configurations: in one (denoted as p–Pb), the proton beam at 4 TeV energy was pointing towards the negative z direction in the ALICE reference system [3], while the lead ions at 1.58 TeV per nucleon energy moved in the opposite direction; in the other configuration (denoted as Pb–p), the directions of both proton and lead ion beams were reversed. The nucleon–nucleon centre-of-mass energy for both configurations resulted in $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Due to the asymmetry

Table 3.1: Details of pp, p-Pb and Pb-p data period and run numbers used in this analysis

System/Energy	Data Period	Analyzed runs	No. of events after event selection criteria*
$\sqrt{s_{NN}} = 5.02$ TeV p-Pb,	LHC13b	195478, 195479, 195480, 195481, 195482, 195483	24.9 M
	LHC13c	195529, 195531, 195566, 195567, 195568, 195592, 195593, 195596	65.7 M
$\sqrt{s_{NN}} = 5.02$ TeV Pb-p,	LHC13f	196433	1.2 M
$\sqrt{s} = 5.02$ TeV pp,	LHC15n	244340, 244343, 244351, 244377	23 M

* The event selection criteria is discussed in Sec. 3.1.2.

of the beam energies, the nucleon–nucleon centre-of-mass system in p–Pb collisions is shifted in rapidity by $\Delta y = 0.465$ with respect to symmetric pp collisions in the direction of the proton beam. In the following, the variable η_{lab} indicates the pseudorapidity in the laboratory reference frame. For pp collisions, the centre-of-mass frame is the same as the laboratory frame. The details of the data period and run numbers are shown in Table 3.1.

3.1.2 Event selection

Physics selection:

In pp collisions, a sample of inelastic (INEL) events is selected using a minimum bias (MB) trigger condition, which requires the detection of at least one particle in either of the two V0 scintillator arrays or in the SPD. For p–Pb and Pb–p data samples, non-single diffractive (NSD) events are selected using a MB trigger condition, which required signals in both V0A and V0C.

Rejection of background events:

The background events, such as beam–gas or beam–halo interactions occurring

outside the interaction region, are rejected using the timing information from the V0 detector. Pile-up events, in which two or more collisions are detected as single events, are minimized using the procedure outlined in Ref. [4].

Vertex selection:

Events are further selected by restricting the reconstructed primary vertex position along the beam axis within ± 10 cm from the nominal interaction point (IP) ($z = 0$).

After applying all selection criteria, about 23 M INEL pp collisions, 90 M NSD p–Pb events, and 1.2 M NSD Pb–p collisions are considered for this analysis.

Centrality determination in p–Pb collisions:

In p–Pb collisions, the centrality is determined by exploiting the pseudorapidity coverage of various detectors [5]. In this analysis, the following centrality estimators are considered.

Multiplicity-based centrality estimators

V0A estimator: It is based on the amplitude measured by V0 scintillator array in the Pb-going side, $2.8 < \eta_{\text{lab}} < 5.1$;

CL1 estimator: It is defined based on the number of clusters in the outer layer of the SPD, $|\eta_{\text{lab}}| < 1.4$;

Energy-based centrality estimator

ZNA estimator: It makes use of the energy deposited in the neutron calorimeter in the Pb-remnant side at large pseudorapidity ($|\eta_{\text{lab}}| > 8.8$).

Multiplicity-based centrality selection is performed by fitting the multiplicity distribution of the number of SPD clusters or the amplitude measured by V0A with a Glauber Monte Carlo (MC) model [6, 7] combined with a simple model for particle

production, which assumes that the multiplicity at midrapidity has an average value proportional to N_{part} and a probability distribution described by a Negative Binomial Distribution (NBD) (see Fig. 3.2(a)). More details about this method can be found in Ref. [5]. However, in p–Pb collisions, multiplicity fluctuations have a large influence on the centrality determination compared to the same effect in heavy-ion collisions, as these fluctuations are sizable compared to the width of the N_{part} distribution. Other effects, originating, e.g., from the fragmentation of partons produced in hard scatterings, were found to bias the estimation of the centrality based on measurements of particle multiplicity [5].

In contrast, the centrality estimation using the energy measured at very large rapidity by the ZNA neutron calorimeter in the Pb-going direction introduces minimal bias. The ZNA detects slow neutrons emitted from nuclear deexcitation processes or knocked out by wounded nucleons [8, 9]. The value of N_{part} is calculated using two procedures. The first one is the fitting of the energy spectrum obtained from the calorimeter by a Slow-Nucleon Emission (SNM) model (which is developed based on the parametrization of results at lower energy p–A experiments [5, 8]) coupled to the Glauber MC model (see Fig. 3.2(b)). However, the estimation of N_{part} with this method is model-dependent. The second procedure is based on a hybrid method, as discussed in detail in Ref. [5]. In this method, the values of N_{part} for each centrality class are obtained under the following assumptions:

$N_{\text{part}}^{\text{high-}p_{\text{T}}}$: The yield of high- p_{T} charged particles at midrapidity is proportional to the number of inelastic nucleon–nucleon collisions (N_{coll});

$N_{\text{part}}^{\text{Pb-side}}$: The charged-particle multiplicity in the Pb-going direction is proportional to the number of wounded target nucleons.

The detailed calculations are discussed in Ref. [5]. The centrality classes used in this analysis are 0–5% (most central (higher multiplicity) collisions), 5–10%, 10–20%, 20–40%, 40–60%, 60–80% and 80–100% (most peripheral (lower multiplicity)

collisions) for all the considered estimators.

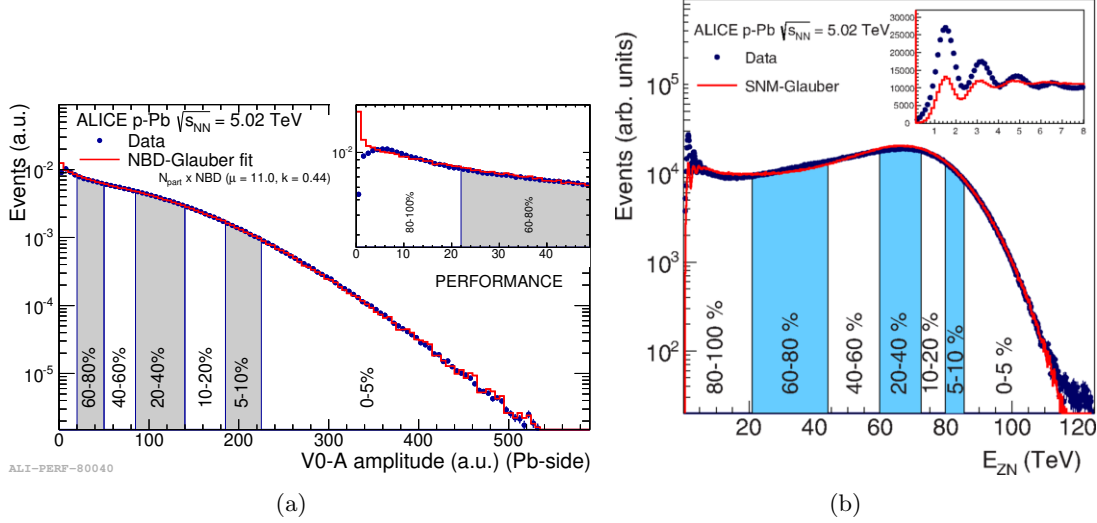


Figure 3.2: (a) Distribution of V0A amplitude in p-Pb collisions fitted by NBD-Glauber shown by red line. (b) Distribution of the neutron energy spectrum measured by ZNA. The distribution is compared with the corresponding distribution from the SNM-Glauber model, shown by the red line. Centrality classes are indicated in both figures. The figures are adapted from Ref. [5].

3.1.3 PMD Data cleanup (hot/noisy cell removal)

As described earlier in Sec. 2.4.4, each PMD plane (CPV or PRE) has 20 modules, which are read out by 100 chains, each consisting of 768 channels/cells. That means one PMD plane consists of 76,800 cells. Now, some of these cells exhibit a high noise level and record hits most of the time. The hit frequency of these cells is considerably higher compared to the other normal cells. These noisy cells are termed as “hot cells”. The ADC values of these hot cells are also lower than those of other normal cells. Due to their noisy nature, hot cells must be removed before the reconstruction of raw data. Before the removal of hot cells, the pedestal (the baseline or offset in the signal obtained from Front End Electronics boards when there are no actual signals of the incident particles on the detector) is subtracted from the real signal for each cell as described in Ref. [10].

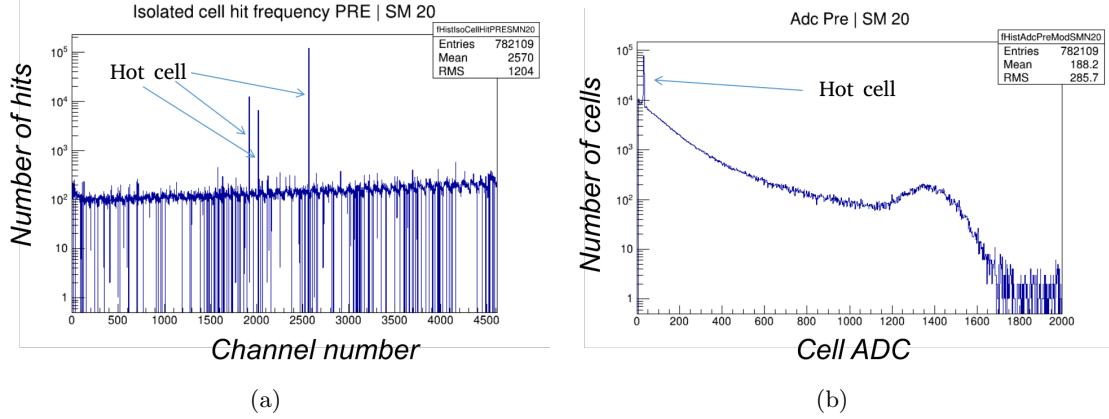


Figure 3.3: (a) The number of hits for each channel is plotted along the Y-axis for one of the preshower modules before hot cell removal. (b) The cell ADC distribution of the same module before hot cell removal. Spikes visible in the plots indicate the hot cells present in the data. The distributions are obtained for the run number 195478 in the LHC13b dataset of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 3.3(a) shows the hit frequency distribution of each cell of module 20 in the PRE plane for the run number 195478 in the LHC13b dataset of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Hot cells are indicated in the figure. It is also found that there are some spikes in the lower ADC values of cell ADC distribution of the same module (see Fig. 3.3(b)) due to the presence of hot cells.

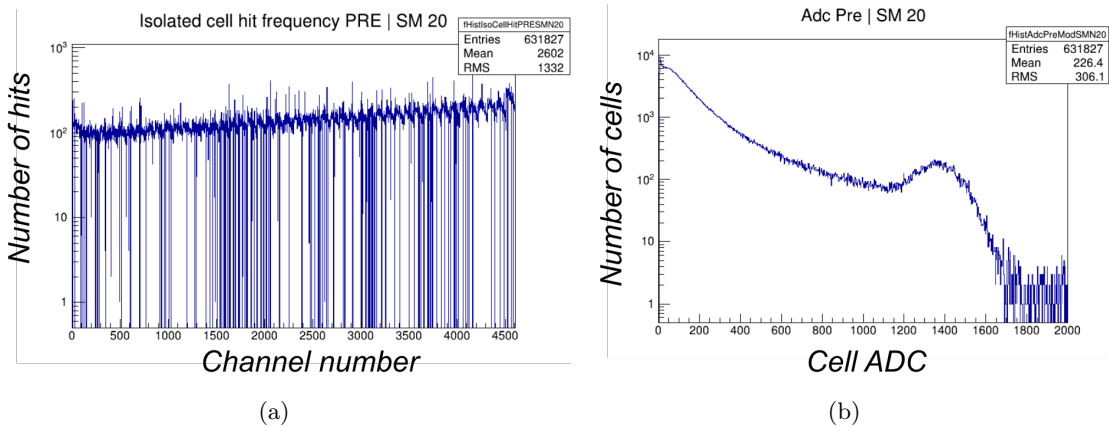


Figure 3.4: (a) The number of hits for each channel is plotted along the Y-axis for the same module as in Fig. 3.3 after hot cell removal. (b) The cell ADC distribution of the same module after hot cell removal. No spikes, i.e. no hot cells, are visible in the plots. The distributions are obtained for the run number 195478 in the LHC13b dataset of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Using an algorithm described in Ref. [10], the noisy/hot cells are identified, and the corresponding row-column information of these hot cells is stored in the Offline Conditioned Data Base (OCDB). These cells are excluded during the reconstruction of raw data. The algorithm is based on the expectation that the cells within a small η ring of width 0.1 over full azimuth are fired uniformly, i.e. the distribution of the number of hits in the cells within that small ring is expected to be Gaussian. For the presence of hot cells, the distribution will deviate from Gaussian.

Figure 3.4 shows the hit frequency and cell ADC distributions of the same module of the same run number as in Fig. 3.3 after data cleanup. It can be observed that the distributions look reasonable once these hot cells are removed.

In addition to hot cells, during data-taking, it might happen that some modules or chains were non-functional due to some technical problems. The row-column information of all these non-functional modules and chains are also stored in the OCDB and excluded during reconstructions.

3.1.4 Gain correction

The PMD is a granular detector with a large number of cells. Since the design, fabrication, and all other parameters are the same for all cells, one can expect a similar response when a known particle of a given energy is allowed to pass through them. However, in practice, their responses are different due to several limitations, e.g. there may be microscopic differences in shapes and sizes of the cells, the gas flow through the cells may be non-uniform, etc. It is observed in test beam experiments that PMD modules show a cell-to-cell gain variation of less than 10% [10, 11]. To remove this artifact while performing physics analysis, a procedure is adopted to make the gain of each cell in a module uniform [10]. At first, the ADC distribution of all isolated cells in a module is obtained, and the mean (say IsoMeanMod) of the distribution is determined. Isolated cells are considered because they are expected to be affected by the Minimum Ionizing Particles (MIPs). Then, the ADC

distribution for the individual isolated cells of the same module is obtained, and the means of these distributions (IsoMean1, IsoMean2, IsoMean3, and so on) are determined. A normalization factor known as the “Gain Factor” is calculated for each cell, which is defined as $\text{IsoMeanMod}/\text{IsoMean1}$, $\text{IsoMeanMod}/\text{IsoMean2}$, $\text{IsoMeanMod}/\text{IsoMean3}$, etc. The gain factors are stored in the OCDB file, and these factors are multiplied by the cell ADC value during the data reconstruction. Figure 3.5 shows gain factors for module 20 of the PRE plane for the run number 195478 in the LHC13b dataset. For this particular module and run number, the gain varies around 10%.

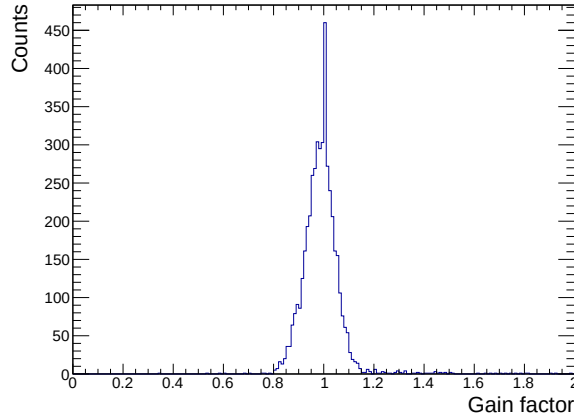


Figure 3.5: Cell-wise gain factors for module 20 of PRE plane for the run number 195478 in the LHC13b dataset of p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

3.1.5 Occupancy

Occupancy is defined as the ratio of the number of cells fired in a pseudorapidity bin to the total number of cells in that pseudorapidity bin. The cell occupancy for the preshower detector plane is obtained using the data after cleanup and calibration and plotted in Fig. 3.6 as a function of pseudorapidity, with a bin size of 0.2 units. The occupancy is shown for p–Pb data at 5.02 TeV for minimum bias and most central (0–5%) events [2] along with results of pp data at 0.9 TeV [12]. The overall

occupancy for most central p–Pb events is going from 0.26% to 2.8%, whereas for minimum bias p–Pb events, the occupancy is reduced, going from 0.09% to 1.17%.

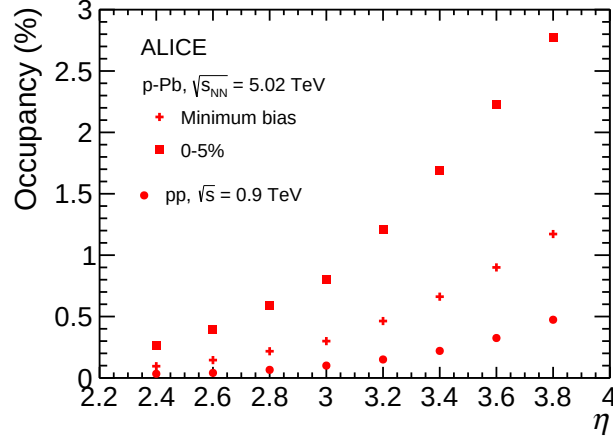


Figure 3.6: Occupancy as a function of pseudorapidity for pp collisions at 0.9 TeV and p–Pb collisions at 5.02 TeV for ALICE data.

3.1.6 Photon reconstruction

Reconstruction of photons is performed on cleaned and calibrated data. An incident photon is expected to deposit a larger amount of energy (measured in ADC units) and produce a signal in a larger number of cells compared to an incident charged hadron on the PRE plane of the PMD. Using a nearest-neighbor clustering algorithm [10, 13, 14], contiguous cells having non-zero energy deposition are grouped together, forming clusters. These clusters are known as super clusters. Two super clusters are separated by the cells having zero energy deposition. This is called crude clustering, which is used in this analysis.

After reconstruction, all information is stored in terms of clusters. Each cluster carries information, such as the number of fired cells contained in the cluster, the position of the centroid of the cluster, and the total energy deposition in the cluster.

3.1.6.1 Photon–hadron discrimination

The reconstructed clusters consist of clusters originating from both incident photons and charged hadrons. To discriminate between photon and hadron clusters, a suitable thresholds on the number of fired cells and the energy deposited in clusters are applied. The number of clusters that satisfy the discrimination threshold conditions is termed as $N_{\gamma\text{-like}}$ clusters. A similar condition in discrimination threshold as used in Ref. [11], namely number of cells greater than 2 and energy deposition greater than 9 times the MPV (Most Probable Value of the charged pion ADC distribution from a Landau distribution function fitted to the data), is applied to obtain the distributions of $N_{\gamma\text{-like}}$ clusters. The $N_{\gamma\text{-like}}$ clusters provide a photon-rich sample; however, there are contaminations due to residual background from hadron clusters and from secondary particles (i.e. particles produced in interactions with the upstream material in front of the PMD) that reduce the purity of the sample. The application of the rejection criteria also removes some of the actual photons from the sample. The rejection of actual photons and contamination from hadronic contributions within the sample of $N_{\gamma\text{-like}}$ clusters can be estimated by measuring quantities such as efficiency and purity using MC simulations as discussed in Sec. 3.1.8.

3.1.7 Quality checks

After the photon reconstruction process is completed, we perform quality assurance tests of the reconstructed data before physics analysis.

3.1.7.1 Study of cluster XY-distributions

First, we study the XY-distribution of clusters in the preshower plane of the PMD. The distribution of clusters for pp, p–Pb, and Pb–p collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shown in Fig. 3.7, 3.8, and 3.9 respectively. The left plots are for reconstructed data, while the right plots are for anchored simulation (see Sec. 3.1.8). The X-axis

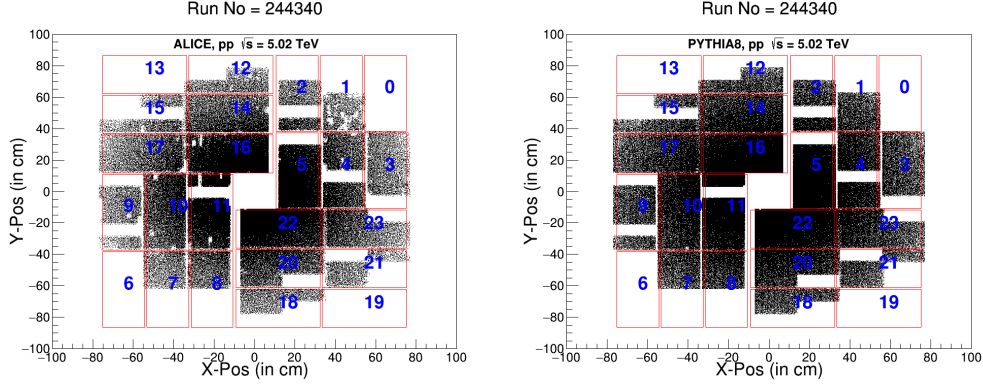


Figure 3.7: Distribution of clusters in the preshower plane of PMD in pp collisions at $\sqrt{s} = 5.02$ TeV obtained from ALICE data (left) and PYTHIA 8 (right).

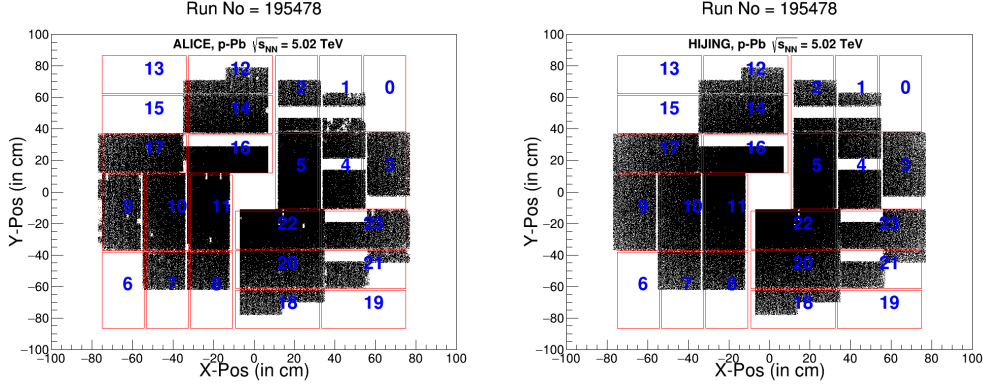


Figure 3.8: Distribution of clusters in the preshower plane of PMD in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV obtained from ALICE data (left) and HIJING (right).

and Y-axis represent the X-position and Y-position of the clusters, respectively. The numbers shown on the plot correspond to the module number. The non-functional modules and chains during the actual data taking are removed from the simulation as well. If there is any presence of a hot cell, it should be visible in the plots as the concentrated points. After the data cleanup and calibration, no hot cell is visible in the plots.

3.1.7.2 Study of correlation between PMD and V0A

The V0A detector is positioned in front of the PMD and has the pseudorapidity coverage $2.8 < \eta_{lab} < 5.1$ that overlaps with the PMD coverage ($2.3 < \eta_{lab} < 3.9$). The

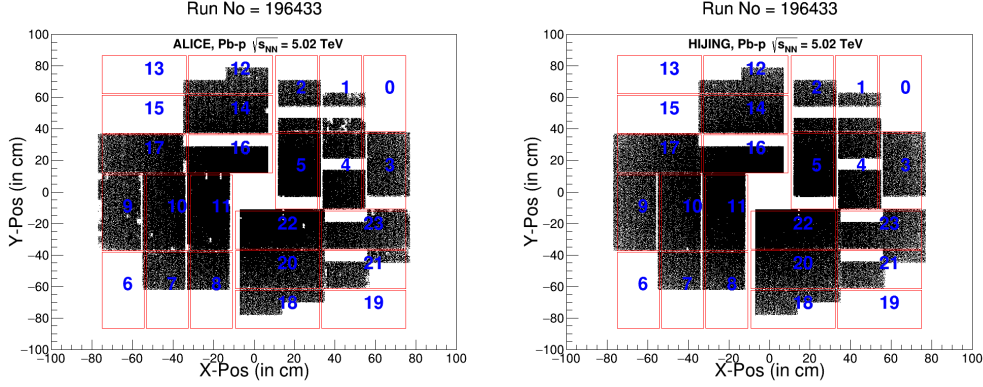


Figure 3.9: Distribution of clusters in the preshower plane of PMD in Pb-p collisions at $\sqrt{s_{NN}} = 5.02$ TeV obtained from ALICE data (left) and HIJING (right).

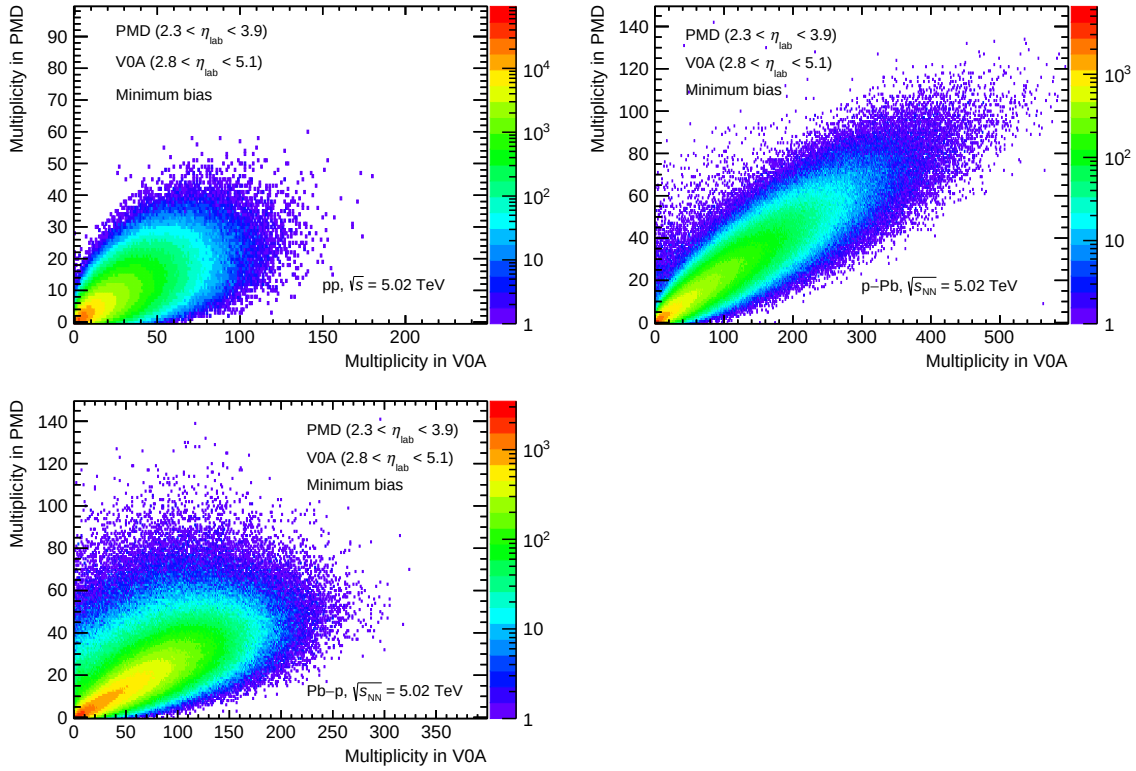


Figure 3.10: Correlation between $N_{\gamma\text{-like}}$ clusters and the raw multiplicity from V0A detector in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions.

V0A detects charged particles while the PMD measures inclusive photons (mostly from π^0 decay). Therefore, we expect a correlation between the multiplicities measured by V0A and PMD. Figure 3.10 shows the correlation between $N_{\gamma\text{-like}}$ clusters

from the PMD and the raw multiplicity from the V0A detector for pp (top left), p-Pb (top right), and Pb-p (bottom) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Although these multiplicities are at a raw level without any corrections, nevertheless, a reasonable correlation is observed, as expected.

3.1.8 Theoretical Monte Carlo models and simulation framework

In the measurements of inclusive photon multiplicity, the corrections for instrumental effects and the evaluation of the systematic uncertainties are performed with the help of Monte Carlo (MC) event generators. For pp collisions, PYTHIA 8 (v8.243) with the Monash 2013 tune [15] and EPOS LHC [16] are used whereas HIJING (v1.36) [22] and DPMJET (v3.0-5) [17] are used for p-Pb collisions.

The PYTHIA 8 event generator is a standard tool for the generation of high energy physics collisions dominantly based on $2 \rightarrow 2$ hard scattering processes. In pp interactions, the total hadronic cross section is obtained from the parameterization of Donnachie and Landshoff [19]. The diffractive components of the inelastic cross-section are described by Schuler-Sjostrand model [20]. Multiparton interactions (MPI) are described by an impact-parameter dependent approach [21] where protons are considered as extended objects, and therefore, collisions may vary from central to peripheral. More central means a bigger overlap between the colliding cloud of partons, which leads to a large number of average MPIs per collision, and thereby, the number of produced particles is increased. MPI are also relevant to describe the modelling of soft underlying event (UE) in PYTHIA 8. An MPI-based model is implemented in PYTHIA 8 to introduce beam remnants and colour reconnection wherein all the gluons of lower- p_{T} interactions are merged with the colour-flow dipoles of a higher- p_{T} one in such a way as to minimize the total string length [22, 23]. It has been shown that colour reconnection plays an important role in describing the scale of charged-particle pseudorapidity density as a function of multiplicity [24] in pp collisions. The description of hadronization mechanisms is based

on the Lund string fragmentation framework [25]. In Monash tune of PYTHIA 8, the parameters relevant for initial-state radiation and MPI are tuned by using the minimum-bias, Drell-Yan, and underlying event data from the Tevatron, SPS and LHC.

EPOS is a parton-based MC model with flux tube initial condition for hadron-hadron collisions. It can also be used for heavy-ion collisions as well as cosmic ray air shower simulations. EPOS uses parton-based Gribov Regge theory to describe soft interactions. EPOS LHC is the updated version of EPOS tuned to LHC data. In this tune, the modelling of radial flow has been modified via a different parametrization for a small volume with a high density of thermalized matter (core) reached in pp interactions [16] compared to the large volume produced in heavy-ion collisions.

HIJING is a pQCD-inspired MC model aimed particularly at the study of jets and multiple minijets productions and their interactions with the dense partonic medium produced in heavy-ion collisions. It also allows the study of particle production in high-energy hadron-hadron and hadron-nucleus collisions. In pA and AA collisions, multiple interactions are simulated using binary approximation and the Glauber model and the parton shadowing effects are taken into account using a parameterized parton distribution function inside the nucleus. HIJING uses PYTHIA to generate kinematic variables for hard scatterings and JETSET for jet fragmentation. The soft interactions in HIJING are described by Lund FRITIOF [26] and Dual Parton Model (DPM) [27]. For the jet fragmentation and hadronization, HIJING uses the prescription described in the Lund fragmentation model.

The DPMJET is a multi-purpose MC model based on the Dual Parton Model capable of simulating hadron-hadron, hadron-nucleus, nucleus-nucleus, photon-hadron, photon-photon and photon-nucleus interactions from a few GeV up to the highest cosmic-ray energies. It uses Glauber–Gribov multiple scattering formalisms to calculate the nuclear cross sections. DPMJET III combines all features of DPMJET II, DTUNUC 2 and PHOJET 1.12. It uses Reggeon theory for soft interactions and

perturbative QCD for hard interactions.

The generated particles from these event generators are transported through the experimental setup using the GEANT 3 software package [16], which includes a detailed description of the apparatus geometry and the detector response via the AliRoot software framework [29]. These simulations include realistic experimental conditions and exact detector settings as used during the data-taking and are known as “anchored simulations”. For example, in the case of PMD simulation, all hot and non-functional detector cells, as observed in the experimental data, are discarded from the simulations as evident from Fig. 3.7 (right), 3.8 (right), and 3.9 (right). The reconstruction and analysis of these simulated events are performed using the same algorithms as used in the case of experimental data. The number of photons produced from the event generators within the PMD coverage before passing through the GEANT 3 framework (i.e. without detector effects) are called as true or incident photons (abbreviated $N_{\gamma\text{-true}}$ or $N_{\gamma\text{-incident}}$). The number of photons which are reconstructed by the PMD after the detector effects are called as reconstructed or detector-level photons (abbreviated $N_{\gamma\text{-like}}$). In the simulation, the response of the PMD (in terms of the number of fired cells and energy deposition) to the incident particles is found to reproduce fairly well the results from the test beam data as discussed in Ref. [11]. Table 3.2 summarizes the details of simulated data samples used in this analysis.

3.1.8.1 Efficiency and Purity

As discussed in Sec. 3.1.6, the $N_{\gamma\text{-like}}$ clusters are contaminated by secondary particles and hadronic clusters. The efficiency (ϵ_γ) and purity (f_p) of obtaining $N_{\gamma\text{-like}}$ clusters are determined using the anchored simulations. The ϵ_γ and f_p are defined as

$$\epsilon_\gamma = \frac{N_{\gamma\text{-detected}}}{N_{\gamma\text{-incident}}}; \quad f_p = \frac{N_{\gamma\text{-detected}}}{N_{\gamma\text{-like}}};$$

where $N_{\gamma\text{-incident}}$ is the number of photons which are produced by the MC generators

Table 3.2: Details of MC production used in this analysis

Generator name	MC Period	No. of events after event selection criteria [*]
HIJING	LHC20e1	13.7 M (p-Pb) and 3.4 M (Pb-p)
HIJING (+10% material) [†]	LHC21c12a	7 M (p-Pb) and 1 M (Pb-p)
DPMJET	LHC21c11	16 M (p-Pb) and 1 M (Pb-p)
PYTHIA8	LHC21j2a	1 M
EPOS LHC	LHC21j7, LHC21j7b	0.5 M

^{*} The same event selection criteria as discussed in Sec. 3.1.2 are considered in simulation.

[†] Here, we have increased the density of the material as a part of the systematic study as discussed in Sec. 3.2.1.

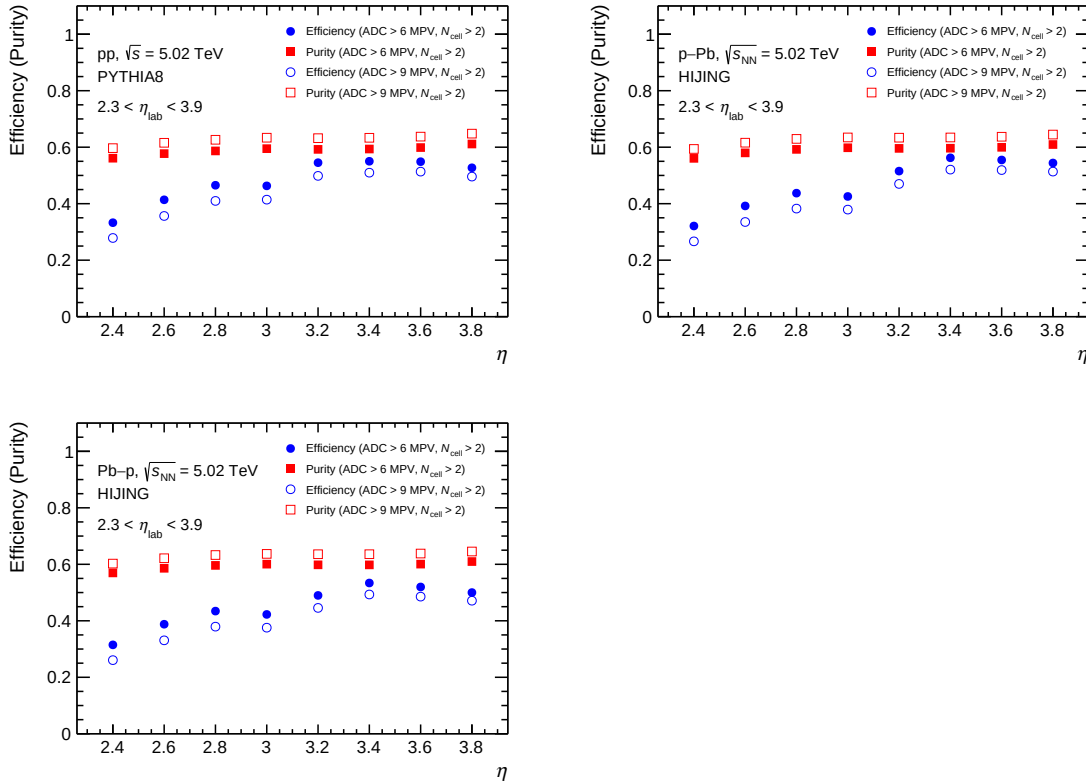


Figure 3.11: Efficiency and purity as a function η for pp (top left), p-Pb (top right), and Pb-p (bottom) collisions.

within the PMD coverage and $N_{\gamma\text{-detected}}$ is the number of identified/actual photon clusters from the sample of $N_{\gamma\text{-like}}$ clusters. The efficiency and purity values obtained

with various thresholds are shown in Fig. 3.11. The efficiency of the detector is found to mildly depend on the pseudorapidity, and its values lie within 30 to 55%. It is also observed that purity is not much sensitive to pseudorapidity. As expected, for higher (lower) threshold cuts, purity is higher (lower), and efficiency becomes low (high). Figure 3.12 shows the values of efficiency and purity as a function η for various centrality classes obtained using V0A (top left), ZNA (top right), and CL1 (bottom) estimators in p-Pb collisions. We found that both efficiency and purity of the detector have mild dependence on centrality.

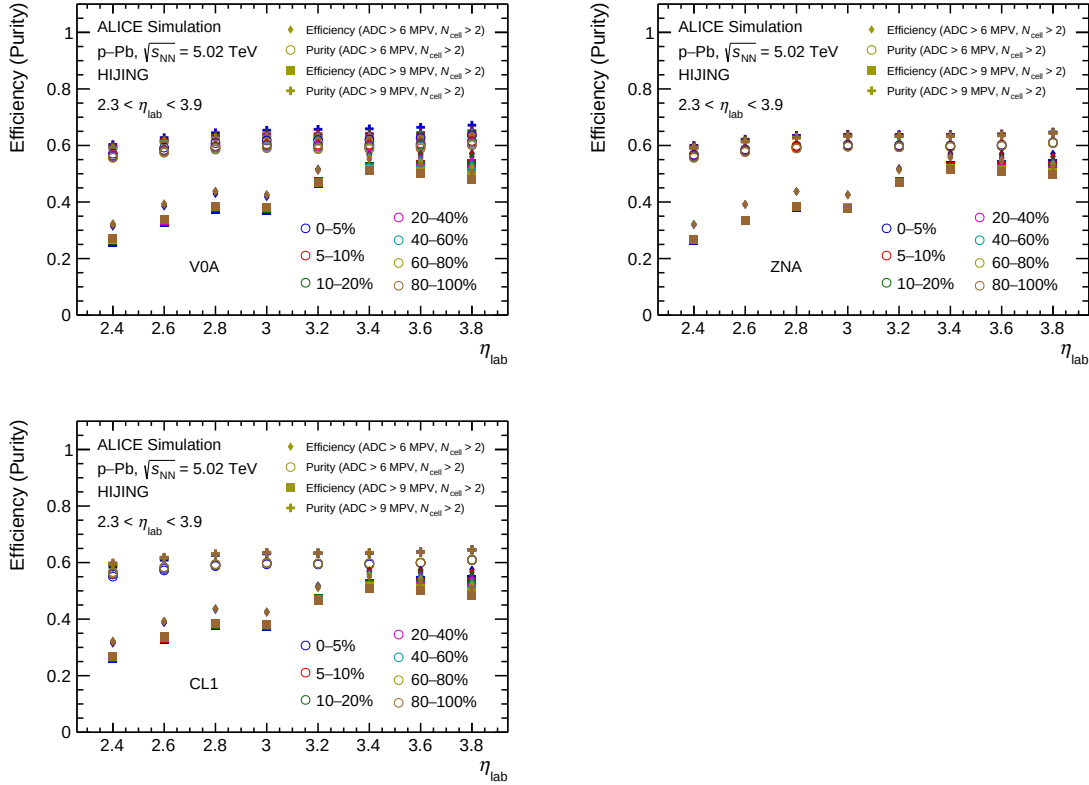


Figure 3.12: Efficiency and purity as a function η for various centrality classes obtained using V0A (top left), ZNA (top right) and CL1 (bottom) estimators in p-Pb collisions.

3.1.9 Uncorrected photon multiplicity and pseudorapidity distributions

After completing the quality assurance checks of the reconstructed data, we obtain the multiplicity ($P(N_{\gamma\text{-like}})$) and pseudorapidity distributions ($dN_{\gamma\text{-like}}/d\eta_{\text{lab}}$) of $N_{\gamma\text{-like}}$ clusters. These distributions are not yet corrected for instrumental/detector effects and, therefore, are termed as “uncorrected distributions”. Figure 3.13 shows the distributions of $P(N_{\gamma\text{-like}})$ and $dN_{\gamma\text{-like}}/d\eta_{\text{lab}}$ in the forward pseudorapidity region $2.3 < \eta_{\text{lab}} < 3.9$ for minimum bias pp, p-Pb, and Pb-p collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The uncorrected $dN_{\gamma\text{-like}}/d\eta_{\text{lab}}$ as a function of η for seven centrality classes in p-Pb collisions are shown in Fig. 3.14 for V0A (top left), ZNA (top right), and CL1 (bottom) centrality estimators.

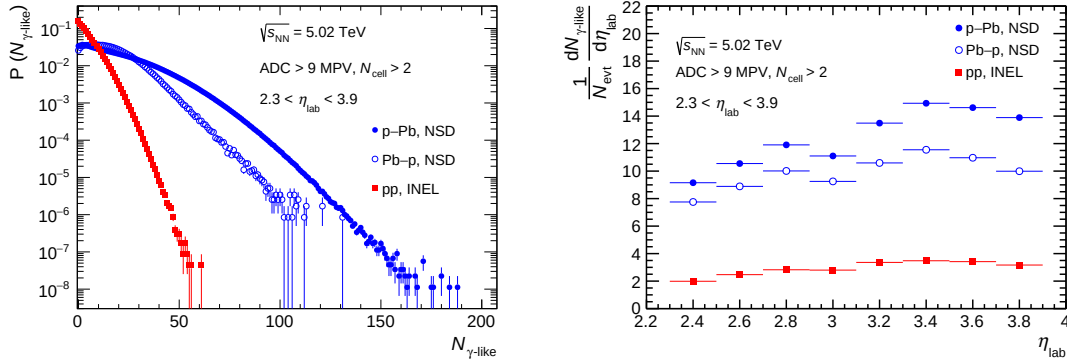


Figure 3.13: Uncorrected multiplicity (left) and pseudorapidity (right) distributions of $N_{\gamma\text{-like}}$ clusters for $\text{ADC} > 9$ MPV and $N_{\text{cell}} > 2$ in pp, p-Pb, and Pb-p collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

3.1.10 Correction procedure

The uncorrected distributions of $N_{\gamma\text{-like}}$ clusters are distorted by several instrumental effects such as photon detection inefficiency, limited acceptance, contaminations from hadrons and secondary particles etc. A set of correction procedures is adopted to obtain the corrected N_{γ} distributions.

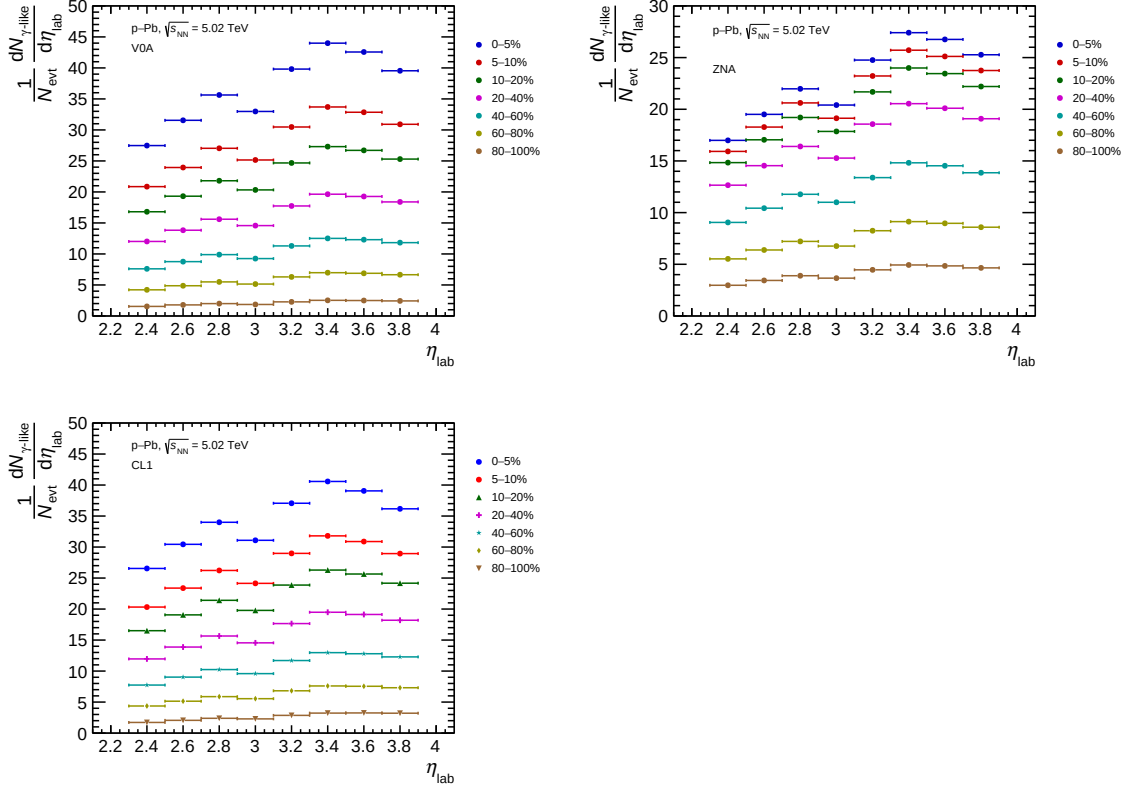


Figure 3.14: Uncorrected pseudorapidity distributions of $N_{\gamma\text{-like}}$ clusters in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for seven centrality classes for VOA (top left), ZNA (top right) and CL1 (bottom) centrality estimators.

3.1.10.1 Method of unfolding

These instrumental effects are corrected for via a response matrix R_{mt} extracted using anchored MC simulations. PYTHIA 8 with the Monash 2013 tune to generate pp collisions while HIJING event generator is used for p-Pb (and Pb-p) collisions. Inelastic pp collisions can be classified into two processes: diffractive and non-diffractive (ND). The ND interactions are the dominant processes in pp collisions. According to Regge theory [30], diffractive scattering occurs via the exchange of Pomerons. In single diffractive (SD) processes, the exchanged Pomeron interacts, and one of the protons breaks up, producing particles of the diffractive system of mass M_X . In double diffractive (DD) processes, both protons break up. It was found

that the M_X distribution for the SD processes in experimental data [31, 32] differs from the one predicted by PYTHIA 8 simulations [33]. To account for this effect in simulation, diffraction-tuned event generators (which can reproduce diffraction cross sections and the shapes of the M_X distribution obtained from data) were used in previous charged-particle measurements by ALICE [4, 34]. In this work, the M_X distribution of SD events in PYTHIA 8 with the Monash 2013 tune is reweighted to match the diffraction-tuned PYTHIA simulation used in previous 7 TeV analysis [4]. The response matrix in pp collisions is constructed using this reweighted PYTHIA 8 simulation.

Figure 3.15 shows the graphical representation of the detector response matrices for minimum bias pp, p-Pb, and Pb-p collisions in terms of the correlation between the true photon multiplicity ($N_{\gamma\text{-true}}$) from the event generator and the reconstructed photon multiplicity ($N_{\gamma\text{-like}}$) in the simulated events. The mean ($\langle N_{\gamma\text{-like}} \rangle$) and width ($\sigma_{N_{\gamma\text{-like}}}$) of the distribution of $N_{\gamma\text{-like}}$ are presented in Fig. 3.16 and Fig. 3.17 as a function of $N_{\gamma\text{-true}}$ for pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The resolution of photon multiplicity reconstruction in pp (p-Pb) collisions at $N_{\gamma\text{-true}} = 44$ (140) is found to be $\sim 12\%$ ($\sim 6\%$). Simulation studies have shown that the PMD is sensitive to transverse momenta (p_{T}) as low as ~ 50 MeV/ c [11]. In the correction procedure, true photons of all p_{T} are considered, which makes the present photon measurement inclusive. In the simulation, the fraction of inclusive photons having p_{T} below 50 MeV/ c is estimated to be about 16% for both pp and p-Pb collisions. The matrix element R_{mt} represents the conditional probability that an event with true multiplicity t is measured as an event with multiplicity m . The distorted measured distribution (M) can be expressed as $M = R_{mt}T$. One can, therefore, recover the true distribution (T) for given M as

$$T = R_{mt}^{-1}M. \quad (3.1)$$

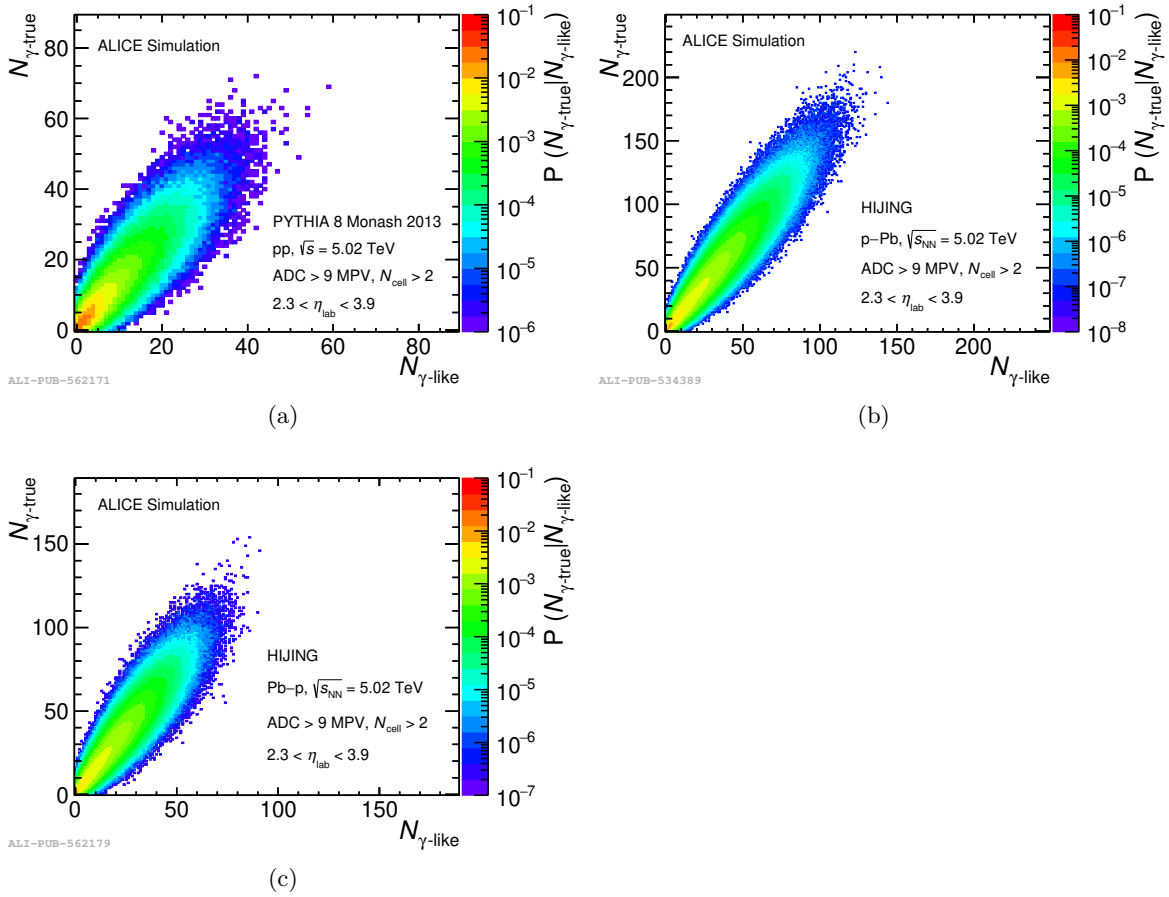
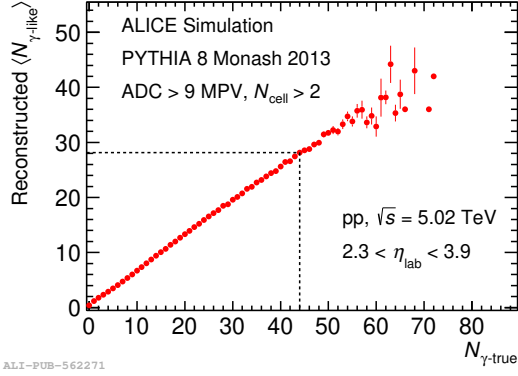


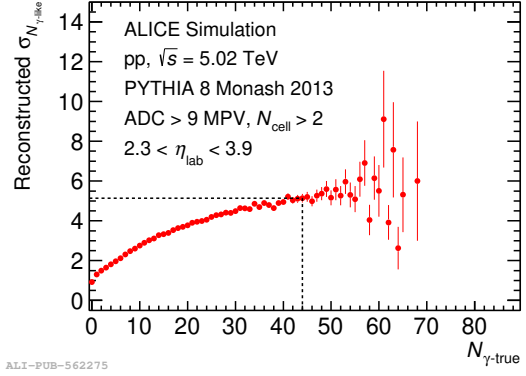
Figure 3.15: Graphical representation of the detector response matrices for three different collision systems: pp (a), p-Pb (b) and Pb-p (c). The reconstructed and true photon multiplicities are denoted as $N_{\gamma\text{-like}}$ and $N_{\gamma\text{-true}}$, respectively, obtained from simulations using PYTHIA 8 with the Monash 2013 tune for pp collisions and HIJING for p-Pb and Pb-p collisions.

However, the matrix R_{mt} may be singular and one can calculate inverse matrix R_{mt}^{-1} only if R_{mt} is not singular. Furthermore, even if R_{mt} can be inverted, the results obtained with Eq. 3.1 contain oscillations mainly because of finite statistics in the response matrix. To overcome this problem, a regularized unfolding method based on Bayes' theorem [35] using the RooUnfold software package [36] is used to correct the measured $N_{\gamma\text{-like}}$ distributions following the description outlined in Refs. [4, 11, 34, 37, 38].

In order to optimize the parameters (number of iterations) of the Bayesian un-

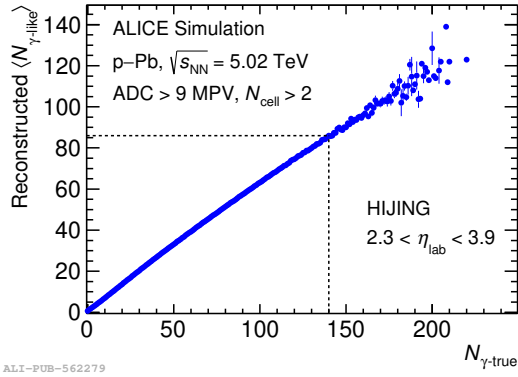


(a)

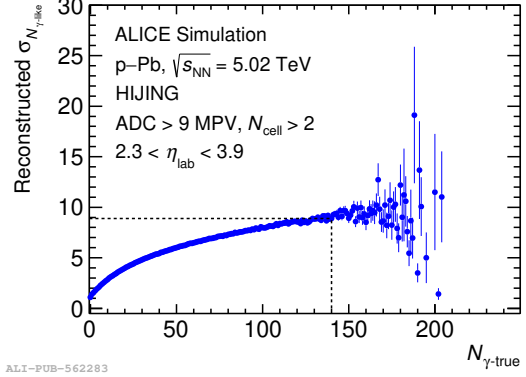


(b)

Figure 3.16: The mean (a) and width (b) of the distribution of reconstructed photon multiplicity ($N_{\gamma\text{-like}}$) as a function of true photon multiplicity ($N_{\gamma\text{-true}}$) are presented for pp collisions at $\sqrt{s} = 5.02$ TeV. The dotted lines correspond to $N_{\gamma\text{-true}} = 44$ up to which the results are reported in this work.



(a)



(b)

Figure 3.17: The mean (a) and width (b) of the distribution of reconstructed photon multiplicity ($N_{\gamma\text{-like}}$) as a function of true photon multiplicity ($N_{\gamma\text{-true}}$) are presented for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The dotted lines correspond to $N_{\gamma\text{-true}} = 140$, up to which the results are reported in this work.

folding method, a MC closure test is performed using simulations. The simulated data are divided into two statistically independent samples for the closure test. The response matrix is built using one set, whereas the other set is used to obtain the reconstructed ($N_{\gamma\text{-like}}$) distributions, correct them using Eq. 3.1, and compare the result to the true distributions. The sensitivity of the results is checked by varying

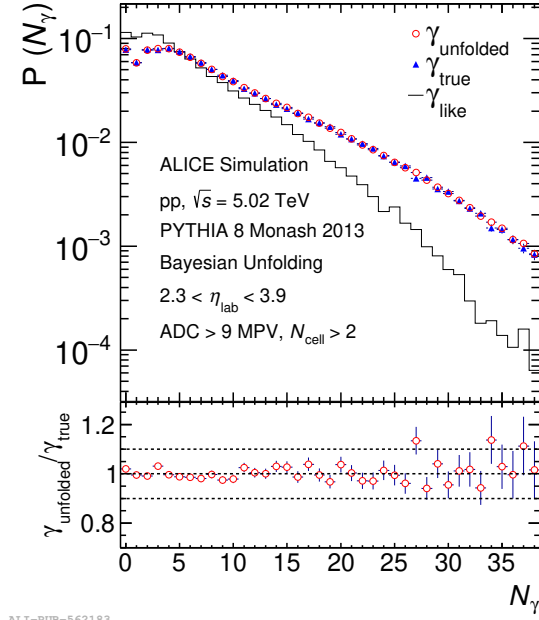
the number of iterations, and a value corresponding to the best performance of the closure test is chosen as the optimized number of iterations. To understand the best performance, we measure the Q -value, which is defined as

$$Q = \frac{1}{t'' - t' + 1} \sum_{t=t'}^{t''} \left| \frac{T_t - U_t}{e_t} \right|, \quad (3.2)$$

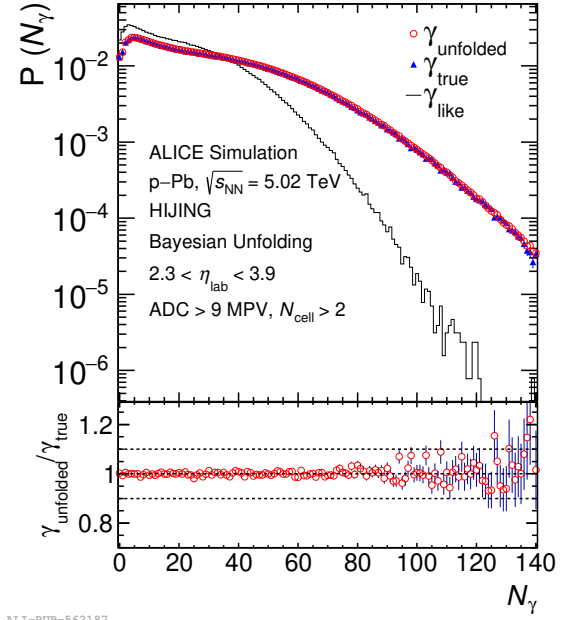
where T_t and U_t are the true and unfolded distributions and e_t is the statistical uncertainty on T_t . In Eq. 3.2, it is clearly observed that when U_t is close to T_t , the value of Q tends to zero. Thus, the optimized number of iterations is set to the number for which Eq. 3.2 gives the minimum Q -value.

Figure 3.18 shows the performance of the closure tests for pp (Fig. 3.18(a)), p-Pb (Fig. 3.18(b)), and Pb-p (Fig. 3.18(c)) collisions for the optimized number of iterations (1 for pp, 4 for p-Pb, and 2 for Pb-p collisions). The upper panels show the true, reconstructed ($N_{\gamma\text{-like}}$) and unfolded photon multiplicity distributions. In the bottom panels, the ratios of the unfolded to the true photon multiplicity distributions are shown. The ratio plots indicate that there is good agreement between the unfolded and true distributions except at high multiplicities where fluctuations arise due to the limited size of the simulated sample. The measured distributions of $N_{\gamma\text{-like}}$ clusters in experimental data are unfolded using the optimized number of iterations. An alternate method of unfolding, Singular Value Decomposition (SVD) [39], is also used and consistent results are obtained. In this method, the response matrix can be factorized in the form $R_{mt} = USV^T$, where U and V are orthogonal matrices and S is a diagonal matrix with non-negative diagonal elements. These diagonal elements are called singular values of the matrix R_{mt} . Regularization is applied by using a smooth cut-off on small singular-value contributions suppressing large fluctuations in the unfolded distribution.

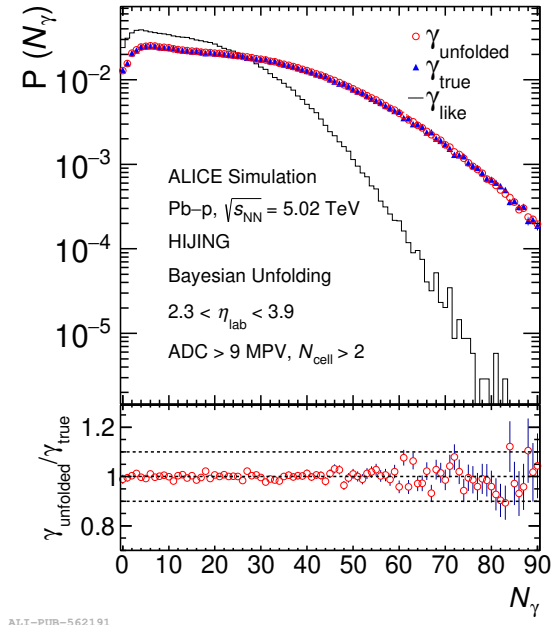
To correct the distribution of $dN_{\gamma\text{-like}}/d\eta_{\text{lab}}$, we first divide the whole coverage ($2.3 < \eta_{\text{lab}} < 3.9$) into eight η_{lab} rings and obtain the distributions of $P(N_{\gamma\text{-like}})$



(a)



(b)



(c)

Figure 3.18: MC closure test of the unfolding method for pp (a), p-Pb (b), and Pb-p (c) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The reconstructed, unfolded and true photon multiplicity distributions are presented in the top panels. The ratios of unfolded to true multiplicity distributions are shown in the bottom panels.

for each of these rings. Then, we perform the unfolding of $P(N_{\gamma\text{-like}})$ separately for eight η_{lab} rings using the same unfolding procedure. Mean values of the unfolded multiplicity distributions in each η_{lab} ring are determined to obtain the unfolded pseudorapidity distribution of inclusive photons.

3.1.10.2 Corrections for trigger and vertex reconstruction efficiency

The unfolded results in MB collisions are then corrected for the trigger (ϵ_{Trig}) and vertex reconstruction (ϵ_{Vtx}) efficiencies. A similar procedure as discussed in Ref. [11] is adopted to estimate ϵ_{Trig} and ϵ_{Vtx} using MC simulations. These efficiencies can be defined as

$$\epsilon_{\text{Trig}} = \frac{N_{\text{Trig}}}{N_{\text{All}}}, \quad \epsilon_{\text{Vtx}} = \frac{N_{\text{TrigVtx}}}{N_{\text{Trig}}} \quad (3.3)$$

where N_{All} and N_{Trig} correspond to the number of all simulated events and of triggered events, respectively, and N_{TrigVtx} corresponds to triggered events with reconstructed vertex. The values of ϵ_{Trig} and ϵ_{Vtx} for pp, p-Pb, and Pb-p collisions are reported in Table 3.3. The effect of ϵ_{Trig} and ϵ_{Vtx} on the observable, $dN_{\gamma}/d\eta_{\text{lab}}$ is studied by calculating the correction factors which are defined as,

$$C_{\text{Trig}} = \frac{\frac{1}{N_{\text{All}}} \frac{dN_{\gamma\text{true}}}{d\eta_{\text{lab}}}(\text{All})}{\frac{1}{N_{\text{Trig}}} \frac{dN_{\gamma\text{true}}}{d\eta_{\text{lab}}}(\text{Trig})}, \quad C_{\text{Vtx}} = \frac{\frac{1}{N_{\text{Trig}}} \frac{dN_{\gamma\text{true}}}{d\eta_{\text{lab}}}(\text{Trig})}{\frac{1}{N_{\text{TrigVtx}}} \frac{dN_{\gamma\text{true}}}{d\eta_{\text{lab}}}(\text{TrigVtx})}.$$

The unfolded pseudorapidity distributions are then multiplied with these correction factors to obtain the corrected distributions. Similarly, C_{Trig} and C_{Vtx} are estimated as a function of $N_{\gamma\text{-true}}$ and the unfolded multiplicity distributions are then corrected by multiplying the content of each multiplicity bin by its C_{Trig} and C_{Vtx} values.

The V0AND trigger used to select p-Pb events is not fully efficient for NSD events. The correction for the V0AND trigger inefficiency and the imperfect description in the MC of the vertex reconstruction efficiency would mainly concern the most peripheral event class (80–100%). In this work, centrality classes have

Table 3.3: Trigger and vertex reconstruction efficiencies for INEL events in pp collisions and NSD events in p-Pb and Pb-p collisions. Uncertainties listed are total uncertainties. Statistical uncertainties are negligible.

System	Trigger efficiency (%)	Vertex reconstruction efficiency (%)
pp	94.5 ± 1.2	95.0 ± 0.6
p-Pb	98.5 ± 0.9	99.8 ± 0.1
Pb-p	98.5 ± 0.9	99.8 ± 0.1

been defined as percentiles of the visible cross section and the centrality-dependent pseudorapidity distributions are not corrected for trigger inefficiencies as was also reported in Ref. [5].

3.2 Estimation of systematic uncertainties

The contributions of the different sources of systematic uncertainties associated with the measurements of multiplicity and pseudorapidity distributions of inclusive photons in minimum bias pp, p-Pb, and Pb-p collisions are summarized in Table 3.4. For the multiplicity distributions of all three collision systems, the values of systematic uncertainties for different sources are presented as a function of N_γ in Fig. 3.19 and reported in Table 3.4 for three characteristic multiplicity values at 0, the mean $\langle m \rangle$, and when $P(N_\gamma) = 10^{-3}$. For the pseudorapidity distributions, we evaluate the systematic uncertainty as a function of η and finally consider a band based on the highest value of the uncertainty to avoid bin-to-bin fluctuations. Tables 3.5, 3.6, and 3.7 summarize the contributions of the different sources of systematic uncertainties for the measurements of pseudorapidity distributions in centrality classes of p-Pb collisions. The results of p-Pb collisions in centrality classes are not affected by the uncertainties on the event selection and diffraction mass. The total systematic uncertainties are calculated by adding the contributions from the individual sources in quadrature. The methods used for the estimation of the systematic uncertainties

Table 3.4: Contributions to systematic uncertainties (in percent) in the measurements of pseudorapidity and multiplicity distributions of inclusive photons in pp, p-Pb, and Pb-p collisions. For multiplicity distributions, numbers are given at multiplicity values of 0, the mean $\langle m \rangle$ and when $P(N_\gamma) = 10^{-3}$.

Sources	$dN_\gamma/d\eta_{\text{lab}}$ analysis			$P(N_\gamma)$ analysis								
	pp	p-Pb	Pb-p	pp			p-Pb			Pb-p		
				N_γ 0	N_γ $\langle m \rangle$	$P(N_\gamma)$ 10^{-3}	N_γ 0	N_γ $\langle m \rangle$	$P(N_\gamma)$ 10^{-3}	N_γ 0	N_γ $\langle m \rangle$	$P(N_\gamma)$ 10^{-3}
Upstream material	7.0	8.2–10.1	8.7–9.9	3.0	2.5	20.0	15.2	3.4	34.0	18.5	3.7	37.2
Hadron and secondary contamination	1.9	1.9	2.0	1.4	1.4	7.5	6.7	1.2	1.2	0.7	1.1	7.2
Event generator for response matrix	2.5	3.2	1.0	2.6	3.0	5.0	3.2	3.6	16.0	3.0	3.5	14.4
Unfolding method	3.1	0.6	1.1	25.0	3.7	23.0	11.0	1.2	1.2	11.0	3.0	3.0
Event selection efficiency	1.2	0.9	0.9	19.0	1.6	1.6	33.5	1.2	0.7	34.0	1.0	0.8
Diffraction Shape	2.1	n/a	n/a	1.3	4.0	5.3	n/a	n/a	n/a	n/a	n/a	n/a
Diffraction ratio	2.3	n/a	n/a	7.4	4.6	0.2	n/a	n/a	n/a	n/a	n/a	n/a
Total	8.9	9.1–10.8	9.1–10.2	32.8	8.4	32.0	39.3	5.4	37.6	40.3	6.0	40.7

are discussed in the following subsections.

Table 3.5: Contributions to systematic uncertainties (in percent) in the measurements of centrality dependent pseudorapidity distributions of inclusive photons using the V0A estimator in p–Pb collisions.

Sources	0–5%	5–10%	10–20%	20–40%	40–60%	60–80%	80–100%
Upstream material	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1
Hadron and secondary contamination	1.38	1.54	1.65	2	1.98	2.9	3.8
Event generator for response matrix	1.04	2.79	2.34	1.1	2.82	2.52	1.74
Unfolding method	1.1	1.9	2.28	2.8	2.6	3.5	6.9
Total	8.5–10.3	9.0–10.8	9.0–10.8	9.0–10.7	9.3–11.0	9.7–11.3	11.5–13.0

3.2.1 Effect of upstream material

One of the major contributions to the systematic uncertainties comes from the uncertainty in the implementation of upstream material in front of the PMD (i.e., the material between the nominal IP and the PMD) in the GEANT 3 description of the ALICE apparatus. At forward rapidity, the material budget was studied in detail for the charged-particle multiplicity measurements [34, 40, 41] (see also Sec. 4.2.1). Based on this study, an upper limit of the material budget uncertainty of 10% is considered in this analysis. To study the effect of this on photon counting in p–Pb and Pb–p collisions, two response matrices using the HIJING event generator are considered, one with the default material description and the other with a 10% in-

Table 3.6: Contributions to systematic uncertainties (in percent) in the measurements of centrality dependent pseudorapidity distributions of inclusive photons using the CL1 estimator in p-Pb collisions.

Sources	0–5%	5–10%	10–20%	20–40%	40–60%	60–80%	80–100%
Upstream material	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1
Hadron and secondary contamination	2.1	2.3	2.1	2.3	2.4	2.1	3.1
Event generator for response matrix	3.0	3.0	3.1	3.0	2.9	3.1	3.0
Unfolding method	1.7	2.9	2.6	2.9	3.1	2.8	2.8
Total	9.2–10.9	9.5–11.2	9.4–11.0	9.5–11.1	9.6–11.2	9.5–11.1	9.7–11.3

crease in the overall material of the ALICE apparatus. The measured distribution of $P(N_{\gamma\text{-like}})$ in data is then unfolded using these two different matrices. The difference between the two unfolded multiplicities determines the systematic uncertainty due to the material in front of the PMD. The green line in Fig. 3.19 shows the variation of the uncertainty values as a function of N_{γ} in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions. A similar procedure is applied for each η_{lab} interval to obtain the systematic uncertainties for the pseudorapidity distributions of inclusive photons in MB events and all centrality classes. The systematic uncertainty due to material effects for pp collisions is taken from the previously published paper on inclusive photon measurement in pp collisions at $\sqrt{s} = 0.9, 2.76$, and 7 TeV [11].

Table 3.7: Contributions to systematic uncertainties (in percent) in the measurements of centrality dependent pseudorapidity distributions of inclusive photons using the ZNA estimator in p-Pb collisions.

Sources	0–5%	5–10%	10–20%	20–40%	40–60%	60–80%	80–100%
Upstream material	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1	8.2–10.1
Hadron and secondary contamination	2.1	1.3	1.6	1.6	2.1	1.7	2.6
Event generator for response matrix	1.4	1.8	2.2	3.2	3.8	3.3	2.7
Unfolding method	2.8	1.9	2.0	1.7	2.7	2.8	3.0
Total	9.1–10.8	8.7–10.5	9.0–10.7	9.2–10.9	9.7–11.3	9.5–11.1	9.6–11.2

3.2.2 Contamination in the photon sample

The photon-hadron discrimination conditions in terms of energy deposition and number of cells in clusters are optimized to minimize contaminations from hadronic clusters and secondary particles. The purity of the photon sample with the default threshold condition (energy deposition greater than 9 times the MPV and number of cells greater than 2) is found to be 65%. To estimate the systematic uncertainty due to the correction for the contamination, the analysis is repeated with a different threshold condition on energy deposition (greater than 6 times the MPV). The unfolded distributions are obtained for both cases, and the difference between these two distributions is quoted as the systematic uncertainty. The red line in Fig. 3.19

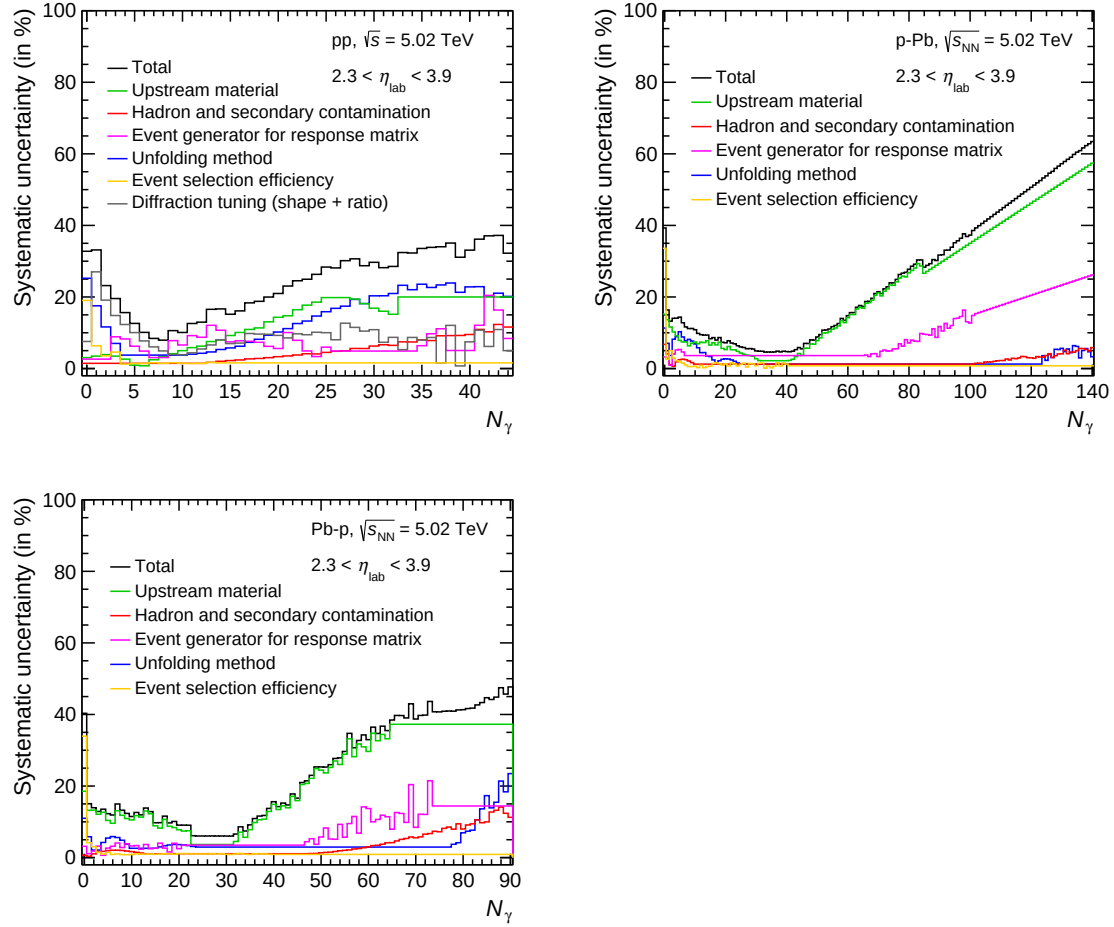


Figure 3.19: Breakdown of the contributions of the different sources of systematic uncertainties to the multiplicity distributions of inclusive photons in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

shows the variation of the uncertainty values as a function of N_γ in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions. By applying a higher threshold condition on energy deposition (greater than 12 times the MPV), the estimated systematic uncertainty with respect to the default threshold condition is found to be of the same order as the quoted one.

3.2.3 Unfolding procedure

As discussed in Sec. 3.1.10, we rely on MC models to unfold the multiplicity and pseudorapidity distributions of $N_{\gamma\text{-like}}$ clusters. The sensitivity of the unfolded results to the choice of the MC models used in the unfolding procedure is estimated by comparing the results obtained using the response matrices from two different event generators. For pp collisions, two separate response matrices are built using PYTHIA 8 with the Monash 2013 tune and EPOS LHC, whereas for p-Pb and Pb-p collisions, those are constructed using HIJING and DPMJET. These matrices are used to unfold the measured distributions of $P(N_{\gamma\text{-like}})$ and $dN_{\gamma\text{-like}}/d\eta_{\text{lab}}$ in data. The difference in the unfolded distributions is considered as the systematic uncertainty. The magenta line in Fig. 3.19 shows the variation of the uncertainty values due to the choice of the MC models as a function of N_γ in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions. The effect of the choice of the unfolding method is determined by using an alternative unfolding method, SVD, in addition to the default Bayesian method. The difference in the unfolded results is considered as the systematic uncertainty and the corresponding uncertainty values are presented as a function of N_γ in Fig. 3.19 (blue line).

3.2.4 Event selection efficiency

The systematic uncertainty due to possible imperfections in the correction for the event selection efficiency is determined by estimating the trigger and vertex reconstruction efficiencies using two different event generators. For pp collisions, the efficiency values are computed from events simulated with the PYTHIA 8 with Monash 2013 tune and EPOS LHC generators, while HIJING and DPMJET are used to obtain these efficiencies in p-Pb and Pb-p collisions. The orange line in Fig. 3.19 shows the variation of the systematic uncertainty values as a function of N_γ in pp (top left), p-Pb (top right), and Pb-p (bottom) collisions. This uncertainty mostly

influences the zero multiplicity bin in the multiplicity distributions, and it reduces significantly at large multiplicity because single and double diffraction contributions become smaller when going to higher multiplicity.

3.2.5 Diffraction mass distributions

As described in Sec. 3.1.10, the central values of the final results in pp collisions are determined using simulations with the PYTHIA 8 event generator with the Monash 2013 tune reweighted to match the measured M_X distribution in SD events. The uncertainty associated with this procedure is estimated by taking the difference between the results obtained with the reweighted mass distribution and the default one from PYTHIA 8 with Monash 2013 tune. The uncertainty related to the fractions of SD and DD events produced by PYTHIA 8 is also evaluated by varying those fractions by $\pm 30\%$ of their nominal values. The gray line in Fig. 3.19 shows the values of uncertainty arising due to unknown SD mass distributions and fractions of SD and DD events.

3.3 Results and discussions

The multiplicity and pseudorapidity distributions of inclusive photons in the forward pseudorapidity interval $2.3 < \eta_{\text{lab}} < 3.9$ measured using the PMD for pp collisions at $\sqrt{s} = 5.02$ TeV and p-Pb and Pb-p collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are presented and discussed in this section. The distributions are obtained without any selection on the transverse momentum of the photons. The obtained results are compared with predictions from MC models and available experimental measurements of charged particles.

3.3.1 Multiplicity distributions

The measured multiplicity distributions of inclusive photons are presented as probability distributions ($P(N_\gamma)$) as a function of N_γ in Fig. 3.20. The systematic uncertainty is represented by the gray bands, and the statistical uncertainty is smaller than the marker size. The measurements are obtained for pp and for both configurations of p–Pb collisions in the pseudorapidity interval $2.3 < \eta_{\text{lab}} < 3.9$. The average photon multiplicity for pp collisions is 6.44 ± 0.36 (sys), for p–Pb collisions is 29.38 ± 1.88 (sys), and for Pb–p collisions is 24.59 ± 1.52 (sys). The multiplicity range in p–Pb collisions reaches up to 140, which is about 5 times larger than its mean multiplicity. The average multiplicity in pp collisions is about 4.5 times smaller than that in p–Pb collisions. The different multiplicity distributions and average values in p–Pb and Pb–p collisions arise from the different particle production in the p-going and Pb-going hemispheres as well as from the difference in the rapidity coverage of the PMD in the centre-of-mass frame because of the Δy shift of ± 0.465 units between p–Pb and Pb–p collisions.

The results in pp collisions (Fig. 3.20(a)) are compared to the predictions from PYTHIA 8 with the Monash 2013 tune [15], PYTHIA 6 (v6.425) with the Perugia 2011 tune [42], PHOJET (v1.12) [43], and EPOS LHC [16] event generators. The ratios between MC predictions and data are shown in the bottom panels. It is observed that PYTHIA 8 with the Monash 2013 tune and EPOS LHC are unable to reproduce the inclusive photon production in pp collisions at $\sqrt{s} = 5.02$ TeV at high multiplicities. On the other hand, the Perugia 2011 tune of PYTHIA 6 and PHOJET are found to fairly describe the data within uncertainties.

The multiplicity distributions in p–Pb collisions (Fig. 3.20(b)) are compared to predictions obtained from HIJING, DPMJET, and AMPT (v2.25) [44]. None of the models could reproduce the shape of the distributions in the full multiplicity range. HIJING is closer to the data points at intermediate multiplicities. The tail

of the distribution at high multiplicity can be described by both HIJING and AMPT models within uncertainties. For Pb–p collisions (Fig. 3.20(c)), DPMJET strongly underestimates the data at high multiplicity. HIJING describes the data slightly better in the full range of multiplicity compared to AMPT.

These experimental results are expected to provide new constraints on inclusive photon production mechanisms implemented in theoretical models.

In Fig. 3.21, the measured multiplicity distributions are fitted by a weighted sum of two Negative Binomial Distributions (NBDs) (Eq. 3.4) to extract the relative contributions from soft and semihard processes in the particle production mechanisms. In Eq. 3.4, the subscripts and superscripts in the parameters indicate the respective components. The α_{soft} parameter gives the fraction of soft events. The NBD distribution, P_{NBD} , has the following parameters: the average multiplicity $\langle n \rangle$, which is found to increase with increasing $\sqrt{s}$, and the shape parameter, k , which decreases with increasing $\sqrt{s}$ in hadronic collisions [4, 11, 34].

$$P(n) = \lambda[\alpha_{\text{soft}}P_{\text{NBD}}(n, \langle n^{\text{soft}} \rangle, k^{\text{soft}}) + (1 - \alpha_{\text{soft}})P_{\text{NBD}}(n, \langle n^{\text{semihard}} \rangle, k^{\text{semihard}})] \quad (3.4)$$

where

$$P_{\text{NBD}}(n, \langle n \rangle, k) = \frac{\Gamma(n+k)}{\Gamma(k)\Gamma(n+1)} \frac{(\langle n \rangle/k)^n}{(1 + \langle n \rangle/k)^{n+k}}. \quad (3.5)$$

Double NBDs do not describe the value $P(0)$, therefore, the bin $N_\gamma = 0$ is excluded from the fit and a normalization factor λ is introduced to account for this. The systematic uncertainties associated with a) the change of photon–hadron discrimination thresholds, b) the tuning of event generator for diffraction, c) the effect of upstream material, and d) the correction of event selection efficiency produce a correlated shift of the multiplicity distributions. These correlated uncertainties are, therefore, not considered in the fitting procedure. The other sources of systematic uncertainties (uncorrelated) are taken into account in the fit. The obtained parameters from these fits are printed in bold in Table 3.8. The other set of parameters

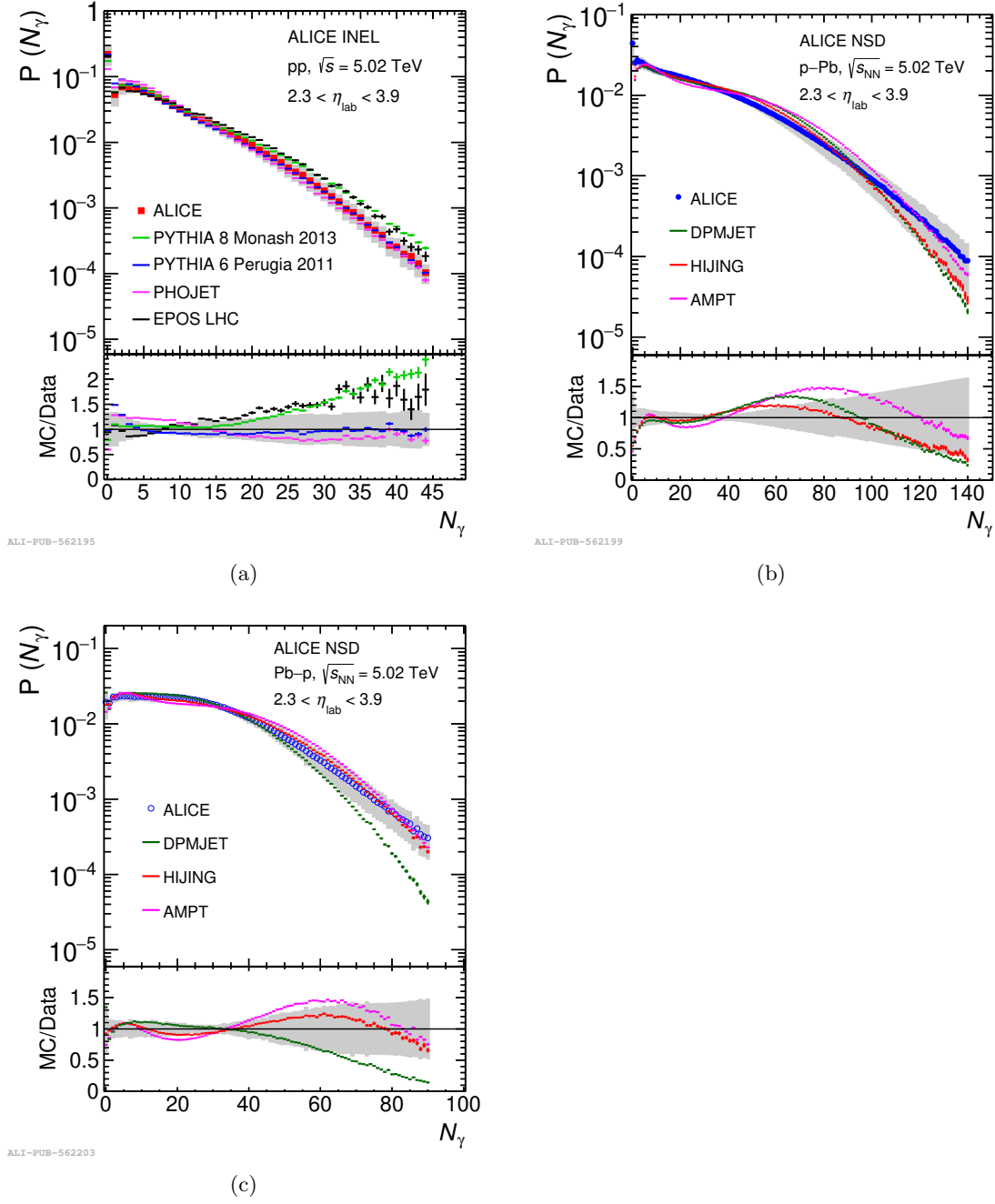
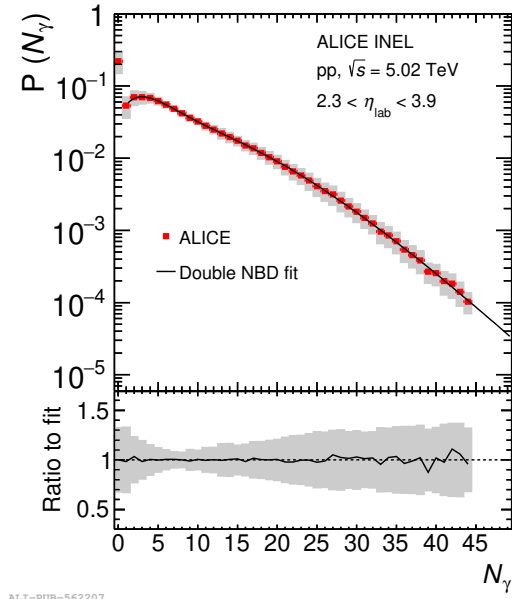
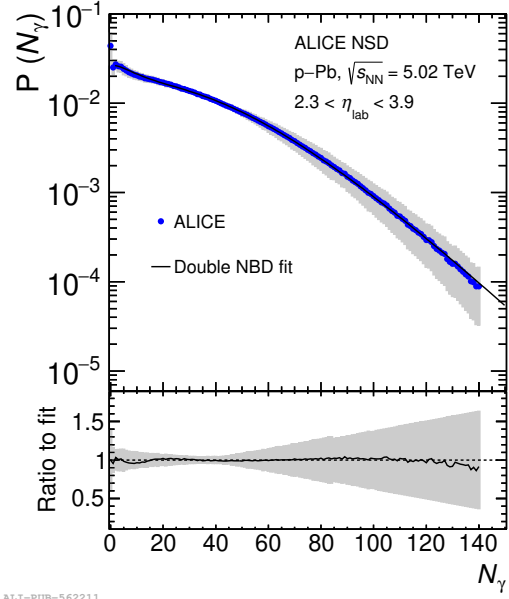


Figure 3.20: Top panels: Inclusive photon multiplicity distributions measured within $2.3 < \eta_{\text{lab}} < 3.9$ in pp (a), p-Pb (b), and Pb-p (c) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Results from various MC predictions are superimposed. Bottom panels: The ratios between MC results and data are shown. Shaded boxes represent the systematic uncertainties.

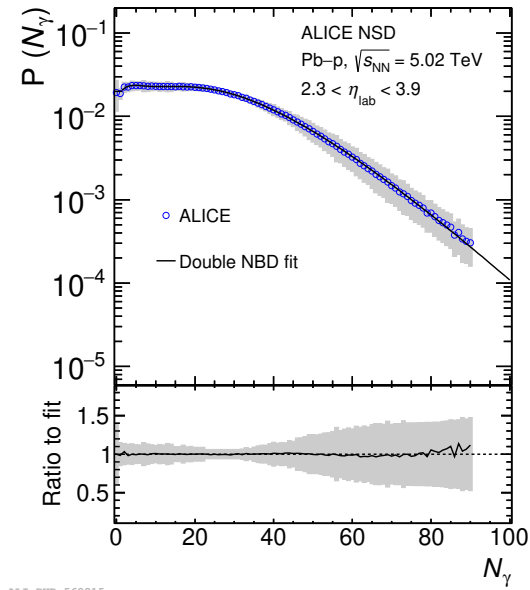
reported in Table 3.8 is obtained from the fitting of the data by considering both correlated and uncorrelated uncertainties to provide an estimate of how much the



(a)



(b)



(c)

Figure 3.21: Top panels: Multiplicity distribution of inclusive photons fitted to double NBDs for pp (a), p-Pb (b), and Pb-p (c) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Bottom panels: The ratio of the data to the fit is presented. Shaded boxes represent the systematic uncertainties.

fit parameters change due to the presence of correlations in the systematic uncertainties.

Table 3.8: Double NBD fit parameters for the inclusive photon multiplicity distributions. The obtained parameters from fits to the data by considering only uncorrelated uncertainties are printed in bold. The other set of parameters is obtained when both correlated and uncorrelated uncertainties are considered in the fitting procedure.

Collision System	λ	α_{soft}	k^{soft}	$\langle n^{\text{soft}} \rangle$	k^{semihard}	$\langle n^{\text{semihard}} \rangle$
pp	0.79 ± 0.03	0.60 ± 0.19	2.97 ± 1.16	4.65 ± 1.01	4.56 ± 1.79	13.47 ± 2.60
	0.79 ± 0.04	0.61 ± 0.28	2.97 ± 1.74	4.67 ± 1.60	4.64 ± 2.76	13.55 ± 4.07
Pb-p	0.99 ± 0.01	0.29 ± 0.10	1.65 ± 0.30	8.92 ± 2.10	4.09 ± 0.39	31.08 ± 1.31
	0.99 ± 0.01	0.31 ± 0.13	1.60 ± 0.33	9.70 ± 4.00	4.22 ± 0.65	31.56 ± 2.14
p-Pb	0.99 ± 0.01	0.62 ± 0.10	1.10 ± 0.05	18.76 ± 2.50	3.89 ± 0.30	47.21 ± 1.28
	0.98 ± 0.01	0.60 ± 0.11	1.10 ± 0.10	18.80 ± 3.60	3.64 ± 0.40	46.18 ± 1.72

The double NBD fit describes the data within uncertainties. The results show an increase in the mean multiplicity of inclusive photons with system size, whereas the shape parameter decreases with system size. Moreover, it is observed that $\langle n^{\text{semihard}} \rangle \approx 3\langle n^{\text{soft}} \rangle$ which is consistent with the results of charged-particle production at central and forward rapidities in pp collisions [4, 34].

3.3.2 Pseudorapidity distributions in NSD and INEL events

The pseudorapidity distributions of inclusive photons measured within $2.3 < \eta_{\text{lab}} < 3.9$ in pp, p-Pb, and Pb-p collisions are presented in Fig. 3.22. The gray bands represent the systematic uncertainty, and the statistical uncertainty is smaller than the marker size. The measurements are compared to the predictions from MC event generators, and the ratios between MC results and data are shown in the bottom panels.

In pp collisions (Fig. 3.22(a)), PHOJET and PYTHIA 6 with the Perugia 2011 tune models show better agreement with the data compared to EPOS LHC and PYTHIA 8 with the Monash 2013 tune. All model predictions are however found to be compatible within about 20% from the measured values, but the η_{lab} dependence is flatter in the data than in the models.

In p–Pb collisions the value of pseudorapidity density of inclusive photons is found to be slightly larger than that for Pb–p collisions as expected due to the fact that the PMD measures particles produced in the Pb-going direction in the former configuration and in the p-going direction in the latter, and also due to the different rapidity ranges covered by the PMD in the centre-of-mass frame for p–Pb and Pb–p collisions as discussed in Sec. 3.3.1. The data are compared to several models with different descriptions of particle production, all shifted by $\Delta y = 0.465$ to take into account the shift to the laboratory system. It is observed that HIJING describes both p–Pb and Pb–p results within systematic uncertainties. AMPT overpredicts the data in the Pb-going side and reproduces the measurements within uncertainties in the p-going side. DPMJET underestimates the multiplicity in the p-going side. One can observe that the DPMJET curve lies in between AMPT and HIJING in the Pb-going side and goes below in the p-going side. This suggests that DPMJET predicts a slightly narrower distribution. It is also noted that all models lie within about 15% from the data points.

The same models that do not reproduce the high-multiplicity part of the $P(N_\gamma)$ distribution in MB collisions, provide a fair description of the multiplicity of inclusive photons, $dN_\gamma/d\eta_{\text{lab}}$, at forward rapidities in pp, p–Pb, and Pb–p collisions.

The simultaneous comparison of the measured $P(N_\gamma)$ and $dN_\gamma/d\eta_{\text{lab}}$ distributions to the predictions of different event generators has, therefore, the potential of further constraining the models of inclusive photon production in high energy hadronic collisions.

The $dN_\gamma/d\eta_{\text{lab}}$ distributions measured in the pseudorapidity interval $2.3 < \eta_{\text{lab}} < 3.9$ in INEL pp collisions at various centre-of-mass energies are compared in Fig. 3.23(a). Two additional systematic uncertainties (diffraction shape and diffraction ratio) are considered in this analysis, and they lead to a total systematic uncertainty that is slightly larger at $\sqrt{s} = 5.02$ TeV with respect to the other energies. However, the total systematic uncertainty at all energies mostly comes from the 10% uncertainty

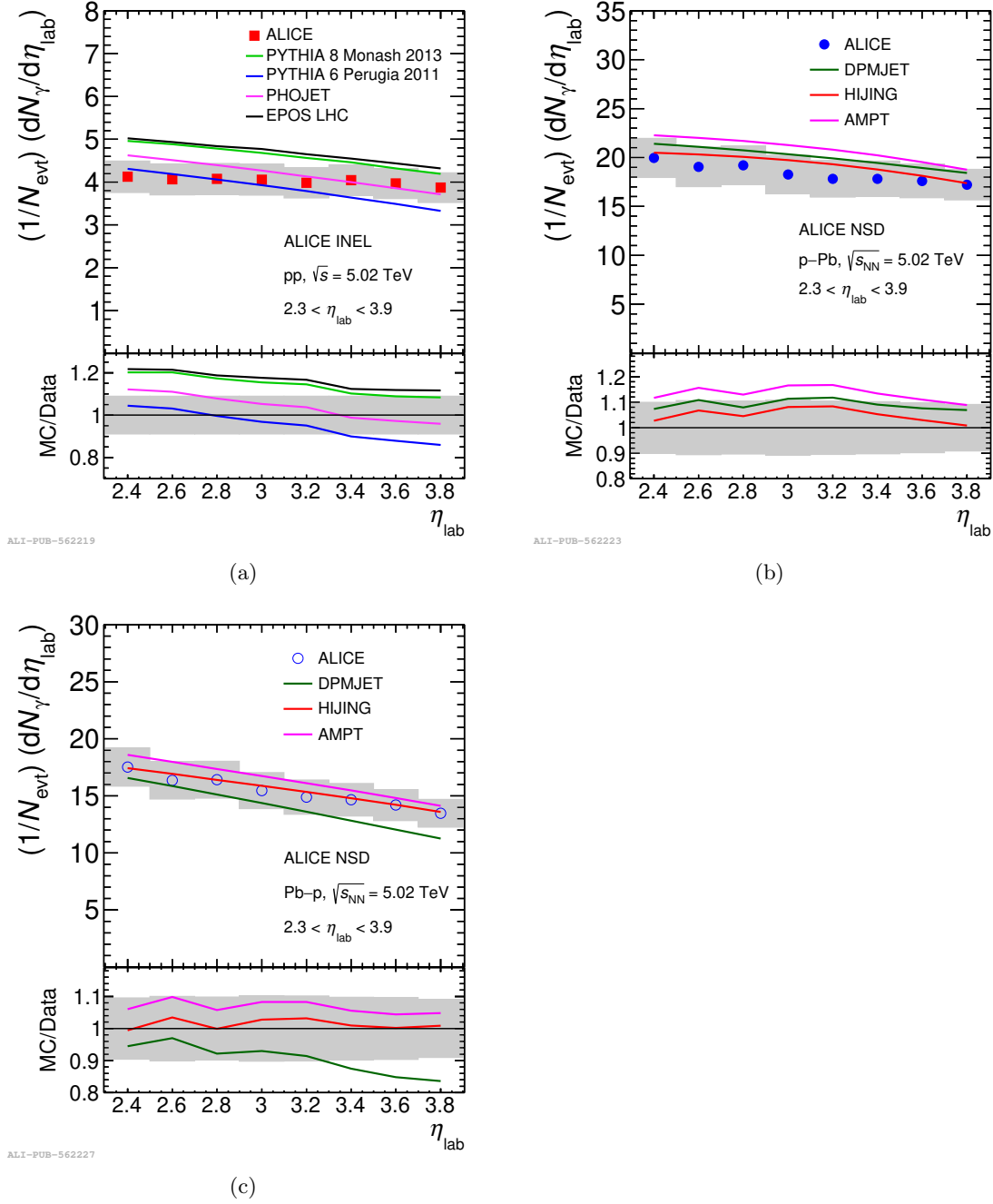


Figure 3.22: Top panels: Pseudorapidity distribution of inclusive photons measured within $2.3 < \eta_{\text{lab}} < 3.9$ in pp (a), p-Pb (b), and Pb-p (c) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Results from various MC predictions are superimposed. Bottom panels: The ratios between MC results and data are shown. Shaded boxes represent the systematic uncertainties.

on the upstream material in front of the PMD. The material uncertainty shows essentially no $\sqrt{s}$ variation and is therefore fully correlated over all energies. A smooth

increase of the inclusive photon multiplicity with increasing collision energy is observed. The average photon multiplicity $\langle N_\gamma \rangle$ within $2.3 < \eta_{\text{lab}} < 3.9$ as a function of $\sqrt{s}$ is shown in Fig. 3.23(b). The results of the measurements of $\langle N_\gamma \rangle$ are given in Table 3.9.

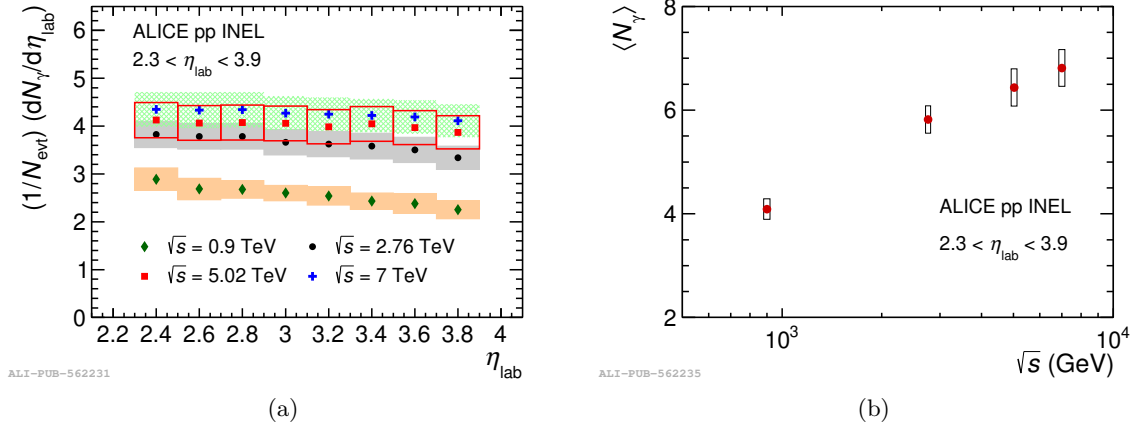


Figure 3.23: (a) Comparison of $dN_\gamma/d\eta_{\text{lab}}$ measured at forward rapidity in INEL pp collisions for various centre-of-mass energies, (b) average photon multiplicity within $2.3 < \eta_{\text{lab}} < 3.9$ as a function of collision energy in INEL pp collisions. The results at 0.9, 2.76, and 7 TeV are taken from Ref. [11].

Table 3.9: The average photon multiplicity $\langle N_\gamma \rangle$ within $2.3 < \eta_{\text{lab}} < 3.9$ for various centre-of-mass energies in INEL pp collisions. The quoted errors are systematic uncertainties. Statistical uncertainties are negligible. Data points at 0.9, 2.76, and 7 TeV are taken from Ref. [11].

$\sqrt{s}$ (TeV)	$\langle N_\gamma \rangle$
0.9	4.09 ± 0.20
2.76	5.82 ± 0.26
5.02	6.44 ± 0.36
7	6.81 ± 0.35

Since the dominant contribution to inclusive photon production comes from π^0 decays, the number of produced photons should be similar to the charged-particle multiplicity. The comparison between the pseudorapidity distribution of inclusive

photons in INEL pp and NSD p-Pb (combined with results of Pb-p mirrored with respect to $\eta_{\text{lab}} = 0$) events measured at forward rapidity and that of charged particles at midrapidity by ALICE [45, 46] and CMS [47] are presented in Fig. 3.24. It is observed that the inclusive photon production at forward rapidity follows the trend of charged-particle production at midrapidity. The predictions from the different event generators are also displayed in Fig. 3.24, and they show similar values for charged-particle (dashed lines) and photon (solid lines) multiplicity at forward and backward pseudorapidities, while at midrapidity, the photon and charged-particle pseudorapidity density differ. The origin of this difference is due to a mass effect in the transformation between dN/dy and $dN/d\eta$ at $\eta \approx 0$. The measured $dN_{\text{ch}}/d\eta_{\text{lab}}$ in p-Pb collisions is well described by both HIJING and DPMJET event generators. HIJING reproduces better the $dN_{\gamma}/d\eta_{\text{lab}}$ compared to DPMJET. For pp collisions, both PYTHIA 8 with the Monash 2013 tune and EPOS LHC overpredict the photon and charged-particle multiplicity.

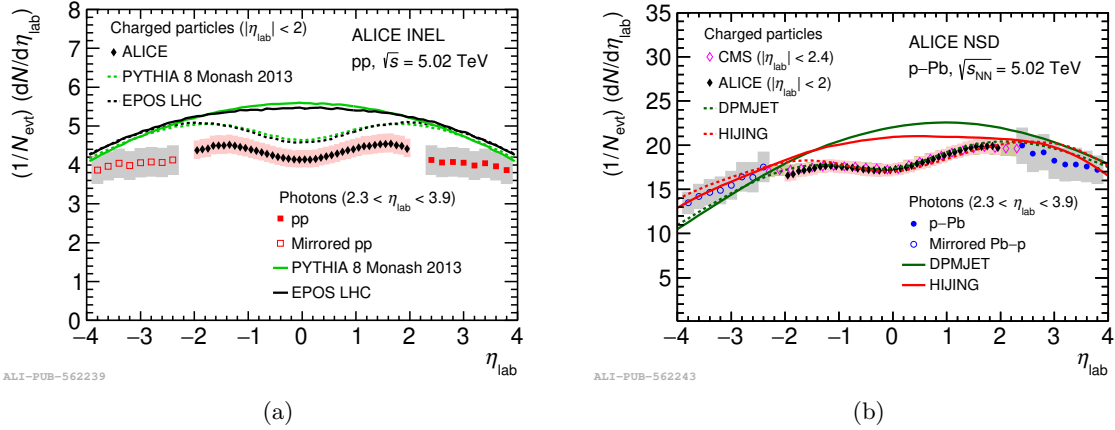


Figure 3.24: The pseudorapidity distributions of inclusive photons are compared with charged-particle measurements at midrapidity by ALICE [46] in pp collisions (a) and both ALICE [45] and CMS [47] in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV (b). Mirrored data points of pp and Pb-p results and predictions from various MC models are superimposed.

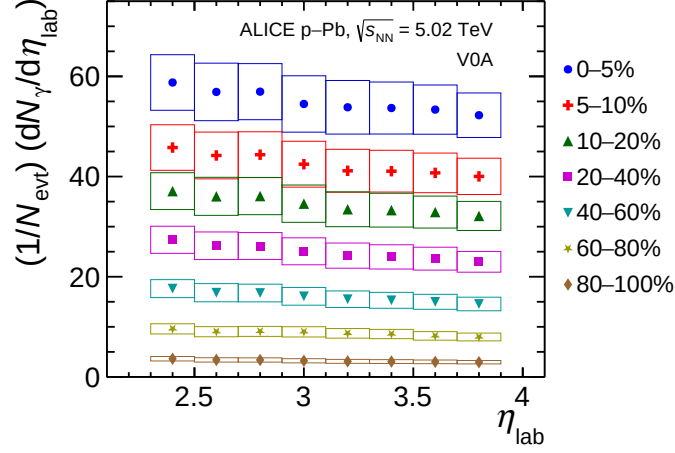


Figure 3.25: Pseudorapidity distributions of inclusive photons measured within $2.3 < \eta_{\text{lab}} < 3.9$ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for several centrality classes and for V0A centrality estimator.

3.3.3 Pseudorapidity distributions in centrality classes of p-Pb collisions

The pseudorapidity distributions of inclusive photons as a function of pseudorapidity measured in p-Pb collisions for several centrality classes are presented in Fig. 3.25 for V0A centrality estimator and in Fig. 3.26 for CL1 (top) and ZNA (bottom) estimators. The analysis is not performed for the Pb-p configuration, hence only one pseudorapidity interval is covered for the photon measurements, namely the one in the Pb-going direction, and the ZNA measures the energy of the neutrons emitted in the direction of the Pb beam. The multiplicity in the most central (0–5%) collisions when considering the V0A or CL1 (ZNA) estimator reaches ~ 3 (~ 2) times larger value compared to that measured in MB events. The lower values of $dN_{\gamma}/d\eta_{\text{lab}}$ in case of central events selected with the ZNA estimator is, most probably, due to the saturation of forward neutron emission [5]. The systematic uncertainty represented by open boxes mostly comes from the uncertainty on the upstream material in front of the PMD. To understand further the evolution of $dN_{\gamma}/d\eta_{\text{lab}}$ with centrality, the distributions in each centrality interval are divided by the distribution in the most peripheral (80–100%) event class and presented

in Fig. 3.27. With increasing pseudorapidity, the ratios are observed to increase linearly with a slope whose magnitude increases for central events, being highest for the most central (0–5%) collisions. HIJING shows a similar trend and explains the data within measured uncertainties except for the 0–5% and 40–60% event classes.

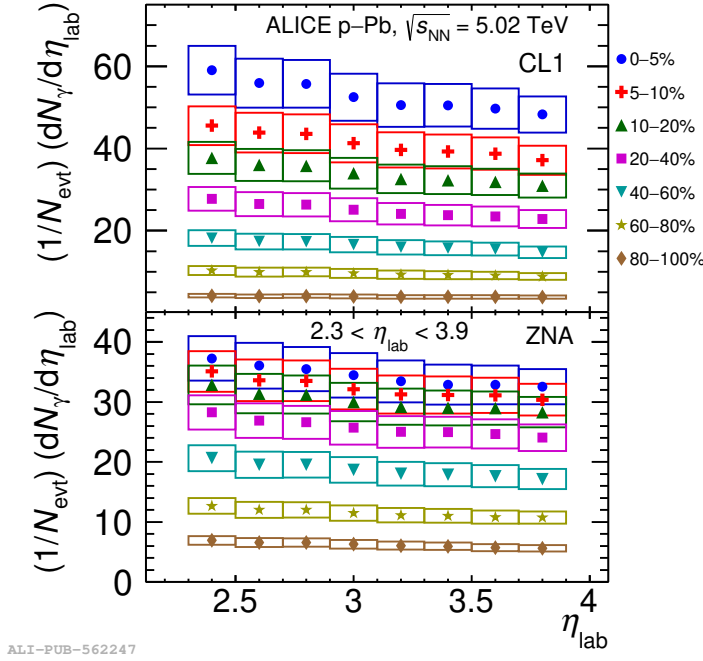


Figure 3.26: Pseudorapidity distributions of inclusive photons measured within $2.3 < \eta_{\text{lab}} < 3.9$ in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for several centrality classes and for two centrality estimators: CL1 (top) and ZNA (bottom).

The results are compared in Fig. 3.28 to similar measurements of charged particles at midrapidity by ALICE [5] for selected centrality intervals (0–5%, 20–40% and 80–100%) determined with the CL1 (top panel) and ZNA (bottom panel) estimators. A clear asymmetric shape of $dN_{\text{ch}}/d\eta_{\text{lab}}$ is observed for most central collisions, and the shape becomes symmetric (like in pp) in the most peripheral event class. Figure 3.28 also reports the comparison of the measured $dN_{\gamma}/d\eta_{\text{lab}}$ with HIJING predictions for the three considered centrality classes. The $dN_{\text{ch}}/d\eta_{\text{lab}}$ distributions at midrapidity are better described by the model in the case of the ZNA estimator. In the most peripheral (80–100%) collisions, HIJING overpredicts (underpredicts)

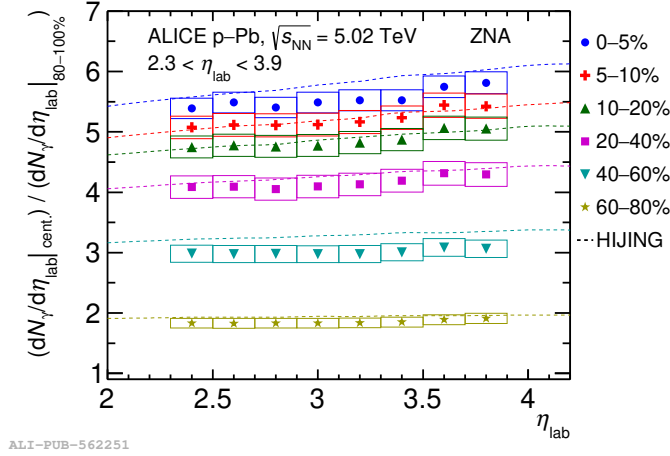


Figure 3.27: Ratios of $dN_\gamma/d\eta_{\text{lab}}$ distributions measured in different centrality classes to that in the most peripheral (80–100 %) centrality class. The corresponding HIJING predictions are shown by dotted lines.

the $dN_{\text{ch}}/d\eta_{\text{lab}}$ for the CL1 (ZNA) estimator. The model describes the values of $dN_\gamma/d\eta_{\text{lab}}$ at forward rapidity to within 15% except for the 0–5% CL1 class and the 80–100% ZNA class where the model prediction is compatible with the data points within 5%.

Table 3.10: The average photon multiplicity $\langle N_\gamma \rangle$ within $2.3 < \eta_{\text{lab}} < 3.9$ for various centrality classes defined using CL1 and ZNA centrality estimators in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The corresponding values of $\langle N_{\text{part}} \rangle$ are taken from Ref. [5]. The quoted errors are systematic uncertainties. Statistical uncertainties are negligible.

Centrality	CL1		ZNA		
	$\langle N_{\text{part}}^{\text{NBD-Glauber}} \rangle$	$\langle N_\gamma \rangle$	$\langle N_{\text{part}}^{\text{high-}p_T} \rangle$	$\langle N_{\text{part}}^{\text{Pb-side}} \rangle$	$\langle N_\gamma \rangle$
0–5%	16.60 ± 1.66	84.44 ± 8.65	13.50 ± 1.08	14.30 ± 1.14	54.98 ± 5.59
5–10%	14.60 ± 1.46	65.82 ± 6.96	13.10 ± 1.05	13.30 ± 1.06	51.65 ± 5.09
10–20%	13.00 ± 1.30	54.23 ± 5.67	12.30 ± 0.98	12.40 ± 0.99	48.18 ± 4.82
20–40%	10.49 ± 0.94	39.95 ± 4.22	10.73 ± 0.86	10.60 ± 0.85	41.22 ± 4.22
40–60%	7.18 ± 0.52	26.28 ± 2.79	7.81 ± 0.62	7.74 ± 0.62	29.82 ± 3.20
60–80%	4.40 ± 0.88	15.21 ± 1.60	5.05 ± 0.40	5.00 ± 0.40	18.36 ± 1.93
80–100%	2.76 ± 0.63	6.34 ± 0.68	3.03 ± 0.24	3.06 ± 0.24	9.93 ± 1.05

The obtained values of average photon multiplicity $\langle N_\gamma \rangle$ at forward rapidity

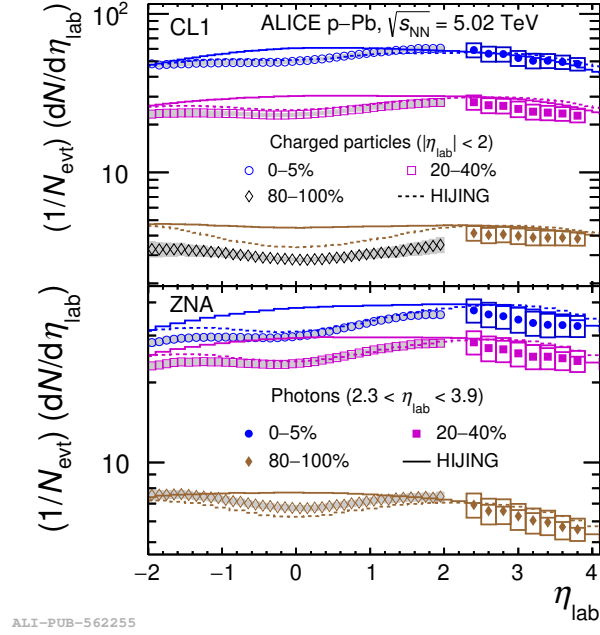


Figure 3.28: Pseudorapidity distribution of inclusive photons measured within $2.3 < \eta_{\text{lab}} < 3.9$ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV compared with the charged-particle measurements [5] and to HIJING predictions for three centrality classes and for two centrality estimators: CL1 (top), ZNA (bottom).

($2.3 < \eta_{\text{lab}} < 3.9$) as a function of $\langle N_{\text{part}} \rangle$ for the two centrality estimators in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are presented in Fig. 3.29(a) and listed in Table 3.10. The systematic uncertainties are represented by the colour bands. The values of $\langle N_{\text{part}} \rangle$ for the different centrality classes for both the estimators are taken from Ref. [5]. The data point for pp collisions at $\sqrt{s} = 5.02$ TeV is also included for reference. The average photon multiplicity $\langle N_{\gamma} \rangle$ divided by the average number of participants is presented as a function of $\langle N_{\text{part}} \rangle$ in Fig. 3.29(b). The $\langle N_{\gamma} \rangle / \langle N_{\text{part}} \rangle$ ratio has a steeper increase with $\langle N_{\text{part}} \rangle$ for the CL1 centrality estimator than for the ZNA one. This could be attributed to the strong multiplicity bias as described in Ref. [5]. It is noted that the curve does not point towards the pp result. When the ZNA is used for the centrality estimation along with the hybrid method to determine the average number of participant nucleons ($N_{\text{part}}^{\text{high-}p_{\text{T}}}$ or $N_{\text{part}}^{\text{Pb-side}}$), the inclusive photon multiplicity is found to scale with $\langle N_{\text{part}} \rangle$ within

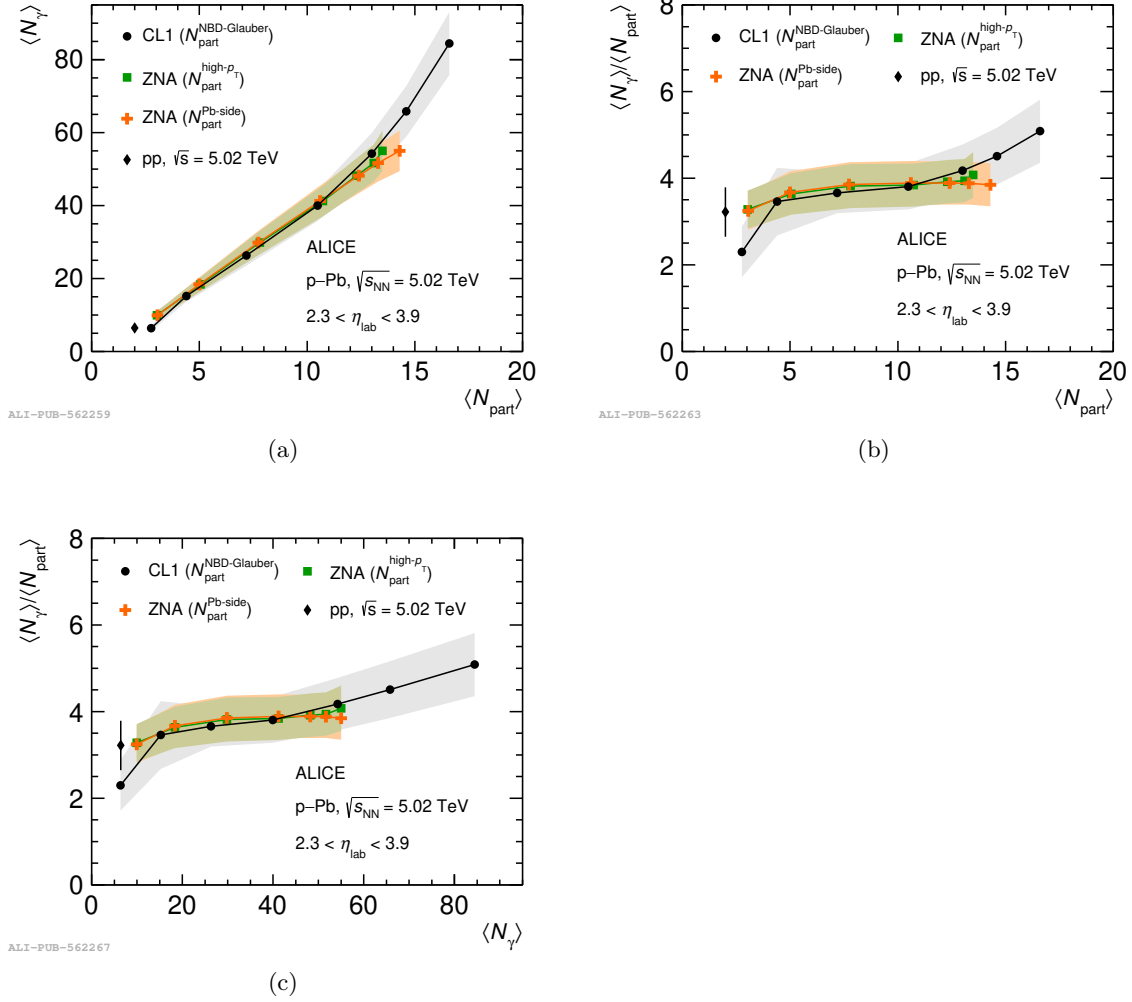


Figure 3.29: (a) The average photon multiplicity $\langle N_\gamma \rangle$ within $2.3 < \eta_{\text{lab}} < 3.9$ as a function of the average number of participants for various centrality estimators in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Values of $\langle N_\gamma \rangle / \langle N_{\text{part}} \rangle$ are shown as a function of $\langle N_{\text{part}} \rangle$ (b) and $\langle N_\gamma \rangle$ (c). The lines between the data points are to guide the eye. The data point for pp collisions at $\sqrt{s} = 5.02$ TeV is also included for reference.

uncertainties and to point towards the pp data point at low $\langle N_{\text{part}} \rangle$. Moreover, the range in $\langle N_{\text{part}} \rangle$ for the ZNA centrality selection is more limited (that could be because of saturation of forward neutron emission [5]) than what is obtained by particle-multiplicity-based centrality estimators. This effect is also emphasized in Fig. 3.29(c) where the same quantity $\langle N_\gamma \rangle / \langle N_{\text{part}} \rangle$ is presented as a function of $\langle N_\gamma \rangle$. Similar results were observed for charged-particle multiplicity at midrapidity

reported by the ALICE Collaboration [5].

3.4 Summary

In summary, this chapter presents the multiplicity and pseudorapidity distributions of inclusive photons measured in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in the forward pseudorapidity region ($2.3 < \eta_{\text{lab}} < 3.9$) using the data obtained from the PMD of ALICE. The centrality dependence of $dN_{\gamma}/d\eta_{\text{lab}}$ in p-Pb collisions is studied for the first time at the LHC. The evolution of the average photon multiplicity $\langle N_{\gamma} \rangle$ with $\sqrt{s}$ in pp collisions and with $\langle N_{\text{part}} \rangle$ in p-Pb collisions is also presented. The $P(N_{\gamma})$ distributions are found to be well described by the double NBD functions. The $dN_{\gamma}/d\eta_{\text{lab}}$ at forward rapidity is observed to follow the trend of similar measurements of charged particles at midrapidity, indicating that the production mechanisms for charged and neutral pions are similar. The obtained results are compared to predictions from various MC event generators. None of the considered event generators reproduces the measured $P(N_{\gamma})$ distributions in the reported multiplicity range. However, the $dN_{\gamma}/d\eta_{\text{lab}}$ distributions are relatively better described by the same generators.

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Chapter 4

Charged-particle multiplicity distributions in p–Pb collisions

This chapter reports the measurements of primary charged-particle multiplicity distributions in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for four increasingly wider pseudorapidity ranges, $-2.4 < \eta_{\text{lab}} < 2.4$, $-3.0 < \eta_{\text{lab}} < 3.0$, $-3.4 < \eta_{\text{lab}} < 3.4$, and $-3.4 < \eta_{\text{lab}} < 5.1$ in the laboratory system [1, 2]. The measurements are performed using the combined information from the Silicon Pixel Detector (SPD) [3] and the Forward Multiplicity Detector (FMD) [4] of ALICE. The multiplicity distributions are parametrized with double negative binomial distributions. The measurements are compared with predictions from simulations performed with HIJING [5], DPMJET [6] and PYTHIA 8/Angantyr [7], and with calculations from QCD saturation-based IP-Glasma model. We calculate the mean ($\langle N_{\text{ch}} \rangle$), standard deviation (σ), skewness (S), and kurtosis (κ) of the multiplicity distributions in data and compare them with the same predicted by the considered event generators. This comparison provides a quantitative description of the performance of these models and helps in tuning them to accurately simulate the underlying physics processes involved in particle production.

4.1 Analysis details

The data analysis procedure for measuring the multiplicity distributions of charged particles consists of several steps, as shown in Fig. 4.1. A brief description of the different steps followed in this analysis procedure is presented in the next subsections.

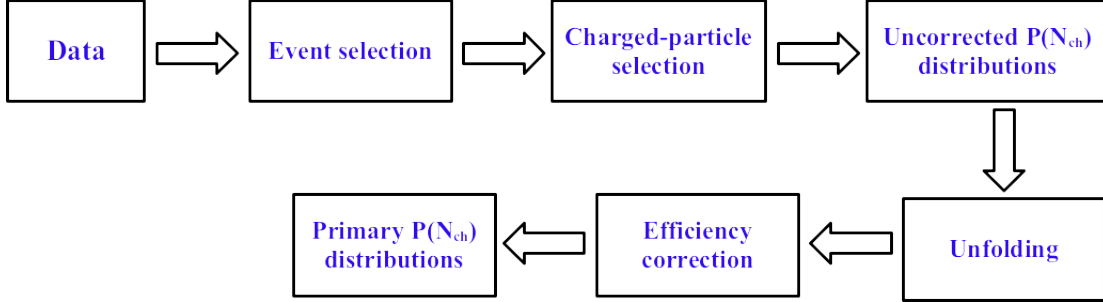


Figure 4.1: The flowchart showing the steps involved in the data analysis for the measurement of charged-particle multiplicity.

Table 4.1: Details of p–Pb data period and run numbers used in this analysis

System/Energy	Data Period	Analyzed runs	No. of events after event selection criteria
p–Pb, $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$	LHC13b	195478, 195479, 195480 195481, 195482, 195483	8.7 M

4.1.1 Data sample

This analysis uses p–Pb data of centre-of-mass energy, 5.02 TeV, collected in the year 2013. The details of the data period and run numbers are given in Table 4.1. The FMD cannot operate during high-intensity data-taking due to a large read-out time ($\approx 80 \mu\text{s}$) and integration time ($= 2 \mu\text{s}$). This means that for the forward multiplicity analysis, we are limited to low-intensity data-taking. So, the LHC13b data period is chosen because it is the one with the lowest rate and, hence, the lowest pileup. The previous $dN_{\text{ch}}/d\eta$ analysis also used the same data [8]. During

the 2016 p–Pb campaign, the interaction rate was high. Due to this high rate, the FMD suffered high levels of background noise. Therefore, p–Pb 2016 data are not used for the present analysis.

4.1.2 Monte Carlo simulation

In this analysis, we have used HIJING [5] and DPMJET [6] Monte Carlo (MC) event generators anchored to p–Pb data for the correction procedure and the evaluation of systematic uncertainties. A discussion on HIJING, DPMJET, and anchored simulation can be found in Sec. 3.1.8 of Chapter 3. The MC details and the number of events analyzed are reported in Table 4.2.

Table 4.2: Details of MC production used in this analysis

Generator name	MC Period	No. of events after event selection criteria
HIJING (default material)	LHC20e1	7.4 M
HIJING (+10% material)	LHC21c12a	4.2 M
HIJING (-5% material)	LHC21c12b	4.1 M
DPMJET	LHC21c11	8.3 M

4.1.3 Event selection

The similar physics selection and background rejection criteria as discussed in Sec. 3.1.2 of Chapter 3 are considered in this analysis.

Vertex selection: Events are selected if the vertex z -position, $|v_z| < 4$ cm from the nominal interaction point (IP) ($z = 0$). This stringent requirement for vertex selection is used to maximize the coverage between the SPD and the FMD, as can be seen in Fig. 4.2. The green area is the designed maximum acceptance of the SPD and FMD. The red area is the actual coverage as a function of vertex position. The non-covered areas are mostly excluded from this analysis. To determine the vertex position accurately, the maximum error allowed for

the measurement of the longitudinal vertex position is 0.2 cm. Events are selected if the number of tracks contributing to primary vertex reconstruction is greater than 0. The vertex distribution along the z axis is shown in Fig. 4.3. The selection of $|v_z| < 4$ cm is also shown by black vertical lines in Fig. 4.3.

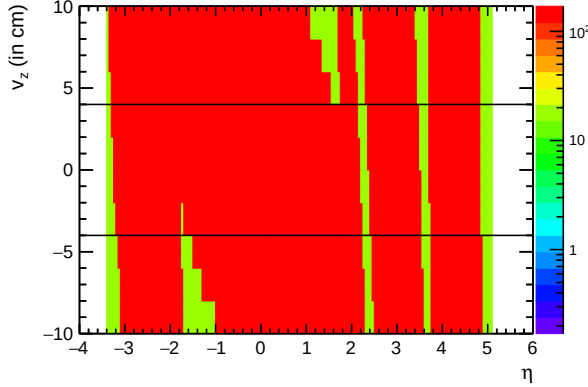


Figure 4.2: Green: Designed maximum acceptance of the SPD and FMD. Red: actual coverage as a function of vertex position. The horizontal black lines on the y axis identify the vertex selection used in this analysis.

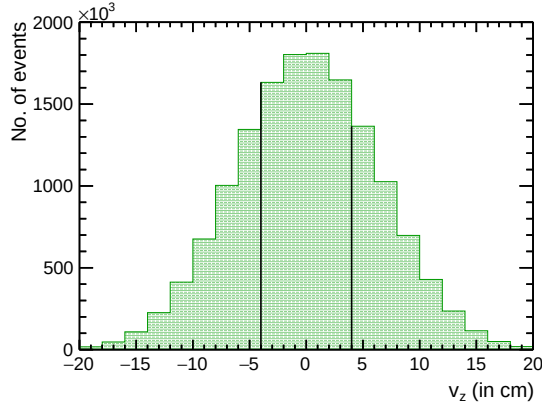


Figure 4.3: The distributions of v_z in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the LHC13b data period. The vertical black lines identify the vertex selection used in this analysis.

4.1.4 Charged-particle selection

This analysis is focused on primary charged particles. These are defined as charged particles with a mean proper lifetime τ larger than 1 cm/ c , which is either a) produced directly in the interaction, or b) from decays of particles with τ smaller than 1 cm/ c , excluding particles produced in interactions with material [9].

The measurement of multiplicity in central rapidity ($|\eta_{\text{lab}}| < 2$) region is carried

out using the SPD detector [3]. Charged particles can deposit energy and produce signals in more than one pixel of the SPD. The offline reconstruction combines such adjacent pixel signals into a single cluster. The clusters from the two layers of SPD, together with the primary vertex, are combined to form tracklets [10], allowing the selection of primary charged particles with very high efficiency. Charged-particle multiplicity is then determined by counting the number of tracklets.

The charged-particle multiplicity measurement at forward rapidity region ($-3.4 < \eta_{\text{lab}} < -1.7$ and $1.7 < \eta_{\text{lab}} < 5.1$) is carried out using the FMD detector [4]. The FMD records the energy deposited by charged particles that traverse each silicon strip (denoted as E_{strip}). Figure 4.4 shows the calibrated response for a single FMD strip to charged particles accumulated over many events. The large peak at zero arises from the intrinsic noise of the detector strip and the noise accumulated during readout. This noise can easily be removed by online pedestal subtraction [11]. A charged particle, when hitting the detector, can deposit energy in a single strip or multiple adjacent strips. A sharing algorithm [12] is applied to merge signals of those adjacent strips. The algorithm loops over all the FMD strips; if $E_{\text{strip}} < E_{\text{low}}$ (cut set to remove remaining pedestal peak), E_{strip} is set to zero. If $E_{\text{low}} < E_{\text{strip}} < E_{\text{high}}$, the signal in the adjacent strip (E_{adj}) is being checked. Then, if $E_{\text{adj}} > E_{\text{low}}$, the two signals are merged into a single cluster to represent the hit of a single particle. Finally, if $E_{\text{strip}} > E_{\text{high}}$, then the signal is considered as a single hit.

E_{low} : This is the low sharing threshold cut. It is defined as the lowest energy that can be accepted as a component of a shared signal. This cut removes pedestal remnants left in the data after the online pedestal subtraction. The E_{low} cut is fixed at $0.15\Delta E/\Delta E_{\text{MIP}}$ for the inner rings and $0.18\Delta E/\Delta E_{\text{MIP}}$ for the outer rings of the FMD. Here, ΔE is the energy loss and ΔE_{MIP} is the energy of the Minimum Ionizing Particle (MIP). The optimum value of E_{low} is considered

as 0.15, and then it is varied between 0.12 and 0.18 to study the effect of this parameter on the final results.

E_{high} : This is high sharing threshold cut. This cut determines when we consider a signal in a given FMD strip as corresponding to the traversal of a single particle entirely within the strip boundaries, i.e., the particle did not deposit energy in neighbouring strips. The optimum value of E_{high} is considered as 1.00, and then it is varied between 0.9 and 1.5 to study the effect of this parameter on the final distributions.

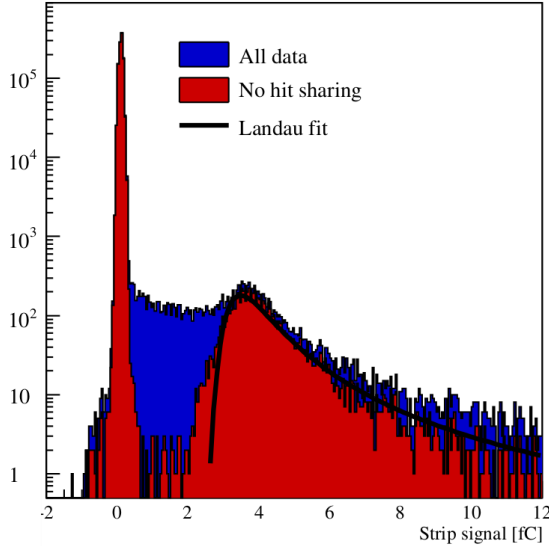


Figure 4.4: The distribution of signals from a single silicon strip is shown. The blue distribution corresponds to all signals seen in that strip. A large set of signals having energies between the pedestal peak and the MIP peak is seen in this distribution. The red one corresponds to the distributions when the shared hits are removed. The figure is adapted from Ref. [11].

After applying the sharing filter, another cut, E_{hit} (hit threshold or density cut) is applied. Signals above this cut are counted as particles. If $E_{\text{strip}} < E_{\text{hit}}$, the strip is considered as empty. When more than one charged particle hits the detector, it can be difficult to fit the distribution, although it is still a convolution of a Landau and a Gaussian. The peak of the Landau distribution will be shifted with respect to the one when only a single particle hits the detector by an amount of $n(E_{\text{MPV}} + \xi \ln n)$, where, n is number of particles traversing the strip, E_{MPV} corresponds to single-particle peak, and ξ is the width of the Landau distribution. To estimate the most probable number of particles in a strip in a single event, the

Poisson statistical approach [12] is considered, assuming that the particles which traverse the same region of the detector are randomly distributed. The optimum value of E_{hit} is considered 1.00, and then it is varied between 0.9 and 1.1 to study the effect of this parameter on the final results.

4.1.5 Uncorrected charged particle multiplicity distributions

After obtaining the number of charged particles from the SPD and FMD, the multiplicity distributions of charged particles in the four pseudorapidity regions - a) $-2.4 < \eta_{\text{lab}} < 2.4$, b) $-3.0 < \eta_{\text{lab}} < 3.0$, c) $-3.4 < \eta_{\text{lab}} < 3.4$, and d) $-3.4 < \eta_{\text{lab}} < 5.1$ are studied in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In Fig. 4.5, the uncorrected charged-particle multiplicity distributions ($P(N_{\text{ch}}^{\text{Raw}})$) in different pseudorapidity coverages are shown by different markers and colours. Even though the distributions are uncorrected, the multiplicity increases with the increase in the size of the pseudorapidity interval, as expected.

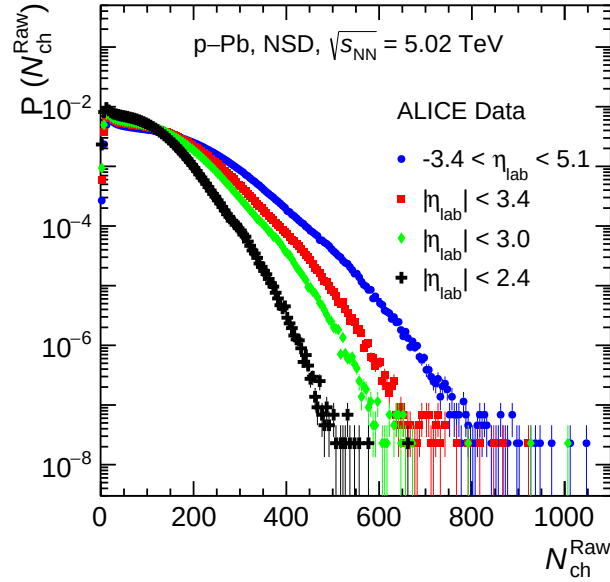


Figure 4.5: Uncorrected multiplicity distributions of charged particles in the four pseudorapidity regions - a) $-2.4 < \eta_{\text{lab}} < 2.4$, b) $-3.0 < \eta_{\text{lab}} < 3.0$, c) $-3.4 < \eta_{\text{lab}} < 3.4$, and d) $-3.4 < \eta_{\text{lab}} < 5.1$ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

4.1.6 Correction procedure

The uncorrected distributions, $P(N_{\text{ch}}^{\text{Raw}})$, are contaminated by the background of secondary particles produced in interactions with the beam pipe and the material that exists in front of the FMD [12, 13]. There are also other instrumental effects, such as detector acceptance and event selection inefficiencies. A set of correction procedures is considered to account for these effects.

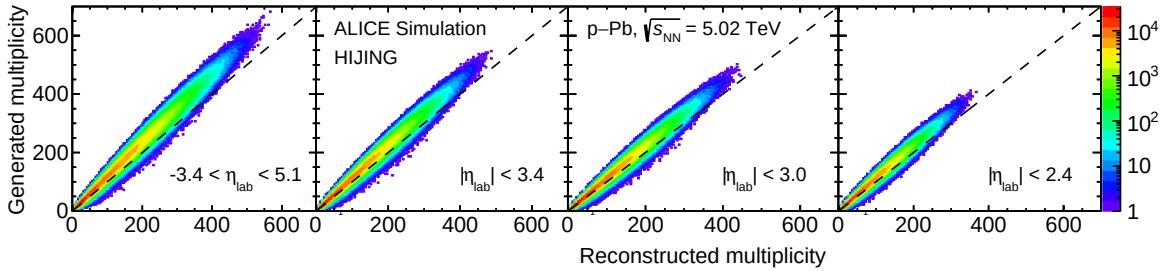


Figure 4.6: Detector response matrices for the four pseudorapidity coverages obtained from HIJING in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

4.1.6.1 Method of unfolding

An unfolding method based on Bayes' theorem [14, 15] is applied to extract the primary charged-particle multiplicity distributions. The inputs to the Bayesian unfolding procedure are the raw, uncorrected measured multiplicity distributions and a response matrix (R) determined from simulations. The response matrix is constructed via simulations, where the input multiplicity of the primary charged-particle is correlated with the simulated observed multiplicity. The simulated observed multiplicity (denoted as detector-level distributions) takes into account effects such as decay and secondary production in material, as well as detector effects such as inefficiencies, acceptance, electronic noise and smearing corresponding to the actual conditions under which the data was recorded. In this work, particles produced directly from the HIJING event generator are referred to as generated (truth-level) particles, which

are transported through the ALICE detector system using the GEANT 3 detector simulation [16] to obtain the detector-level distributions. Similar experimental conditions and reconstruction algorithms are considered in the simulation as were present or were applied to the experimental data. Figure 4.6 shows the graphical representation of response matrices for the four pseudorapidity coverages in p-Pb collisions. The matrix element R_{mt} gives the conditional probability that an event where t primary charged particles were produced is observed to have a multiplicity of m . The detector-level distribution (M) can be expressed as $M = R_{mt}T$. One can therefore obtain the true-level distribution (T) for a given M as

$$T = R_{mt}^{-1}M. \quad (4.1)$$

We employ an iterative algorithm based on Bayes' theorem to find the inverse of the response matrix, R^{-1} . In this procedure, the number of iterations is optimized by performing a series of self-consistencies using simulations. Firstly, the HIJING simulated data are divided into two statistically independent samples. The response matrix is constructed from one sample, while the truth- and detector-level distributions are obtained from the other sample. The detector-level distributions are unfolded using Eq. 4.1 for different number of iterations, and the unfolded results (U) are compared to the truth-level distributions. The number of iterations is then set to the number that minimizes

$$\chi^2 = \sum_t \left(\frac{T_t - U_t}{e_t} \right)^2,$$

where e_t is the error in the truth-level distribution. A similar unfolding performance is examined that tests the model independence of the number of iterations or response matrix. In this case, the truth- and detector-level distributions are obtained using the DPMJET event generator [17] and unfolded using a response matrix constructed using HIJING, and then the unfolded result is compared to the truth-level

distribution from DPMJET. Additionally, the quality of the unfolding (refolding test) is verified by comparing the detector-level distribution to the product $R \otimes U$. In all these tests, a reasonable self-consistency is observed within the statistical uncertainties. The measured distributions in experimental data are then unfolded using the optimized number of iterations.

4.1.6.2 Correction for event selection efficiency

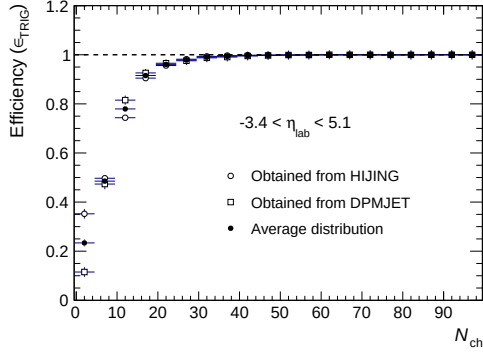
The unfolded distributions are corrected further for the event selection efficiency. Following the prescription given in Ref. [13], the event selection efficiency (ϵ_{TRIG}) is estimated using simulations as:

$$\epsilon_{\text{TRIG}} = \frac{N_{\text{ev, reco}}(\text{TRIG} \ \& \ |v_{z, \text{reco}}| < 4 \text{ cm})}{N_{\text{ev, gen}}(\text{TRIG} \ \& \ |v_{z, \text{gen}}| < 4 \text{ cm})},$$

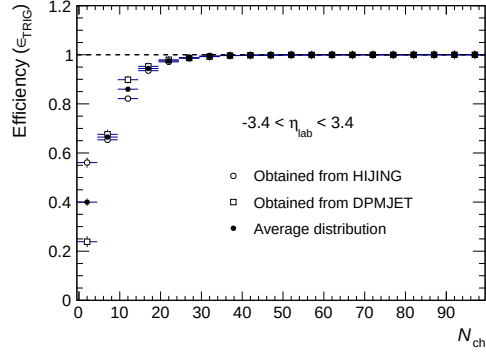
where the numerator and denominator are the number of reconstructed and generated events, respectively, with the selected NSD trigger and the reconstructed primary vertex within ± 4 cm from the nominal IP. The event selection efficiency as a function of generated primary charged-particle multiplicity (N_{ch}) is presented in Fig. 4.7 for the four pseudorapidity coverages. The central points (shown by solid markers) are obtained by averaging the efficiencies found with HIJING and DPMJET event generators. The values of ϵ_{TRIG} are found to be significant at low multiplicities and become negligible above $N_{\text{ch}} > 20$ where the efficiency reaches $\sim 100\%$. The unfolded results are corrected by dividing the content of each multiplicity bin by its ϵ_{TRIG} value.

4.2 Estimation of systematic uncertainties

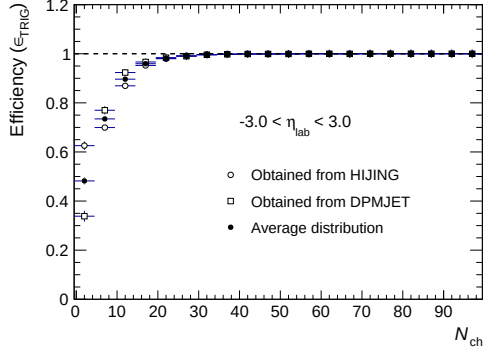
The different sources of systematic uncertainties associated with the measurements of charged-particle multiplicity distributions for four increasingly wider pseudorapidity ranges, $-2.4 < \eta_{\text{lab}} < 2.4$, $-3.0 < \eta_{\text{lab}} < 3.0$, $-3.4 < \eta_{\text{lab}} < 3.4$, and



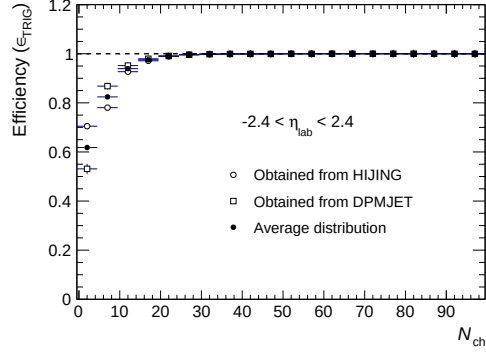
(a)



(b)



(c)



(d)

Figure 4.7: Event selection efficiency as a function of generated primary charged-particle multiplicity (N_{ch}) for different pseudorapidity coverages.

$-3.4 < \eta_{\text{lab}} < 5.1$ are summarized in Table 4.3. The values of systematic uncertainties from different sources are presented as a function of N_{ch} in Fig. 4.8 and reported in Table 4.3 for three characteristic multiplicity values: $N_{\text{ch}} = 2$, the mean $\langle N_{\text{ch}} \rangle$, and the value for which $P(N_{\text{ch}}) = 10^{-3}$, i.e. at low, middle and high multiplicities respectively. The total systematic uncertainty is estimated by summing the contributions from the individual sources in quadrature. A brief discussion on different sources of systematic uncertainties is presented in the next subsections.

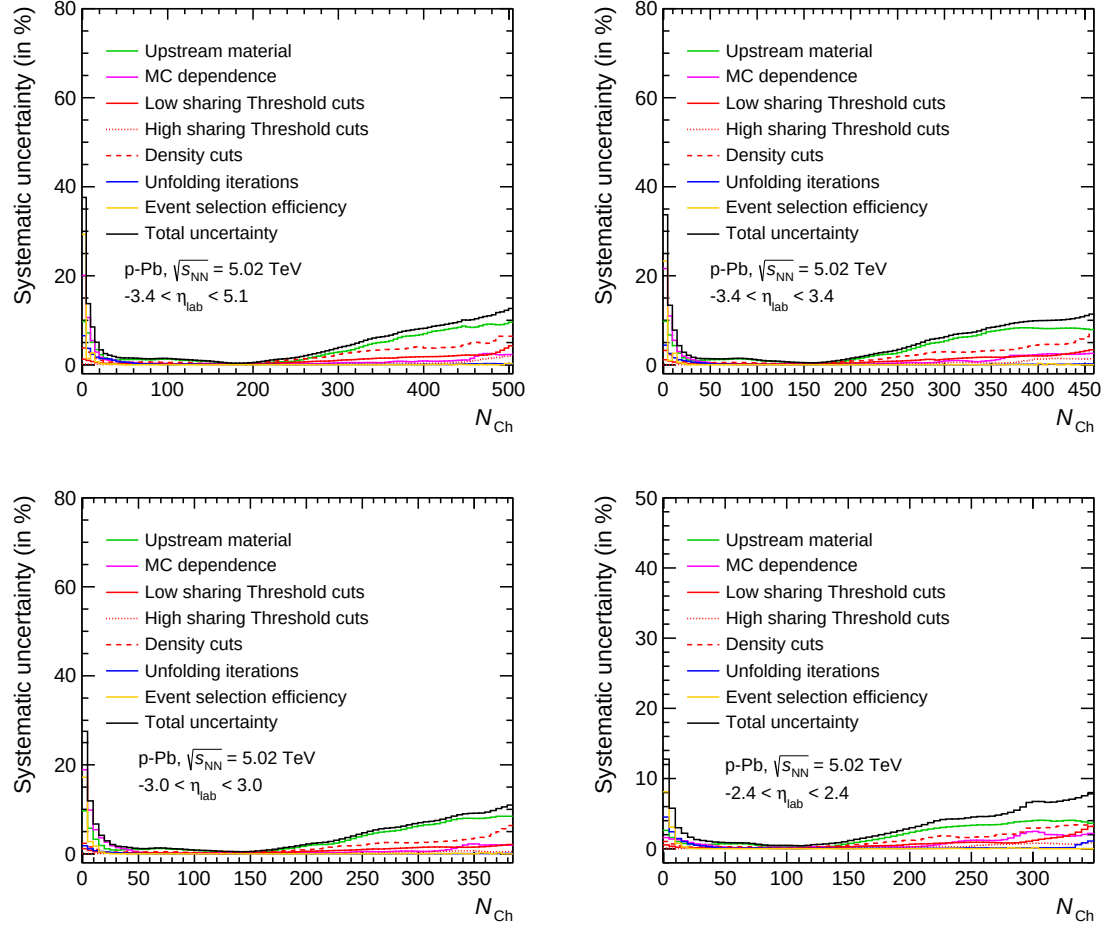


Figure 4.8: Breakdown of the contributions of the different sources of systematic uncertainties to the multiplicity distributions of charged particle measured within $-3.4 < \eta_{\text{lab}} < 5.1$ (top left), $-3.4 < \eta_{\text{lab}} < 3.4$ (top right), $-3.0 < \eta_{\text{lab}} < 3.0$ (bottom left), and $-2.4 < \eta_{\text{lab}} < 2.4$ (bottom right) in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

4.2.1 Effect of upstream material

A proper understanding of the implementation of the upstream material in front of the FMD in the GEANT 3 description of the ALICE experiment is crucial. The amount of uncertainty in the upstream material in front of the FMD is estimated using the data with satellite collisions and GEANT 3 simulations. A satellite collision is a collision that does not happen in the nominal IP, but is displaced by multiples of ± 2.5 ns from the IP, corresponding to ± 37.5 cm (see Fig. 4.9). Therefore, it is pos-

Table 4.3: Contributions to systematic uncertainties (in percent) in the measurements of multiplicity distributions of primary charged particles for different pseudorapidity intervals in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Numbers are given at three characteristic multiplicity values of 2, the mean $\langle N_{\text{ch}} \rangle$, and the value for which $P(N_{\text{ch}}) = 10^{-3}$.

Sources	$-3.4 < \eta_{\text{lab}} < 5.1$			$-3.4 < \eta_{\text{lab}} < 3.4$			$-3.0 < \eta_{\text{lab}} < 3.0$			$-2.4 < \eta_{\text{lab}} < 2.4$		
	$N_{\text{ch}} = 2$	$N_{\text{ch}} = \langle N_{\text{ch}} \rangle$	$P(N_{\text{ch}}) = 10^{-3}$	$N_{\text{ch}} = 2$	$N_{\text{ch}} = \langle N_{\text{ch}} \rangle$	$P(N_{\text{ch}}) = 10^{-3}$	$N_{\text{ch}} = 2$	$N_{\text{ch}} = \langle N_{\text{ch}} \rangle$	$P(N_{\text{ch}}) = 10^{-3}$	$N_{\text{ch}} = 2$	$N_{\text{ch}} = \langle N_{\text{ch}} \rangle$	$P(N_{\text{ch}}) = 10^{-3}$
Upstream material	9.7	0.8	3.7	9.8	0.7	4.3	9.7	0.7	4.4	2.6	0.3	2.8
Event generator for response matrix	20.0	0.3	0.5	21.6	0.2	0.4	18.9	0.2	0.5	1.6	0.2	0.5
Unfolding parameters	6.5	0.1	0.1	4.4	0.04	0.01	1.8	0.02	0.02	4.5	0.05	0.1
Event selection efficiency	29.3	negl.	negl.	23.3	negl.	negl.	17.2	negl.	negl.	8.1	negl.	negl.
Charged-particle detection thresholds	4.0	0.3	3.1	3.4	0.3	2.7	2.6	0.2	2.5	1.2	0.2	1.8
Total	37.6	0.9	5.0	34.0	0.8	5.1	27.5	0.8	5.1	13.0	0.5	4.0

sible to evaluate the number of charged particles which hit the FMD by significantly reducing the amount of upstream material, as evident from Fig. 4.9. The procedure is discussed in detail in Refs. [12, 18, 19]. The uncertainty in the implementation of

the upstream material in GEANT 3 is found to vary from 5 to 10% in the FMD coverage for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. To study the effect of this material uncertainty on the measurements of charged-particle multiplicity distributions, two response matrices are constructed using the HIJING event generator, one with an increase of 10% and another with a decrease of 5% in the overall material description of the ALICE apparatus. The unfolded distributions are obtained using these two response matrices and compared with the one obtained using the response matrix with the default material. The green line in Fig. 4.8 shows the variation of the uncertainty values as a function of N_{ch} measured within $-3.4 < \eta_{\text{lab}} < 5.1$ (top left), $-3.4 < \eta_{\text{lab}} < 3.4$ (top right), $-3.0 < \eta_{\text{lab}} < 3.0$ (bottom left), and $-2.4 < \eta_{\text{lab}} < 2.4$ (bottom right) in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

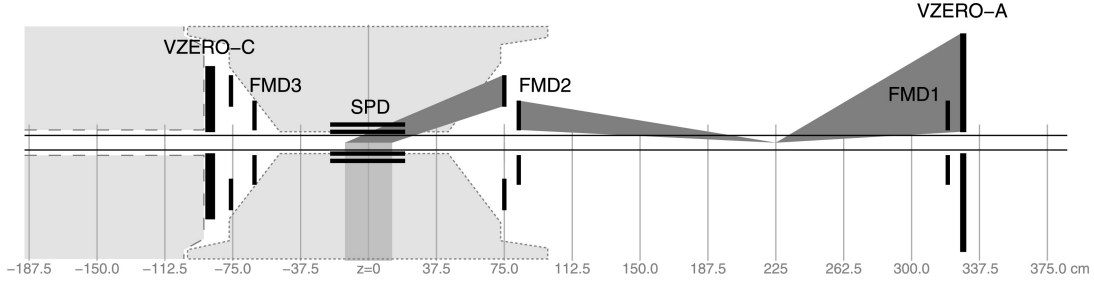


Figure 4.9: Schematic drawing (not to scale) of the cross-section of the ITS, FMD, and V0 and the midpoints of the locations of nominal and ‘satellite’ collision points. The long-dashed line represents the region of dense material that is designed to absorb all particles except $\mu^\pm$. The short-dashed line corresponds to the region of the ITS, which has dense material for its services on the surfaces near FMD2 and FMD3. The region between FMD2, FMD1 and V0A contains only the beam pipe. The shaded dark gray areas denote paths that particles follow from $z = 0$ cm and $z = 225$ cm to FMD2 and V0A such that it is evident how much material they would traverse [12].

4.2.2 Event generator dependence

As discussed in Sec. 4.1.6, we rely on MC models to unfold the uncorrected charged-particle multiplicity distributions. To determine the systematic uncertainty due to the choice of the MC models used in the unfolding procedure, the measured distributions, $P(N_{\text{ch}}^{\text{Raw}})$, in data are unfolded using two separate response matrices

built using HIJING and DPMJET. The average of these two distributions is used as our final measurement. The differences between the average value and both an upward and downward data point are used as an estimate of the systematic uncertainty. The magenta line in Fig. 4.8 shows the variation of the uncertainty values as a function of N_{ch} measured within $-3.4 < \eta_{\text{lab}} < 5.1$ (top left), $-3.4 < \eta_{\text{lab}} < 3.4$ (top right), $-3.0 < \eta_{\text{lab}} < 3.0$ (bottom left), and $-2.4 < \eta_{\text{lab}} < 2.4$ (bottom right) in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

4.2.3 Choice of unfolding parameters

As described in Sec. 4.1.6, the unfolded results are sensitive to the choice of the number of iterations in the Bayesian unfolding procedure. The number of iterations is varied by ± 1 with respect to the default value of iterations. The unfolded distributions are obtained using different number of iterations, and their variations with respect to the nominal results are used as an estimate of the systematic uncertainty. The variation of the uncertainty values are presented as a function of N_{ch} in Fig. 4.8 (blue line).

4.2.4 Event selection efficiency

The systematic uncertainty due to possible imperfections in the correction for the event selection efficiency is evaluated by determining the efficiency values using two different event generators, HIJING and DPMJET. This uncertainty is largest at low N_{ch} values and reduces significantly at larger N_{ch} (see the orange line in Fig. 4.8) because contributions from diffractive processes become smaller when going to higher multiplicity [10, 13, 20].

4.2.5 Charged-particle detection thresholds

As described in Sec. 4.1.4, the recombination of FMD signals (corresponding to the energy of a single particle) shared in the neighbouring strips depends on a lower

threshold (E_{low}) for accepting a signal and an upper threshold (E_{high}) to consider a signal as isolated, i.e., all energy is deposited in a single strip. These lower and upper threshold values are varied within the bounds of the energy loss fits [18, 19] to determine the systematic uncertainty due to the choice of thresholds for merging the signals. The red solid and dotted lines in Fig. 4.8 show the variations of uncertainty values as a function of N_{ch} due to the choice of low and high sharing threshold cuts, respectively. The density cut (E_{hit}) is also varied within the bounds of fits to the energy loss spectra [18, 19] to evaluate the systematic uncertainty which is shown by the red dashed line in Fig. 4.8.

4.3 Results and discussions

The multiplicity distributions of primary charged particles in the wide pseudorapidity interval $-3.4 < \eta_{\text{lab}} < 5.1$ measured using the combined information of SPD and FMD for p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are presented and discussed in this section. The obtained results are compared to predictions from MC models and available experimental measurements.

4.3.1 Multiplicity distributions

Figure 4.10 presents the primary charged-particle multiplicity distributions measured for NSD events in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The colour bands represent the systematic uncertainty. The statistical uncertainties are smaller than the marker size. The distributions are obtained in the four pseudorapidity intervals, $-2.4 < \eta_{\text{lab}} < 2.4$, $-3.0 < \eta_{\text{lab}} < 3.0$, $-3.4 < \eta_{\text{lab}} < 3.4$, and $-3.4 < \eta_{\text{lab}} < 5.1$. These measurements extend the high-multiplicity reach with respect to the previous ALICE results in the central rapidity region [10, 20, 21]. The distributions for $-3.4 < \eta_{\text{lab}} < 5.1$ and $|\eta_{\text{lab}}| < 3.4$ are scaled by a factor of 10 for clarity.

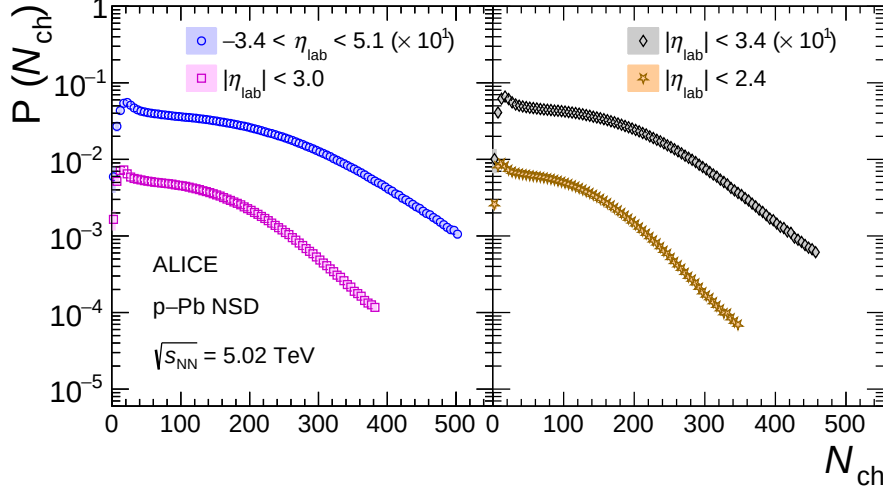


Figure 4.10: Charged-particle multiplicity distributions for different pseudorapidity intervals measured in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for NSD events.

4.3.2 Comparison to theoretical models

In Fig. 4.11, the measured multiplicity distributions are compared to predictions from HIJING [22], DPMJET [17], and PYTHIA 8/Angantyr [7], which are shown by red, black and green lines, respectively. HIJING is a QCD-inspired two-component model that combines perturbative-QCD processes with soft interactions. It also incorporates mechanisms such as multiple mini-jet production, soft excitation and nuclear modification of the initial parton distributions (shadowing). In HIJING, multiple scatterings in nuclear collisions are simulated using a binary approximation and the Glauber model. DPMJET is based on the Glauber–Gribov approach and utilizes Reggeon theory and pQCD to treat soft and hard scattering processes. In the Angantyr model, one considers an extrapolation of pp dynamics to describe nuclear collisions. In the case of p-Pb collisions, the projectile proton participates in multiple sub-collisions with the target nucleons from the Pb nucleus. The number of participating nucleons, called “wounded nucleons”, is calculated from the Glauber model.

The bottom panels of Fig. 4.11 show the ratios between predictions from event

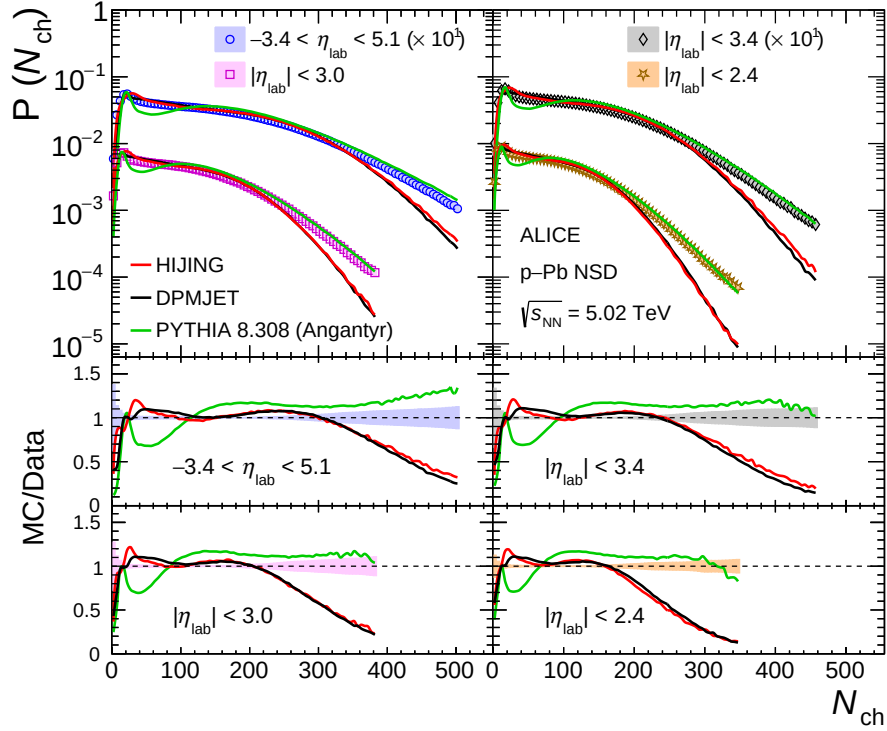


Figure 4.11: Comparison of charged-particle multiplicity distributions to the predictions from HIJING (red line), DPMJET (black line) and PYTHIA 8/Angantyr (green line). The ratios between the model predictions and the data are shown in the bottom panels.

generators and data. In general, none of the event generators can reproduce the data in the full range of multiplicities considered here. The distributions obtained from HIJING and DPMJET are quite similar and describe the data better (to within $\sim 10\%$) in the intermediate multiplicity region than PYTHIA 8/Angantyr, which deviates from data by a maximum of about 30%. However, the tails of the distributions are relatively better reproduced by PYTHIA 8/Angantyr. The agreement between data and PYTHIA 8/Angantyr at high multiplicities becomes worse when going from the midrapidity region ($-2.4 < \eta_{\text{lab}} < 2.4$) to the forward rapidity region ($-3.4 < \eta_{\text{lab}} < 5.1$). All the considered models are also unable to describe the lowest part of the multiplicity distributions, which is dominated by diffractive events.

Table 4.4: The mean values ($\langle N_{\text{ch}} \rangle$) of multiplicity distributions for different pseudorapidity intervals in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The quoted errors are systematic uncertainties for data and statistical uncertainties for models. Statistical errors are negligible for data.

	ALICE p-Pb	HIJING	DPMJET	PYTHIA 8/Angantyr
$-3.4 < \eta_{\text{lab}} < 5.1$				
$\langle N_{\text{ch}} \rangle$	149.36 ± 1.34	144.30 ± 0.07	145.10 ± 0.03	166.50 ± 0.03
σ	106.23 ± 0.30	99.60 ± 0.04	98.25 ± 0.02	106.63 ± 0.02
S	0.76 ± 0.01	0.68 ± 0.001	0.67 ± 0.001	0.62 ± 0.001
κ	-0.02 ± 0.02	-0.19 ± 0.003	-0.21 ± 0.001	-0.14 ± 0.001
$ \eta_{\text{lab}} < 3.4$				
$\langle N_{\text{ch}} \rangle$	123.60 ± 1.00	118.20 ± 0.05	118.00 ± 0.03	136.60 ± 0.02
σ	88.60 ± 0.30	81.70 ± 0.04	80.01 ± 0.02	88.50 ± 0.02
S	0.83 ± 0.01	0.71 ± 0.001	0.71 ± 0.001	0.68 ± 0.001
κ	0.27 ± 0.02	-0.04 ± 0.003	-0.03 ± 0.001	0.12 ± 0.001
$ \eta_{\text{lab}} < 3.0$				
$\langle N_{\text{ch}} \rangle$	110.00 ± 0.90	104.30 ± 0.04	105.00 ± 0.02	120.90 ± 0.02
σ	78.60 ± 0.30	72.21 ± 0.03	71.55 ± 0.02	78.14 ± 0.01
S	0.79 ± 0.01	0.71 ± 0.001	0.71 ± 0.001	0.64 ± 0.001
κ	0.08 ± 0.02	-0.09 ± 0.003	-0.07 ± 0.001	-0.04 ± 0.001
$-2.4 < \eta_{\text{lab}} < 2.4$				
$\langle N_{\text{ch}} \rangle$	89.53 ± 0.45	83.20 ± 0.03	84.60 ± 0.02	97.90 ± 0.02
σ	65.43 ± 0.17	58.12 ± 0.02	58.43 ± 0.01	64.72 ± 0.01
S	0.88 ± 0.01	0.75 ± 0.001	0.75 ± 0.001	0.73 ± 0.001
κ	0.43 ± 0.02	0.09 ± 0.003	0.09 ± 0.001	0.25 ± 0.001

The four moments ($\langle N_{\text{ch}} \rangle$, σ , S , and κ) of the measured multiplicity distributions at different pseudorapidity intervals are summarized in Table 4.4 and presented in Fig. 4.12, along with predictions from various event generators. These moments are used to quantitatively describe various features of the distributions. As expected, the $\langle N_{\text{ch}} \rangle$ and σ increase with increasing pseudorapidity interval. As seen in Fig. 4.12(a), HIJING and DPMJET underpredict the $\langle N_{\text{ch}} \rangle$ by $\sim 5\%$ while PYTHIA 8/Angantyr overpredicts the $\langle N_{\text{ch}} \rangle$ by $\sim 10\%$. Figure 4.12(b) shows that the values of σ are similar for data and PYTHIA 8/Angantyr; however, both HIJING and DPMJET underestimate the data by $\sim 10\%$. The skewness (a measure of asymmetry) is positive and maximum for $-2.4 < \eta_{\text{lab}} < 2.4$. HIJING and DPMJET underestimate the measured S by $\sim 12\text{--}17\%$, whereas PYTHIA 8/Angantyr underpredict the same by $\sim 22\%$. The kurtosis (a measure of tailedness) exhibits a similar behaviour

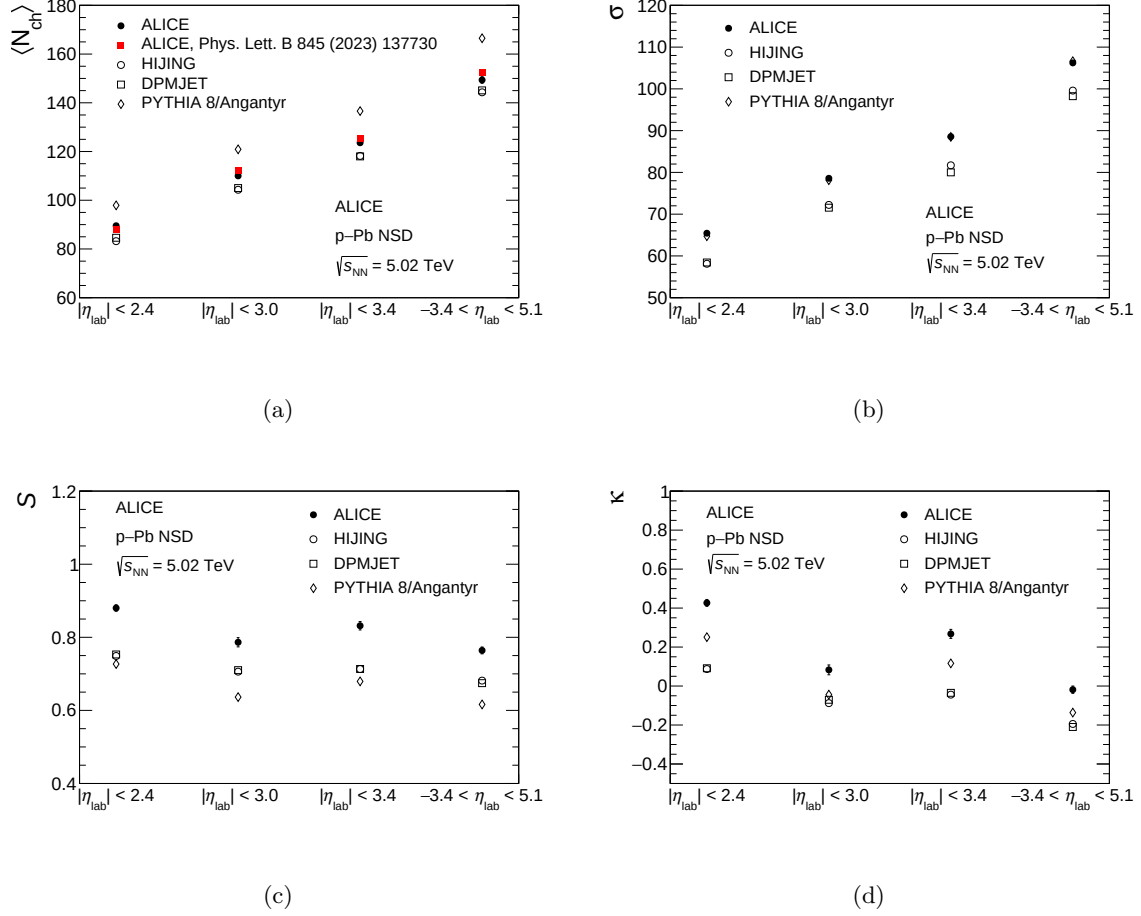


Figure 4.12: Four moments: $\langle N_{\text{ch}} \rangle$ (a), σ (b), S (c), and κ (d) of multiplicity distributions for different pseudorapidity intervals in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Predictions from event generators are superimposed.

like S but is smaller in magnitude. One can also notice that both HIJING and DPMJET predict negative κ for $|\eta_{\text{lab}}| < 3.4$ and $|\eta_{\text{lab}}| < 3.0$. Overall, the values of κ predicted by PYTHIA 8/Angantyr are closer to data than the other two models; however, they are still significantly different from the measured values in the data. The discrepancies between models and data will help to identify areas where the models need improvement or refinement.

In Fig. 4.12(a), the $\langle N_{\text{ch}} \rangle$ values have also been compared to previous ALICE measurements of pseudorapidity distributions where the data correction procedure is significantly different [8]. The results of the two independent measurements are

consistent within errors.

The scaled distribution of charged particle multiplicities for $-2.4 < \eta_{\text{lab}} < 2.4$ as a function of $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ is shown in Fig. 4.13. The distribution is compared to the predictions from the Colour Glass Condensate (CGC) [23] based IP-Glasma model [24]. The CGC framework generates particle multiplicities following a Negative Binomial distribution [25]. Moreover, the multiplicity distribution that originates from the decay of Glasma flux tubes [26] is a NBD with parameter $k \propto Q_s^2 S_{\perp}$ (k is related to standard deviation, see Sec. 4.3.3). The Q_s denotes the gluon saturation scale, and $S_{\perp}$ is the transverse overlap area of the collision [24]. The CGC-based IP-Glasma model includes several levels of fluctuations, such as fluctuations of the positions of nucleons inside the nucleus, fluctuations of the colour charges, fluctuations in the gluon fields, etc. These lead to fluctuations in global observables, such as multiplicity. In Fig. 4.13, two predictions of the IP-Glasma model [24] are shown, each corresponding to different normal fluctuations in the colour charge density. The model predictions underestimate the data at both low and high multiplicities but do better at intermediate multiplicities.

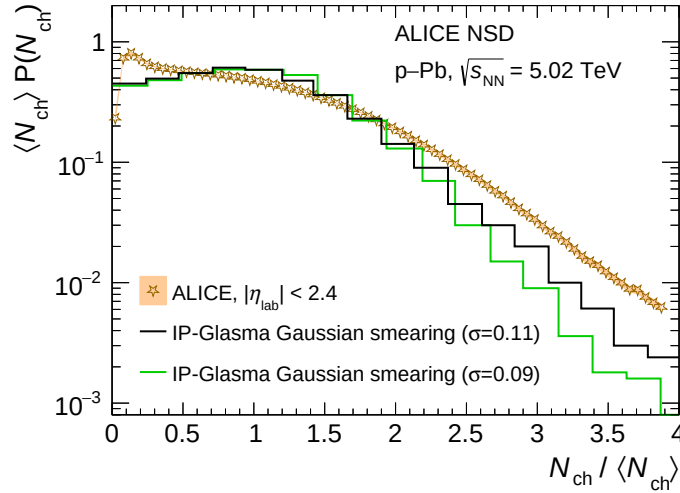


Figure 4.13: Scaled charged-particle multiplicity distributions as a function of $N_{\text{ch}}/\langle N_{\text{ch}} \rangle$ for $-2.4 < \eta_{\text{lab}} < 2.4$ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV compared to IP-Glasma model calculations [24].

4.3.3 Parametrization of multiplicity distributions with double NBDs

Experimental measurements in pp and p $\bar{p}$ collisions [20, 27, 28] showed that the multiplicity distributions of produced particles can be described by a single NBD, as given below in Eq. 4.2

$$f_{\text{NBD}}(n; \langle n \rangle, k) = \frac{\Gamma(n+k)}{\Gamma(k)\Gamma(n+1)} \frac{(\langle n \rangle/k)^n}{(1 + \langle n \rangle/k)^{n+k}} \quad (4.2)$$

where $\langle n \rangle$ denotes the mean multiplicity and the parameter k is related to standard deviation given by $\sigma/\langle n \rangle = \sqrt{1/\langle n \rangle + 1/k}$. However, single NBD failed to describe the data for larger pseudorapidity intervals and for larger $\sqrt{s}$ [10, 13, 21]. The weighted sum of two NBDs of the functional form

$$g(n; \langle n \rangle_1, k_1, \langle n \rangle_2, k_2, \lambda, \alpha) = \lambda[\alpha f_{\text{NBD}}(n; \langle n \rangle_1, k_1) + (1 - \alpha) f_{\text{NBD}}(n; \langle n \rangle_2, k_2)] \quad (4.3)$$

was then considered (according to the two-component model discussed in Refs. [29, 30] and found to explain the data better at LHC energies [10, 13, 31, 32]. The double NBDs represent two classes of events (soft: events without minijets or jets and semihard: events with minijets or jets) [29, 30, 32]. In Eq. 4.3, $\langle n \rangle_1$ and $\langle n \rangle_2$ are the mean multiplicities of the soft and hard components, respectively, and the parameter α reflects the fraction of soft events [29, 30, 32]. The parameters k_1 and k_2 are related to standard deviations of the distributions associated with the soft and hard components, respectively.

In this work, the double NBD function (given by Eq. 4.3) is fit to the measured multiplicity distributions. The first few bins are not considered in the fitting procedure, and a normalization factor λ is introduced to account for this. The measured data and the double NBD distribution (green line) for the best fit are shown in Fig. 4.14. The obtained parameters from the fit are summarized in Table 4.5. The double NBD function reasonably describes the data within the uncertainties.

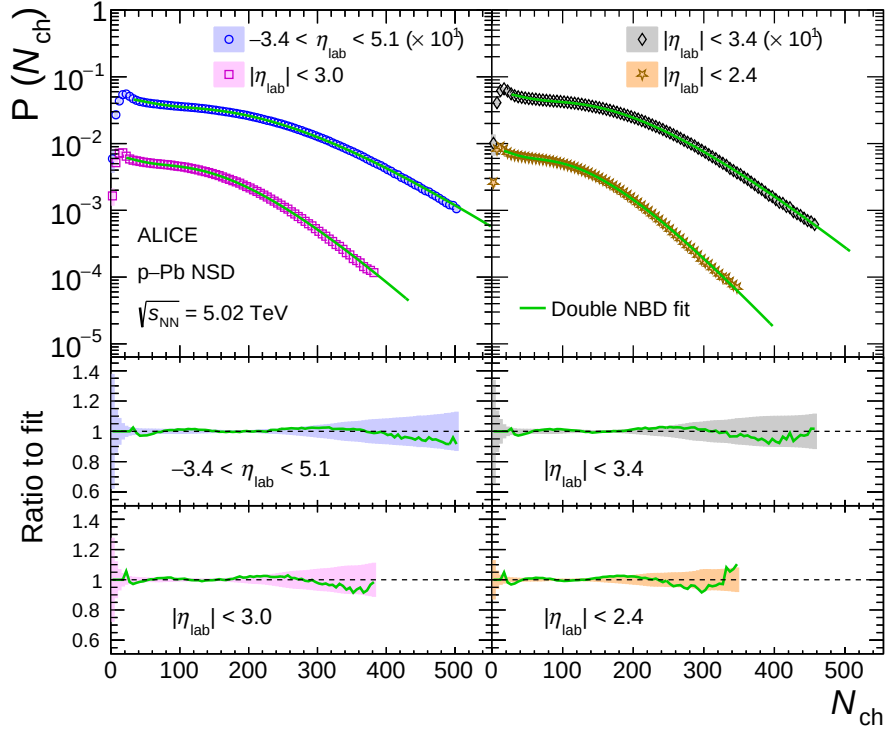


Figure 4.14: Charged-particle multiplicity distributions for different pseudorapidity intervals measured in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for NSD events. The green lines show fits to double NBDs. The ratios of the data to the fits are shown in the bottom panels.

Table 4.5: Double NBD fit parameters for charged-particle multiplicity distributions of NSD events in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

Pseudorapidity coverage	λ	α	k_1	$\langle n \rangle_1$	k_2	$\langle n \rangle_2$
$-3.4 < \eta_{\text{lab}} < 5.1$	1.03 ± 0.01	0.57 ± 0.03	1.27 ± 0.04	92.94 ± 6.60	4.87 ± 0.17	225.20 ± 1.69
$ \eta_{\text{lab}} < 3.4$	1.03 ± 0.01	0.56 ± 0.03	1.25 ± 0.04	76.30 ± 4.61	4.88 ± 0.14	181.60 ± 1.19
$ \eta_{\text{lab}} < 3.0$	1.02 ± 0.01	0.56 ± 0.03	1.25 ± 0.04	69.51 ± 4.42	4.86 ± 0.16	163.40 ± 1.14
$-2.4 < \eta_{\text{lab}} < 2.4$	1.03 ± 0.01	0.57 ± 0.02	1.18 ± 0.03	56.00 ± 2.98	4.75 ± 0.13	131.60 ± 0.72

Figure 4.15 shows the dependence of double NBD parameters on the size of the pseudorapidity interval in p–Pb collisions in comparison with pp measurements [13]. Both $\langle n \rangle_1$ and $\langle n \rangle_2$ increase with the increase in η_{lab} , and it is found that $\langle n \rangle_2 \simeq 3\langle n \rangle_1$ for both pp and p–Pb collisions. The parameters α , k_1 , and k_2 are independent of the width of the measured pseudorapidity interval for p–Pb collisions, unlike in

pp where they are found to have a mild dependence on the width of η_{lab} coverage.

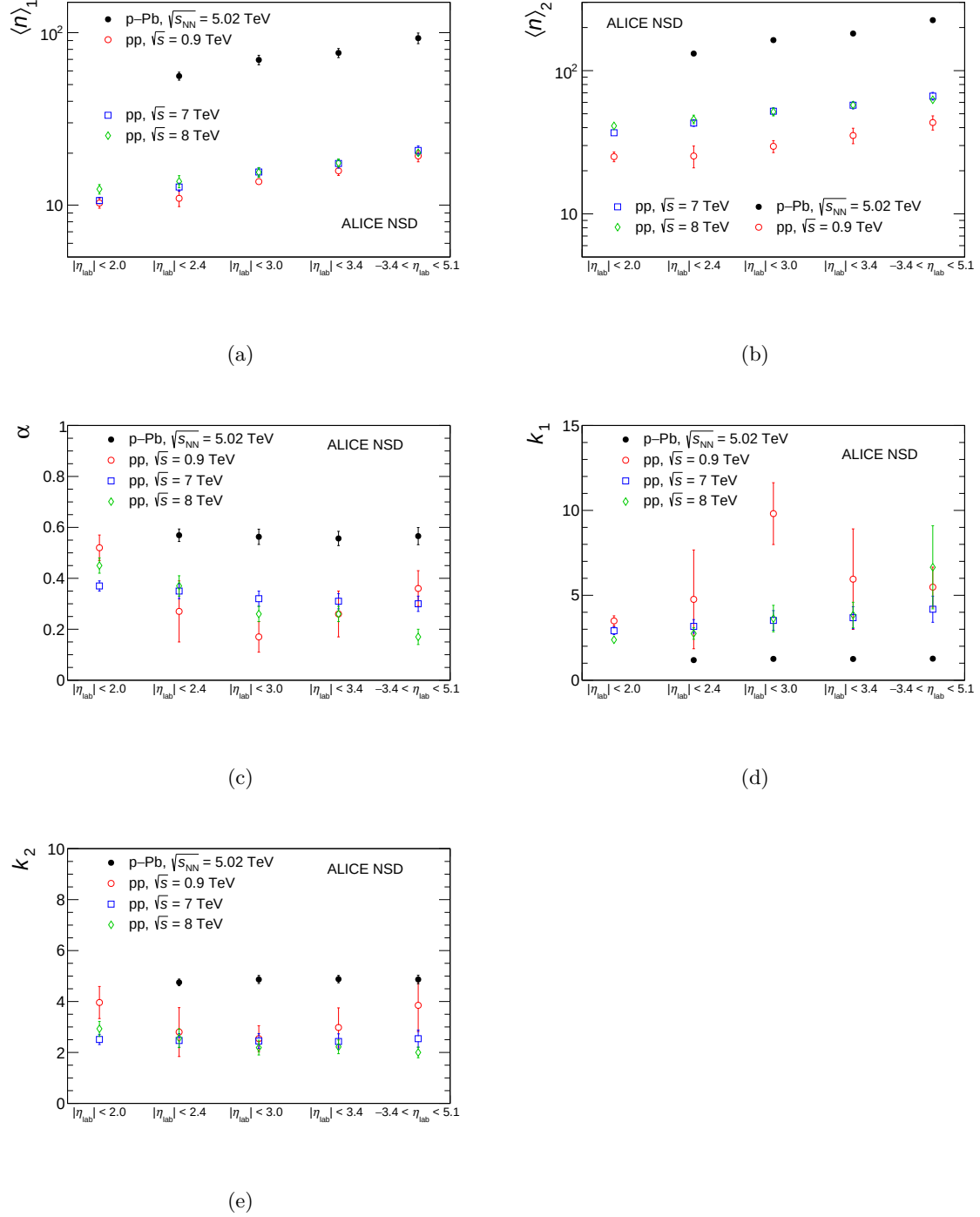


Figure 4.15: The pseudorapidity dependence of the double NBD parameters: $\langle n \rangle_1$ (a), $\langle n \rangle_2$ (b), α (c), k_1 (d), and k_2 (e) in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in comparison with pp measurements at $\sqrt{s} = 0.9, 7$, and 8 TeV.

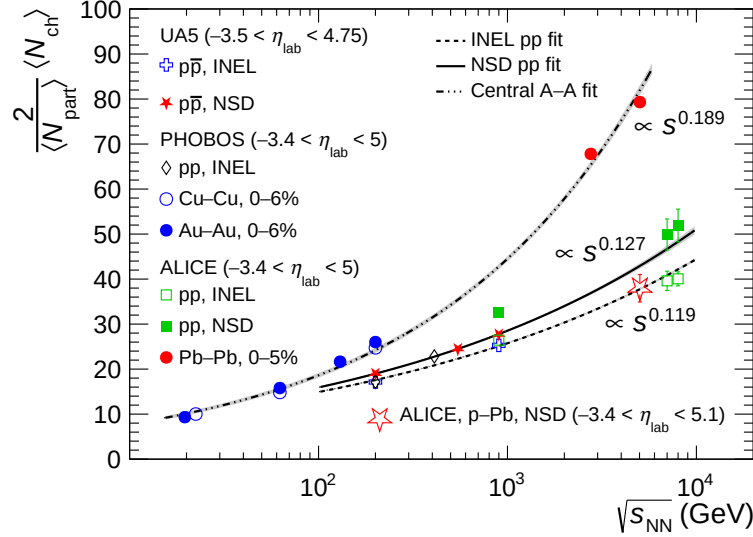


Figure 4.16: Values of $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$ for minimum bias pp [13, 33], p $\bar{p}$ [34], p-Pb and central AA [12, 18, 35] collisions as a function of $\sqrt{s_{\text{NN}}}$ are shown. The s -dependencies of INEL pp (p $\bar{p}$) and NSD pp (p $\bar{p}$) collisions are proportional to $s^{0.119}$ and $s^{0.127}$ respectively. The results from central AA collisions are proportional to $s^{0.189}$. The bands represent the uncertainties on the extracted power-law dependencies.

4.3.4 System-size and energy dependence of $\langle N_{\text{ch}} \rangle$

In order to understand and compare the evolution of bulk particle production with collision energy and system size, the mean charged-particle multiplicity is normalized by the average number of participating nucleons ($\langle N_{\text{part}} \rangle$) and then presented as a function of $\sqrt{s_{\text{NN}}}$ in Fig. 4.16 for different collision systems. The $\langle N_{\text{part}} \rangle$ is estimated using Glauber model calculations [33, 35–37]. The data from inelastic and non-single diffractive pp (p $\bar{p}$) collisions [13, 33, 34] and central heavy-ion collisions [12, 18, 35] are displayed. The dependence of $\langle N_{\text{ch}} \rangle$ on $\sqrt{s_{\text{NN}}}$ is fitted with a power-law function of the form $\alpha \cdot s^\beta$, resulting in $\beta = 0.1186 \pm 0.0004$, 0.127 ± 0.003 , and 0.189 ± 0.004 for INEL pp (p $\bar{p}$), NSD pp (p $\bar{p}$), and central AA collisions. The fit results are presented with their uncertainties shown by shaded bands. The results clearly show that the $\langle N_{\text{ch}} \rangle$ increases faster with energy in central AA collisions than in pp collisions.

The value of $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$ measured in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is ~ 2 times lower than the Pb–Pb data at the same energy and falls on the INEL pp curve indicating that the strong rise in central heavy-ion collisions may not be solely related to the multiple collisions undergone by the participants since the proton in p–Pb collisions also encounters multiple nucleons [35].

4.4 Summary

In summary, this chapter reports the measurements of multiplicity distributions of primary charged particles in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using the data obtained from the SPD and FMD of ALICE. The multiplicity distributions are obtained in four pseudorapidity ranges, $-2.4 < \eta_{\text{lab}} < 2.4$, $-3.0 < \eta_{\text{lab}} < 3.0$, $-3.4 < \eta_{\text{lab}} < 3.4$, and $-3.4 < \eta_{\text{lab}} < 5.1$. The multiplicity distributions are parametrized with double NBDs, which provide a good description of the data. The $\langle N_{\text{ch}} \rangle$ values of the multiplicity distributions are in agreement with previous measurements of $dN_{\text{ch}}/d\eta$ reported by ALICE. The data are compared with predictions from various theoretical models. The PYTHIA 8/Angantyr describes the data better at high multiplicities compared to HIJING and DPMJET, whereas in the intermediate multiplicity region, HIJING and DPMJET reproduce the data better compared to PYTHIA 8/Angantyr. The CGC-based IP-Glasma model is also unable to explain the data. The dependence of $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$ on $\sqrt{s_{\text{NN}}}$ is parametrized with a power-law function, showing that the multiplicity increases faster with increase in $\sqrt{s_{\text{NN}}}$ in heavy-ion collisions compared to pp and p–Pb collisions.

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Chapter 5

Summary

In summary, this thesis presents two important measurements on particle production at the LHC: a) inclusive photon multiplicity and its pseudorapidity distributions at forward rapidity ($2.3 < \eta < 3.9$) in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, and b) charged-particle multiplicity distributions over a wide pseudorapidity interval ($-3.4 < \eta < 5.1$) in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Both measurements are performed using the ALICE experimental data for the first time at the LHC. A fully indigenously built Photon Multiplicity Detector (PMD) is used to measure inclusive photon multiplicity, while the combined information of the Silicon Pixel Detector (SPD) and Forward Multiplicity Detector (FMD) are used to determine charged-particle multiplicity. The data analysis procedures of these two measurements start with extracting the raw signal, obtaining the uncorrected distributions followed by corrections for instrumental and other effects using the unfolding method, and finally estimating the systematic uncertainties from various sources. All these steps are discussed in great detail in this thesis along with a brief discussion of the collider facility, the LHC, and various sub-systems of the experimental apparatus, the ALICE. The final corrected data are compared to results from various experiments and to predictions from theoretical models to draw important physics conclusions. The summary of these two measurements are briefly discussed below.

Measurements of inclusive photon multiplicity

The multiplicity and pseudorapidity distributions of inclusive photons are measured at forward pseudorapidity, spanning the range from 2.3 to 3.9, using a preshower detector, the PMD. Photons are reconstructed in two steps: (i) finding clusters of hits on the preshower plane of the PMD and (ii) discriminating between photons and charged hadrons. The clustering is performed using a nearest neighbour clustering algorithm. Each cluster is characterized by the number of cells (cluster N_{cell}) contained in it and the total energy (measured in terms of ADC) deposited in that cluster. Suitable photon-hadron discrimination thresholds are applied based on the cluster N_{cell} and ADC content to obtain a photon-rich sample, known as $N_{\gamma\text{-like}}$ clusters. A Bayesian unfolding technique is then used to correct the distributions of $N_{\gamma\text{-like}}$ clusters affected by instrumental effects and the contamination from hadron clusters. The unfolded distributions are also corrected for trigger and vertex reconstruction efficiencies. Systematic uncertainties from various sources (effect of upstream material in front of the PMD, hadron and secondary photon contaminations, event generator dependence, unfolding method) are estimated and then added in quadrature to obtain the total systematic uncertainty.

In p-Pb collisions, with the present statistics, the measured N_{γ} reaches up to 140, which corresponds to 5 times larger than its $\langle N_{\gamma} \rangle$. The $\langle N_{\gamma} \rangle$ in pp collisions is found to be ~ 4.5 times smaller than that in p-Pb collisions. The multiplicity distributions are parametrized with double negative binomial distributions that give a good representation of the data. The pseudorapidity distributions of photons are obtained for various centrality classes for the first time in p-Pb collisions at the LHC. The centrality classes are determined by measuring the charged-particle multiplicity in the outer layer of the SPD at midrapidity (denoted as CL1 estimator) and the energy deposited in the Pb-remnant side of the neutron calorimeter at beam rapidity (denoted as ZNA estimator). The $dN_{\gamma}/d\eta_{\text{lab}}$ in the highest centrality class (0–5%),

when considering the CL1 (ZNA) estimator, reaches values thrice (twice) as large as those in minimum bias events.

The results are compared to similar measurements of charged particles at midrapidity and predictions from various event generators (PYTHIA 6 with the Perugia 2011 tune, PYTHIA 8 with the Monash 2013 tune, PHOJET, EPOS LHC for pp collisions and HIJING, DPMJET, AMPT for p-Pb and Pb-p collisions). The PYTHIA 8 generator with the Monash 2013 tune and the EPOS LHC generator do not reproduce the multiplicity distribution in pp collisions at high multiplicities, whereas PYTHIA 6 with the Perugia 2011 tune and PHOJET better describe the data within uncertainties. For p-Pb collisions, none of the considered MC models could explain the multiplicity results in the full range. However, HIJING and AMPT can reproduce the tail of the distribution for both p-Pb and Pb-p collisions. Interestingly, compared to multiplicity distributions, the pseudorapidity distributions of inclusive photons are better described by all the considered MC models. The model predictions are found to describe the data within 20%. The pseudorapidity density of inclusive photons at forward rapidity follows the η_{lab} dependence of charged-particle multiplicity at midrapidity in pp and for various centrality classes in p-Pb collisions. This can be attributed to the fact that the major contribution to inclusive photons comes from the decay of neutral pions, and therefore, the number of produced photons should be similar to that of charged particles. The models give similar pseudorapidity densities for photons and charged particles only at forward rapidity, where the difference between η and y is negligible. The HIJING describes the centrality evolution of both photon and charged-particle production within about 10–12%. The $\langle N_\gamma \rangle$ divided by the $\langle N_{\text{part}} \rangle$ scales linearly with both $N_{\text{part}}^{\text{high-}p_T}$ and $N_{\text{part}}^{\text{Pb-side}}$ estimated by the energy deposited in the ZDC and the trend with $\langle N_{\text{part}} \rangle$ is consistent with the data point from pp collisions at $\sqrt{s} = 5.02$ TeV.

These results of inclusive photon production in pp and p-Pb collisions provide important input for the tuning of theoretical models and MC event generators and

help to establish the baseline measurements to interpret the Pb–Pb data.

Measurements of primary charged-particle multiplicity

The multiplicity distributions of primary charged particles are measured for the first time in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV over a wide pseudorapidity (more than eight units) coverage, $-3.4 < \eta_{\text{lab}} < 5.1$, the widest possible among the four large LHC experiments. In addition to $-3.4 < \eta_{\text{lab}} < 5.1$, the multiplicity distributions are also obtained for the other three pseudorapidity ranges, $-2.4 < \eta_{\text{lab}} < 2.4$, $-3.0 < \eta_{\text{lab}} < 3.0$, $-3.4 < \eta_{\text{lab}} < 3.4$. The charged-particle multiplicity is determined by counting the number of tracklets using the SPD detector at midrapidity ($|\eta_{\text{lab}}| < 2$) while at forward rapidity ($-3.4 < \eta_{\text{lab}} < -1.7$ and $1.7 < \eta_{\text{lab}} < 5.1$) the measurement is done based on the deposited energy signals in the FMD and the number of charged particles are calculated by employing Poisson statistical approach. Corrections for instrumental effects (detection inefficiency, limited acceptance, etc.) and contaminations from secondary particles are performed using the Bayesian unfolding method. The unfolded distributions are further corrected for the event selection inefficiency. Systematic uncertainties from various sources (effect of upstream material in front of the FMD, event generator dependence, unfolding parameters) are evaluated and then added in quadrature to obtain the total systematic uncertainty.

The measured charged-particle multiplicity distributions are compared to the predictions from three event generators (HIJING, DPMJET, and PYTHIA 8/Angantyr) and the calculations from the CGC-based IP-Glasma model. None of the considered event generators are found to reproduce the shape of the measured distributions. In particular, both HIJING and DPMJET strongly underestimate the tails of the distributions but predict the data comparatively better at intermediate multiplicities. PYTHIA 8/Angantyr reproduces the data better at high multiplicities than HIJING and DPMJET. The lowest part of the multiplicity distributions,

where the diffractive content is expected to be higher, is not described by any of the generators. A quantitative comparison between data and models is made by studying the moments of the multiplicity distributions. Different models show varying degrees of agreement with the data, but none of them completely capture the observed behaviour of charged-particle multiplicity distributions. The CGC-based IP-Glasma model underestimates the data at both low and high multiplicities but reproduces the measurements comparatively better at intermediate multiplicities. Double negative binomial distributions are used to fit the multiplicity distributions and are found to explain the data within the uncertainties.

Finally, the values of $\langle N_{\text{ch}} \rangle$ normalized by $\langle N_{\text{part}} \rangle$ are calculated for different collision systems and studied over a wide range of collision energies. The dependence of $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$ on the centre-of-mass energy is parametrized by a power-law function, which shows that the multiplicity increases faster with energy in central heavy-ion collisions compared to pp and p-Pb collisions.

The present measurements provide an essential input for tuning the parameters in the theoretical models, improving our understanding of the charged particle production mechanisms in p-Pb collisions. Moreover, they will help to establish baselines for the interpretation of similar measurements in Pb-Pb collisions.

List of corrections

List of corrections

I would like to thank the Referee for reviewing my thesis and providing his/her valuable comments which improve the quality of the thesis. All of your suggestions are incorporated in the corrected version of the thesis. The list of corrections made in the thesis is prepared and given below.

Sl. No.	Referee's comments/suggestions	Corrections
1.	Page No. 116 Line no. 3: Fig. 4.3.2 to be replaced by Fig. 3.20	Fig. 4.3.2 has been replaced by Fig. 3.20 in the corrected thesis
2.	Page No. 117 Line no. 7: Fig. 4.14 to be replaced by Fig. 3.21	Fig. 4.14 has been replaced by Fig. 3.21 in the corrected thesis
3.	Page No. 117 Last Line: Table 4.5 to be replaced by Table 3.8	Table 4.5 has been replaced by Table 3.8 in the corrected thesis
4.	Page No. 118 First Line: Table 4.5 to be replaced by Table 3.8	Table 4.5 has been replaced by Table 3.8 in the corrected thesis