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博士学位论文

ALICE 实验 5.02 TeV 质子-质子和质子-铅-核

碰撞中伴随粒子产生性质的研究

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摘 要

大型离子对撞机实验 (ALICE) 是位于欧洲核子研究中心 (CERN) 大型强子对撞机 (LHC) 上的四大实验之一。通过 LHC 上的相对论重离子碰撞, 将巨大的粒子动能转化为热能, 形成极端高温高能量密度环境, 重现大爆炸宇宙之初的物质形态。然而, 随着 LHC 上在小系统碰撞 (例如质子-质子和质子-铅核撞) 中观测到二粒子角度关联、类集体流等一批新物理现象, 引起了人们对小系统碰撞研究的极大兴趣和关注, 人们试问这种类流现象的出现是否代表在小系统碰撞中也发生了类 QGP 物质现象? 出现在高能-核碰撞中的部分子能量损失及其核压低是否也会重现在小系统碰撞中? 伴随着部分子喷注粒子产生的物理背景行为的影响又如何? 同时, 小系统碰撞又是核-核碰撞中众多重要物理观测量和判别新物理现象产生的基准信息。围绕着这一系列热点问题和核-核碰撞中对夸克物质信号及其性质测量参考的物理需要, ALICE 实验展开了对小系统碰撞物理研究的热潮。

在一对高能强子-强子碰撞中, 除了人们最感兴趣的硬部分子散射作用外, 实际还存在诸多软过程和半硬过程的粒子产生, 我们把这类粒子称作 Underlying Events (UE), 也称之为硬过程产生时的伴随粒子事件, 它们是硬过程产生测量中的主要背景成分, 使得实验测量变得极为复杂。在一对强子碰撞中, 伴随粒子事件主要由部分子 (夸克和胶子) 相互作用初态和末态辐射 (Initial state radiation: ISR, Final state radiation:FSR) 多重部分子相互作用 (Multi-parton interactions:MPI), 以及碰撞束流相互作用剩余体等构成。由于 UE 事件是强子碰撞中任何信号部分子相互作用发生时的伴随组分, 因此, 为了精确测量小系统碰撞中的信号观测量, 实验上需要清晰地分离出由 UE 事件产生引起的背景组分, 实验上对这一组分的观测和分离具有极大地挑战性。因此, 对 UE 事件的研究和理解显得极为重要。

在单个碰撞中我们并不能区分硬散射和 UE 事件, 但是从实验上可以找出对 UE 事件特别敏感的拓扑区间和找出对 UE 特别敏感的可观测量。传统的 UE 分析依赖于对三个不同拓扑区域中的粒子产生的测量, 这三个区域与事件的领头粒子沿方位角上可划分为: Toward(前向)、Transverse (横向) 和 Away (背向) 三个朝向。前向和背向区域主要由硬过程产生的粒子为主导, 因此对 UE 相对不敏感。相比之下, 横向区域有 UE、ISR 和 FSR 的贡献, 但横向区域对 UE 更敏感, 其中定义的观测值是 UE 测

量的主要焦点。许多实验已经报道了在不同的质心系能量下应用横向区域法的 UE 测量。本工作的主要目的是, 研究质心系能量 $\sqrt{s} = 5.02$ TeV 质子-质子和质子-铅核碰撞中 UE 事件粒子产生行为及其性质。

本论文工作首次报告了 LHC ALICE 实验中质心系能量 $\sqrt{s_{NN}} = 5.02$ TeV pp 和 p-Pb 碰撞中 UE 事件粒子产生性质的观测结果。我们通过带电粒子数和粒子横动量 (p_T) 总和密度作为领头粒子 (leading particle, 亦称之为事件触发粒子: trigger particle) 横动量 (p_T^{trig}) 的函数, 来定量描述 UE 事件行为。我们分别测量了前向、横向和背向三个区域的 UE 事件行为, 给出了中心赝快度区 ($|\eta| < 0.8$) 在三种不同 p_T 阈值 (0.15、0.5 和 1 GeV/c) 下的观测结果。横向区域中的事件行为对 UE 事件最为敏感, 在 pp 和 p-Pb 碰撞中二者表现出类似的粒子产生, 即随 p_T^{trig} 急剧增加, 然后在 $p_T^{\text{trig}} \approx 5$ GeV/c 时达到饱和。已发表的 pp 碰撞结果与其它质心能量下测量的 UE 事件的结果进行了比较。还分析了前向区和背向区在减去横向区域测量的贡献后的观测结果。我们的进一步分析发现, 当 $p_T^{\text{trig}} > 10$ GeV/c 时, pp 和 p-Pb 碰撞中剩余的喷注粒子密度是一致的; 而当 p_T^{trig} 值较低时, p-Pb 碰撞中的事件活动 (jet like signals) 略高于 pp 碰撞中的事件活动。测量结果与 PYTHIA 8 和 EPOS LHC 蒙特卡罗事件发生器的预测结果进行了比较。

本论文的结构和内容如下: 第一章介绍高能碰撞的历史背景和物理基础。这包括标准模型进而引入相对论重离子碰撞和小系统碰撞的概念及基础, 以及紧密联系实验结果预言和比较的蒙特卡诺产生器。第二章介绍高能碰撞中伴随事件 (UE)、多重部分子相互作用等物理概念, 研究基础和现状, 是本论文研究工作动机所在。包括基于对伴随事件 (UE) 的解释以及之前通过不同实验为 UE 进行的工作。第三章简介大型重离子实验探测装置 ALICE 探测器及与本研究工作的数据获取和分析工作密切相关的 ALICE 子探测器的结构、功能和性能的介绍。第四章讨论本研究工作的分析方案和方法、数据、事件和粒子径迹的筛选、数据质量控制及各类观测量分布的检验、重建粒子径迹效率校正, 以及系统误差的估算方案。第五章详细讨论了事件观测量的分析方案和策略的交叉检验、以及与蒙特卡诺模拟结果和与发表结果的比较。最后给出了 pp 和 p-Pb 碰撞中 UE 事件产生、jet-like 事件产生, 以及 UE 事件产生的能量依赖的实验观测的最终结果。这些结果获得 ALICE 国际合作组批准已投稿国际杂志并被杂志同意接受发表。最后, 第六章给出本研究工作的结论和对该本课题研究发展的展望。

关键词: ALICE 实验; 质子-质子碰撞; 质子-铅核碰撞; 多重部分子相互作用; 初态和末态辐射; 伴随事件产生与测量; 蒙特卡诺研究.

Abstract

The LHC is the experimental setup to test the theoretical predictions made by the standard model. The interactions of the fundamental particles which form hadrons are explained by the strong interaction theory called quantum chromodynamics (QCD). QCD provides a good explanation of hadron collider data to conduct a more precise experiment to test the theory, a technique called perturbative QCD (pQCD) is adopted. It is a subfield of particle physics by using the fact that the strong coupling constant α_s is small in high energy and short-distance interactions, thus allowing the perturbation theory techniques to be applied.

ALICE (A Large Ion Collider Experiment) is one of the biggest experiments performed on the LHC at CERN. It is devoted to collecting the data from high-energy heavy ion collisions, where a new state of nuclear matter that is thought to exist in the early universe can be created in QGP (quark-gluon plasma). From the analysis of data we can investigate its formation and properties. The data that ALICE collects are obtained from different detectors which can form ALICE. Other than heavy ion collisions small collisions system based on pp and p-Pb collisions are also under investigation at LHC. In this work TPC, ITS, and V0 detectors are used, which are also considered in this research work.

The main goal of this work is to study underlying event (UE) in small collision systems. The components of particle production in hadronic interactions, which are not directly related to the hardest partonic interaction, are studied. It includes the multi-parton interaction (MPI), initial and beam remnants. The UE and the LHC simulations are critical to fully grasping the LHC physics program at CERN's Large Hadron Collider (LHC). This is due to the fact that the UE is a component of the same proton-proton collision that any signal-partonic interaction occurs in. In order to comprehend the backdrops to other observables in small collisions systems, it is necessary to have a good understanding of the UE.

A hard scattering and the UE cannot be distinguished in an individual collision, however there can be observables that can be estimated that are particularly sensitive to the UE. Traditional UE analysis relies on measuring particle production in three distinct topological regions at an azimuthal angle to the event's leading particle: toward, away, and transverse. The Toward and Away regions are dominated by particle production from the hard process and are hence relatively insensitive to the UE. In contrast, transverse region has contributions from UE, ISR, and FSR but the transverse region is more sensitive to the UE, and observables defined inside it are the primary focus of UE measurements. A number of experiments have reported UE by using transverse region method at different center-of-mass energies. The goal of this work is to perform the UE analysis in pp collisions at $\sqrt{s} = 5.02$ TeV it is the

first time that results for this energy are presented pp collisions at $\sqrt{s} = 5.02$ TeV is analysed and also the same method is used for p–Pb collisions with same $\sqrt{s_{\text{NN}}}$ energy and same thresholds of transverse momentum.

We report about the properties of the underlying event measured with ALICE at the LHC in pp and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The event activity, quantified by charged-particle number and summed- p_{T} densities, is measured as a function of the leading-particle transverse momentum ($p_{\text{T}}^{\text{trig}}$). These quantities are studied toward, away, and transverse regions. Results are presented for three different p_{T} thresholds (0.15, 0.5 and 1 GeV/ c) at mid-pseudorapidity ($|\eta| < 0.8$). The event activity in the transverse region, which is the most sensitive to the underlying event, exhibits similar behaviour in both pp and p–Pb collisions, namely, a steep increase with $p_{\text{T}}^{\text{trig}}$, followed by a saturation at $p_{\text{T}}^{\text{trig}} \approx 5$ GeV/ c . The results obtained in this analysis from pp collisions are compared with existing measurements at other centre-of-mass energies, e.g. 0.9, 7 and 13 TeV. The quantities in the toward and away regions are also analyzed after the subtraction of the contribution measured in the transverse region. The remaining jet-like particle densities are consistent in pp and p–Pb collisions for $p_{\text{T}}^{\text{trig}} > 10$ GeV/ c , whereas for lower $p_{\text{T}}^{\text{trig}}$ values the jet-like particles production is slightly higher in p–Pb than in pp collisions. The measurements are compared with predictions from the PYTHIA 8 and EPOS LHC Monte Carlo event generators.

Keywords: ALICE experiment; pp interaction; p–Pb interaction; underlying event production and measurement; Monte Carlo simulation; multiple partonic interactions; initial state radiation and final state radiation

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Abbreviation

Abbreviation	Description
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
CERN	European Organization for Nuclear Research
CMS	Compact Muon Solenoid
CDF	Collider Detector at Fermilab
DCA	Distance of Closest Approach
FSR	Final state radiation
GEANT	GEometry ANd Tracking
ISR	Initial state radiation
ITS	Inner Tracking System
LHC	Large Hadron Collider
MC	Monte Carlo
MPI	Multiple Parton Interactions
QA	Quality Assurance
QCD	Quantum Chromo-Dynamics
QED	Quantum Eletro-Dynamics
QGP	Quark-Gluon Plasma
Reco	Reconstruced
SDD	Silicon Drift Detector
SPD	Silicon Pixel Detector
TOF	Time Of Flight
TPC	Time Projection Chamber
TRD	Transition Radiation Detector
UE	Underlying event



Chapter 1 High-Energy Collisions

1.1 The Standard Model

The theory of modern era is standard model (SM) theory that explains the basic interactions of the nature which interact within the dynamics of subatomic nuclear particle. These interactions are electromagnetic, weak and strong nuclear interactions. Initially, in the middle of the 20th century till the end this model was continuously developing but the achievement was made to get the existing form of SM in the mid of 1970s when the presence of quarks was confirmed in an experimental observation. It explains the basic elements of the cosmos (particles of elementary nature) and their interactions [1].

In the SM, all elementary particles of matter are spin 1/2 particles. These particles are classified into two categories: leptons and quarks. Leptons are further subdivided into neutrinos that are electrically neutral, and charged leptons with charge -1 . Also, quarks are divided into two categories, type up and type down quarks, with electric charge of $+2/3$ and $-1/3$ respectively. Every one of these quarks has a corresponding anti-quarks, with the same properties but opposite electric charge and quantum numbers. Each of these categories involves exactly three quarks, and so it is possible to group them into three families, or generations [2]. To introduce interactions between particles, it is necessary to impose that the Lagrangian of the system reverences gauge local symmetries; this request leads to the introduction of spin 1 particles, called gauge bosons, which mediate the interactions. The symmetry group $SU(2) \otimes U(1)$ gives the electroweak interactions, while $SU(3)$ gives the strong interaction. If all the particles used are massless then electroweak interaction is possible, else mass terms will not provide explanations about gauge symmetry. When these particles interact with the Higgs scalar field and gauge symmetry spontaneously breaks, their masses are restored. Furthermore, on the basis of the free Dirac Lagrangian for fermions:

$$\mathcal{L} = \sum_f \bar{\Psi}_f (i\partial - m_f) \Psi_f \quad (1.1)$$

It is feasible to introduce the interactions enforcing the invariance of the Lagrangian



regard to a local gauge symmetry group. The particles matching to the interaction fields are termed gauge bosons.

The $SU(2)$ invariance needs three vector bosons. A linear combination of them gives the $W^\pm$ charged bosons which are responsible for the charged currents, while the third combines with the $U(1)$ invariance boson to produce both electromagnetic interactions (mediated by the photon γ) and the weak neutral interactions (mediated by the Z_0 boson).

The strong interactions described by the Quantum Chromodynamics (QCD) theory and generated by the $SU(3)$ symmetry group are shown in the table 1.

Interactions	Boson	Electric charge	Mass (GeV/c)
Electromagnetic	γ	0	0
Weak	$W^\pm$	± 1	80.399 ± 0.023
	Z	0	91.1876 ± 0.0021
Strong	g	0	0

Table 1: The interactions between particles together with the gauge bosons and their properties [2].

Quarks

As the quark scheme is symmetric which helps to organized the baryons and mesons into different families. In 1964, Zweig and Gell-Mann gave the detail description about the three fundamental constitutes of quarks with the help of mathematical symmetries. These quarks are named as, up, down and strange quarks. The endorsement for the concoction of neutron and proton was first established in late 60s till 70s of 19th century, so fundamental component of neutron and proton is quarks. The quarkonium j/ψ was recognized surprisingly in SLAC (Stanford Linear Accelerator Collider) in the year 1974, after that it was established as a quarks and anti-quarks pairs[2]. The charm quark is the newly discovered quark on the fourth number in the list. Maskawa, Cabbibo and Kobayashi are the three theorists who explained the quarks as a six quarks scheme. After all these developments there came to exist six kinds of quarks, up, down, strange, charm, top and bottom, also they have their anti-quarks pair. A heavy meson was discovered in 1977 at the Fermilab in an experiment after the model with six quarks was completed. Quark's parameters specified in the



standard model is shown in the table 2.

Intrinsic Spin $\frac{1}{2}$ properties of Quarks			
Generation	Particle	Charge (e)	Mass (GeV)
I	Up (u)	$+2/3$	0.005
	Down (d)	$-1/3$	0.009
II	Charm (c)	$+2/3$	1.5
	Strange (s)	$-1/3$	0.16
III	Top (t)	$+2/3$	171.2
	Bottom (b)	$-1/3$	4.20

Table 2: Quark Parameters with charge described in Standard Model [2].

Leptons

During the first decade of 19th century electron, neutrino and muon were the familiar particles. As these particles are less massive, that is why they show different behavior than mesons and baryons. In all these particles muon is the heaviest variant of electron. The mass of muon is 9 times smaller than the proton whereas the mass of electron is 2000 times less than that of proton. Neutrinos are the massless particles. The weak nuclear force is the mediator for electron and muon. As compared to proton and neutron these particles don't have ability to produce mesons and baryons to a large extent during high energy collisions. In an experiment of high energy beam in 1962 it was proved that muon and electron have their own neutrinos [2].

As these are the fundamental particles so that experiment has also confirmed the evidence for the existence of fundamental particles as a pair in different generations. Immediately after the discovery of j/ψ meson, tau a heavy lepton is revealed in 1974. There are three families of leptons with six types of leptons named as electron, electron-neutrino, muon, muon-neutrino, tau, tau-neutrino [2]. Lepton is being considered as a fundamental and undividable component of matter that is why they are also called as elementary particle. Electron is the first charged lepton and it was theoretically predicted in the mid of 19th century by many theorists [3, 4] but experimentally was confirmed by J. J. Thomson in 1897 [5]. After that muon becomes the next lepton and its discovery was made by Carl D. Anderson [6] in 1936 but scientists of that time wrongly identified it as meson. In the given table 3 parameters of lepton described in the SM is shown.



Intrinsic Spin $\frac{1}{2}$ properties of Leptons			
Generation	Particle	Charge (e)	Mass (GeV)
I	Electron (e)	-1	5.1×10^{-4}
	Electron Neutrino (ν_e)	0	$< 0.8 \times 10^{-8}$
II	Muon (μ)	-1	0.105
	Muon Neutrino (ν_μ)	0	2.7×10^{-4}
III	Tau (τ)	-1	1.777
	Tau Neutrino (ν_τ)	0	< 0.035

Table 3: Lepton Parameters with charge and mass as described in Standard Model [2].

1.2 Quantum Chromodynamics

The quantum field theory of strong interactions mediated by massless gluons is known as quantum chromodynamics (QCD). SU(3) local gauge symmetry is non-Abelian in this case, hence it's non-Abelian. It is concerned with color charge, i.e., red, green, and blue, and all freely propagating particles are color singlet states; free quarks and gluons are absent [7]. Quantum chromodynamics (QCD) provides an effective account of data from hadron colliders, and it should be regarded an experimentally confirmed fact. For high-mass particle physics research, proton-antiproton and proton-proton colliders are essential tools, providing a way to attain greater center-of-mass energies than is feasible with circular e^+e^- colliders. The underlying process in hadron-hadron collisions is the interaction of two partons, which can be either quarks, antiquarks or gluons. To get more insight we point out [8] and [9].

The Lagrangian of QCD, omitting for now gauge-fixing terms, is

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_{\alpha\beta}^A F_A^{\alpha\beta} + \sum_{\text{flavors}} \bar{q}_a (i\not{D} - m)_{ab} q_b \quad (1.2)$$

The second term represents a set of spin-1/2 quarks, interacting with a gauge field hiding in the covariant derivative $\not{D}$ (Dirac indices have been suppressed). The gauge interaction corresponding to QCD is SU(3), with the gauge charge conventionally referred to as “color” [10]. Quarks (antiquarks) live in the fundamental (anti-fundamental) representation of SU(3), so a quark field carries a color index: q_a , where a runs from 1 to 3. The gauge fields, called gluons, live in the adjoint



(dimension 8) representation. Note $SU(3)$ is non-Abelian, so the field strength term $-\frac{1}{4}F_{\alpha\beta}^A F_A^{\alpha\beta}$ contains self-interaction terms:

$$F_{\alpha\beta}^A = [\partial_\alpha \mathcal{A}_\beta^A - \partial_\beta \mathcal{A}_\alpha^A - gf^{ABC} \mathcal{A}_\alpha^B \mathcal{A}_\beta^C] \quad (1.3)$$

The indices $\{A,B,C\}$ run over the eight color degrees of freedom for the gluon. The interaction terms mean that the gluons themselves carry color charge.

1.2.1 Color confinement

Due to the fact that the force between two color charges remains constant as they are separated, the energy builds until a quark–antiquark pair is spontaneously formed, converting the original hadron into a pair of hadrons rather than isolating a color charge as was the case before. Color confinement is widely known through lattice QCD calculations and decades of experimentation, despite the fact that it has not been demonstrated analytically [11]. The twin phenomena of confinement and asymptotic freedom have significant ramifications for the phenomenology of quantum gravity. It follows from confinement that quarks and gluons are not “particles” in the sense of asymptotic states that propagate freely, but rather are poorly defined “particles”. Quarks are bound together in hadrons by a very strong coupling, which prevents individual quarks from ever being separated [10].

1.2.2 Asymptotic freedom

As the energy scale of interactions grows, the intensity of interactions between quarks and gluons asymptotically diminishes (and the corresponding length scale decreases). The strong interaction coupling constant α_s is used to describe the strength of strong interaction. the precision of α_s determinations and the multitude of results from various processes and ranges of energies provided experimental proof [12, 13] of the concept of asymptotic freedom. Lattice QCD predicts QGP. In real QCD, the cou-



pling runs logarithmically [14] with the energy,

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \frac{\partial \alpha_s}{\partial \ln Q^2} = \beta(\alpha_s) \quad (1.4)$$

where the function driving the energy dependence, the beta function, is defined as

$$\beta(\alpha_s) = -\alpha_s^2(b_0 + b_1\alpha_s + b_2\alpha_s^2 + \dots) \quad (1.5)$$

A solution of equation 1 in 1-loop approximation, i.e. neglecting β_1 and higher order terms, is

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln \frac{Q^2}{\mu^2}} \quad (1.6)$$

by using the Λ the above equation can be written as

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln \frac{Q^2}{\Lambda^2}} \quad (1.7)$$

where

$$\Lambda^2 = \frac{\mu^2}{e^{1/\beta_0\alpha_s(\mu^2)}} \quad (1.8)$$

95 1.3 Hard scattering

Hard or highly penetrating probes originate from hard scattering of partons (quarks and gluons) and are characterized typically by either large momentum transfer (i.e., large 4-momentum transfer squared Q^2), large transverse momentum (p_T) or a large mass (m) scale [15]. Thus by definition, hard probes are highly penetrating observables used to explore properties of matter that cannot be viewed directly. Examples of these observables include radiation, high p_T particles, jets, and particles with heavy quarks even at low p_T . The cross-section for hard scattering can be written in the form of following way:

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{i,j} \left(p_1, p_2, \alpha_s(\mu_R^2), \frac{Q^2}{(\mu_F^2)}, \frac{Q^2}{(\mu_R^2)} \right) \quad (1.9)$$

96 The development is drawn in Figure 1.1. In this formula P_1 and P_2 . represents the

incoming hadrons having 4-momenta, $p_1 = x_1 P_1$ and $p_2 = x_2 P_2$ are the 4-momenta of the partons partaking in the hard scattering, where x_i are the parton's Bjorken- x values. Where Q is denoted as the development distinguishing scale, i.e., p_T of the outgoing jets. The PDFs $f_i(x, \mu_F^2)$ are expressed in terms of factorization notion scale μ_F^2 presented previously. The re-normalization term is represented by μ_R . To provide assistance for the ultra-violet (UV) divergence of the theory in the QCD it is initiated. The re-definition of the coupling constant α_S is captivated for this divergence. After which it is served as a "running constant". The short distance

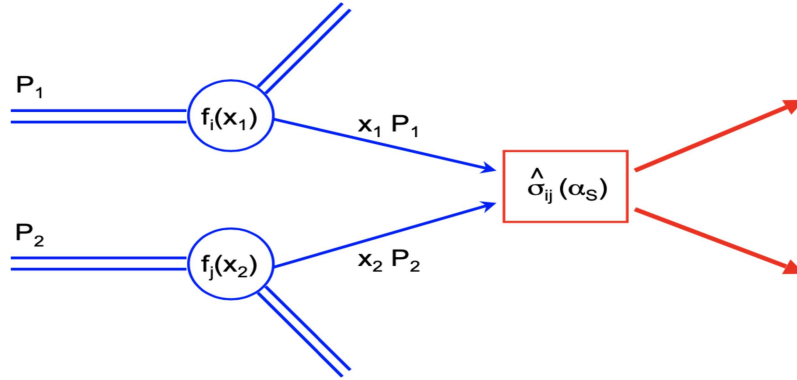


Figure 1.1: Factorization for the hard scattering cross-section is represented Schematically. $f_{i,j}$ is the PDFs of protons, the short distance cross-section is $\hat{\sigma}_{i,j}$ and $x_i P_i$ the 4-momenta of partons partaking in the hard scattering. Figure adapted from [16].

cross-section is quantified by $\hat{\sigma}_{i,j}$ whereas i and j is the parton's scattering. The parton scattering cross-section resembles with it at leading order (LO). For long distance scattering this term is taken out as a factor at higher order. That's why it is considered purely for short-distance. As QCD has a property of asymptotic freedom i.e., small coupling at high energy therefore perturbation expansion of α_S is used to express short distance cross-section.

1.3.1 Jet production

Every event at an e^+e^- collider that produces strongly interacting particles, and every event at a hadron collider, involves jets in a fundamental way. The ability to measure and understand jets is therefore central to collider physics.

Let's deliberate the first situation where a pair of partons with high p_T are produced



after the hard collision takes place. This activity can be expressed by a $2 - to - 2$ or $(2 \rightarrow 2)$ scattering. The two partons produced in the final states are perceived like two jets as these sprinkled alone showers of hadrons. In this case study we will not consider the some of the effects such as efficiency of detector. Also, we will ignore the resolution or details of the jet finder algorithms but undertake only the precise affluence of the partons with jet. k_T is often known as the small intrinsic transverse momentum, inside the nucleon, of partons. We ignore k_T as it is small then the two jets are fabricated as a back-to-back jet in azimuth so this balances the transverse momentum p_T in the laboratory frame. The boost-invariant variables for cross-section of two jets are defined as:

$$\frac{d^3\sigma}{dy_3 dy_4 dp_T^2} = \frac{1}{16\pi\hat{s}^2} \sum_{i,j,k,l=q,\bar{q},g} \frac{f_i(x_1,\mu^2)}{x_1} \frac{f_j(x_2,\mu^2)}{x_2} \cdot \overline{\sum} |\mathcal{M}(ij \rightarrow kl)|^2 \frac{1}{1+\delta_{kl}} \quad (1.10)$$

115 and Figure 1.2 is its diagrammatic explanation. The terms y_3 and y_4 are the rapidities
116 of partons going out in the laboratory frame.

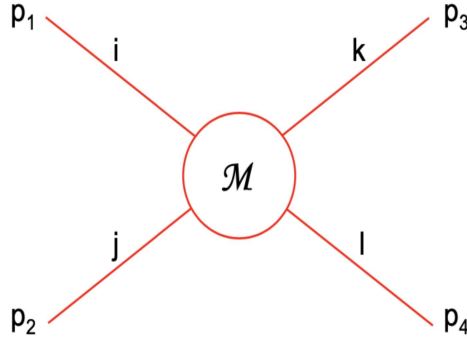


Figure 1.2: $(2 \rightarrow 2)$ scattering is shown in this diagram. where $p_{1,2}$ are the momenta of the incoming partons and $p_{3,4}$ are for the outgoing partons. $\mathcal{M}$ describes the elements of matrix for the elementary scattering.

The squared momentum existing in the center of mass of partons is shown by the $\hat{s}$ which is included in one of the Mandelstam variables:

$$\hat{s} = (p_1 + p_2)^2 \quad \hat{t} = (p_1 - p_3)^2 \quad \hat{u} = (p_2 - p_3)^2 \quad (1.11)$$

117 In equation (1.10) the sum $\sum$ is taken over whole arrangements of incoming partons
118 (i,j) and outgoing partons (k,l). The function f_i , known as PDFs (parton distribution

functions), are calculated as a whole scale such as $\mu = \mu_F = \mu_R$. The total of all the final obtained and average of all the spin and color states are represented by $\overline{\sum}$. The elements of the matrix used for elementary scattering of partons is indicated by the symbol $\mathcal{M}$. Figure 1.3 shown the illustration of the elements of matrix at lowest order. In this representation we didn't consider their crossed partners. Investigative equation related to this illustration can be discovered in [8]. In the initial state gluon's related activities have higher probability as color factor of gluons is greater than that of quarks.

The most simple and common case to study is where we have more than two partons in the final state. Its means developing types $2 \rightarrow 3, 4, 5$ and so on. At lowest order the cross section of n -partons can be expressed as σ^n , for this reason we consider the tree shaped diagram but having no internal loops. Therefore, we are compelling this explanation for additional real quarks and gluons devoted by the stretched legs of outgoing partons in Figure 1.3. The cross-section can be written:

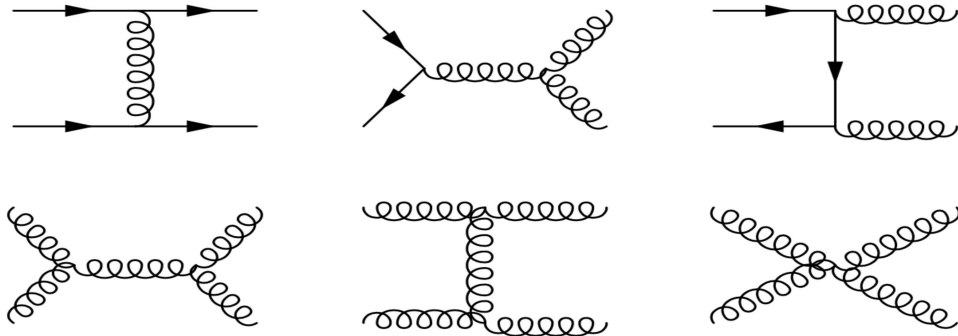


Figure 1.3: Cross section of the two jet's contribution shown in the lowest order diagrams.

$$\sigma^n = \sum_{i,j,k_1,\dots,k_n=q,\bar{q},g} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}^{i,j \rightarrow k_1, \dots, k_n} \quad (1.12)$$

which is a simplification of (1.9). The elements of the matrix for LO is seen in [17], Where typical bremsstrahlung configuration is displayed, overlooked other emission of gluons such as collinear and soft emission. α_s^n is proportional to the cross-section of each n -jet.

1.4 Heavy ion collisions

Figure 1.4 displays a schematic depiction of transverse plane in impact of two symmetric heavy-ions. Normally, the beam axis is considered as z-axis. The impact parameter(b) is defined as the vertical distance between the centers of the two nuclei in the transverse plane and it computes the overlap region of the colliding nuclei. Central collisions are categorized by a small impact parameter, which recommends that the collision is approximately head-on and most of the nucleons cooperate in the interaction with each other. Thus, the central collisions would have maximum final

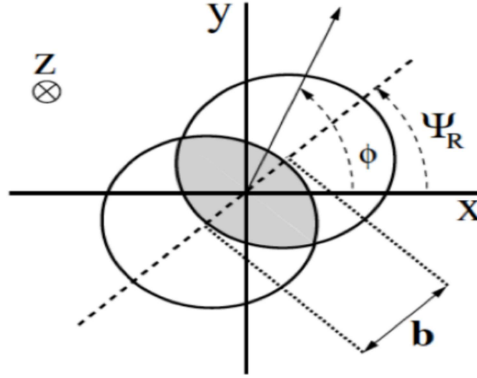


Figure 1.4: The transverse plane of ultra-relativistic heavy ion collisions [18].

state multiplicity. On the other hand, peripheral collision has large impact parameter and a few nucleons participate in the collision. Figure 1.5 shows the correlation of the final state charged particle multiplicity with impact parameter and number of participants.

Generally, centrality classes are defined in terms of percentiles of the nucleus-nucleus cross section. Centrality selection and finding the number of participants and spectators in heavy-ion collisions are quite crucial because they are needed to normalize the other measured observables prior to the comparison with other collision systems (relatively smaller systems like pp and p-Pb collisions). Centrality selection can be ended in the following ways [18]: 1. From the correlation between centrality and the number of final state charged particles in the collision and, 2. from the measurement of the number of outside in the collision. The first method trusts on the selection

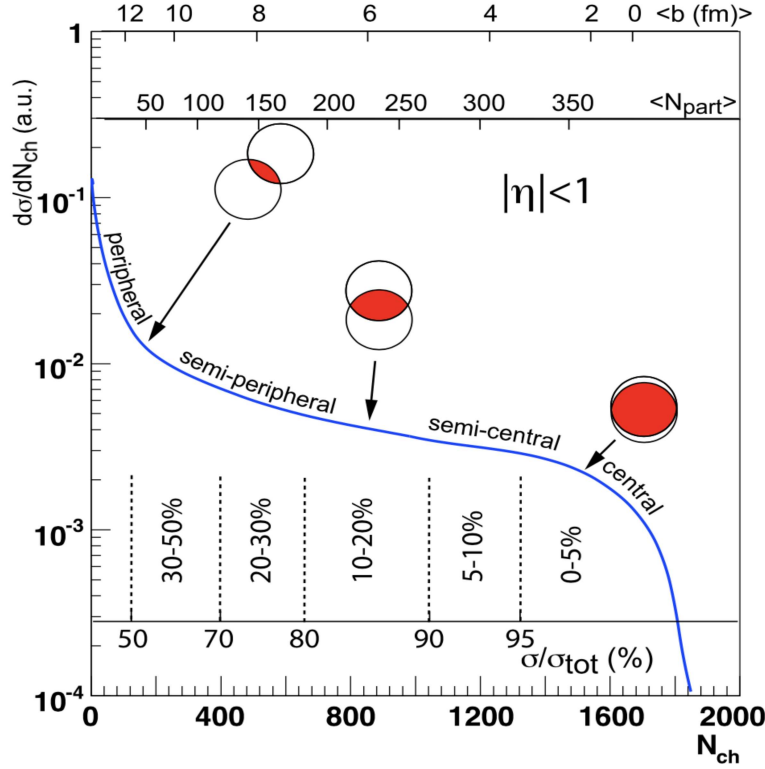


Figure 1.5: Cartoon showing the correlation of the final state charged particle multiplicity with impact parameter and number of participants[19].

of a geometrical model for the hadronic procedures while the latter manipulates the measurement of the energy of the spectator nucleons in the forward calorimeters/detectors. A parallel scheme based on final state multiplicity is expended for dividing the events in small collision systems like pp and p-Pb collisions. Event plane in heavy-ion collisions is defined by the event plane angle (Ψ_R) and the impact parameter (b) vector as depicted in Figure 1.4. Thus, to determine the event plane of a collision, the impact parameter vector is required.

1.4.1 Space-time evolution

The graphical diagram of the space-time evolution of relativistic nucleus-nucleus collision with and without a deconfined state is shown in Figure 1.6. Let us start at $z = 0$ and $t = 0$, when a collision between two heavy-ions takes place. For a central heavy-ion collision, a very hot and dense matter is predictable to be formed, which



is illustrated in the right side of Figure 1.6.

Pre-equilibrium stage: The interaction among partons (quarks and gluons) provides to a profuse production of deconfined quarks and gluons at $t \leq 1fm/c$. Particles with very high momentum are frequently created in this step.

QGP evolution: After the fireball extends its critical energy density and temperature, the deconfined equilibrium is attained. Then, the fully deconfined state of partons form QGP. Lattice QCD calculations specify that QGP is created beyond a critical energy density of $1\text{ GeV}/fm^3$ or beyond the critical temperature. The elastic and inelastic interactions between quarks and gluons in QGP lead to the thermalization phase. Due to the inelastic interactions, the flavor configuration of the partons of the system changes. Because of the high internal pressure and temperature, the system begins to enlarge rapidly. When the system cools down, QGP starts transforming into a hadron gas. This is known as the mixed phase.

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

However, another scenario of space-time evolution could also be possible when the matter produced in the heavy-ion or hadronic collisions do not meet the high temperature/energy density criteria. It is depicted in the left side of Figure 1.6. In this case, the system is left with hadronic degrees of freedom only. Just after the collisions a pre-hadronic phase is created. Then the nucleons can recombine into new hadrons

and the produced hadrons can be detected after the hadron gas phase freeze-out.

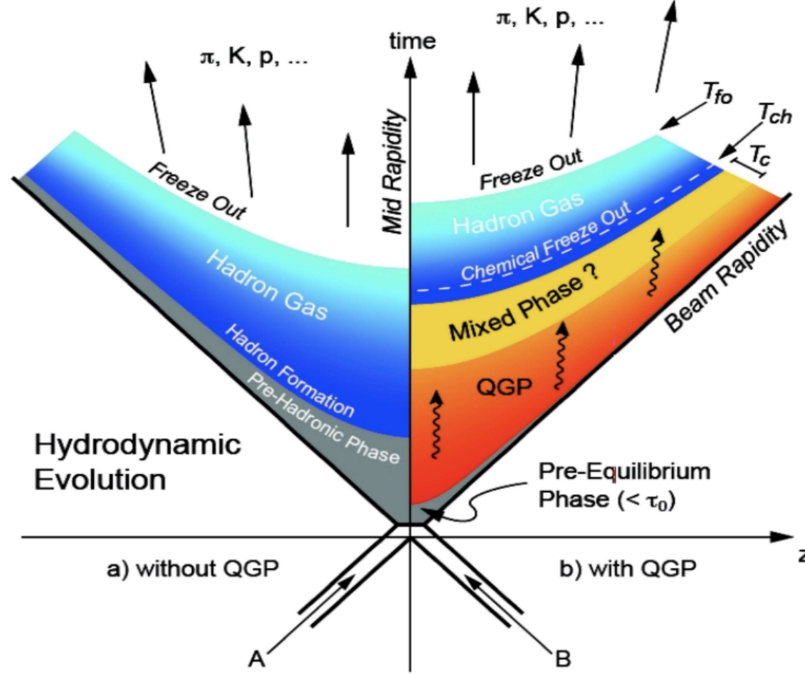


Figure 1.6: A schematic diagram of the space-time evolution of relativistic nucleus-nucleus collision.

1.4.2 Signature of QGP and experimental probes

As QGP has very short lifetime (few fm/c) therefore we don't have a direct observable for the recognition of the QGP, unlike the ordinary electromagnetic plasma. If medium is obtained from QGP, it initially expands, then cools down and finally hadronizes to evolve into final state hadrons. In the experimental setup, it is impossible to observe this formation step by step on each stage.

Adequately, we can quantify the time integrated final state quantities like charged particle multiplicities, multiplicities of photons or leptons, particle transverse momentum spectra, energy, anisotropic flow etc. However, different developments during the time advancement of fireball resulting in final state observables preserve some information in time. Diverse signatures of QGP comprising Strangeness enhancement is one of the most elegant property of QGP.



1.5 Small systems

Different measurements performed at the LHC have revealed an unexpected presence of the near-side ridge and other signs of collectivity in p-Pb and pp collisions, referred to as small systems. Since in heavy-ion collisions these effects are caused by the formation and collective expansion of a quark-gluon plasma (QGP), such observations in small systems have triggered the ongoing debate about their origin. The study of small systems includes the analysis of two-particle angular correlations, charge balance functions, anisotropic flow and transverse momentum (p_T) spectra of identified hadrons.

The major objectives of the thesis are to analyze the traditional Underlying Event in pp and p-Pb collisions at TeV along with the comparative studies with different Monte-Carlo models. To perform precise Standard Model [7] measurements and to search for new physics phenomena at hadron colliders, it is important to have a good understanding not only of the primary short-distance hard scattering process, but also of the accompanying interactions of the rest of the proton-proton collision collectively termed the underlying event (UE) [20]. Some properties have been measured for small systems is given in brief details below.

- **Proton-Proton Collisions** To equate the results of heavy-ion collisions, the results of pp collisions were largely considered as reference measurements by the community of heavy-ion, prior to the runs at LHC with high energy. Indeed, substantial quark-gluon plasma signals need a comparison of heavy-ion and pp collisions, necessitating a full understanding of pp collisions.

Since hadron collisions were previously solely examined as a reference by the heavy-ion community, the CMS collaboration's discovery of near-side correlations in pp collisions in September 2010 came as a huge surprise [21]. The community began to wonder if this may represent a collectivity signal in tiny systems, however it was quickly argued that the near-side ridge could be described within the Color Glass Condensate framework [22].

Figure 1.7 shows the ridge-like structure discovered by CMS in high multiplicity events with momenta ranging from 1–3 GeV to 7 TeV. The difference in pseudorapidity between the two particles is $\Delta\eta$, whereas the difference in azimuthal

angle is $\Delta\phi$. CMS investigated the long-range structure of two particle correlation functions with pseudorapidity $2.0 < \Delta\eta < 4.8$. The correlation is described as

$$R(\Delta\eta, \Delta\phi) = \left\langle (\langle N \rangle - 1) \left(\frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle \quad (1.13)$$

where S represents the signal and B represents the random background distributions, the average number of tracks per event per each multiplicity bin is given by $\langle N \rangle$, and the final $R(\Delta\eta, \Delta\phi)$ is calculated by averaging per each multiplicity bins, more details can be seen here ref [21].

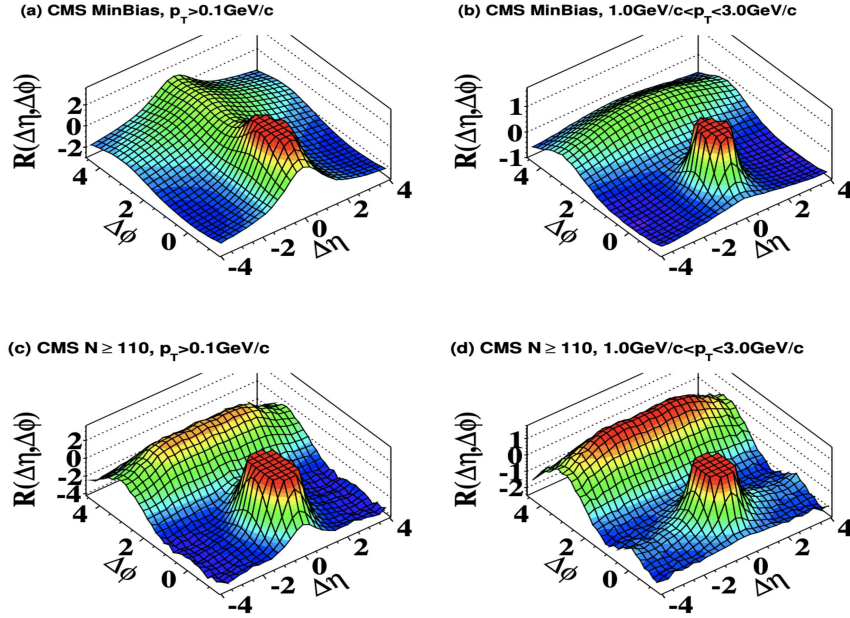


Figure 1.7: 2-D display of two-particle correlation for high multiplicity minimum bias events analyzed by CMS for pp collisions at $\sqrt{s} = 7$ TeV [21].

- **Proton-Lead Collisions:** Like pp collisions, proton-lead (p-Pb) collisions were primarily used as a control and reference measurement for heavy-ion collisions. Moreover, several of the common heavy-ion observables show no substantial divergence from an incoherent superposition of AA collisions. Comparing p-Pb to pp collisions allows determination of initial state effects, e.g., gluon saturation and effects of a possible color-glass condensate, and discrimination between different nuclear parton distribution functions. Furthermore, our overall understanding of these high energy nuclear collisions and the initial state of nuclei

would be strengthened, if we could understand pp, p-Pb collisions in a consistent framework. Some observations, however, point to effects at low p_T that might be of collective origin, as shown in the following.

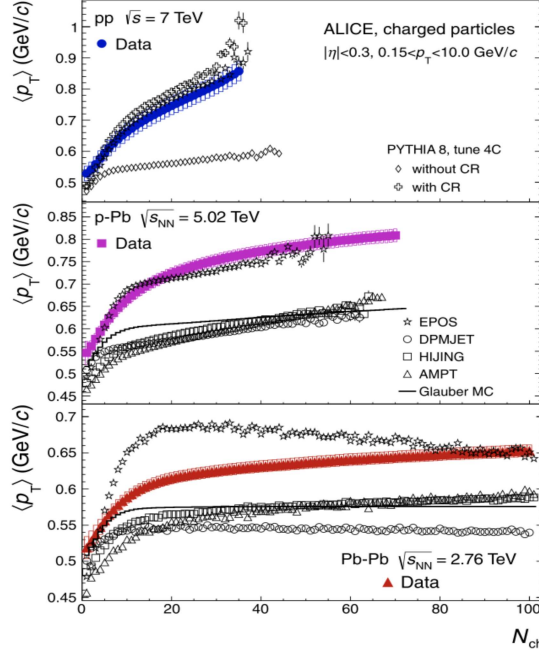


Figure 1.8: Average transverse momentum $\langle p_T \rangle$ as a function of charged-particle multiplicity N_{ch} measured in pp (upper panel), p-Pb (middle panel), and Pb-Pb (lower panel) collisions in comparison to model calculations [23].

Multiplicity Dependence of the Transverse Momentum: Figure 1.8 illustrates the average transverse momentum as a function of charged particle multiplicity in pp, p-Pb, and Pb-Pb collisions, using data obtained at $\sqrt{s} = 7$ TeV, $\sqrt{s} = 5.02$ TeV, and $\sqrt{s} = 2.76$ TeV, respectively. A substantial rise in p_T with N_{ch} is evident in pp collisions (upper panel), which may be explained as an impact of color reconnections between strings formed in multiple-parton interactions [24].

Multiplicity Dependence of Identified-Particle Spectra: The definition of fluid quark-gluon plasma depends upon the observations of the elliptic flow, which indicates a correlation between space and momentum variables. In AA collisions, different flow patterns are detected and measured using a Fourier decomposition. Radial flow is the isotropic (zero-order) harmonic, while elliptic flow, as previously noted, is the second order harmonic. Radial effects have

been seen in p-Pb collisions at the LHC, in particular. In p-Pb collision at

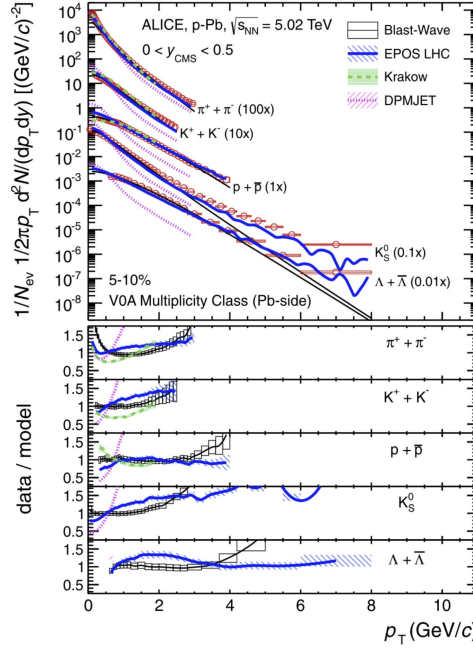


Figure 1.9: Transverse momentum distributions of pion, kaon and proton with model comparison in the V0A multiplicity class ranging from 5 – 10% [25].

$\sqrt{s_{\text{NN}}} = 5.02$ TeV, the transverse momentum distributions of pions, kaons, protons, and lambdas exhibit an evolution with multiplicity comparable to that seen in AA collisions (Figure 1.9). In heavy-ion collisions, the hardness of the spectra as a function of event multiplicity, which is greater for heavier particles, is related to the system's collective radial expansion. Models that integrate final state effects, such as EPOS, provide a more accurate description of the data, as demonstrated in the preceding measurement in Figure 1.8.

1.6 MC generators

Monte Carlo Models are based on the techniques of the concept of randomness in the behavior of physical processes introduced by quantum mechanics. The integrity of event generators is that this randomness can be simulated by the use of Monte Carlo techniques. Initially an event generator is selected then it becomes a function which each time is called give a Number R in the range between 0 and 1, such that the inclusive distribution of numbers R is flat in the range [26].



1.6.1 PYTHIA 8

Events are initially generated starting from a primary process that defines the type of the event. For LHC energy scale, this process is mostly the leading order pQCD partonic scattering. To set up the model calculations, some basic tunable parameters has to be specified. One of the main tunable parameters is the cut off $p_{(T,0)}$, which damps the QCD cross section for $p_T \ll p_{(T,0)}$. This parameter accounts for color screening effects. First and final-state radiation interleaved with MPI will follow in pQCD calculations, as well as the structure of beam remains. In this model, the impact parameter of the pp collision determines the number of MPI that will be generated. Finally, a realistic partonic structure that includes both jets and UE activity is obtained.

The partonic configuration is hadronized using string fragmentation as described by the Lund string model [27], followed by subsequent decays of unstable particles. Individual lengthy threads connected to the remains are substituted by shorter supplementary strings linking partons from distinct MPIs in collisions with several MPIs. This mechanism, called color reconnection, has been introduced to reproduce the increase of the average transverse momentum with multiplicity observed in data [26]. For the comparison with measured observables, MC simulated samples with Monash-2013 [28] tune and NNPDF2.3 LO PDF set [29] are used. MPIs are usually present in collisions. A mechanism known as color re-connection which long strings connected to the remnants are replaced by shorter additional strings connecting partons from different MPIs, is introduced. This mechanism reproduces the increase of the average transverse momentum with multiplicity observed in data [26]. MC simulated samples with Monash-2013 [28] tune and NNPDF2.3 LO PDF set [29] are used to mimic measured observables.

1.6.2 EPOS LHC

The EPOS LHC [30] event generator can be used to simulate both small system (pp, pA) and heavy ion (AA) interactions. The multiple scattering approach in EPOS LHC is based on a combination of Gribov-Regge theory and pQCD [31]. Multiple elementary collisions occurring in parallel give rise to parton ladder, which also



include initial- and final-state radiation. In parton ladder, collision energy is shared among each, leading to the conservation of the total collision energy in the hadronic process. After the initial scatterings, the strings hadronic based on the local density of string segments per unit volume with respect to a critical-density parameter. Event-by-event, two distinct regions are formed: high-density regions called “core” including collective expansion and hadronization including radial and longitudinal flow effects, and low-density regions called corona. The EPOS LHC tune parameters used in this paper is adapted from parameter set used to describe all LHC data at any energy and collision system [32].



Chapter 2 The Underlying Event

2.1 The Underlying Event

As the UE is an intrinsic part of the same proton-proton collision as any signal partonic interaction, a deep understanding of the UE features and an accurate Monte Carlo [33] description of its properties is important for the LHC [34] physics programme. As it is significantly influenced by physics not currently calculable from first principles, the measurement of the UE properties is crucial not only for better understanding of the mechanisms involved but also to provide input for empirical tuning of the free parameters of phenomenological UE models in MC event generators. More details is provided in the upcoming sections.

In order to acquire a better grasp of the UE in hadronic collisions, we first investigate the basic case of jet generation in e^+/e^- collisions, which is the most straightforward scenario. On the left in figure 2.1, the event display documented by the OPAL experiment at LEP [35] is shown in detail. (The axis of the beam is shown to be perpendicular to the page in the figure.) Because of their collision, the two colliding leptons combine to form a virtual vector boson (γ^* or Z^*) that produces a quark/anti-quark pair, which then splinters into two back-to-back jets. The pale blue color of the outgoing jets may be noticed in the drawing. Despite the possibility that more jets could be boosted by QCD radiation, there is no other way to help the multi-particle final state.

At a collision energy of 7 TeV, the ALICE detector captured an event demonstration (in the $r\phi$ plane) on the right side of figure 2.1. Three jets have been reassembled in this case (we'll ignore the elements of the jet finding technique for now): the jet regions are visible in green-colored fields, and the tracks corresponding to each jet are visible in red. Additionally, a large number of soft particles (magenta lines) that are not associated with the jets encroach on the event (and not present in the LEP case).

If, for example, the jet-finding processes combine these inputs with the particles that are actually good for jets, this can make it hard to measure the shape and energy of the jet. We define the UE as the particle flow module in a hadronic collision that

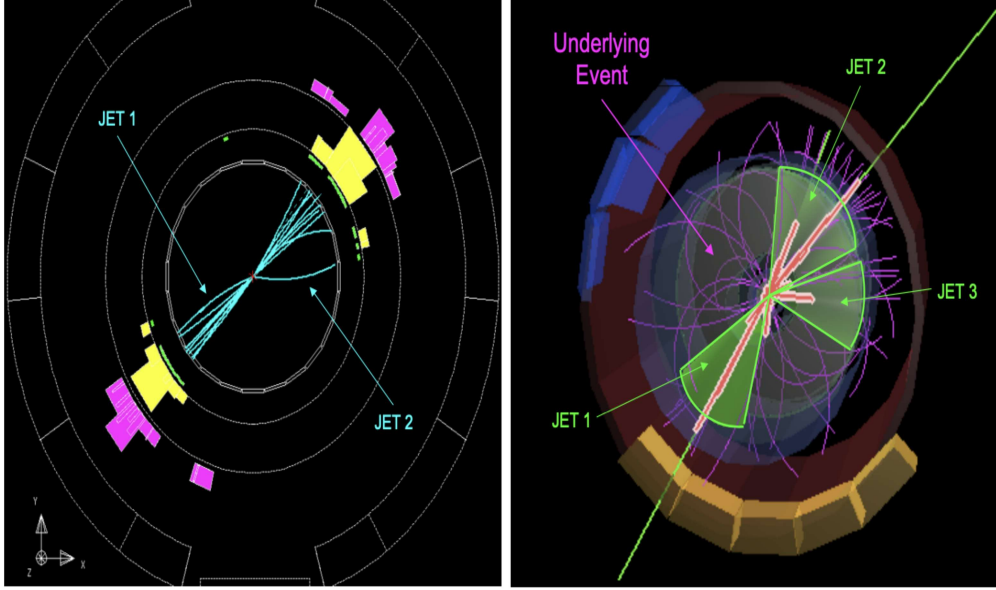


Figure 2.1: Left: a di-jet event in e^+/e^- collisions at LEP (as seen by the OPAL experiment). No UE is present in two back-to-back airplanes. Right: hadronic collision at $\sqrt{s} = 7$ TeV seen by the ALICE detector. Three reconstructed jets are shown in green areas and red tracks. The UE is shown in magenta tracks.

348 does not originate from the toughest partonic scattering in a fully broad-spectrum
 349 way. Nonetheless, this is an ambiguous description. It is necessary, for example, to
 350 participate in the analysis of both the initial and final state radiations (ISR and
 351 FSR). Particles resulting from these advancements are frequently integrated into
 352 the explanation of the UE, rather than being considered to be a component of the
 353 most difficult scattering. More broadly, the final hadronic state results from the
 354 hadronisation of partons that are likely to have originated from separate processes,
 355 making it difficult to pinpoint the precise origin of a final-state particle. Refer to
 356 figure 2.2 to see how the situation is depicted. The process of hadronization and
 357 consecutive hadronic decays is depicted in green. The fact that the first protons are
 358 colorless particles adds to the confusion of this picture even more. The result will be
 359 a color flux linking the beam remnants and the hardest scattering when the beam is
 360 fragmented during the process.

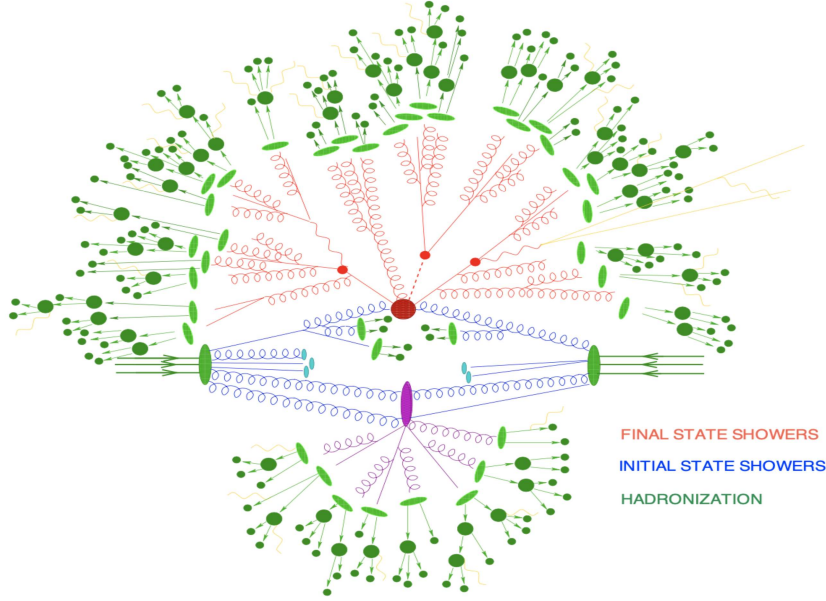


Figure 2.2: A rough drawing of a genuine pp collisions [39].

2.1.1 Multiplicity of charged particles

Multiplicity and transverse energy flow is considered to be the global features of an event. These features are defined by the geometry and the number of nucleons which interacts. Whereas geometry includes impact parameter and shape as well as orientation of the collision volume. During heavy-ion collisions large amount of primary charged particles are produced. The multiplicity of primary charged particles is served as a main observable. With these observables the properties of matter is characterized which is produced during the collisions [36]. In pp collisions at high energy large number of charged particles produced containing quarks and gluons explode out from the colliding protons. The multiplicity distribution $P(N_{\text{ch}})$, due to produced charged particles (N_{ch}), depends upon the number of collisions between them. Generally it depends on the mechanism adopted for production and underlying produced particles. In particular, $P(N_{\text{ch}})$ is a good method to investigate the density obtained by gluon distribution during collision of hadrons after saturation [37]. Calculating the digital sum of clusters in the SPD acceptance, the digital sum of energy loss signals in the FMD acceptance, or the average of the two if the SPD and FMD [38] acceptance overlap, yields the raw multiplicity distributions. The more charged particles that



are made, the more likely it is that all events will happen. At low multiplicities large trigger inadequacies exist and must be fixed for. Figure 2.3 shows charged particle multiplicity distributions for INEL pp collision with different model comparison at $\sqrt{s} = 7$ TeV.

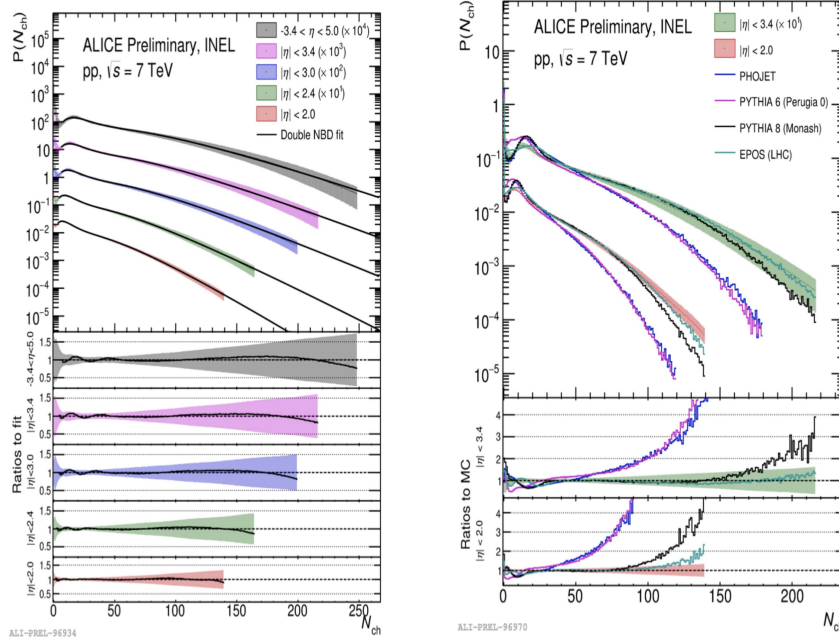


Figure 2.3: Left: charged-particle multiplicity distributions for INEL pp collisions at fits to the data using double NBDs. Ratios of the data to the fits are also shown. Right: comparison of multiplicity distributions for INEL events to PYTHIA 6 Perugia 0, PYTHIA 8 Monash, PHOJET and EPOS LHC at 7 TeV [37].

2.1.2 Multi-Parton Interaction (MPI)

We can't describe hadronic collider UE and minimum bias characteristics without bringing MPI formalism to Monte Carlo event generators [26, 40–43]. A 2-to-2 ($2 \rightarrow 2$) scattering process is used in multi-parton interactions to produce an equal number of partons in the final state, as shown in the figure 2.4.

As a result of collimated sprays of hadrons in the final state, the two final state partons are visible as jets. Without taking into account partons' modest inherent transverse momentum (often referred to as k_T), the two jets are created back-to-back in azimuth and balanced in p_T when the laboratory frame is used as the reference

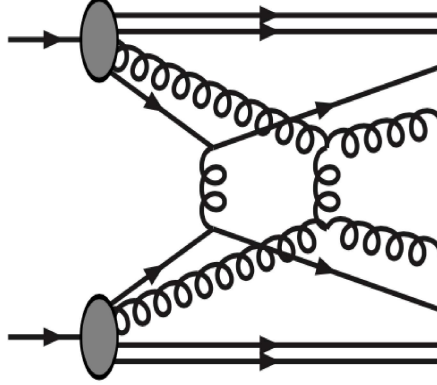


Figure 2.4: Schematic illustration of a 2→2 hard scattering interaction [45].

391 frame. The two processes also vary in how they are influenced by the minimum jet- p_T
392 decision and by the energy at the center-of-mass of the particle [44]. Single scattering
393 is the primary QCD mechanism, and MPI are a power adjustment to this process in
394 particular. The following is a function of the p_T^2 scale that describes the QCD hard
395 2-to-2 cross-section:

$$\frac{d\sigma_{int}}{dp_T^2} = \sum_{i,j,k,l} \int dx_1 \int dx_2 \int d\hat{t} f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}^{i,j \rightarrow k,l}}{d\hat{t}} \delta\left(p_T^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) \quad (2.1)$$

396 where, $\hat{s} = x_1 x_2$, $\hat{s}$ is the possible momentum in the partonic center-of-mass frame,
397 $\hat{t} = (p_1 - p_3)^2$ and $\hat{u} = (p_2 - p_3)^2$. The process hardness is assumed to be supplied by
398 the p_T scale, i.e. $Q^2 = p_T^2$. In the limit of small transferred momenta $|\hat{t}| \ll \hat{s}$ where
399 $p_T^2 = \frac{\hat{t}\hat{u}}{\hat{s}} \simeq |\hat{t}|$ for constant α_S and neglecting the x -dependence, the integrated
400 interaction cross-section may be written as:

$$\sigma_{int}(p_{T,min}) = \int_{p_{T,min}}^{\sqrt{s}/2} \frac{d\sigma}{dp_T} \propto \frac{1}{p_{T,min}^2} \quad (2.2)$$

401 This cross-section diverges in the limit $p_{T,min} \rightarrow 0$. Already at values of $p_{T,min}$ of
402 a few GeV/c, the integrated interaction cross-section surpasses the total hadronic



cross-section σ_{TOT} [45]. To put it simply, if an event has n interactions, it will count n times in σ_{int} , but only once in σ_{TOT} . The average number of interactions as a function of the $p_{\text{T,min}}$ value may therefore be expressed as follows:

$$\langle n \rangle(p_{\text{T,min}}) = \frac{\sigma_{\text{int}}(p_{\text{T,min}})}{\sigma_{\text{TOT}}} \quad (2.3)$$

Assuming free incoming and outgoing partons, perturbative QCD calculations assume that the incoming hadrons are color singlets. Due to the fact that single color charges cannot be resolved, the coupling is lowered when the gluon transferred has a low p_{T} , or equivalently a long transverse wavelength. A color-screening length scale, proportional to the distance over which a color charge is compensated, may be introduced. This distance must be less than the proton radius, which gives $p_{\text{T,min}} \simeq \Lambda_{\text{QCD}}$ as a first estimate, although it is not a known number in general. In order to recreate the experimental findings, it is acceptable to use a cut-off value in the computations, generally in p_{T} space.

2.1.3 Impact parameter dependence

MPI strongly depends upon the impact parameter assuming that initial state is same for all hadronic collisions. Generally in every collision the variation of impact parameter "b" [43] plays an important role. Classically it is defined as the distance of closest approach without including the Fourier transformation of momentum transfer. A small "b" is responsible for high probability of multi-parton interaction as large portion of colliding hadrons overlaps. On the contrary large "b" means no overlap hence no multi-parton interaction.

To quantify the concept of hadronic matter overlap, the spherically symmetrical distribution of matter within a resting hadron, $\rho(x)d^3x = \rho(r)d^3x$, may be assumed. All parton species and momenta are assumed to have the same geographic distribution for simplicity's sake. Several other matter distributions have been tested with various results. Even if a Gaussian ansatz makes the following computations particularly apparent, there is no reason why this should be the preferred form in all cases. Indeed, it seems to result in a distribution of multiplicity that is too narrow and a pedestal



effect that is too weak. A double Gaussian is the next most straightforward option, however it does produce more fluctuations.

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left\{-\frac{r^2}{a_1^2}\right\} + \frac{\beta}{a_2^3} \exp\left\{-\frac{r^2}{a_2^2}\right\} \quad (2.4)$$

As a result, the whole amount of hadronic matter has a radius of a_1 , and the distribution has an outer ring with a radius of a_2 , which contains a fraction of β of the total amount of hadronic matter. A deeper interpretation of this ansatz might be that it represents an intermediary step toward a hadron with three distinct core areas ('hot spots'), each indicating the existence of three valence quarks that collectively carry β of the proton momentum. Alternatively, a pion cloud might surround a hard hadronic core. For example, the predictions of the t distribution in elastic scattering might be affected by such characteristics, but they are of little relevance to the present problems at hand.

The time-integrated overlap $\mathcal{O}(b)$ between the matter distributions of colliding hadrons during a collision with impact parameter "b" is given by

$$\begin{aligned} \mathcal{O}(b) &\propto \int dt \int d^3x \rho(x,y,z) \rho(x+b,y,z+t) \\ &\propto \frac{(1-\beta)^2}{2a_1^2} \exp\left\{-\frac{b^2}{2a_1^2}\right\} + \frac{2\beta(1-\beta)}{a_1^2+a_2^2} \exp\left\{-\frac{b^2}{a_1^2+a_2^2}\right\} + \frac{\beta^2}{2a_2^2} \exp\left\{-\frac{b^2}{2a_2^2}\right\} \end{aligned} \quad (2.5)$$

$$(2.6)$$

A proper scale adjustment of the z and t coordinates has eliminated the need for boosted $\rho(x)$ distributions. $\Omega(b)$ of eikonal models is closely connected to the overlap function $\mathcal{O}(b)$, which is discussed in detail in Ref. [45]; nonetheless, it is more straightforward in its spirit.

The wider the overlap $\mathcal{O}(b)$ is, the more probable it is that partons in the colliding hadrons interact, illustrated in the figure 2.5.

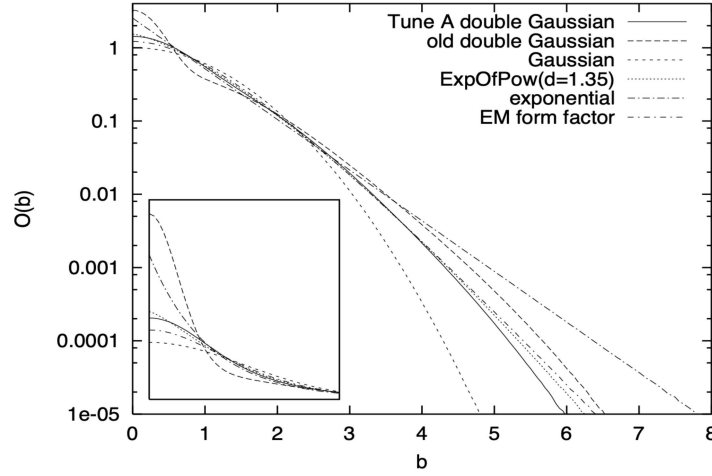


Figure 2.5: Overlap profile $\mathcal{O}(b)$ as a function of impact parameter "b" [45].

2.1.4 Beam remnants

The remaining valence content and the amount of sea quarks necessary to maintain the overall flavor are used to flavor the beam remnant, which is a collection of partons. Gluons are assumed to be in the residual, but they aren't explicitly said to be. They are thought to be the confinement clouds around quarks and the unsolved originators of sea-quark pairs.

This means that a remnant may include a number of items, yet the color arrangement might lead to simplifications. A di-quark may be connected with a color anti-triplet qq pair in the residue, a baryon with a color singlet qqq triplet, and a meson with a color singlet $q\bar{q}$ pair, as shown in figure 2.6. When hadrons are created, conventional string fragmentation relative probabilities are used to choose spin and other quantum quantities, such as π or ρ , and so on.

As a result, a $q\bar{q}$ system with a high invariant mass defines a string that may split into multiple mesons rather than collapsing into a single meson. This might theoretically be described dynamically, but it would need the addition of some non-perturbative parameters to characterize the proton's division into arbitrary-mass subsystems. At this time, we believe it is only necessary to investigate a few particular situations in order to determine which partons to allow in the development of composite structures.

Thus a $q\bar{q}$ system with large invariant mass would define a string that could fragment

468 into several mesons, rather than collapse to a single meson. In principle this could be
469 modeled dynamically, but it would require the introduction of some non-perturbative
470 parameters, to describe the partitioning of the proton into arbitrary-mass subsystems.
471 At this point, we consider it meaningful only to study a few specific scenarios for
472 which partons to allow in the formation of composite objects.

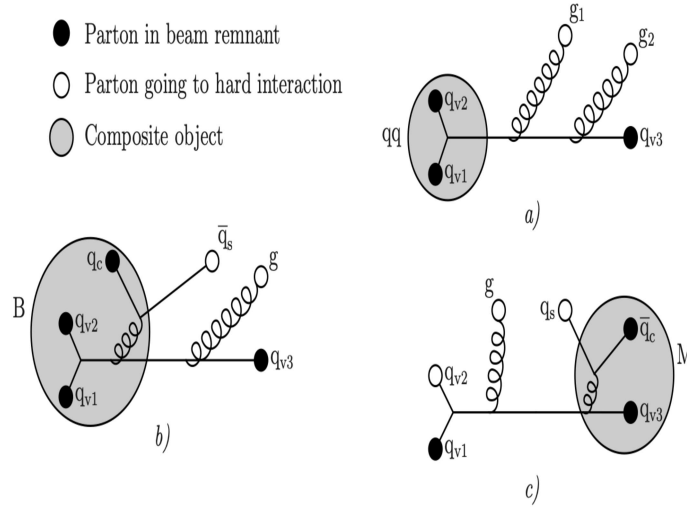


Figure 2.6: Examples of the formation of composite object in a baryon beam remnant: (a) di-quarks, (b) baryon and (c) meson [45].

- 473 1. It does not create composite objects from the *ab initio*. All partons function as
474 single units, either as quark endpoints or kinks (gluons) on strings that split
475 normally.
- 476 2. Composite structures can be created, but only if all of the partons participating
477 are valence quarks.
- 478 3. Color singlet subsystems (i.e. hadrons) may be formed using both valence and
479 sea quarks, while color singlet subsystems (i.e. hadrons) can only be formed
480 using valence quarks.
- 481 4. Color singlets may be made using sea quarks.

482 Because valence quarks tend to have similar velocities, they are more likely to form
483 low-mass complexes, while sea quarks may be more dispersed and so less likely to
484 form such systems. [45].

2.2 The transverse regions method

UE activity may be measured using a variety of techniques, one of which is the Transverse Regions Method. Topological cuts may be used to separate the two leading partons in the perturbative QCD interaction and measure the residual activity as a function of the transmitted momentum scale (Q^2) [46]. Experiments may be used to find out what happens when a charged particle's transverse momentum changes in three different directions: toward, transverse, and away from it, azimuthally perpendicular to the direction of travel in which it is moving. The leading jet and charged particle density or energy density can then be calculated from this data. For the first time in 1988, Marchesini and Webber [47] suggested using Transverse regions as a way to quantify the UE. These investigations show that the transverse energy E_T generated in a high-energy hadronic collision is plotted against the distance in pseudo-rapidity from the leading-jet axis.

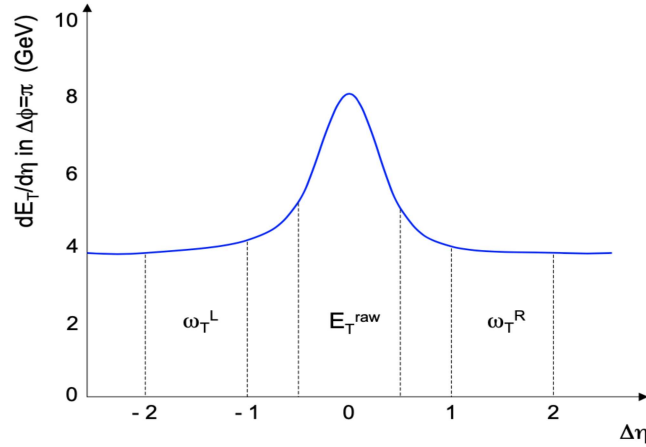


Figure 2.7: As a function of the pseudo-rapidity distance from the leading jet, the transverse energy distribution in jet occurrences is shown [46].

To illustrate the E_T distribution, see figure 2.7, where the area labeled E_T^{raw} gathers fragmentation from the leading jet and $\omega_T^{L,R}$ represents transverse energies in the rapidity intervals $1 < |\Delta\eta| < 2$. As a result, the pedestal energy provides an estimate of the UE:



$$\omega_T^{ped} = \frac{1}{2}(\omega_T^L + \omega_T^R) \quad (2.7)$$

Figure 2.8 shows the pedestal energy as a function of the leading jet's transverse energy for $\sqrt{s} = 630$ GeV (SPS collider) and 1.8 TeV (Tevatron). The most recent LHC results are discussed briefly in the following section.

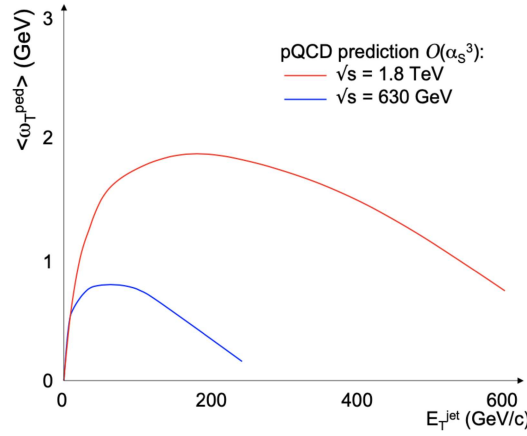


Figure 2.8: The mean pedestal energy in pp collisions predicted by LO pQCD as a function of the leading-jet energy [46].

2.2.1 UE measurement at Tevatron and RHIC enrgies

In addition to the original analysis based on charged-particle jets [20], CDF published many more studies of the UE, including one where the Transverse areas are circles in the $\eta\phi$ space centred at $\pi/2$ radians from the leading jet, a comparison between jet and di-jet events [46], and a comparison of jet-and Drell Yan-triggered events [48]. Two distinct sections ($\pi/6 + \pi/6$ radians) make up the Transverse region. The region known as TransMAX is the one in which the total p_T of the enclosed particles is the highest. This area is more vulnerable to the UE's hard component (QCD radiation). The second section (TransMIN) solely gathers beam remnant fragmentation and MPI. Observables such as the charged-particle density or the cumulative p_T density define each zone.



An example of plots from a CDF analysis [48] of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV are shown below. Only charged particles with $p_T > 0.5$ GeV/ c and $|\eta| < 1$ are considered in this study. The MidPoint [49] cone-based method is used to rebuild calorimetric jets, and the leading jet must be inside $|\eta| < 2$. The average density of charged particles, and the distribution of the summed p_T of charged particles in the three regions is shown as a function of the leading-jet p_T in figures 2.9 and 2.10, respectively.

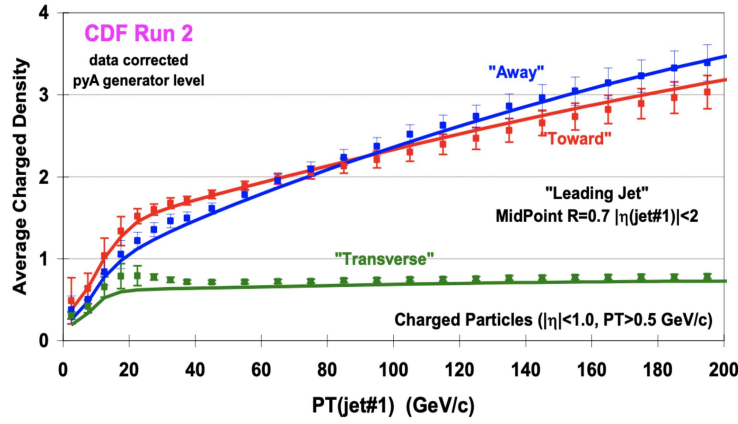


Figure 2.9: Corrected charged-particle density ($p_T > 0.5$ GeV/ c and $|\eta| < 1$) as a function of the leading-jet p_T for detector effects and compared with Pythia Tune A (pyA) for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [46].

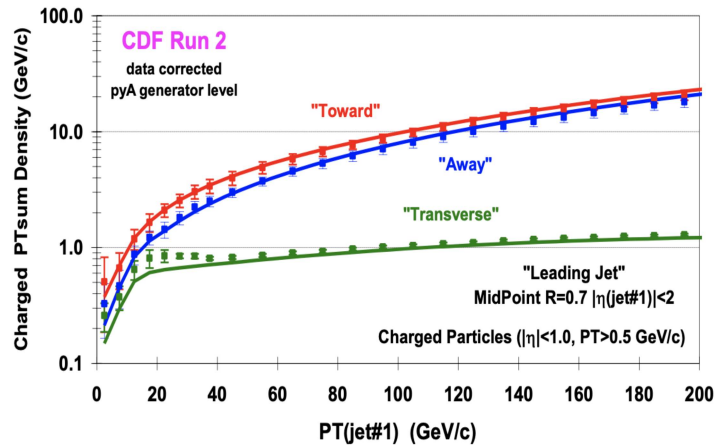


Figure 2.10: Corrected summed p_T density of charged-particles ($p_T > 0.5$ GeV/ c and $|\eta| < 1$) as a function of the leading-jet p_T for detector effects and compared with Pythia Tune A (pyA) for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [46].



Using the transverse region approach, the UE in pp collisions at $\sqrt{s} = 200$ GeV was determined in the STAR experiment at RHIC [50]. Uncorrected charge particle concentrations in TransMIN and TransMAX regions as a function of reconstructed leading jet- p_T are shown in fig 2.11. Only tracks with $p_T > 0.2$ GeV/c are considered [50] and are rebuilt using the seedless cone algorithm SIScone [51] with a radius of 0.7. At least one jet may be discovered in the star acceptance ($|\eta| < 1$), as shown by the black spots, while the red points indicate the position of two back-to-back jets. According to the results of this basic simulation, at RHIC energies, a sampling bias is responsible for the separation of the TransMIN and TransMAX regions.

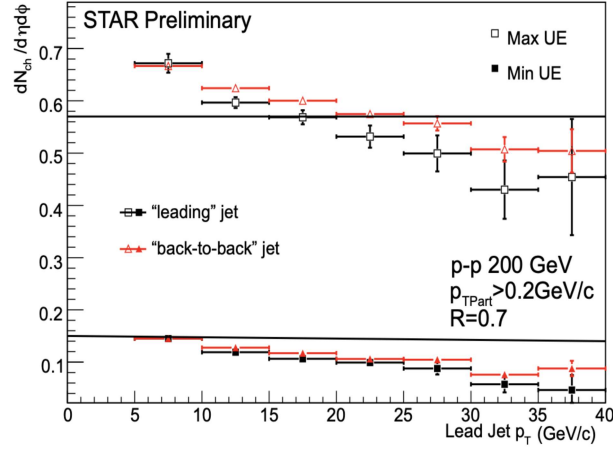


Figure 2.11: STAR detector measures the density of charged particles in the TransMIN and-TransMAX sectors. [50].

2.2.2 UE studies by ATLAS collaboration

The ATLAS collaboration has studied the UE properties in pp collisions at different energies, i.e., $\sqrt{s} = 0.9, 7$ and 13 TeV [52–54] respectively as a function of p_T^{leading} . The number density in the Transverse zone for collision energies of 0.9 and 7 TeV is shown in Fig. 2.12. Particles having $p_T > 0.5$ GeV/c, and $|\eta| < 2.5$ are taken into account. For $\sqrt{s} = 0.9$ and 7 TeV, the number density distribution saturates at roughly 0.4 and 1, respectively. In Fig 2.13 (left) shows the average p_T as a function of N_{ch} in transverse region in pp collisions at $\sqrt{s} = 13$ TeV. The correlation with transverse charged-particle multiplicity N_{ch} is a correlation between two different “soft” properties. This distribution is modeled to within 5% for all N_{ch} by most of

the generators and an underestimation of $\langle p_T \rangle$ is visible until $N_{\text{ch}} \gtrsim 15$. The best modeling is from EPOS, whose maximum undershoot is $\sim 3\%$ at low N_{ch} but which follows the data closely for higher transverse multiplicities. Herwig7 shows the largest variations, from a $\sim 7\%$ undershoot at low N_{ch} to a 5% overshoot at $N_{\text{ch}} \approx 30$. In Fig 2.13 (right) shows the average p_T as a function of p_T^{leading} in transverse region in pp collisions at $\sqrt{s} = 13$ TeV. Herwig7 performs better than all the other generators when considering the correlation between transverse region $\langle p_T \rangle$ and p_T^{leading} .

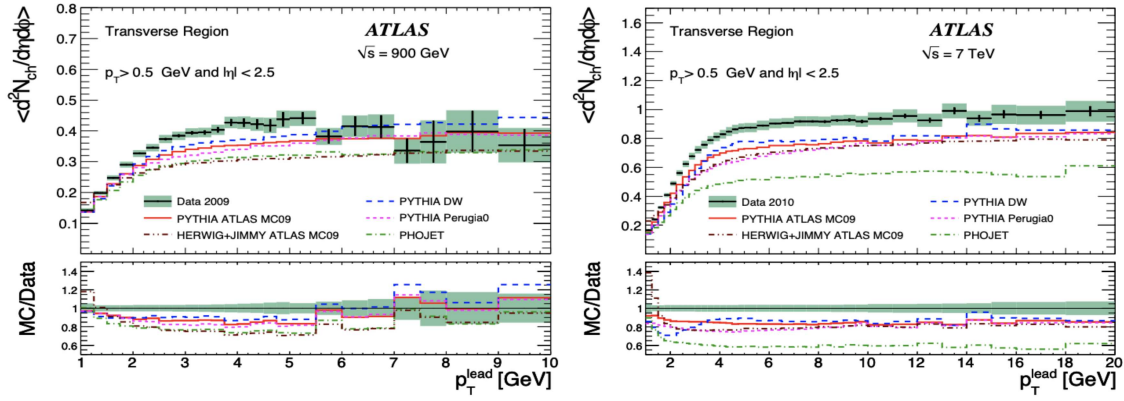


Figure 2.12: Charged-particle density in the Transverse regions at $\sqrt{s} = 0.9$ TeV (left) and $\sqrt{s} = 7$ TeV (right) measured with ATLAS detector. Data is corrected for detectors effect for $p_T > 0.5$ GeV/c and $|\eta| < 2.5$ [52, 53].

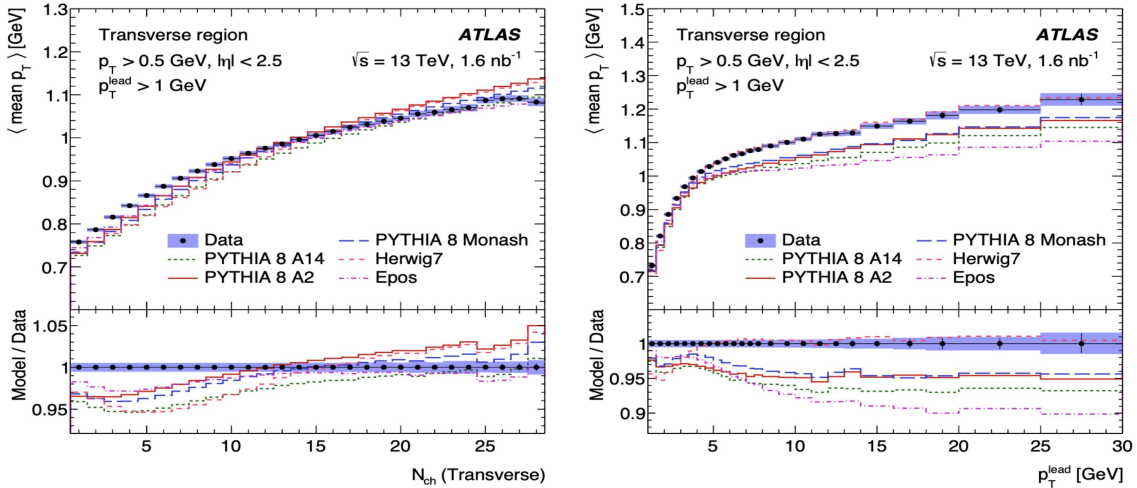


Figure 2.13: Mean charged-particle transverse momentum $\langle p_T \rangle$ in the Transverse regions as a function of N_{ch} transverse (left) and p_T^{leading} (right) measured with ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV. Data is corrected for detectors effect for $p_T > 0.5$ GeV/c and $|\eta| < 2.5$ [54].



2.2.3 UE studies by CMS collaboration

The CMS collaboration has also carried out [55–60] the similar studies of the UE in pp collisions as a function of the p_T^{leading} at various energies, i.e., $\sqrt{s} = 0.9, 2.76, 7$ and 13 TeV. In Fig. 2.14 shows the comparison of number density and $\sum p_T$ density as a function of p_T^{leading} in pp collisions at different energies for data as well as models. As we go from low to high center of mass energy the number density and $\sum p_T$ density increase by a factor of approximately 20-30%. In model comparison PYTHIA 8 describes the data well where as HERWIG overestimate the data after $p_T^{\text{leading}} > 5$ GeV/c. Figure 2.15 is the energy dependence of pp collisions at $\sqrt{s} = 2.76, 7$ and 13 TeV measured by CMS in terms of average number density and average $\sum p_T$ density as a function of p_T^{leading} in combined transverse and toward regions.

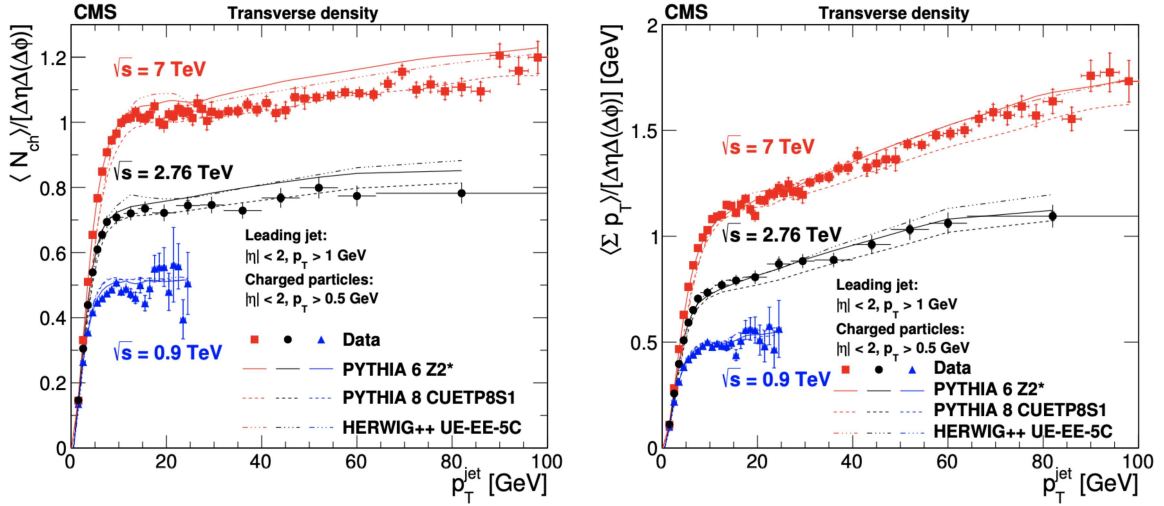


Figure 2.14: Comparison of number density (left) and $\sum p_T$ density (right) in pp collisions at various energies, i.e., $\sqrt{s} = 0.9, 2.76, 7$ TeV. Measured by CMS for $p_T > 0.5$ GeV/c and $|\eta| < 2$ [59].

2.2.4 UE studies by ALICE collaboration

The ALICE collaboration have also reported [61, 62] a similar analysis of the UE in pp collisions as a function of the p_T^{leading} at various energies, i.e., $\sqrt{s} = 0.9, 7$ and 13 TeV. In Fig. 2.16 shows the number density and $\sum p_T$ density as a function of p_T^{leading} in pp collisions at $\sqrt{s} = 13$ TeV with ALICE. This also includes the model comparison with PYTHIA 8 and EPOS LHC. At low p_T^{leading} , there is a steep rise

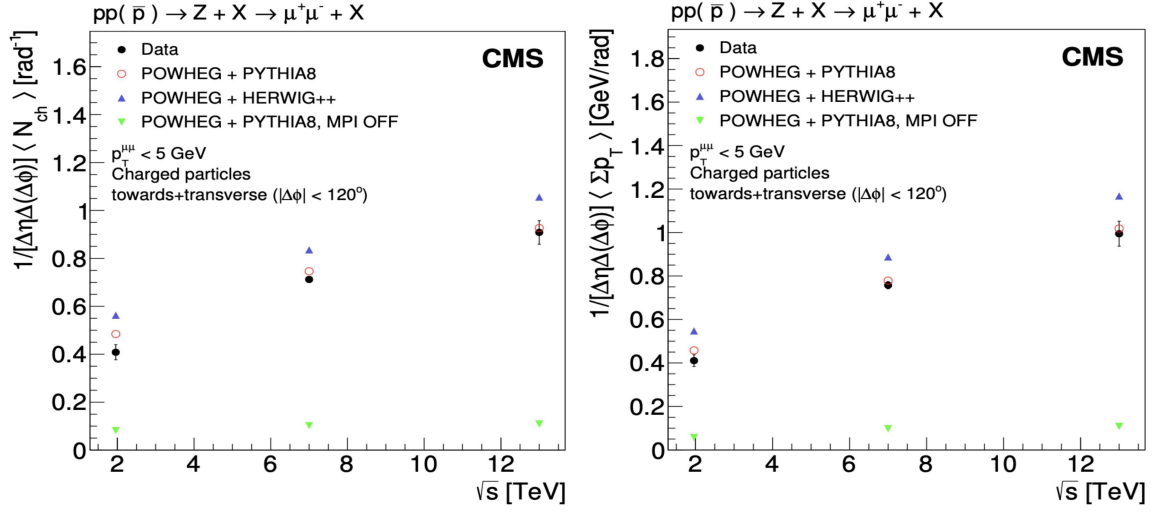


Figure 2.15: Average number density (left) and $\sum p_T$ density (right) in pp collisions as a function of center of mass energy in combined transverse and toward regions with different model predictions [60].

in event activity followed by a change to a smaller gradient at $p_T^{\text{leading}} \approx 5 \text{ GeV}/c$, the plateau region. Above this value in particular for the number density, the event activity becomes almost independent of p_T^{leading} , while it continues to rise for $\sum p_T$. In Fig. 2.17 shows the R_T analysis is performed using a track transverse momentum threshold of p_T cut $> 0.15 \text{ GeV}/c$ and by selecting events in the plateau region ($p_T^{\text{leading}} > 5 \text{ GeV}/c$). The distribution has been fitted by a modified NBD. Within the experimental uncertainties, the NBD fit gives a good description of the data up to $R_T = 3$, and it slightly overestimates the data with increasing R_T , by about 14% at $R_T = 5$. The distribution is also compared with the calculations from PYTHIA 8 and EPOS LHC.

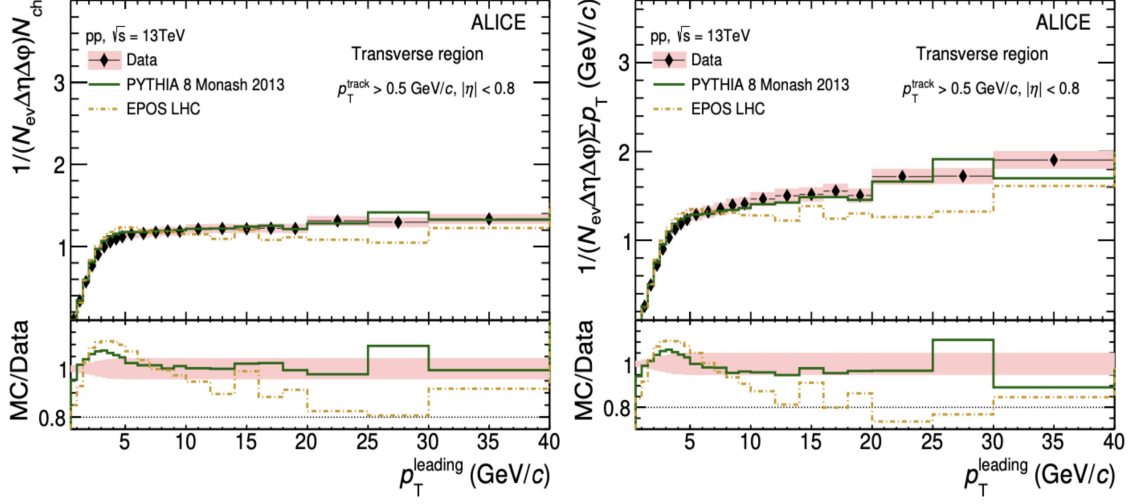


Figure 2.16: Number density N_{ch} (left) and $\sum p_T$ (right) distributions as a function of p_T^{leading} compared to MC predictions in Transverse region for p_T cut > 0.5 GeV/c [60].

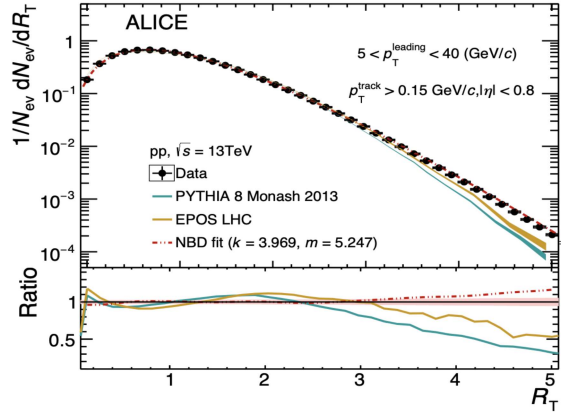


Figure 2.17: R_T probability distribution in the transverse region w.r.t charged particles p_T compared to MC predictions for p_T cut > 0.15 GeV/c [60].



Chapter 3 A Large Ion Collider Experiment (ALICE) at LHC

3.1 Large Hadron Collider (LHC)

From the ancient times, searching for the unknown has been the inborn nature of Mankind, which is also one of the core ideologies of ultimate research in the basic sciences. To discover the nature of the Universe, an engineering wunderkind, "Large Hadron Collider (LHC)" was constructed at CERN, Geneva. In CERN (European center for Nuclear Research), the Large Hadron Collider (LHC) was built in 1998 to 2008, considered to be the world's biggest and greatest particles accelerator. Scientists and engineers from different countries all around the world has participated to construct [34]. It is installed inside the underground tunnel of about 27 kilometers in the circumference across Switzerland and France border at a depth of about 50-150 m. The main idea behind, to construct such a high energy particle accelerators, is to gather experimental evidence of various theories related to particle high energy physics, particularly to endorse the presence of missing Higgs boson anticipated by peter Higgs in his theoretical explanation of Standard Model [63]. On 8th of the September 2008, the LHC was run first time after successful installation but immediately it shut down after 9 days. Because magnetic quench was occurred which harms the superconducting magnets and vacuum pipes was polluted by the burst of helium gas due to electric fault [64]. In 23rd of November, 2009 it has begun it's operation again magnificently at energy of 450 GeV per beam [65]. Figure 3.1 shows the CERN accelerator with four main LHC experiment (ALICE, ATLAS, CMS and LHCb) around the LHC ring.

In the beginning the LHC was devised to run collisions of proton-proton (pp) at the energy $\sqrt{s} = 14$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. On 30th of the march 2010, two beams collide at 3.5 TeV which set the world record for the highest energy man made particle collisions [66]. These colliders are used as a research tools for accelerating particles at high kinetic energy and observing their impact with other particles. Different detectors are installed at different position of LHC to explore different kind of operations. In the Run 2 from 2015 to 2018, LHC has specified to run pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

607 and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. One day run to Xe-Xe collisions was also
608 considered by the LHC at $\sqrt{s_{NN}} = 5.44$ TeV as a special case. Presently, LHC is
609 in the long shut down during the period 2019 to 2020, because it experiencing a
610 major upgrade to enhance the luminosity in run three, which is the ultimate goal
611 to discover new achievement on physics. Along the circumference of the LHC, four
612 major experiments are positioned at the four different interaction points.

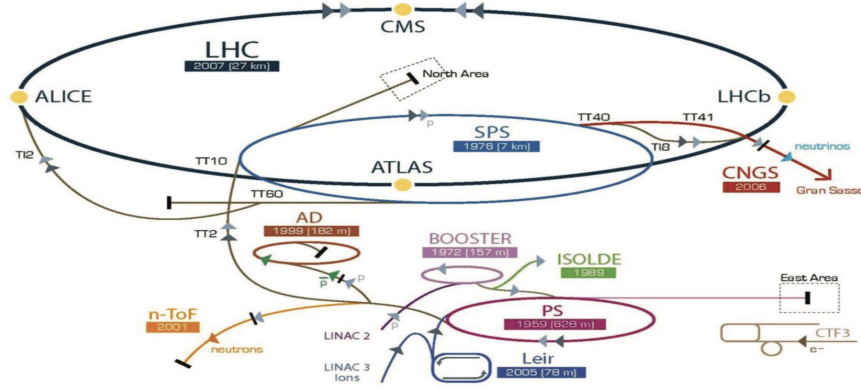


Figure 3.1: CERN accelerator complex showing the four main LHC experiments (ALICE, ATLAS, CMS and LHCb) around the LHC ring at Switzerland-France border [67].

613 **A Toroidal experiment LHC ApparatuS (ATLAS)** is one of the all purpose
614 detector installed at LHC. Its aim is to discover extremely massive particle which
615 can not be identified at low energy. To discover Higgs Boson and traces of physics
616 beyond standard model is also one of the basic purpose to build it. When a beam
617 of high energy particles possibly proton beam hit at the middle along the beam axis
618 of the detector, a huge bulk of high energy particles are created these contain the
619 energies of extensive range. It detects inclusive spectrum of signals rather of aiming
620 material existence process that includes in particle production. It is built in June
621 2007, weighing 7000 Tones with length of 44 meters and almost 25 meters is in
622 diameter [68, 69].

623 **Compact Muon Solenoid (CMS)** is also known as one of the multipurpose de-
624 tector intended to analyze various aspects of interaction of protons at 14 TeV, centre
625 of mass energy of LHC particle [70]. Almost 3600 scientists and students are chosen
626 to represent 38 countries, worked jointly to built CMS and make it operational. Ev-
627 eryone of them belongs to 183 scientific institutions all over the world. The key ideas
628 to build CMS is to open up new physics at TeV scale, to come across the discovery



of Higgs boson and to study several aspects of heavy ion collision. The study based on CMS is useful to accumulate the evidence of physics beyond Standard Model.

Large Hadrons Collider Beauty (LHCb) is especially designed to know experiments of b-physics which measures the parameters of CP violation in the interactions of b-hadrons (heavy particle containing bottom quark). The explanation of matter-antimatter asymmetry of the universe is concluded on the basis of the study of LHCb. This detector detects the observational measurement of production cross-section and electroweak physics in the forward region. From 54 scientific institutes, representing 14 countries to collaborate to build and operate the detector [71]. The location of this detector is at 8 point on LHC tunnel close to Fernery-Voltaire, France just over the border of from Geneva.

3.2 A Large Ion Collider Experiment (ALICE)

ALICE is also considered as a one of the major detectors which is positioned at the Large Hadron Collider at CERN. It is basically devoted for witnessing the heavy ion interactions at LHC. Its working is based on the major principle of analyzing and studying several phases of matter inside the nucleus above the critical temperature region in that region the temperature is very large. The large temperature regions are unfolded by QCD which is responsible for transition of quarks and gluons to move independently in a deconfined state. The energy density of LHC at CERN is much higher as compared to those conquered by SPS and RHIC [72]. During the formation of quark-gluon plasma (QGP) large temperature and energy density are generated, which is assumed to sustained up to a few millionths of a second after the Big Bang. One of the foremost objective of ALICE is to reinvent this embryonic state of matter in the laboratory and observe its evolution stages with time, which will be useful to through light on issues about how matter is structured and the mechanisms that confine quarks and gluons. Schematic layout of ALICE detector is shown in figure 3.2.

This gives a possibility to explore the matter inside the nucleus and its characteristics at high energy scale in detail. This is also beneficial for inspecting the dynamics of hadronic matter by causing transition from deconfined matter. It is believed to have existence up to few millionths of a second after the Big Bang happened before quarks

and gluons were bounded together to materialize into protons and neutrons. ALICE is dedicated to explore the dynamics of the infant Universe through the Quark Gluon Plasma in heavy-ion collisions. ALICE also explores QGP-like scenario in pp collisions. The most important features of the ALICE detector, which makes it different from other experiment, are its outstanding competency of particle identification by the help of precise energy loss, time of flight, transition and Cherenkov radiation, electromagnetic calorimetry and muon spectrometry. ALICE has wide pseudorapidity coverage, which is shown in figure 3.3 with each detector acceptance.

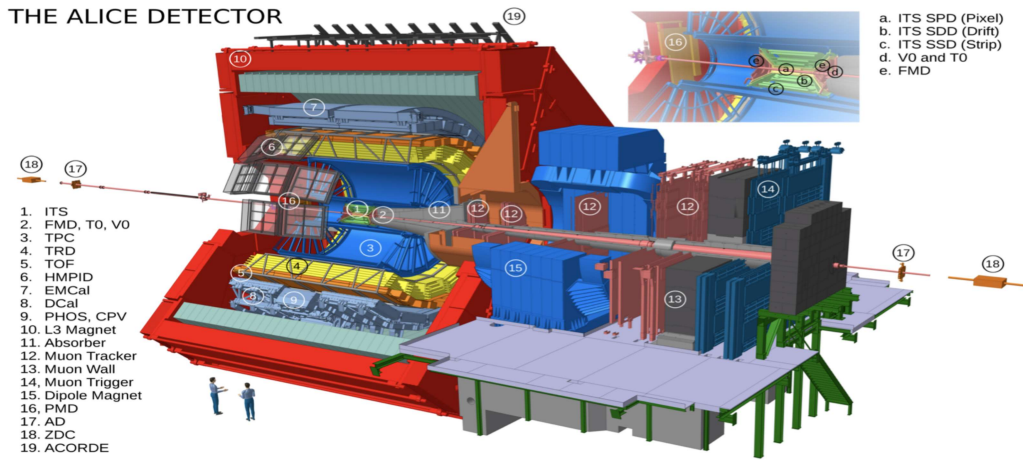


Figure 3.2: Schematic layout of ALICE detector [73].

3.2.1 Detector's Construction

The ALICE is positioned in a vast cavern 56m underneath the ground in the territory of Serisy in France border. It is heritedly enveloped by the solenoid magnet that worked for L3 experiment. The system containing magnetic colling was gone through the cross check up after the wipe out of L3 experiment. With this complete and carefull inspection, the revamping of the external circuit was done so that to prepare the magnet for working at 0.5 Tesla, which is the necessary and standard field for them for operating conditions. It is obligatory for ALICE tracking technique, so that it measure particles of wide range of transverse momentum also having broad range of resolution, by the help of system based on cooling.

The standardization of the field is also the fundamental obligation while tracking

the particles having high multiplicity environment. This is triumphed by reducing the diameter of axial distance in between the magnets located at its doors. 200 tons of iron cap are fitted to attain this condition. The subsequent standardized field provides alterations while measuring the volume of inner tracking system, less than 2 % of the theoretical implication; it can be helpful to segregate in ALICE central detectors having wide range of identification for witnessing the categorization of central detectors [72].

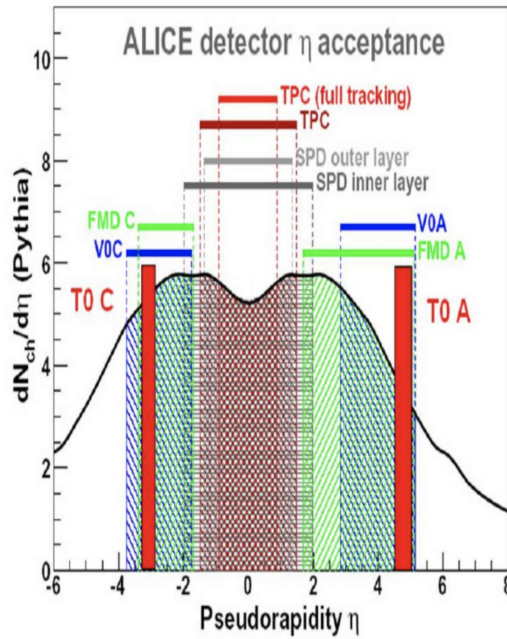


Figure 3.3: Pseudo-rapidity coverage of ALICE sub-detectors [74]

3.2.2 Central Barrel detectors

The central barrel is surrounded in a large solenoidal magnet (L3 magnet, taken from LEP experiment), which keeps the magnetic field at 0.5 T and it shields pseudo-rapidity interval of $-0.9 < \eta < 0.9$ (polar angle 45° to 135°) and full azimuth. Central barrel encompasses of Inner Tracking System (ITS) [75], Time Projection Chamber (TPC) [76], Transition Radiation Detector (TRD) [77], Time of Flight (TOF) [78] detector, Cherenkov counter (HMPID) [79], Photon Spectrometer



(PHOS) [80], Electro-magnetic calorimeter (EMCAL) [81] and the ALICE Cosmic Ray Detector (ACORDE) [82]. The central detectors are mainly used for tracking, vertex reconstruction, particle identification and measurement of track momentum. The details of the central barrel detectors are discussed in the following sub-sections. Special emphasis is given to ITS, TPC and TOF detectors, as the ALICE data analyses based on the use of these detectors extensively.

3.2.3 Inner Tracking System (ITS)

The Inner Tracking System comprises of the cylindrically shaped developed sheets made up of silicon. The points where the interaction occurs are encased by these sheets for appraising the features of outgoing particles. One of the purpose of these sheets is to precisely pin point the location of hitting point of outgoing particles with an accuracy up to the fraction of millimeters. ITS characterizes the particles holding quarks with heavy mass from the point where it decays. When it is devised to function alone, ITS depends on the low momentum spectrometer because of this the efficiency of tracking capacity of the ALICE for transverse momenta comes to below 100 MeV/c. The geometric layout is shown in figure 3.4. The main purpose of ITS is the precise determination of primary and secondary vertices. In sequence with different detectors such as TPC or TOF, ITS is capable of determining the location of the points where major and minor vertexes develop. Which is very useful to discover small residual particles such as hyperons and D or B meson with great accuracy. ITS has following layers made up silicon detectors incorporating from the point where it interacts.

(SPD) Silicon Pixel Detector's two layers

(SDD) Silicon Drift Detector's two layers

(SSD) Silicon Strip Detector's two layers

Silicon Pixel Detector (SPD), the innermost detector in the ITS, plays an important role in the determination of primary and secondary vertices. The foremost idea of this detector is to notice of the leading vertex and for magnitude of the collision factors of the non-leading tracks. The area which has a very high density is also controlled by SPD. It can function at high radiation levels, the incorporated levels of standard running scenario, of total dose and fluence are projected to be 220 krad and

at very high track densities about $50 \text{ tracks}/\text{cm}^3$. SPD has the hybrid silicon pixels in the arrangement of a two dimensional matrix of reverse-biased silicon detector diodes. In SPD every pixel is just like a chip, where 99% of channels are working by connecting them with sensors. The thickness of sensor and chips are $200 \mu\text{m}$ and $300 \mu\text{m}$ respectively. The signals obtained is recorded on the pixels. The diodes are connected through a conductive solder bump to contacts on a read out chips which correspond to the input of readout cells by printed circuit having 3 flexible layers. The SPD contains 107 cells and 1200 readout pixel chips. Each pixel chip of SPD also provides a Fast-OR digital pulse whenever a pixel or a group of them detects a particle signal above the threshold, which makes SPD capable of generating a prompt trigger. There is a readout card, inside that card ASIC chips are embedded. Slow performance during run, smaller diodes stress to the optical links and complex outgoing data are recorded by the help of ASIC chips. These ASIC chips are also useful to find placement points of pixel chips.

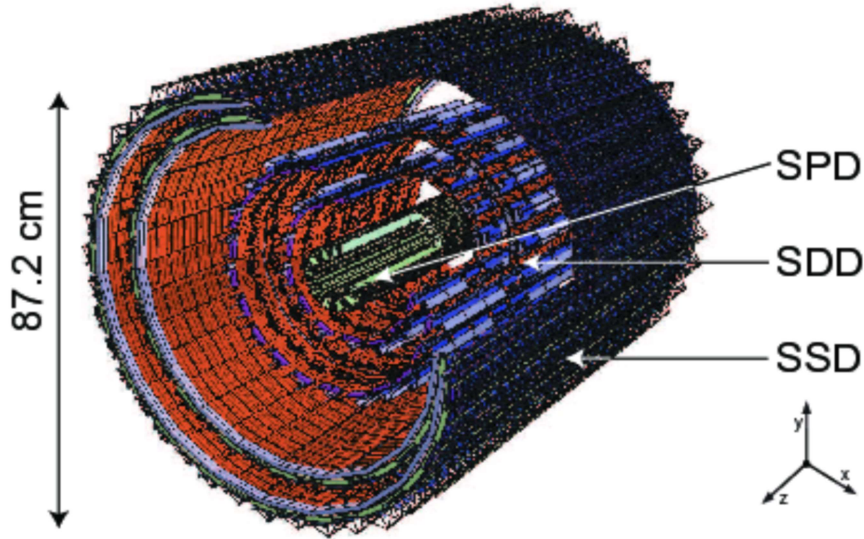


Figure 3.4: Schematic layout of Inner Tracking System (ITS) [75].

Silicon Drift Detector (SDD) are the intermediate layers (3rd and 4th) of the ITS. The SDD is about $300 \mu\text{m}$ of thickness and is stored with individually 22 ladders and modules in calm to confirm full angular exposure, devising six sectors each structure has formed by the set of ITS layers at its center. A high voltage divider, for drift's structure and field mechanism, is assimilated inside the sensor



and CMOS. Where CMOS is used as a charge provider to perceive drift velocity. SDD provides very high precision position information with position resolution of $35 \mu\text{m}$. Neutron transmutation provides high resistivity with homogeneously. For this purpose a material with high resistivity is obtained by using n-type doped silicon material. Silicon slices on industrial scale is manufactured by the yield of around 50 %. A conversion cable is devoted for the detector is made up of Aluminum polyimide micro cables. These cables are used to bias unconventionally the two aspects of module. A thicker cable connected to the transition cable having high voltage divider is associated with it. The output received from this cable is up to 6 kV. it also provides the information of the energy loss (dE/dx), which can be used for particle identification.

Silicon Strip Detector (SSD) is the outermost pairs of layer of ITS. Its construction is taken place in 36 phases, all the ladders have 26 double sided strips made up of silicon slices. At corner sides of ITS cylinder in two cone shaped framework similar to the assembly of SDD. Light weight hard carbon fibers growing in a set of triangular string is installed as a regulator. These cone shape casing protect SDD and SSD and provide source to protect SSD ladders and forward multiplicity detector in silicon rings. Automated tape closeness technology is installed. This technology is associated with flexible micro cables of aluminium polyimide and that is useful to diffuse signals at the front end from the detector. There are pre-amplified chips are installed for controlling continuous yields and organized parameter. It is formed in CMOS technology with radiation tolerant of $0.25 \mu\text{m}$ to get shape HAL25 twelve for each element. It delivers a two dimensional quantity of the track position along with the dE/dx data.

3.2.4 Time Projection Chamber (TPC)

Time Projection Chamber of ALICE is served as an essential mainline apparatus. TPC is cylindrical in shape with an inner radius of 80 cm and an outer radius of 250 cm. The schematic layout of TPC is shown in figure 3.5. It occupies an active volume of 88 m^3 covering length of 500 cm along the beam axis. While functioning without any combination of other detector, TPC contribute the precise momentum measurement of the all-inclusive charged particle having lesser momentum than 10

GeV/c. Specifically TPC momentum measurement is about $100 \text{ GeV}c^{-1}$, in group-
ings with additional tracking procedures. Besides details concerning charged particle
detection it is collected with the help of energy loss measurement. The major goal of
TPC is to conquer improved momentum resolution is about few percent for particles,
devising momentum range $< 5 \text{ GeV}c^{-1}$ and 10% for the range $100 \text{ GeV}c^{-1}$ when com-
bined in arrangement with other detectors used for tracking purposes. The tracking
series is classified in the TPC controls resolution on the measurement of energy loss
and the working principle is also shown schematically in figure 3.6. The equivalence
measurements of pairs of particles consuming short comparative momentum range
needs two tracks resolution which is better than $5 \text{ MeV}/c$ in four momentum space.
A new tracking algorithm is established for reestablishment and simulation to sanc-
tion these executions. By using high-quality track reinstatement which is impartial
of the particles momentum lower $100 \text{ MeV}/c$ efficiencies above than 95 percent can
be attained [76].

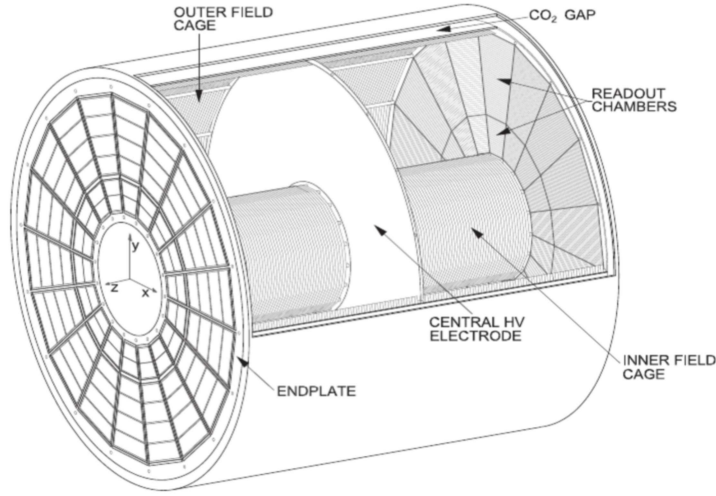


Figure 3.5: Showing different sections of Time Projection Chamber (TPC) [76][83].

During the data taking from the summer 2008 (cosmics) until the end of 2010, it
contains four vessels in the shape of cylinder with a length of 5m. Out of these four
cylindrical vessels two vessels are named as field cage vessels. The mixture consist
of Ne (90)-Co₂ (10) gas in enclosed in these field cage vessels. These cylindrical
vessels inside TPC express vigorous drift volume with radii of length 0.9 m and 2.5

m. High voltage inside TPC provides remoteness of the process which is provided by supplementary vessels containing CO_2 . At the center of field cage vessels a high voltage electrode is suspended. The electrode produces the field for drift up to 100 kV and direction of electrode is parallel to the axis of cylinder.

When a charged particle crosses through the gas volume, it stimulates and ionizes gas atoms along its track. As a result, the charged particle loses an amount of energy per unit track length (dE/dx) which is distinctive for each particle type. The free electrons flow towards the end plates of the cylinder under the effect of the electric field and the ions flow towards the high voltage cathode located at the centre of the TPC. The magnetic field is positioned parallel to the electric field such that the traveling electrons are not induced by it. At the end of drift path of the electrons, they are amplified by an avalanche process around the anode wires. For the readout of the signal the Multi-Wire Proportional Chambers (MWPCs) at the end plates are used. There are two end plates and each end plate has 36 readout chambers arranged in 18 trapezoidal segments. Each sector contains an Outer Readout Chamber (OROC) and an Inner Readout Chamber (IROC).

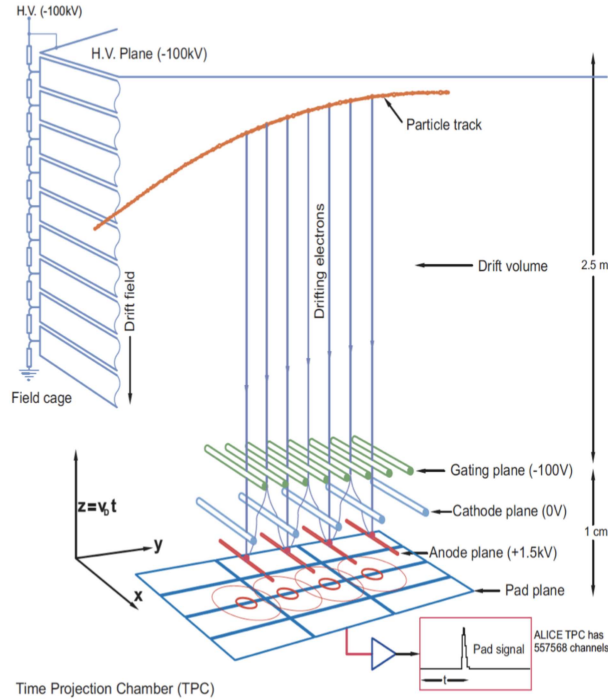


Figure 3.6: The Schematic illustration of the working principle and the read-out chamber of the TPC [84].

The tracks are reconstructed in TPC, from 3d space points and the transverse momentum (p_T) can be obtained from the curvature of the track. TPC can reconstruct a primary track of momentum (p) from 100 MeV/c up to 100 GeV/c. The figure 3.7 shows the tracks reconstructed inside TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during 2015. Besides the reconstruction of track, TPC also plays vital role for particle identification. The particle identification in the TPC is completed by the synchronized measurement of the charge, momentum and precise energy loss of each particle that crosses through the chamber.

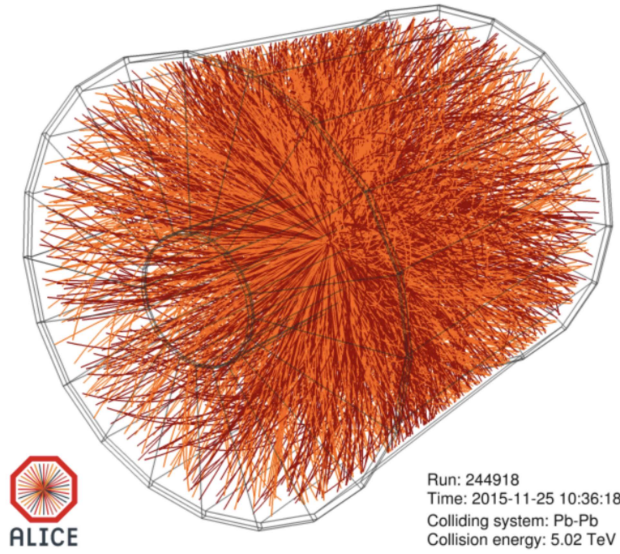


Figure 3.7: Event display of the tracks reconstructed inside TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during 2015 [85].

Bethe-Bloch formula describes the energy loss in TPC which is parameterized by a function originally proposed by ALEPH collaboration [86].

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_1 - \beta^{P_4} \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right) \quad (3.1)$$

Here beta is the particle velocity and gama is the Lorentz factor. The parameters P1 to P5 are the fit parameters extracted for each data taking period [84]. In the low-velocity region, the energy loss decreases and at a relativistic limit the ionization value becomes minimum. At this region, the particles are called minimum ionization



particles (MIP). Figure 3.8 shows specific energy loss (dE/dx) of the tracks as a function of momentum using TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [87]. The solid line denotes the potentials from Bethe-Bloch formula. At low momentum, the particles can be celebrated on a track-by-track basis. On the other hand, at higher momentum particles can be distinguished on a statistical basis via multi-Gaussian fits to the difference between the dE/dx measured and dE/dx parameterized by Eq 3.1. Another important approach to identify particles is via $n\sigma$ cut, where σ is the resolution. n is defined in the following way.

$$n\sigma = \frac{dE/dx_{measured} - dE/dx_{expected}}{\sigma_{TPC}^{PID}} \quad (3.2)$$

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

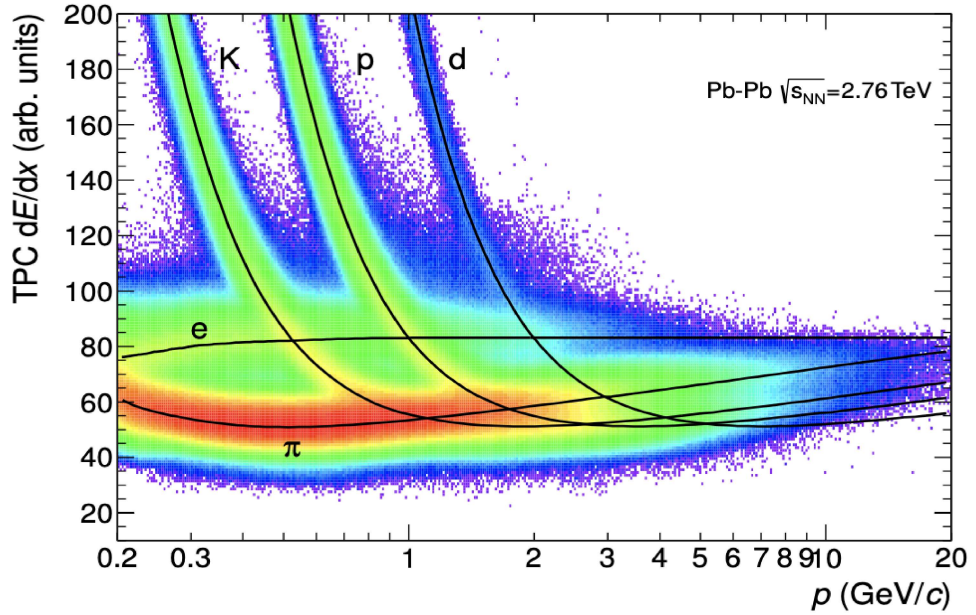


Figure 3.8: Specific energy loss (dE/dx) of the tracks as a function of momentum using TPC in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [87].

819 **Transition Radiation Detector (TRD):** To differentiates and classify the elec-
820 trons having high momentum from pions a detector called transition radiation de-
821 tector is used. It work on the matching of the capability of the transition radiation

emitted by the ultra-relativistic electron when it passes through different objects whereas the tracking information is provided by the ITS and TPC. The TRD is worked like an electron spectrometer that appreciate beauty meson and charm meson through the semi leptonic decays with the controlling operation of its e^+e^- . Huge momentum is devised by triggering on the electron. The electronics working for TRD allows the hadrons dealings. This is skilled of fast tracking capacity.

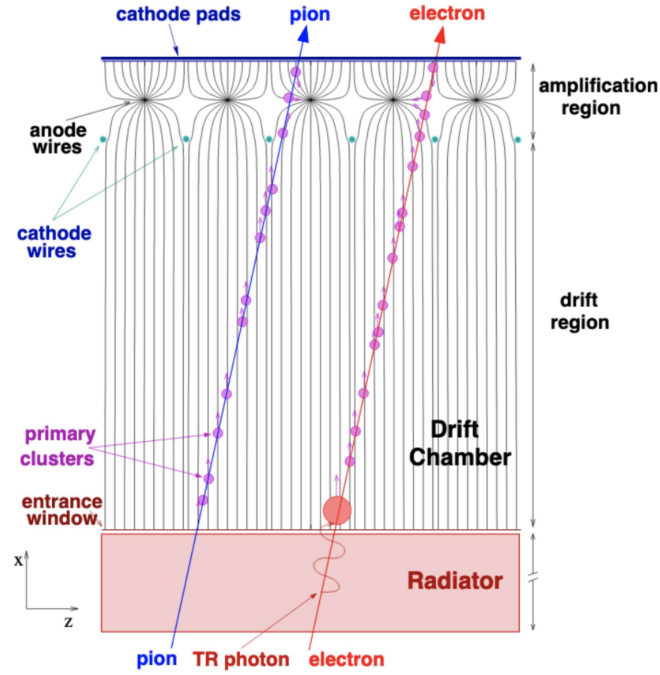


Figure 3.9: schematic corss-sectional view of a module and working principle of TRD[89].

Basic detection principle of TRD consist of a foil inside radiator, a fiber made up of polypropylene which is settled among the three glass of fibers imposed by Rohacell foil, along with time dilation compartment having readout pad made up of cathode and packed with the mixture of heavy gas. Such a six units are stacked together to complete one module. 108 super modules are required to entire azimuthal coverage. The TRD is placed in the radial position $2.9 < r < 3.7$ m from the interaction point. It includes full azimuthal angle and pseudo-rapidity region, $0.84 < |\eta| < 0.84$. It is involved of six layers of radiators followed by a drift chamber. The TRD is devoted for the electron detection for $p_T > 1$ GeV/c, where the TPC cannot detect the electrons via the dE/dx measurements. When the charged particles pass the edge of two media of different dielectric constant, transition radiation is released, with



839 photons in the KeV range. The electrons beyond threshold momentum discharge
840 differently as compare to pions. So the TRD can extend the pion rejection capability
841 of the TPC up to very high momenta. The electron identification is crucial for the
842 analysis of electron spectra and study of light and heavy vector meson resonances by
843 their leptonic decay channel. Figure 3.9 shows the schematic cross-sectional view of
844 a module and working principle of TRD [89].

845 3.2.5 Time Of Flight (TOF)

846 Time Of Flight detector is installed at the outer most portion of the inner barrel
847 in the ALICE detector, because of the slow movement of the heavy particles so it
848 takes plentiful time to touch the surface of the detector. The TOF detector is made
849 up of gaseous cylindrical detector comprises of Multi-gap Resistive Plate Chamber
850 (MRPC). The capacity of TOF to measure the inclusive charged hadrons with dis-
851 tinct classification is based on the combination with tracking information such as
852 charged, momentum and energy loss collected by ITS and TPC. To attain superb
853 time resolution and advances the functioning for categorization of pions, kaons and
854 protons in the intermediate range of momentum, Multi-gap Resistive Plate Chamber
855 (MRPC) technology is introduced. Two sheets of five peer plate compartments taking
856 thin gap are arranged in TOF. Strips of dissimilar lengths are build up on barrel of
857 3.7 m radius are assembled in the stack of compartment [78].

858 It is positioned around the TRD at a radial distance of 2.70-3.99 m covering polar
859 angles 45° to 135° within $|\eta| < 0.9$. The main principle to installed TOF is to detect
860 particles in the intermediate momentum region, where TPC cannot differentiate the
861 hadrons by dE/dx measurement. When a charged particle passes across the detector,
862 it ionizes the gas and the high electric field amplifies the ionization across electron
863 avalanche, which are motionless due to the resistive plates. TOF detector is also
864 capable to distinguish particles with 99.9 percent efficiency and a time resolution
865 about 85 ps for Pb-Pb and 120 ps in pp collisions. The charged particles can be
866 identified by the $n\sigma$ cut, which is defined by,



$$n\sigma = \frac{t_{measured} - t_{expected}}{\sigma_{TOF}^{PID}} \quad (3.3)$$

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

High Momentum Particle Identification Detector (HMPID): The High Momentum Particle Identification Detector is obligated to comprehensive features of predictable hadrons of $pt > 1 \text{ GeV}/c$ [79]. This detector was contemplated as a single-handed procedure developing tool which has approval rate of 5% of the intermediate pod sector area. This detector will enhance the PID potential of the ALICE by sanctioning the detection of the particles independent of the momentum space adaptable through loss of energy in the ITS, TPC and time-of-flight estimation (in TOF). The HMPID was elevated to widen the valuable series of π/K and K/p biasing. The working of HMPID is focused on proximity-focusing Ring Imaging Cherenkov (RICH) counters with C_6F_{14} (perfluorohexane) a radiator liquid and the compartment of multi cable proportion consuming pad containing read out ultra violet detector. A trim layer of CsI photocathode vaporizes on the pad plane. The solid angle concealed by HMPID $-0.6 < \eta < 0.6, 57.61^\circ$ azimuthally recording at a distance of 5m from the point of contact [90]. When a charged particle crosses through the detector the electromagnetic radiation is radiated in a cone and the Cherenkov photons radiated by a fast charged particle crossing the radiator, are spotted by a photon counter comprises of 10 m^2 of active CsI photocathode area.

Photon Spectrometer (PHOS): From the center to the outer side of the detectors of the ALICE Photon Spectrometer (PHOS) is celebrated. PHOS detector encompasses solid angle of $220^\circ - 320^\circ$ azimuthally, whereas $-0.12 < \eta < 0.12$ and positioned at 4.6m from point of interaction. PHOS is a high resolution electromagnetic calorimeter and the main physics aims are to study the characteristics of the initial phase of the collision, study probes for de-confinement like jet quenching and validating the pQCD results. It has 5 modules with 3584 tungsten crystals ($PbWO_4$) in each module. The position of PHOS in ALICE is shown in figure 3.10. A large section of $PbWO_4$ calorimeter, consuming multi wire proportional compartment to letting the

prevention of charged particle, is used to gauge photons having high resolution and categorize alongside charged hadrons. For advancement of the output in the form light from PbWO_4 crystals, calorimeter is developed to secure at the temperature of -25°C . By the feature of two photon decay channel to pinpoint neutral mesons, section of calorimeter specifies position resolution. Extra characterization of the particle is completed by the help of selected additional parameters like TOF, measurements after isolation etc. These studies are performed via the measurements of direct and thermal photons, neutral pions and eta mesons. The Charged Particle Veto (CPV), a set of MWPCs, is placed in front of PHOS to reject charged particles.

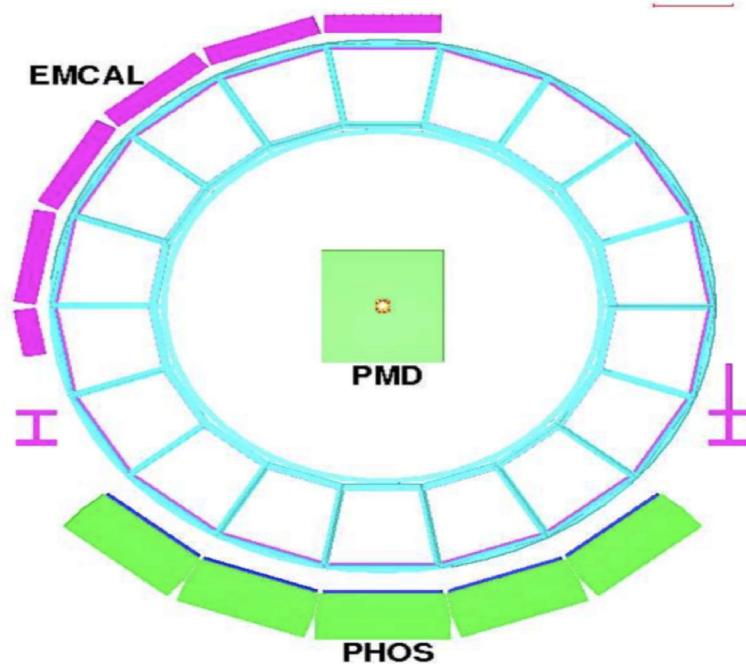


Figure 3.10: ALICE setup with PHOS, EMCAL and PMD[91].

3.3 Forward Detectors

The forward detectors are surrounded by VZERO (V0) detector [92], TZERO (T0) detector [92], Zero Degree Calorimeter (ZDC) [93], Photon Multiplicity Detector (PMD) [94] and Forward Multiplicity Detector (FMD) [92]. A short explanation of these detectors are reviewed below. A particular importance on V0 detector is discussed as V0 is the main detector used as trigger and multiplicity estimator in the

ALICE data analyses.

3.3.1 VZERO (V0) detector

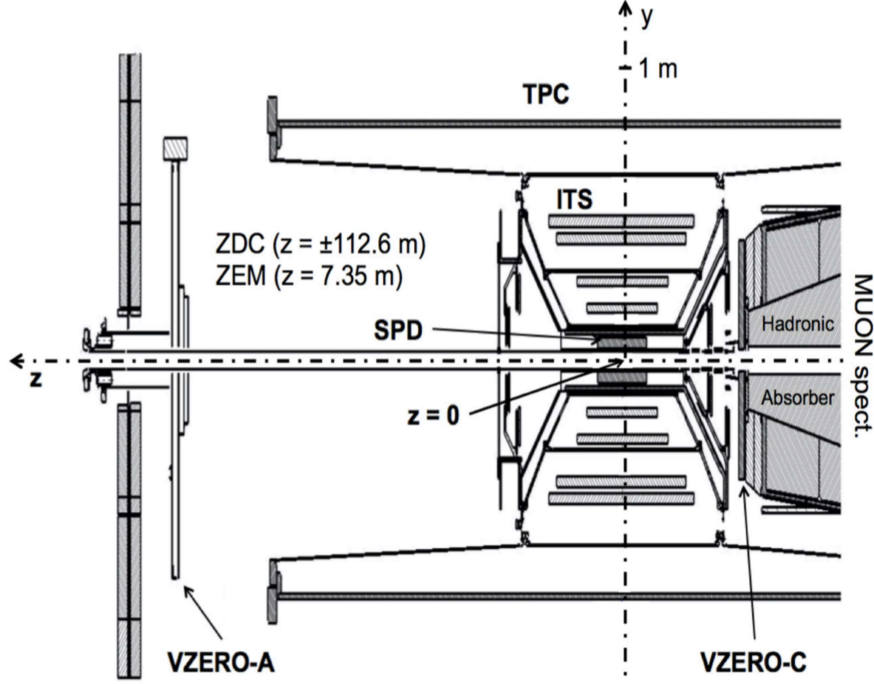


Figure 3.11: Position of the two VZERO arrays within the general layout of the ALICE [95].

V0 detectors are made up of plastic scintillators situated both sides of the interaction point. It is of two kind the one in forward direction is known as VZERO-A (V0- A) and the other one is on backward direction known as VZERO-C (V0-C). The pseudo-rapidity coverage range for V0-A is $2.8 < |\eta| < 5.1$ and is $3.7 < |\eta| < 1.7$ for V0-C both cover full azimuth. The detectors are articulated in 4 rings and each ring is further divided into 8 sectors, which is articulated in 32 counters. Position of the two V0 arrays within the general layout of the ALICE is shown in figure 3.11.

V0 detector is used for several different purposes. It is managed to run as a minimum bias trigger for central barrel detectors. The particles creating from early making from initial collisions and from secondary interactions in the vacuum chamber elements, specify the trigger information for central barrel detectors. The reliance between the number of recorded particles on the V0 arrays and the number of primary produced particles is monotonic. Thus, the V0 works as a pointer of the centrality of the

collision through the multiplicity recorded in the event. Cuts on the total charge
and the number of fired counters can be useful to achieve rough centrality triggers
[95]. There are three such triggers called, the multiplicity, semi-central and central
triggers.

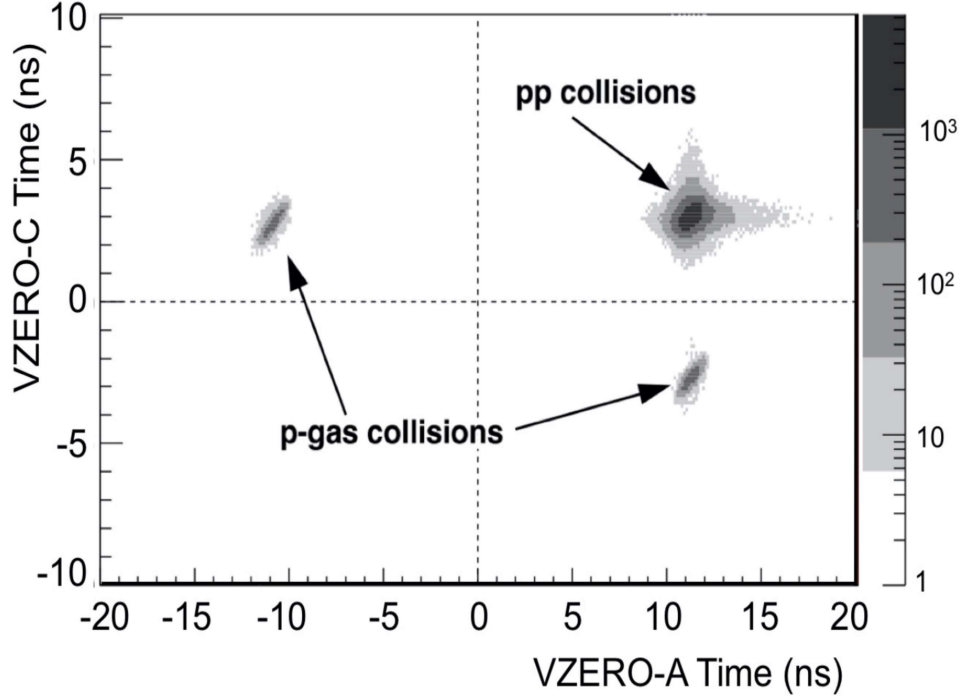


Figure 3.12: Timing criteria to discriminate beam-beam and beam-gas events using the average time response correlation of V0 detectors [95].

929

The contact point of proton and residual gas in the vacuum chamber can produce
tracks in the detectors and these incorrect events can be eradicated by using the
Minimum Bias p-Gas trigger (PG). The timing benchmarks is adopted to differentiate
beam-beam and beam-gas events using the average time response correlation of V0
detectors, which is shown in figure 3.12.

3.3.2 TZERO (T0) detector

T0 detector consists of two arrays of Cherenkov counters, named as T0-A and T0-
C. T0-A detector is positioned at the opposite side of the Muon spectrometer, at a
distance of 3.75 m from the point of interaction. It has the range of $4.61 < |\eta| < 5.92$.

T0-C is situated opposite to that of T0-A at a distance of 7.27 m from the point of interaction with pseudo-rapidity range $3.28 < |\eta| < 2.97$. the time resolution property of T0 is high which can quantify the collision time with an accuracy of 25 ps. This collision time is considered as a reference time for Time of Flight detector. T0 can also deliver a pre-trigger to TRD and can also produce minimum bias and multiplicity triggers.

Zero Degree Calorimeter (ZDC): Four tiny calorimeters installed inside the LHC tunnel are identified as a zero degree calorimeter. Whereas the point of interaction inside that tunnel is at a distance of 110m far from zero degree calorimeter. ZDCs are comprising on the assembly made up of tantalum or brass in cased by the fiber of quartz. Neutron and proton which are emitted by the first LHC dipole are detected by tantalum zero degree calorimeter and brass zero degree calorimeter respectively. This keeps the data after triggering and quantify the impact parameter. During the heavy-ion collisions there are participants and spectators. Those nucleons which participate in the collisions are considered as a participants and the nucleons which don't participate in the collisions and travel along the beam line are considered as a spectators. Participants and spectators in heavy-ion collisions are displayed in figure 3.13. The ZDCs are prepared by the matrix of quartz fibres and of heavy metal plates. The positions of ZDCs are depicted in figure 3.14.

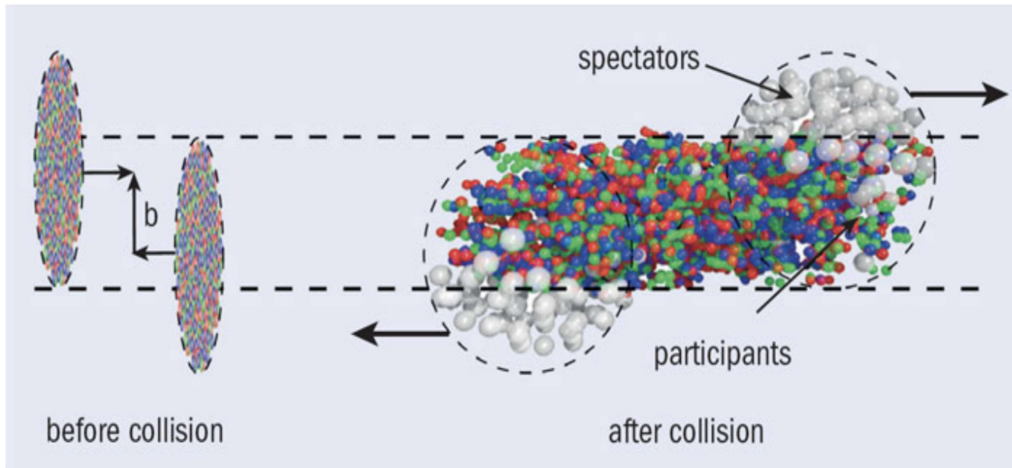


Figure 3.13: Left: Two heavy ions before collision, Right: Spectators and participants after collision [96].

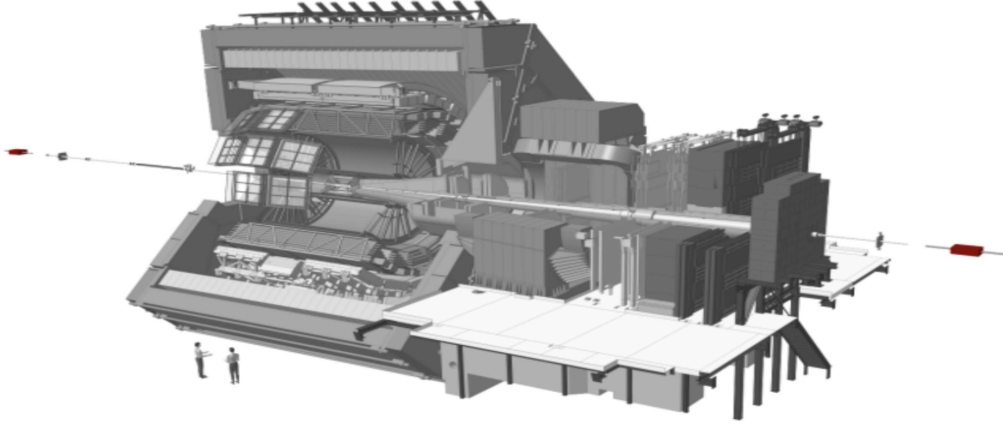


Figure 3.14: Position of the two ZDCs (highlighted in red) within the general layout of the ALICE [93].

958 3.3.3 Photon Multiplicity Detector

959 A framework of hexagonal shape cells, resembling like honeycomb, properly related
960 in size with chambers put together with non active lead converter. Then these are
961 combined together to built photon multiplicity detector. The multiplicity of photons
962 discharged in pp and Pb-Pb collisions in the forward rapidity region is measured by
963 PMD, which is the main purpose of this detector in search of new physics. It is also
964 helpful to analyze the determination of the reaction plane. The PMD is situated in
965 the forward region of ALICE at a distance of 3.67 m from the interaction point. It
966 shields pseudo-rapidity range $2.3 < |\eta| < 3.9$ and full azimuth. The location of PMD
967 in ALICE shown in figure 3.15. The PMD is also known as a pre-shower detector,
968 because lead converter is sandwiched between two planes of gaseous proportional
969 counters.

970 3.3.4 Forward Multiplicity Detector (FMD)

971 Five sheets made up of pads of silicon detectors are arranged in a way to get forward
972 multiplicity detector. The muon spectrometer is surrounded by FMD, two of them are
973 on one side while three on other side. The FMD is installed at forward and backward
974 rapidities $3.4 < |\eta| < 1.7$ and $1.7 < |\eta| < 5.0$ with full azimuthal coverage. It is

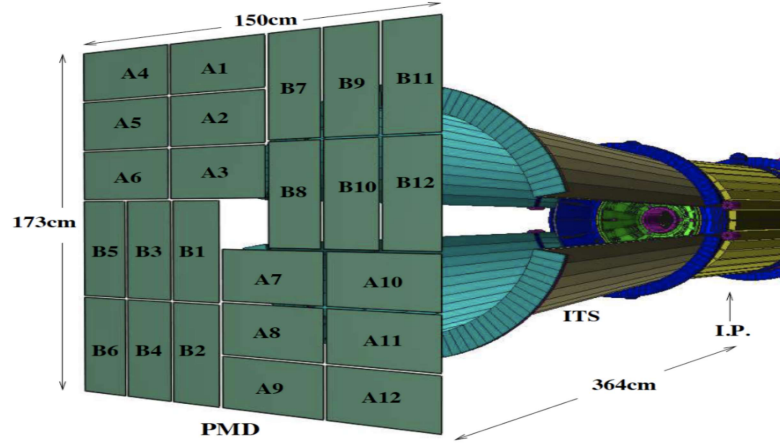


Figure 3.15: The position of PMD in ALICE [89].

also worked to regulate the multiplicity of the charged particles and determine the reaction plane. Common phase space of FMD and PMD permits to analyze charged-neutral particle fluctuations and correlations. It is installed in a position away from the interaction point in front of the muon spectrometer, which is used to increase the range of the charged particle multiplicity coverage.

3.4 Online and Trigger

ALICE has the central online systems used to controlled the data taking activities. The Detector Control System (DCS) permits to function the detector hardware from a central interface. The Data AcQuisition (DAQ) system is accountable for outlining the configuration of the detectors during data taking activities. It has two types of interface known as Trigger (TRG) and High-Level Trigger (HLT) systems. Experiment Control System (ECS) is worked to coordinate all the processes of the central systems (DAQ, TRG and HLT). The detectors can function independently which is identified as standalone mode. Standalone mode is used to execute commissioning, calibration and debugging activities. During the physics data taking, the detectors are assembled in partitions which can control simultaneously with a given set of trigger inputs.



992 3.4.1 Central Trigger Processor (CTP)

993 The ALICE trigger system contains Central Trigger Processor (CTP) and a High
994 Level Trigger (HLT) [97, 98]. For each detector, the CTP comprises of 24 Local
995 Trigger Units (LTU). The first level trigger is named as a L0 and the second level
996 is known L1. L0 is supplied after $1.2 \mu\text{s}$ and L1 is supplied after $6.5 \mu\text{s}$. The final
997 trigger, L2, is supplied after $100 \mu\text{s}$. After the L2 trigger the event is saved and the
998 output of the CTP moves towards the LTUs of each detectors. Then the output is
999 shifted to the front end electronics of the detector through Low Voltage Differential
1000 Signalling (LVDS) cables and optical fibres.

1001 3.4.2 High Level Trigger (HLT)

1002 To select useful events, HLT authorizes a firmware and software through the filtering
1003 mechanism. HLT accepts the raw data via Detector Data Links (DDL). Then it
1004 obtains hits and clusters and executes the basic calibration. After that the event is
1005 reconstructed for each individual detector and the choice of event is implemented
1006 with the reconstructed physics observables. HLT also implements data compression.

1007 3.4.3 Data Acquisition (DAQ)

1008 The DAQ system manages the data flow from the electronics of the detector to
1009 the permanent storage. The Local Data Concentrators (LDCs) read out the events
1010 from the optical DDLs. The LDC accumulates the data into the sub-events and they
1011 are distributed to Global Data Collectors (GDCs). The GDCs records the events
1012 to Transient Data Storage (TDS). Then it is transferred to the tape (PDS) in the
1013 storage.

1014 3.5 Offline Framework

1015 ALICE offline analysis depends upon the AliRoot software background platform and
1016 is sustained by the ROOT platform to catch up the advantages of unlike accessi-
1017 ble portion like prearranged containers, assimilated input and output arrangements



elaboration. C^{++} is a software design tool, consisting of extensive arrangement of effectiveness of the formulas based on mathematics, multi bound fit and minimization, gadget for citations, complete background scrutiny of figures and channel station toolkit for graphical users. AliRoot is used to perform full set of complete tasks e.g. reconstruction and simulation of the events, data analysis .etc. [99].

A virtual technique based on Monte-Carlo is used to develop virtual machine. By the help of these machine a variety of particle transport codes are developed and used to control run time between packages. GEANT3, GEANT4 and FLUKA are recently debugged to achieve a new crossing point then this information is used to approve new geometry of the ROOT package [100]. This new package is helpful to visualize the geometry of the detector and serve as a tool for construction and browsing of trail. By using the new ROOT package an interface is defined for feeding and kind of geometry and also its uncertainties .e.g. where am I and what is the by product after varying geometry or if any extension application is applied which changes the geometry.

These makeover looks of user interface support in plentiful means such as demonstration of events, its simulation and reconstruction and also for visualization of an event by consuming the same geometrical shape. The working of ALICE offline framework is the same as it is used to work at CERN. ALICE environment is also known as AliEn, which is the key expansion of ALICE offline framework. AliEn is disseminated frame work for computing. It is operational for global dispersed simulation and resubmitting of jobs [72].

3.5.1 ROOT Framework

After facing difficulties in computing data analysis for various years René Brun and Fons Rademakers had established communicating tools and simulation platform. These tools guided affluent projects such as PAW, PIAF and GEANT as the old libraries developed by the FORTRAN twenty years before had reached to their limits. Besides all these facts, these are enough prominent but it also couldn't scale up to antagonize offer to LHC. Whereas the data collected at LHC is barely such a high degree of any order bigger than the data stored in any of the previously performed experiment. The research and studies of computer science had been already partic-



ipating the vibrant part in the elaboration, advancement and development for the mankind specifically in the field of programming based on object oriented design. Burn and Fons were likely to carry out benefits from it. In NA49 the experiment at CERN, the ROOT had developed its outlook. This experiment has initiated the extraordinary quantity of data per run .i.e. 10 Terabytes. This amount of data delivers the perfect circumstances of expanding and testing the forthcoming generation of data analysis. One couldn't uncover the ROOT restrictions to established the new fact about CINT, its C++ interpreter. Masa Goto from japan has formulated CINT. This is an autonomous software package which is exercised by the ROOT used in the command line tool and processing of script.

This framework has a substantial and relaxed elaboration flair to ease comprehensively trusts of the unlike and profound ability of the consumer society. The development of this framework is a perpetual exchange among consumers and designers. When it arrives to gathering and deduction of excessive extent of data, physics enrich the technique by its Terabytes, nonetheless superfluous arenas and productiveness practice nearby overdue as they improvement further and further data throughout time. The interaction of ROOT with its clients is assisted within the boundary of graphical user through command line tool. The set of modules having logically and satisfactory incorporated is provided by the ROOT which is useful to operate internally through the bus of objects. The analyst parameters provides information for the bus which creates the broad Run Time Type Information (RTTI). The ROOT is formulated by this RTTI to get a perfect transportation module. The absolute data from experiment use sequence based on that module and it is built by DAQ. It uses the memory classes from user and public to get database, analysis and data presentation.

3.5.2 ALICE Grid and ALIEN

To manage and analyze massive amount of data dispersed among computing resources, the concept of ALICE Grid was established. In ALICE Grid, the data processing is spread to several computing centers situated at world-wide [101]. The dispersed computing infrastructure, which is useful to work in the LHC experimental program, is succeeded under Worldwide LHC Computing Grid (WLCG) project. The



ALICE grid involves Models of networked analysis at regional centers (MONARC), which is categorized into different stages and tiers. All real data create from CERN, which is called Tier-0. Tier-1, which are huge regional computing centers, share with CERN for the taking part in a safe storage of the data. Tier-2 are the slightly small centers which are logically clustered around Tier-1. The principal role for Tier-2 is to complete Monte-Carlo simulations and user analysis tasks. ALICE Offline project also acquires ALICE ENvironment (ALIEN), which permits ALICE users to have transparent access to grid computing and storage resources.

3.5.3 Simulation in the ALIROOT Framework

The detector description and data structure is defined by the different interface classes which is tagged in the central module known as STEER. Central module, needed for virtual Monte Carlo, also provides the particle stack implementations and to run steering. To develop the event generator module the interface class AliGenerator is used. The AliDetector module specifies the environment for particular module of detector [102]. The interface TVirtualMC be responsible for the transportation of MC through virtual MC. These full modules set is agreed with track steering, which is the basic ingredients of base module. These user defined modules have different intend for different sub-detector's corresponding. These modules of each detector are distinguishable for every distinctive module and these are independent of each other.

For different stages during the simulation procedure, a large amount of data produced by framework for simulation developed by AliRoot. A directory containing temporary files is settled by ALICE-ENvironment (ALIEN) which authorizes blatant entry of allocated sets of data. The MC based transport code provides the exact description of the particle when a particle walk through the detector, such as energy deposition and position are characterized by the number of so-called hits. Unprocessed data taken earlier without adding effect of noise and minimum threshold for subtraction is referred to as integrated digits. The detector converts these hits in the form of signals. This technique lays stressful effects during heavy ion interaction's simulation so it needs a detail explanation in separate section. On concluding this discussion more than few signal events are extracted from one original event, thus it reduces the time for computation and also less space is required for data to store. AliRoot



1111 simulation framework in the form of component view is shown in the Figure 3.16.

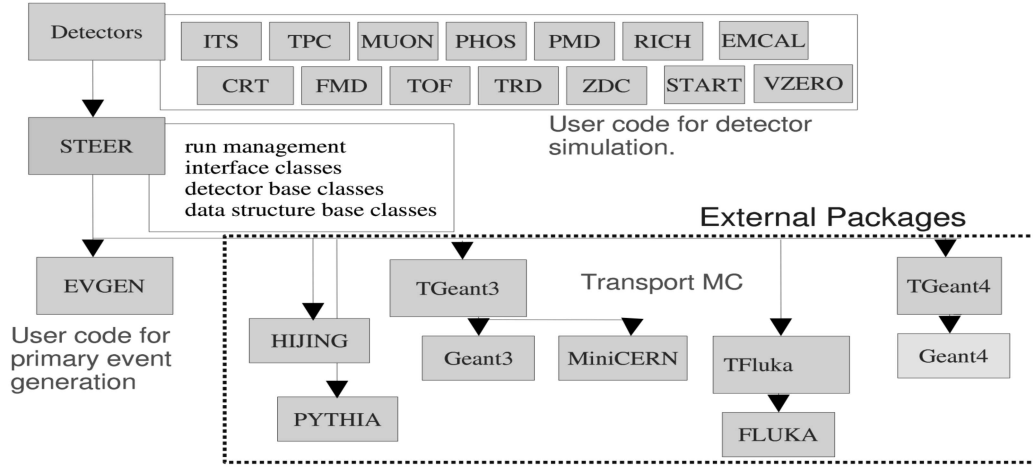


Figure 3.16: A view of AliRoot simulation framework with its major components [102].

Chapter 4 Analysis Procedure

4.1 Introduction

The global event characterization was one of the first tasks conducted by all LHC experiments [103–108]. Measurements of pseudo-rapidity density ($dN_{\text{ch}}/d\eta$), multiplicity distributions, the transverse momentum (p_T) spectrum and the correlation $\langle p_T \rangle$ vs. multiplicity have been reported in pp collisions at different center-of-mass energies. The studies of Underlying Event (UE) activity are also included (see e.g. [103, 104]), it is worth mentioning that UE pp data at $\sqrt{s} = 5.02$ TeV is missing. The UE activity is everything which does not belong to the main partonic scattering. From the phenomenological point of view, it includes contributions from Multi-Partonic Interactions (MPI), Initial- and Final-State Radiation as well as from beam remnants. In MPI-based models such as PYTHIA 8 and EPOS LHC, the height of the plateau is sensitive to the impact-parameter dependence upon the number of MPI per event [43]. Figure 4.1 shows an illustration of underlying event.

The underlying event is an important element of the hadronic environment within which all physics at the LHC, from Higgs searches to physics beyond the standard model, take place. Many aspects of the underlying event are constrained by LHC data. However, the physics is so complex, spanning non-perturbative and perturbative QCD, and including sensitivities to multi-scale and very low- x physics. For this reason, and also for planning purposes, it is critical to have models containing our best physical knowledge and intuition, tuned to all relevant available data.

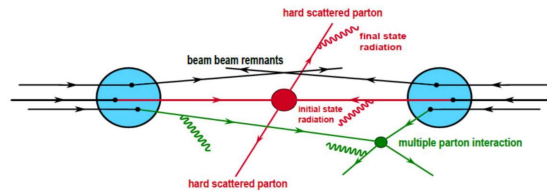


Figure 4.1: An illustration of underlying event in pp collision.

In Underlying Event (UE) studies we measured the components of particle production in hadronic interactions, which are not directly related to the hardest interaction. The Transverse region method has been adopted for UE studies by ALICE [62], CDF [48], STAR [50], ATLAS [52] and CMS [55] collaborations. The UE results



are valuable inputs to tune Monte Carlo event generators, e.g., to describe the uncorrelated background in jet studies. These studies are also helpful to provide high precision predictions for Standard Model (SM) and lead new ways in searches for physics beyond the SM, where a good description of the UE is needed to understand backgrounds.

4.2 Underlying Event observables

The Underlying Event observables can be studied with respect to the leading track (i.e. the track with the highest transverse momentum in the event). The traditional UE analysis is based on the measurement of particle production in three distinct topological regions on their relative azimuthal angle with respect to the leading particle i.e. transverse, towards and away regions but transverse region is more sensitive for UE. In this work, the UE observables in pp and p-Pb collisions for similar event classes (same p_T^{trig} and same $\sqrt{s_{\text{NN}}}$) are compared. The only primary charged particles in the limited acceptance of ALICE central barrel detector system is considered. Results are obtained for associated particles within the pseudo-rapidity range ($|\eta| < 0.8$) and for three different thresholds of the transverse momentum, $p_T^{\text{trig}} > p_T > 0.15, 0.5$, and 1 GeV/c in each topological region. It is quantified with the primary charged-particle number density:

$$\left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\varphi} \right\rangle(p_T^{\text{trig}}) = \frac{1}{\Delta\eta \Delta\varphi} \frac{1}{N_{\text{ev}}(p_T^{\text{trig}})} N_{\text{ch}}(p_T^{\text{trig}}), \quad (4.1)$$

and the summed transverse-momentum density:

$$\left\langle \frac{d^2 \sum p_T}{d\eta d\varphi} \right\rangle(p_T^{\text{trig}}) = \frac{1}{\Delta\eta \Delta\varphi} \frac{1}{N_{\text{ev}}(p_T^{\text{trig}})} \sum p_T(p_T^{\text{trig}}), \quad (4.2)$$

where $N_{\text{ev}}(p_T^{\text{trig}})$ is the total number of events with the leading particle in a given p_T^{trig} interval; $N_{\text{ch}}(p_T^{\text{trig}})$ and $\sum p_T(p_T^{\text{trig}})$ stand for multiplicity and sum of the p_T of all reconstructed tracks within a given topological region, respectively. Finally, $\Delta\eta$ is the pseudorapidity interval used in the analysis.

The charged-particle number and the summed- p_T densities in the toward and away regions after the subtraction of the event activity in the transverse region as a function of p_T^{trig} are also analyzed here.



The charged-particle number density in the jet-like signal is derived from the difference between the number density in the toward (or away) region and that in the transverse region:

$$\left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\varphi} \right\rangle^{\text{jet toward(away)}}(p_{\text{T}}^{\text{trig}}) = \left[\left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\varphi} \right\rangle^{\text{toward(away)}} - \left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\varphi} \right\rangle^{\text{transverse}} \right](p_{\text{T}}^{\text{trig}}). \quad (4.3)$$

1150 In the same way, the summed- p_{T} density in the jet-like signal is obtained as follows:

$$\left\langle \frac{d^2 \sum p_{\text{T}}}{d\eta d\varphi} \right\rangle^{\text{jet toward(away)}}(p_{\text{T}}^{\text{trig}}) = \left[\left\langle \frac{d^2 \sum p_{\text{T}}}{d\eta d\varphi} \right\rangle^{\text{toward(away)}} - \left\langle \frac{d^2 \sum p_{\text{T}}}{d\eta d\varphi} \right\rangle^{\text{transverse}} \right](p_{\text{T}}^{\text{trig}}). \quad (4.4)$$

1151 The ratio between these two quantities gives the average transverse momentum in
1152 the jet-like signal:

$$\langle p_{\text{T}} \rangle^{\text{jet toward(away)}} = \left\langle \frac{d^2 \sum p_{\text{T}}}{d\eta d\varphi} \right\rangle^{\text{jet toward(away)}} / \left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\varphi} \right\rangle^{\text{jet toward(away)}}. \quad (4.5)$$

1153 The three topological regions [109] corresponding to the azimuthal-angle intervals
1154 defined below and are also illustrated in Fig. 4.2.

- 1155 – Toward: $|\Delta\varphi| < 60^\circ$,
- 1156 – Transverse: $60^\circ < |\Delta\varphi| < 120^\circ$, and
- 1157 – Away: $|\Delta\varphi| > 120^\circ$.

1158 where, $|\Delta\varphi| = |\varphi^{\text{assoc}} - \varphi^{\text{trig}}|$.

1159 4.3 Data sample

1160 In this analysis results for pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are discussed.
1161 The list of runs is chosen based on the recommendations from ALICE DPG. For pp
1162 collisions data taking period is LHC15n which is recorded by ALICE in 2015 with
1163 pass4, it includes new treatment for TPC and distortion maps also bugs found pass3
1164 for PID is fixed in this period. The total number of events for all trigger is 194 M
1165 but for minimum bias (MB) trigger, i.e., kINT7 the number of events are 133 M.

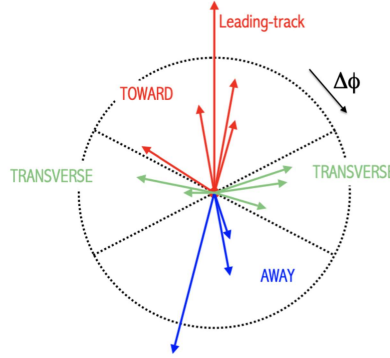


Figure 4.2: Definition of the different topological regions: toward, transverse and away.

The list of runs used for the analysis of the pp data is the following:

- **LHC15n (pass4)**: 244340, 244343, 244351, 244355, 244359, 244364, 244377, 244411, 244416, 244418, 244421, 244453, 244456, 244480, 244481, 244482, 244483, 244484, 244531, 244540, 244542, 244617, 244618, 244619, 244626, 244627, 244628.
- **LHC17e2**: This is the MC production anchored to data, Pythia 8 Monash.

Regarding p–Pb collisions data taking period is LHC16q, is recorded in 2016 by ALICE with pass1-CENT-wSDD. Where all the events are in CENT cluster with SDD readout signals. Total number of events are 766 M for all trigger whereas for MB trigger, i.e., kINT7,CENT with 330 M events. The list of runs used for the analysis of the p–Pb data is the following:

- **LHC16q (pass1-CENT-wSDD)**: 265332, 265334, 265335, 265336, 265338, 265339, 265342, 265343, 265344, 265377, 265378, 265381, 265383, 265384, 265385, 265387, 265388, 265419, 265420, 265421, 265422, 265424, 265425, 265426, 265427, 265435, 265499, 265500, 265501, 265521, 265525, 265309.
- **LHC17f2a-cent-fix**: This is the MC production anchored to data, EPOS LHC.

4.4 Event and Track Selection

Not all events are used for analysis. Thus, for simulated events as well as for real data an event selection needs to be applied. In this analysis, minimum-bias (MB)



events were selected using the high purity V0-based MB and trigger which needed a charged-particle signal coincident in the V0A and V0C arrays. For high-luminosity data collecting, the trigger is the same as that employed in LHC Run 1 [87]. The MB trigger used for this analysis is kINT7. To protect full geometrical acceptance in the ITS around the supposed interaction point, a primary vertex position along the z -axis within ± 10 cm ($|vz| < 10$ cm) is achieved for offline analysis for additional event selection. A multiple interaction point detection technique based on SPD information rejects pile-up situations. The offline event selection is optimized to reject beam-induced background by exploiting the timing signals in the two V0 sub-detectors. The event selection also requires at least one track with a minimum transverse momentum ($p_T = 0.15, 0.5$, and 1.0 GeV/ c) in the acceptance range $|\eta| < 0.8$.

In this analysis standard track cuts 2015 for ITS and TPC in Pb–Pb collisions (StandardITSTPCTrackCuts2015PbPb) is implemented. The ITS and TPC detectors are the main tracking devices covering the pseudorapidity region $|\eta| < 0.8$ for full-length tracks. They are located inside a solenoidal magnet providing a 0.5 T magnetic field, allowing the tracking of particles with $p_T \gtrsim 0.15$ GeV/ c . Charged particles are reconstructed with the ITS and TPC detectors, providing a measurement of the track transverse momentum p_T and azimuthal angle ϕ , which are used in the analysis. Tracks are required to have at least two hits in the ITS detector, of which at least one in either of the two innermost layers. In addition, tracks are required to have a number of crossed TPC pad rows larger than $0.85 \times L$, where L (in cm) is the geometrical track length calculated in the TPC readout plane, excluding the information from the pads at the sector boundaries (≈ 3 cm from the sector edges). The number of TPC clusters associated to the track is required to be larger than $0.7 \times L$.

Some other cuts for track selection are also shown in the following list:

- The ratio of crossed TPC pad rows to the number of findable TPC clusters is required to be larger than 0.8, and the fraction of TPC clusters shared with another track should be less than 0.4;
- The fit quality for the ITS and TPC track points must satisfy $\chi_{\text{ITS}}^2/N_{\text{hits}} < 36$ and $\chi_{\text{TPC}}^2/N_{\text{clusters}} < 4$, respectively, where N_{hits} and N_{clusters} are the numbers of hits in the ITS and the number of clusters in the TPC, respectively;



- 1215 – To select primary particles, tracks having a large distance of closest approach
1216 (DCA) to the reconstructed vertex in the longitudinal ($d_z > 2 \text{ cm}$) and radial
1217 ($d_{xy} > 0.018 \text{ cm} + 0.035 \text{ cm} \times (\text{GeV}/c) \times p_T^{-1}$) directions are rejected;
- 1218 – Only tracks with $\chi_{\text{TPC-ITS}}^2 < 36$ are included in the analysis, where $\chi_{\text{TPC-ITS}}^2$
1219 is calculated by comparing the track parameters from the combined ITS and
1220 TPC track reconstruction to those derived only from the TPC and constrained
1221 by the interaction point [110].

1222 4.5 Quality Assurance checks for pp and p-Pb collisions

1223 To estimate the quality of data at different stages of MC simulation and comparison
1224 for MC and real data reconstruction the quality assurance (QA) checks are performed.
1225 The concurrence between data and MC while observing the QA checks provides the
1226 tracks to able to study different kinematics of different distribution.

1227 4.5.1 $\eta - \varphi$ correlation

1228 To observe the QA, we will begin with the detector acceptance. For this $\eta - \varphi$
1229 correlations in both of pp and p-Pb collisions are observed, shown in figure 4.3.
1230 Figure 4.3a shows the ratios of data to MC after normalising the yields in the $\eta - \varphi$
1231 space for pp (left) and p-Pb (right). Whereas in the Figures 4.3b and 4.3c show the
1232 comparison of data with MC. φ and η distributions which is extracted from the $\eta - \varphi$
1233 correlation for pp (left) and p-Pb (right). It can be observed, MC is consistent with
1234 data excluding the large discrepancies of inefficient SPD regions.

1235 4.5.2 Z-vertex and multiplicity distributions

1236 Vertex reconstruction is essential for each event, as it effects the measurements of
1237 other elementary measurements, therefore Z-vertex distribution is of high interest.
1238 For example it influence multiplicity distribution if Z-vertex distribution for data and
1239 reconstructed MC is shifted. The Z-vertex distributions shown in Fig. 4.4, it can be
1240 observed that the reconstructed MC gives a good description of data in pp and p-Pb

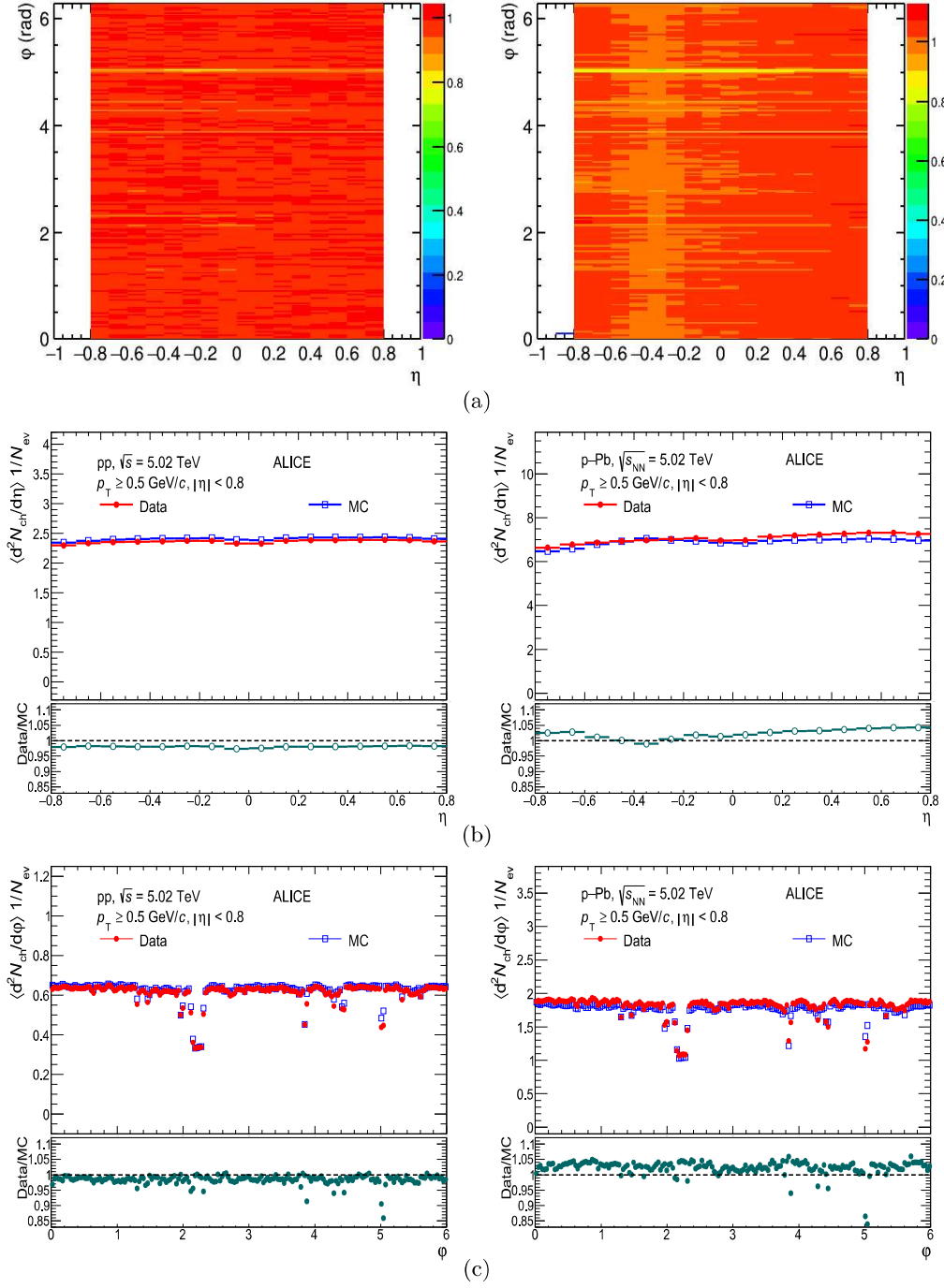


Figure 4.3: The η - ϕ distribution for pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (a) data to MC ratio in the η - ϕ space; (b) upper panel: η distribution for data and MC, bottom panel: ratio of data to MC; (c) upper panel: ϕ distribution for data and MC, bottom panel: ratio of data to MC, for p_T cut > 0.5 GeV/c and $|\eta| < 0.8$.

collisions. Whereas Fig. 4.5 is description of multiplicity distributions compared with data and MC, normalized by number of events.

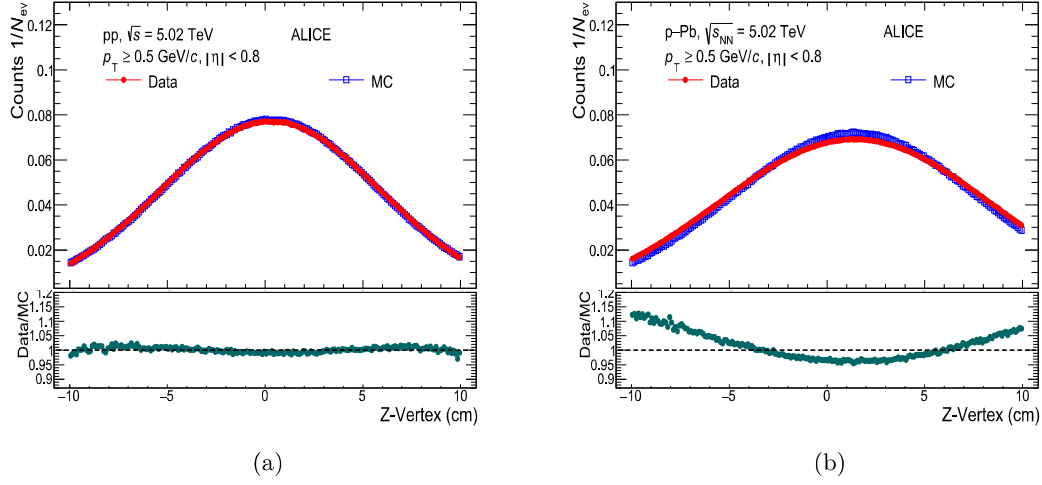


Figure 4.4: Z-vertex distributions (a) in pp collisions at $\sqrt{s} = 5.02$ TeV; (b) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV along with data to MC ratio for p_T cut > 0.5 GeV/c and $|\eta| < 0.8$.

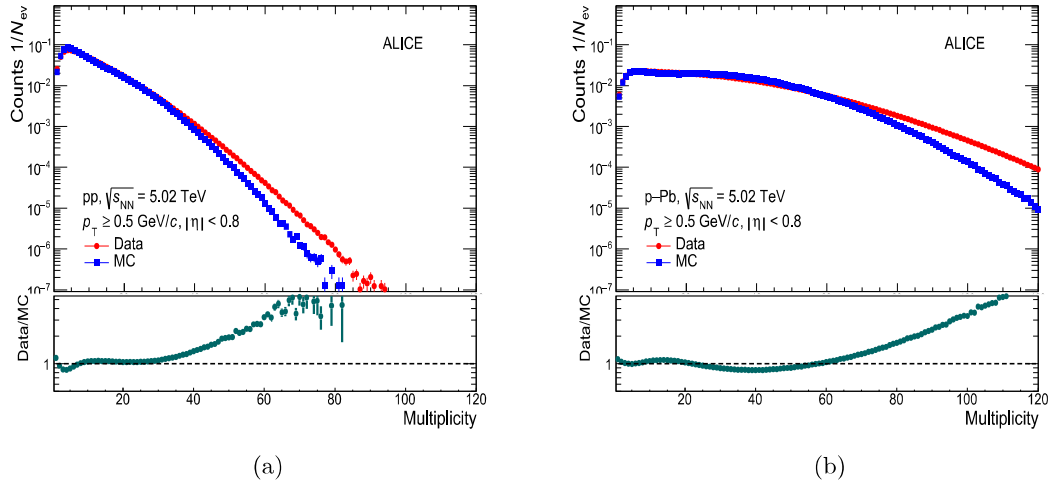


Figure 4.5: Multiplicity distributions (a) in pp collisions at $\sqrt{s} = 5.02$ TeV; (b) and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV along with data to MC ratio.

1243 4.5.3 p_T , p_T^{leading} and $\sum p_T$ spectra

1244 The UE observables, average number density and average summed p_T densities, de-
 1245 pends upon highest transverse momentum of track in an event, i.e. p_T^{leading} . So, it is
 1246 a good practice to observe QA tracks showing p_T , p_T^{leading} and $\sum p_T$ spectra. It is
 1247 observed that in pp collisions PYTHIA 8 MC model agrees with the data but in p-Pb
 1248 collisions EPOS LHC MC model is less efficient in agreement with data. p_T cut > 0.5
 1249 GeV/c is mainly focused in this analysis while other p_T cuts are also analyzed. //,
 1250 Figures 4.6 and 4.7 show the p_T , p_T^{leading} and $\sum p_T$ spectrum for pp collisions at



1251 $\sqrt{s} = 5.02$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, respectively.

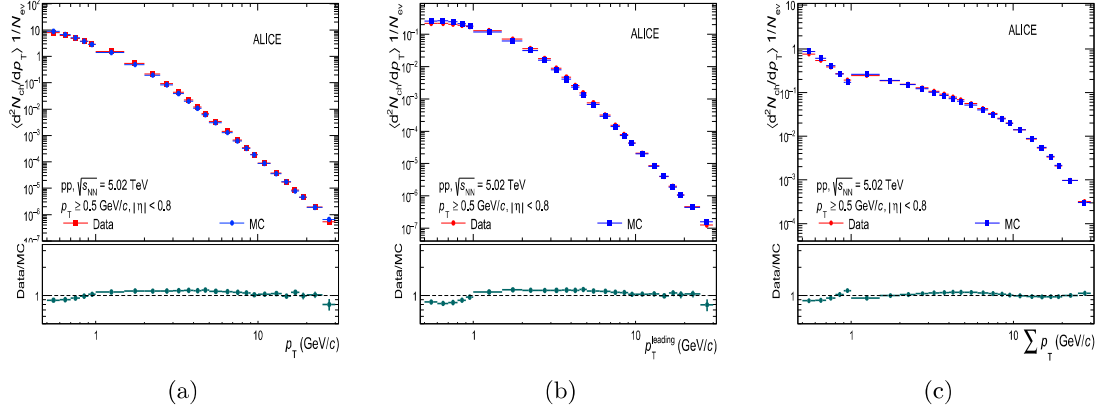


Figure 4.6: The distributions in pp collisions at $\sqrt{s} = 5.02$ TeV (a) p_T ; (b) p_T^{leading} ; (c) $\sum p_T$ spectra for data and MC.

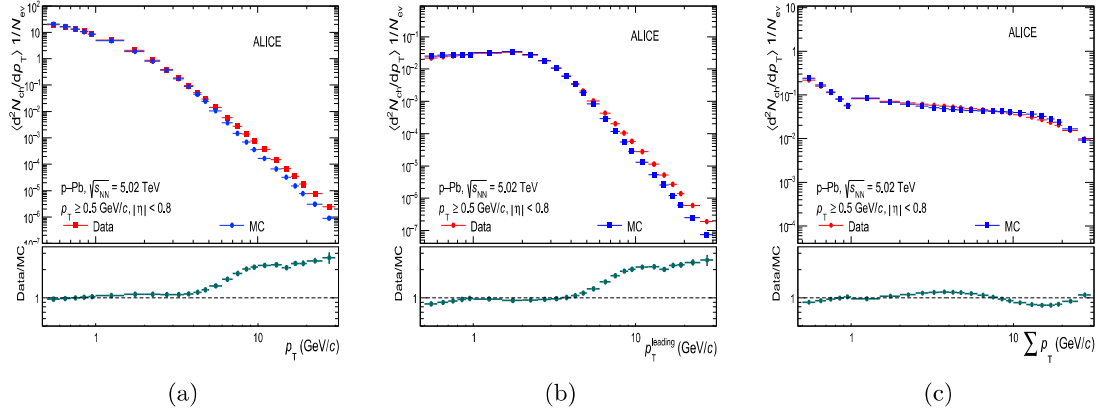


Figure 4.7: The distributions in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (a) p_T ; (b) p_T^{leading} ; (c) $\sum p_T$ spectra for data and MC.

1252 4.6 Correction procedure

1253 The correction procedure is briefly described below.

- 1254 1. The p_T spectra are extracted for each topological region as a function of p_T^{trig} .
 1255 This gives the number of tracks within a given p_T interval ($\Delta p_{T,i}$) and for a
 1256 given p_T^{trig} event class: $\Delta N_{\text{trk.}}(\Delta p_{T,i}; p_T^{\text{trig}}) = \Delta N_{\text{trk.,i}}$.
- 1257 2. These p_T spectra are corrected for efficiency ($\epsilon_{\text{trk.}}$) and contamination from sec-
 1258 ondaries ($C_{\text{sec.}}$). For this we follow the standard strategy from PWG-LF [111].



- 1259 3. Then the obtained results are normalized to the number of events in each p_T^{trig}
1260 bin: $N_{\text{ev}}(p_T^{\text{trig}})$.
- 1261 4. The average charge particle number density and average sum p_T density are
1262 both derived from these p_T spectra.
- 1263 5. After performing the above mentioned steps, these average charge particle num-
1264 ber, and sum p_T densities are further corrected for the leading track misidenti-
1265 fication ($C_{\text{lead.}}$) and selection bias ($C_{\text{sel.}}$).

1266 The fully corrected charge particle number, and sum p_T densities are derived as
1267 indicated by expressions 4.6 and 4.7. In both cases, the rightmost factor indicates
1268 the corrections which are applied at track level, while the leftmost factor displays
1269 those applied at event level.

1270 – **Fully corrected average number density:**

$$\left[\frac{C_{\text{sel.}} \times C_{\text{lead.}}}{N_{\text{ev}}} \right] (p_T^{\text{trig}}) \times \left[\frac{1}{\Delta\eta\Delta\phi} \sum_i [\Delta N_{\text{trk.,i}} \times C_{\text{sec.}}/\epsilon_{\text{trk.,i}}] \right] \quad (4.6)$$

1271 – **Fully corrected average $\sum p_T$ density:**

$$\left[\frac{C_{\text{sel.}} \times C_{\text{lead.}}}{N_{\text{ev}}} \right] (p_T^{\text{trig}}) \times \left[\frac{1}{\Delta\eta\Delta\phi} \sum_i [\Delta N_{\text{trk.,i}} \times C_{\text{sec.}}/\epsilon_{\text{trk.,i}}] \times p_{T,i} \right] \quad (4.7)$$

1272 where, i is the bin index of the uncorrected transverse momentum distribution, $p_{T,i}$
1273 is the corresponding bin center, and $\Delta N_{\text{trk.,i}}$ is the bin content.

1274 A detailed description of each correction factor can be found in the next sub-sections.

1275 4.6.1 Leading-track misidentification

As discussed in [61, 112], for the estimation of the leading-track misidentification correction, we can neglect the effect related with the different orientation of the reconstructed leading-track with respect to the real one. Therefore, the probability to misidentify the leading track depends essentially on its p_T . The bias can be evaluated

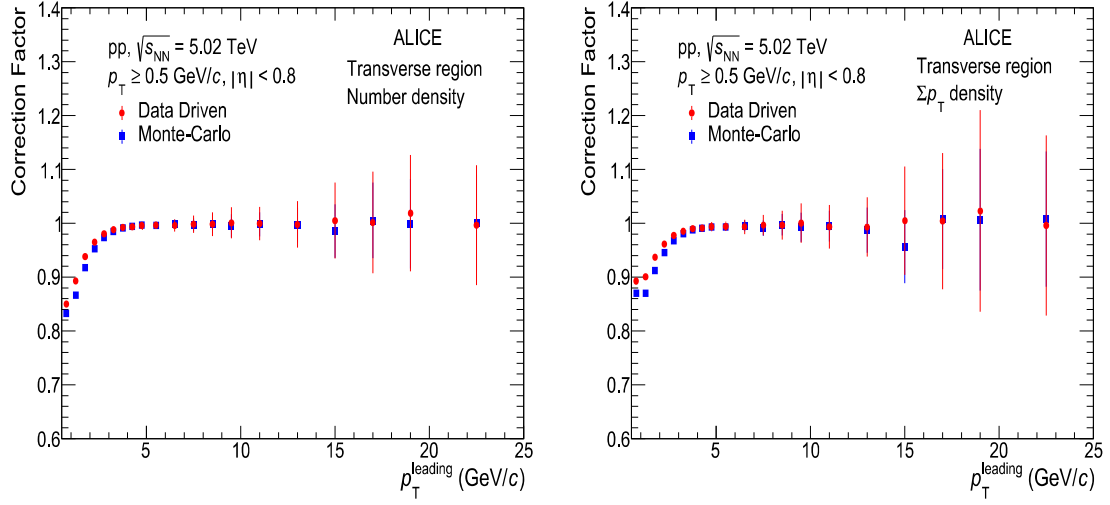


Figure 4.8: Left) Leading-track misidentification bias for number density in transverse region, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure are shown. Right) Leading-track misidentification bias for $\sum p_T$ density, correction factor vs. leading-track p_T for Monte Carlo and data driven procedures are shown. Results for transverse region in pp $\sqrt{s} = 5.02$ TeV are displayed.

either from pure Monte Carlo or with a data driven procedure. In the first scenario the corrections come from the ratio between events defined by true or reconstructed leading track. In the data driven procedure we start from the measured distributions and for each event the tracking efficiency is applied a second time on data (the first being applied naturally by the detector performance). Namely with the help of a random number generator and the efficiency information, one decides if the leading-track is correctly reconstructed. In the positive case it is used to define the topological regions (event class A). Otherwise the sub-leading track is used (event class B). The correction factors are calculated as follows (examples reported below are for the number density):

$$C_{\text{lead.}}(p_T^{\text{leading}}) = \frac{\text{number density for the event class } A}{\text{number density for the event class } A + B}(p_T^{\text{leading}}) \quad (4.8)$$

1276 The correction factors for pp and p-Pb collisions are shown in figures 4.8 and 4.9
1277 in transverse region, respectively. The correction factors for other regions is seen in
1278 appendix 6.2.

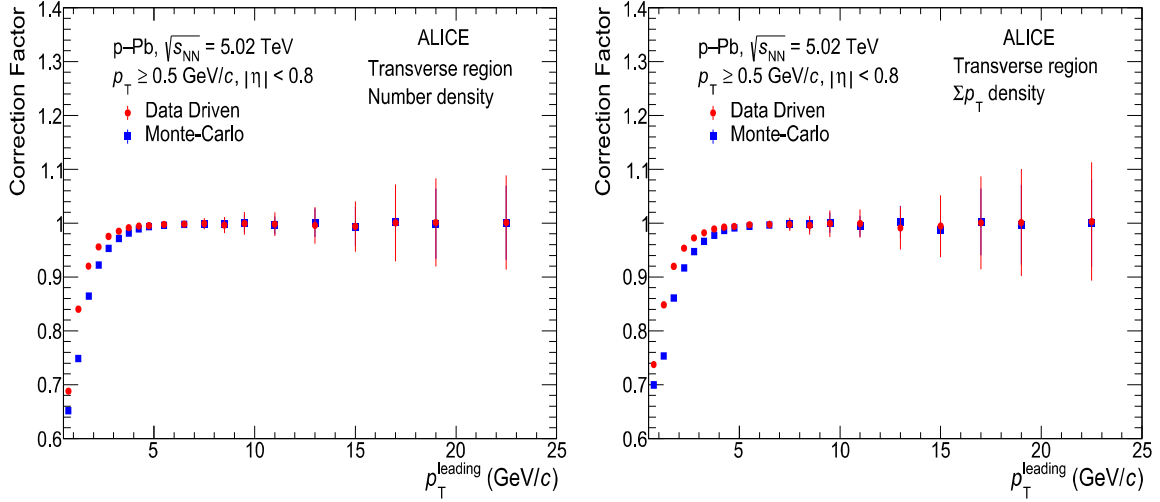


Figure 4.9: Left) Leading-track misidentification bias for number density in transverse region, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure are shown. Right) Leading-track misidentification bias for $\sum p_T$ density, correction factor vs. leading-track p_T for Monte Carlo and data driven procedures are shown. Results for transverse region in p-Pb $\sqrt{s_{NN}} = 5.02$ TeV are displayed.

1279 4.6.2 Track contamination

1280 Track contamination correction method includes the rejection of the secondary tracks
1281 which are wrongly recognized as primary tracks, moreover, these secondary tracks
1282 also pass through track selection cuts. Secondary tracks are usually formed by weak
1283 decays of strange particles, photon conversions or hadronic interactions in the detec-
1284 tor material and other secondary sources. Relying on Monte Carlo information, the
1285 definition of this correction factor is the ratio between the number of reconstructed
1286 tracks matching a generated primary track and the number of reconstructed track.

1287 Given that Pythia does not reproduce correct amount of strangeness, we use a data
1288 driven method. To reproduce the strangeness we chose the DCA_{xy} distributions from
1289 weak decays, interaction with the material and primary charged particles. Then we
1290 use the DCA_{xy} distribution from data and perform a template fit based on the MC
1291 shapes. This is done for each p_T interval, and for $-3 < DCA_{xy} < 3$ cm. The fraction of
1292 primaries in each p_T interval is estimated after considering the p_T dependent DCA_{xy}
1293 cut. Figures 4.10 and 4.11 show the correction from secondary-track contamination
1294 as a function of p_T ($C_{sec.}(p_T)$) for pp and p-Pb data, respectively.

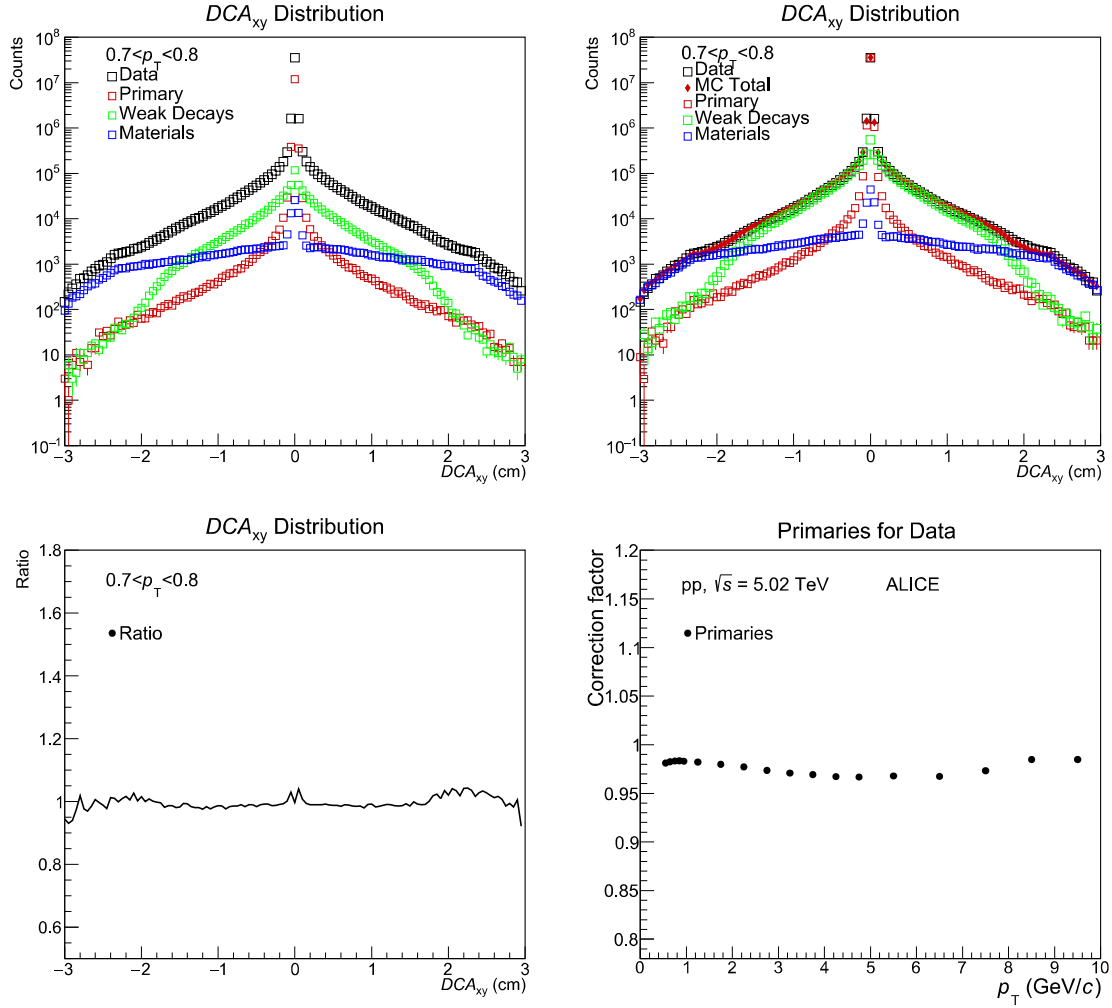


Figure 4.10: (Upper left panel w/o fit) data DCA_{xy} (black) and MC DCA_{xy} distributions from different sources: primaries (red), weak decays (green) and interaction with the material (blue). Tracks with transverse momentum between $0.7 < p_T < 0.8$ GeV/c in pp collisions were considered. (Upper right panel with fit) The MC distributions are compared with that from data (black). The result from the MC Multi-template fit is shown as yellow markers. (Bottom left panel) The data-to-fit ratio is shown as a function of DCA_{xy} . (Bottom right panel) Fraction of primaries as a function of p_T .

4.6.3 Tracking efficiency

The p_T spectra were corrected for tracking inefficiencies derived from MC, this correction is defined as the number of reconstructed primary particles over the number of generated primary particles in the chosen kinematic range. However, it is known that the relative single-particle abundances in Monte Carlo differ from data. This would not affect the analysis at all if the single particle tracking efficiencies were

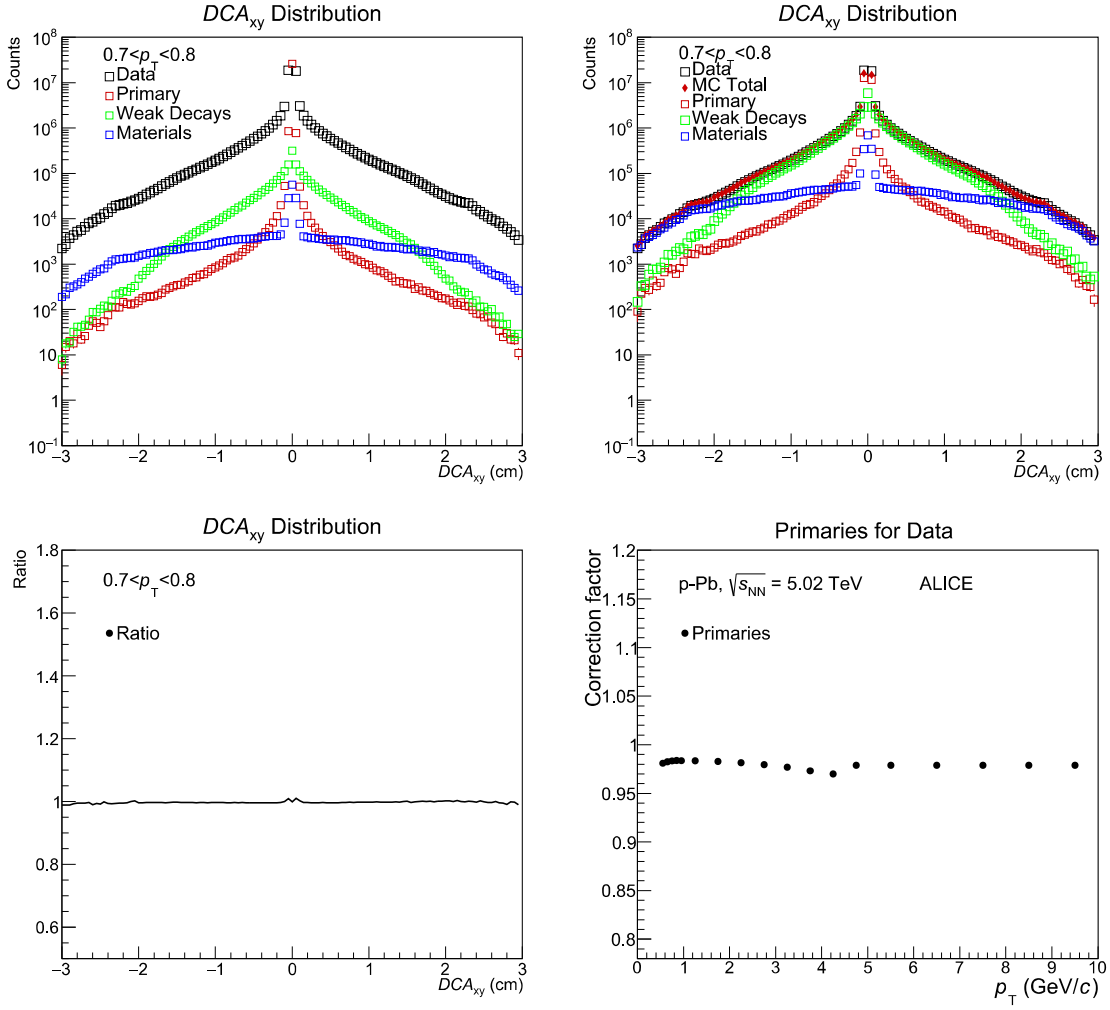


Figure 4.11: (Upper left panel w/o fit) data DCA_{xy} (black) and MC DCA_{xy} distributions from different sources: primaries (red), weak decays (green) and interaction with the material (blue). Tracks with transverse momentum between $0.7 < p_T < 0.8$ GeV/c in p-Pb collisions were considered. (Upper right panel with fit) The MC distributions are compared with that from data (black). The result from the MC Multi-template fit is shown as yellow markers. (Bottom left panel) The data-to-fit ratio is shown as a function of DCA_{xy} . (Bottom right panel) Fraction of primaries as a function of p_T .

1301 equal. This however is not the case, mainly due to different lifetimes of the particle
1302 species. For that reason the tracking efficiency is reweighed with particle composition
1303 (measured by ALICE). The correction was inherited from R_T analysis [113] which
1304 used the same runs as analyzed in this analysis, as well as the same event and track
1305 selection.

1306 Figure 4.12 shows the tracking efficiency as a function of p_T ($\epsilon_{\text{trk.}}(p_T)$). The decrease

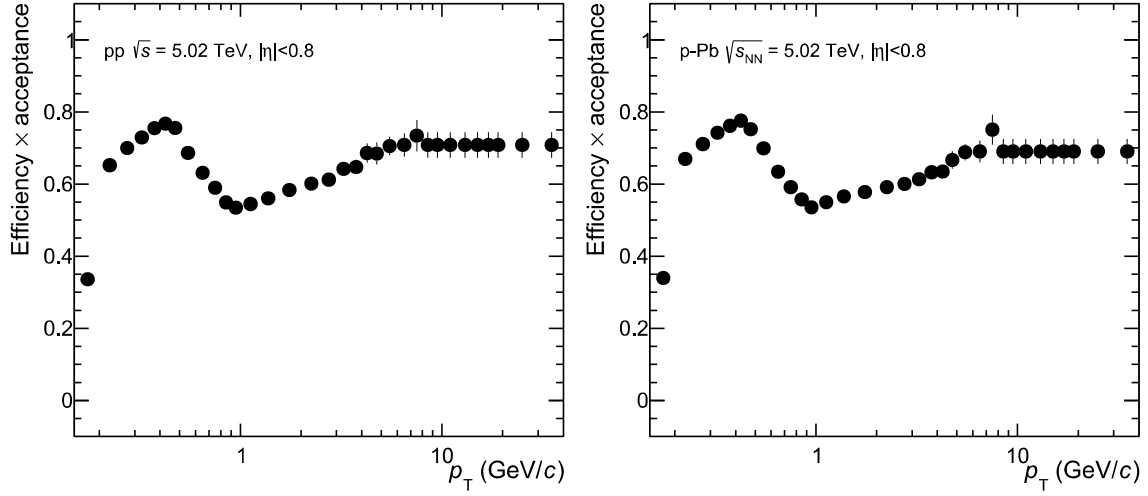


Figure 4.12: Tracking efficiency as a function of p_T for pp (left) and p-Pb (right) collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

in efficiency in the range 1-3 GeV/c can be explained by the presence of straight (high p_T) tracks falling in the dead areas between TPC sectors. At high p_T the efficiency is determined by geometry only and has a constant value of about 70%. In order to extend the efficiency correction to high p_T without being governed by statistical fluctuations, the estimated efficiency is fitted with a constant function at high p_T range.

4.6.4 Event selection

The selection bias is evaluated with UE observables at generator level, we consider all inelastic events (event class A') and those which pass the physics selection (event class B'). The correction factors are calculated as follows (example for number density):

$$C_{\text{sel.}}(p_T^{\text{leading}}) = \frac{\text{number density for the event class } A'}{\text{number density for the event class } B'}(p_T^{\text{leading}}) \quad (4.9)$$

Figure 4.13 shows the correction factor due to selection bias.

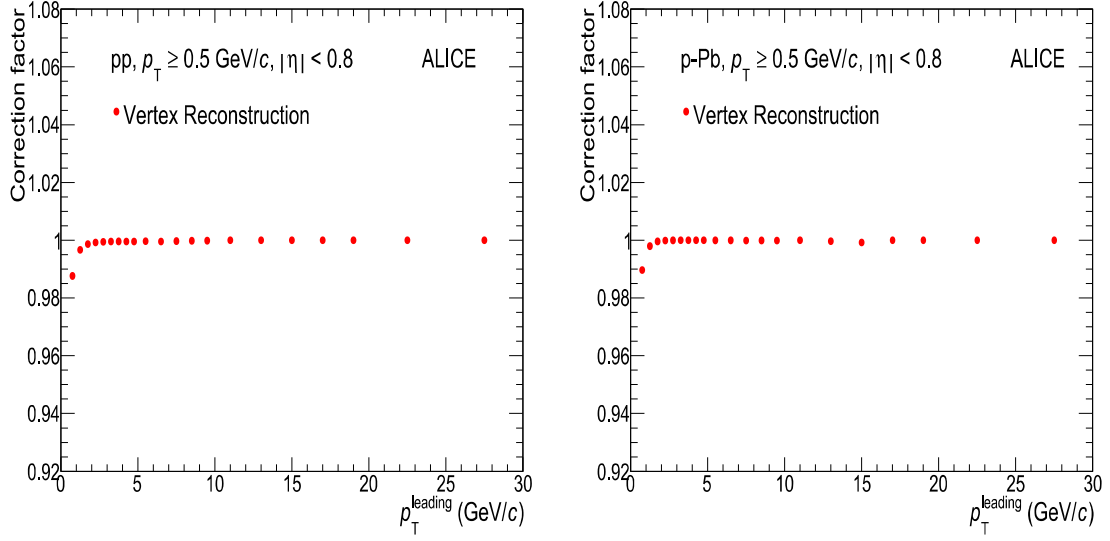


Figure 4.13: Effect of event selection, the correction factors for pp and p-Pb are shown in the left and right panels, respectively

4.7 Systematics Uncertainties

We have performed the variations listed below, and then we check the effects on the final observables: i.e. the underlying event observables as a function of p_T^{leading} for each topological region (Near Side (NS), Away Side (AS) and Transverse Side (TS)), as well as for NS-TS and AS-TS. The same was done for the average p_T for the NS-TS and AS-TS. The variations with respect to the default results were assigned as systematic uncertainties.

- **Secondary Contamination:** We have varied the fit range for the MC template fit. We used $-1 < DCA_{xy} < 1$ cm and $-2 < DCA_{xy} < 2$ cm. The maximum deviation with respect to the default interval ($-3 < DCA_{xy} < 3$ cm) was assigned as systematic uncertainty due to contamination.
- **Correction Method:** The MC non-closure was assigned as systematic uncertainty due to the correction method. More details on the MC-closure test can be found in Sec. 5.1.1
- **Track Selection:** The systematic uncertainties associated to the track selection were calculated varying the track quality cuts. We have varied the track cuts up to ± 10 % with respect to the default values. These uncertainties are estimated



by running the full analysis, varying only one track cut at a time. Specifically, the maximum DCA_z is varied in between 1 cm - 5 cm and the minimum number of crossed rows in TPC are varied from 100 to 130. We varied the upper limits of the track fit quality parameters in the ITS (χ^2/N_{hits}) and the TPC ($\chi^2/N_{\text{clusters}}$) in the ranges of 25-49 and 3-5, respectively. We also tested the impact on the analysis of at least one reconstructed point in SPD. The maximum deviation of each of the sources to the default set is assigned as systematic uncertainty for that particular source. To get the total systematic uncertainty due to track cuts is evaluated by the quadrature sum of the each individual sources. The variation of the track cuts is the same to that used in Ref. [114]. The systematic uncertainties from track cuts variations for different topological regions in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV can be seen in Fig 4.14 and 4.15, respectively. We use a zeroth order polynomial after 10 GeV/ c to obtain the total systematic uncertainties due to track cuts.

- **Misidentification Bias:** The systematic uncertainty due to leading track misidentification is derived from the difference between the data driven method to get the correction, and that which use the MC information.
- **Event Selection Bias:** The systematic uncertainty due to event selection cut is obtained by varying the cut on the z component of the vertex position: 5 cm and 15 cm were used instead 10 cm. The maximum difference obtained from these variation is considered to be the uncertainty due to event selection cut.

The total systematic uncertainties for the three topological regions in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV can be seen in Figures 4.16 and 4.17, respectively. We use a zeroth order polynomial after 10 GeV/ c for obtaining the total systematic uncertainties.

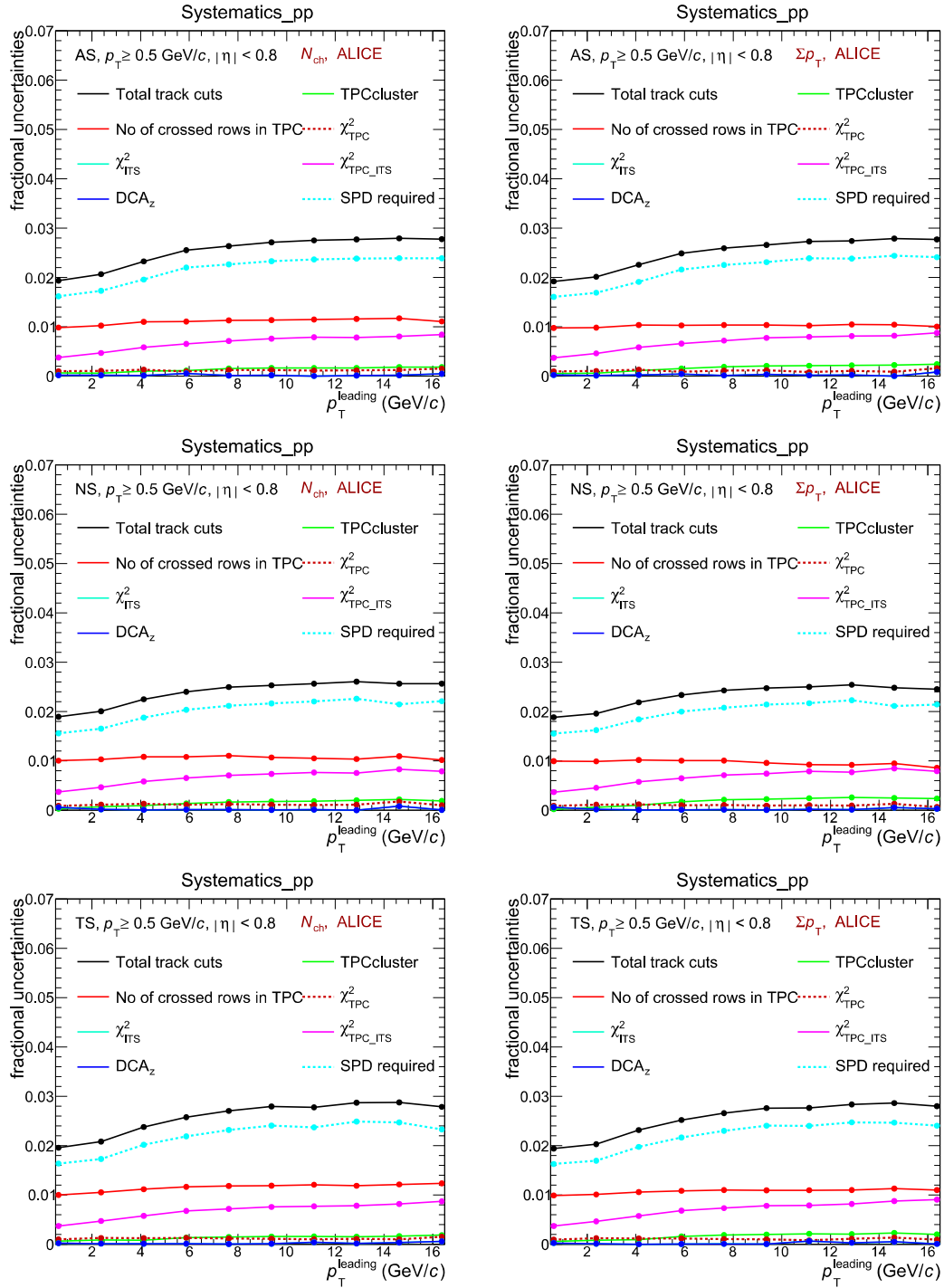


Figure 4.14: Relative systematic uncertainty due to track selection in pp collisions at $\sqrt{s} = 5.02$ TeV. Results for number density (left panel) and total p_T (right panel) are shown for the three topological regions: away region (top), towards region (middle) and transverse region (bottom).

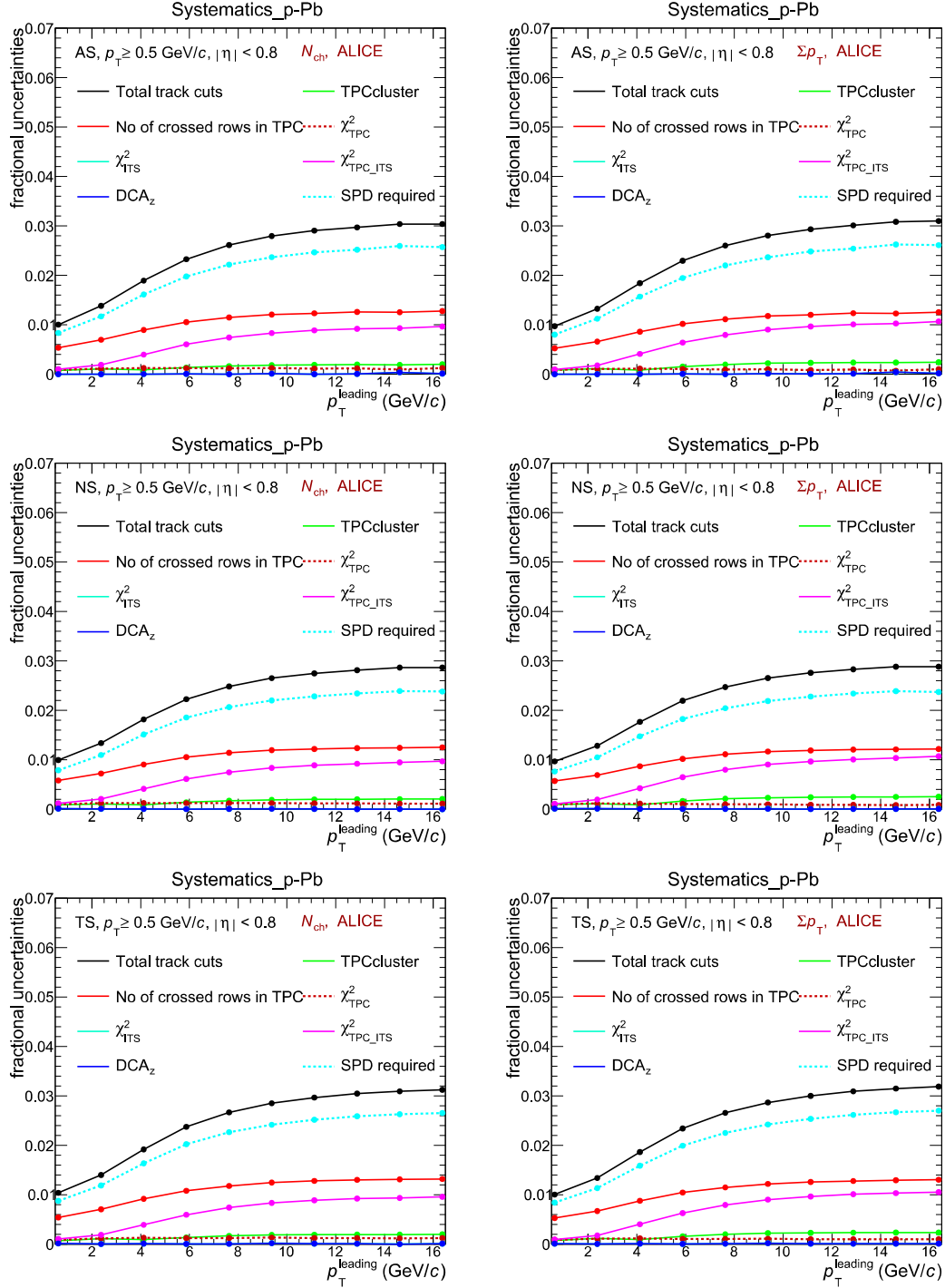


Figure 4.15: Relative systematic uncertainty due to track selection in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results for number density (left panel) and total p_T (right panel) are shown for the three topological regions: away region (top), towards region (middle) and transverse region (bottom).

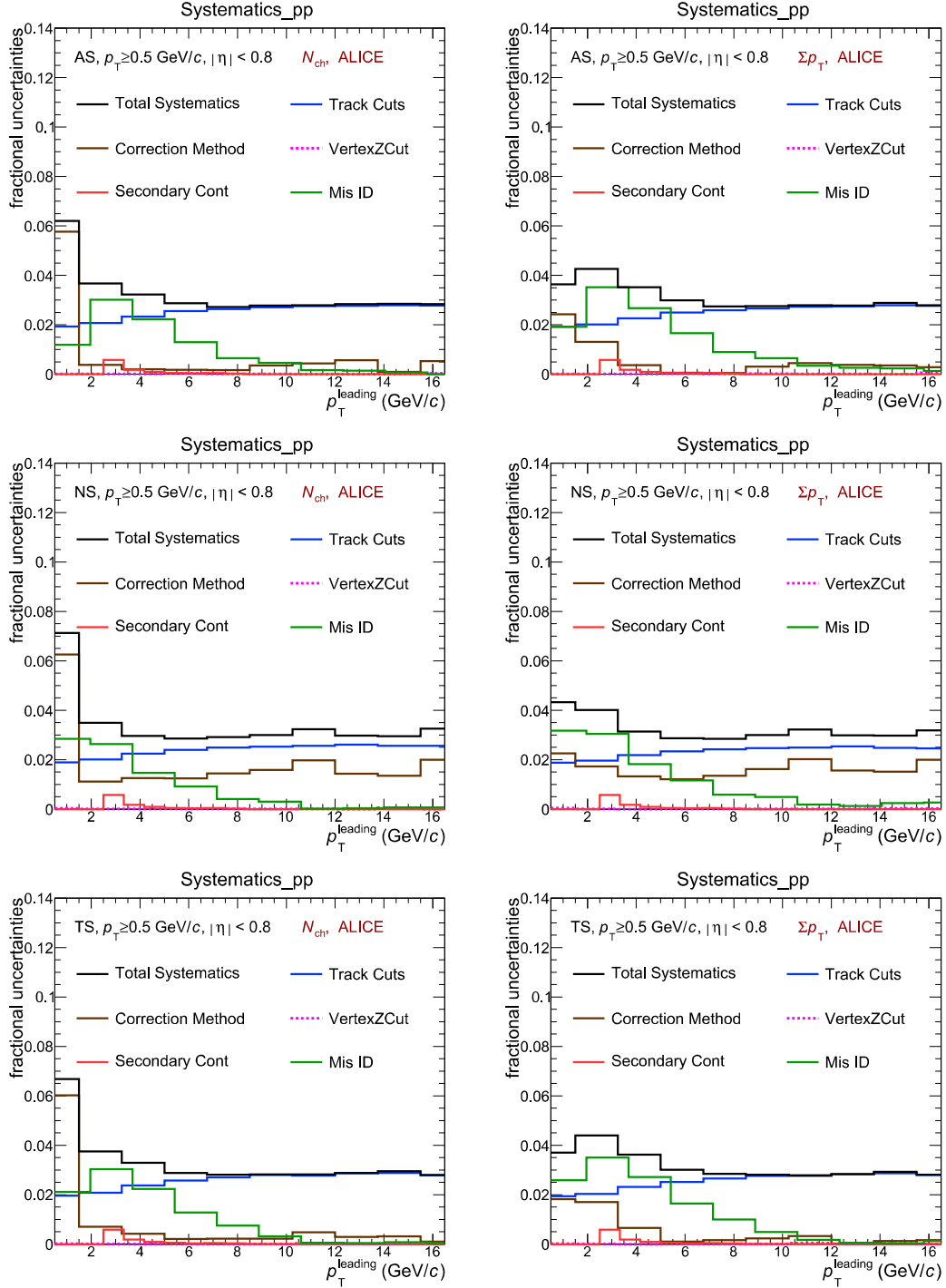


Figure 4.16: Total systematic uncertainty for pp collisions at $\sqrt{s} = 5.02$ TeV. Results for number density (left panel) and total p_T (right panel) are shown for the three topological regions: away region (top), towards region (middle) and transverse region (bottom).

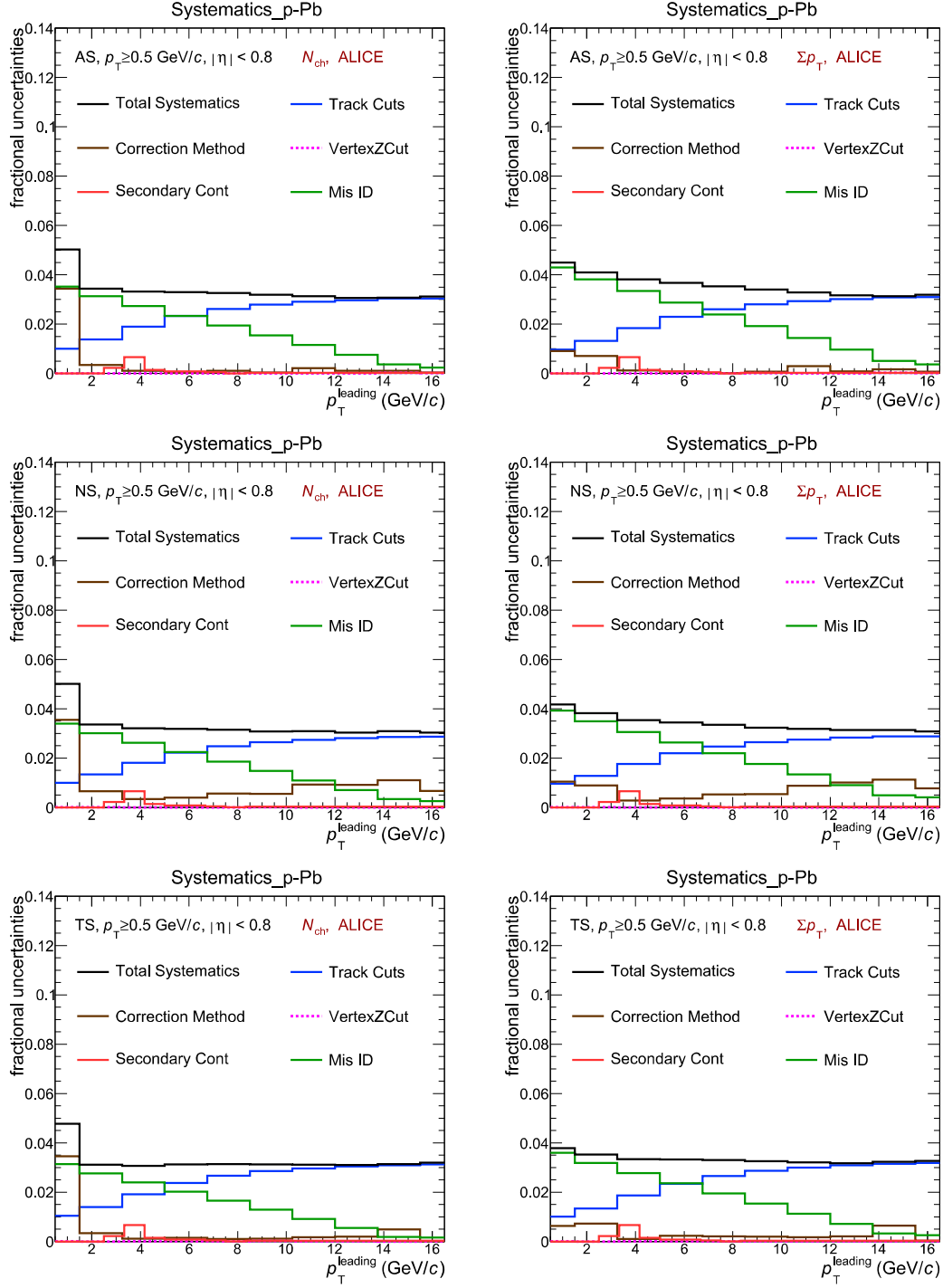


Figure 4.17: Total systematic uncertainty for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results for number density (left panel) and total p_T (right panel) are shown for the three topological regions: away region (top), towards region (middle) and transverse region (bottom).



Chapter 5 Results

5.1 Cross checks

5.1.1 MC closure test

Monte-Carlo closure test is considered to be a milestone to check on the analysis strategy for correction. In this procedure, we divide the MC sample into two halves, take the corrections from one half and apply on the other half. Figures 5.1 and 5.2 show the MC closure test for pp and p-Pb collisions, respectively. The grey band around unity (in the ratio plots) indicates the size of the uncertainty which was assigned.

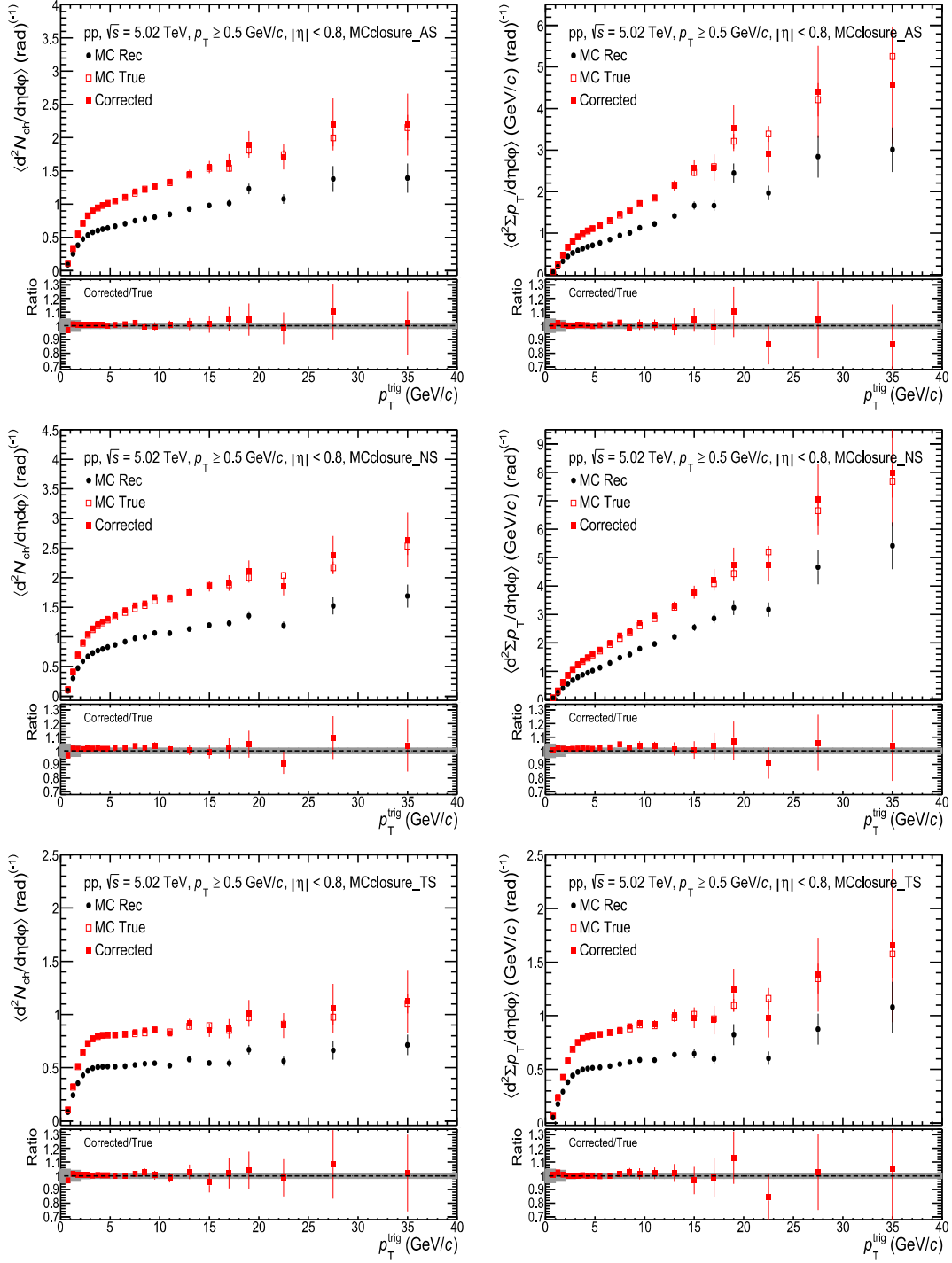


Figure 5.1: Monte Carlo closure test for number density (left) and sum p_T (right) in pp collisions at $\sqrt{s} = 5.02$ TeV. Results for the three topological regions: away region (top), towards region (middle) and transverse region (bottom) are shown.

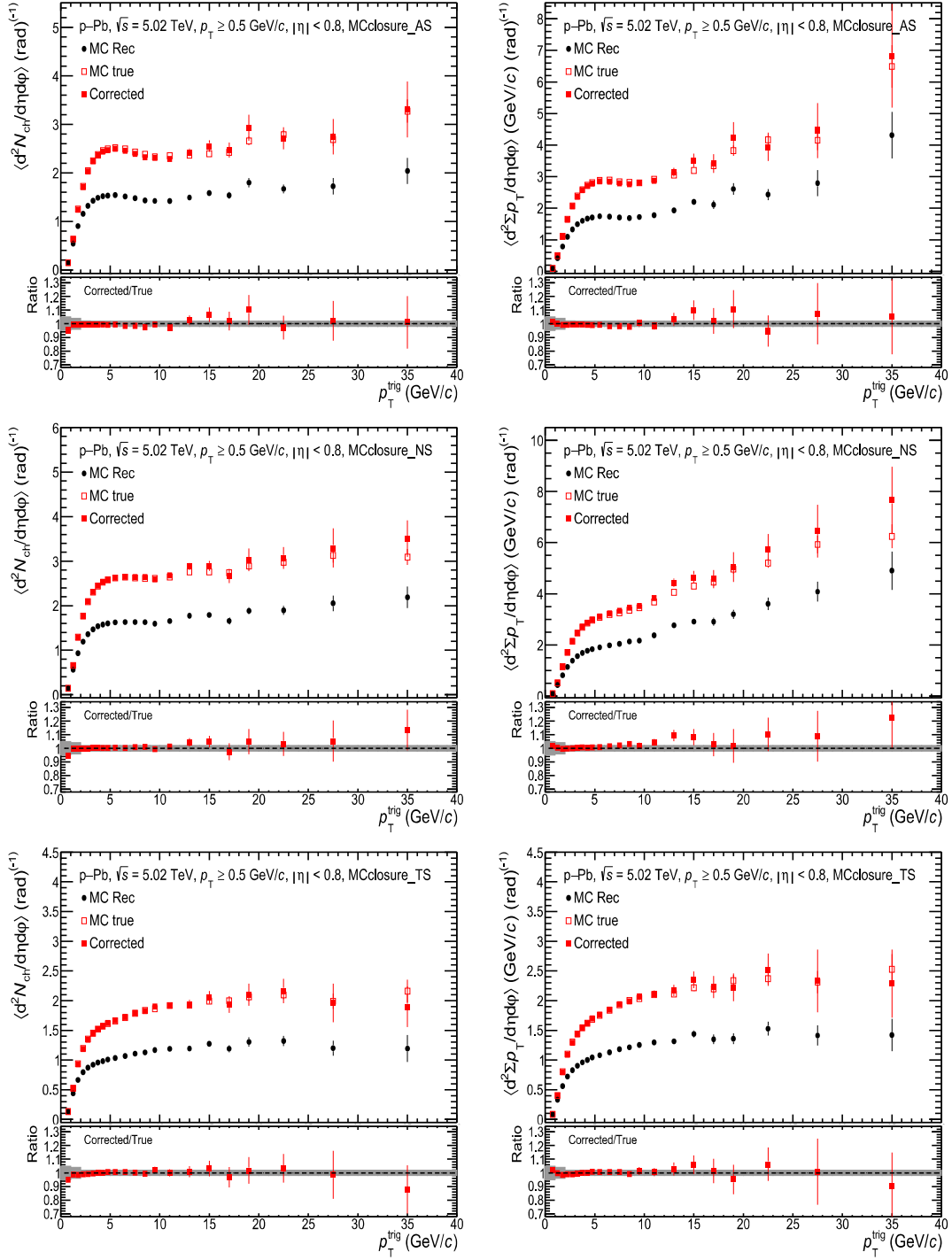


Figure 5.2: Monte Carlo closure test for number density (left) and sum p_T (right) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results for the three topological regions: away region (top), towards region (middle) and transverse region (bottom) are shown.



5.1.2 Comparison with published results

The method adopted in this analysis was also used to reanalyses pp data at 13 TeV [62], and the obtained results are compared with the published results. Figure 5.3 shows such a comparison for number density. The observed differences at low p_T^{leading} are covered by systematic uncertainties.

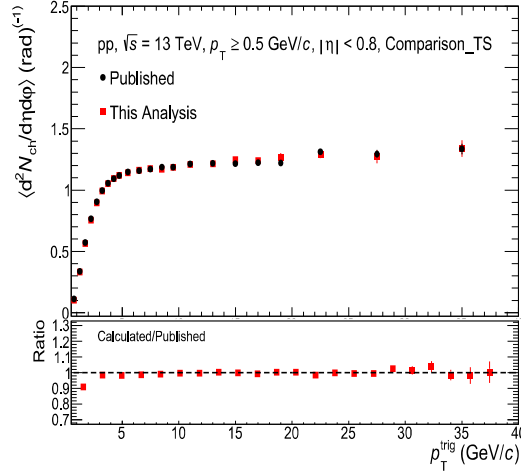


Figure 5.3: The comparison between published results ($p_{(T,\text{min})} \geq 0.5$ GeV/c in pp collisions at $\sqrt{s} = 13$ TeV) and those obtained from this analysis.

5.2 Results and Discussion

5.2.1 Underlying-event observables: pp compared to p–Pb collisions

Figure 5.4 compares the charged-particle number density as a function of p_T^{trig} in the transverse region for the three p_T thresholds: 0.15 GeV/c, 0.5 GeV/c, and 1 GeV/c. The results from pp and p–Pb collisions exhibit similar behaviour: the number density steeply rises for low p_T^{trig} , and it flattens at $p_T^{\text{trig}} \approx 5$ GeV/c (plateau region). In the plateau region, the event activity in p–Pb collisions is ≈ 2 times larger than the one measured in pp collisions. This increase is smaller than that observed (about a factor of 3) for the charged-particle multiplicity densities $dN_{ch}/d\eta$ in non-single-diffractive p–Pb collisions compared to pp collisions at the same nucleon-nucleon centre-of-mass energy [115]. It should also be noted that for both collision systems increasing the p_T threshold from 0.15 GeV/c to 1.0 GeV/c reduces the charged-particle number density by about a factor of 4. For pp collisions, the charged-particle number density

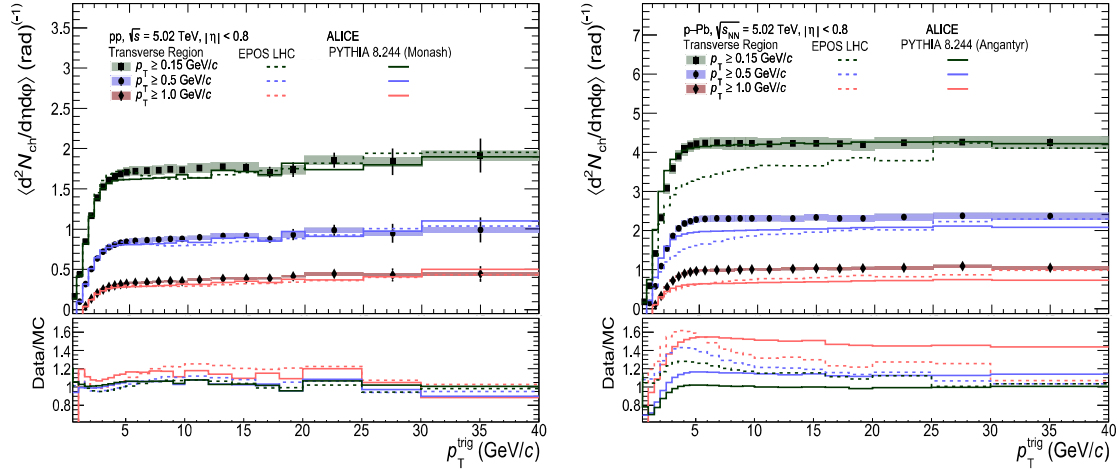


Figure 5.4: Charged-particle number density as a function of p_T^{trig} measured in the transverse region for pp (left) and p-Pb collisions (right) at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Measurements were performed considering three p_T thresholds for associated charged particles: $p_T > 0.15$ GeV/c, $p_T > 0.5$ GeV/c, and $p_T > 1$ GeV/c. Data are compared with PYTHIA 8 and EPOS LHC predictions. The colored boxes and the error bars represent the systematic and statistical uncertainties, respectively.

shows a slightly increasing trend with increasing p_T^{trig} in the plateau region ($p_T^{\text{trig}} > 5$ GeV/c). This increase is more pronounced for larger values of the p_T threshold for associated tracks, indicating an increased contribution of correlated hard processes (initial- and final-state radiation) to the transverse region. For example, for the p_T threshold $p_T > 1$ GeV/c, the charged-particle number density increases from 0.3 to 0.45 (i.e., by about 50%) when p_T^{trig} is increased from 5 to 40 GeV/c. Whereas for the p_T threshold $p_T > 0.15$ GeV/c, the increase is less than 10%. In contrast, for p-Pb collisions the charged-particle number density in the plateau region is flat for all the p_T thresholds. This behaviour also suggests that the contamination from the main partonic scattering in the transverse region is smaller in p-Pb than in pp collisions.

Figure 5.4 also shows the predictions of the event generators. EPOS LHC better describes the p_T^{trig} dependence of the charged-particle multiplicity density for pp collisions relative to p-Pb collisions. However, at $p_T^{\text{trig}} \approx 3$ GeV/c, the EPOS LHC predictions for pp collisions exhibit a bump that is not seen in the data and is not present in the PYTHIA 8/Monash results. For p-Pb collisions, EPOS LHC significantly underestimates the charged-particle number density, and it does not reproduce the trend with p_T^{trig} and the value at the plateau observed in data. In contrast, PYTHIA 8/Angantyr qualitatively reproduces the measured trends with p_T^{trig}

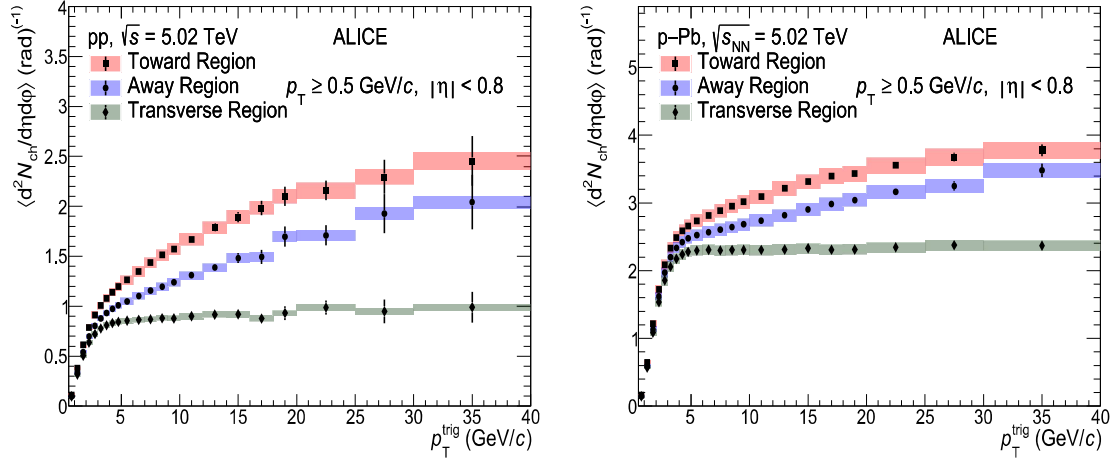


Figure 5.5: Charged-particle number density as a function of p_T^{trig} measured in pp (left) and p-Pb collisions (right) at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Measurements were performed considering associated charged particles with $p_T > 0.5$ GeV/c. Results for the toward, transverse and away regions are displayed. The colored boxes and the error bars represent the systematic and statistical uncertainties, respectively.

in p-Pb collisions, providing a good quantitative description of the data for the lowest p_T threshold ($p_T > 0.15$ GeV/c), while it underestimates the measured densities in the plateau region for higher p_T thresholds. In the following, measurements with the p_T threshold requirement of 0.5 GeV/c for associated particles are reported and discussed. Results for other p_T thresholds ($p_T > 0.15$ GeV/c and > 1.0 GeV/c) are presented in Appendix 6.2

Figure 5.5 shows the charged-particle number density as a function of p_T^{trig} measured in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Results are presented for the toward, transverse, and away regions. The p_T^{trig} dependence in all regions is similar for both collision systems. For $p_T^{\text{trig}} \gtrsim 5$ GeV/c the charged-particle number density becomes almost independent of p_T^{trig} (plateau) in the transverse region, as already pointed out above, while in the toward and away regions it continues to rise with increasing p_T^{trig} . The continuous rise observed for the toward and away regions can be attributed to the fact that produced particles in these regions do not originate only from the UE, but have also a contribution due to fragments from hard scatterings, which are mainly collimated in azimuth. The contribution from fragments increases with p_T^{trig} causing the rise of event activity. A qualitatively similar behaviour in pp and p-Pb collisions is observed. However, the event activity in the toward and away regions in pp collisions increases faster with p_T^{trig} than in p-Pb collisions, namely, the increase of



the particle density from $p_T^{\text{trig}} = 5 \text{ GeV}/c$ up to $p_T^{\text{trig}} = 40 \text{ GeV}/c$ amounts to a factor of ≈ 2 and ≈ 1.4 in pp and p-Pb collisions, respectively. Moreover, at $p_T^{\text{trig}} = 35 \text{ GeV}/c$ the relative level of the event activity in the transverse region with respect to that in the toward (away) region is ≈ 0.4 and ≈ 0.60 (≈ 0.5 and ≈ 0.65) for pp and p-Pb collisions, respectively. This indicates that the UE contribution to the toward and away regions is larger in p-Pb than in pp collisions, which is expected because of multiple nucleon-nucleon collisions in a single p-Pb collision that give a large additional UE, with respect to MPI in the same pp collision.

Figure 5.6 shows comparisons between the data from pp collisions and the predictions of event generators for both the primary charged-particle number, and the summed- p_T densities in the three considered azimuthal regions (toward, away, and transverse). Although the modelling of the UE activity in PYTHIA 8/Monash is completely different with respect to that implemented in EPOS LHC, both models qualitatively describe the measured charged-particle densities in the three azimuthal regions. In the away region, within uncertainties, PYTHIA 8/Monash describes the data better than EPOS LHC in the full p_T^{trig} range of the measurement. The maximum deviation of EPOS LHC with respect to data is around 10% and 20% for the number density and summed- p_T density, respectively, in the p_T^{trig} interval 5–15 GeV/c. Regarding the toward region, PYTHIA 8/Monash predictions overestimate the event activity by 10% for $p_T^{\text{trig}} < 5 \text{ GeV}/c$, whereas for higher p_T^{trig} PYTHIA 8/Monash describes the data quite well. The situation is the opposite for EPOS LHC: at low p_T^{trig} EPOS LHC describes well the event activity, but it significantly underestimates the particle densities for higher p_T^{trig} ($> 8 \text{ GeV}/c$) by $\approx 30\%$.

Figure 5.7 shows data-to-model comparisons for the case of p-Pb collisions. For the transverse region, as already pointed out above, PYTHIA 8/Angantyr provides a better qualitative description of the measured trend of the charged-particle number densities as compared to EPOS LHC. However, both PYTHIA 8/Angantyr and EPOS LHC underestimate the charged-particle summed- p_T (number) density for $p_T^{\text{trig}} > 5 \text{ GeV}/c$ by more than 20% (10%). While for PYTHIA 8/Angantyr this discrepancy stays roughly constant up to $p_T \approx 3 \text{ GeV}/c$, for EPOS LHC the discrepancy increases up to 50% at $p_T \approx 3 \text{ GeV}/c$. For the toward and away regions, as visible from the ratio plots in the bottom panels of Fig. 5.7, PYTHIA 8/Angantyr does not describe the trend with p_T^{trig} of both the event-activity variables, in particular in the



range $1 < p_T^{\text{trig}} < 5 \text{ GeV}/c$, where the event activity increases more steeply in the data than in the PYTHIA 8/Angantyr predictions. At higher p_T^{trig} ($5 < p_T^{\text{trig}} < 10 \text{ GeV}/c$) the ratio between the data and PYTHIA 8/Angantyr flattens, however a discrepancy by about 10% (30%) between the data and the model predictions is observed for the charged-particle number (summed- p_T) densities. The description of the data by EPOS LHC is slightly better than that of PYTHIA 8/Angantyr for $p_T^{\text{trig}} < 8 \text{ GeV}/c$. However, in that p_T^{trig} interval EPOS LHC predicts bump structures in the toward and away regions which are not seen in data. For higher p_T^{trig} EPOS LHC overestimates the event activity. The inclusion of these data in future MC tunings would be relevant to improve the modelling of the UE in p-Pb collisions.

5.2.2 Event activity in the jet-like regions

Figure 5.8 shows the jet-like contribution to the charged-particle number and summed- p_T densities in the toward and away regions as a function of p_T^{trig} for pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. As discussed earlier, the event activity for the jet-like signals is obtained from the event activity in the toward and away regions after subtracting the event activity in the transverse region (see Eq. 4.3 and Eq. 4.4). In contrast to the behaviour observed for the toward and away regions, where at $p_T^{\text{trig}} \approx 5 \text{ GeV}/c$ the event activity tends to flatten out, the densities in the jet-like signals rise with increasing p_T^{trig} in the entire range of the measurement.

At high p_T^{trig} ($p_T^{\text{trig}} > 10 \text{ GeV}/c$), the event activity in the jet-like signals exhibits a remarkable similarity between measurements in pp and p-Pb collisions for both charged-particle multiplicity and summed- p_T densities. Within 10%, this feature is reproduced by both PYTHIA 8/Angantyr and EPOS LHC. At low p_T^{trig} ($p_T^{\text{trig}} < 10 \text{ GeV}/c$), the models overestimate the event activity in the jet-like signals measured in p-Pb collisions. The disagreement is more remarkable for EPOS LHC than for PYTHIA 8/Angantyr. For pp collisions, PYTHIA 8 slightly overestimates the event activity, while EPOS LHC underestimates the particle densities. For $p_T^{\text{trig}} < 10 \text{ GeV}/c$, the event activity in pp collisions scaled to that in p-Pb collisions is smaller than unity, reaching a minimum of ≈ 0.8 at $p_T^{\text{trig}} \approx 3 \text{ GeV}/c$. This behaviour is not reproduced by PYTHIA 8/Angantyr, which gives a ratio above unity for $p_T^{\text{trig}} > 1 \text{ GeV}/c$. In contrast, EPOS LHC exhibits a similar pattern, but the size of the effect is



much larger than in data. The main difference between PYTHIA 8/Angantyr and EPOS LHC is that EPOS LHC incorporates collective flow, which is expected to be significant in the p_T^{trig} interval where we observe the differences between measurements in pp and p-Pb collisions. Given that (radial and elliptic) flow is larger in p-Pb than in pp [25, 116], its contribution to the toward and away regions is expected to be higher in p-Pb than in pp collisions. In particular, the elliptic azimuthal correlations modulate the background according to: $B(\Delta\varphi) = B_0(1 + 2V_2 \cos(2\Delta\varphi))$, where $V_2 \approx v_2^{\text{trig}} v_2^{\text{assoc}}$ is approximately given by the product of anisotropic flow coefficients for trigger and associated particles at their respective momenta [117]. From Pb-Pb results we expect the effect to be the largest at intermediate transverse momenta and decreases for high transverse momentum particles [118].

Finally, the average transverse momentum of particles in the toward and away regions after subtracting the UE contribution estimated from the transverse region are shown in Fig. 5.9 as a function of p_T^{trig} for pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Within uncertainties, the average p_T values are consistent in pp and p-Pb collisions in the measured p_T^{trig} interval. The PYTHIA 8 tunes considered in this paper do not reproduce this behaviour. They predict that in the away region the average p_T for the jet-like signal in pp collisions is about 20% (10%) larger than in p-Pb collisions for $p_T^{\text{trig}} < 2$ GeV/c ($p_T^{\text{trig}} > 5$ GeV/c). For the toward region, the situation is similar at high p_T^{trig} ; however, for $p_T^{\text{trig}} < 2$ GeV/c, the average p_T in p-Pb collisions is about 20% larger than in pp collisions. Although the main source of this discrepancy is the underestimation of the average p_T in p-Pb collisions by PYTHIA 8/Angantyr, the prediction for pp collisions is lower than the measured average p_T in the away region. The agreement of PYTHIA 8/Monash with pp data is better for the toward region. On the other hand, EPOS LHC reproduces the average p_T for the two collision systems better than PYTHIA 8/Angantyr. Although, for $p_T^{\text{trig}} < 10$ GeV/c, EPOS LHC predicts the average p_T in the toward region to be larger in pp as compared to p-Pb collisions, leading to a bump-like structure in the ratio of pp over p-Pb results, which is not observed in the data.



5.2.3 Energy dependence of the underlying event in pp collisions

This subsection discusses the collision-energy dependence of the charged-particle number density in the transverse region. Given that data from experiments at RHIC, the Tevatron and the LHC, are available for the p_T threshold, $p_T > 0.5 \text{ GeV}/c$, our results for that p_T threshold are compared with existing measurements at other centre-of-mass energies. Figure 5.10 (left) compares the UE activity obtained in pp collisions at $\sqrt{s} = 5.02 \text{ TeV}$ to those obtained at other LHC energies, namely $\sqrt{s} = 0.9, 7$, and 13 TeV [61, 62]. Between the two higher energies, $\sqrt{s} = 7$ and 13 TeV , the number density in the plateau increases by about 30%. A similar increase was reported considering associated particles with $p_T > 0.15 \text{ GeV}/c$ [62]. More information about the $\sqrt{s}$ -dependence in the transverse region can be obtained by comparing the shapes of the number density as a function of p_T^{trig} . One attempt using the data provided by the ATLAS collaboration has been reported in Ref. [119]; a similar comparison was performed by the ALICE collaboration [62].

Following the approach presented in Ref. [62], the height of the plateau for different collision energies is quantified by fitting a constant function in the range $5 < p_T^{\text{trig}} < 10 \text{ GeV}/c$ (the fit functions are also shown in the left panel of Fig. 5.10). The fitting range was restricted to that common range in order to be consistent with the procedure used for the measurements at other centre-of-mass energies. Larger fitting ranges were also considered, and consistent results were obtained. The shapes of the particle densities as a function of p_T^{trig} are then compared after dividing the densities by the level of the plateau, as estimated from the fit to a constant value. The results are shown in Fig. 5.10 (right). The coverage extends beyond the fitting range for the two higher energies, i.e. to $p_T^{\text{trig}} > 10 \text{ GeV}/c$. In this range, the densities agree within the statistical and systematic uncertainties. In the rise region ($p_T^{\text{trig}} < 5 \text{ GeV}/c$), one observes a clear ordering among the four collision energies, the lowest energy having the highest density relative to the plateau. Moreover, at lower $\sqrt{s}$, the plateau values seem to be reached at a slightly lower p_T^{trig} . This feature is also observed in pp collisions simulated with PYTHIA 8 event generator [119].

Figure 5.11 shows the $\sqrt{s}$ dependence of the charged-particle number density measured in the transverse azimuthal interval and in the high p_T^{trig} interval of the plateau region. Results from various experiments at RHIC [50], the Tevatron [20, 54, 121],



1549 and the LHC [53, 56, 60, 62, 103] are displayed. The ATLAS, CDF, CMS, and STAR
1550 data points are taken from the compilation reported by the STAR collaboration [50].
1551 The event activity shows a modest increase from $\sqrt{s} = 0.2$ up to 0.9 TeV, for higher
1552 energies it exhibits a steeper rise. This behaviour is described by a function of the
1553 form $\propto s^{0.27} + 0.14 \log(s)$, in which the power-law term describes the UE contribu-
1554 tion, whereas the logarithmic term describes the contribution from ISR and FSR.
1555 The parametrisation was taken from Ref. [120]. A comparison to the charged par-
1556 ticle multiplicity at mid-pseudorapidity in minimum-bias pp data, where $dN_{\text{ch}}/d\eta$
1557 can be parameterised as $dN_{\text{ch}}/d\eta \propto s^{0.114}$ [121], suggests that the UE contribution
1558 increases faster with centre-of-mass energy than the charged particle multiplicity in
1559 minimum-bias pp collisions.

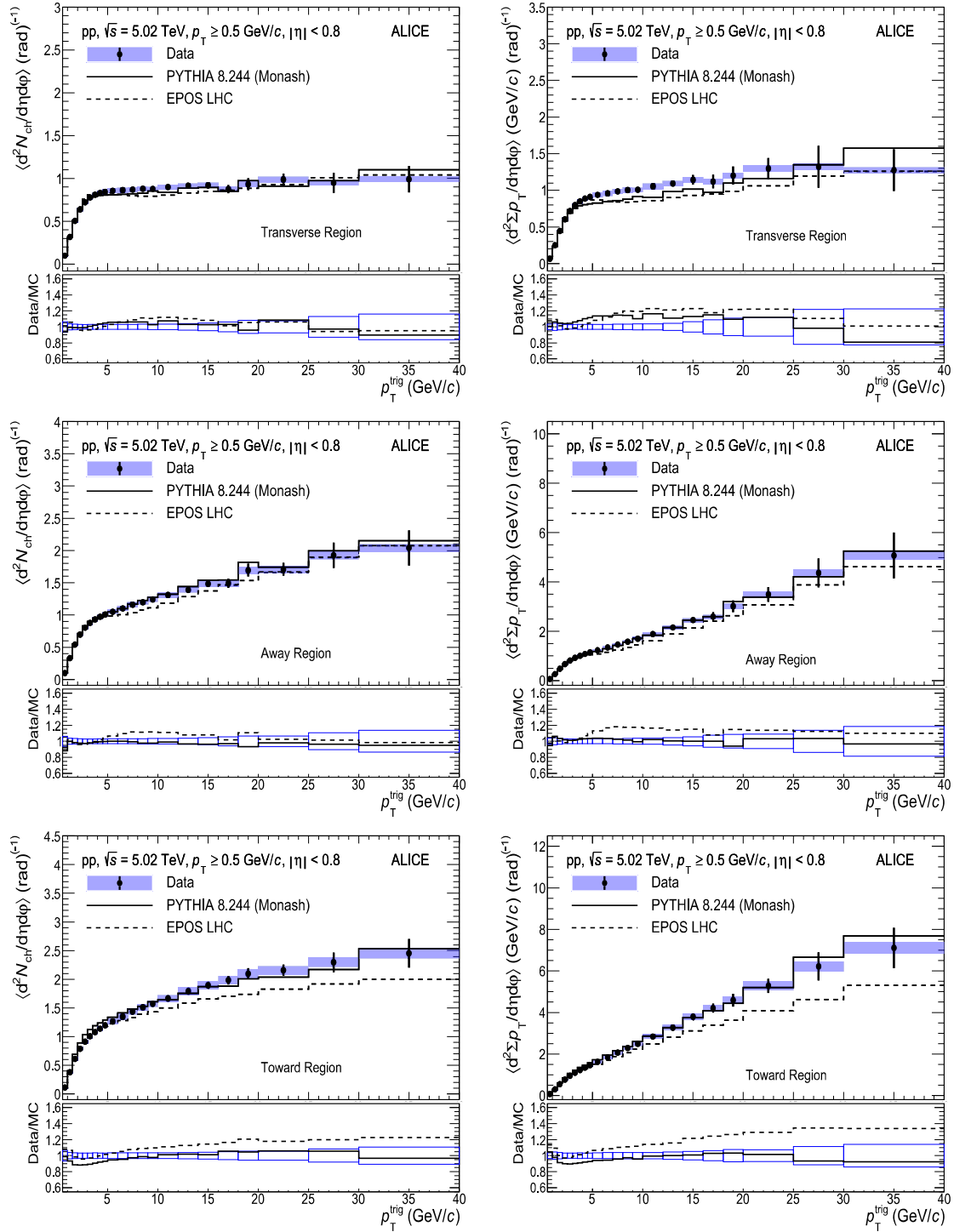


Figure 5.6: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in pp collisions at $\sqrt{s} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 0.5 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Monash (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

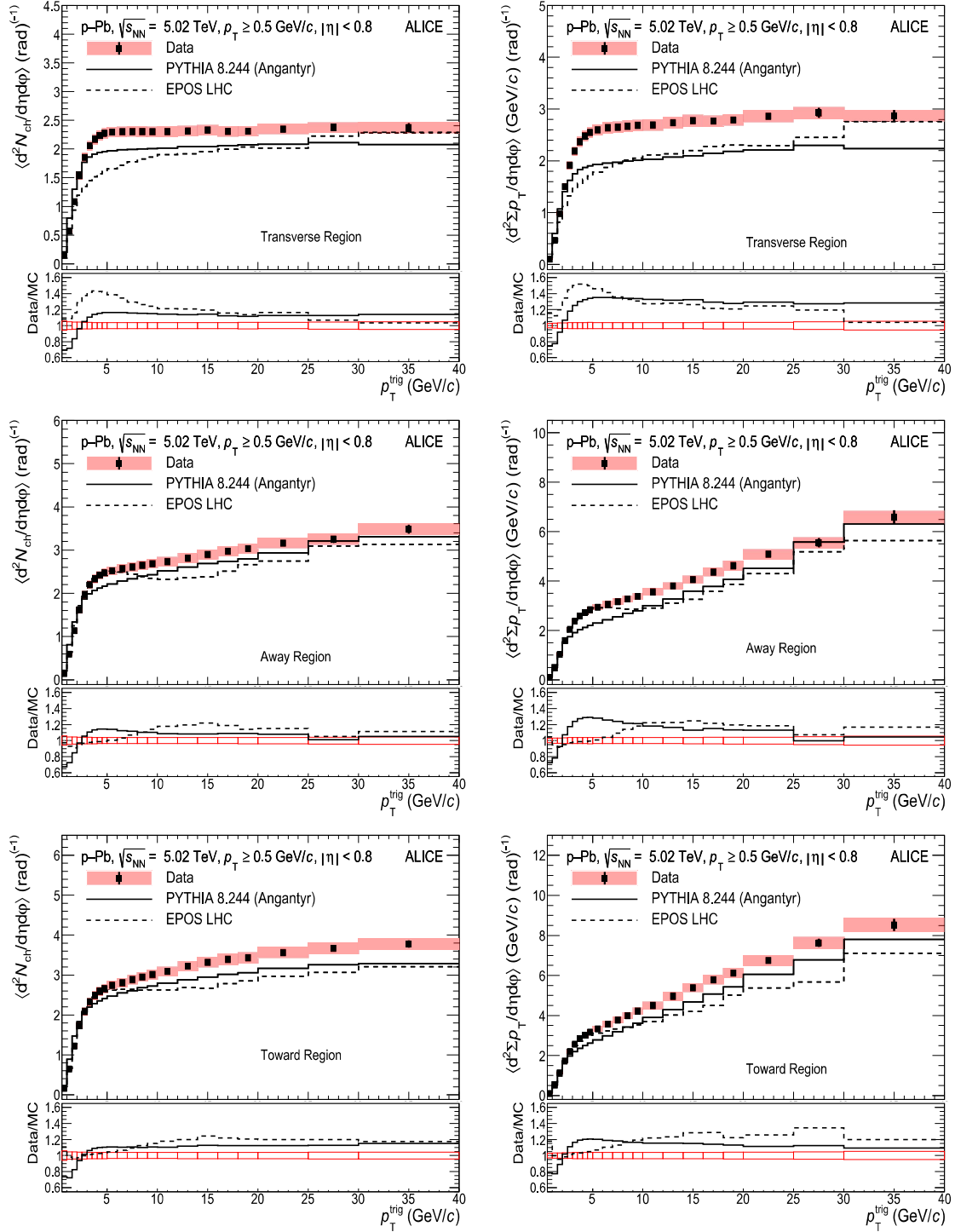


Figure 5.7: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 0.5 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Angantyr (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

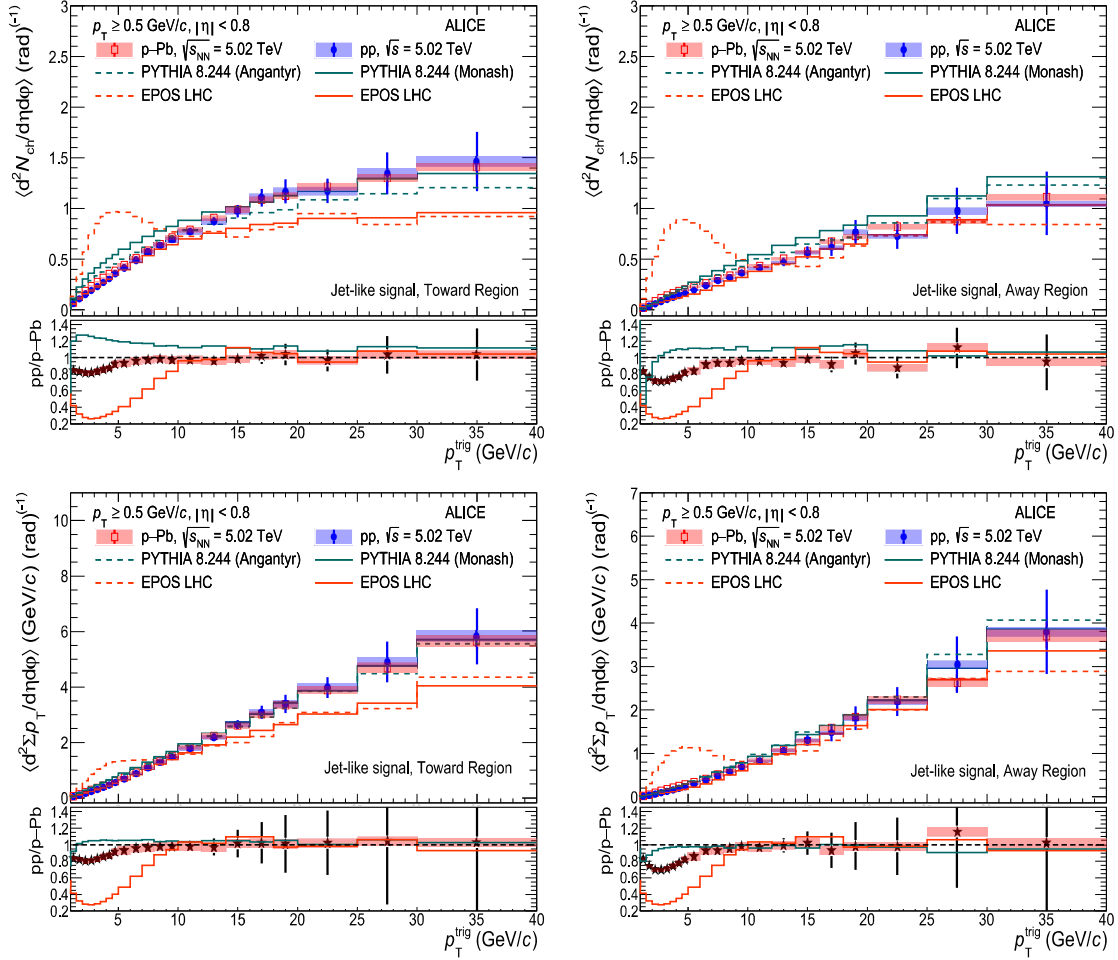


Figure 5.8: Upper panels: charged-particle number (top) and summed- p_T (bottom) densities as a function of p_T^{trig} in pp (blue) and p-Pb (red) collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Results for the toward (left) and away (right) regions, after the subtraction of the number density in the transverse region, are shown. Lower panels: charged-particle densities measured in pp collisions normalized to those in p-Pb collisions. Data are compared with PYTHIA 8 (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

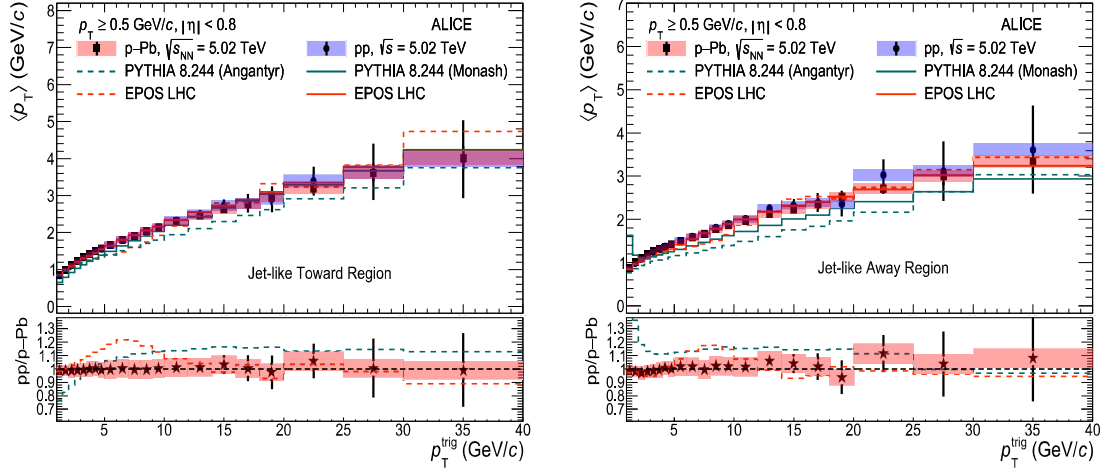


Figure 5.9: Upper: average transverse momentum as a function of p_T^{trig} in the jet-like toward (left) and away (right) regions measured in pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Details about the jet-like signal isolation can be found in the text. Bottom: average transverse momentum measured in pp collisions normalized to that measured in p-Pb collisions. Data are compared with PYTHIA 8 (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

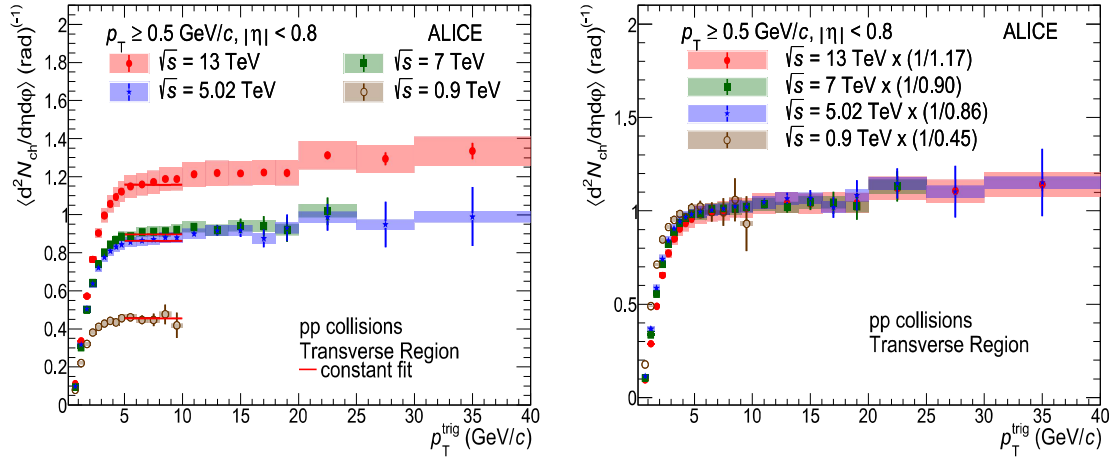


Figure 5.10: Left: charged particle number density in the transverse region as a function of p_T^{trig} for pp collisions at $\sqrt{s} = 0.9, 5.02, 7$, and 13 TeV. A constant function (solid lines) is used to fit the data in the range $5 < p_T^{\text{trig}} < 10$ GeV/c. Right: number densities scaled by the pedestal values obtained from the fit in order to compare the shapes. The colored boxes represent the systematic uncertainties and vertical error bars indicate statistical uncertainties.

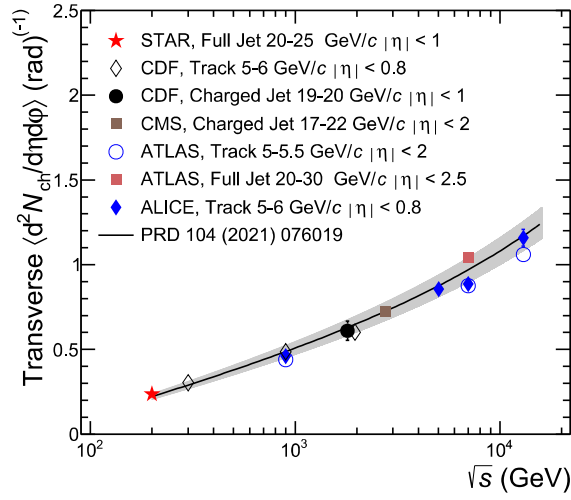


Figure 5.11: Center-of-mass energy dependence of the number density in the plateau region, results from various experiments at RHIC [50], Tevatron [20, 54, 121] and LHC [53, 56, 60, 62, 103] are displayed. Except for the ALICE data point for pp collisions at $\sqrt{s} = 5.02$ TeV, all the values were taken from the compilation reported by the STAR collaboration [50]. Error bars represent statistical and systematic uncertainties summed in quadrature. The data for the transverse region are compared with a parametrization of the form $s^\alpha + \beta \log(s)$, where the first term describes the MPI-sensitive region and the second one describes that more sensitive to ISR and FSR [120].



Chapter 6 Conclusions and prospects

6.1 Conclusions

In this present work, the measurements of underlying-event observables performed in pp and p-Pb collisions at a centre-of-mass energy per nucleon-nucleon collisions of 5.02 TeV were reported. The analysis was carried out following the strategy introduced by the CDF collaboration consisting of the definition of three azimuthal regions relative to the highest transverse momentum particle in the collision (p_T^{trig}). The charged-particle production is measured within the pseudorapidity interval $|\eta| < 0.8$; and it is quantified with the number and summed- p_T densities considering particles above a given p_T threshold. Three p_T thresholds are considered: 0.15, 0.5, and 1 GeV/ c . These quantities are reported as a function of p_T^{trig} , and for the toward, away, and transverse azimuthal regions. The transverse region is the most sensitive to the underlying event; while the toward and away regions include both the UE and jet fragments from the main partonic scattering. For the isolation of the jet-like signal, the event activity in the transverse region is subtracted from those measured in the toward and away regions. Results for pp collisions are compared with data at other centre-of-mass energies and with MC predictions. In addition, the event activities measured in pp and p-Pb collisions are compared with each other at the same p_T^{trig} value. The main conclusions of the present work are listed below.

- The underlying-event observables in pp collisions follow the same behaviour as observed at lower centre-of-mass energies. In the transverse region the charged-particle densities measured in the three azimuthal regions exhibit a fast rise for $p_T^{\text{trig}} < 5$ GeV/ c followed by a flattening at higher p_T^{trig} (plateau). Data for the three azimuthal regions relative to the leading particle are reproduced by the PYTHIA 8 event generator with the Monash tune. EPOS LHC predicts a slightly different behaviour in particular at p_T^{trig} around 3 GeV/ c where a bump structure is observed in the three azimuthal regions which is not observed in the data.
- The underlying-event observables in p-Pb collisions qualitatively behave like in pp interactions. The particle densities in the transverse region exhibit a saturation at $p_T^{\text{trig}} \approx 5$ GeV/ c . PYTHIA 8/Angantyr qualitatively reproduces this sat-



uration but underestimates the particle densities. The EPOS LHC model does not describe the saturation and underestimates the event activity within the measured p_T^{trig} interval. For the toward and away regions, above the onset of the plateau, data exhibit a slower increase of the particle densities with increasing p_T^{trig} than that observed in pp collisions. EPOS LHC and PYTHIA 8/Angantyr underestimate the particle densities at high p_T^{trig} ($> 8 \text{ GeV}/c$). At lower p_T^{trig} , EPOS LHC predicts a bump structure at $p_T^{\text{trig}} \approx 4 \text{ GeV}/c$ which is not seen in data. For $p_T^{\text{trig}} < 3 \text{ GeV}/c$, EPOS LHC describes the particle densities, whereas PYTHIA 8/Angantyr overestimates those in data by up to 30%.

- The particle densities in the toward and away region after subtraction of the UE contribution as a function of p_T^{trig} in pp collisions are consistent with those measured in p–Pb collisions for $p_T^{\text{trig}} > 10 \text{ GeV}/c$, i.e., no modification of the jet-like yield in p–Pb collisions relative to pp collisions is found. At lower p_T^{trig} , the charged-particle densities are larger in p–Pb collisions relative to pp collisions. This behaviour is expected given the larger collective flow effects in p–Pb collisions relative to pp collisions. This feature is qualitatively captured by the EPOS LHC generator, which incorporates collective flow effects in the modelling of the system created in the collision. However, the size of the effect is significantly larger in EPOS LHC than in data. An opposite trend is instead predicted by simulations with PYTHIA 8/Angantyr, which do not include collective effects. The average p_T as a function of p_T^{trig} was also measured. The average p_T values measured in pp and p–Pb collision are found to be consistent between each other in the entire p_T^{trig} interval of the measurement. Simulations with EPOS LHC predict instead a slightly lower average p_T for jet-like signal in p–Pb collisions as compared to pp collisions for $p_T^{\text{trig}} < 10 \text{ GeV}/c$, while PYTHIA 8 with the Monash and Angantyr tunes do not provide a good description for this observable.

The measurements reported in this article represent important input for the tuning of some of the parameters of the event generators in order to improve the modelling of soft particle production in pp and p–Pb collisions. Moreover, they can contribute to the understanding of the origin of collectivity in pp and p–Pb collisions.



6.2 Prospects

The data presented in this thesis can be useful to constrain the Monte Carlo model parameters in order to improve the modeling of the soft particle production in pp and p-Pb collisions. A cross check was performed for different multiplicity classes obtained using EPOS LHC as a generator of p-Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results show multiplicity dependent of EPOS LHC at different multiplicity classes with different multiplicity estimator i.e. VOA. Figure 6.1 shows the number density study as a function of $p_{\text{T}}^{\text{leading}}$ in three different topological regions for $p_{(\text{T},\text{min})} \geq 0.5 \text{ GeV}/c$.

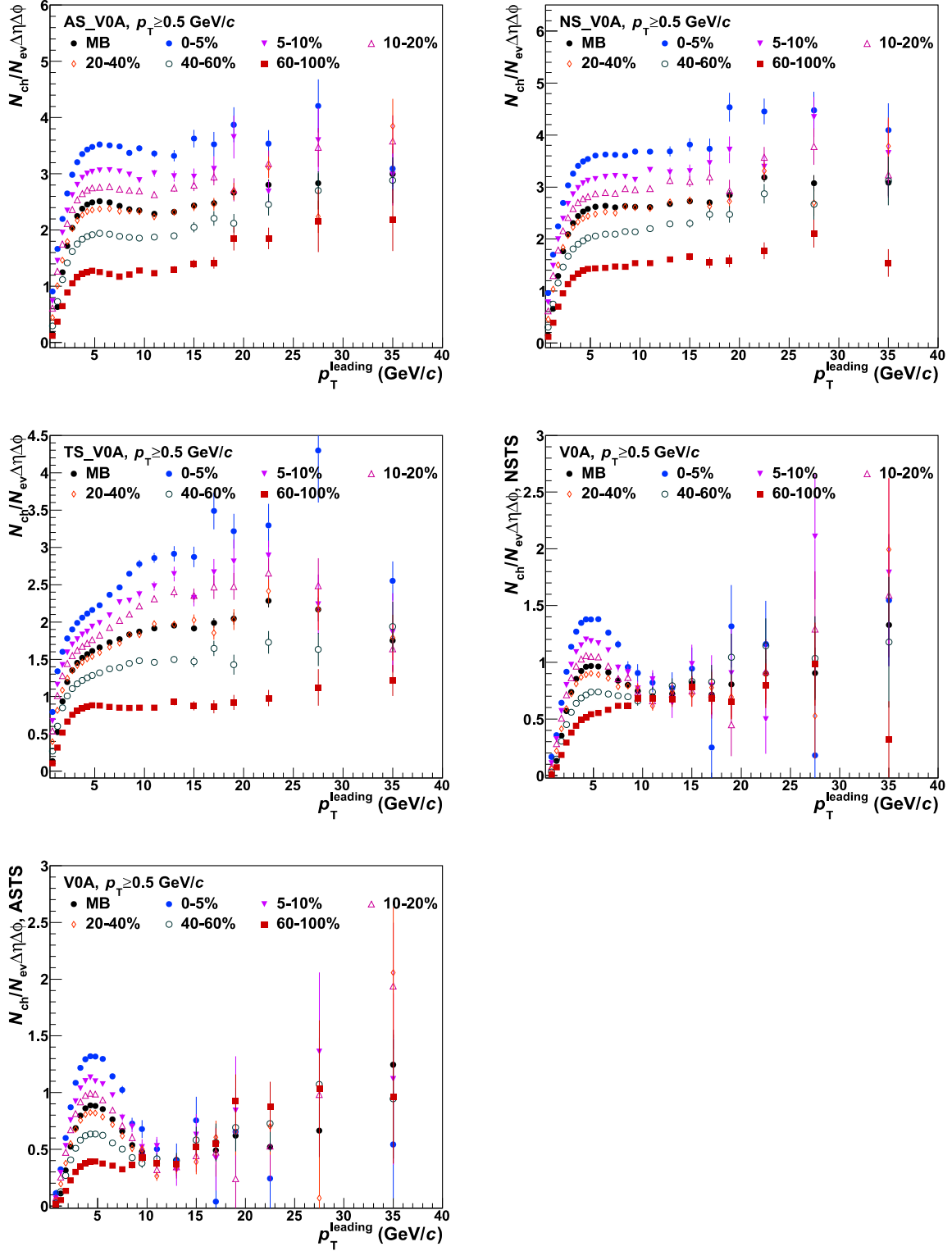


Figure 6.1: The different multiplicity classes by using V0A multiplicity estimator for three different topological regions with $p_{\text{T}(\text{min})} \geq 0.5$ GeV/c in p-Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and jet like region (NS-TS and AS-TS) for the same multiplicity classes.



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List of Publications

1923

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1926

1. “Underlying Event studies and search for jet-like modifications in pp and p-Pb collisions with ALICE at the LHC”, [on behalf of the ALICE collaboration], <https://pos.sissa.it/398/344/>., Published :PoS.

1927

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2. “Underlying-event properties in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with ALICE”, [ALICE collaboration].<https://inspirehep.net/literature/2071174>. JHEP.

1930

1931

3. “A Comprehensive study of energy dependence of particle ratios in pp collisions from SPS to LHC energies”. Published EPJP.

1932

1933

4. “Study of Baryon number transport using model simulations in pp collisions at LHC energies”. Under peer reviewed.

1934

1935

5. Along with this i have 158 papers published in ALICE collaboration with other ALICE members. Among them 2 papers are published in nature physics.



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Ahsan Mehmood Khan



Appendix A

1980

1981 Leading Track Misidentification

For pp collisions at $\sqrt{s} = 5.02$ TeV.

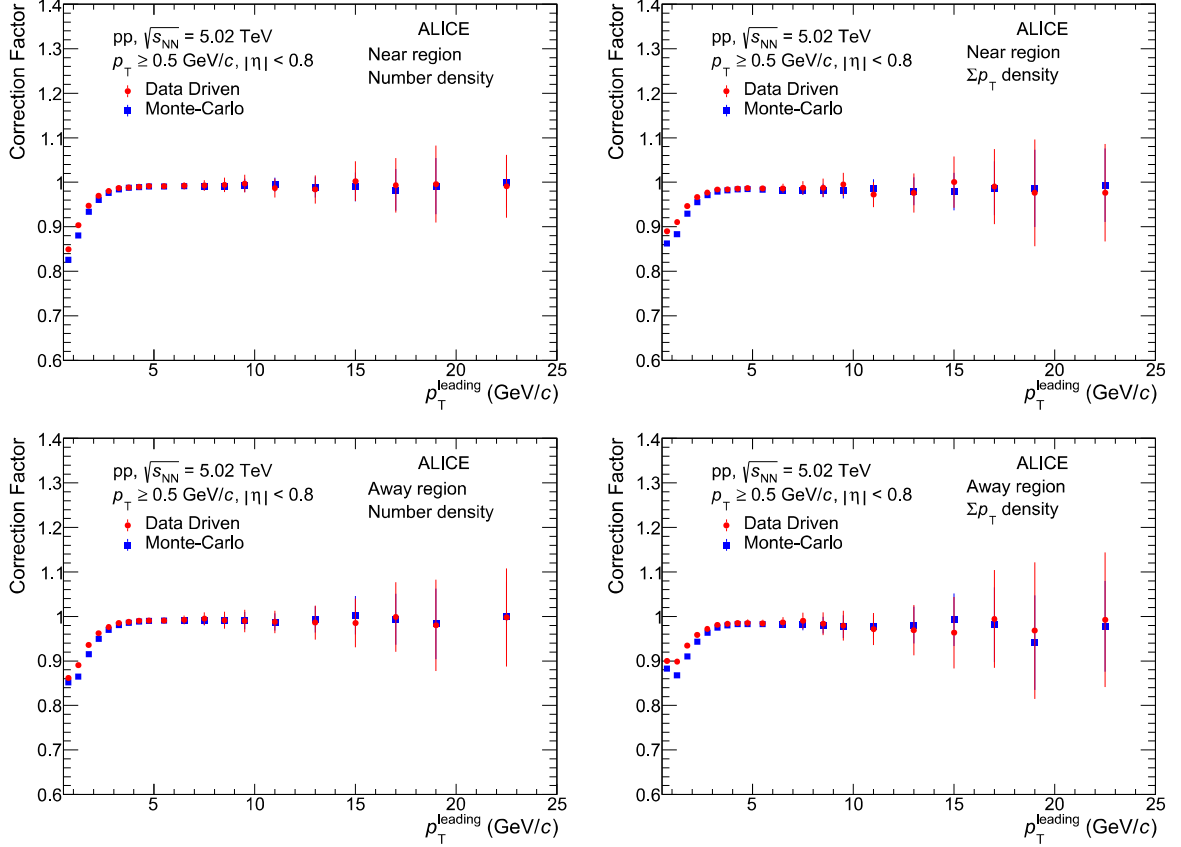


Figure .2: Leading-track misidentification bias for number density (left) and $\sum p_T$ density (right) in toward (upper panel) and away (bottom panel) regions, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure for pp collisions at $\sqrt{s} = 5.02$ TeV are shown.

1982



For p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

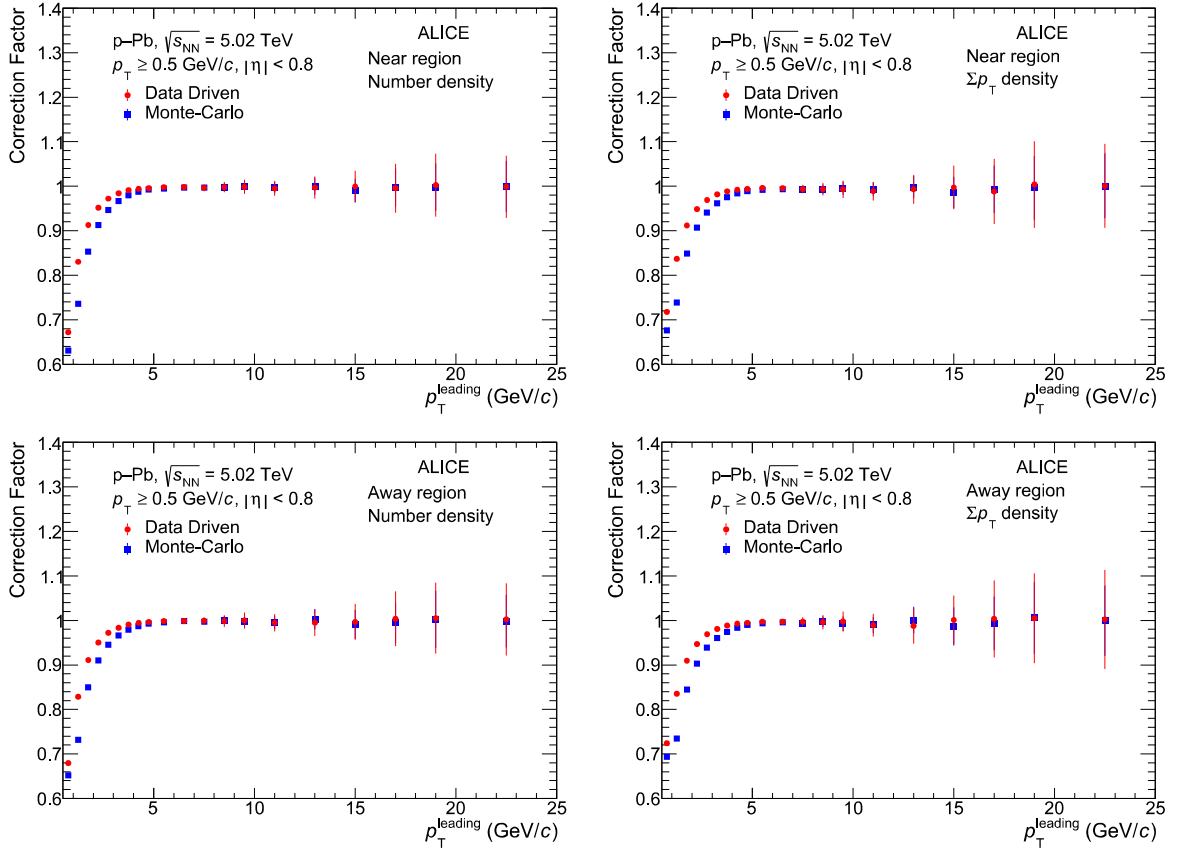


Figure .3: Leading-track misidentification bias for number density (left) and $\sum p_T$ density (right) in toward (upper panel) and away (bottom panel) regions, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown.



Appendix B

1984

1985 Track Contamination

For pp collisions at $\sqrt{s} = 5.02$ TeV.

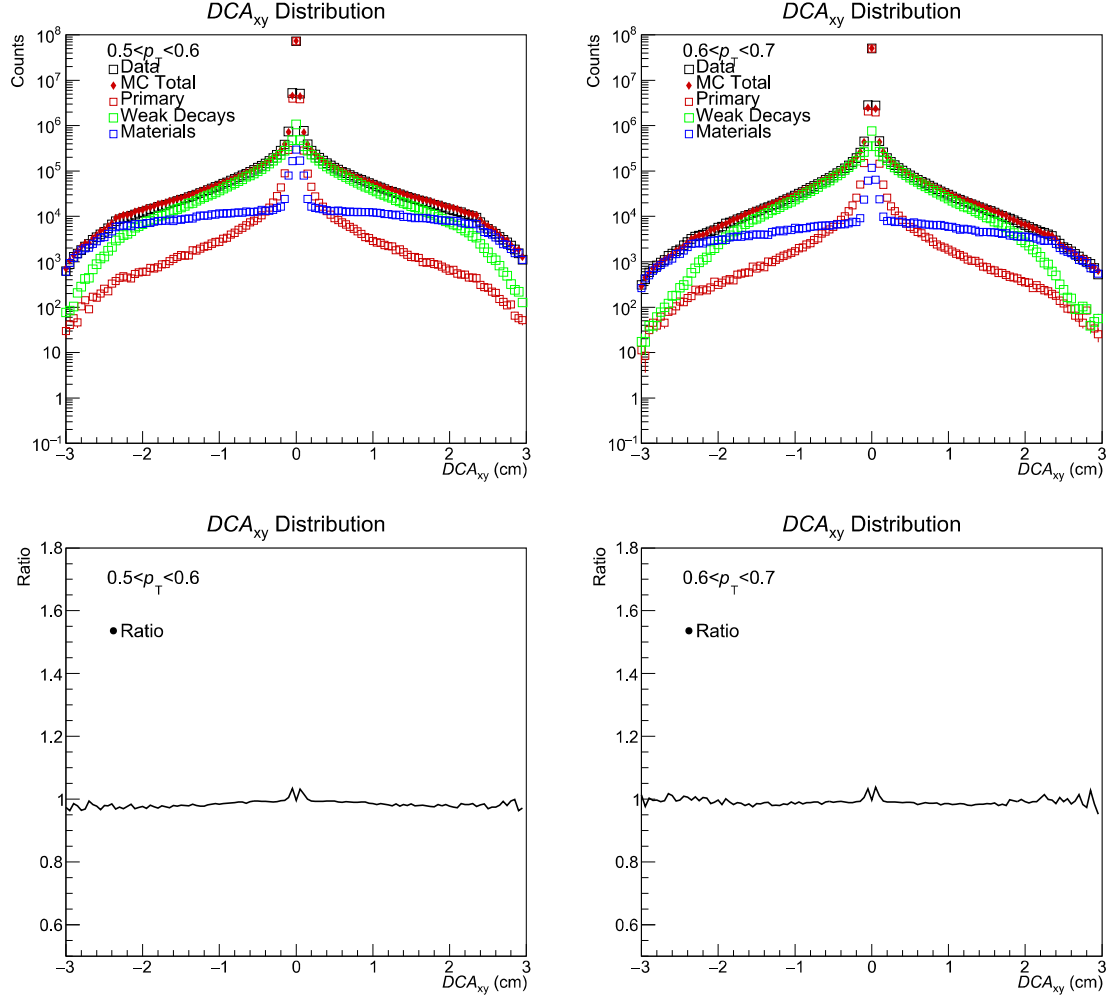


Figure 4: Leading-track misidentification bias for number density (left) and $\sum p_T$ density (right) in toward (upper panel) and away (bottom panel) regions, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure for pp collisions at $\sqrt{s} = 5.02$ TeV are shown.

1986



For p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

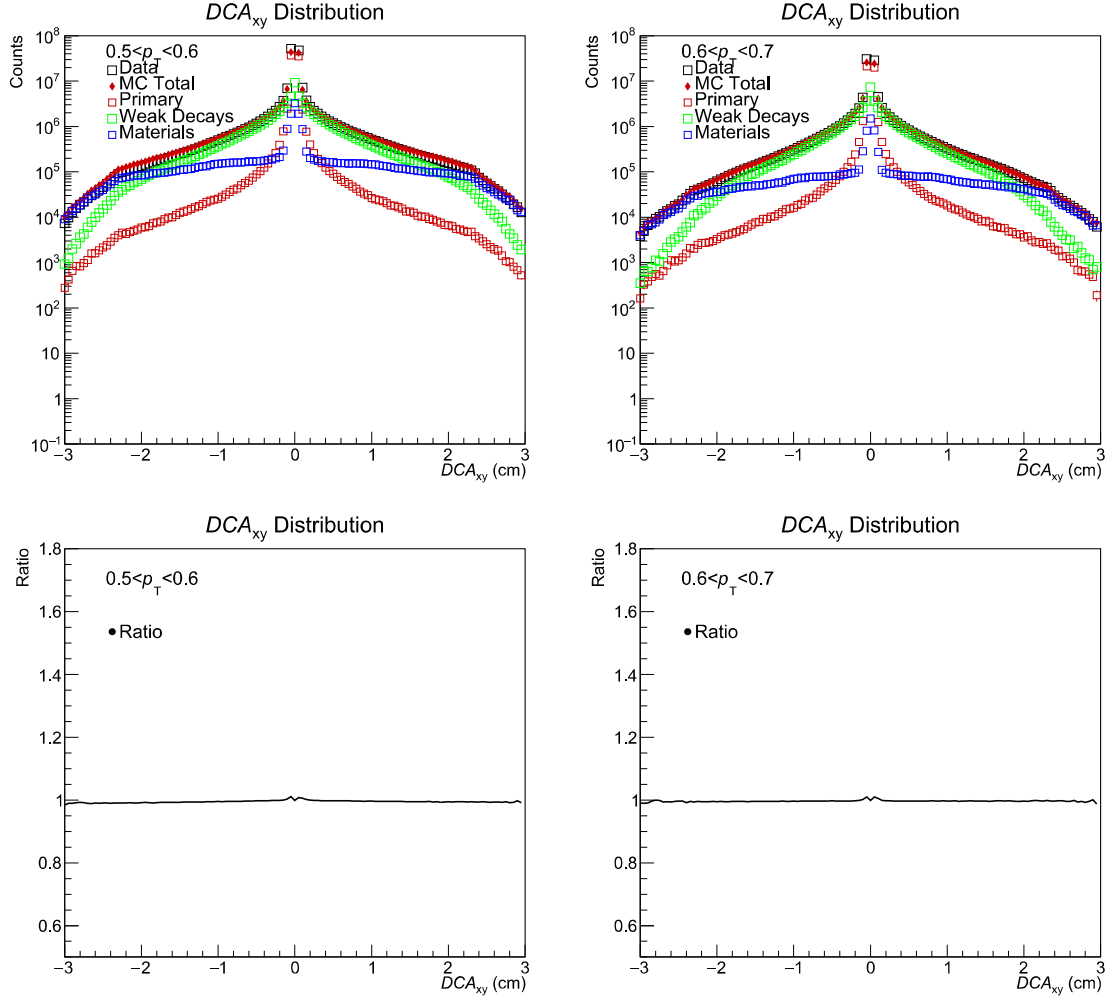


Figure .5: Leading-track misidentification bias for number density (left) and $\sum p_T$ density (right) in toward (upper panel) and away (bottom panel) regions, correction factor vs. leading-track p_T for Monte Carlo and data driven procedure for pp collisions at $\sqrt{s} = 5.02$ TeV are shown.



Appendix C

1988

1989 **Charged particle densities as a function of p_T^{trig} for others p_T**
1990 **cut-off**

1991 The charged-particle number and summed- p_T densities as a function of p_T^{trig} measured
1992 in pp collisions at $\sqrt{s} = 5.02$ TeV, in the transverse, away, and toward regions for the
1993 p_T cut-off 0.15 GeV/ c and 1 GeV/ c are shown in figures [.6](#) and [.7](#), respectively.

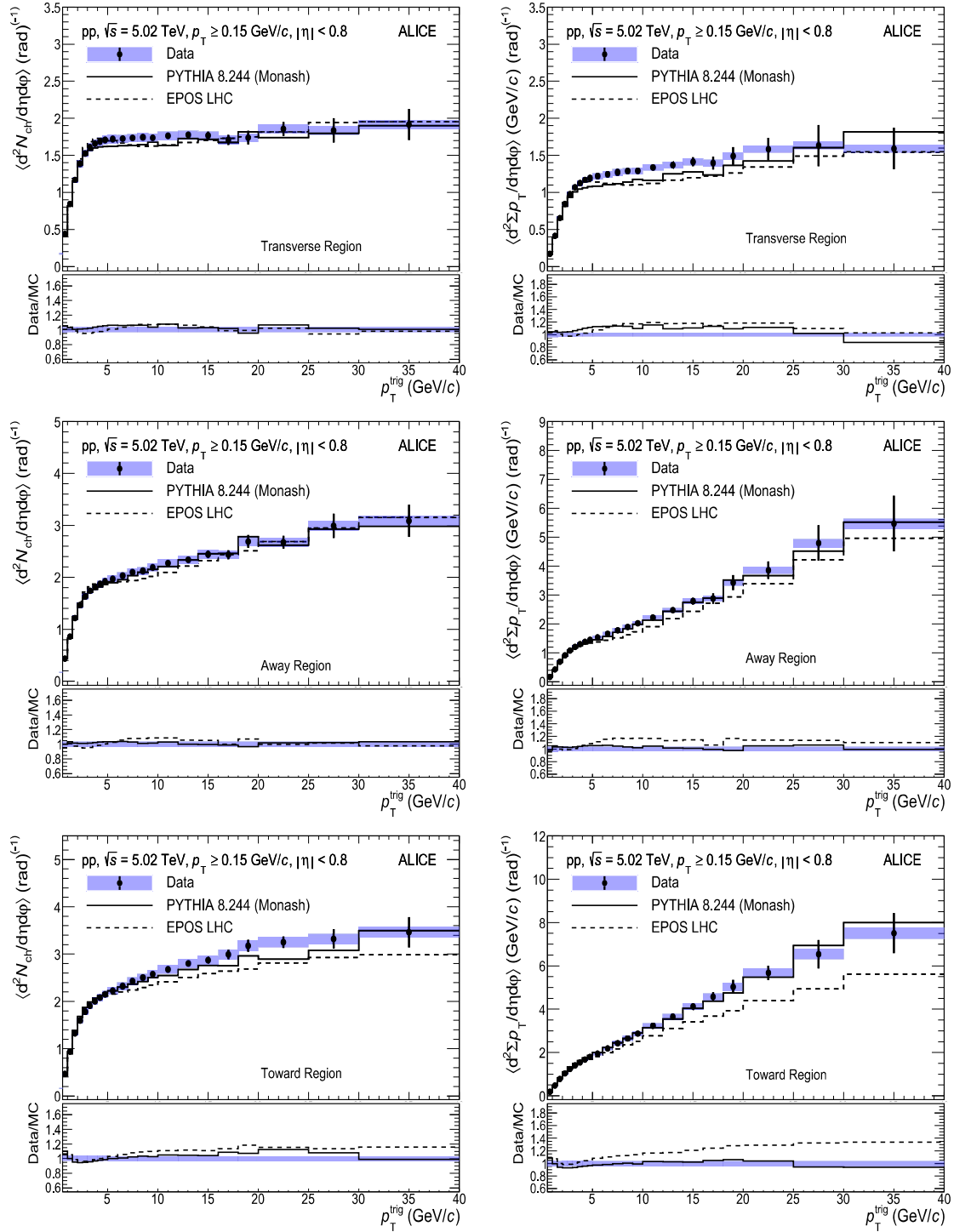


Figure .6: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in pp collision at $\sqrt{s} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 0.15 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Monash (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

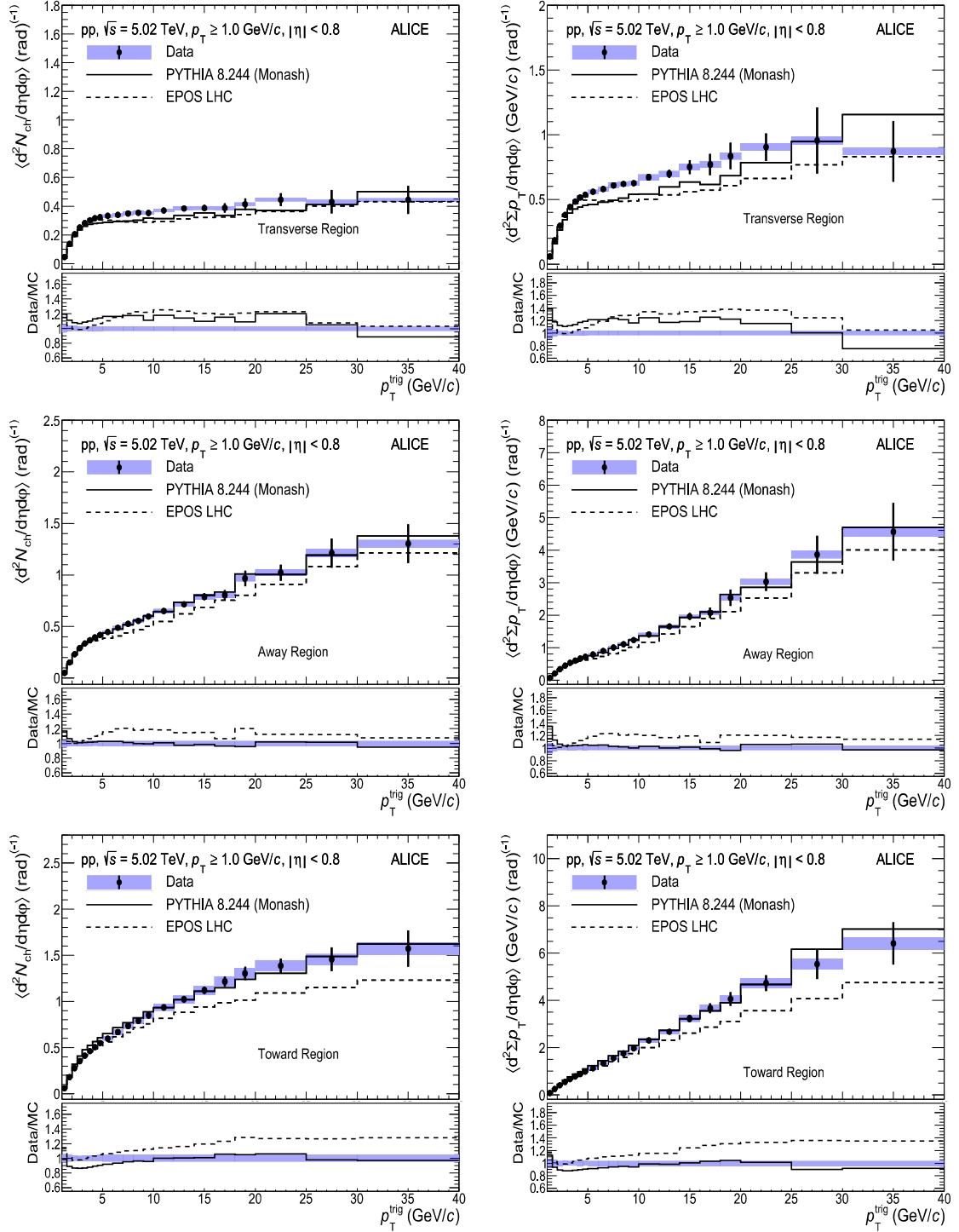


Figure .7: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in pp collision at $\sqrt{s} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 1 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Monash (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.



1994 The charged-particle number and summed- p_T densities as a function of p_T^{trig} measured
1995 in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, in the transverse, away, and toward regions
1996 for the p_T cut-off 0.15 GeV/ c and 1 GeV/ c are shown in figures .8 and .9, respectively.

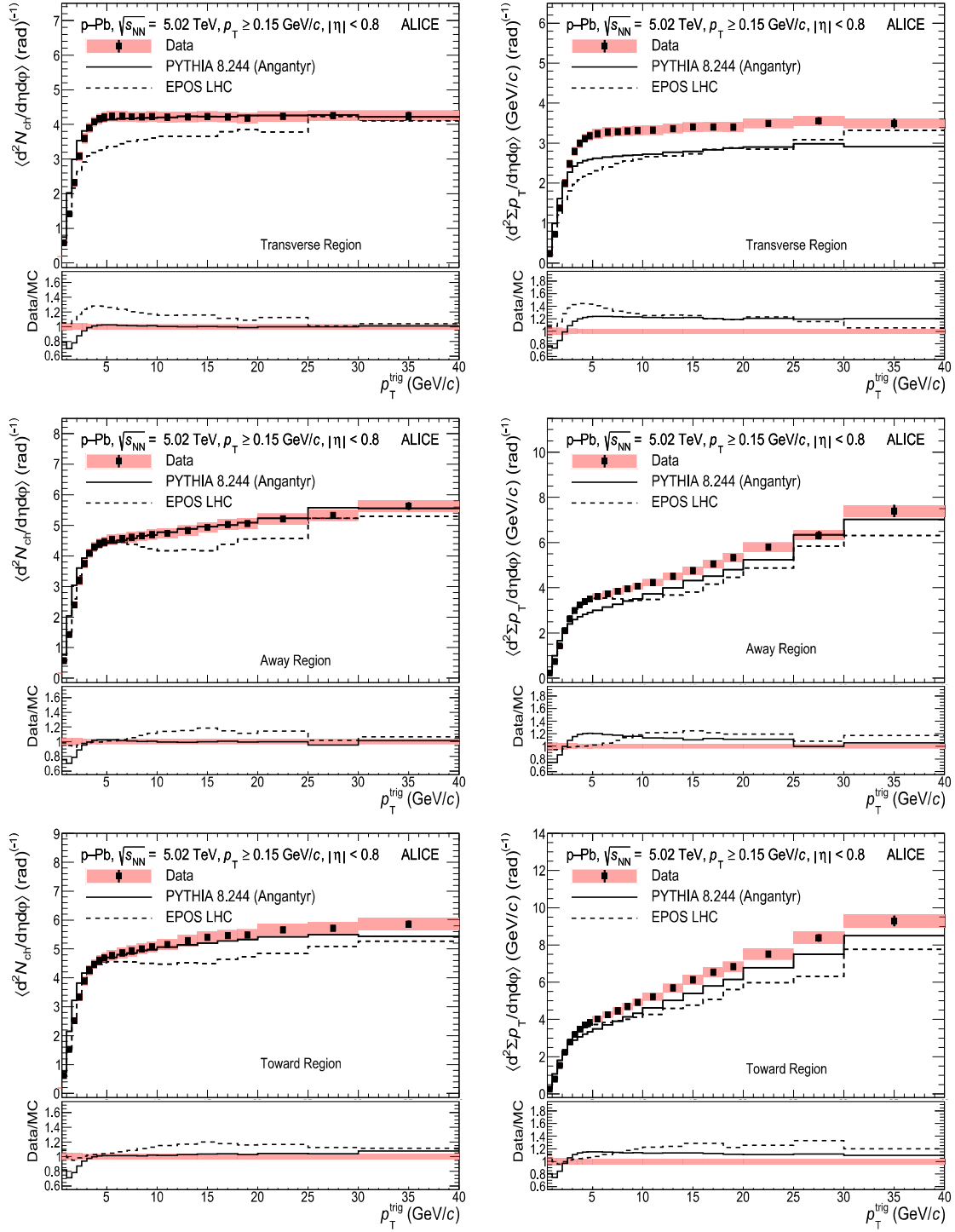


Figure 8: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in p-Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 0.15 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Angantyr (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.

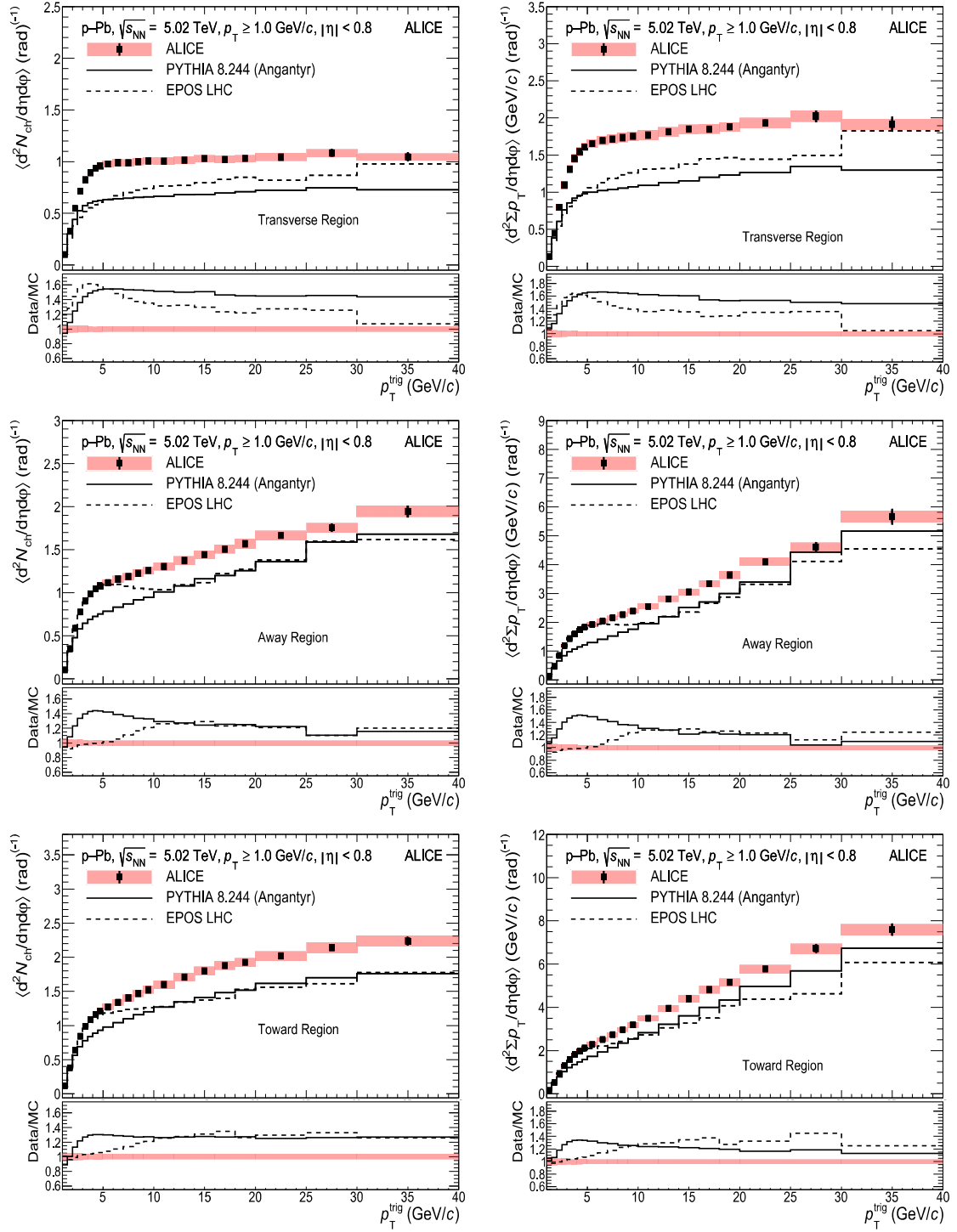


Figure .9: The charged-particle number (left) and summed p_T (right) densities as a function of p_T^{trig} in p-Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are displayed. Results for the transverse (top), away (middle) and toward (bottom) regions were obtained for the p_T cut-off value 1 GeV/c. The boxes and the error bars represent the systematic and statistical uncertainties, respectively. Data are compared with PYTHIA 8/Angantyr (solid line) and EPOS LHC (dashed line) predictions. The data-to-model ratios are displayed in the bottom panel of each plot.