



AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE
WYDZIAŁ FIZYKI I INFORMATYKI STOSOWANEJ

KATEDRA ODDZIAŁYWAŃ I DETEKCJI CZĄSTEK

Praca dyplomowa

Measurement of charged particles spectra in ultra-central ultra-relativistic
heavy ion collisions in the ATLAS experiment

Pomiar spektr cząstek naładowanych w ultracentralnych
ultrarelatywistycznych zderzeniach ciężkich jonów w eksperymencie ATLAS

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Kraków, 2025

Abstract

Ultra-relativistic heavy-ion collisions provide a unique opportunity to study Quantum Chromodynamics (QCD) under extreme conditions of temperature and energy density. The resulting quark-gluon plasma (QGP) can be characterized through the analysis of final-state particles. At high collision centrality, variations in the initial system size are minimized, allowing changes in track multiplicity to be primarily attributed to fluctuations in initial energy density and temperature.

This analysis investigates potential modifications to the transverse momentum (p_T) spectrum of charged particles in the high- p_T range, attributed to interactions with the QGP. Using data from the 1% most central Pb–Pb collisions recorded by ATLAS at $\sqrt{s_{NN}} = 5.02$ TeV, events were divided into bins based on track multiplicity ($\tilde{n}_{\text{trk}}$). The resulting p_T spectra were compared using distribution ratios and high- p_T track yields as a function of $\tilde{n}_{\text{trk}}$.

No statistically significant modification of the p_T spectrum was observed across multiplicity bins. Furthermore, the data do not support the predicted proportionality between p_T and track multiplicity derived from the Linear Boltzmann Transport model.

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1 Introduction

In central heavy-ion collisions, a short-lived state of matter characterized by deconfined quarks and gluons, known as the quark-gluon plasma (QGP) is created. This medium can be studied through its effects on the distributions of particles that interact with it via the strong nuclear force.

In ultra-central collisions, where the impact parameter varies minimally, the system size remains nearly constant. As a result, track multiplicity and particle distribution parameters are primarily influenced by fluctuations in the initial energy density and temperature. The average transverse momentum – p_T , of particles is observed to increase with higher collision centrality (Figure 1.1). This analysis aims to further explore such modifications by comparing transverse momentum spectra within the top 1% most central collisions, across a range of track multiplicities, quantified as the number of tracks per event that pass all selection criteria, denoted $\tilde{n}_{\text{trk}}$.

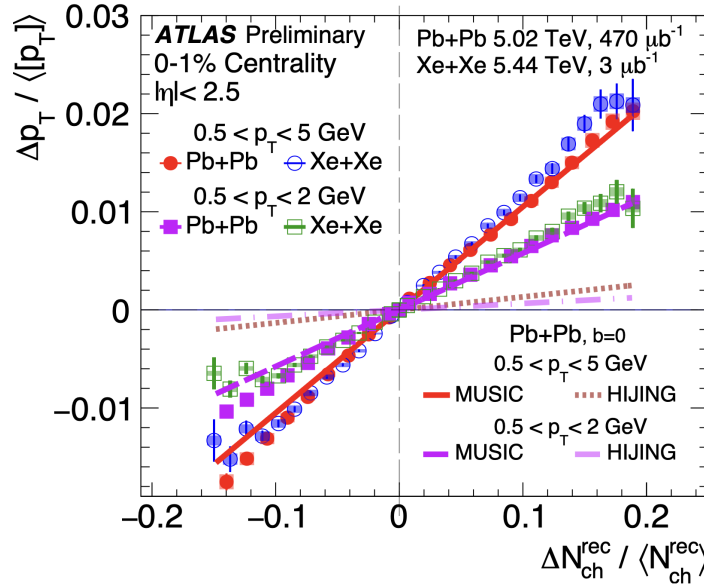


Figure 1.1: $\Delta p_T / \langle p_T \rangle$ and $\Delta N_{ch} / \langle N_{ch} \rangle$ correlation in the 0% – 1% centrality range for Pb-Pb and Xe-Xe collisions, for two p_T ranges [1]

To investigate these p_T modifications, events were divided into five bins based on $\tilde{n}_{\text{trk}}$, and the corresponding p_T spectra in each sub-range were compared.

Two complementary methods were used for the comparison: (1) evaluating the ratio of p_T distributions, and (2) estimating track yields within a specified transverse momentum range. The spectra ratio method helps identify subtle changes in the yield or shape of the distributions. Meanwhile, comparing high- p_T track yields allows testing theoretical predictions from the Linear Boltzmann Transport Model, which suggests a specific dependence of transverse momentum on track multiplicity.

Chapter 2 provides a theoretical introduction to the physical processes relevant to this analysis, including heavy-ion collisions, ultra-central collisions, and the quark-gluon plasma (QGP), covering topics such as color confinement and the QGP phase diagram. This section also includes a derivation, based on the Linear Boltzmann Transport model, of the proportionality between transverse momentum and track multiplicity, which is later tested using the analyzed data.

Chapter 3 offers an overview of the ATLAS detector, where the analyzed data were collected, and introduces the specific detector subsystems used throughout the analysis, such as the Forward Calorimeter and the Zero Degree Calorimeter (ZDC).

Chapter 4 describes the particle tracking procedure employed to reconstruct trajectories, primarily based on the Kalman filter.

Chapter 5 briefly outlines the codebase and frameworks used for generating NTuples from AOD files and for performing the analysis.

In **Chapter 6**, the NTuples and trigger configurations used in the analysis are listed.

Track and event selection criteria are presented in **Chapter 7** and **Chapter 8**, respectively. These sections also discuss the application of Monte Carlo and prescale-based weights, the pile-up removal procedure, based on track multiplicity, energy deposits in the Forward Calorimeter (E_T^{FCal}), and the correlation between ZDC energy and E_T^{FCal} , and include cutflow plots and transverse momentum distributions illustrating the effects of each selection.

Chapter 9 introduces the core analysis methods applied to selected tracks, including event subdivision into $\tilde{n}_{\text{trk}}$ ranges, and $\langle T_{AA} \rangle$ value estimate for each range. Additional plots show the impact of selection cuts and Monte Carlo weights on parameter distributions.

Finally, **Chapter 10** presents the key results, interpreted in terms of momentum transfer and transverse momentum spectrum modifications induced by the quark-gluon plasma.

2 Heavy ion collisions

In addition to pp collisions at the Large Hadron Collider (LHC) also heavy ions are collided. These were primarily lead–lead (Pb–Pb) nuclei at a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ (2018). The high energies of the projectiles result in collisions in which ions are disintegrated and multiple elementary hadronic processes concentrated in an area of size of nucleus occur. As a result, for an instant, a very high temperatures and energy densities lead to creation of abundance of deconfined quark and gluons, so called quark-gluon-plasma (QGP). This conditions provide a unique environment to test Quantum Chromodynamics (QCD) – the theory describing the strong interaction, under extreme conditions.

The formation of the QGP in heavy-ion (HI) collisions is of particular interest, as it recreates conditions similar to those of the early universe. During its earliest moments, the universe was also filled with deconfined quarks and gluons, forming a QGP phase that persisted until expansion and cooling brought the temperature below the QCD phase transition at Hagedorn temperature equal approximately $T \simeq 150 \text{ MeV}$. Unlike the highly dynamic and fluctuating environment of HI collisions, the early universe likely exhibited a high degree of homogeneity [2].

In heavy-ion collisions, the large kinetic energy of the ions results in significant Lorentz contraction, causing the projectiles to appear as flattened disks along the axis of motion. **Figure 2.1** illustrates such a collision. The nucleons within the colliding ions can be categorized as either participants, which interact directly in the collision, or spectators, which pass through unaffected.

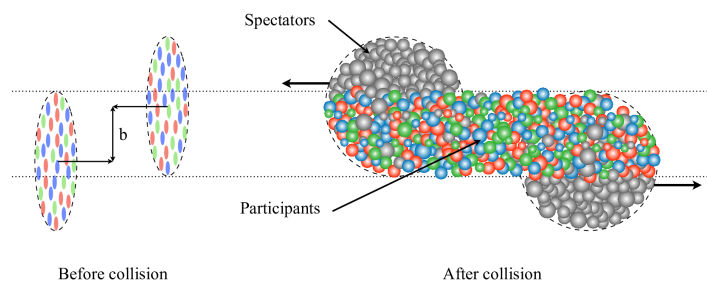


Figure 2.1: A schematic view of a heavy-ion collision [3]

The participants are nucleons directly involved in the collision, responsible for the production of QGP, while the spectators do not experience sufficiently strong electromagnetic or nuclear forces to undergo significant scattering.

The **Figure 2.1** also introduces the impact parameter b , which defines the transverse distance between the centers of the two colliding ions. Ultra-central HI collisions, the focus of this thesis, correspond to events with a minimal value of $b \sim 0$.

In a typical collision, most incident partons undergo soft interactions, losing a portion of their

initial energy without experiencing substantial deflection. Consequently, these partons acquire low transverse momentum after the collision [4].

Within the QCD framework, heavy-ion collisions can be modeled as the interaction of two disks composed of strongly interacting transverse color fields and associated color charges. This interaction generates a longitudinal color field, which reduces the total energy of the two-disk system by filling the space between the receding nuclei. The longitudinal field subsequently decays into $q\bar{q}$ pairs [4, 5].

A small fraction of incident partons undergo hard, perturbative interactions that, albeit with relatively low probability, lead to the production of high- p_T particles [4].

In contrast, ultra-central collisions involve nearly all nucleons participating in the scattering process. The final state of such collisions can contain up to 30,000 particles, reflecting an extremely high entropy environment [6].

A particularly important but rare class of heavy-ion collisions involves the production of high- p_T partons. These events may also produce electroweak bosons and energetic parton pairs. The latter traverse and interact with the quark–gluon plasma formed in the collision zone. Due to the instability of the resulting products and the hadronization driven by color confinement, cone-shaped jets of photons, leptons, and $q\bar{q}$ pairs are produced [6]. Observable effect of hard partons passing through the QGP are of interest in this thesis. In particular the degree of their modification as a function of QGP temperature is expected result of the analysis.

2.1 Ultra-central collisions

Ultra-central heavy-ion collisions (UCC) are a subset of heavy-ion collisions characterized by the maximal geometric overlap of the colliding ions. Theoretically, the centrality of a collision is defined by the impact parameter b , which represents the transverse distance between the centers of the two colliding nuclei [5]. Although b is a well-defined and widely used variable in theoretical studies, it cannot be directly measured in experiments.

In experimental heavy-ion physics, centrality can be determined in several ways. One of the them is to use the observed event multiplicity of charged tracks near midrapidity, denoted as N_{trk} . Another, superior approach is to measure energy in the forward direction. This method exploits the strong correlation between this energy and the impact parameter b – small values of b correspond to high energies, whereas peripheral events (large b) result in significantly reduced detector activity. This approach assumes a monotonic decrease of the energy with increasing b . It is also primary method because calorimeters that measure this energy can be modeled semi-analytically.

The relationship between forward energy and b is typically modeled using the Monte Carlo implementation of the Glauber model. Properties of the collision that cannot be measured directly – such as the number of participating nucleons (N_{part}) or the number of binary nucleon–nucleon collisions (N_{coll}) – can be inferred from large-scale simulations of minimum bias events. By fitting the simulated energy distribution to data using the Glauber model, centrality classes can be defined based on deposited energy thresholds [5, 7].

Figure 2.2 shows the E_T^{FCal} distribution for the MinBias and UCC data streams, with superimposed centrality intervals defined by energy deposits. The plot also illustrates the corresponding impact parameter – b values for each centrality range.

In theoretical treatments, a mathematically rigorous definition of event centrality defined in terms of track multiplicity – N_{trk} , based on the integral of the differential cross-section normalized by the total inelastic scattering cross-section is expressed as

$$c_b = \frac{1}{\sigma_{\text{inel}}^{AA}} \int_0^b \frac{d\sigma}{db'}, db', \quad (2.1)$$

where b is the impact parameter, $d\sigma/db$ denotes the differential cross-section of a nucleus–nucleus

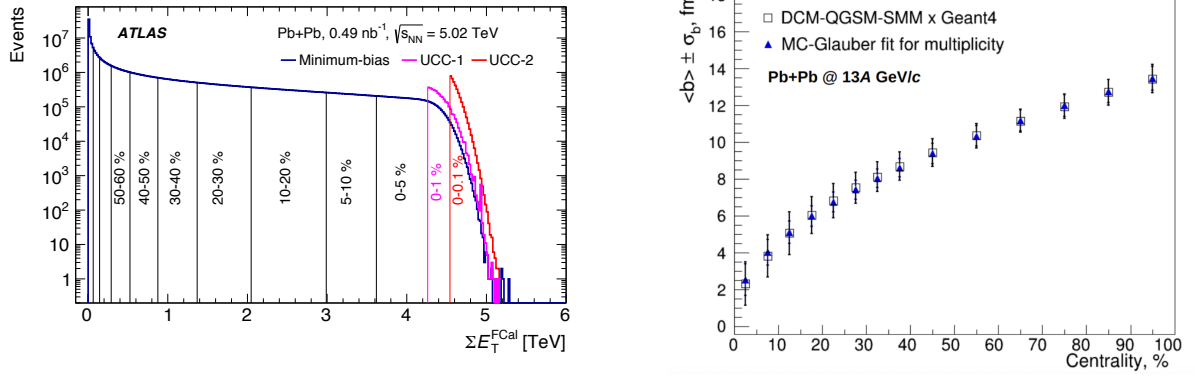


Figure 2.2: (left) Measured energy deposition in the Forward Calorimeter (E_T^{FCal}) for MinBias and UCC data stream, with superimposed centrality cuts [8]. (right) Estimated average impact parameter b as a function of event centrality [5]

collision, and $\sigma_{\text{inel}}^{AA}$ is the total inelastic cross-section for nucleus–nucleus interactions.

A promising novel approach to investigating the hydrodynamic properties of the QGP phase involves analyzing the mean transverse momentum in 1% centrality events [9]. At such small impact parameters, the size of the initial quark–gluon plasma is nearly fixed, and final-state observables are dominated by fluctuations in the initial conditions. Variations in track multiplicity and charged particle momenta are primarily attributed to fluctuations in the initial entropy and temperature. According to relativistic hydrodynamics – the most accurate theoretical framework for describing the QGP, the track multiplicity reflects the initial entropy, while the transverse momentum encodes information about the system’s temperature. These quantities are essential for probing the QGP, as they offer direct insight into its equation of state [10].

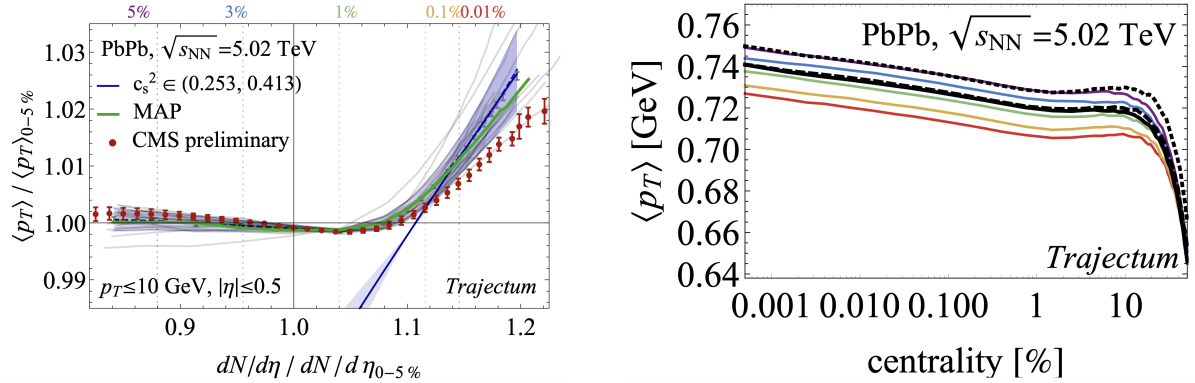


Figure 2.3: (left) The mean transverse momentum against the charged track multiplicity for the ultra-central events, normalized by the central 5% class. Blue band is the averaged (1σ) of the gray lines which represent twenty likely parameters settings. The green line represents the most likely result. The positive curve slope for high track multiplicity range can be understood by the speed of sound at the system initialization temperature. (right) Mean transverse momentum dependency on the event centrality [10]

2.2 Quark gluon plasma

According to Quantum Chromodynamics (QCD), sufficiently high baryon densities and temperatures give rise to an exotic state of matter known as the quark–gluon plasma (QGP). The primary experimental frontier for investigating this novel regime is hadron accelerators, most

notably the Large Hadron Collider (LHC). Heavy-ion collisions, predominantly involving lead nuclei, at the current center-of-mass energy of 5.36 TeV, induce a transition from ordinary hadronic matter to the QGP. Ultra-central collisions (UCCs), although rare, produce a fireball of nearly fixed size, whose final state is largely governed by fluctuations in the system's initial entropy and temperature.

The quark–gluon plasma is generally defined as a localized (in space and time), deconfined state of quarks and gluons that are in both kinetic and chemical equilibrium. Within the QGP, constituents are free to propagate throughout the system volume, in contrast to the confinement observed in hadronic matter. As such, the QGP resembles an ionized gas, where ions and electrons move freely and are not bound by electromagnetic interactions to nearby sources of electric field [11].

Color confinement

The composite constituents of hadrons – quarks, are assigned an additional quantum degree of freedom known as color. While observable matter, such as baryons and mesons, remains colorless (having no net color charge), quarks themselves are labeled with a color charge, conventionally denoted as red, green, or blue. The requirement of a net zero color charge implies the phenomenon of color confinement, which dictates that quarks cannot be observed as free particles, they are always bound within color-neutral combinations.

Although the existence of quarks is well established through experimental evidence, their individual isolation has never been observed, reinforcing the validity of the confinement hypothesis. Color confinement is widely believed to originate from gluon-gluon self-interactions, as gluons themselves carry color charge and can interact with one another, unlike photons in quantum electrodynamics (QED) [12].

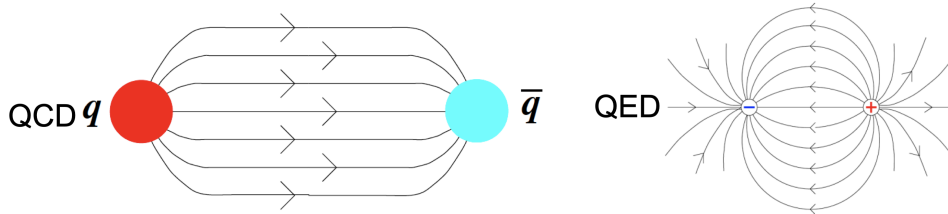


Figure 2.4: Comparison of the field line shapes for two interacting charges, electric charges in QED and color charges in QCD. In the case of two opposite electric charges, field lines extend radially near the sources and are modified at larger distances to merge with those of the opposite charge. In contrast, for two color charges described by QCD, the field lines form a ‘tube’ structure due to gluon self-interaction and the attractive force between the color charges. The resulting constant energy density leads to color confinement and quark hadronization [13]

Qualitatively, color confinement can be understood through the process of $q\bar{q}$ hadronization – the formation of an additional meson as a result of the spatial separation of an initial $q\bar{q}$ pair. The interaction between the quarks is mediated by virtual gluons, which carry color charge and thus attract each other. As the quarks are pulled apart, the color field lines between them do not spread radially, as in quantum electrodynamics (QED), but instead become compressed into a narrow, tube-like structure.

This contrast in field geometries is illustrated in Figure 2.4. In QCD, as the separation increases, the energy density within the flux tube remains approximately constant. Consequently, the total energy stored in the color field grows linearly with distance, eventually becoming large enough to favor the creation of a new $q\bar{q}$ pair from the vacuum, leading to hadronization.

Potential energy between these two quarks, follows the relationship

$$V(\mathbf{r}) \sim \kappa \cdot r. \quad (2.2)$$

The string tension constant κ has been experimentally measured to be approximately $\kappa \sim 1 \text{ GeV}$. This corresponds to extraordinarily large forces – on the order of $\mathcal{O}(10^5) \text{ N}$, acting between any two quarks, regardless of their separation. Such an immense interaction strength between color-charged particles underlies the phenomenon of color confinement, whereby no isolated color charge has ever been observed [12].

The potential that accurately describes the quark–antiquark interaction over both short and long distance scales is the Cornell potential, given by [14]

$$V(\mathbf{r}) = \frac{-A(r)}{r} + K \cdot r + \text{const}, \quad (2.3)$$

where the first term dominates at short distances, exhibiting Coulomb-like behavior, while the second term represents the linear confinement at large distances.

The apparent absence of confinement in the quark–gluon plasma (QGP) does not contradict the principle of color confinement, as the overall system remains color neutral.

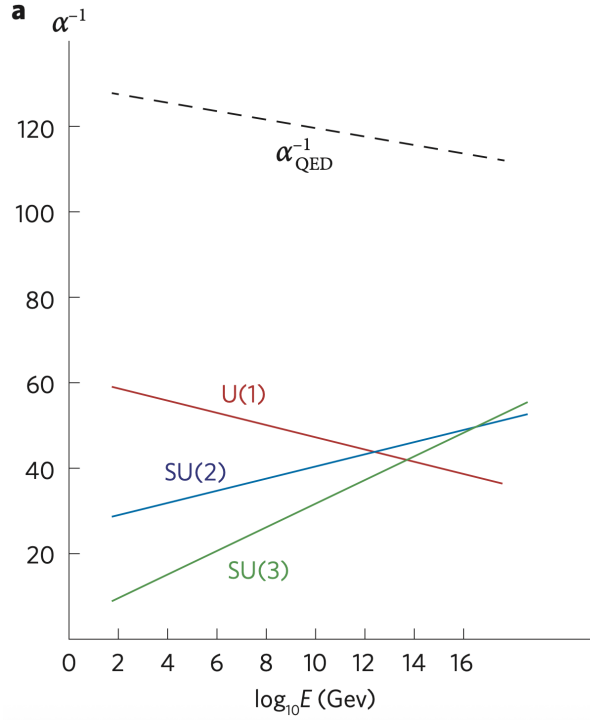


Figure 2.5: Running of the inverse of the quantum electromagnetic coupling constant α_{QED} with logarithm of energy in the standard model $\text{SU}(2) \times \text{SU}(2) \times \text{U}(1)$ [15]

Asymptotic freedom

Another phenomenon critical to understanding the QGP is asymptotic freedom in QCD. The probability amplitude for a given process depends on propagators and vertices in Feynman diagrams, where each vertex contributes according to the coupling constant α . In QED, the nominal coupling is given by $\alpha_{\text{QED}} = e^2/4\pi\epsilon_0\hbar c$ (with e the electric charge, $\hbar = h/2\pi$, and c the speed of light in vacuum). However, due to the running coupling constant effect, α depends on the four-momentum transfer q^2 . The value α_{QED} corresponds to the low-energy limit, while at other energy scales it evolves according to:

$$\alpha_{\text{QED}}^{-1}(Q^2) = \alpha_{\text{QED}}^{-1}(Q_0^2) \left[1 - \frac{\alpha_{\text{QED}}(Q_0^2)}{3\pi} \ln \left(\frac{Q^2}{Q_0^2} \right) \right], \quad Q^2 \gg Q_0^2, \quad (2.4)$$

where $Q^2 = -q^2$. The running of α_{QED} decreases slowly (logarithmically) with increasing energy transfer, as shown in [Figure 2.5](#). Its value changes from $\alpha_{\text{QED}}^{-1}(Q^2 \sim 0) \approx 137.036$ to $\alpha_{\text{QED}}^{-1}(Q^2 \sim M_Z^2) \approx 128.940$, where $M_Z = 91.188 \text{ GeV}$ is the mass of the Z boson [\[16, 17\]](#).

A similar running is observed in QCD, with a crucial difference: the slope of the running coupling has the opposite sign. In quantum chromodynamics, the coupling increases at low energy transfers Q^2 . This behavior makes perturbative solutions of QCD infeasible, since higher-order Feynman diagram contributions do not diminish. As a result, non-perturbative approaches such as lattice QCD become essential. This behavior is illustrated in [Figure 2.6](#).

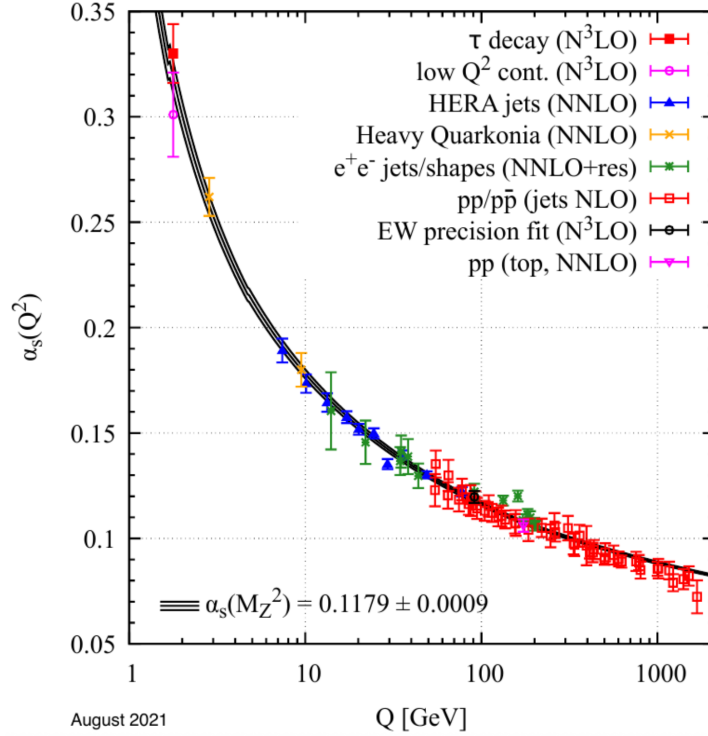


Figure 2.6: The QCD running coupling constant as a function of four momentum transfer q^2 . Value combined from multiple experiments, for wide energy range [\[18\]](#)

The value of the strong coupling constant – α_s is not constant across the energy scale and varies with the four-momentum transfer (Q^2). At leading order (1-loop approximation), it is given by:

$$\alpha_s(Q^2) = \frac{g_s^2}{4\pi} = \frac{1}{\beta_0 \ln(Q^2/\Lambda_{\text{QCD}}^2)}, \quad (2.5)$$

where β_0 is the coefficient of the QCD beta function at one-loop order, g_s is the strong interaction coupling constant, and Λ_{QCD} is the QCD energy scale, which depends on the renormalization scheme used [\[19\]](#).

At $Q = \Lambda_{\text{QCD}}$, α_s diverges, indicating the breakdown of the perturbative approximation. For energy scales below Λ_{QCD} , perturbative QCD becomes invalid, and non-perturbative techniques such as lattice QCD must be used. In the low Q^2 regime, the large value of α_s explains the confinement of quarks i.e., the phenomenon that quarks are never observed as free particles.

Conversely, at high energy transfers, the strong coupling becomes small. For example, at $|q| \sim 1 \text{ GeV}$, $\alpha_s \sim \mathcal{O}(1)$, making perturbative series poorly convergent. However, at much higher

energies, e.g., $|q| > 100$ GeV, $\alpha_s \sim 0.1$, enabling accurate perturbative calculations. This energy-dependent behavior of the coupling constant is known as asymptotic freedom.

In the quark-gluon plasma (QGP), created in high-temperature environments (above the Hagedorn temperature), the high energy transfer leads to small α_s values. This allows quarks and gluons to interact weakly and move freely over short distances, justifying the use of perturbative QCD. As the system cools and α_s increases, color confinement is restored, and quarks hadronize into bound states.

2.3 QGP phase diagram

Lower coupling constants at higher system temperatures induce a transition from a hadron gas to a quark-gluon plasma, reflecting the deconfinement of quarks and gluons. This new system of freely propagating quarks signals the formation of a novel state of matter. Its relation to the hadron gas phase, observed in low-energy nuclear physics, is depicted in the nuclear phase diagram – Figure 2.7.

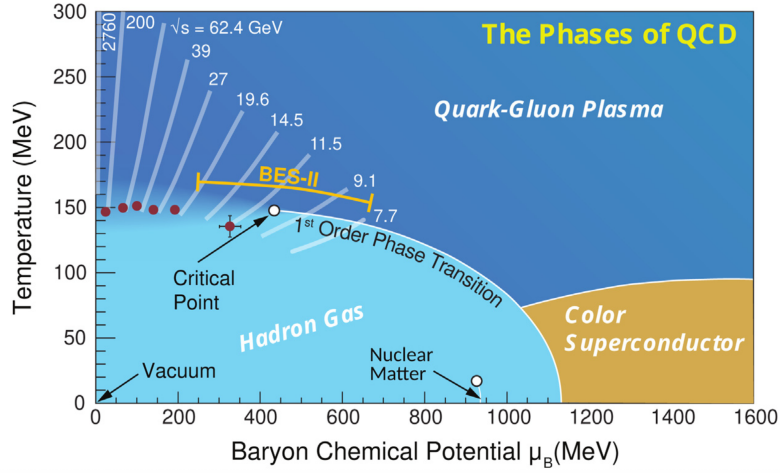


Figure 2.7: A schematic phase diagram for QCD, plotted in parameter space defined by systems temperature and baryon chemical potential. Red dots superimposed on the plot indicate center-of-mass energy ($\sqrt{s}$) for various experiments [20]

The phase diagram is plotted in the parameter space defined by the system's temperature and baryon chemical potential (μ_B), which is defined as the change in system energy U with respect to a change in baryon number N_B [21]:

$$\mu_B = \frac{\partial U}{\partial N_B}. \quad (2.6)$$

Low temperatures and low baryon chemical potentials correspond to the hadron gas phase, in which quarks are confined within color-neutral hadrons such as baryons, this region defines ordinary nuclear matter.

At low temperatures and high baryon densities, the system may enter the color superconducting phase. This state is described as a degenerate Fermi gas of quarks with a condensate of Cooper pairs near the Fermi surface, potentially exhibiting a color analogue of the Meissner effect. High quark densities, quantified by a large baryon chemical potential, effectively reduce the strong coupling α_s , enabling calculations from first principles via perturbative QCD. In this regime, spontaneous breaking of the color gauge symmetry by quark Cooper pairing is predicted. Such extreme conditions are expected to exist in the cores of neutron stars [19, 22].

At higher temperatures, quarks can overcome confinement and form a quark-gluon plasma (QGP). The transition from the hadron gas phase to the QGP strongly dependent on the value

of μ_B . Depending on μ_B , the phase transition can be of either first or second order.

A first-order phase transition is marked by a discontinuity in the first derivative of the free energy with respect to a thermodynamic parameter, while a second-order (or continuous) transition features continuous first derivatives but discontinuities in the second derivatives of the free energy [23]. Both types of transitions can occur within the same physical system, depending on the value of a control parameter. A classic example is the Ising ferromagnet transition between states of positive and negative magnetization [20], illustrated in Figure 2.8.

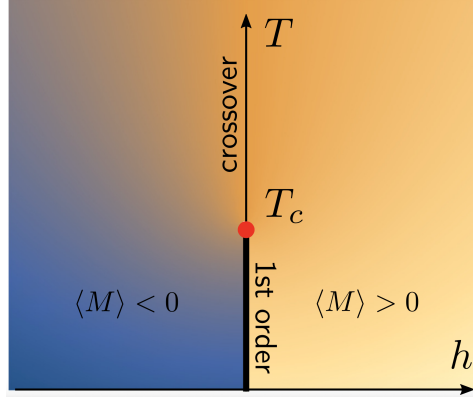


Figure 2.8: The phase diagram of an Ising ferromagnet illustrates the nature of the phase transition as a function of temperature. Below the critical temperature (T_c), the transition is of first order, characterized by a discontinuous change in the parameter. For temperatures above T_c , the transition becomes a continuous crossover, where the system undergoes a smooth change without a latent heat

The nature of the phase transition is determined by the system's critical temperature T_c . In the Ising ferromagnet model, a first-order transition occurs when the system temperature is below T_c , while for $T > T_c$, the transition becomes continuous (a crossover).

A similar behavior is observed in the formation of the quark–gluon plasma (QGP). At high baryon chemical potential (μ_B), the transition from hadronic matter to QGP is predicted to be first-order. In contrast, for low values of μ_B – the regime accessible in current high-energy collider experiments, the transition is a smooth crossover.

Lattice QCD calculations suggest that this crossover occurs at a temperature of approximately $T \approx 150$ MeV for small μ_B values. Such conditions can be recreated in relativistic heavy-ion collisions, where the large number of participating nucleons provides sufficient entropy density for QGP formation [19]. It is further predicted that at higher μ_B , a critical point is reached, beyond which the transition becomes first-order.

Experimental efforts to locate this QCD critical point have been undertaken at RHIC (Brookhaven), through heavy-ion collisions at various center-of-mass energies. However, no definitive experimental evidence for a first-order phase transition or the critical point has yet been observed.

QGP evolution

Shortly after the ion collisions, numerous nucleon–nucleon inelastic scattering processes produce a spatially localized medium of partons that are not in chemical or kinetic equilibrium. The resulting energy density exceeds the threshold for QGP formation – 0.13 GeV/fm^3 , as predicted by lattice QCD calculations [24]. At this energy density, the deconfinement of quarks and gluons is expected.

The stages in the evolution of the system, from the formation of an equilibrated quark–gluon plasma to the emergence of color-neutral particles detectable in experiments, can be summarized

as follows [25]

1. Thermalization of the system;
2. Expansion and cooling of the QGP;
3. Hadronization – crossover transition to a hadronic gas;
4. Chemical freeze-out;
5. Kinetic freeze-out.

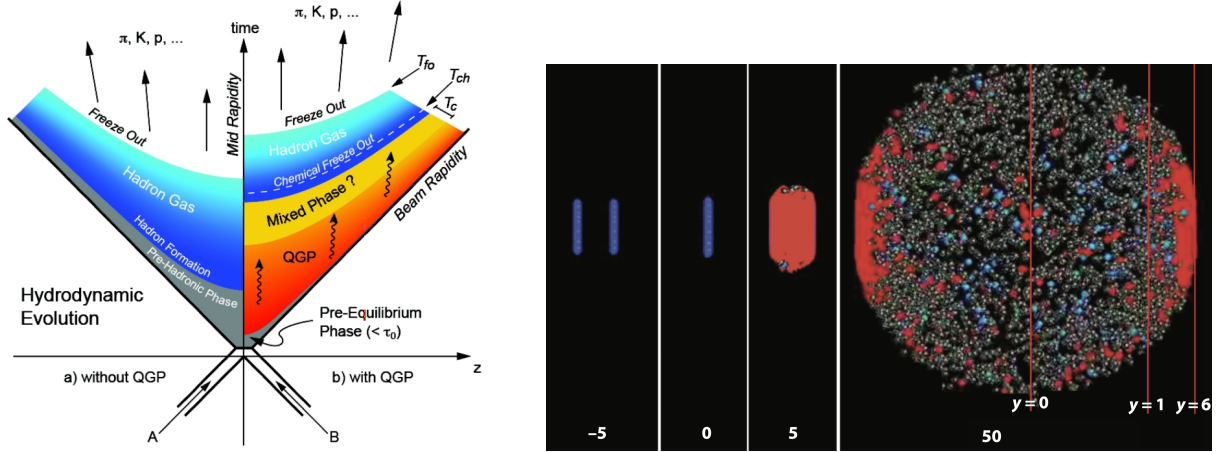


Figure 2.9: (left): Evolution of the quark–gluon plasma in Minkowski-like spacetime [26]. (right): Snapshot of an ultra-central Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV at various times. Figure adapted from [4]; full QGP evolution video available at [27]

Within the first 1 fm/c, partons in the initially created system undergo multiple inelastic scatterings, establishing kinetic equilibrium. This moment defines the formation of the quark–gluon plasma, enabling the use of thermodynamic formalism to describe the system.

At the moment of heavy-ion (HI) collisions, the system is out of both chemical and thermal equilibrium. Chemical equilibrium is defined as the state when particle abundances become stable on average. Thermal equilibrium occurs when the QGP as a whole reaches a uniform temperature. After this point, particle spectra remain unchanged [24].

In the QGP phase, the medium experiences an outward boost called radial flow, which increases the particles’ transverse momentum (p_T). Spatial anisotropies in the system’s geometry translate into anisotropic flow of final-state particles. This arises from pressure gradients that induce momentum anisotropy in the outgoing partons. The effect is quantified by a Fourier expansion of the azimuthal angle distribution of final state particles $dN/d\varphi$ [25].

The system’s expansion, governed by relativistic hydrodynamics, cools the quark–gluon plasma until it reaches the crossover temperature, approximately $T_c \approx 156$ MeV [25]. This marks a second-order phase transition to a hadron gas, restoring quark confinement – free quarks and gluons become bound into color-neutral hadrons. Hadron abundances at this stage can be estimated using the thermal equilibrium hadron-resonance gas model [25].

The next key stage in QGP evolution is the chemical freeze-out temperature, T_{chem} , at which particle yields become fixed. Fits to a large set of particle abundances measured by the ALICE experiment in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV estimate $T_{\text{chem}} \approx 153$ MeV, very close to the crossover temperature [25].

After chemical freeze-out, particle scattering continues but at a reduced rate as the system expands with mostly fixed particle yields. During this stage, particle kinematic parameters are

established. Scattering among resonance decay products can alter their kinematics, complicating reconstruction, while hadron scattering can regenerate resonance states [25].

2.4 Linear Boltzmann transport model

Track multiplicity as proxy for temperature

The initial energy density produced in colliding system can be expressed as [28]

$$\varepsilon \approx \frac{N}{A} \frac{d\langle E \rangle}{dy} \frac{1}{2t}, \quad (2.7)$$

where N/A is the number of incident nucleons per unit area, t – time. y denotes rapidity, defined as [29]

$$y = \ln \sqrt{\frac{E + p_z}{E - p_z}} = \ln \frac{E + p_z}{m_T}, \quad m_T = \sqrt{m^2 + p_T^2}, \quad (2.8)$$

The quantity p_z denotes the longitudinal component of a particle's momentum. A key property of the rapidity is that its difference remains invariant under a Lorentz boost along the beam axis.

The ratio N/A can be interpreted as the inverse of the effective elementary area, expressed as $1/d_0^2$.

$$\frac{N}{A} = \frac{A}{\pi(1.2 \cdot A^{2/3} \text{fm})^2} = \frac{A^{1/3}}{4.5 \text{fm}^2} = \frac{1}{d_0^2}. \quad (2.9)$$

Assuming d_0 value in the range 0.3 fm – 1.0 fm, the estimate of the energy density is

$$\varepsilon \approx \frac{1 \text{ GeV}}{td_0^2}. \quad (2.10)$$

For the time $t_0 = 1 \text{ fm}/c$, the initial energy density is of the order of magnitude $1 \text{ GeV fm}^{-3} - 10 \text{ GeV fm}^{-3}$.

An alternative formulation, derived from Bjorken's boost-invariant 1D hydrodynamics [28], and more suitable for this analysis, takes the form presented in [30].

$$\varepsilon = \frac{3}{2} \frac{dN_{ch}}{dy} \frac{\langle m_T \rangle}{S_n \tau_{prod}}, \quad (2.11)$$

where ε – energy density, S_n – nuclear overlap area, m_T – transverse mas, τ_{prod} – the production time at which quark-gluon plasma is produced. N_{ch} stands for the number of charged particles, which in the case of the analysis is equivalent to the N_{trk} formulation.

Value of the production time is given by [30]

$$\tau_{prod} = \frac{2.405 \hbar}{\langle m_T \rangle}. \quad (2.12)$$

In Color String percolation Model (CSPM), above critical temperature, only massless particles are present, thus

$$\langle m_T \rangle = \sqrt{\langle p_T \rangle^2 + m_0^2}, \quad (2.13)$$

where m_0 is mass of pion. The pion mass is used because the color suppression factor $F(\xi)$, where ξ is the percolation density parameter, is identical for charged particles and pions in the transverse momentum range of 0.12 GeV to 1.0 GeV. The average p_T is taken from experimental data [30].

Since the analysis does not rely on the rapidity determination, it is advantageous to express the energy density in terms of $dN_{ch}/d\eta$. This transformation involves a Jacobian, leading to the formula provided in [31]

$$\frac{dN_{ch}}{d\eta} = \frac{dN_{ch}}{dy} \left| \frac{dy}{d\eta} \right| = \left(1 + \frac{m^2}{p_T^2 \cosh^2 \eta} \right)^{-1/2} \frac{dN_{ch}}{dy}. \quad (2.14)$$

The $dN_{ch}/d\eta$ can alternatively be expressed as [32]

$$\frac{dN_{ch}}{d\eta} = n_{pp} \left((1-x) \frac{\langle N_{part} \rangle}{2} + x \langle N_{coll} \rangle \right), \quad (2.15)$$

where x – fraction of hard partonic interactions, n_{pp} – average charged-particle multiplicity in a single proton-proton collision, N_{part} – number of participant nucleons, N_{coll} – number of collisions.

Linking previous equations, it can be noted that track multiplicity, expressed as $dN_{ch}/d\eta$ serves as a initial energy density proxy

$$\varepsilon \propto \frac{dN_{ch}}{d\eta}. \quad (2.16)$$

Outside the critical region, where $T > 1.3 \cdot T_c$, the equation of state for the quark–gluon plasma implies that the energy density is proportional to T^4 [33]. By combining this with the proportionality between energy density and charged-particle multiplicity, one arrives at

$$T \propto \left(\frac{dN_{ch}}{d\eta} \right)^{1/4}. \quad (2.17)$$

Thus, event track multiplicity can serve as a observable for sampling the system’s initial temperature.

Linear Boltzmann Transport model

A way to understand of impact of system temperature on hard scattering is provided by Linear Boltzmann Model [34].

The LBT model, grounded in perturbative QCD, is a widely adopted tool for describing parton propagation within the quark–gluon plasma (QGP).

When a high-energy quark or gluon – particle that interact via the strong nuclear force propagate through the QGP medium, multiple parton scatterings occur, inducing gluon bremsstrahlung. These scatterings result in transverse momentum broadening and energy loss of the parton. Given the nature of the interaction, assuming a dense hadronic medium (QGP) has formed, the yield of high- p_T particles is expected to be suppressed. This phenomenon, known as jet quenching, has been observed both at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). In events with collinear jet pairs, jet quenching may appear as a significant reduction in the energy of one of the jets.

The LBT framework combines a kinetic description of parton propagation with a hydrodynamic model of medium evolution. It tracks not only the scattered partons but also the thermal recoil of medium constituents, enabling the study of both jet transport and jet-induced medium excitations, an important feature for probing jet quenching effects.

To improve the accuracy of the modeling, the version of the LBT model used in this context replaces the small-angle approximation for parton scattering with the full set of $2 \rightarrow 2$ elastic parton scattering processes, employing the complete scattering matrix.

When considering only $2 \rightarrow 2$ scatterings, the propagation of partons through the quark–gluon plasma can be described using a set of linear Boltzmann equations [34]

$$\begin{aligned}
 & p_1 \cdot \partial f_a(p_1) \\
 &= - \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \int \frac{d^3 p_3}{(2\pi)^3 2E_3} \int \frac{d^3 p_4}{(2\pi)^3 2E_4} \\
 &\quad \times \sum_{b(c,d)} [f_a(p_1) f_b(p_2) - f_c(p_3) f_d(p_4)] |\mathcal{M}_{ab \rightarrow cd}|^2 \\
 &\quad \times S_s(s, t, u) (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4),
 \end{aligned} \tag{2.18}$$

sum $\sum_{b(c,d)}$ is taken over the flavor of the initial thermal parton, b , for all combinations of final-state parton flavors, c and d . The matrix element $\mathcal{M}_{ab \rightarrow cd}$ corresponds to the amplitude of the $2 \rightarrow 2$ parton scattering process, summed over the final-state spin and color. The variables s , t , and u denote the Mandelstam variables [35], and f_i represents the phase-space distribution of the thermal partons.

Highly energetic partons propagating through the quark–gluon plasma undergo multiple scatterings with the medium, which modify their momentum. This momentum exchange is governed by the scattering matrix element $\mathcal{M}_{ab \rightarrow cd}$, and leads to an increase in the mean squared transverse momentum over time, referred to as transverse momentum broadening.

The mean squared transverse momentum per unit length is described by the jet transport parameter – $\hat{q}$. This parameter quantifies both the strength of the jet–medium interaction and the local gluon number density.

Since the analysis is focused on the top 1% most central Pb–Pb collisions, the variation in the impact parameter b and the initial QGP geometry is minimal. This justifies the assumption that the mean squared transverse momentum per unit length, $\hat{q}$, is proportional to the total transverse momentum transfer.

The derivation of $\hat{q}$ in the Linear Boltzmann Transport model assumes a small-angle approximation of the $2 \rightarrow 2$ scattering cross section. This assumption is well justified, as in the high-energy limit $E \gg T$, the t -channel gluon and quark scattering cross sections can be approximated using their small-angle limits [34].

$$\frac{d\sigma_{ab}}{dq_\perp^2} \approx C_{ab} \frac{2\pi\alpha_s}{q_\perp^4}, \quad \left(C_{gg} = \frac{9}{4}, \quad C_{qg} = 1, \quad C_{qq} = \frac{4}{9} \right) \tag{2.19}$$

where strong coupling constant $\alpha_s = g^2/4\pi$ is assumed constant and equal $\alpha_s = 0.3$, $q_\perp$ is the transverse momentum transfer per scattering, and is independent of the parton’s flavor.

Following the Equation 2.19, the scattering rate for the high energy partons, in the thermal quark gluon plasma equal [34]

$$\Gamma_g \approx \sum_{b=q, \bar{q}_i} \Gamma_{gb \rightarrow gb} \approx 42 \cdot C_A \cdot \xi(3) \frac{\alpha_s T^3}{\pi \mu_D^2}, \tag{2.20}$$

$$\Gamma_q \approx \sum_{b=q, \bar{q}_i} \Gamma_{qb \rightarrow qb} \approx 42 \cdot C_F \cdot \xi(3) \frac{\alpha_s T^3}{\pi \mu_D^2}, \tag{2.21}$$

where $\xi(3) \approx 1.202$ – Apery’s constant, $C_A = N_c$, $N_c = 3$ – number of colors in QCD, $C_F = (N_c^2 - 1)/2N_c$, μ_D – Debye screening mass equal

$$\mu_D^2 = \frac{g^2 T^2}{3} \left(N_c + \frac{N_f}{2} \right), \tag{2.22}$$

where $N_f = 3$ – number of active quark flavors in the QGP.

The small-angle approximation, together with the scattering rate formulas Γ_g and Γ_q introduced above, leads to the following expression for the mean transverse momentum broadening

squared per mean free path [34]

$$\begin{aligned}\hat{q}_a &= \langle q_\perp^2 / \lambda \rangle = \sum_{b,(cd)} \int_{\mu_D^2}^{s/4} dq_\perp^2 \frac{\sigma_{ab \rightarrow cd}}{dq_\perp^2} \rho_b q_\perp^2 \\ &= \Gamma_a \langle q_\perp^2 \rangle \approx C_a \frac{42 \cdot \xi(3)}{\pi} \alpha_s^2 T^3 \ln \left(\frac{s^*}{4\mu_D^2} \right),\end{aligned}\tag{2.23}$$

where $C_a = C_F = 4/3$ for quarks, and $C_a = C_F = 3$ for gluons, $\ln s^* = \langle \ln s \rangle$, s – center-of-mass energy squared for each parton-parton interaction.

The key takeaway from Equation 2.23 is the proportionality between $\hat{q}$ and temperature:

$$\hat{q} \propto T^3.\tag{2.24}$$

The temperature dependence of the Debye mass can be neglected since it appears only inside a logarithmic function.

By incorporating the temperature dependence on track multiplicity derived in Equation 2.17, the relation between $\hat{q}$ and track multiplicity becomes

$$\hat{q} \propto \left(\frac{dN_{ch}}{d\eta} \right)^{3/4}.\tag{2.25}$$

Hence, for high- p_T particles, the yield distribution is expected to change with the track multiplicity $dN_{ch}/d\eta$ as in the above formula.

3 Experiment and detector overview

3.1 ATLAS Coordinate system

The beam and interaction points are defined within a Cartesian coordinate system, where the axes are oriented as follows

- the x -axis points towards the center of the LHC ring;
- the y -axis points vertically upward, perpendicular to the plane of the ring, towards the surface of the Earth;
- the z -axis is aligned with the direction of the beam [36].

The x - and y -axes define a plane that is perpendicular to both the beam axis and the solenoidal magnetic field of the inner detector. The total transverse momentum is measured through the track curvature in this magnetic field, providing the momentum component in the plane defined by the x - and y -axes.

The Cartesian coordinate system is used mostly for interaction point parametrization. Spherical system derived from Cartesian is usually used to describe reconstructed tracks. The spherical system is defined as

- azimuth angle: $\varphi = \arctan y/x$, $\varphi \in [0, 2\pi]$;
- polar angle: $\theta = \arctan \sqrt{x^2 + y^2}/z$, $\theta \in [0, \pi]$;
- pseudorapidity: $\eta = -\ln \tan \theta/2$.

3.2 Parameter definitions

The analysis relies on the following variables

- p_T – transverse momentum, total momentum component perpendicular to the beam axis (z -axis), momentum laying in the xy plane;
- η – pseudorapidity;
- φ – azimuth angle;
- E_T^{FCal} – transverse energy deposition in the forward calorimeter (FCal) system;
- N_{trk} – track multiplicity, total number of tracks reconstructed in the event;
- $\tilde{n}_{\text{trk}}$ – number of tracks that pass all the selection requirements;
- d_0 – transverse distance between the interaction point and the *perigee*¹ – see [Figure 3.1](#);

¹Closest to the beam track point of the particle trajectory.

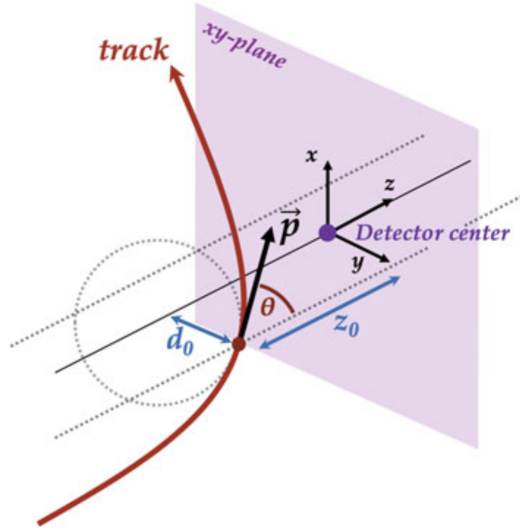


Figure 3.1: Transverse – d_0 , and longitudinal – z_0 track impact parameter, with respect to the interaction point [37]

- z_0 – longitudinal distance between the interaction point and the *perigee* – see Figure 3.1;
- σ_{d_0} – uncertainty of the transverse impact parameter d_0 ;
- σ_{z_0} – uncertainty of the longitudinal impact parameter z_0 .

3.3 Large Hadron Collider

General information

The Large Hadron Collider (LHC) is the world largest particle acceleration, which can also deliver the highest possible center-of-mass energy ($\sqrt{s}$). It is located at the french–swiss border and consists of multiple particle accelerating stages. Detailed layout is presented in the Figure 3.2.

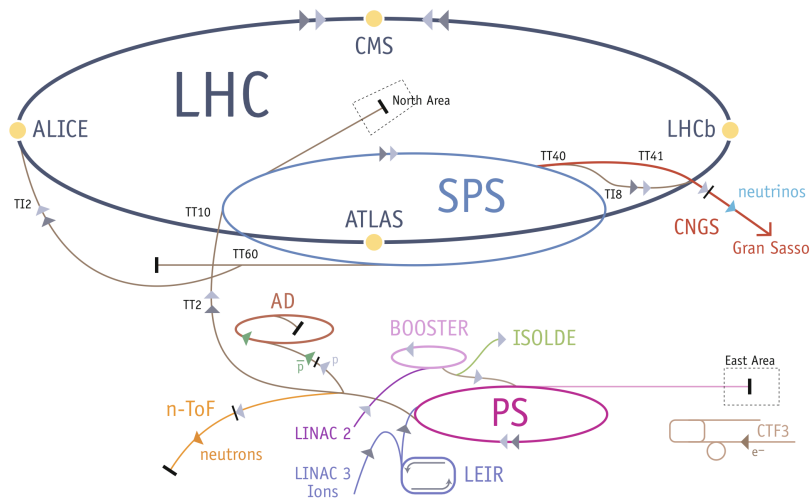


Figure 3.2: The LHC accelerator complex [38]

The LHC operates in two main modes – proton-proton, and heavy ion collisions, most notably

lead-lead collisions. The center-of-mass energy in the current run (Run 3, 2024) for p-p collisions reached $\sqrt{s} = 13.6$ TeV and $\sqrt{s_{NN}} = 5.36$ TeV² [39, 40].

For proton physics, the accelerating process starts with the linear accelerator – LINAC 2 increasing proton energy to 50 MeV. This stage is followed by four synchrotron – BOOSTER (1.4 GeV), Proton Synchrotron (PS) (25 GeV), Super Proton Synchrotron (SPS) (450 GeV) [38].

The main LHC ring consists of two separate vacuum beam pipes, each containing particles circulating in opposite directions. These pipes are surrounded by powerful dipole magnets, which bend the particle trajectories, and quadrupole magnets, which focus the beams. Extensive cryogenic systems maintain the superconducting conditions required for magnet operation. The two counter-rotating beams intersect at four points around the ring, corresponding to the locations of the major experiments: ATLAS, ALICE, CMS, and LHCb.

Luminosity

Besides center-of-mass energy, another key parameter of the accelerator, determining its data output is luminosity. Instantaneous luminosity is a function of beam and accelerators properties

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}, \quad (3.1)$$

where N_1, N_2 – number of particles per bunch, f – revolution frequency, N_b – number of bunches in the accelerator, σ_x, σ_y – horizontal and vertical bunch width [41].

Luminosity is linked to expected reaction rate by a concept of integrated luminosity

$$\mathcal{L}_{int} = \int_0^t \mathcal{L}(t') dt'. \quad (3.2)$$

Then, the expected number of events (R) equals

$$R = \mathcal{L}_{int}\sigma_p, \quad (3.3)$$

where σ_p is the process cross-section [41].

3.4 ATLAS detector

ATLAS is the biggest general purpose detector at the LHC, which covers a wide range of physics, such as Higgs boson and top quark production or research of the dark matter. It covers full azimuth angle and pseudorapidity range varying by detector system.

The ATLAS detector consists of the following principal active components

- Inner Detector:
 - Pixel Detector;
 - Semiconductor Tracker (SCT);
 - Transition Radiation Tracker (TRT);
- Calorimeters:
 - Electromagnetic calorimeter;
 - Hadron calorimeter;
- Muon spectrometer;

² $\sqrt{s_{NN}}$ is a center-of-mass energy for a nucleons pair, quantity used for ion physics.

- Forward detectors:
 - Luminosity Cherenkov Integrating Detector (LUCID);
 - Zero Degree Calorimeter (ZDC);
 - Atlas Forward Proton (AFP);
 - Absolute Luminosity For ATLAS (ALFA).

Vital for the tracking process is also the magnet system which consists of two major elements – solenoid and toroid magnet. The Inner Tracker is immersed in the 2 T magnetic field, inducing charged particles curvature allows to estimate transverse momentum.

3.4.1 Inner Detector

The Inner Detector is the innermost subsystem of the ATLAS experiment and is primarily responsible for the reconstruction of charged particle trajectories. This capability enables precise measurements of transverse momentum, as well as the reconstruction of both primary and secondary vertices for particles with transverse momentum above a certain threshold, typically 0.5 GeV. Transverse momentum p_T is determined by analyzing the curvature of charged particle tracks in the uniform magnetic field of 2 T generated by the surrounding solenoid.

Situated closest to the beam axis, the Inner Detector is exposed to the highest levels of radiation and track density. Reliable tracking in this challenging environment requires extremely high spatial resolution, which is achieved through the use of advanced semiconductor detectors, primarily pixel sensors.

The detector has a cylindrical geometry with a radius of approximately 1.15 m and an overall length of 7 m [42], as illustrated in [Figure 3.3](#).

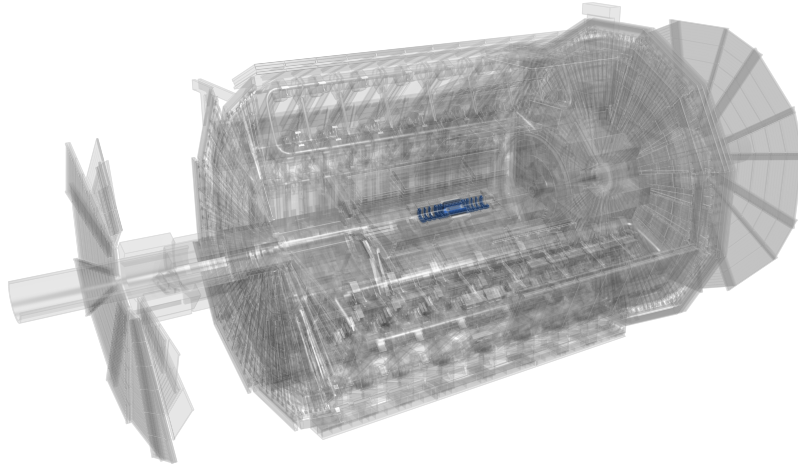


Figure 3.3: The Inner Detector subsystem of ATLAS [43]

The Inner Detector provides tracking coverage for pseudorapidities $\eta < 2.5$ and supports electron identification within $\eta < 2.0$. The required transverse momentum resolution for charged particles is given by $\sigma_{p_T}/p_T = 0.05\% \cdot p_T \oplus 1\%$, where the terms are combined in quadrature.

A more detailed view of the Inner Detector layout is shown in [Figure 3.4](#).

Pixel detector

The Pixel Detector is the innermost part of the ATLAS Inner Detector, positioned just 3.3 cm from the beam axis. It comprises 92 million electronic channels connected to silicon pixel sensors with dimensions of $50\,\mu\text{m} \times 400\,\mu\text{m}$ in the outer layers and $50\,\mu\text{m} \times 250\,\mu\text{m}$ in the innermost layer. The small pixel size enables a high-precision position resolution of $10\,\mu\text{m}$ in the $(R - \varphi)$ plane. The silicon pixel thickness is $285\,\mu\text{m}$ [44, 42].

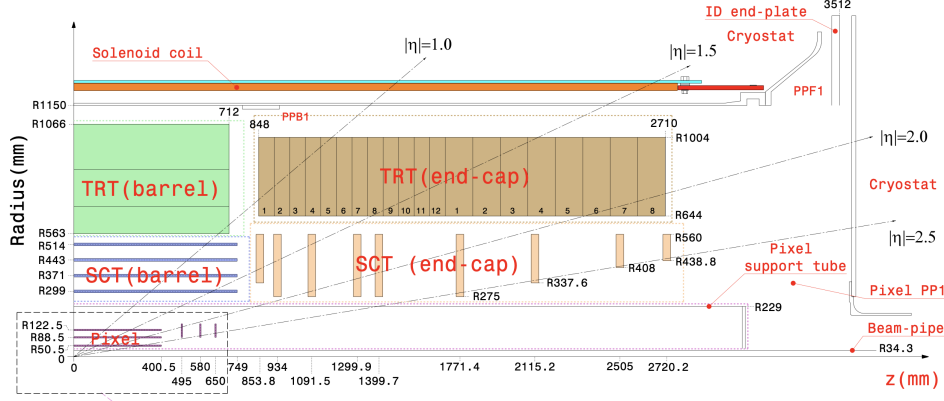


Figure 3.4: Schematic layout of the Inner Detector subsystems [42]

Semiconductor Tracker

The Semiconductor Tracker (SCT) is positioned directly adjacent to the Pixel Detector. It consists of over 4,000 semiconductor modules, providing a position measurement precision of $25\text{ }\mu\text{m}$. The SCT is divided into two segments: the barrel and the end-cap, the latter defining the particle tracking range of the Inner Detector in terms of pseudorapidity η .

Each semiconductor module is equipped with two pairs of silicon strip detectors, with strips rotated by 40 mrad relative to each other. This stereo configuration enables precise position measurement in the direction perpendicular to the strips, improving track reconstruction accuracy [45]. The SCT was designed to ensure that each charged particle produces four precise position measurements, contributing to high-resolution tracking.

Transition Radiation Tracker

TRT in contrast to the previous 2 layers is not composed of semiconductor sensors. Its purpose is also slightly different, besides only providing position measurement, TRT plays critical core in particles identification.

The active component in the Transition Radiation Tracker are 4mm straws acting as drift tubes with length varying by TRT component. For a gas detector a process of transition radiation is associated, which is emission of electromagnetic radiation by a charged particle crosses a boundary between two materials with different dielectric constant. The probability of radiation emission increases with higher Lorentz factor (γ). Hence, it is mostly observed for ultra-relativistic particles such as electrons. Due to this TRT property the straw tubes serve as a vital component in differentiating electrons from hadrons (pions, kaons).

3.4.2 Calorimeters

The ATLAS calorimeters are a system of components designed to measure energy deposition. This is achieved by absorbing the energy of most particles. To ensure a compact calorimeter geometry, high-density absorbing materials are placed between the active media. This setup reduces the detector volume needed for efficient energy measurement.

The two main designs implemented in the geometry are the liquid argon (LAr) calorimeter and the tile calorimeter. In the LAr calorimeter, materials like copper or tungsten are used as absorbers, generating ‘showers’ of lower-energy secondary particles from the initial high-energy particle. These secondary particles ionize the liquid argon, producing measurable electric currents. Liquid argon is chosen as the active detector medium due to its stability over time, radiation hardness, and linear operational response. The electromagnetic (EM) barrel, EM end-cap

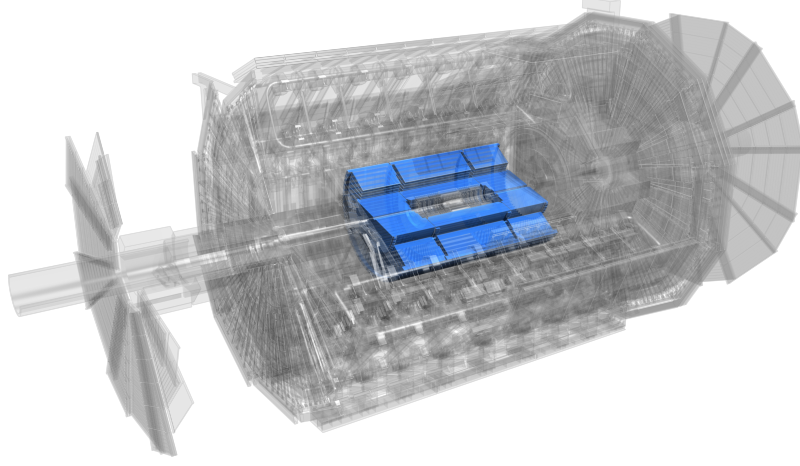


Figure 3.5: Calorimeter subsystem of ATLAS [43]

(EMEC), hadronic end-cap (HEP), and LAr forward (FCal) calorimeters utilize this technology [46].

In the LAr design, an accordion structure is employed to maximize azimuthal angle coverage and facilitate rapid signal extraction at both the front and rear of the electrodes. To maintain argon in its liquid state, this segment of the calorimeter is maintained at a temperature of -184°C [46].

The tile calorimeter is positioned in the outermost layer of the calorimeter system, providing energy measurement for particles that do not deposit all their energy in the LAr calorimeter. Steel plates serve as absorbers, generating low-energy particle showers, while plastic scintillators produce photons that provide information on the deposited energy. The tile calorimeter consists of three segments: one barrel and two extended barrels on either side along the z -axis. Its polar angle coverage is $|\eta| < 1.7$ [42].

The thickness of the calorimeters is expressed in terms of radiation lengths, denoted as X_0 . It is defined as the mean length over which the energy of an electron is reduced by a factor of $1/e$ [47]. For the EM calorimeter, the thickness is at least $22 \cdot X_0$, and for $|\eta|$, it increases to approximately $33 \cdot X_0$ [42].

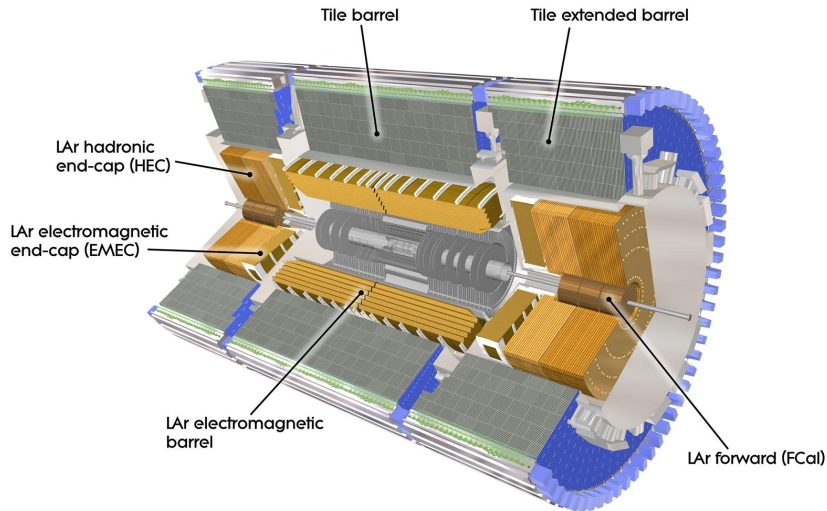


Figure 3.6: Detailed layout of ATLAS calorimeter systems [46]

Pseudorapidity coverage

A key property of the calorimeter system that defines its usable range is its coverage in the plane along the beam axis. This value is quoted separately for energy measurement and for its use as a trigger input.

For the EM calorimeter, the energy measurement coverage is $|\eta| < 3.2$, while the trigger coverage is $|\eta| < 2.5$. All hadronic calorimeter segments (barrel and end-cap) have coverage of $|\eta| < 3.2$ for both energy measurement and trigger input [42].

The hadronic forward calorimeter (FCal) was designed to measure energy deposition for particles produced at very small polar angles with respect to the beam axis. Therefore, its coverage is $3.1 < |\eta| < 4.9$ for both energy measurement and trigger input [42].

Energy resolution

Another critical parameter for quantifying the performance of calorimeters is the relative energy resolution (σ_E/E). This parameter is typically expressed as the quadratic sum of an energy-dependent term (usually $\sim E^{-1/2}$) and a constant term

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b. \quad (3.4)$$

The coefficient a is statistical and related to the fluctuations in the production of secondary particles due to the primary particle's interaction with the absorber. More energetic tracks generate more secondary particles, thereby reducing the uncertainty in the energy measurement. The term b arises from systematic uncertainties, such as detector calibration issues or non-uniformity in the detector response. This term is independent of the incident particle's energy.

Required resolution for the calorimeter subsystems is [42]

- EM calorimeter – $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$;
- barrel and end-cap hadronic calorimeter – $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$;
- forward hadronic calorimeter – $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$.

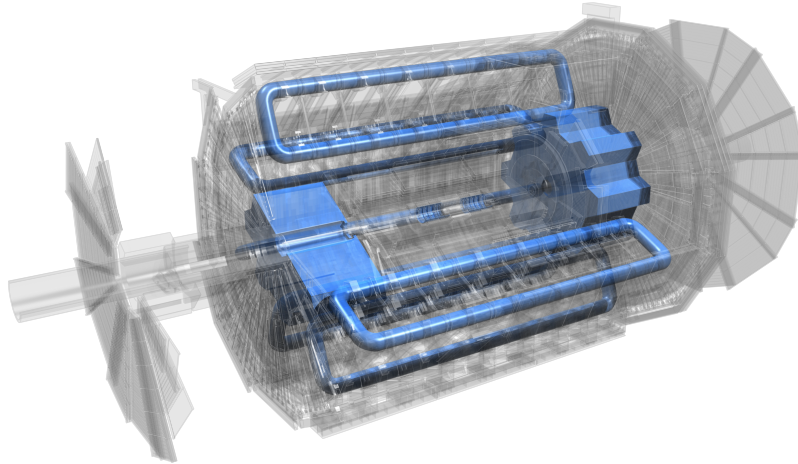


Figure 3.7: The magnet system of ATLAS [43]

3.4.3 Magnet system

The entire ATLAS detector is immersed in the magnetic field for the purpose of the particle tracking. Tracks curvature in the static magnetic field, allows for transverse momentum determination. The magnet system comprises of two main elements

- the solenoid – provides 2 T magnetic field for the Inner Detector;
- the barrel toroid and two-end cap toroids – generate 0.5 T and 1.0 T magnetic field for the muon detector and both end-cap regions.

The solenoid magnet is located between ID and EM calorimeter, hence is required to have minimal material thickness not to affect particles energy deposition. It is achieved by basing the magnetic design on superconducting materials (NbTi). The conductor and coil-winding technology for the barrel toroid is essentially the same as for the solenoid [42].

3.4.4 Muon spectrometer

The muon spectrometer is the outermost layer of the ATLAS detector, dedicated to detecting weakly interacting muons. The tracking of these particles is possible due to the magnetic field generated by the toroid magnet. The spectrometer provides momentum measurement within the range $|\eta| < 2.7$ and triggering within $|\eta| < 2.4$ [42].

The required transverse momentum resolution for muons is $\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV [42].

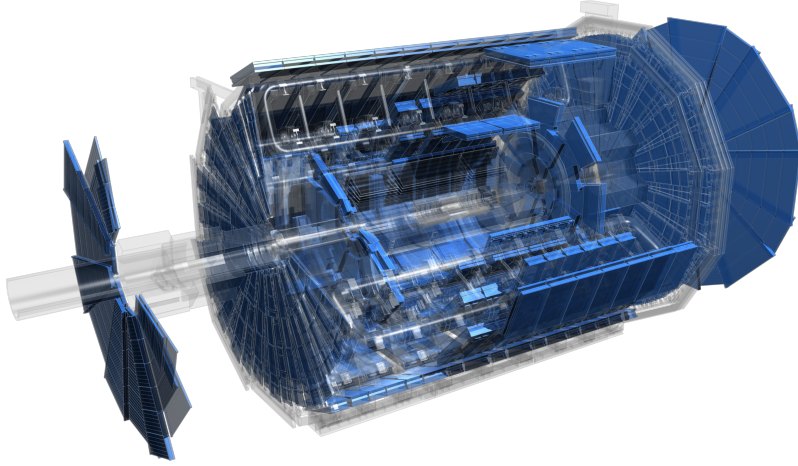


Figure 3.8: The muon spectrometer in ATLAS [43]

The muon spectrometer incorporates five distinct detector technologies: Thin Gap Chambers (TGC), Resistive Plate Chambers (RPC), Monitored Drift Tubes (MDT), Small-Strip Thin-Gap Chambers (sTGC), and Micromegas [48]. Precise position measurements (better than 0.1 mm) are achieved using Monitored Drift Tubes. These consist of 3 mm aluminum tubes filled with gas, which becomes ionized when a charged particle passes through.

3.4.5 Zero Degree Calorimeter

The final detector system crucial for the outlined analysis is the Zero Degree Calorimeter (ZDC). This detector consists of two systems located outside the main ATLAS detector volume, positioned at distances of -140 m and 140 m from the interaction points (ZDC A and ZDC C). Each system contains one electromagnetic (EM) module and three hadronic modules [42].

The significant distance from the interaction point and the location near the beam pipe provide coverage for neutral particles in the high pseudorapidity range, $|\eta| > 8.3$. This is vital for centrality determination, especially in heavy-ion collisions. Additionally, data from the ZDC plays a crucial role in the pile-up cut for Pb-Pb collisions [42].

4 Particle tracking

Particle tracking is one of the initial steps in event reconstruction, following the signal generation in the silicon Inner Detector sensors. This detector component, described in more detail in [Section 3.4.1](#), provides spatial coordinate information of ionized sensors. For particle tracking mostly pixel detector and semiconductor tracker (SCT) are utilized. During the clusterization process, the information from individual pixel or strip sensors is converted into space-points¹.

Clustering

Space-point coordinates do not strictly correspond to a single pixel position, as a charged particle can induce a response in multiple adjacent pixels due to charge sharing. This effect must be accounted for, as it reduces the charge collected by an individual sensor element, potentially making it insufficient to surpass the signal threshold.

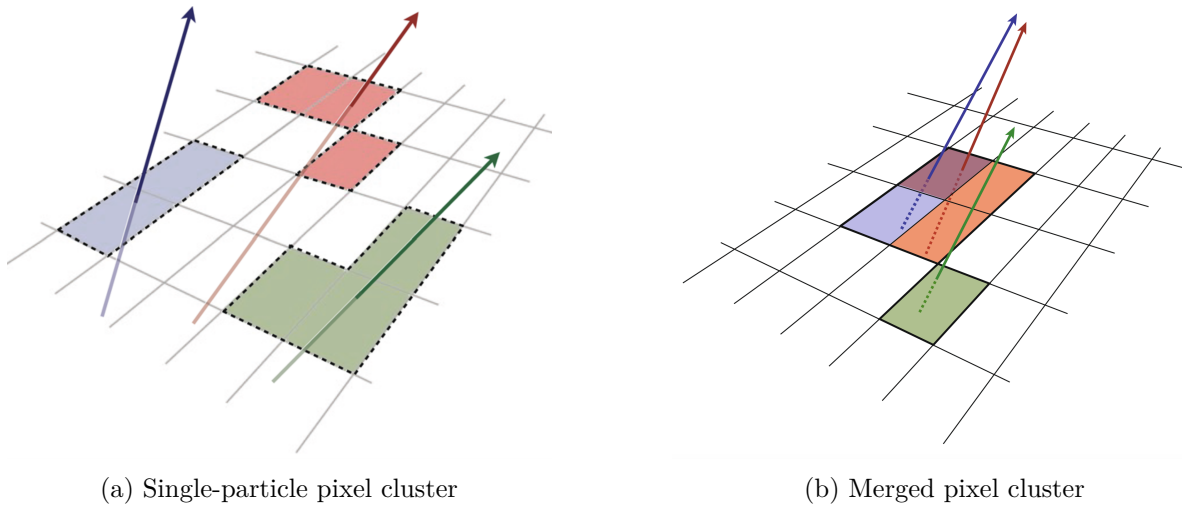


Figure 4.1: Single-particle and merged pixel clusters [\[49\]](#)

Raw measurements are translated into cluster positions using connected component analysis (CCA), which groups adjacent pixels or strips into a single cluster, yielding one space-point. In pixel detectors, each cluster typically corresponds to one space-point. In contrast, for the Semiconductor Tracker (SCT), data from both stereo strip layers are combined to form a single cluster [\[49\]](#).

In the barrel pixel detector, a cluster typically consists of approximately two pixels in the r - φ plane and between one and three pixels in the longitudinal (η) direction. The cluster size depends on the track's path length through the sensor, which varies with the incident angle relative to the sensor plane [\[49\]](#).

¹**Space-points** – a three-dimensional point indicating the ionization position on the sensor, used as input for the particle tracking algorithm. Point coordinates where the charged particle came into contact with the Inner Detector material.

In environments with a high density of particle tracks, the separation between clusters may become too small for the CCA algorithm to distinguish them as individual entities. As a result, a single cluster may merge the energy depositions from multiple particles. A comparison of these two cases is shown in [Figure 4.1](#) [49].

Reconstructed clusters and corresponding space-points are subsequently used for initial seeds generation, composed of three space-points. This approach allows a first momentum estimate, while maximizing possible space-points number of combinations. To ensure high track purity² number of requirements are imposed on seeds such as seed-type-dependent momentum and impact parameter requirement, or ensuring that particle trajectory is compatible with at least one additional space-point. Purity depends also on subdetector whose space-points are used for seed generation. Thus, at this stage only SCT data is used.

4.1 Combinatorial Kalman filter

To build a complete track candidate, a combinatorial Kalman filter is implemented. It is an iterative procedure whose underlying concept is extrapolating particle trajectory to the next detector layer and correct parameters estimate by a new space-point. This algorithm consists of several steps, in which iteration from the first to the last data point is performed. In contrast to a more crude χ^2 method, Kalman filter reduces computation complexity, and size of a matrix that must be inverted at each step, by integrating to a track candidate just one new space-point at the time. Kalman approach requires inverting a 2×2 matrix at each iteration, which is described by an analytical formula. In contrast χ^2 method involves handling matrix whose dimensional is proportional to $2n$, when each of n space-points is described by 2 parameter (in a xy plane).

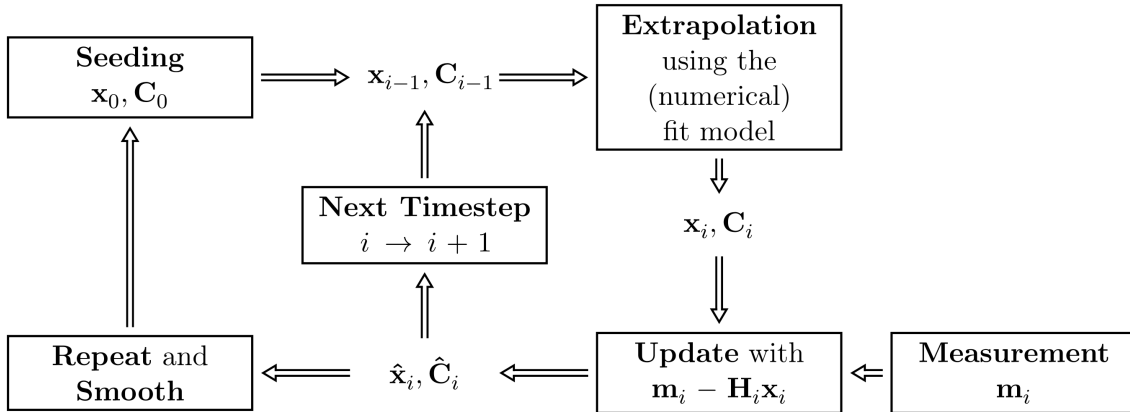


Figure 4.2: Schematic Kalman filter procedure [50]

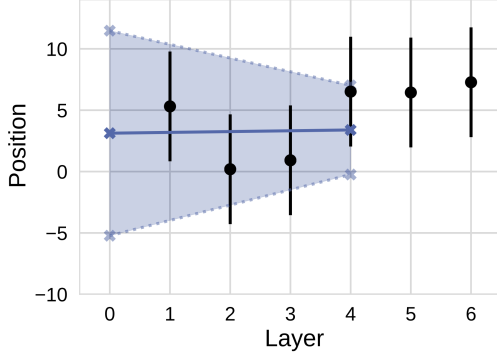
To present an example of combinatorial Kalman filtering, a linear model fitting to m measurements of (x, y) will be assumed, where x_i is discrete. The state of the parameter fitted to the model in each iteration step i can be expressed as $\mathbf{x}_i = (y_i, s)^T$. For linear function the fit is parameterized by y position and slope s [50]. The state in the next step can be expressed by an extrapolating formula

$$\mathbf{x}_i \longrightarrow \mathbf{x}_{i+1} = \begin{pmatrix} y_i + s_i \Delta x_i \\ s_i \end{pmatrix} = \mathbf{F}_i(\mathbf{x}_i) = \begin{pmatrix} 1 & \Delta x_i \\ 0 & 1 \end{pmatrix} \cdot \mathbf{x}_i, \quad (4.1)$$

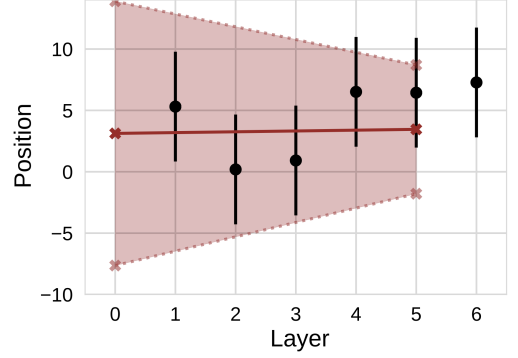
where $\mathbf{F}_i$ is a function dependent on the step i and given by the fit model. Following the extrapolation procedure, the fit parameters estimates is corrected by the new measurement point

²Fraction of seeds that result in a quality track candidate.

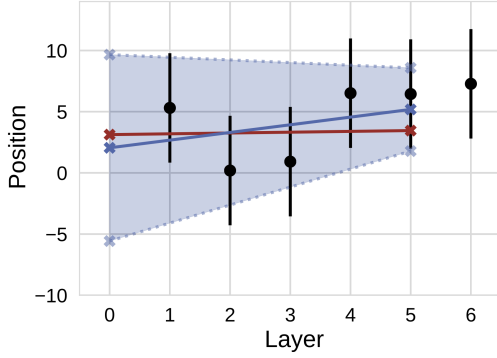
m_i included in the model. The Figure 4.2 presents the schematic description of the Kalman filter. The Figure 4.3 visually depicts the idea of the fitting procedure.



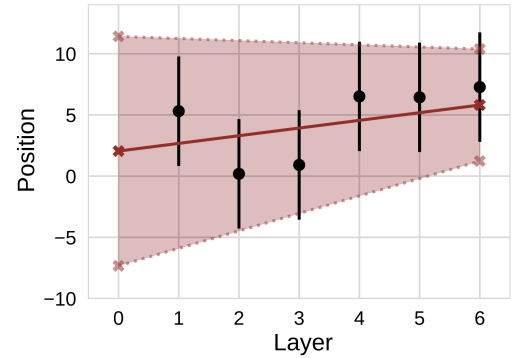
(a) Estimate of the parameters for x points in the first 4 layers



(b) Extrapolation for the point in the fifth layer



(c) Update of the fit parameters due to another point included in the fit



(d) Updated fit line extrapolated for another layer

Figure 4.3: Example of one fitting iteration in the Kalman filter, blue line – estimate of the model parameters, blue band – uncertainties of the estimate, red line – model extrapolation, red band – uncertainty of the model extrapolation [50]

Following the parameters extrapolation, the new state and covariance matrix are updated by new information. To further improve fit to the measurement points, the procedure can be repeated, where results of the former run, is used as a seed for the next one. To avoid overfitting, measurement uncertainty are artificially increased. Also, this algorithm can be executed in the reverse order to compute average state at each measurement, which is reference as a smoothing procedure.

Track scoring

The last particle tracking step is track scoring and ambiguity solving. The χ^2 metric is used to quantitatively measure quality of track fitting to the space-points. Holes³ decrease the χ^2 score of the track. Due to merged cluster, it is possible for two tracks to share the same space-point. No cluster can be shared by more than 2 tracks and no track should be based on more than 2 shared clusters [49].

³Intersection of a particle track with Inner Detector sensors, where no cluster was identified.

5 Analysis framework

The analysis was conducted using the ROOT C++ framework, specifically with ROOT version 6.34.04. The complete analysis code is available in the corresponding `GitLab` repository: https://gitlab.cern.ch/shoroden/qgp_analysis [51].

The analysis extensively employed the `FunRootAna` framework, which introduces a more functional programming approach to ROOT-based analyses [52, 53].

For this purpose, `NTuple` files [54] were generated from the raw `AOD` files [55]. The `AOD` (Analysis Object Data) format contains all the essential detector-level information required for physics analyses, based on calibrated and filtered raw data. These `NTuple` files were tailored to the analysis by storing only the relevant track and event-level parameters.

The raw `AOD` files were processed using the `Athena` framework [56], specifically with the `vnpt_ntuples_prod` pipeline [57], based on `AnalysisBase`, 25.2.29. The output included jet information and detailed track parameters such as d_0 and z_0 , while restricting the dataset to central events ($E_T^{\text{FCal}} > 4 \text{ TeV}$).

All the result plots, presented mostly in [Chapter 9](#) and [Chapter 10](#), were generated using the `quick-root-plots` framework [58].

6 Dataset

The analysis was performed using data collected by the ATLAS detector during 2018 (Run 2), featuring Pb–Pb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV.

The dataset covers the pseudorapidity range $|\eta| < 2.5$ and is primarily based on the UCC (ultra-central collisions) data stream. To validate pile-up rejection cuts and compare results with reference analyses, events from the MinBias data stream were also used. This stream is designed to provide a representative and unbiased sample of inelastic collisions. All selected events satisfy the Good Runs List (GRL) criteria.

The detector layout relevant to this analysis is described in [Section 3.4](#). The Inner Detector operates within a 2 T magnetic field.

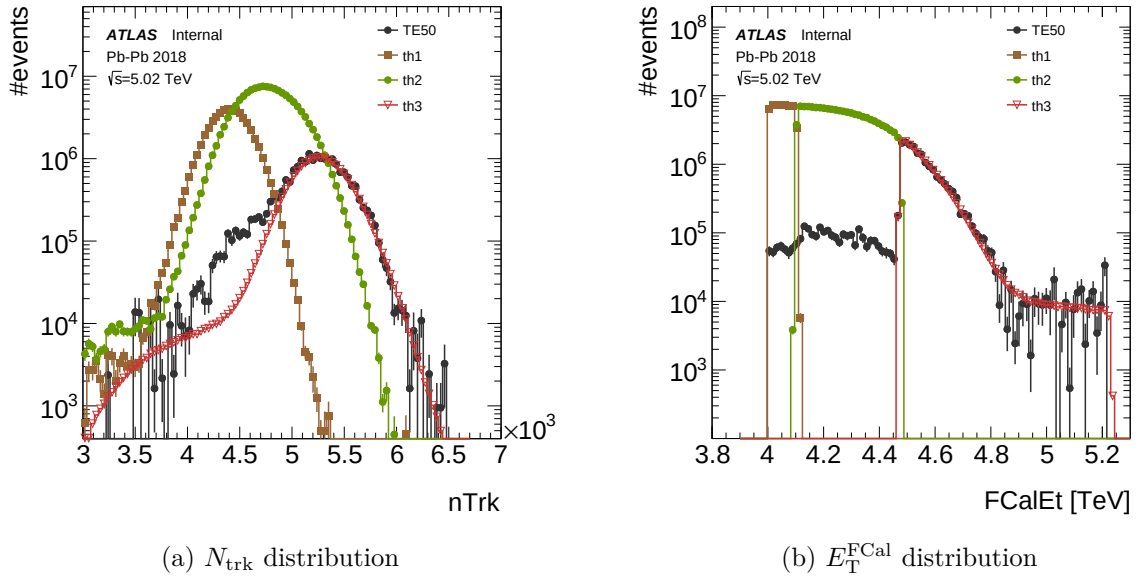


Figure 6.1: N_{trk} and $E_{\text{T}}^{\text{FCal}}$ distribution for a single trigger

For the MinBias 2018 events, the following triggers were used:

- HLT_mb_spitrk_ion_L1ZDC_A_C_VTE50;
- HLT_noalg_mb_L1TE50.

For the 2018 UCC events, the following triggers were required:

- HLT_noalg_mb_L1TE50;
- HLT_hi_th2_ucc_L1TE12000;
- HLT_hi_th3_ucc_L1TE12000.

These triggers are described in detail in [Chapter 8](#). Pile-up events in the UCC dataset were removed according to the procedure outlined in [Section 8.2](#).

[Figure 6.1](#) shows $E_T^{\text{FCal}} N_{\text{trk}}$ distributions, for triggers used in the analysis.

NTuples used in the analysis were generated using the framework introduced in [Chapter 5](#). The AOD files used for **MinBias** and **UCC** data streams are listed in [Table 6.1](#) and [Table 6.2](#), respectively. In total, data from 27 **MinBias** runs and 29 **UCC** runs were included in the analysis.

Table 6.1: AOD files for MinBias 2018 data

Data stream	Dataset
MB	data18_hi.00366011.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366092.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367165.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00365627.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00366691.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366337.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366627.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367099.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367365.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367318.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366860.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366878.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367023.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00365678.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00367233.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366754.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366919.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366931.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366142.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00366383.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00367363.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00365602.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00365681.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00366526.physics_MinBias.merge.AOD.f1030_m2048
MB	data18_hi.00365573.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00365709.physics_MinBias.merge.AOD.f1030_m2055
MB	data18_hi.00366476.physics_MinBias.merge.AOD.f1030_m2048

Table 6.2: AOD files for UCC 2018 data

Data stream	Dataset
UCC	data18_hi.00366413.physics_UCC.merge.AOD.f1027_m2048
UCC	data18_hi.00366337.physics_UCC.merge.AOD.f1027_m2037
UCC	data18_hi.00366268.physics_UCC.merge.AOD.f1027_m2037
UCC	data18_hi.00366142.physics_UCC.merge.AOD.f1027_m2037
UCC	data18_hi.00366011.physics_UCC.merge.AOD.f1027_m2037
UCC	data18_hi.00366528.physics_UCC.merge.AOD.f1027_m2048
UCC	data18_hi.00366476.physics_UCC.merge.AOD.f1027_m2048

Continued on next page

Data stream	Dataset
UCC	data18_hi.00366627.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366691.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366754.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366805.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366860.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366878.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366919.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366931.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00366994.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367023.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367099.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367134.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367165.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367170.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367233.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367273.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367318.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367321.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367363.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367364.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367365.physics_UCC.merge.AOD.f1030_m2048
UCC	data18_hi.00367384.physics_UCC.merge.AOD.f1030_m2048

7 Track selection and weights

The reconstructed tracks satisfy stringent criteria, primarily aimed at reducing the fake track rate. For the purpose of this analysis, high purity is preferred over efficiency. This is achieved by applying additional selection requirements during the analysis. These criteria follow those outlined in the ATLAS note *Azimuthal anisotropies of charged particles with high transverse momentum in Pb+Pb collisions at 5.02 TeV* (ANA-HION-2023-04-INT1) [59].

All tracks used in the analysis satisfy the following selection criteria:

- **HITight** track selection;
- $p_T > 1 \text{ GeV}$ – to exclude low- p_T particles, which have the highest fake track rate;
- $|\eta| < 2.5$;
- $|d_0/\sigma_{d_0}| < 3$;
- $|d_0| \leq 0.47 \cdot \exp(-0.15 \cdot p_T) + 0.19 \cdot \exp(-0.00034 \cdot p_T)$ – the requirement is illustrated in [Figure 7.1](#);
- $|z_0 \sin \theta / \sigma_{z_0 \sin \theta}| < 3$;
- $\Delta R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} < 0.4$ – used to match tracks to jets. A high- p_T track without a corresponding jet within this cone is likely due to misreconstruction. Here, $\Delta\varphi$ and $\Delta\eta$ denote the differences in azimuthal angle and pseudorapidity between the track and the jet, respectively. Because only high p_T tracks are expected to match jets, this selection requirements is effective only for $p_T > 20 \text{ GeV}$ [60].

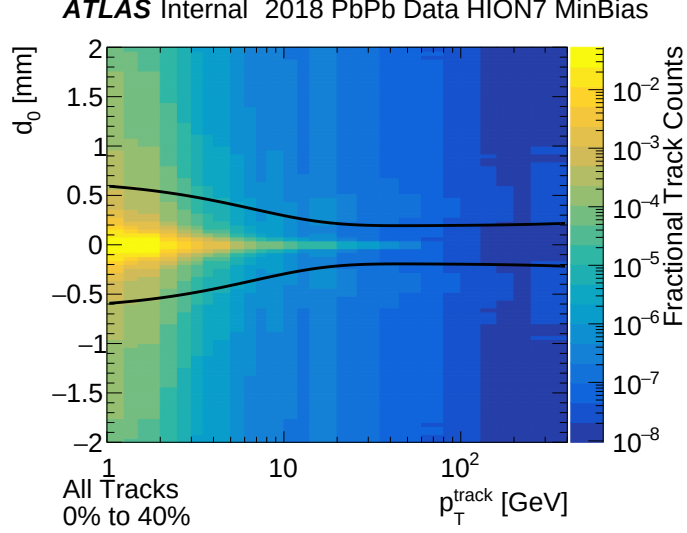
To evaluate $\sigma_{z_0 \sin \theta}$ via uncertainty propagation, it was assumed that $\sigma_\theta \ll \sigma_{z_0}$. This is a justified approach, since track angles are measured with very high precision in ATLAS.

A tighter requirement on d_0 is applied compared to the standard **HITight** selection to suppress secondary tracks, particularly at high p_T .

The track selection criterion involving the number of SCT holes, as described in ANA-HION-2023-04-INT1, was not applied in this analysis due to the unavailability of this parameter in the provided datasets.

The **HITight** track selection ensures the following criteria are satisfied [59]:

- $|\eta| < 2.5$;
- at least one Insertable B-Layer (IBL) hit is required if a hit is expected; otherwise, at least one B-Layer hit is required if expected;
- the combined number of pixel hits (including IBL) and crossed dead sensors must be at least 2, i.e., $N_{\text{Pix}} \geq 2$;
- the combined number of Semiconductor Tracker (SCT) hits and crossed dead sensors must satisfy:


 Figure 7.1: Visualization of the exponential d_0 , p_T -based cut [60]

- $N_{\text{SCT}} \geq 4$ for $p_T > 0$ MeV;
- $N_{\text{SCT}} \geq 6$ for $p_T > 300$ MeV;
- $N_{\text{SCT}} \geq 8$ for $p_T > 400$ MeV;
- transverse impact parameter with respect to the primary vertex: $|d_0^{\text{PV}}| < 1$ mm;
- longitudinal impact parameter with respect to the primary vertex: $|z_0^{\text{PV}} \sin \theta| < 1$ mm;
- track fit quality: $\chi^2/\text{dof} < 6$.

7.1 Track weights

To account for missing and fake tracks in the data set, a Monte Carlo simulation is used to estimate the reconstruction efficiency and fake rates as functions of p_T , η , and N_{trk} . The reconstruction efficiency ε is defined as:

$$\varepsilon(p_T, \eta, N_{\text{trk}}) = \frac{\text{N generated particles matched to tracks}}{\text{N number of generated particles}}. \quad (7.1)$$

The fake rate f is given by:

$$f(p_T, \eta, N_{\text{trk}}) = \frac{\text{N reconstructed tracks unmatched to tracks}}{\text{N tracks}}. \quad (7.2)$$

The quantity ρ is defined as

$$\rho(p_T, \eta, N_{\text{trk}}) = \frac{\varepsilon(p_T, \eta, N_{\text{trk}})}{1 - f(p_T, \eta, N_{\text{trk}})}. \quad (7.3)$$

The weight assigned to each track, defined by the parameters $(p_T, \eta, N_{\text{trk}})$, is then given by

$$\xi_{\text{trk}}(p_T, \eta, N_{\text{trk}}) = \frac{1}{\rho(p_T, \eta, N_{\text{trk}})}. \quad (7.4)$$

Parameters distribution

One-dimensional projections of the track counts as a function of parameters p_T , η , and N_{trk} for truth particles, reconstructed, matched, and unmatched tracks are shown in [Figure 7.2](#) and [Figure 7.3](#). They are obtained from MC simulation of the Hijing generated events in ATLAS detector.

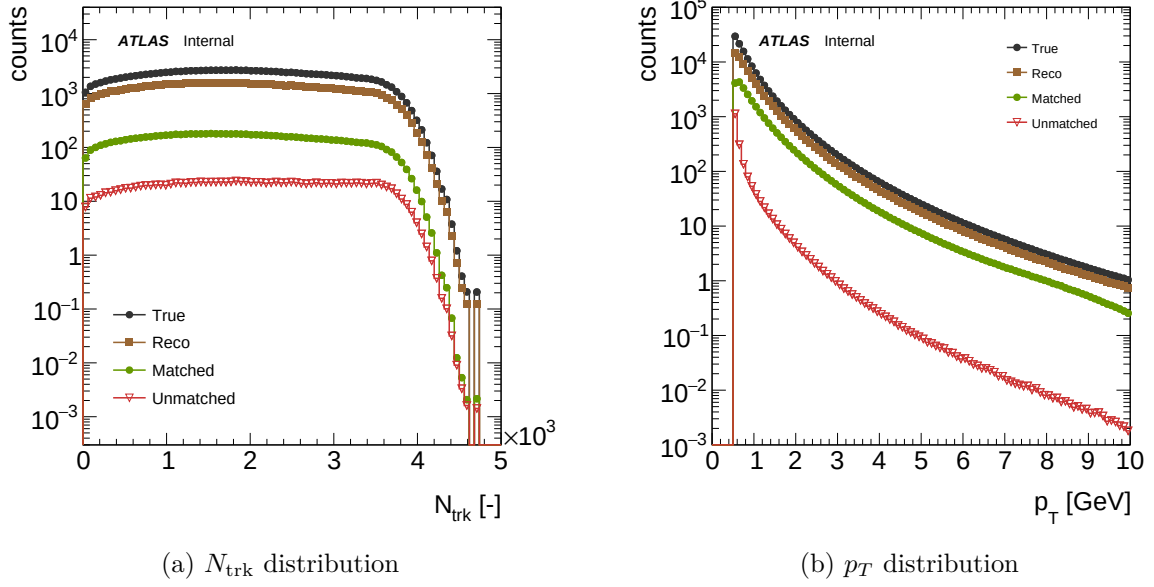


Figure 7.2: The count of generated particles, all, matched and unmatched reconstructed tracks obtained from ATLAS detector response to Hijing generated events as a function of tracks multiplicity (left) and object transverse momenta, p_T (right)

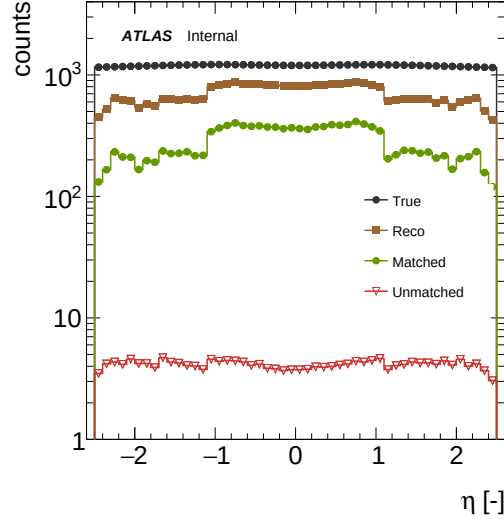


Figure 7.3: As in [Figure 7.2](#) as a function of object pseudorapidity η

Efficiency and fake rate extrapolation to high p_T

Parameter ranges crucial for the QGP analysis include high transverse momentum (well above 10 GeV) and high track multiplicity. Due to the limited coverage of the Monte Carlo dataset and

significantly lower statistics for transverse momentum near p_T of interest the estimates have low statistical precision. For that reason a fit is use to reduce the impact of fluctuations. Both linear and logarithmic functions have been fitted to the p_T distribution in a narrow pseudorapidity slice to determine which is more suitable. Histograms in [Figure 7.4](#) and [Figure 7.5](#) indicate the necessity of extrapolating these distributions. Beyond a cutoff momentum of approximately 4 GeV, the low statistics introduce significant fluctuations in the data distributions.

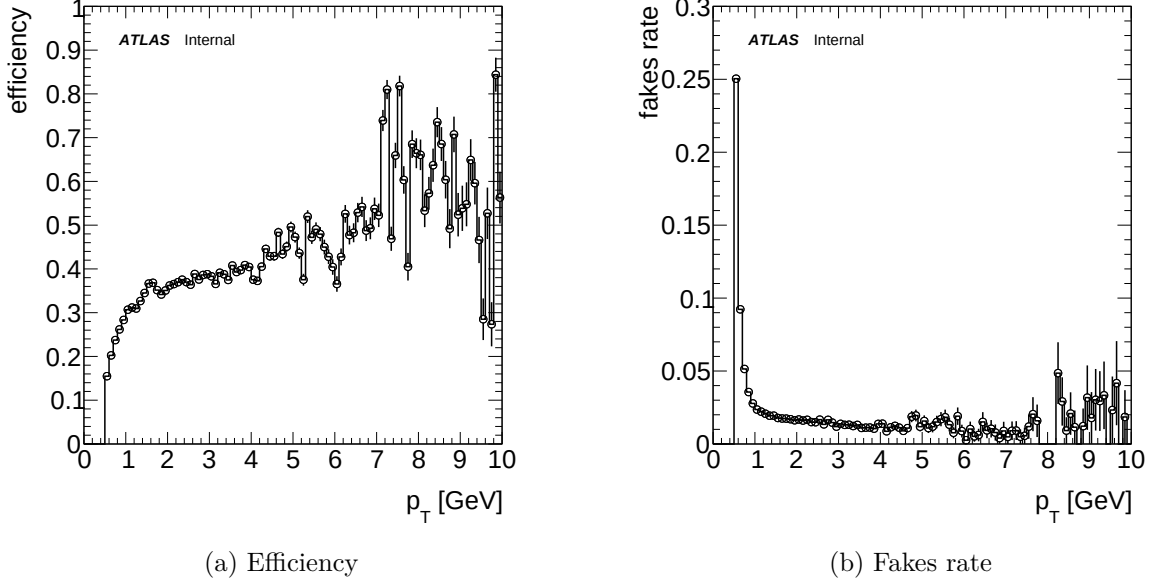


Figure 7.4: Efficiency and fakes rate as a function of p_T at high values of track p_T

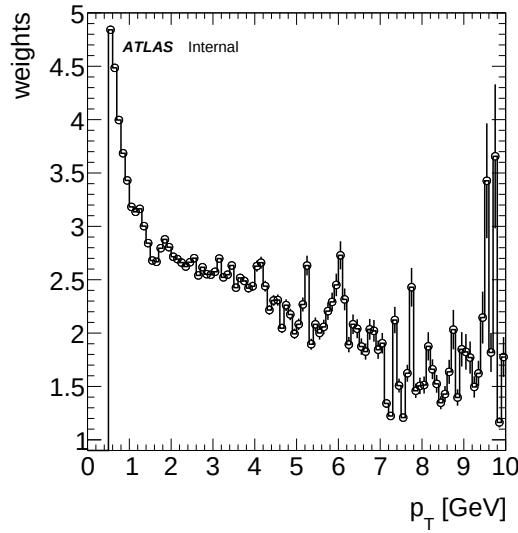


Figure 7.5: Weights as a function of p_T up to a high value of p_T

The linear and logarithmic fit parameters were subsequently used to extrapolate the parameter distributions beyond the low fluctuations region. The goal of this approach was to generate a two-dimensional weight histogram as a function of η and p_T . Weight parametrization as a function of track multiplicity were not introduced as the analysis cover narrow range of multiplicities.

The track multiplicity range was limited to $N_{\text{trk}} \in [3350, 6000]$. The pseudorapidity interval $\eta \in [-2.5, 2.5]$ was divided into 30 equally spaced bins. For each bin, a projection onto the p_T

axis within the corresponding η slice was used to determine the efficiency. Linear and logarithmic function fits were performed on the resulting histograms in the transverse momentum ranges $[2 \text{ GeV}, 6 \text{ GeV}]$ and $[1 \text{ GeV}, 6 \text{ GeV}]$, respectively. The fitted functions and the extrapolated values for the efficiency and weight histograms in two selected η bins are shown in [Figure 7.6](#) and [Figure 7.7](#) for the linear fits, and [Figure 7.8](#) and [Figure 7.9](#) for the logarithmic fits. The procedure has been visualized for different η ranges, as the efficiency varies significantly with pseudorapidity – it reaches much higher values in the central region –

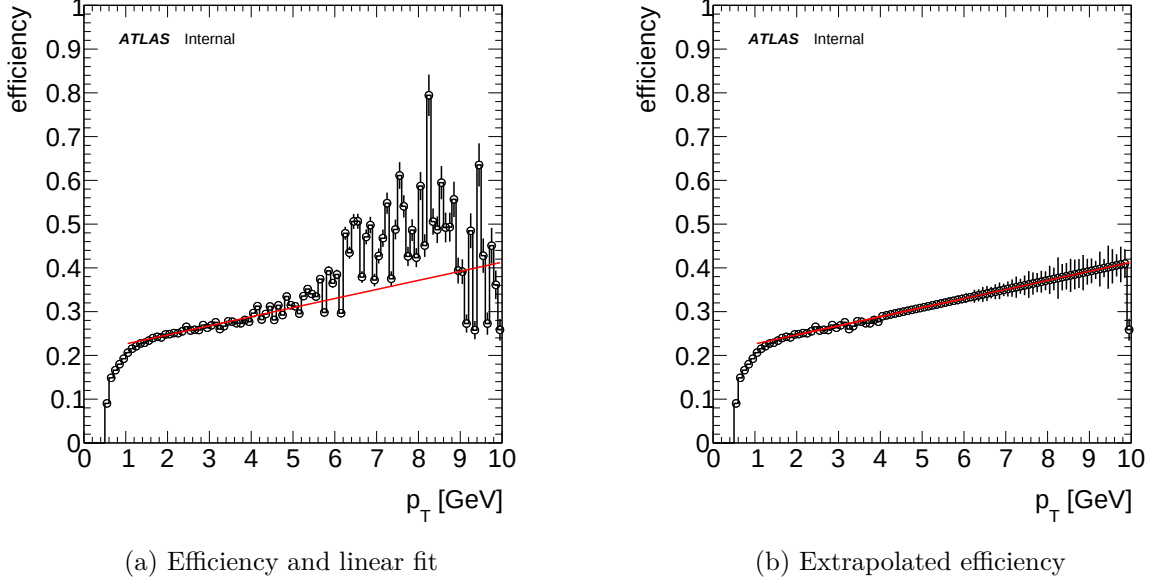


Figure 7.6: Efficiency histogram with linear fit and interpolated values beyond 6 GeV, $\eta \in [-2.5, -2.33]$

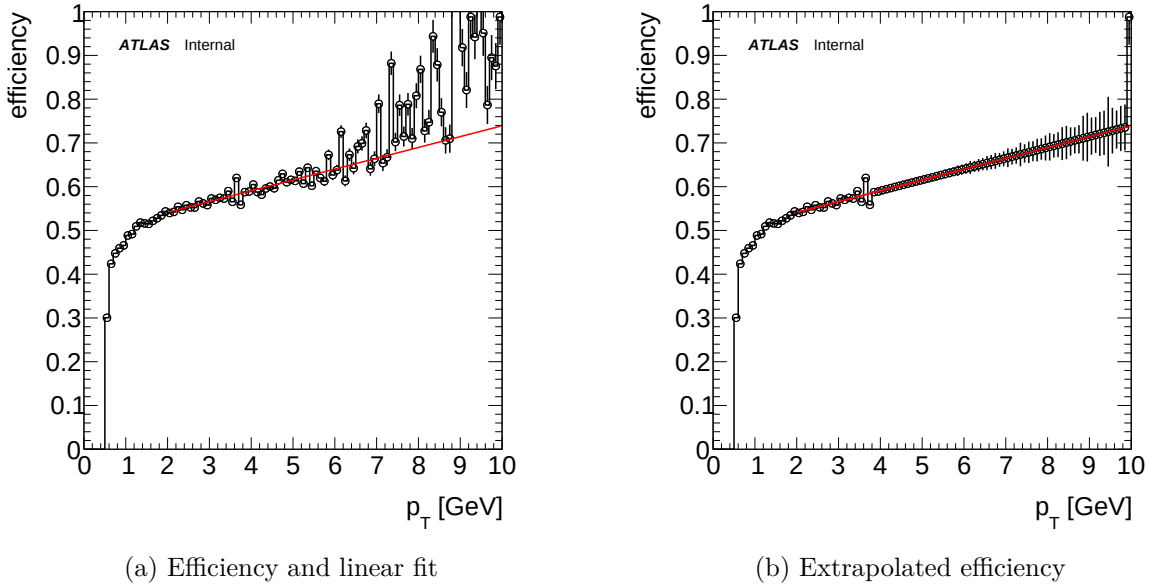
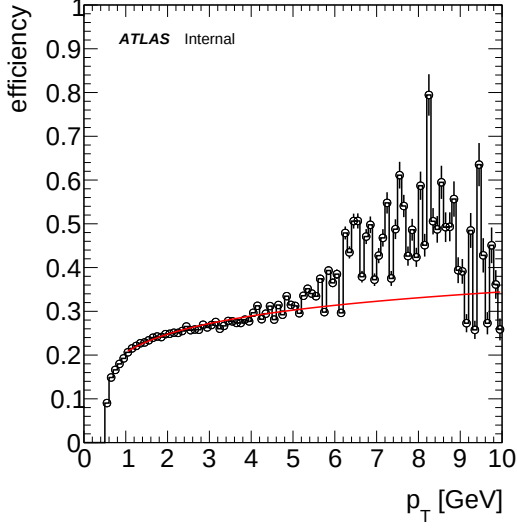
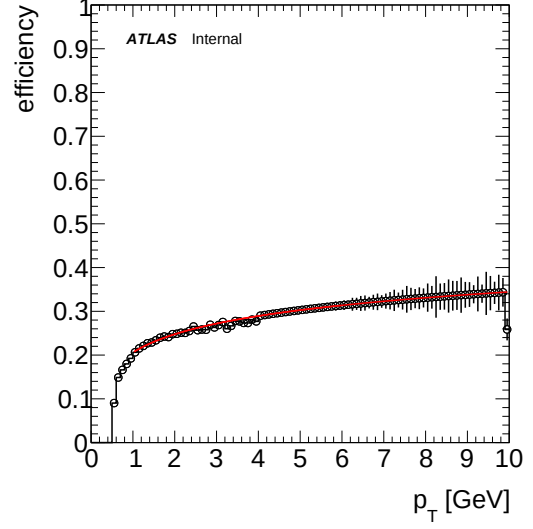


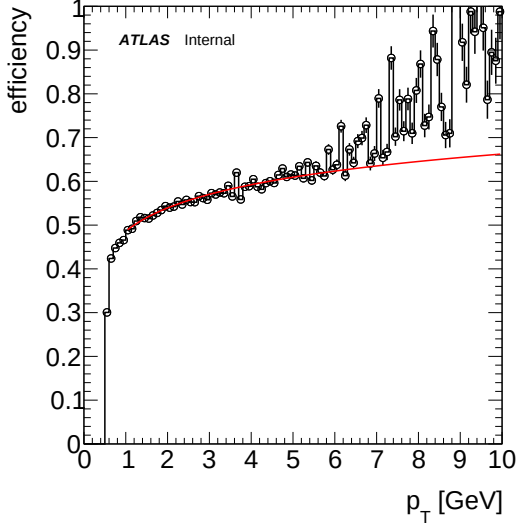
Figure 7.7: Efficiency histogram with linear fit and interpolated values beyond 6 GeV, $\eta \in [0, 0.17]$



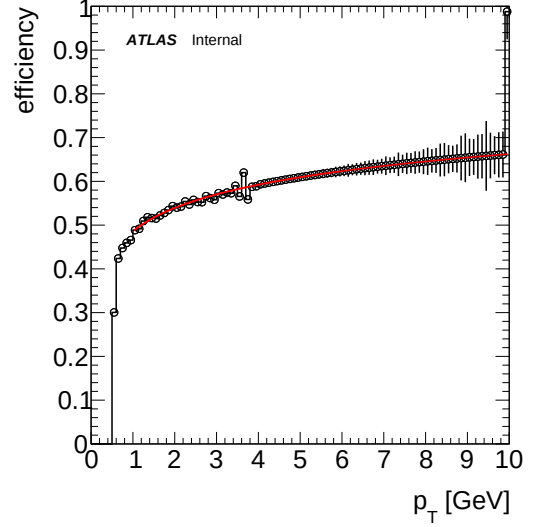
(a) Efficiency and logarithm fit



(b) Extrapolated efficiency

 Figure 7.8: Efficiency histogram with logarithm fit and interpolated values beyond 6 GeV, $\eta \in [-2.5, 2.33]$


(a) Efficiency and logarithm fit



(b) Extrapolated efficiency

 Figure 7.9: Efficiency histogram with logarithm fit and interpolated values beyond 6 GeV, $\eta \in [0, 0.17]$

All fit parameters are summarized in [Table B.1 \(Appendix B\)](#). The noticeable variation in parameter values across different η slices justifies the division in pseudorapidity. Due to the very low fake rates and reduced statistical fluctuations, a similar treatment is not required for the fake rate histograms. The efficiency histograms, with extrapolated bin values above 6 GeV, were then used to evaluate weights according to [Equation 7.1](#), [Equation 7.3](#), and [Equation 7.4](#). [Figure 7.10](#) shows the resulting weight histograms for linear and logarithmic extrapolations in the pseudorapidity range $\eta \in [0, 0.17]$.

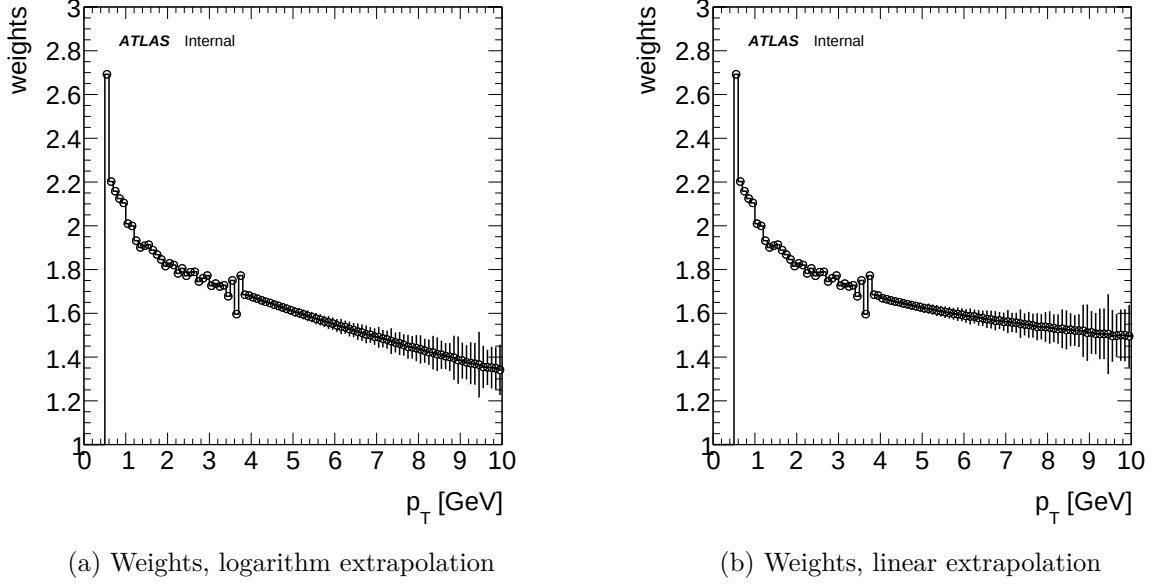


Figure 7.10: Weights histograms calculated using efficiency histograms with extrapolated bin values, $\eta \in [0, 0.17]$

The linear and logarithmic fits performed for each η slice, followed by efficiency extrapolation above a certain p_T threshold and corresponding weight estimation, result in 30 weight distributions as functions of transverse momentum. For efficient access to the track weights ξ_{trk} , these one-dimensional histograms are combined into a single two-dimensional histogram, defining the weights as a function of η and p_T – Figure 7.11. The discrepancy between the two fit methods is minimal and becomes noticeable primarily at high p_T . For tracks with transverse momentum exceeding 10 GeV, the weight corresponding to $p_T = 10$ GeV is assigned, based on the assumption that efficiency and fake rate stabilize at high transverse momentum.

Applying the Monte Carlo-derived weight to each track yields a weight distribution consistent with the histogram shown in Figure 7.12.

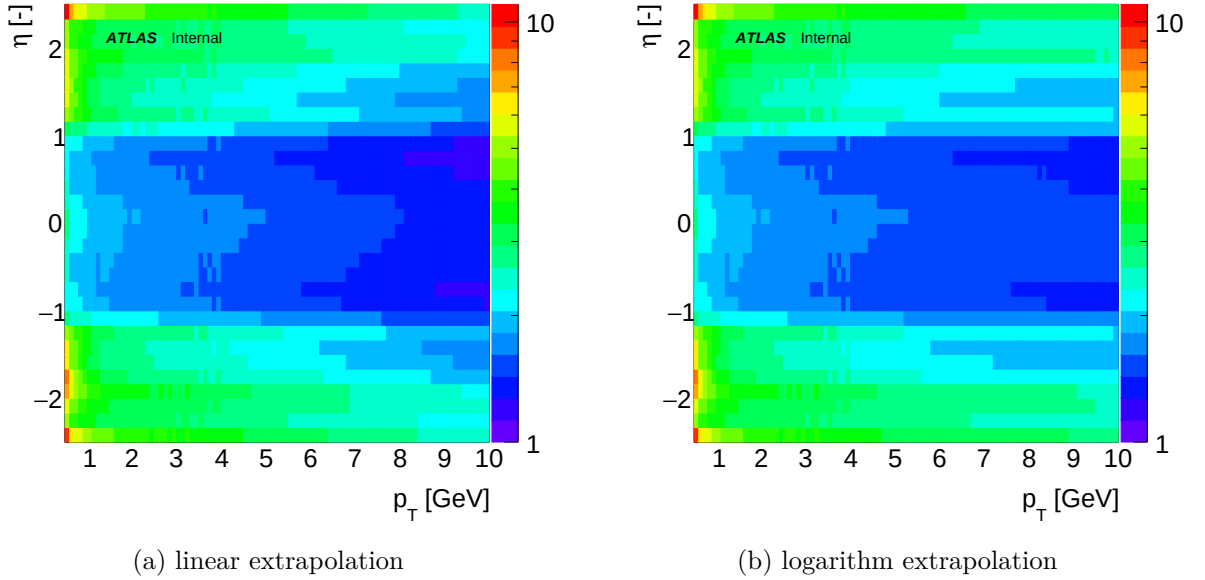


Figure 7.11: Weights histogram as a function of η and p_T

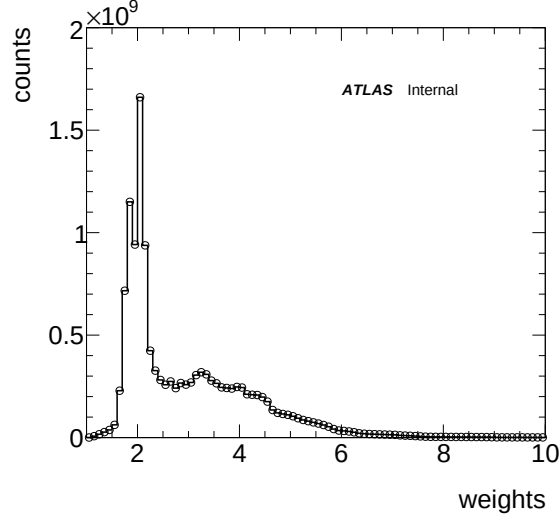


Figure 7.12: Histogram of weights that are applied to tracks for tracks of all p_T and η on 2015 UCC Pb-Pb data

7.2 Track cutflow

The impact of the track selection criteria used in the analysis is summarized in the cutflow plot. This plot shows the number of tracks or events remaining after the successive application of each selection criterion, with each cut applied cumulatively on top of the previous ones.

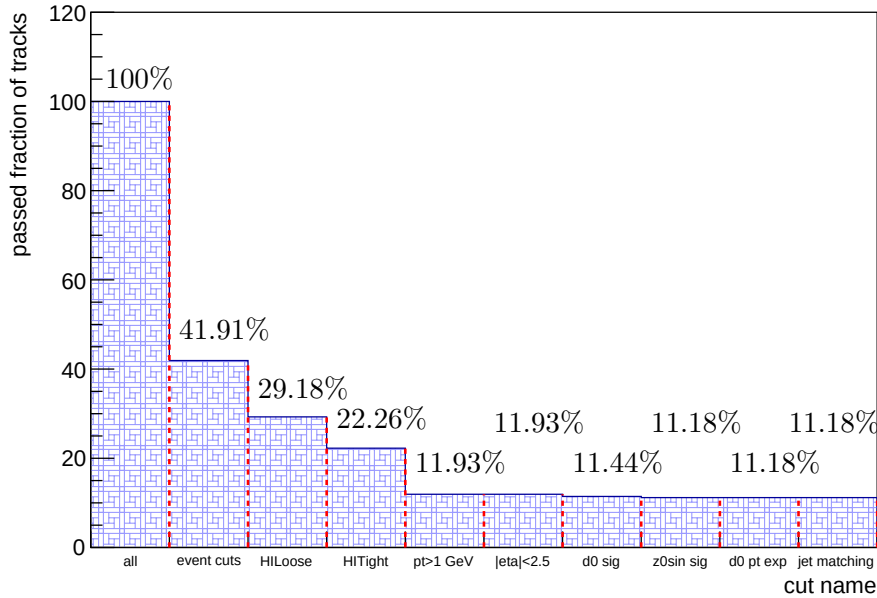


Figure 7.13: Track cutflow histogram showing the relative track yield when additional track selection requirements are included. x -axis description: **events cuts** – all the cuts outlined in the [Chapter 8](#), **d0 sig** – $|d_0/\sigma_{d_0}| < 3$, **z0 sig** – $|z_0 \sin \theta / \sigma_{z_0 \sin \theta}| < 3$, **d0 pt exp** – $|d_0| \leq 0.47 \cdot \exp(-0.15 \cdot p_T) + 0.19 \cdot \exp(-0.00034 \cdot p_T)$, **jet matching** – $\Delta R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} < 0.4$ for tracks whose p_T is above 20 GeV

The cutflow in [Figure 7.13](#) shows that further track requirements, such as those involving

d_0 and z_0 parameters, as well as the jet matching criterion, do not significantly reduce the track count beyond the earlier cuts, especially the **HITight** track quality requirement. The most substantial reduction arises from the cumulative effect of the **HITight** selection. The **HIloose** selection is included primarily to illustrate the difference between the two track quality criteria.

Since the analysis focuses on the high- p_T region, the standard cutflow – [Figure 7.13](#), offers limited insight into these particles, whose yield is orders of magnitude smaller than that of low- p_T tracks. To better understand how the transverse momentum spectrum is shaped by the selection criteria, a p_T cutflow plot was produced, comparing p_T distributions at each selection step.

Two types of p_T -cutflow plots were generated: one with cuts applied cumulatively, and another with each cut applied individually. These plots provide a more detailed view of how each selection influences the overall p_T spectrum, particularly in the high- p_T region.

p_T cutflow

The p_T cutflow plot presents the transverse momentum distribution after each cut, either applied individually or progressively. [Figure 7.14](#) shows the p_T distribution with each cut applied separately, while [Figure 7.15](#) displays the cumulative effect of cuts, analogous to the standard cutflow in [Figure 7.13](#).

From these plots, it can be concluded that nearly all selection criteria noticeably reduce the yield of high- p_T tracks. A distinct discontinuity at 20 GeV is associated with the jet matching cut, which becomes effective at that transverse momentum threshold. Event-level selections (outlined in [Chapter 8](#)) have minimal impact on the p_T distribution. The most stringent reduction comes from the **HITight** requirement, which decreases the high- p_T track yield by approximately $\mathcal{O}(10^5)$.

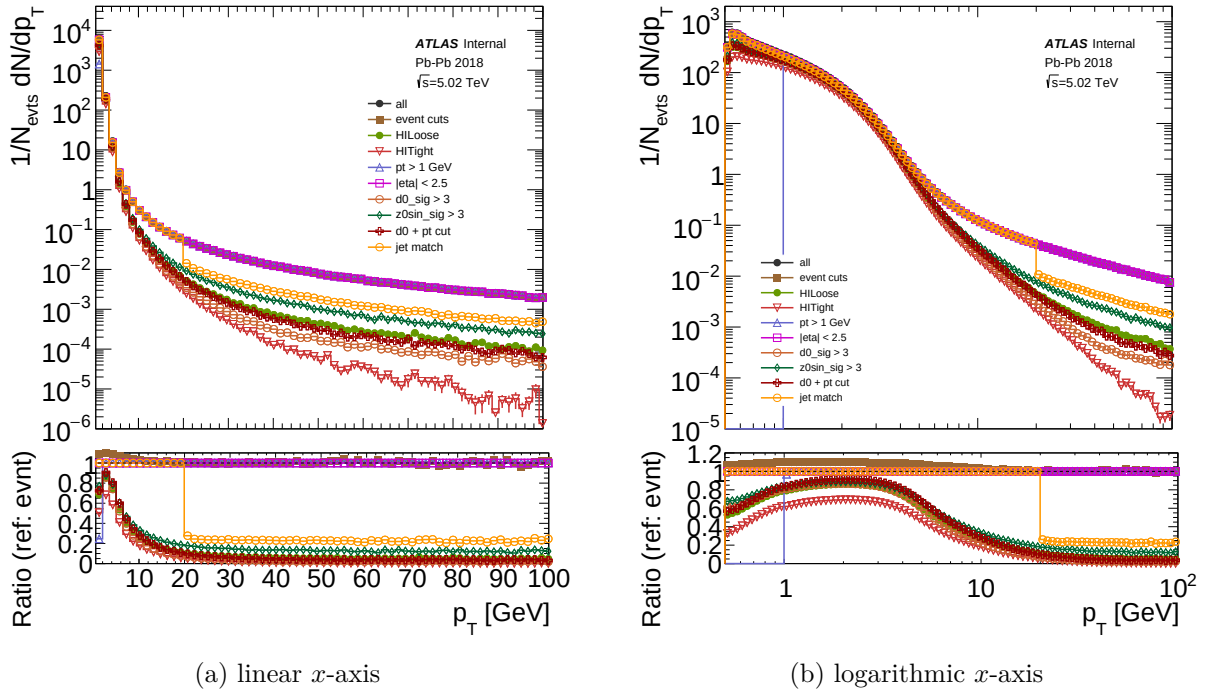


Figure 7.14: The p_T cutflow plot showing impact of each track cut separately on the transverse momentum distribution, one cut at a time included

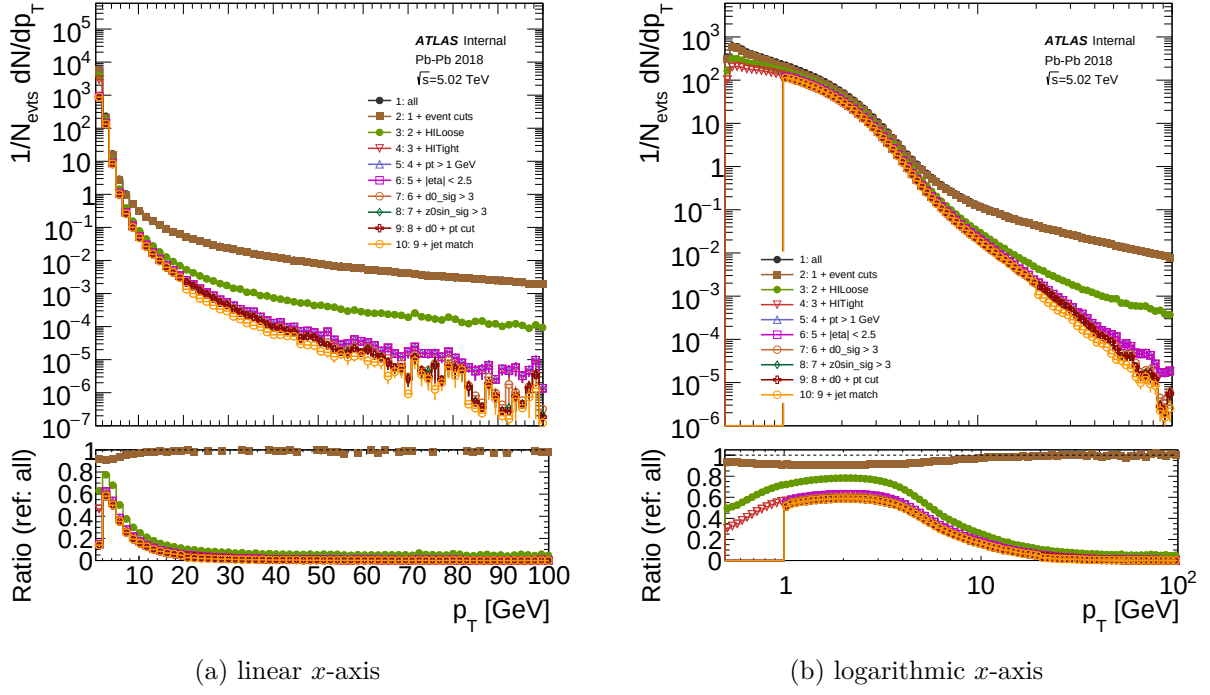


Figure 7.15: The p_T cutflow plot showing impact of each track cut on the transverse momentum distribution, progressively included cuts

8 Event selection and weights

To ensure that only events relevant to the analysis are retained and to suppress those that could distort the results (e.g., pile-up events), a set of selection criteria was applied to the dataset. This analysis focuses on the top 1% most central collisions, with centrality determined using the total E_T^{FCal} energy. An additional selection based on track multiplicity was introduced to restrict the range of events that are subsequently binned according to N_{trk} , as required for the core part of the analysis. The E_T^{FCal} threshold is set to approximately 1% most central value to ensure the selection of highly central events. Selecting events in such way has tendency to pick the pile-up ones. To mitigate pile-up contamination, additional selections were applied based on correlations between E_T^{FCal} and N_{trk} , as well as between E_T^{FCal} and the ZDC energy.

8.1 Events selection

All events included in the analysis must satisfy the following criteria:

- The run and luminosity block must be listed in the Good Run List (GRL);
- At least one of the following triggers must be active:
 - HLT_noalg_mb_L1TE50;
 - HLT_hi_th2_ucc_L1TE12000;
 - HLT_hi_th3_ucc_L1TE12000;
- Pile-up rejection is applied, based on the correlations between E_T^{FCal} and track multiplicity, as well as between ZDC energy and E_T^{FCal} , described in detail in [Section 8.2](#);
- Centrality corresponding to the top 1%, defined by $E_T^{\text{FCal}} > 4.263\,72\,\text{TeV}$;
- The number of selected tracks (as described in [Chapter 7](#)) – $\tilde{n}_{\text{trk}}$, must fall within the range $[900, 1200]$.

UCC triggers

In the trigger naming convention, L1TEX indicates a minimum Level-1 total transverse energy requirement, while thX denotes an online minimum E_T^{FCal} threshold. Specifically, th1, th2, and th3 correspond to E_T^{FCal} thresholds of 4.172 TeV, 4.326 TeV, and 4.500 TeV, respectively [\[61\]](#).

Although the 2018 Pb–Pb dataset included additional UCC triggers, other event selection criteria rendered them unused in this analysis. The full list of 2018 UCC triggers is:

- HLT_hi_th1_ucc_L1TE10000;
- HLT_hi_th2_ucc_L1TE10000;
- HLT_hi_th3_ucc_L1TE10000;

- HLT_hi_th1_ucc_L1TE12000;
- HLT_hi_th2_ucc_L1TE12000;
- HLT_hi_th3_ucc_L1TE12000.

Events from the UCC data stream were used in the analysis.

Centrality cut

The analysis focuses exclusively on the most central Pb–Pb collisions, defined as the top 1% in centrality. This selection is implemented via a threshold on the total E_T^{FCal} energy. Based on centrality cuts derived using the Glauber v3.2 nominal model at 85% efficiency, 1% centrality corresponds to the requirement $E_T^{\text{FCal}} > 4.263\,72\text{ TeV}$ [62].

The centrality intervals are provided in terms of E_T^{FCal} energy, which represents the sum of the transverse energy deposited in the forward (A-side) and backward (C-side) calorimeters. A complete list of centrality thresholds is available at the following URL: twiki.cern.ch [63].

8.2 Pile-up cut

Pile-up is defined as the average number of Pb–Pb collisions occurring within a single bunch crossing. Due to the complexity of event signatures in the heavy-ion regime, only one Pb–Pb interaction can be reliably reconstructed per event. A pile-up event¹ can distort the analysis by introducing inaccurate energy deposition measurements and misestimated track parameters. Pile-up suppression is therefore essential and is performed using selection criteria based on E_T^{FCal} energy, ZDC energy, and charged-particle multiplicity (N_{trk}).

Pile-up cuts are also essential in rejecting from the analysis events resulting from ions collisions with residual gas in the pipes.

For visualization of the pile-up rejection procedure, events from the **MinBias** stream were also included to evaluate the cuts efficiency in the full E_T^{FCal} range and compare them against reference documents.

ZDC and E_T^{FCal} based cut

In Pb–Pb collisions, the primary pile-up rejection criterion is based on the energy measured in the Zero Degree Calorimeters (ZDC). The ZDCs are specifically designed to measure the energy of neutral particles traveling close to the beamline, making them sensitive to spectator neutrons and suitable for pile-up identification.

An anti-correlation between the total E_T^{FCal} energy and the ZDC energy is expected, particularly in the high E_T^{FCal} region. The pile-up rejection is implemented through both lower and upper thresholds on the ZDC energy as a function of E_T^{FCal} . These thresholds are illustrated in [Figure 8.1](#) and are tabulated in [Appendix A](#) [61].

The linear upper ZDC cut, shown as a red line in [Figure 8.1](#) and not included in the tabulated thresholds in [Appendix A](#), is defined as [59]

$$E_{\text{ZDC}} > -113.845 \cdot E_T^{\text{FCal}} + 619.56. \quad (8.1)$$

¹An event in which more than one Pb–Pb collision occurs within a single bunch crossing

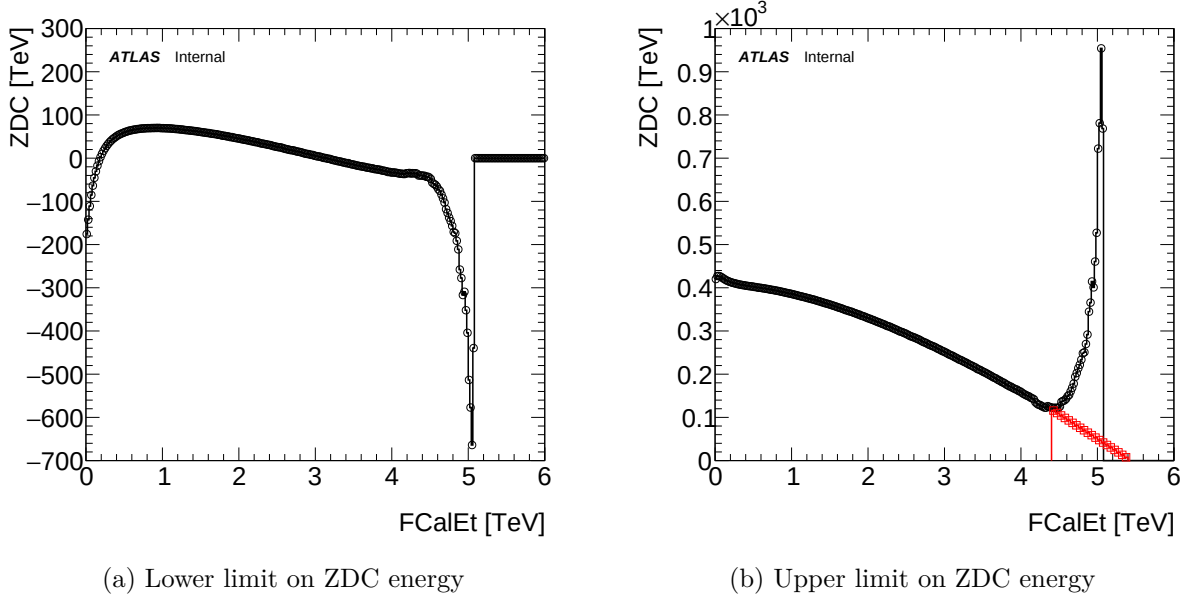


Figure 8.1: Pile-up rejection cut based on the correlation between ZDC and E_T^{FCal} energy. The red line indicates a linear cut defined by Equation 8.1 [59]

N_{trk} and E_T^{FCal} based cut

The N_{trk} and E_T^{FCal} correlation is used as an auxiliary cut, aimed mostly at residual pile-up events from multiple Pb ions collisions, or beam-gas events. When lead ion interacts with pipe gas atoms, typically high energy deposition in FCal is observed, but very few reconstructed tracks (e.g. 400 tracks in 4 TeV event). These pile-up events are suppressed by two linear cuts [60]

$$E_T^{\text{FCal}} < 5 \text{ TeV}, \quad (8.2a)$$

$$E_T^{\text{FCal}} < 0.4 + 0.00115 \cdot N_{\text{trk}}. \quad (8.2b)$$

MinBias data stream

To assess the correctness of the applied pile-up rejection cuts, verify the appropriate ZDC energy scaling, and compare the resulting distributions to reference materials, the cuts were first applied to the MinBias data stream in the E_T^{FCal} range from 0 TeV to approximately 5.5 TeV.

Figure 8.2–Figure 8.7 show scatter plots illustrating the impact of the pile-up suppression cuts on key variable correlations. In particular, the observed correlation between E_T^{FCal} and ZDC energy closely resembles results presented in the literature (e.g., [61] – Figure 8.8), indicating that the applied procedure is consistent and reliable.

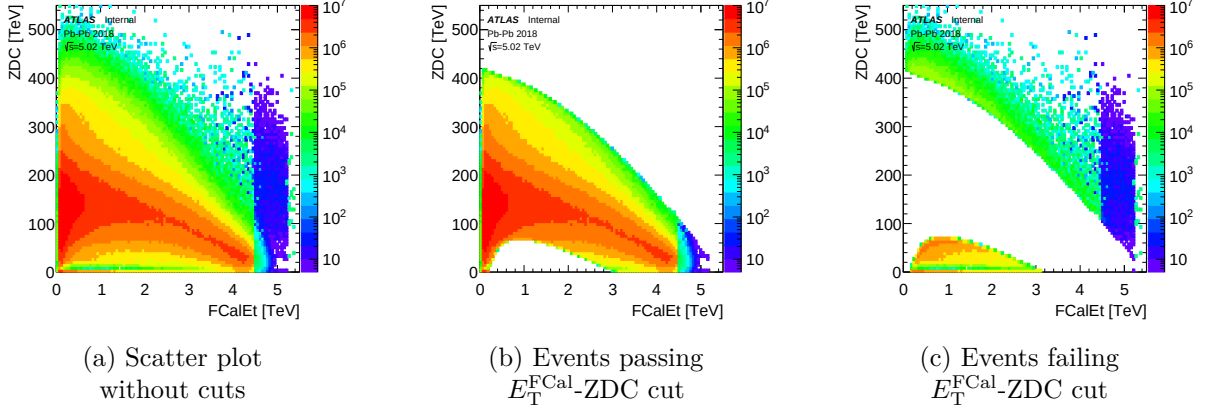


Figure 8.2: Impact of the E_T^{FCal} -ZDC-based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, MinBias data stream

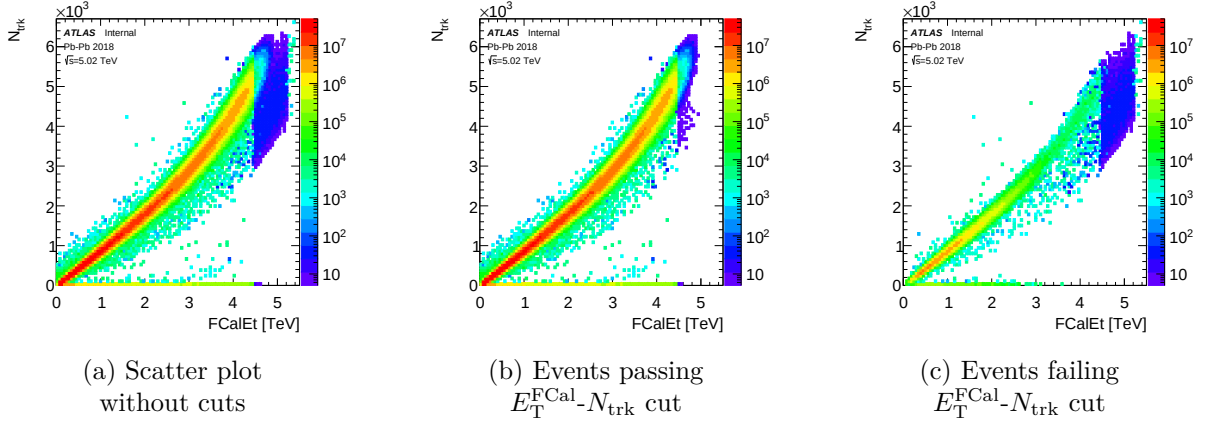


Figure 8.3: Impact of the E_T^{FCal} -ZDC-based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, MinBias data stream

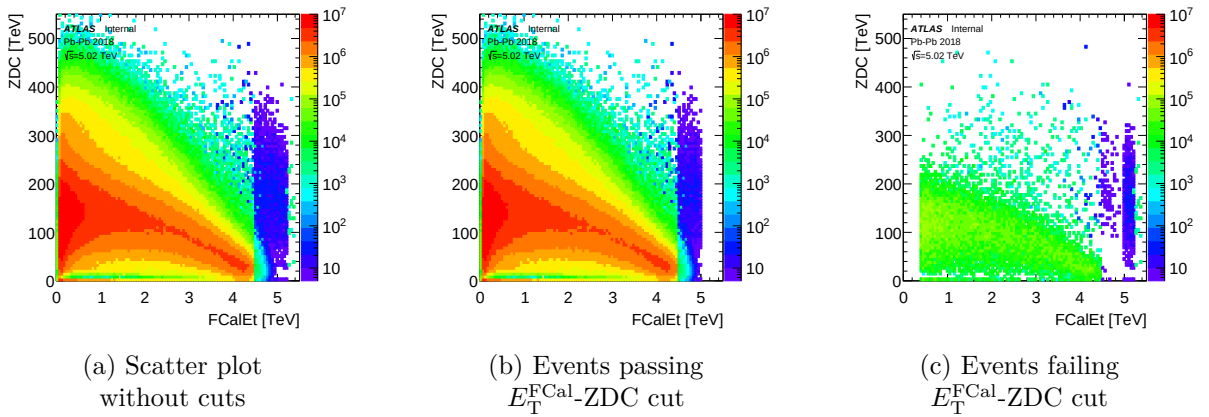


Figure 8.4: Impact of the E_T^{FCal} - N_{trk} -based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, MinBias data stream

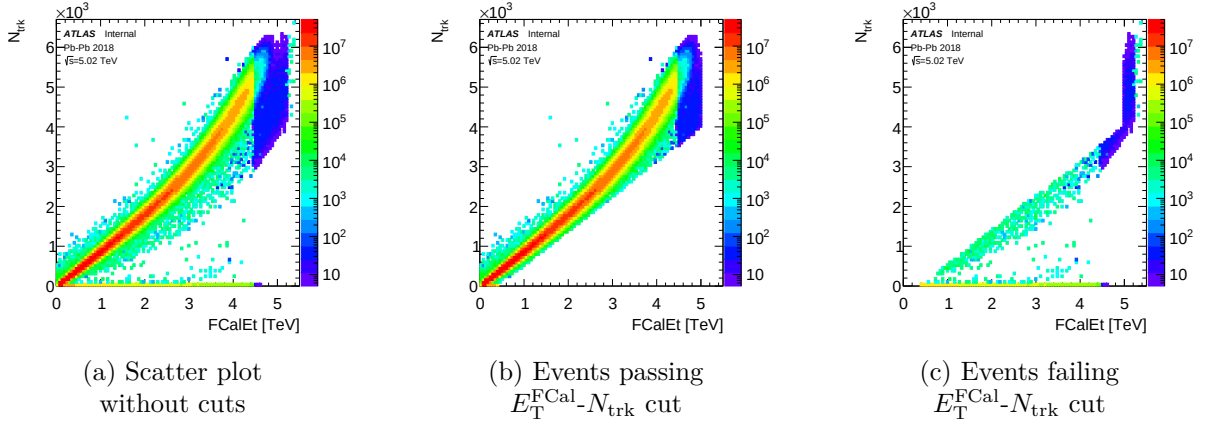


Figure 8.5: Impact of the $E_T^{\text{FCal}}-N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, MinBias data stream

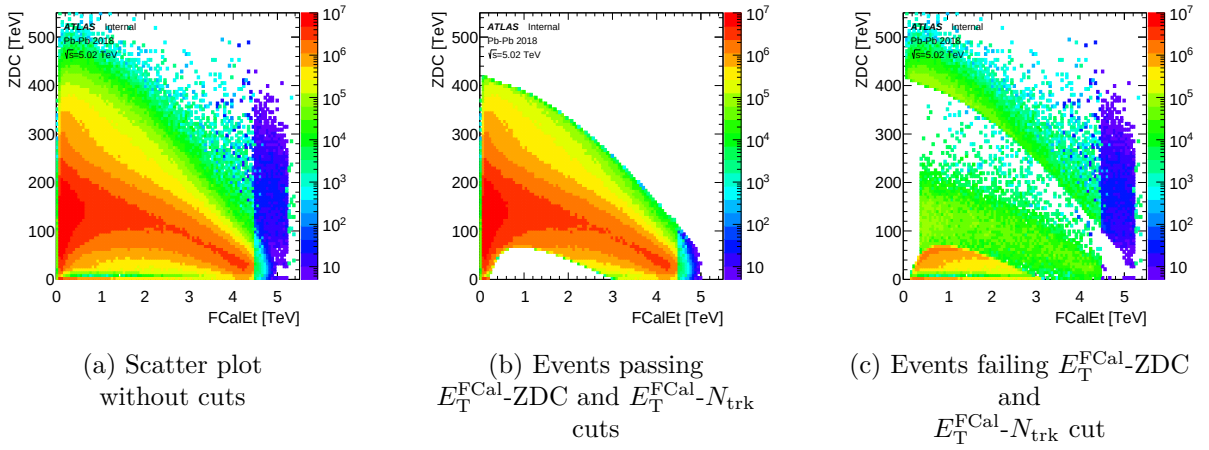


Figure 8.6: Impact of the $E_T^{\text{FCal}}-\text{ZDC}$ and $E_T^{\text{FCal}}-N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, MinBias data stream

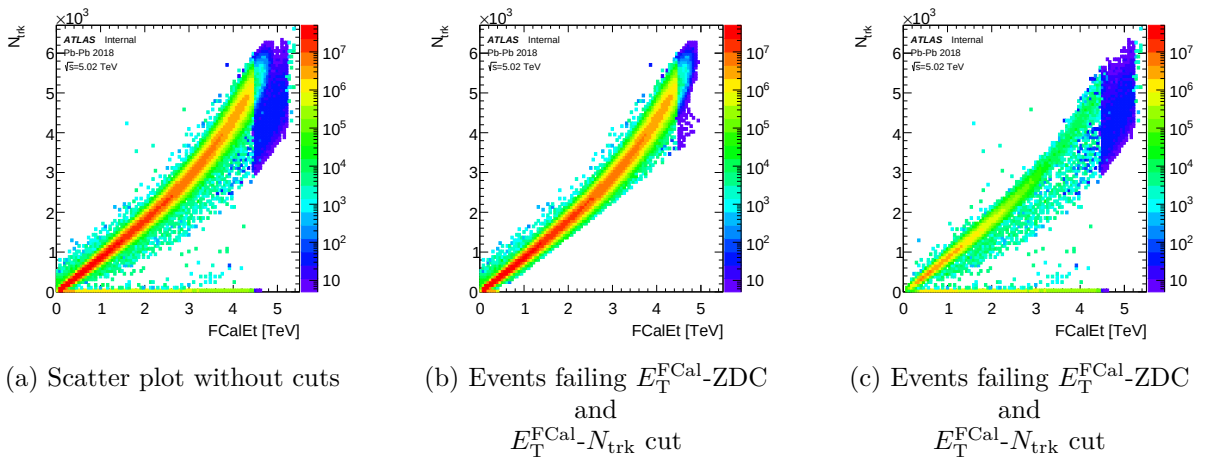


Figure 8.7: Impact of the $E_T^{\text{FCal}}-\text{ZDC}$ and $E_T^{\text{FCal}}-N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, MinBias data stream

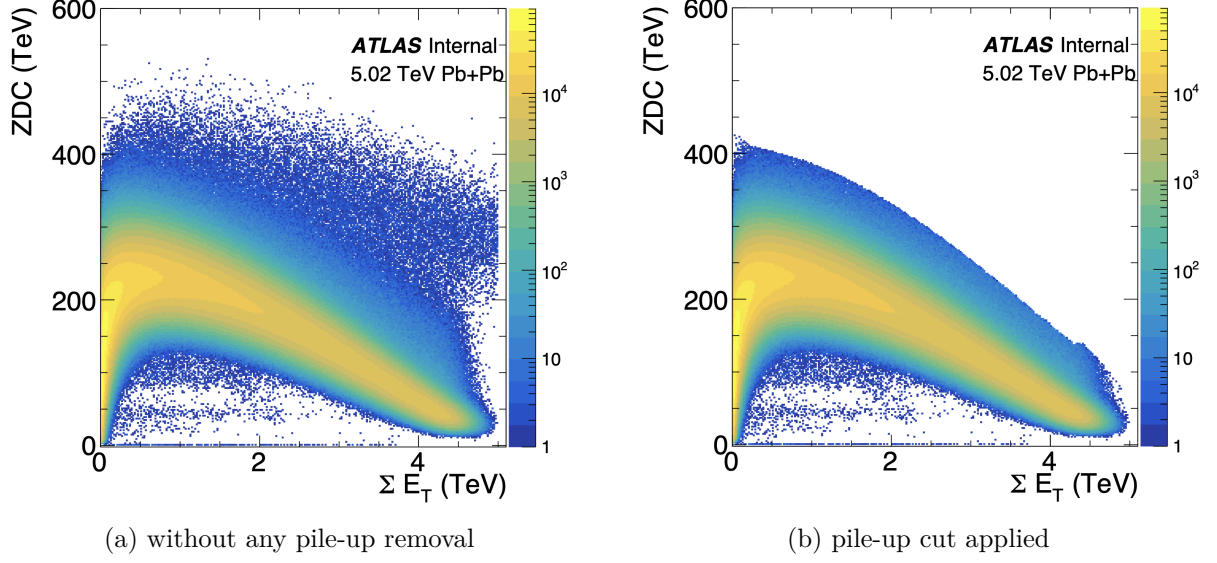


Figure 8.8: Impact of the 6σ significance cut around mean value for the $ZDC-E_T^{\text{FCal}}$ correlation in Pb-Pb collisions [61]

UCC stream

The **MinBias** data stream was used to validate the correctness of the pile-up rejection procedure. However, the primary analysis is performed on the ultra-central collisions (UCC) data stream, making the performance of the pile-up cuts in the corresponding E_T^{FCal} energy range critical. **Figure 8.9** – **Figure 8.14** analogously show the impact of the applied pile-up cuts on the dataset used in the main analysis.

For the UCC data stream, the pile-up cut based on N_{trk} reduces the event count by 1.782 %, while the ZDC-based cut leads to a reduction of 2.790 %. When applied together, both cuts result in a total reduction of 3.737 %. Since only approximately 18.26 % of the rejected events are common to both cuts, it is essential to apply both, as they target largely independent subsets of events.

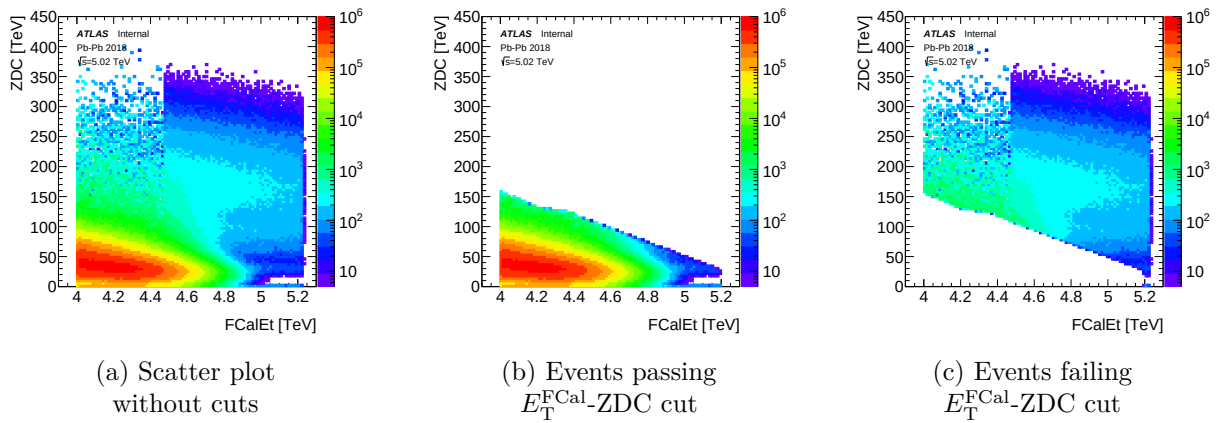


Figure 8.9: Impact of the E_T^{FCal} -ZDC-based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, UCC data stream

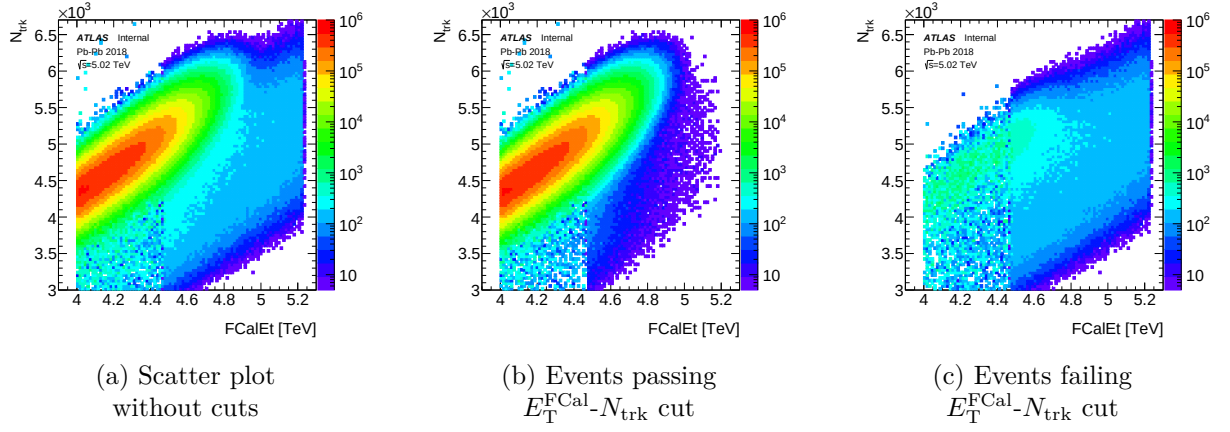


Figure 8.10: Impact of the $E_T^{\text{FCal}}-ZDC$ -based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, UCC data stream

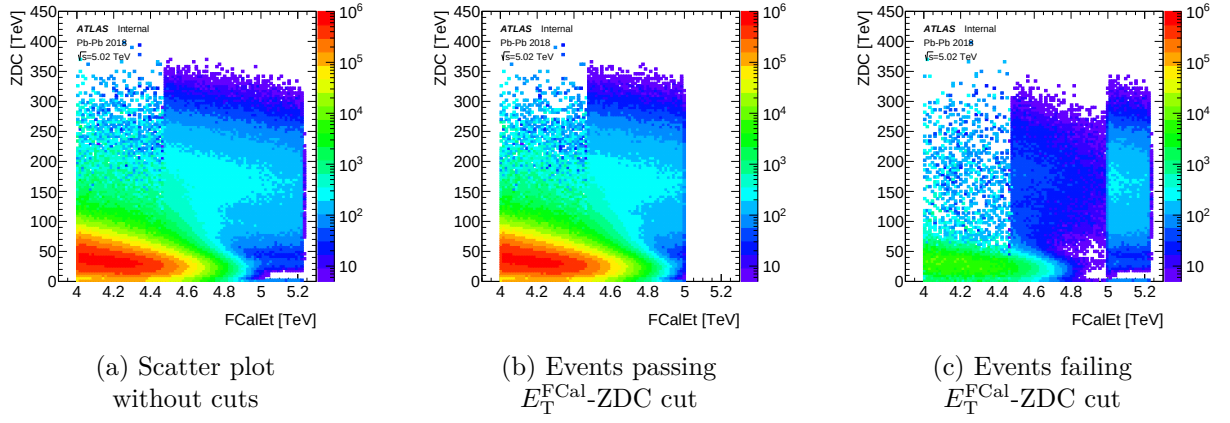


Figure 8.11: Impact of the $E_T^{\text{FCal}}-N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, UCC data stream

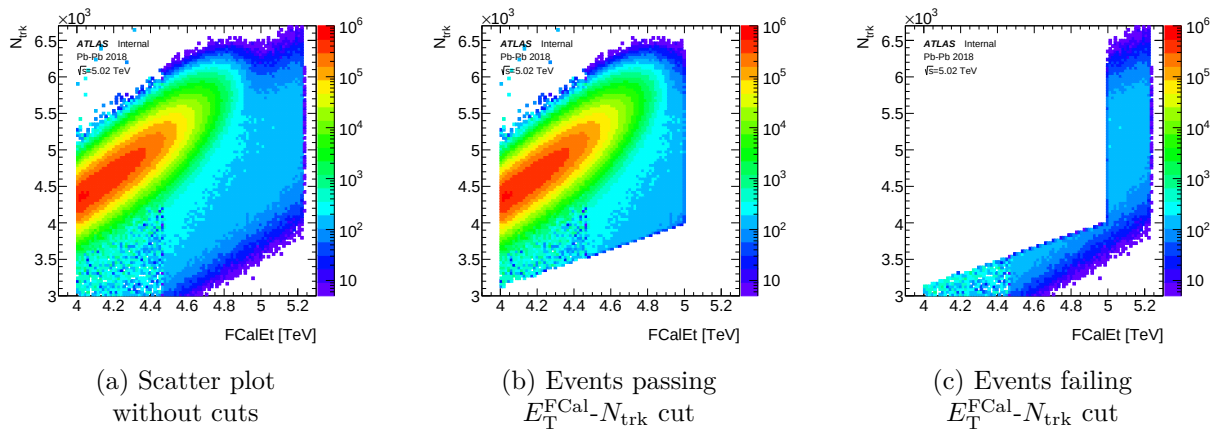


Figure 8.12: Impact of the $E_T^{\text{FCal}}-N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, UCC data stream

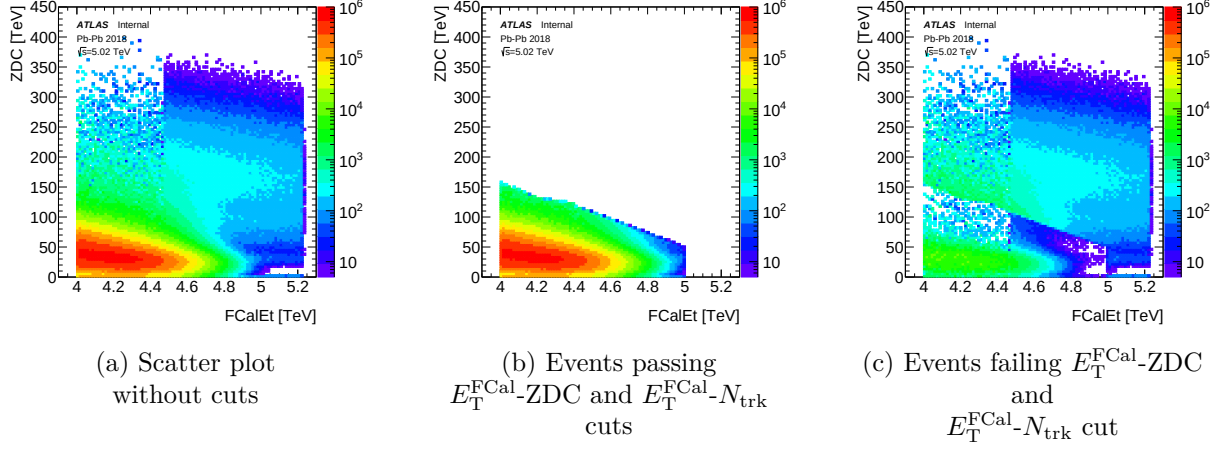


Figure 8.13: Impact of the $E_T^{\text{FCal}}\text{-ZDC}$ and $E_T^{\text{FCal}}\text{-}N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. ZDC energy distribution, UCC data stream

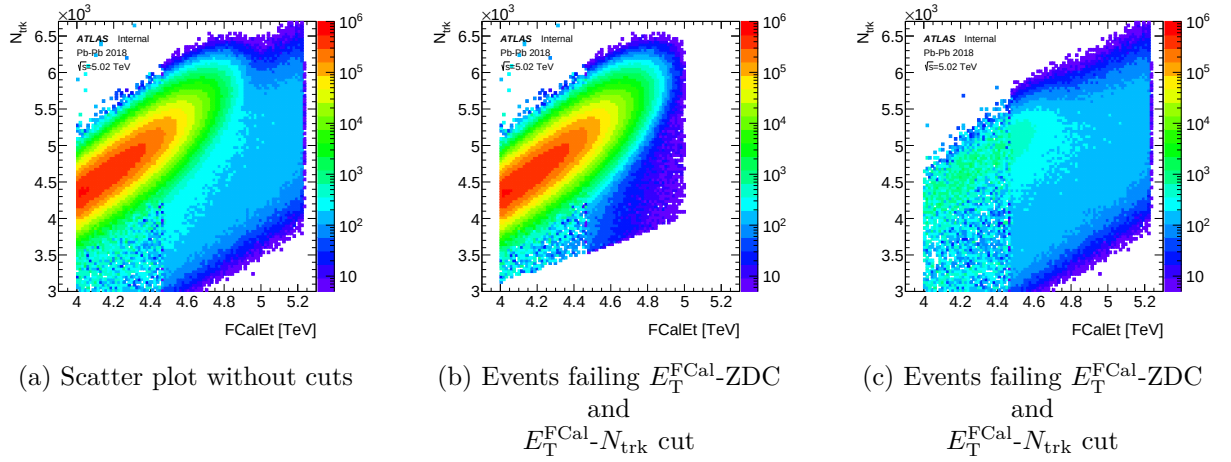


Figure 8.14: Impact of the $E_T^{\text{FCal}}\text{-ZDC}$ and $E_T^{\text{FCal}}\text{-}N_{\text{trk}}$ -based pile-up cut on the E_T^{FCal} vs. N_{trk} distribution, UCC data stream

Pile-up rejection efficiency

In assessing pile-up cuts impact, a useful tool is the ratio of the parameter distribution (N_{trk} , E_T^{FCal} , and ZDC energy) with the cuts applied to the initial distribution. It allows one to determine which range in N_{trk} , ZDC, or E_T^{FCal} originates from pile-up events.

For E_T^{FCal} and ZDC energy, the cut mostly affects the higher values. For E_T^{FCal} , this is partly due to the sharp cut at 5.0 TeV. Also, in the entire UCC range, only the upper bound in the ZDC: E_T^{FCal} cut is effective, thus leading to a reduction in event count for high ZDC energy depositions. For track multiplicity, the pile-up cut is most effective at rejecting pile-up for values far from the mean.

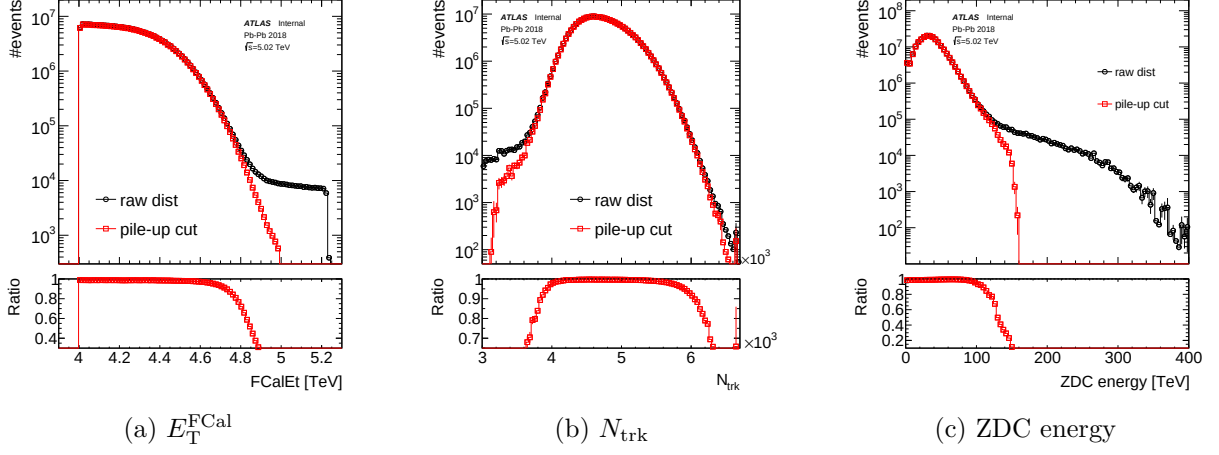


Figure 8.15: Number of events as a function of several event-characterizing quantities, shown for all events and after applying the pile-up removal procedure. Data corresponds to UCC 2018 dataset

8.3 Event weights

In the ATLAS experiment, triggers can generally be categorized as either exclusive or inclusive, a distinction that directly affects the assignment of event weights.

Exclusive triggers are configured so that each event can be selected by only one trigger chain, ensuring a unique prescale factor is applied. An example of such a configuration is shown in [Figure 8.16](#), where the triggers are defined in non-overlapping regions of FCal transverse energy (E_T^{FCal}).

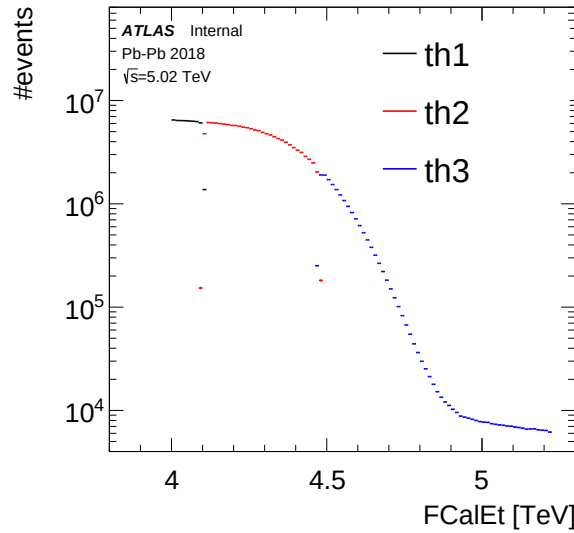


Figure 8.16: Example of exclusive triggers, UCC 2018 data stream, **th1** – `HLT_hi_th1_ucc_L1TE12000`, **th2** – `HLT_hi_th2_ucc_L1TE12000`, **th3** – `HLT_hi_th3_ucc_L1TE12000`

In contrast, inclusive triggers allow for overlapping selection regions, where a single event may satisfy the conditions of multiple trigger paths. In such cases, multiple prescale values may be associated with the same event. The effective event weight must then account for the combined contributions of all relevant triggers.

In general, event weight is defined by prescale factor and trigger prescale.

Let ξ denote total weight assigned to the track. It can be broken up into the event (ξ_{ev}) and track (ξ_{trk}) weight

$$\xi = \xi_{\text{ev}} \cdot \xi_{\text{trk}}. \quad (8.3)$$

Prescale

A prescale (PS, α^i) is an integer factor applied to individual triggers to reduce the rate of recorded events, thereby controlling the data acquisition bandwidth and preventing saturation of storage or processing resources. A prescale factor of N implies that, on average, one in every N events satisfying the trigger condition is recorded. For exclusive, fully efficient triggers, the corresponding event weight is equal to the prescale factor N .

Prescaling can be applied at both the Level-1 (L1) and the High-Level Trigger (HLT) stages. Each stage may independently apply its own prescale factor to a given trigger chain. The effective prescale for such a trigger is the product of the L1 and HLT prescales: $\text{PS}_{\text{eff}} = \text{PS}_{\text{L1}} \times \text{PS}_{\text{HLT}}$.

Due to the gradual reduction in instantaneous luminosity during a fill, as the number of colliding ions decreases, prescale values are adjusted dynamically to maintain a roughly constant output rate. These adjustments manifest as discontinuities in run-dependent monitoring plots, such as the L1 trigger rate versus time or luminosity, as shown in [Figure 8.17](#) and [Figure 8.18](#).

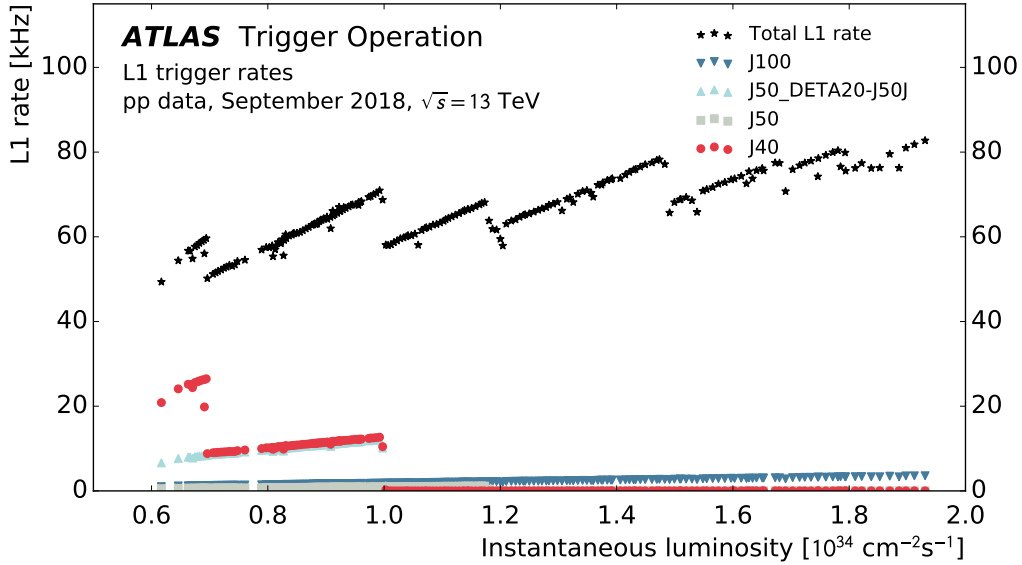


Figure 8.17: Variation of the L1 trigger rate with instantaneous luminosity due to changing prescale factors [\[64\]](#)

For exclusive triggers, the assignment of event weights is straightforward: the weight is directly proportional to the trigger's effective prescale factor. However, for inclusive triggers, where events may be selected by multiple trigger chains with distinct prescales, the computation of event weights becomes nontrivial. In such cases, contributions from all relevant trigger paths must be considered. Moreover, for both exclusive and inclusive triggers, the trigger efficiency should ideally be folded into the event weight, although this is typically $\sim 100\%$ for the high-threshold triggers used in this analysis.

The QGP analysis primarily employs prescaled triggers, with prescale factors typically of order $\mathcal{O}(10^2)$. The sole unprescaled trigger is the high-threshold UCC trigger for the largest $E_{\text{T}}^{\text{FCal}}$ energy deposits – HLT_hi_th3_ucc_L1TE1200.

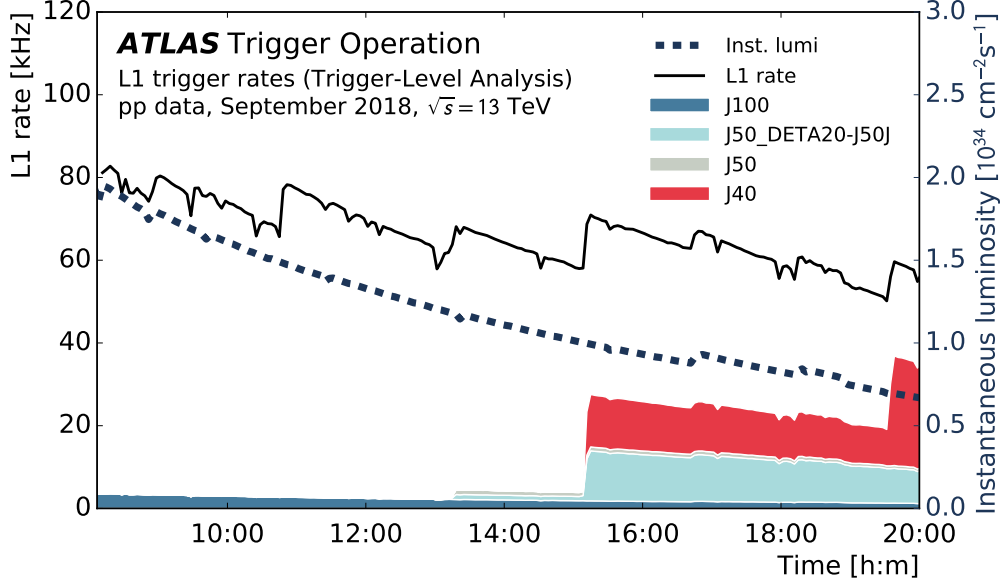


Figure 8.18: L1 trigger rate evolution during a single run, reflecting dynamic prescale adjustments [64]

Trigger efficiency

The trigger efficiency ($\varepsilon_{\text{trig}}$) is estimated with respect to a **MinBias** trigger. We anticipate an error-like function, with ideally sharp turn-on – efficiency is either 0 or 1. Efficiency is determined as a function of track multiplicity value (N_{trk}) as a ratio of event count for analyzed and **MinBias** trigger [65]

$$\varepsilon_{\text{trig}}^i = \frac{N_{\text{ev}}^i(N_{\text{trk}}^{\text{ref}})}{N_{\text{ev}}^{\text{MB}}(N_{\text{trk}}^{\text{ref}})}, \quad (8.4)$$

where N_{ev}^i is the trigger event count as a function of track multiplicity – N_{trk} . For highly efficient trigger, the $\varepsilon_{\text{trig}}^i$ functions resembles the error function with low standard deviation.

Inclusive trigger event weights

When inclusive triggers are used in the analysis, a single event may be selected by multiple triggers, each with different prescale factors and efficiencies. These contributions must be combined into a single event-level weight. This weight is defined as the inverse of the total probability for the event to be recorded by at least one trigger

$$\xi_{\text{ev}} = \frac{1}{P(N_{\text{trk}}^{\text{ref}})}, \quad (8.5)$$

where the combined trigger probability is given by:

$$P(N_{\text{trk}}^{\text{ref}}) = 1 - \prod_{i=1}^{N_{\text{trig}}} (1 - P_{\text{trig}}^i(N_{\text{trk}}^{\text{ref}})). \quad (8.6)$$

Here, $P_{\text{trig}}^i(N_{\text{trk}}^{\text{ref}})$ represents the probability that trigger i selects an event with $N_{\text{trk}}^{\text{ref}}$, and is defined as:

$$P_{\text{trig}}^i(N_{\text{trk}}^{\text{ref}}) = \frac{\varepsilon_{\text{trig}}^i(N_{\text{trk}}^{\text{ref}})}{\alpha^i}, \quad (8.7)$$

where $\varepsilon_{\text{trig}}^i(N_{\text{trk}}^{\text{ref}})$ is the trigger efficiency, and α^i is the corresponding prescale factor [65].

Exclusive trigger event weight

For exclusive triggers, an event can only be recorded by a single trigger. This significantly simplifies the determination of the event weight, as different prescale factors and trigger efficiencies do not need to be combined. In this case, by simplifying Equation 8.6 and Equation 8.7 and assuming $N_{\text{trig}} = 1$, the event weight becomes:

$$\xi_{\text{ev}} = \frac{\alpha^i}{\varepsilon_{\text{trig}}^i}. \quad (8.8)$$

Assuming fully efficient triggers ($\varepsilon_{\text{trig}}^i \equiv 1$), the event weight reduces to the prescale factor:

$$\xi_{\text{ev}} = \alpha^i. \quad (8.9)$$

8.4 Event cutflow

Impact of the above-described selection criteria on the data used in the analysis in the form of cut-flow plow presents Figure 8.19.

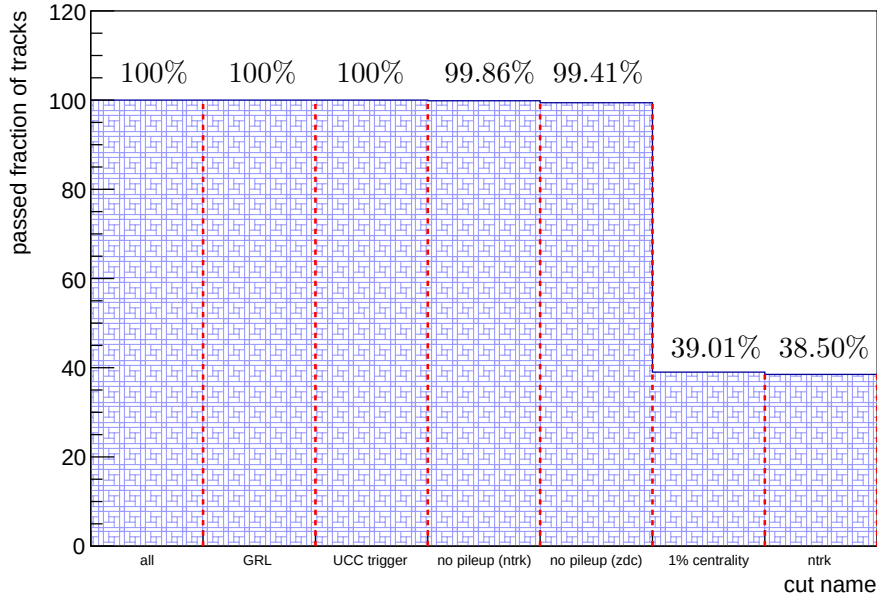


Figure 8.19: Event cut-flow for the 2018 UCC Pb-Pb data. y - axis displays fraction of events that passed each selection

The use of high-quality data, already passing the UCC pre-selection and not requiring a Good Runs List veto, results in minimal event rejection from these criteria. However, during the production of `NTuple` files from the `AOD` format, central events were selected using the condition $E_{\text{T}}^{\text{FCal}} > 4.0 \text{ TeV}$. Given that the 1% centrality threshold is at 4.26372 TeV , a significant fraction of events were rejected by this requirement. This is because the $E_{\text{T}}^{\text{FCal}}$ distribution decreases rapidly at higher values.

p_T cutflow

To better understand the impact of selection cuts on the datasets, particularly on the p_T distribution, which is central to the analysis, a p_T cutflow was also generated, as detailed in [Section 7.2](#). [Figure 7.14](#) shows the p_T distribution when each cut is applied individually, while [Figure 7.15](#) illustrates the distribution with cuts applied progressively.

Analysis of both plots leads to the same conclusion as the event cutflow in [Figure 8.19](#): the only selection with a significant impact on event yield is the 1% centrality requirement. None of the cuts noticeably alter the shape of the p_T distribution.

The apparent discrepancy between the event reduction due to pile-up removal, as shown in [Figure 8.19](#), and the 3.737% reduction quoted in [Figure 8.2](#), arises from the use of different datasets defined by E_T^{FCal} . The earlier value refers specifically to data within the 1% centrality class, corresponding to $E_T^{\text{FCal}} > 4.26372 \text{ TeV}$ – i.e., events usable in the analysis. In contrast, [Figure 8.19](#) considers the broader dataset with $E_T^{\text{FCal}} > 4.0 \text{ TeV}$.

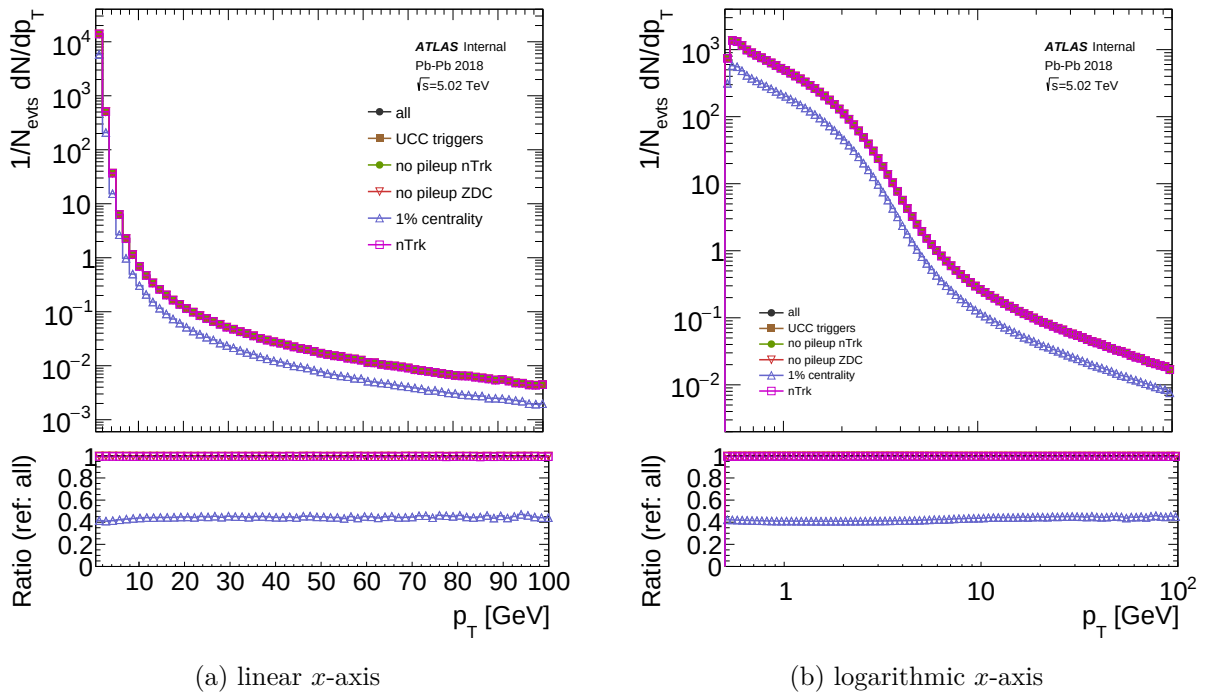


Figure 8.20: The p_T cutflow plot showing impact of each event cut separately on the transverse momentum distribution, one cut at a time included

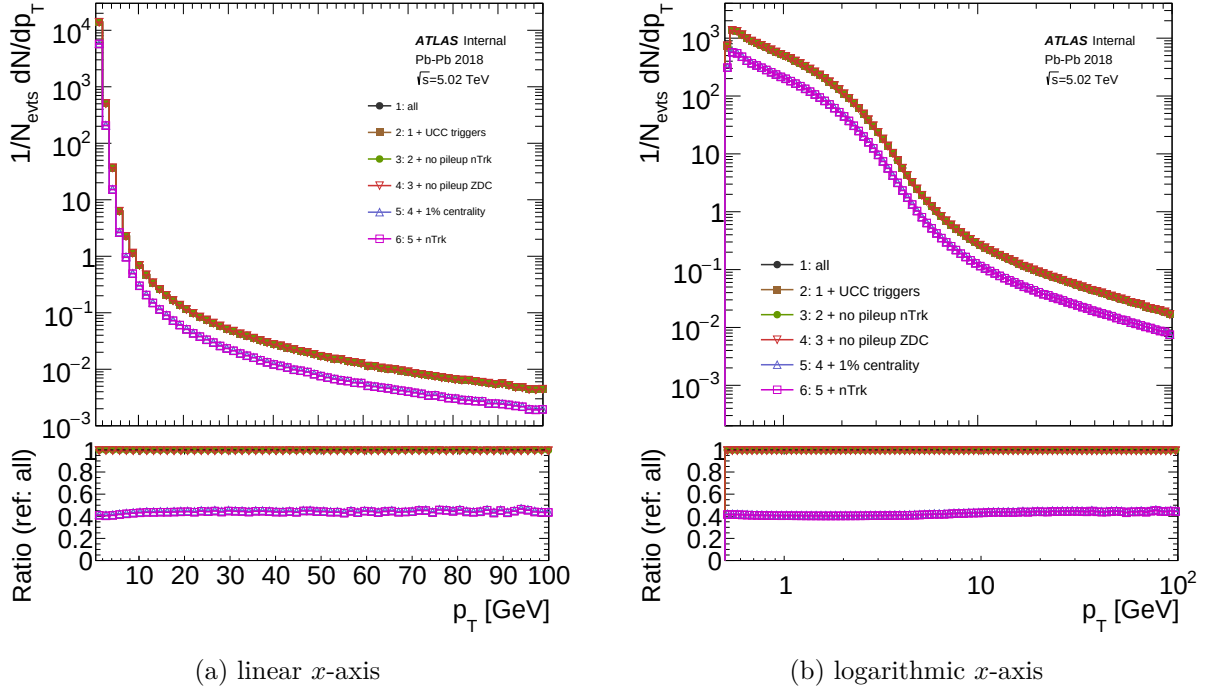
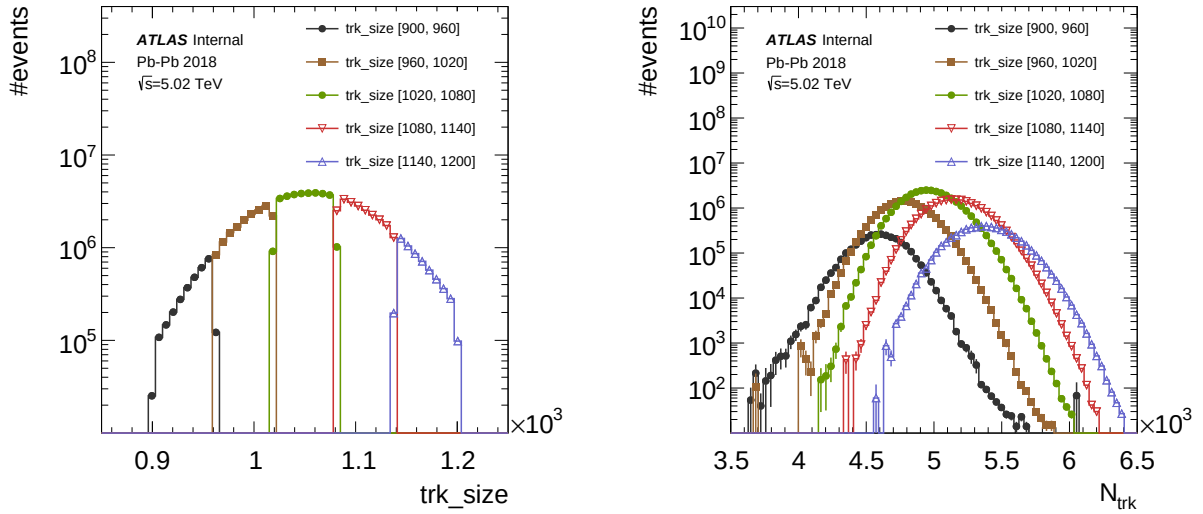


Figure 8.21: The p_T cutflow plot showing impact of each event cut on the transverse momentum distribution, progressively included cuts

9 Analysis methods

The analysis was performed on UCC data stream events that passed the selection requirements outlined in [Chapter 8](#), and the track requirements introduced in [Chapter 7](#). Its primary aim is to investigate the modification of charged particles transverse momentum spectra in the high- p_T range, driven by variations in the initial temperature or energy density. As discussed in [Section 2.4](#), a proxy for these quantities is $dN_{ch}/d\eta$.

The core idea of the analysis is to partition the data into fixed-size bins defined by the number of tracks passing the selection criteria outlined in [Chapter 7](#). The use of the N_{trk} branch in the NTuple (total number of tracks in the event) was avoided, as it can be significantly biased by the high fake track rate in the low- p_T range. For the analyzed UCC collisions, N_{trk} is on the order of 5000. To ensure robustness against low- p_T fake rates, the classification was instead defined in terms of the count of tracks passing stringent quality selection – $\tilde{n}_{\text{trk}}$.



(a) number of tracks passing all the selection – $\tilde{n}_{\text{trk}}$

(b) track multiplicity – N_{trk}

Figure 9.1: Parameters distribution by sub-range defined in terms of $\tilde{n}_{\text{trk}} - N_{\text{trk}}$ and $\tilde{n}_{\text{trk}}$

The multiplicity of $\tilde{n}_{\text{trk}}$ follows a Gaussian distribution. The tails of this distribution are excluded at approximately 3σ level, and the remaining domain is divided into 5 sub-regions. This binning scheme is illustrated in [Figure 9.1](#). While the $\tilde{n}_{\text{trk}}$ distribution exhibits sharp, rectangular cuts, the underlying N_{trk} distribution maintains a Gaussian shape.

The analysis is performed on events with $\tilde{n}_{\text{trk}}$ in the range [900, 1200], which are subsequently divided into five equally spaced sub-ranges.

Owing to the shape of the $\tilde{n}_{\text{trk}}$ distribution and the use of fixed bin widths, the number of events varies across sub-ranges. [Table 9.1](#) lists the lower and upper bounds of each sub-range, along with the relative event count, expressed as a fraction of the total number of events used in the analysis.

Table 9.1: Sub-range lower and upper bound in terms of $\tilde{n}_{\text{trk}}$, and corresponding event counts

range index	0	1	2	3	4
min $\tilde{n}_{\text{trk}}$	900	960	1020	1080	1140
max $\tilde{n}_{\text{trk}}$	960	1020	1080	1140	1200
#event	3.10E+06	1.70E+07	3.18E+07	2.16E+07	5.84E+06
relative #event [%]	3.9	21.44	40.11	27.16	7.36

9.1 p_T ratio plots and track yield

For this event sub-division, two main analysis methods were employed:

- The p_T distribution ratio, which highlights subtle modifications in the transverse momentum spectrum that may not be apparent in the raw p_T distribution due to its wide dynamic range;
- The yield of tracks within a given p_T range, studied as a function of track multiplicity. This observable is expected to follow the $\hat{q}$ -track multiplicity relationship derived from the Linear Boltzmann Transport model, given by [Equation 2.25](#)

$$\hat{q} \propto \left(\frac{dN_{ch}}{d\eta} \right)^{3/4}. \quad (9.1)$$

p_T ratio plots

Each sub-range transverse momentum distribution was first normalized by the number of events in that bin. Subsequently, each distribution was divided, assuming binomial error propagation, by a reference bin. The reference was chosen either as the central sub-range ($\tilde{n}_{\text{trk}} \in [1020, 1080]$) or as the bin with an index lower by one. This ratio distribution was then plotted for the following momentum ranges

- $p_T \in [1.0 \text{ GeV}, 5 \text{ GeV}]$;
- $p_T \in [1.0 \text{ GeV}, 20 \text{ GeV}]$;
- $p_T \in [1.0 \text{ GeV}, 100 \text{ GeV}]$.

Track yield

The value of $\hat{q}$, which characterizes the momentum transfer in the QGP medium, is expected to increase with track multiplicity. Plotting the track yield, defined as the number of tracks in a given p_T range, is therefore expected to follow the trend described by [Equation 2.25](#). Additionally, for each $\tilde{n}_{\text{trk}}$ bin, further metrics were computed, including the square of the particle yield (related to variance) and basic momentum statistics such as the mean and standard deviation.

By plotting the yield distributions for both 5 and 50 subdivisions on the same figure, slight deviations from a linear relationship can be observed.

To account for the centrality-dependent variation in the number of nucleon-nucleon collisions, which also influences track multiplicity, a T_{AA} correction was applied. The nuclear overlap function – T_{AA} , appears as a parameter in the definition of the nuclear modification factor R_{AA} , which compares the normalized yield in Pb–Pb collisions to that in p–p collisions [\[66\]](#):

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{1/N_{evt}, d^2 N_{Pb+Pb}/d\eta dp_T}{d^2 \sigma_{pp}/d\eta dp_T}, \quad (9.2)$$

where $1/N_{evt}, d^2N_{Pb+Pb}/d\eta dp_T$ is the double-differential yield of charged hadrons in Pb–Pb collisions as a function of pseudorapidity and transverse momentum, and $d^2\sigma_{pp}/d\eta dp_T$ is the corresponding cross section in p–p collisions.

To correct for variations in nuclear overlap, each bin was divided by an effective $\langle T_{AA} \rangle$ determined as a function of $\tilde{n}_{trk}$. Since T_{AA} values are typically quoted for centrality intervals defined via E_T^{FCal} , a procedure was implemented to map $\langle T_{AA} \rangle$ values to different binning schemes based on $\tilde{n}_{trk}$. This procedure is detailed in [Section 9.6](#).

Track yield – defined as the number of tracks with transverse momentum within a specified range, and the square of this value, serving as a measure of variance, were estimated for the following ranges

- $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$;
- $p_T \in [15 \text{ GeV}, 100 \text{ GeV}]$;
- $p_T \in [20 \text{ GeV}, 100 \text{ GeV}]$;
- $p_T \in [30 \text{ GeV}, 100 \text{ GeV}]$.

The mean and standard deviation of the number of tracks were evaluated for the following ranges

- $p_T \in [1 \text{ GeV}, 10 \text{ GeV}]$;
- $p_T \in [15 \text{ GeV}, 20 \text{ GeV}]$;
- $p_T \in [20 \text{ GeV}, 30 \text{ GeV}]$;
- $p_T \in [30 \text{ GeV}, 40 \text{ GeV}]$.

9.2 Analysis cuts

In order to assess the cumulative impact of all the selection applied to data – event and track requirements, comparison of initial distributions and after applying analysis cuts is shown in – [Figure 9.2](#) – [Figure 9.5](#).

Of particular interest are plots for event parameters distribution – E_T^{FCal} and N_{trk} – [Figure 9.2](#). They well visualize 1% centrality cut as well as pile-up cut. In the E_T^{FCal} distribution, total absence of events in the low energy range, is caused by the centrality cut, which is equivalent to the requirement of $E_T^{FCal} > 4.26372 \text{ TeV}$. Gradual decrease of plots ratio for the high E_T^{FCal} range can be attributed to the pile-up cut, which among others puts complete veto on events characterized by $E_T^{FCal} > 5.0 \text{ TeV}$. The N_{trk} in the low multiplicity range is affected mostly by the 1% centrality cut, since these both parameters are closely positively correlated.

In the transverse momentum distribution most evident is lack of low- p_T track, due to $p_T > 1 \text{ GeV}$ cut, and significantly reduced yield for high p_T particles. As discussed in the [Figure 7.13](#) the stringent quality criteria reduce yield in the high- p_T .

Azimuthal angle is strongly but uniformly affected by analysis cuts – [Figure 9.4](#). In the η distribution reduced yield is noted for high $|\eta|$ range where track selection suppresses fakes.

The Monte Carlo weights plot – [Figure 9.5](#) shows that mostly high weights tracks were rejected, which indicate reduced ratio of high fake and low efficiency region tracks.

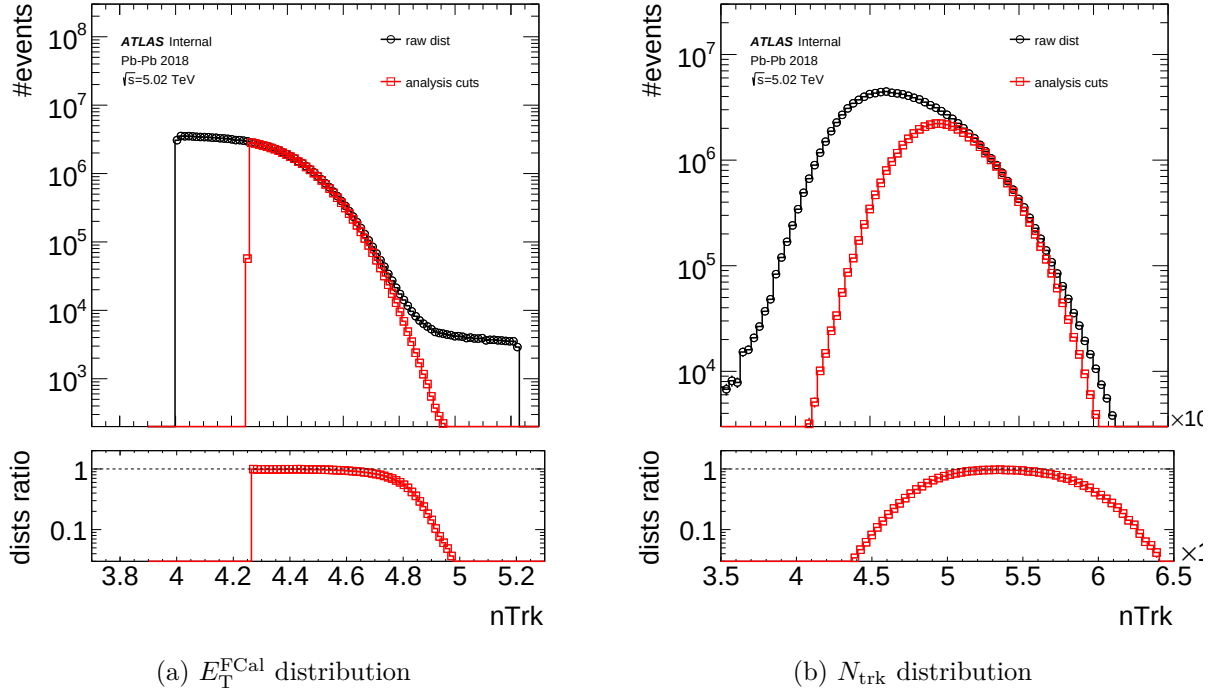


Figure 9.2: Comparison of event parameters distributions before and after applying analysis cuts – E_T^{FCal} and N_{trk} distributions

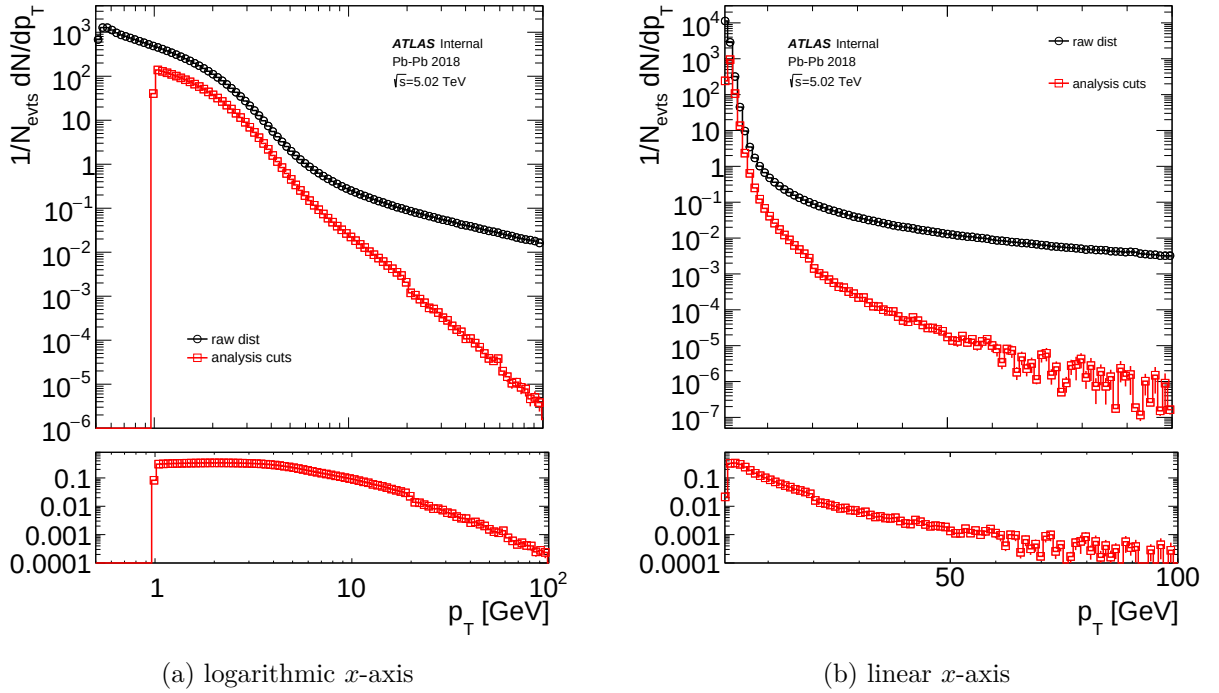


Figure 9.3: Comparison of transverse momentum distribution before and after applying analysis cuts

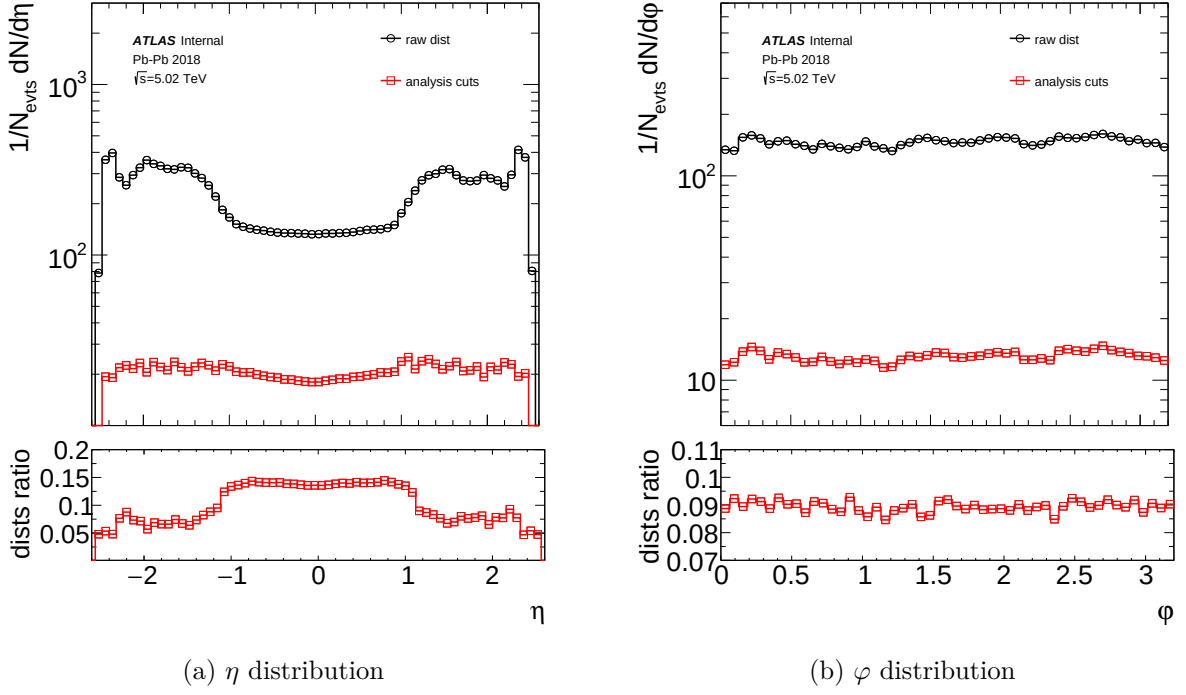


Figure 9.4: Comparison of track parameters distributions before and after applying analysis cuts – η and ϕ distributions

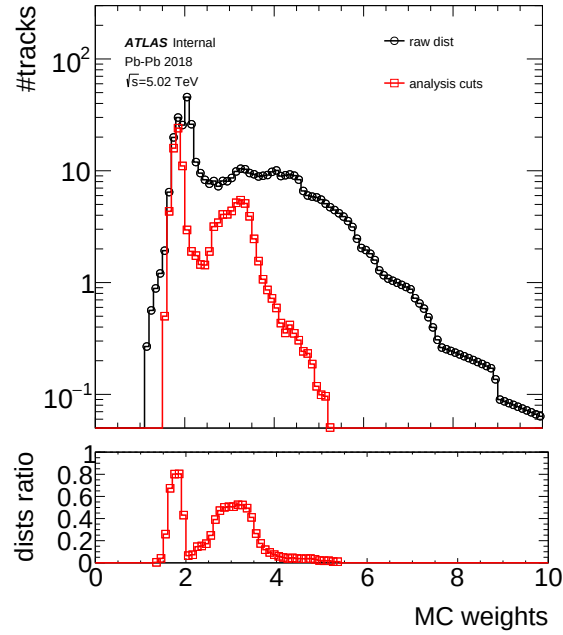


Figure 9.5: Comparison of Monte Carlo weights distributions before and after applying analysis cuts

9.3 MC track weights

The extraction of Monte Carlo track weights were extensively discussed in the [Section 7.1](#). Weight applied to each track is a function of its transverse momentum, pseudorapidity and track multiplicity. It is evaluated as the inverse of ρ

$$\rho(p_T, \eta, N_{\text{trk}}) = \frac{\varepsilon(p_T, \eta, N_{\text{trk}})}{1 - f(p_T, \eta, N_{\text{trk}})}, \quad (9.3)$$

where $\varepsilon(p_T, \eta, N_{\text{trk}})$ – tracking efficiency, $f(p_T, \eta, N_{\text{trk}})$ – fakes rate.

[Figure 9.6](#) and [Figure 9.7](#) plot distribution with and without Monte Carlo track weights. Distributions ratio below allow to assess 'effective' weight as a function of a single parameter. Highest weights in the low- p_T range, can be mostly attributed to high fake tracks rate.

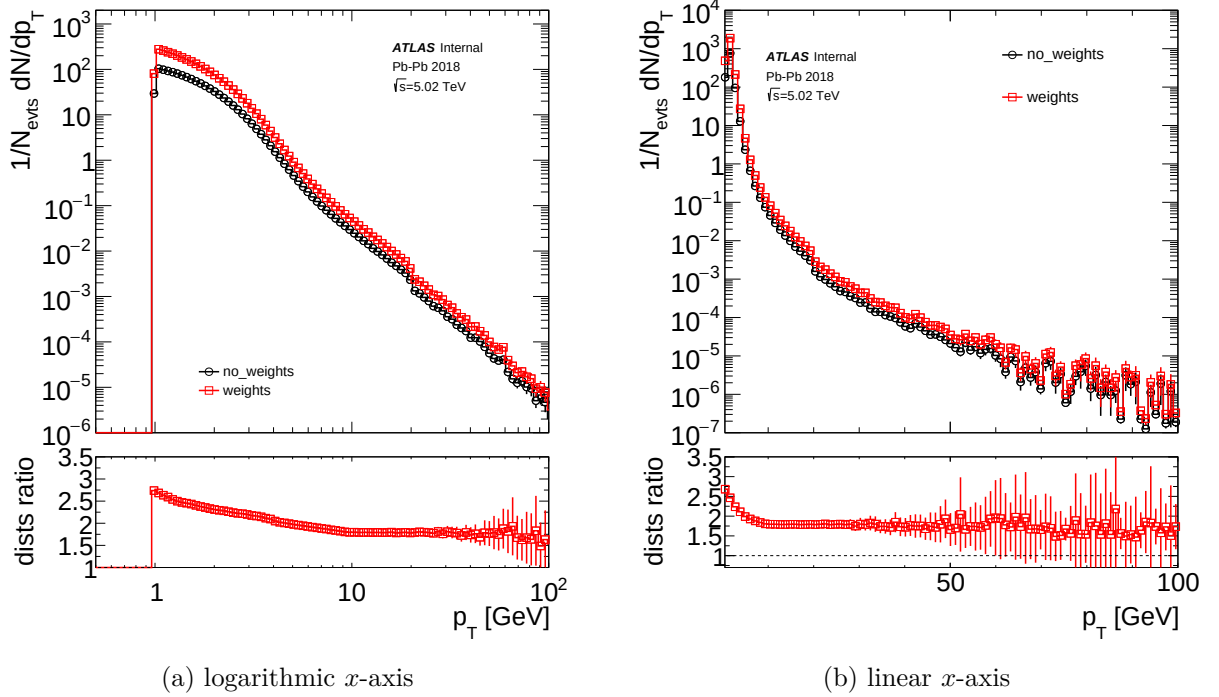


Figure 9.6: Comparison of the transverse momentum distribution with and without track-wise Monte Carlo weights. The ratio plot below indicates that the highest weights are applied in the low- p_T region

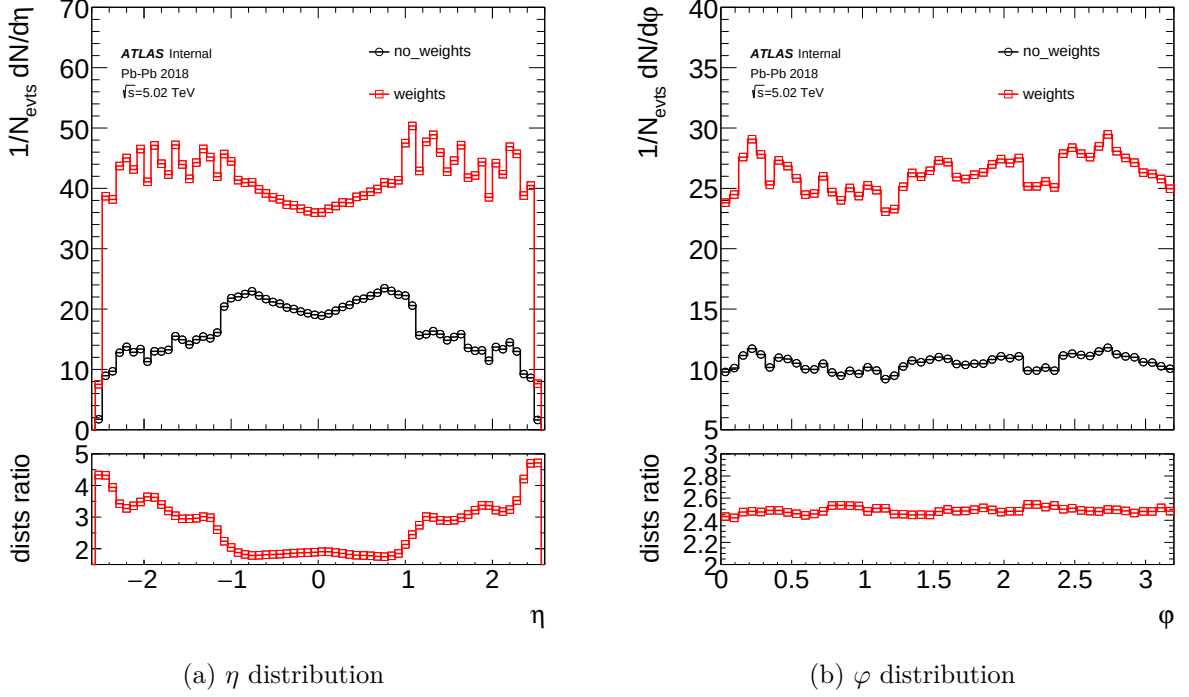


Figure 9.7: Comparison of the pseudorapidity and azimuth angle distribution with and without track-wise Monte Carlo weights. The ratio plot below indicates that the highest weights are applied in the peripheral pseudorapidity range. For ϕ angle no significant variation is observed

9.4 HILoose vs HITight

The choice of track selection requirements is critical to the analysis, as it determines which particles are included and how susceptible the sample is to fake tracks. In this study, the **HITight** requirement was applied, as it imposes more stringent quality criteria on tracks, particularly important in the high- p_T region, where the fake track rate is expected to be more significant. Compared to the **HILoose** criterion, **HITight** noticeably reduces the yield, especially in the high- p_T range, by approximately an order of magnitude – $\mathcal{O}(10^{-1})$.

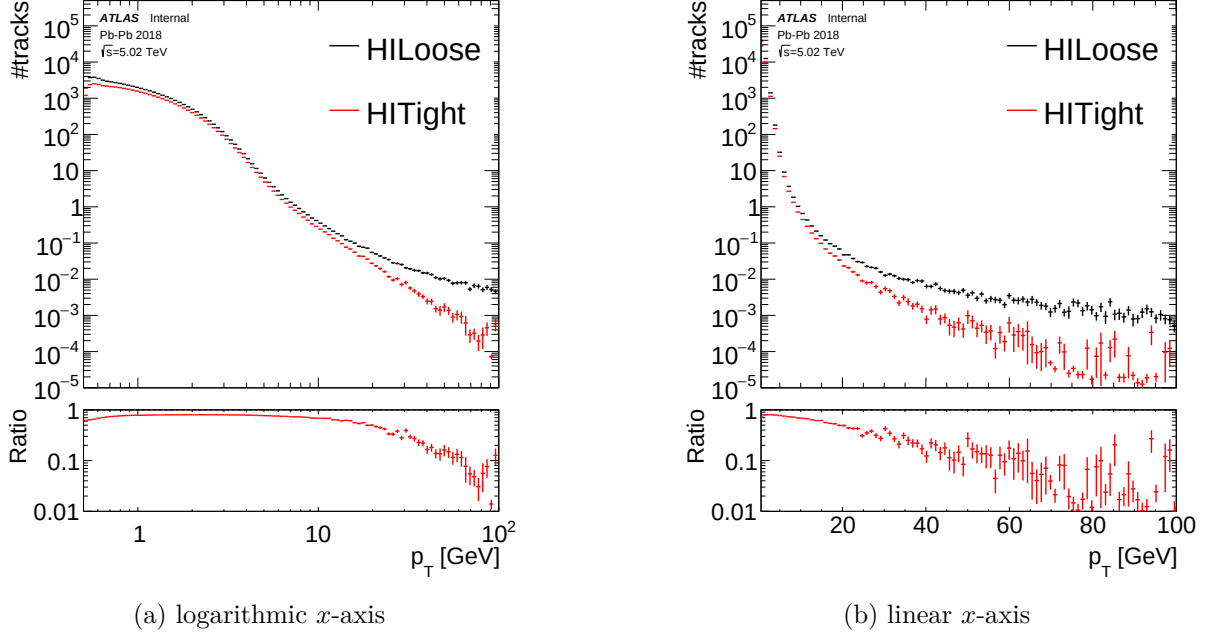


Figure 9.8: Transverse momentum dependence on the track selection requirement. HITight significantly reduces yield especially in the high- p_T range

9.5 Event distributions by sub-range

Plots in this section were generated for the sub-range division based on the $\tilde{n}_{\text{trk}}$ value. Five divisions for events falling in the range $\tilde{n}_{\text{trk}} \in [900, 1200]$ were performed. N_{trk} and $\tilde{n}_{\text{trk}}$ are presented in the Figure 9.1.

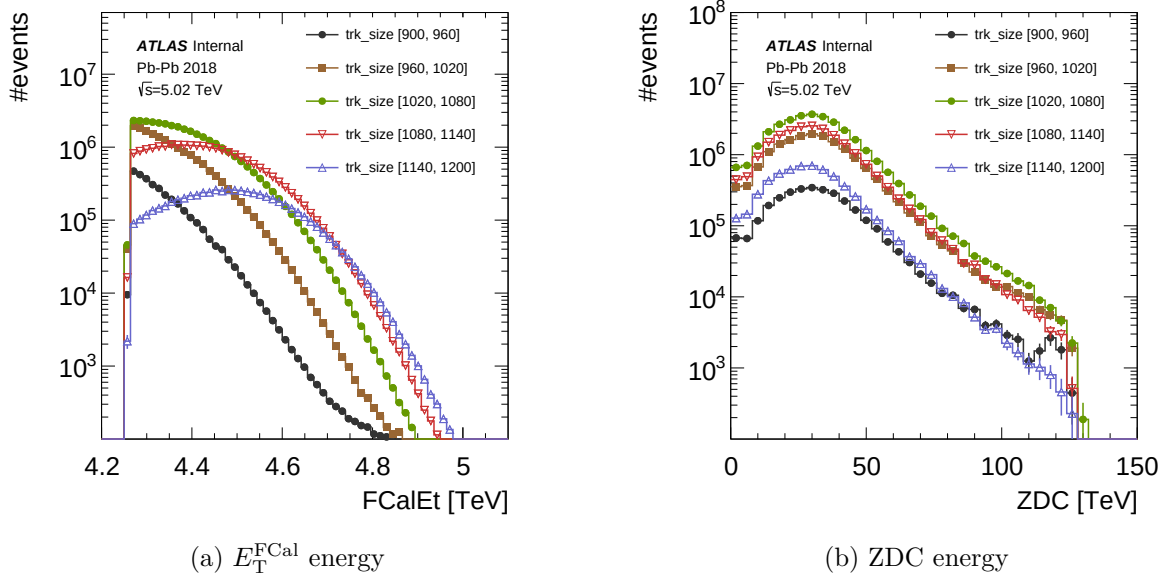
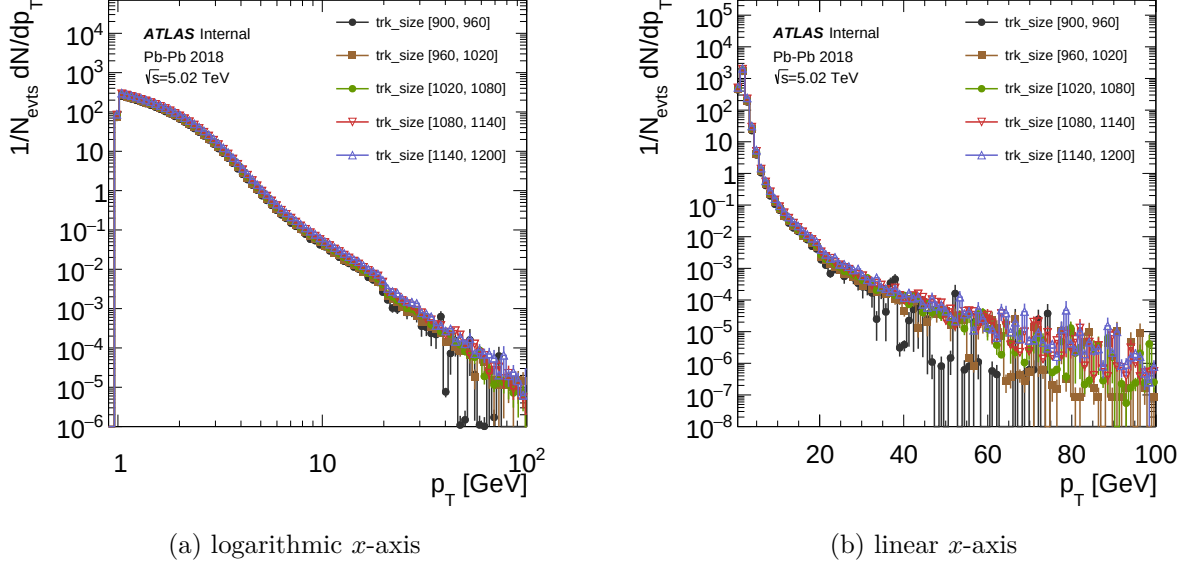
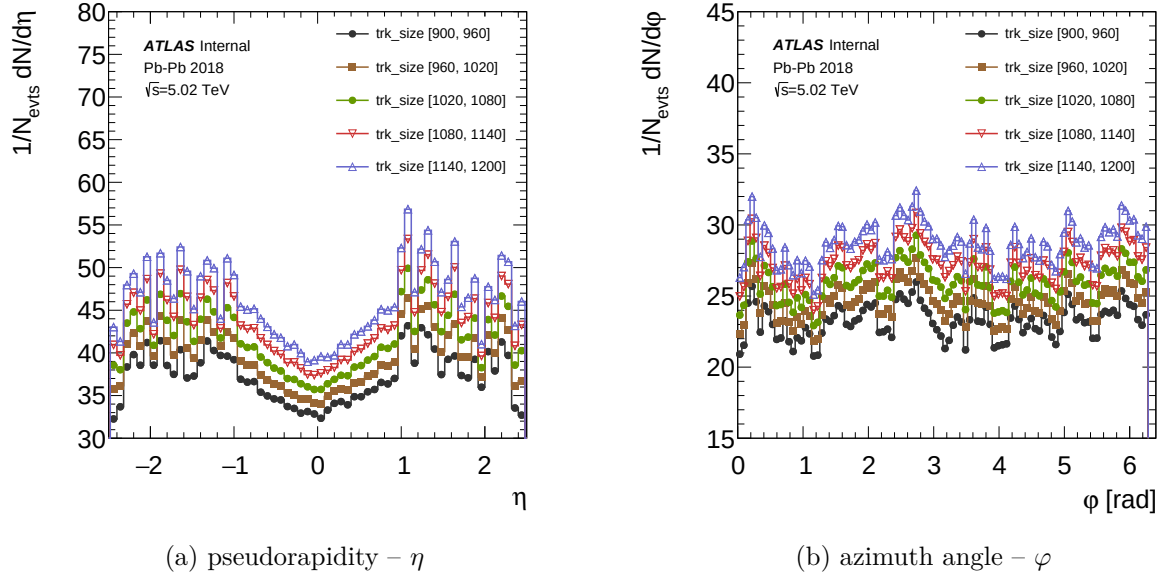


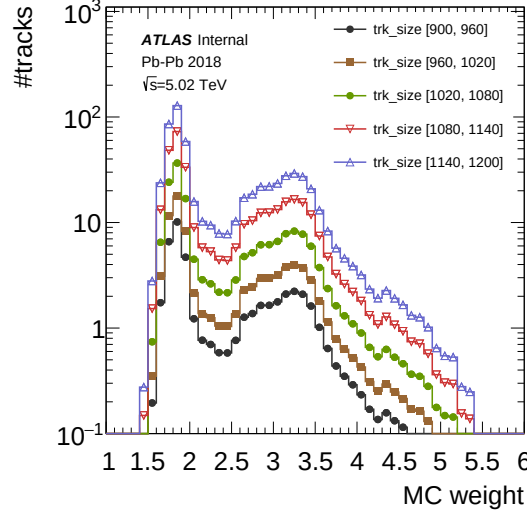
Figure 9.9: Parameters distribution by sub-range defined in terms of $\tilde{n}_{\text{trk}} - E_T^{\text{FCal}}$ and ZDC energy

The E_T^{FCal} distribution shown in Figure 9.9 shifts toward higher energy values as the bin index increases. This is an expected outcome, given the strong positive correlation between N_{trk} and E_T^{FCal} .


 Figure 9.10: Transverse momentum distribution by sub-range defined in terms of $\tilde{n}_{\text{trk}}$

 Figure 9.11: Parameters distribution by sub-range defined in terms of $\tilde{n}_{\text{trk}}$ – η and φ

For the transverse momentum distribution (Figure 9.10), no significant discrepancy is observed across sub-ranges. This is due to the p_T spectrum spanning several orders of magnitude, small changes are not easily visible on such a plot. This observation underscores the need for more sensitive analysis techniques, such as p_T distribution ratio comparisons.

The remaining track parameter distributions – η , φ , and Monte Carlo weights, do not show significant dependence on track multiplicity, as expected. The observed vertical offset is a result of event normalization – bins with higher indices contain more tracks, so the integral of their distributions increases, consistent with the increase in $\tilde{n}_{\text{trk}}$ sub-range boundaries.


 Figure 9.12: Monte Carlo weights distribution by sub-range defined in terms of $\tilde{n}_{\text{trk}}$

9.6 Effective T_{AA}

As outlined in Equation 9.1, the $\langle T_{AA} \rangle$ correction applied to the track yield plots is essential for accounting for varying centrality as track multiplicity changes. Since $\langle T_{AA} \rangle$ values are typically provided in reference documents for centrality intervals, defined in terms of $E_{\text{T}}^{\text{FCal}}$, an extrapolation procedure was implemented to determine the appropriate $\langle T_{AA} \rangle$ factor for each $\tilde{n}_{\text{trk}}$ bin.

Table 9.2 lists the $\langle T_{AA} \rangle$ values for 0.1% ultra-central collision centrality bins, as reported in the corresponding CERN Note [67].

 Table 9.2: T_{AA} factor dependence on centrality range [67]

centrality range	T_{AA}
0.0-0.1%	30.1827
0.1-0.2%	29.5261
0.2-0.3%	29.2093
0.3-0.4%	28.9666
0.4-0.5%	28.7741
0.5-0.6%	28.5962
0.6-0.7%	28.4221
0.7-0.8%	28.2720
0.8-0.9%	28.1269
0.9-1.0%	27.9863

To estimate the contribution of each centrality range to the effective $\langle T_{AA} \rangle$ within a given $\tilde{n}_{\text{trk}}$ sub-range, the $E_{\text{T}}^{\text{FCal}}$ distribution shown in Figure 9.9 was re-binned to align with the centrality intervals listed in Table 9.2. The definition of the 0.1%-width centrality bins for UCC collisions and their relation to $E_{\text{T}}^{\text{FCal}}$ is discussed in Section 9.7.

Figure 9.13 compares the re-binned $E_{\text{T}}^{\text{FCal}}$ distribution to the original distribution across the different $\tilde{n}_{\text{trk}}$ sub-ranges.

From the event yield in each bin of the re-binned $E_{\text{T}}^{\text{FCal}}$ distribution, a weight can be assigned to each 0.1% centrality interval, allowing for the estimation of the corresponding $\langle T_{AA} \rangle$ contribution. The resulting weighted sum of $\langle T_{AA} \rangle$ values is presented in Table 9.3.

As expected, the nuclear overlap function $\langle T_{AA} \rangle$ increases with rising $\tilde{n}_{\text{trk}}$, consistent with

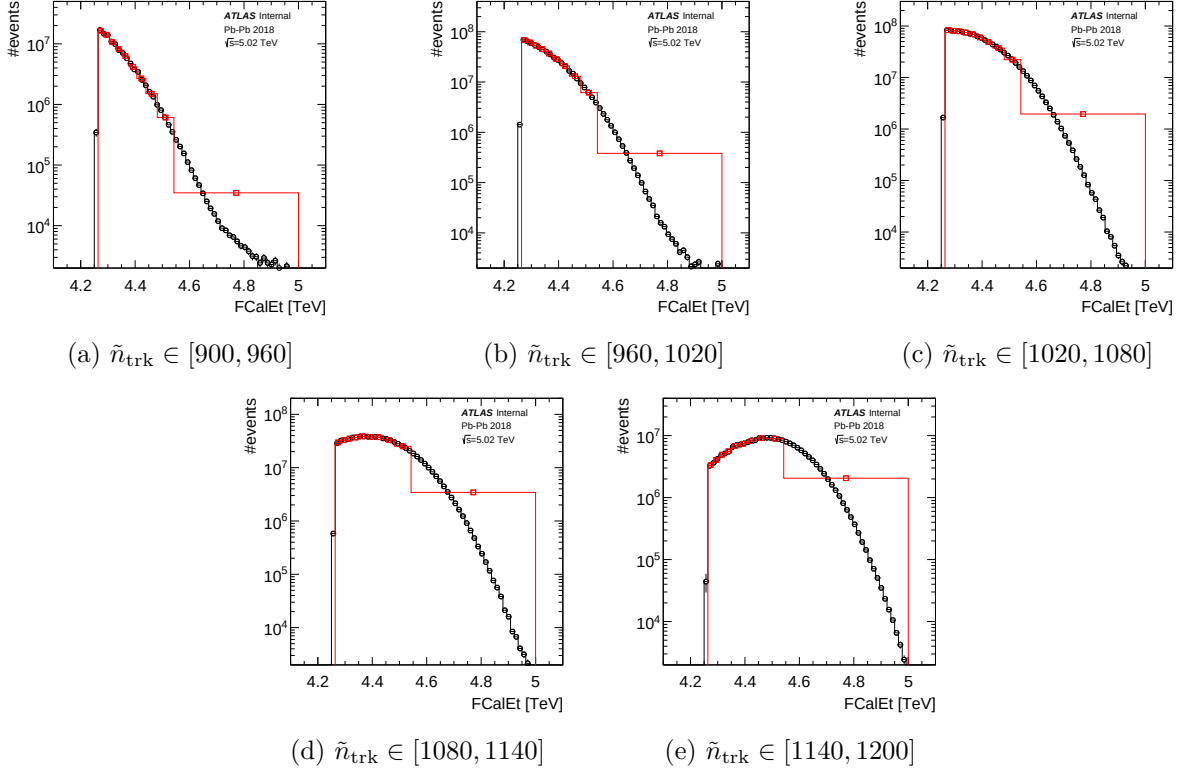


Figure 9.13: $E_{\text{T}}^{\text{FCal}}$ distribution for fixed size bins in each sub-range – black distribution, and the re-binned distribution, that matches the 0.1% centrality ranges introduced in the Table 9.4 – red distribution, normalized by the bin width

the trend observed across centrality intervals. This is due to the strong correlation between $\tilde{n}_{\text{trk}}$ and the centrality of heavy-ion collisions.

$\tilde{n}_{\text{trk}}$	$\langle T_{\text{AA}} \rangle$
[900, 960]	28.4018
[960, 1020]	28.5192
[1020, 1080]	28.7117
[1080, 1140]	28.9972
[1140, 1200]	29.3586

Table 9.3: Effective $\langle T_{\text{AA}} \rangle$ for each $\tilde{n}_{\text{trk}}$ sub-range

9.7 $E_{\text{T}}^{\text{FCal}}$ centrality cuts for 1% centrality

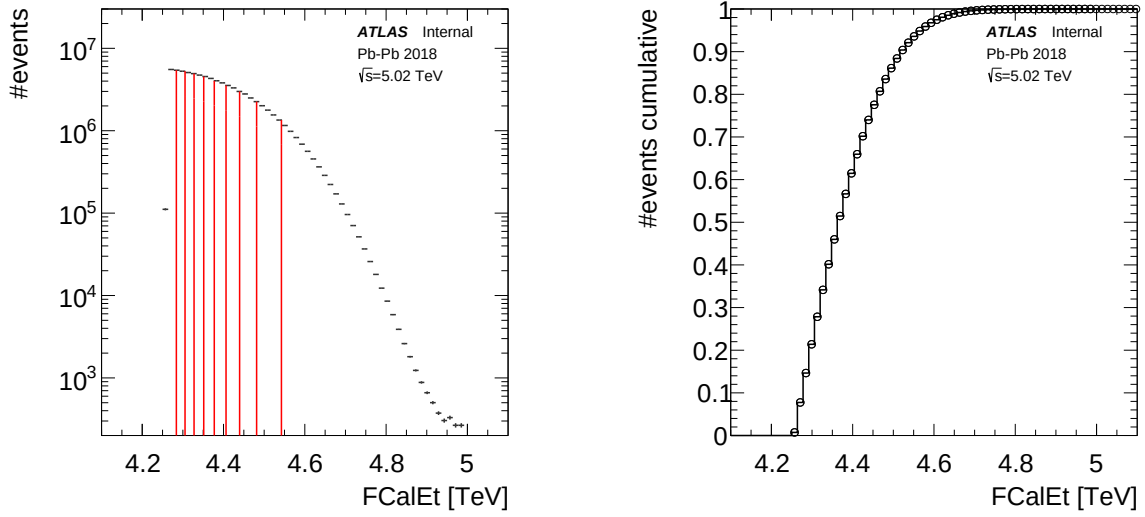
Estimating the effective $\langle T_{\text{AA}} \rangle$ for each $\tilde{n}_{\text{trk}}$ bin requires precise $E_{\text{T}}^{\text{FCal}}$ -based cuts to determine the event yield in each 0.1% centrality interval. These cut values were derived using the Glauber v3.2 model with an 85.5% efficiency threshold [63]. All cut values are listed in Table 9.4.

Centrality cut lines, superimposed on the $E_{\text{T}}^{\text{FCal}}$ distribution, are shown in Figure 9.14a.

To benchmark these values and ensure they accurately describe the dataset, an alternative method based on the normalized cumulative distribution function (CDF) was employed. For the distribution shown in Figure 9.14b, the $E_{\text{T}}^{\text{FCal}}$ value corresponding to each percentile (from the CDF y -axis) was extracted. These results are compared to the reference values from [63] in Table 9.4, showing a generally good agreement between the two methods, with slight deviations appearing at higher centralities.

Table 9.4: E_T^{FCal} cut value for 0.1% width bins in the 1% centrality, cut values adopted from [63] and cumulative distribution function (Figure 9.14b) based cuts, when pile-up events were filtered out

centrality	E_T^{FCal} energy	
	cuts [67]	CDF, pile-up
1.0%	4.26372	4.26372
0.9%	4.28399	4.27650
0.8%	4.30532	4.29706
0.7%	4.32751	4.31885
0.6%	4.35134	4.34197
0.5%	4.37726	4.36704
0.4%	4.40620	4.39515
0.3%	4.43960	4.42780
0.2%	4.48143	4.46856
0.1%	4.54246	4.52811



(a) Fixed bin size E_T^{FCal} distribution with 0.1% centrality cuts values

(b) Cumulative distribution function of the E_T^{FCal} distribution

Figure 9.14: E_T^{FCal} distribution with centrality cuts, and the cumulative distribution function of the E_T^{FCal}

When the E_T^{FCal} distribution is re-binned according to fixed centrality intervals, an approximately equal event yield is expected in each bin. To validate this assumption, Figure 9.15a compares the event yields across bins. A noticeable deficit is observed for the most central bin ($E_T^{\text{FCal}} > 4.54246$ TeV), potentially due to the pile-up rejection, which has the largest impact in the high- E_T^{FCal} region. Differences in pile-up removal strategies may lead to non-uniform bin populations in the re-binned spectrum. Figure 9.15b displays the same spectrum with a reduced y -axis range, allowing for a more detailed assessment of these discrepancies.

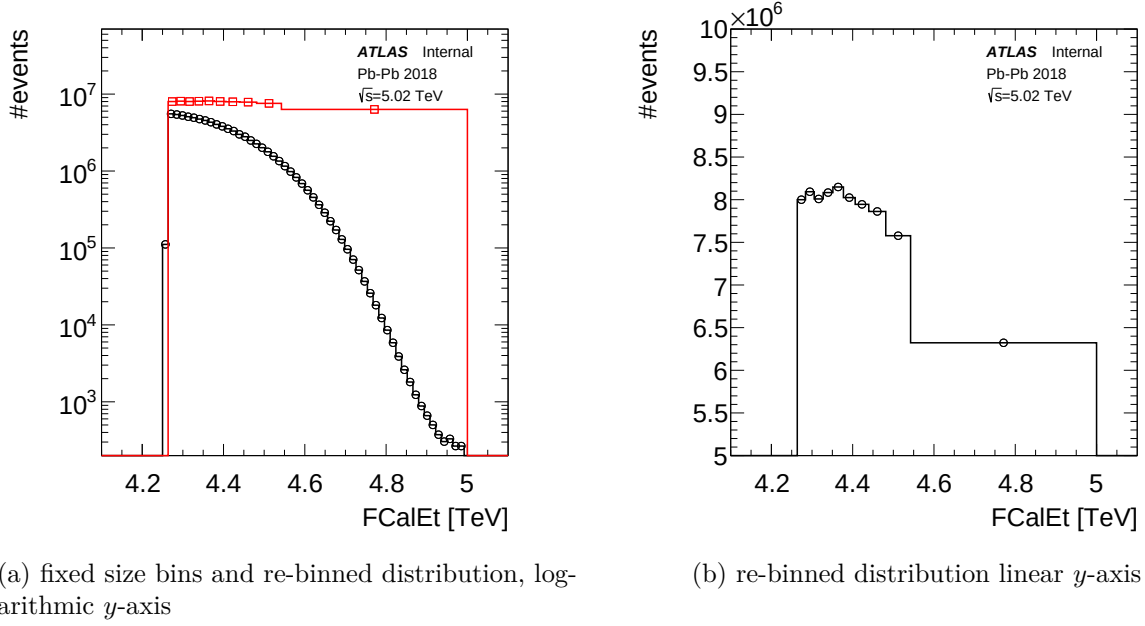


Figure 9.15: E_T^{FCal} distribution for fixed size bins, and the re-binned distribution, that matches the 0.1% centrality ranges introduced in the [Table 9.4](#)

9.8 E_T^{FCal} run-by-run distribution

The E_T^{FCal} distribution plays a central role in determining the weights used for particle yield estimation. Therefore, it is essential to verify the stability of this quantity across different runs and ensure that no significant deviations from the expected trend occur. To assess this, the E_T^{FCal} distribution was plotted separately for each run – see [Figure 9.16](#) and [Figure 9.17](#).

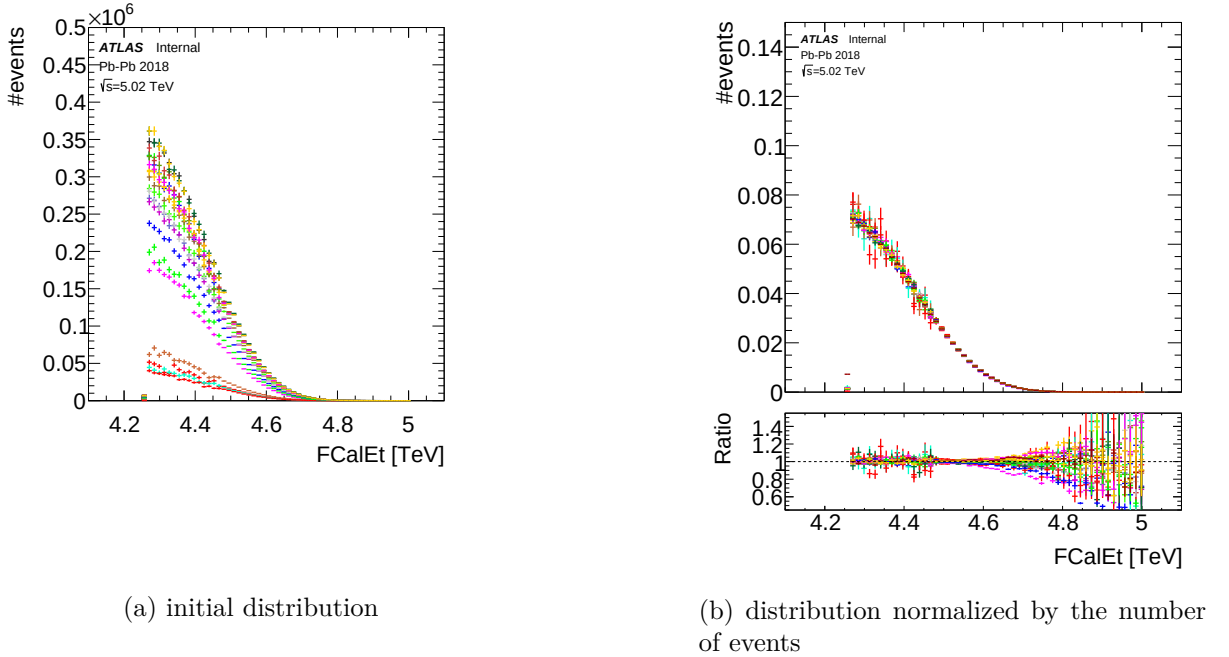
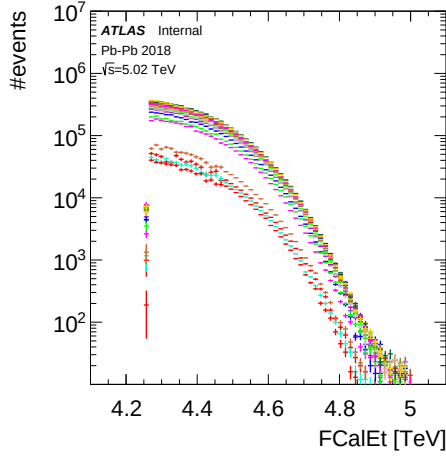
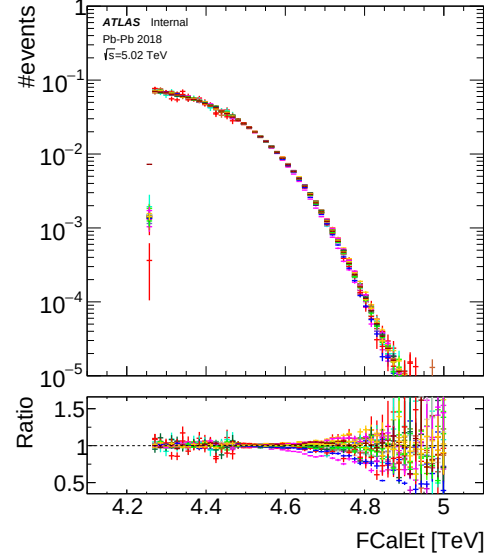


Figure 9.16: Run-by-run E_T^{FCal} distribution, linear x -axis

The distributions, normalized by the number of events per run, closely follow one another, indicating that the E_T^{FCal} energy estimate remains stable throughout the data-taking period.



(a) initial distribution

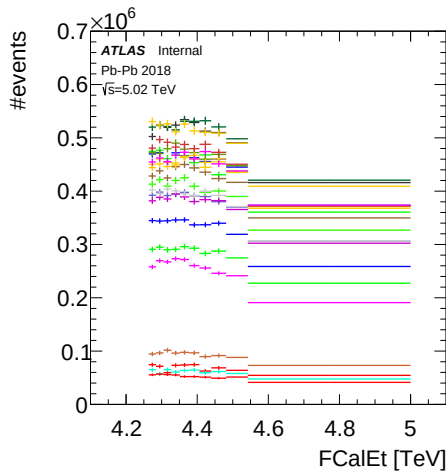


(b) distribution normalized by the number of events

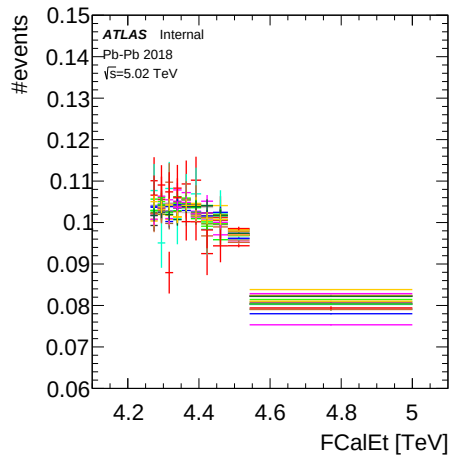
 Figure 9.17: Run-by-run E_T^{FCal} distribution, logarithmic x -axis

Noticeable deviations are only present in regions with large statistical uncertainties and are not considered significant.

To further investigate the impact of histogram binning – particularly with bins corresponding to equal-width centrality intervals, the run-by-run E_T^{FCal} distributions were also plotted in [Figure 9.18](#). Similarly, the most prominent discrepancy is observed in the highest centrality bin. This is likely due to variations in the pile-up removal procedure, which has a more pronounced effect in the high- E_T^{FCal} region.



(a) initial distribution



(b) distribution normalized by the number of events

 Figure 9.18: Run-by-run E_T^{FCal} distribution, histogram binning consistent with fixed width centrality ranges – [Table 9.4](#)

9.9 Jet parameters distribution

Jets are used in the analysis to match them to tracks, which is considered a necessary condition for high- p_T tracks ($p_T > 20$ GeV). Track-to-jet matching is performed using the criteria outlined in [Chapter 7](#). This section provides illustrative distributions of jet parameters to support and clarify the applied track selection cuts.

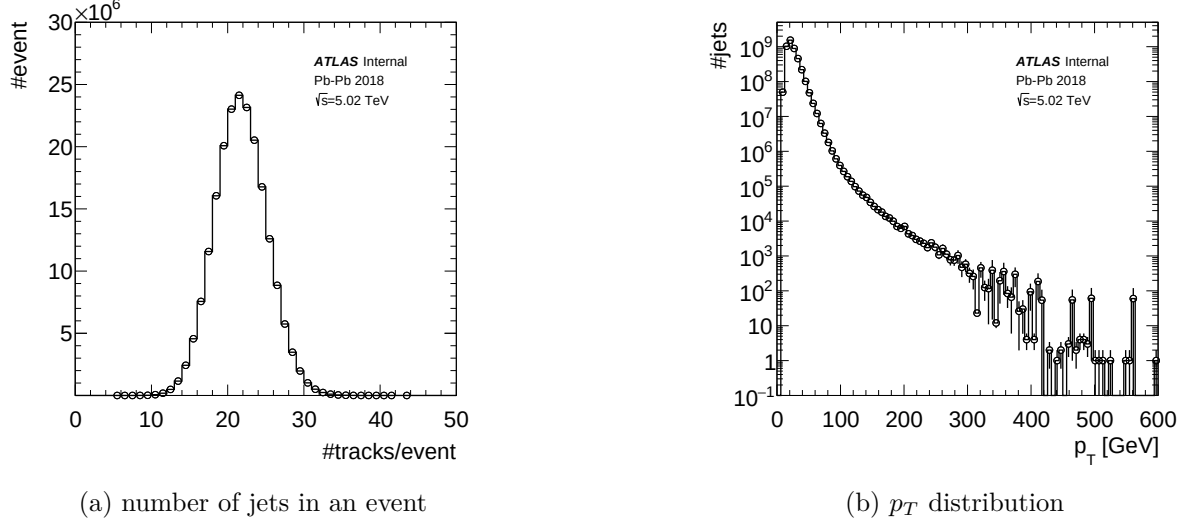


Figure 9.19: Transverse momentum and number of jets in an event distribution for jets

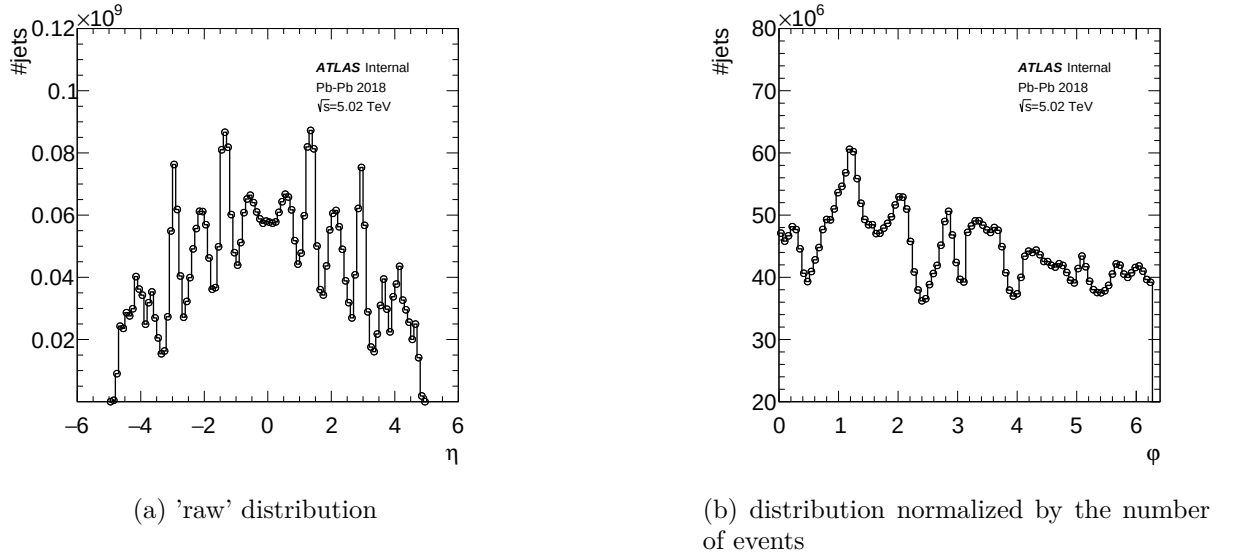


Figure 9.20: Pseudorapidity and azimuth angle distribution for jets

10 Results

The analysis methods used for the p_T distribution modification parametrization are outlined in [Chapter 9](#). They comprise two main approaches: the p_T distribution ratio and the track yield estimation across various transverse momentum ranges.

10.1 Ratio plots

Details of the analysis approach, based on the p_T ratio estimate was introduced in the [Section 9.1](#). Spectra division is evaluated in three p_T ranges

- $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$;
- $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$;
- $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$.

This type of analysis is aimed at investigating medium effect on the p_T spectra in UCC heavy-ion collisions, by varying the initial entropy density, using $\tilde{n}_{\text{trk}}$ (N_{trk}) as a proxy. The expectation is that with increasing $\tilde{n}_{\text{trk}}$ in UCC, the p_T spectra should exhibit signs of a stronger radial push for particles of low p_T and larger suppression at high p_T .

The reference is either the central $\tilde{n}_{\text{trk}}$ bin – [Section 10.1.1](#), or the neighboring bin with a lower index – [Section 10.1.2](#). The result plots for the first approach are presented in [Figure 10.1](#) – [Figure 10.4](#). The last figure shows the ratio plot for the range $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$ with coarser binning, which helps reduce uncertainties in the low-statistics (high- p_T) region.

The lowest transverse momentum range ratio plots primarily serve to show the expected behavior in the region not affected by jets. According to the note [ANA-HION-2018-17-INT1](#) [60], the jet-to-track matching threshold that is relevant at approximately $p_T \simeq 30 \text{ GeV}$, depending on the track momentum resolution (TMR) and jet energy resolution (JMR). Since resolution studies are beyond the scope of this analysis, it is assumed that the range $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$ is not significantly affected by jets.

The low- and medium- p_T ranges exhibit an increasing yield across most of the analyzed intervals. The ratio value in the low- p_T range can be attributed to the varying average $\tilde{n}_{\text{trk}}$ across bins. As a first approximation, the $\tilde{n}_{\text{trk}}$ midpoint can be used as the mean value. For the last two bins, this yields approximate ratios of $1170/1050 \approx 1.11$ and $1110/1050 \approx 1.06$, which very well agrees with ratio plots.

The high- p_T range continues this trend, showing an increase in the ratio for more central heavy-ion collisions. However, the high statistical uncertainties in this region prevent a conclusive interpretation.

To reduce the impact of low-statistics bins, the range $[1 \text{ GeV}, 100 \text{ GeV}]$ was re-binned – [Figure 10.4](#). While in the other cases three bins were merged, here eight bins were combined. Despite this re-binning, the uncertainty remains too large to draw definitive conclusions, though the yield still appears to increase with p_T , consistent with trends seen at lower momenta.

In addition to the fixed reference bin plots, results using a floating reference, where each bin is compared to its immediate neighbor with lower $\tilde{n}_{\text{trk}}$, were also produced. In such ratio plots,

all histograms are expected to follow similar trends, as adjacent bin distributions are compared. This method also shows a yield increase at higher transverse momentum, but again without a conclusive outcome in the highest p_T region due to statistical limitations.

To reduce the impact of the $\tilde{n}_{\text{trk}}$ range selection and to focus purely on the shape comparison of the p_T distribution, analogous plots with integral normalization were produced. Each distribution was divided by the integral of the spectrum within the p_T range used for the ratio. This normalization should eliminate the influence of differences in mean $\tilde{n}_{\text{trk}}$. The resulting plots are presented in [Appendix D](#).

As in the previous case, no definitive conclusions can be drawn due to large fluctuations in the high- p_T region. However, within the uncertainty ranges, no significant discrepancies between ratio plots are observed.

10.1.1 Spectra ratio to the fixed reference bin

Figures in this section show ratio of the p_T spectra with the central bin (referred to as 2nd) is used in denominator.

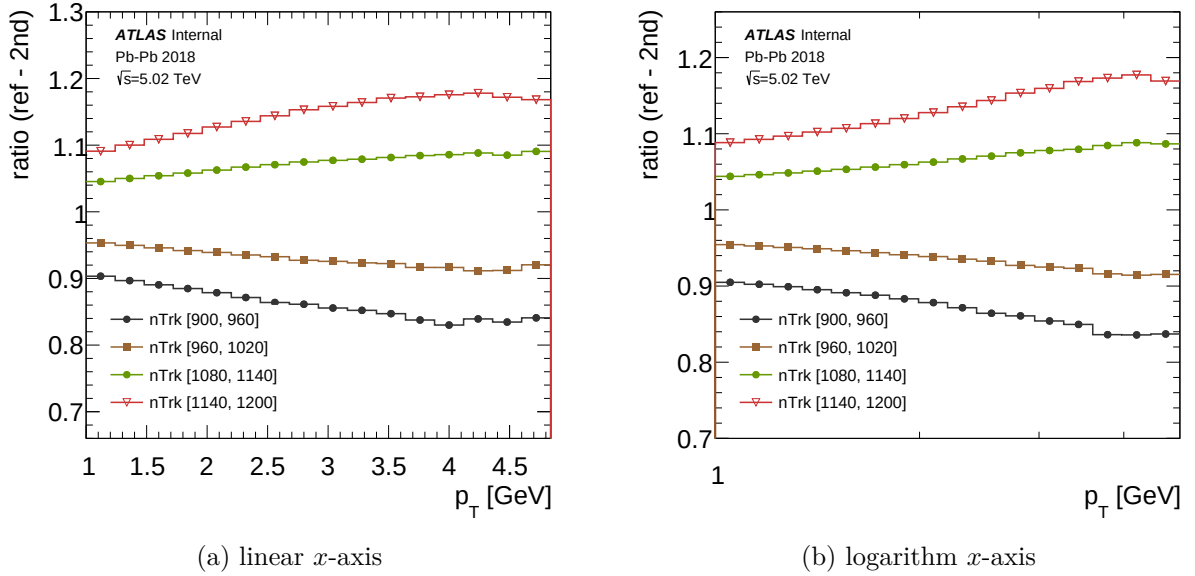


Figure 10.1: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$, p_T spectrum normalized by number of events

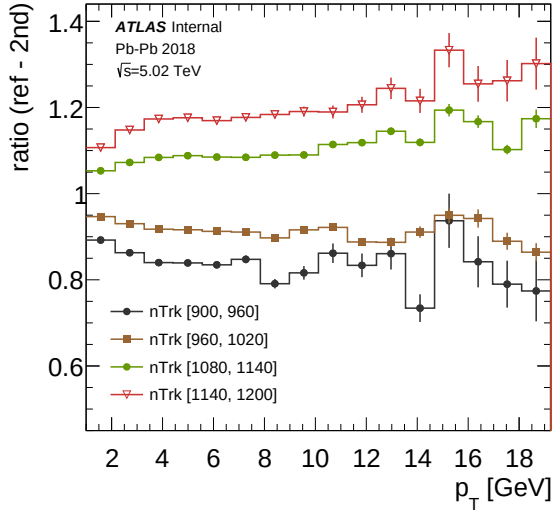
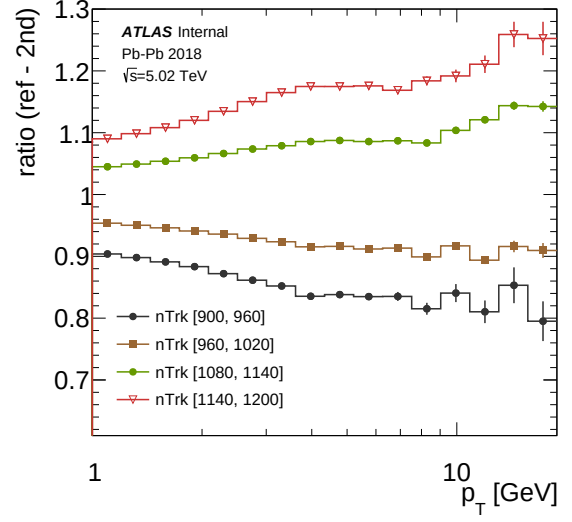

 (a) linear x -axis

 (b) logarithm x -axis

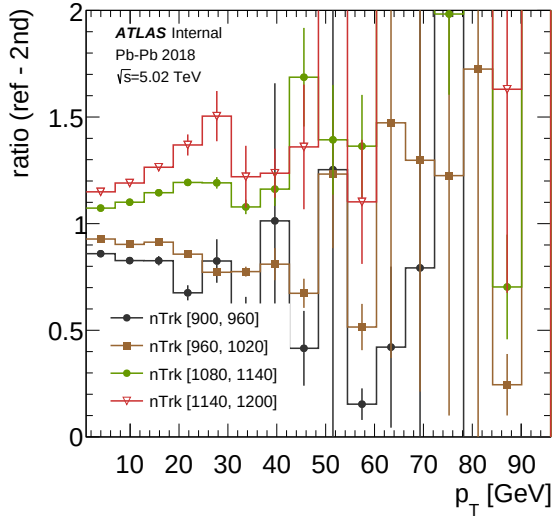
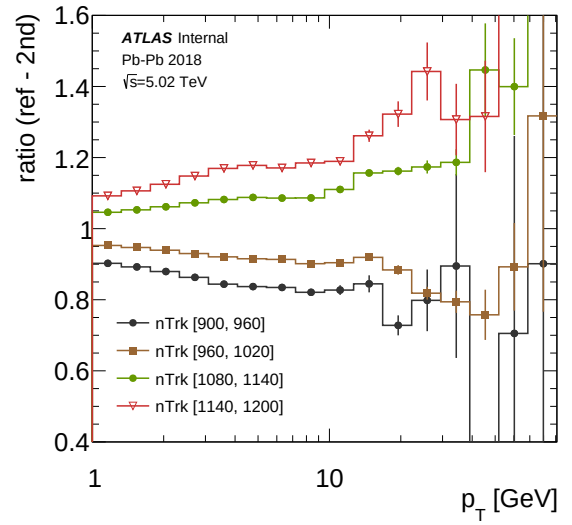
 Figure 10.2: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$, p_T spectrum normalized by number of events

 (a) linear x -axis

 (b) logarithm x -axis

 Figure 10.3: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, p_T spectrum normalized by number of events

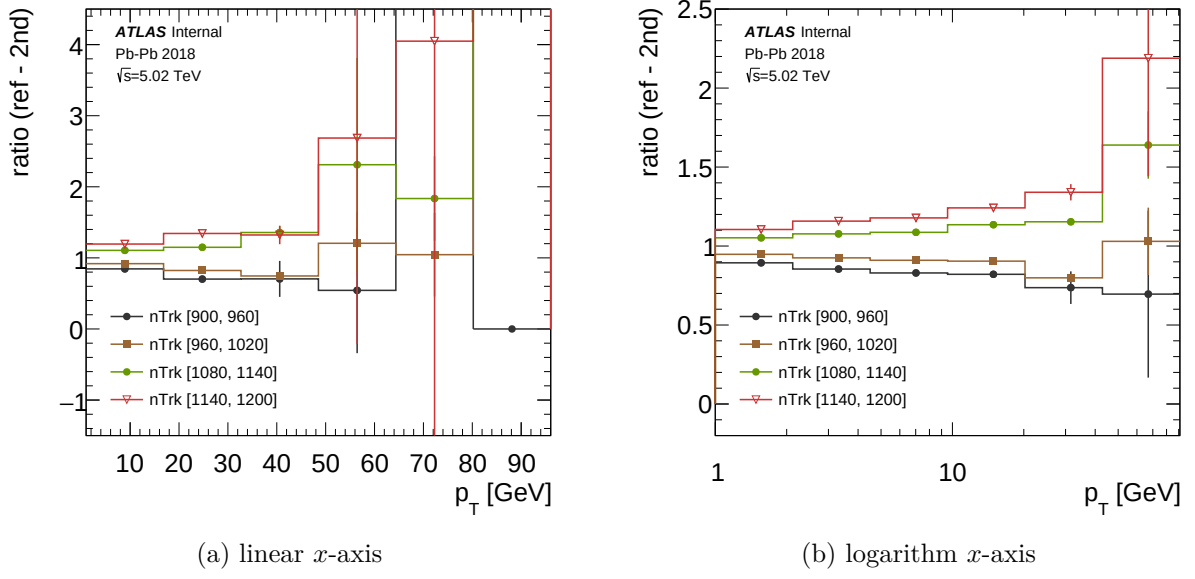


Figure 10.4: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, wider bins, p_T spectrum normalized by number of events

10.1.2 Spectra ratio to the floating reference bin

Figures in this section show p_T spectra ratio when the denominator is the spectra at lower multiplicity (previous bin).

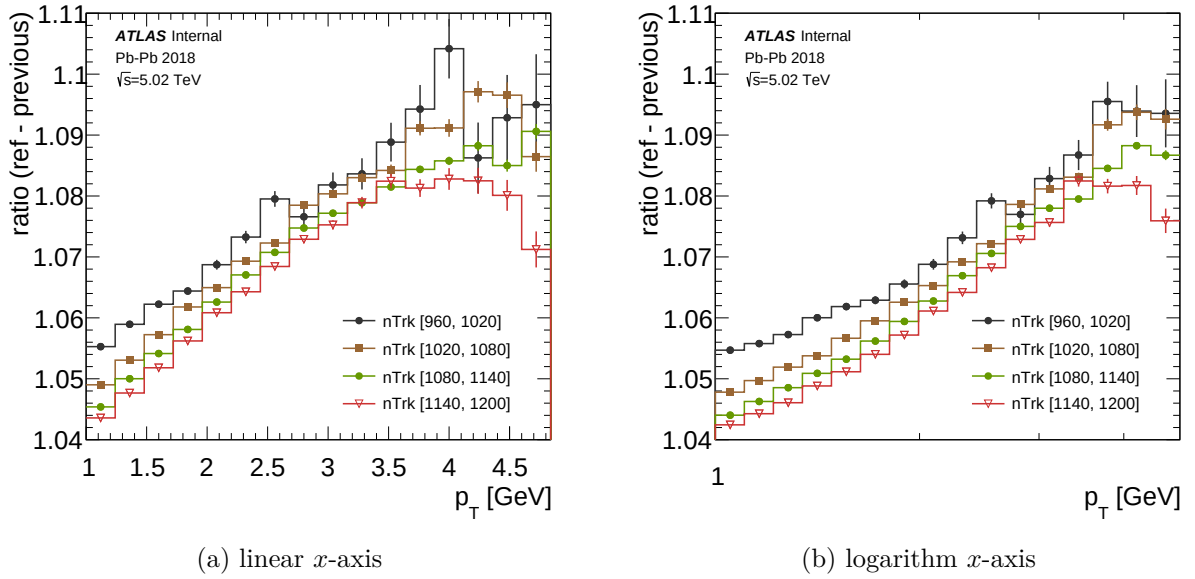


Figure 10.5: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$, p_T spectrum normalized by number of events

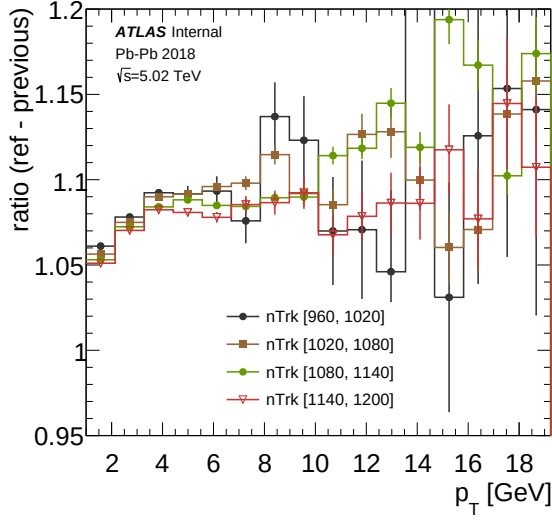
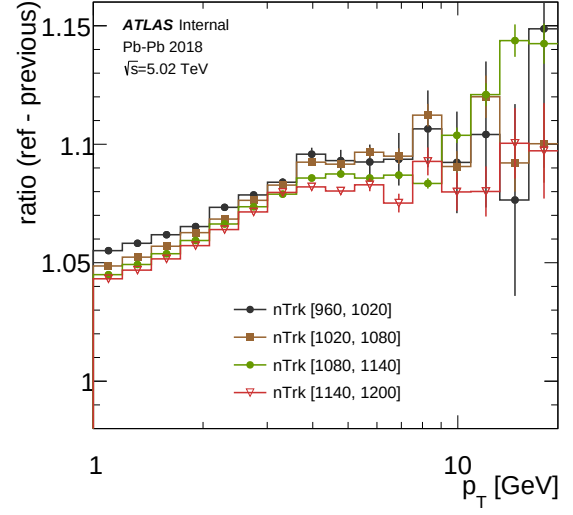

 (a) linear x -axis

 (b) logarithm x -axis

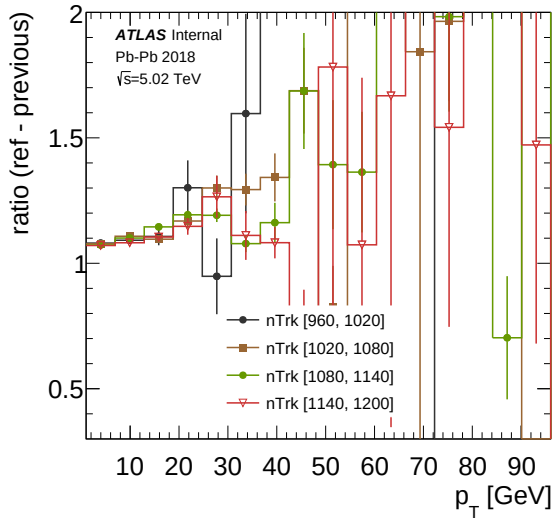
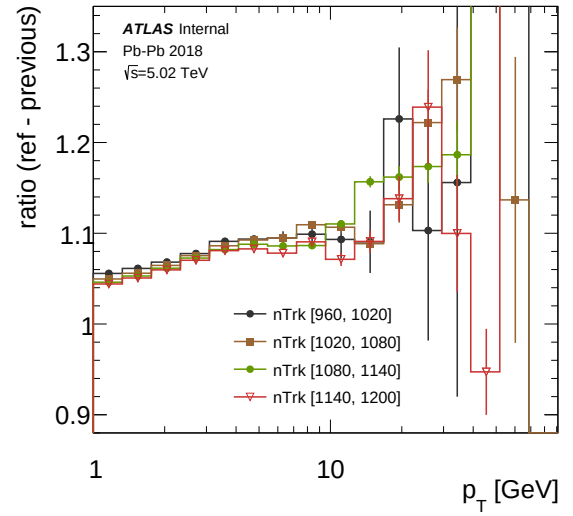
 Figure 10.6: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$, p_T spectrum normalized by number of events

 (a) linear x -axis

 (b) logarithm x -axis

 Figure 10.7: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, p_T spectrum normalized by number of events

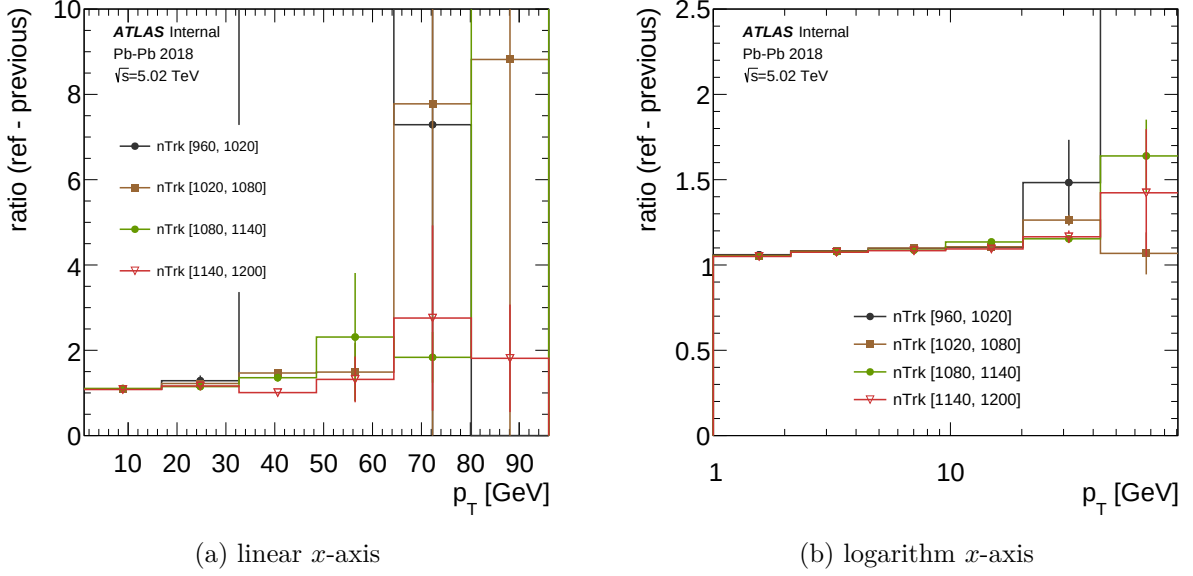


Figure 10.8: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$, wider bins, p_T spectrum normalized by number of events

10.2 Track yield

In order to verify the compliance of experimental data with the model explaining the proportionality between track multiplicity and track yield – Equation 2.25, histograms of the number of tracks with p_T in the given range as a function of track multiplicity were plotted. As in the ratio plots – Section 10.1, all events with $\tilde{n}_{\text{trk}} \in [900, 1200]$ were binned into 5 intervals. Subsequently, a $\langle T_{AA} \rangle$ correction, introduced in Section 9.6, was applied to each bin.

To enable flexible selection of the p_T range for which the track yield is evaluated, the number of tracks was counted separately in narrower intervals, which can later be merged. These include $p_T \in [1 \text{ GeV}, 10 \text{ GeV}]$, $[10 \text{ GeV}, 15 \text{ GeV}]$, $[15 \text{ GeV}, 20 \text{ GeV}]$, $[20 \text{ GeV}, 30 \text{ GeV}]$, $[30 \text{ GeV}, 40 \text{ GeV}]$, and so on. The number of tracks evaluated in this way can be easily merged into wider ranges, such as $p_T \in [15 \text{ GeV}, 100 \text{ GeV}]$. However, the mean transverse momentum and its standard deviation require weighting proportional to the event count in each bin, which was not considered in this analysis. Hence, $\langle p_T \rangle$ and $\sigma(p_T)$ are quoted only for the narrow ranges.

Following the considerations in Section 2.4, momentum transfer in the QGP is expected to be proportional to $(dN_{ch}/d\eta)^{4/3}$, which in this analysis translates into a proportionality to $\tilde{n}_{\text{trk}}^{4/3}$. To test whether the data follow this theoretical prediction, both a linear and a power-law fit were performed on the 5 data points.

Section 10.2.1 presents the track yield dependence along with the fitted functions. The range $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$ was included as a reference for the particle yield in the region not predominantly affected by QGP effects. No significant deviation from a linear trend is observed in any p_T range. For $p_T > 30 \text{ GeV}$, the absence of deviation might be partially attributed to limited statistics.

All fit function coefficients and the corresponding χ^2 values are presented in Table E.1 (Appendix E).

Similarly, plots of the squared number of tracks, which provide information about the variance of this quantity, do not show any significant trend beyond linear growth for any p_T range – see Section 10.2.2.

For the mean p_T (Section 10.2.3) and its standard deviation (10.2.4), both fine and coarse binnings are included. For these quantities, the $\langle T_{AA} \rangle$ correction is not applied, which allows more flexibility in binning. Finer binning enables closer observation of changes in the analyzed

quantities and helps explain anomalous trends, particularly at the lower and upper bounds of the range, which are mostly caused by low statistics. Only in the low- p_T range is any change in mean transverse momentum observed. In the remaining regions, fluctuations make it difficult to reliably interpret any change. As shown in [Table 10.1](#), the mean p_T over the entire range increases with higher $\tilde{n}_{\text{trk}}$ values.

Similarly, for the standard deviation, only in the low- p_T range is the observed change statistically significant.

Table 10.1: Mean transverse momentum by $\tilde{n}_{\text{trk}}$ range for tracks in the range $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$

index	0	1	2	3	4
min $\tilde{n}_{\text{trk}}$	900	960	1020	1080	1140
max $\tilde{n}_{\text{trk}}$	960	1020	1080	1140	1200
$\langle p_T \rangle$ [GeV]	1.501(13)	1.5047(51)	1.5089(35)	1.5133(38)	1.5176(59)

10.2.1 Number of tracks

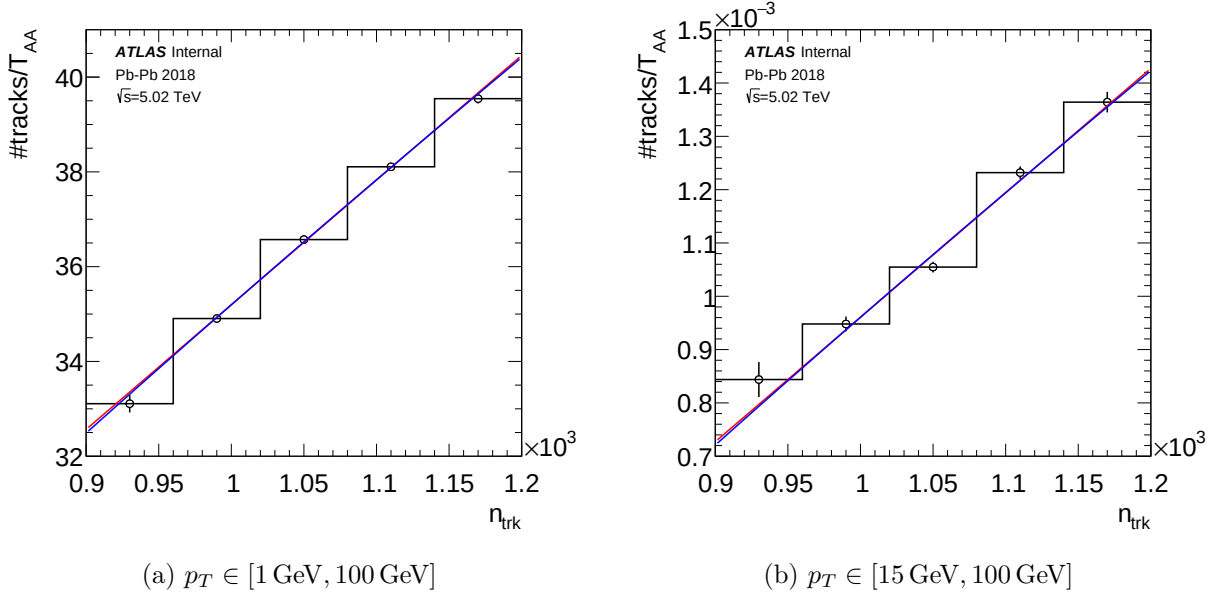


Figure 10.9: Average number of tracks with transverse momentum in the specified range per event, shown as a function of $\tilde{n}_{trk}$. Red line indicates a linear fit, while the blue line represents a power-law fit proportional to $x^{3/4}$. All values are corrected by $\langle T_{AA} \rangle$

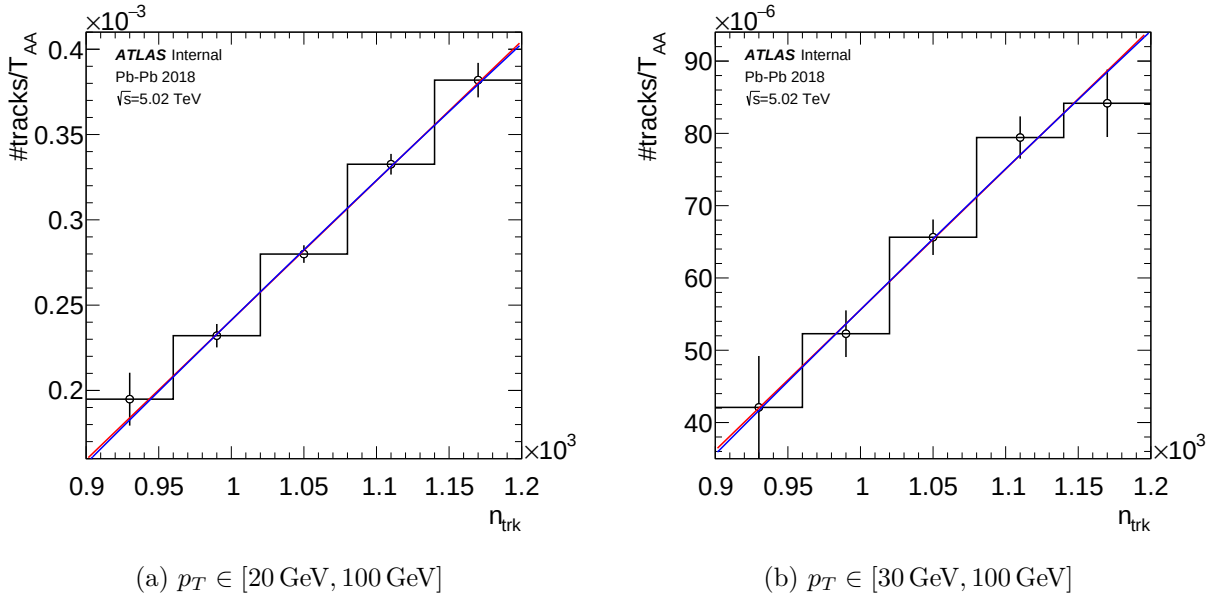
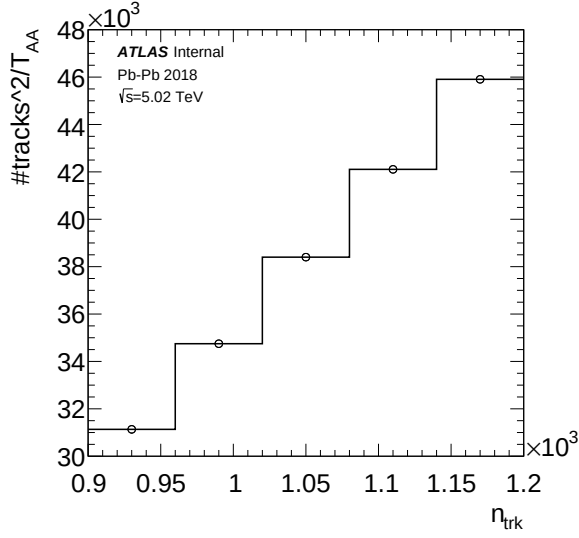
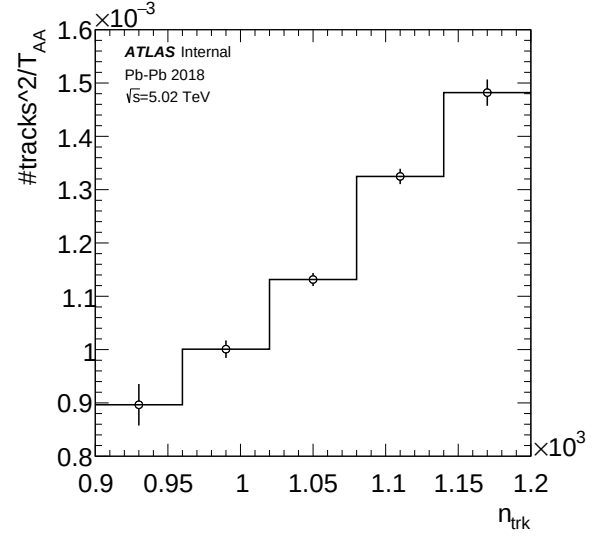
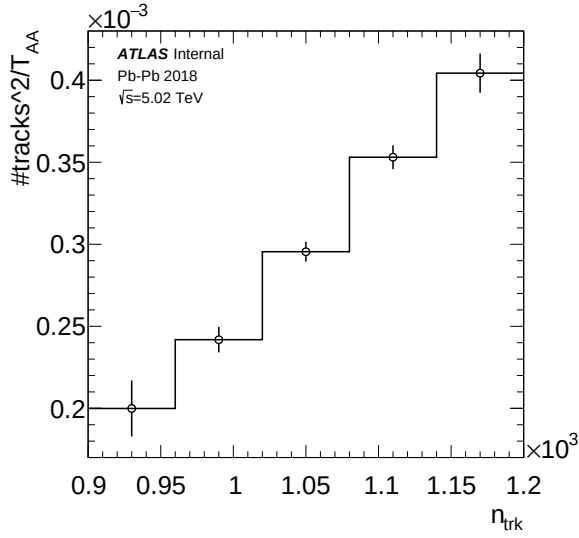
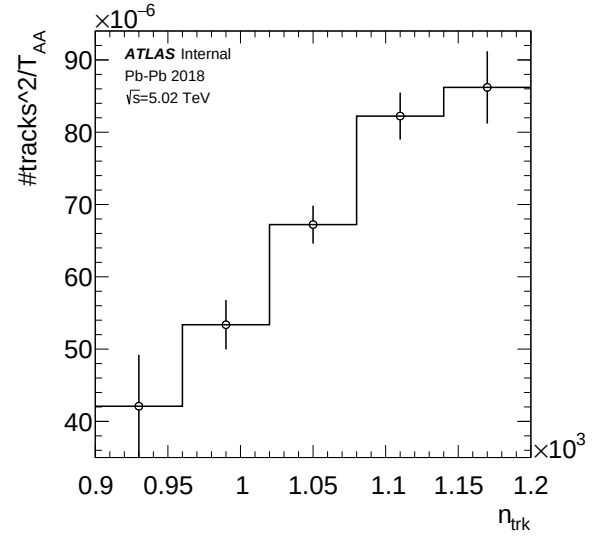
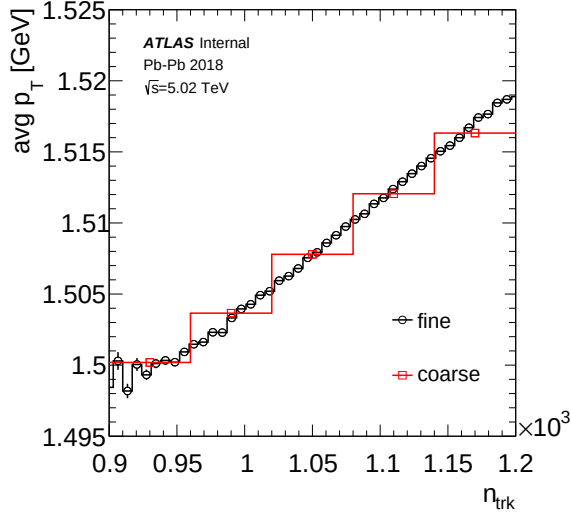
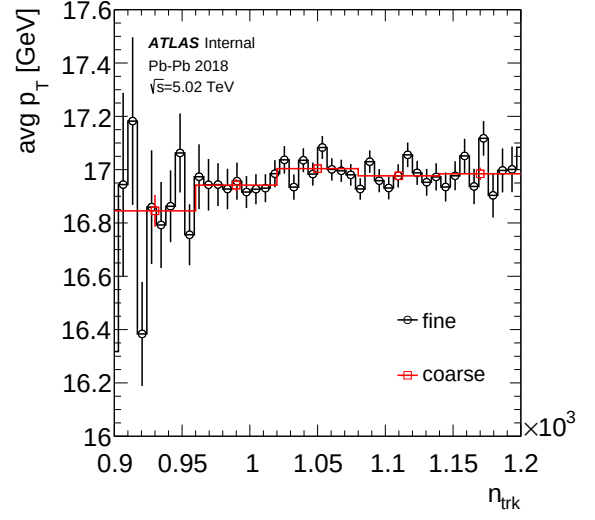
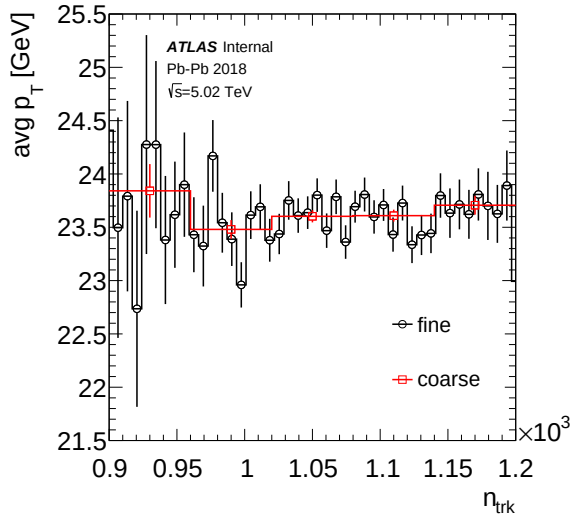
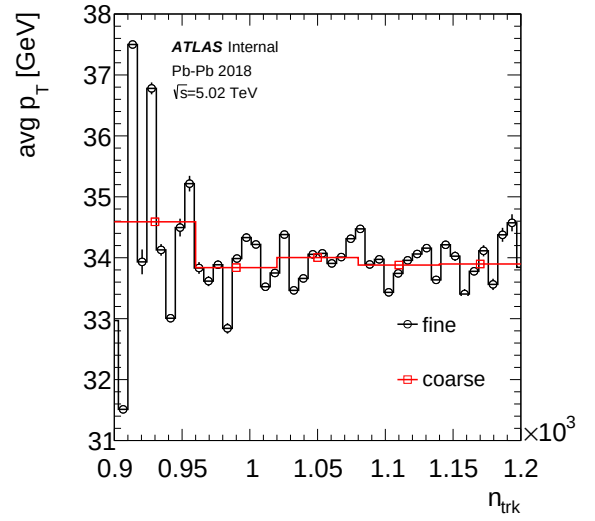


Figure 10.10: Average number of tracks with transverse momentum in the specified range per event, shown as a function of $\tilde{n}_{trk}$. Red line indicates a linear fit, while the blue line represents a power-law fit proportional to $x^{3/4}$. All values are corrected by $\langle T_{AA} \rangle$

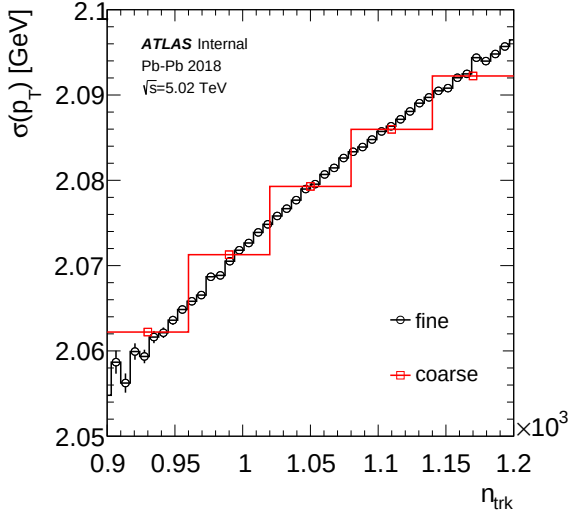
10.2.2 Number of tracks squared

(a) $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$ (b) $p_T \in [15 \text{ GeV}, 100 \text{ GeV}]$ Figure 10.11: Average squared number of tracks with transverse momentum in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$. All values are corrected by $\langle T_{AA} \rangle$ (a) $p_T \in [20 \text{ GeV}, 100 \text{ GeV}]$ (b) $p_T \in [30 \text{ GeV}, 100 \text{ GeV}]$ Figure 10.12: Average squared number of tracks with transverse momentum in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$. All values are corrected by $\langle T_{AA} \rangle$

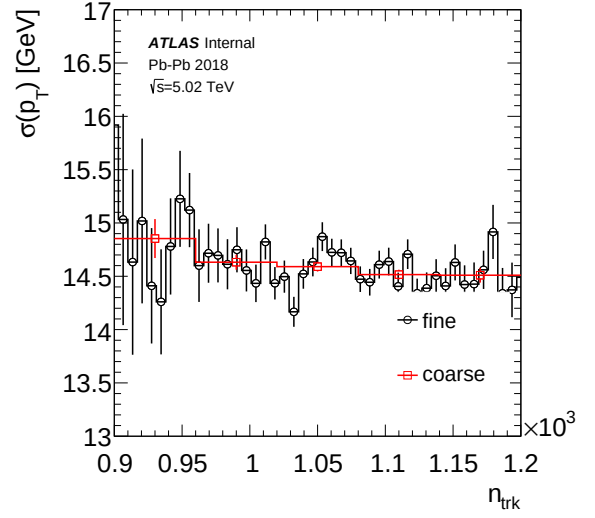
10.2.3 Average transverse momentum

(a) $p_T \in [1 \text{ GeV}, 10 \text{ GeV}]$ (b) $p_T \in [15 \text{ GeV}, 20 \text{ GeV}]$ Figure 10.13: Average transverse momentum of tracks with p_T in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$ (a) $p_T \in [20 \text{ GeV}, 30 \text{ GeV}]$ (b) $p_T \in [30 \text{ GeV}, 40 \text{ GeV}]$ Figure 10.14: Average transverse momentum of tracks with p_T in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$

10.2.4 Standard deviation of the transverse momentum

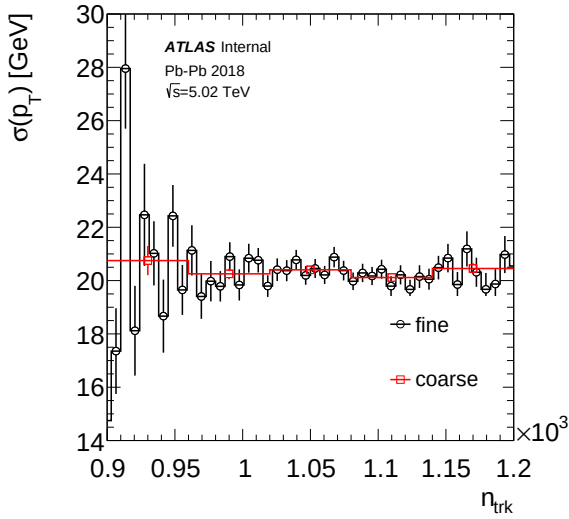


(a) $p_T \in [1 \text{ GeV}, 10 \text{ GeV}]$

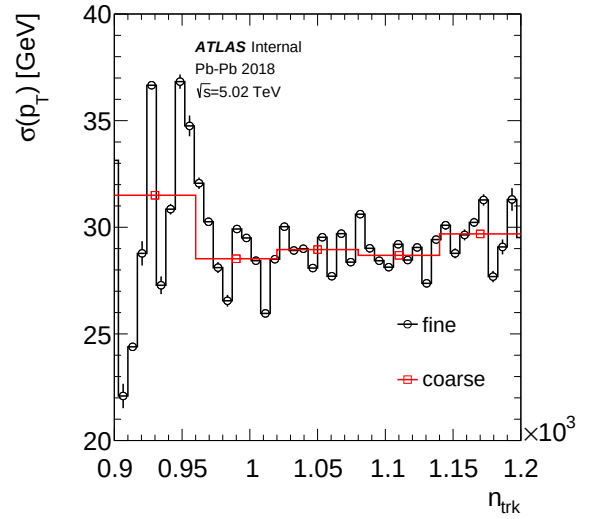


(b) $p_T \in [15 \text{ GeV}, 20 \text{ GeV}]$

Figure 10.15: Average standard deviation for transverse momentum in tracks with p_T in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$



(a) $p_T \in [20 \text{ GeV}, 30 \text{ GeV}]$



(b) $p_T \in [30 \text{ GeV}, 40 \text{ GeV}]$

Figure 10.16: Average standard deviation for transverse momentum in tracks with p_T in the specified range per event, shown as a function of $\tilde{n}_{\text{trk}}$

11 Summary

The outlined analysis aims to investigate the modification of the transverse momentum spectrum with increasing collision centrality. For charged particles affected by the quark-gluon plasma (QGP) medium, a proxy for the initial system energy density and temperature is the track multiplicity – $dN_{ch}/d\eta$. Track multiplicity increases with higher collision centrality. The analysis primarily focuses on parametrizing changes in the p_T distribution, particularly in the high-momentum range $p_T \gtrsim 20$ GeV, as a function of event track multiplicity.

The scope of this analysis is limited to the top 1% most central Pb–Pb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV. Events and tracks passing stringent selection criteria, mainly to suppress fake tracks in both the low- and high- p_T ranges and to reduce pile-up, were divided into 5 sub-ranges defined by the size of the track vector after all selection cuts – $\tilde{n}_{\text{trk}}$. This division yielded 5 transverse momentum distributions.

To identify subtle modifications in the p_T distribution, the spectrum in each bin was divided by a reference – either the central bin or the adjacent bin with a lower $\tilde{n}_{\text{trk}}$ value, i.e., $p_T(i)/p_T(i-1)$. To compare relative yield and distribution shape, normalization was performed both by the number of events and by using the distribution integral. Neither method revealed significant changes in the high- p_T region for increasing centrality. Limited statistics in this range introduced large uncertainties in the ratio evaluation. In the lower transverse momentum region, an increasing yield with higher $\tilde{n}_{\text{trk}}$ is observed.

The Linear Transport Model and the QGP equation of state, predict that the mean momentum transfer for particles affected by the QGP should scale with $\tilde{n}_{\text{trk}}^{3/4}$. To test this, the number of tracks within a specified p_T range was plotted as a function of $\tilde{n}_{\text{trk}}$, corrected by $\langle T_{AA} \rangle$. No significant deviation from linearity, which is evident in the low- p_T range, was observed. The mean and standard deviation of transverse momentum in the higher- p_T region also show no significant deviation from a constant value.

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A ZDC and FCalEt Pile-Up Cut

E_T^{FCal} [TeV]	min E_{ZDC} [TeV]	max E_{ZDC} [TeV]
0.0	-175.70	420.22
0.2	10.13	412.70
0.4	52.04	404.61
0.6	65.34	399.32
0.8	69.51	393.06
1.0	69.51	385.25
1.2	67.20	376.06
1.4	62.84	366.02
1.6	58.10	354.43
1.8	51.91	342.34
2.0	45.28	328.82
2.2	37.34	315.26
2.4	30.28	299.41
2.6	21.35	284.65
2.8	13.64	267.49
3.0	4.98	250.56
3.2	-3.21	232.91
3.4	-11.85	215.15
3.6	-19.20	195.86
3.8	-25.83	175.96
4.0	-33.17	157.48
4.2	-34.74	131.84
4.4	-40.65	122.47
4.6	-72.19	148.85
4.8	-170.77	248.37
5.0	-513.32	722.04
5.2	0.00	0.00
5.4	0.00	0.00
5.6	0.00	0.00
5.8	0.00	0.00

Table A.1: Lower and upper ZDC energy for pile-up cut

B Monte Carlo efficiency fit parameters

Table B.1: Efficiency fit parameters for linear (intercept, slope) and logarithm (scale, offset) function for each pseudorapidity range.

range index	min η	max η	intercept	slope	scale	offset
1	-2.50	-2.33	0.2055	0.0207	0.0601	0.2060
2	-2.33	-2.17	0.2865	0.0169	0.0484	0.2879
3	-2.17	-2.00	0.2757	0.0152	0.0476	0.2730
4	-2.00	-1.83	0.2466	0.0193	0.0624	0.2419
5	-1.83	-1.67	0.2921	0.0219	0.0924	0.2692
6	-1.67	-1.50	0.3151	0.0248	0.0922	0.3016
7	-1.50	-1.33	0.3150	0.0271	0.1081	0.2936
8	-1.33	-1.17	0.3026	0.0236	0.0844	0.2904
9	-1.17	-1.00	0.4195	0.0255	0.0796	0.4133
10	-1.00	-0.83	0.5110	0.0273	0.0922	0.4966
11	-0.83	-0.67	0.5247	0.0291	0.0838	0.5230
12	-0.67	-0.50	0.5186	0.0257	0.0749	0.5159
13	-0.50	-0.33	0.5160	0.0250	0.0760	0.5103
14	-0.33	-0.17	0.5069	0.0245	0.0779	0.4989
15	-0.17	0.00	0.5035	0.0240	0.0800	0.4925
16	0.00	0.17	0.4917	0.0248	0.0766	0.4861
17	0.17	0.33	0.5084	0.0234	0.0741	0.5011
18	0.33	0.50	0.5259	0.0254	0.0783	0.5200
19	0.50	0.67	0.5260	0.0274	0.0797	0.5236
20	0.67	0.83	0.5360	0.0303	0.0867	0.5346
21	0.83	1.00	0.5016	0.0300	0.0881	0.4989
22	1.00	1.17	0.3562	0.0296	0.0695	0.3737
23	1.17	1.33	0.2933	0.0267	0.0846	0.2890
24	1.33	1.50	0.3178	0.0288	0.0987	0.3069
25	1.50	1.67	0.3203	0.0241	0.0860	0.3083
26	1.67	1.83	0.2951	0.0236	0.0798	0.2864
27	1.83	2.00	0.2672	0.0173	0.0490	0.2685
28	2.00	2.17	0.3029	0.0131	0.0455	0.2965
29	2.17	2.33	0.2789	0.0184	0.0504	0.2828
30	2.33	2.50	0.1861	0.0208	0.0590	0.1880

C Run-by-run E_T^{FCal} distributions

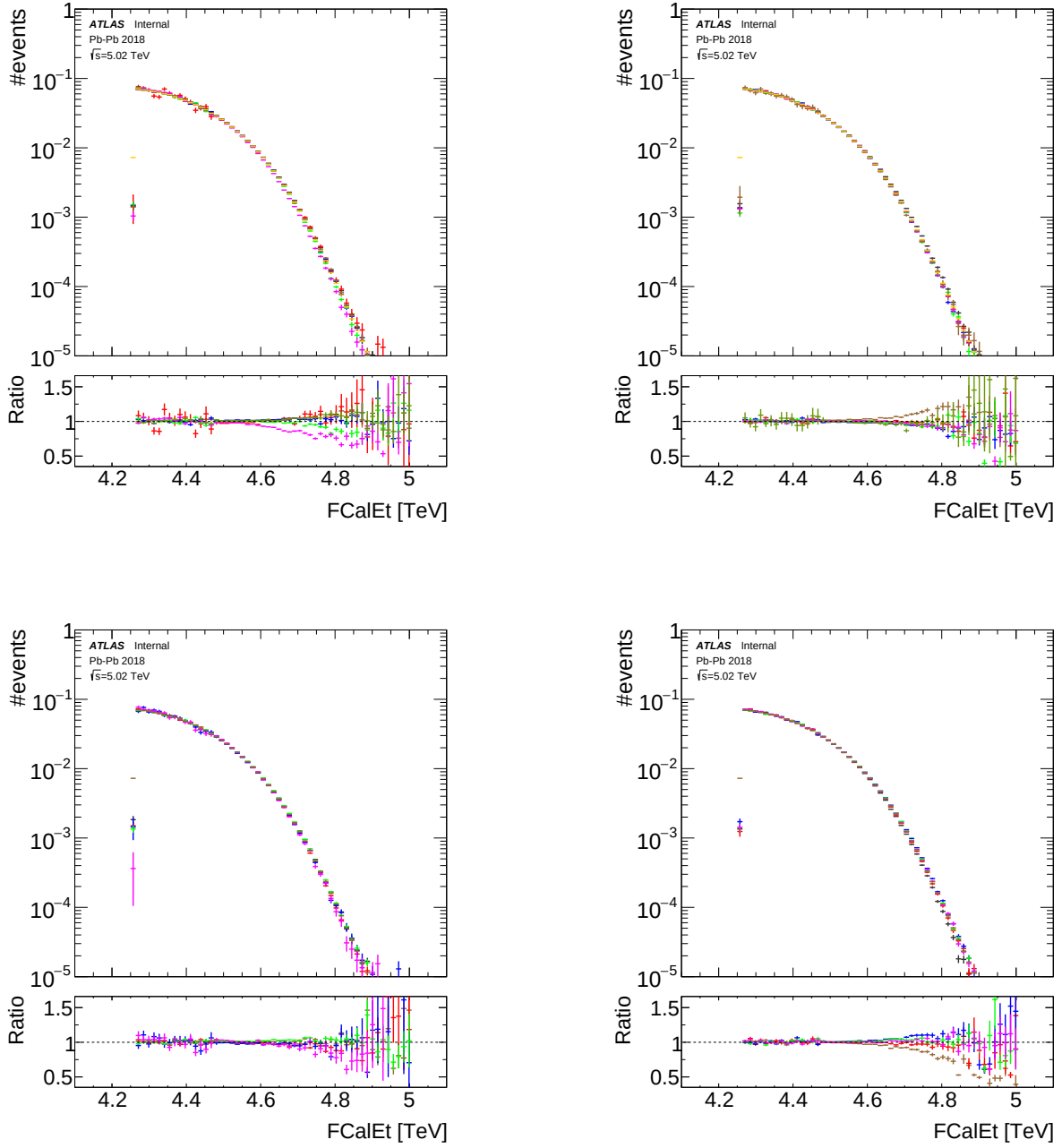
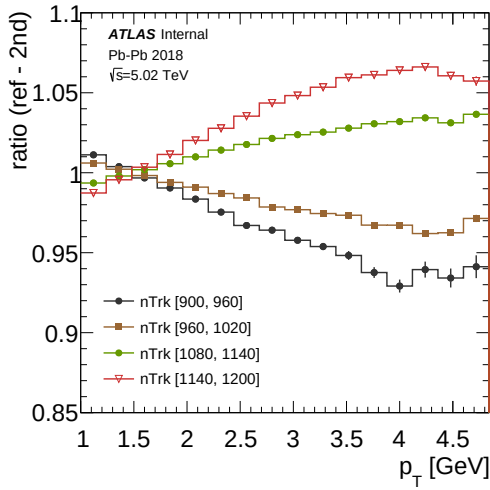


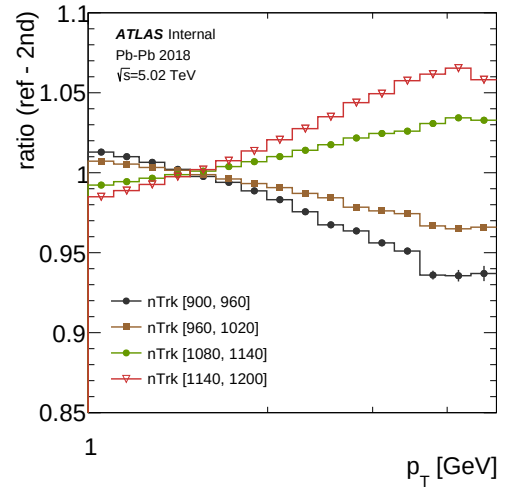
Figure C.1: Run-by-run E_T^{FCal} distributions superimposed on a single plot. Fewer spectra are shown compared to [Figure 9.17](#) to make subtle differences more noticeable

D Integral ratio plots

A Fixed reference bin

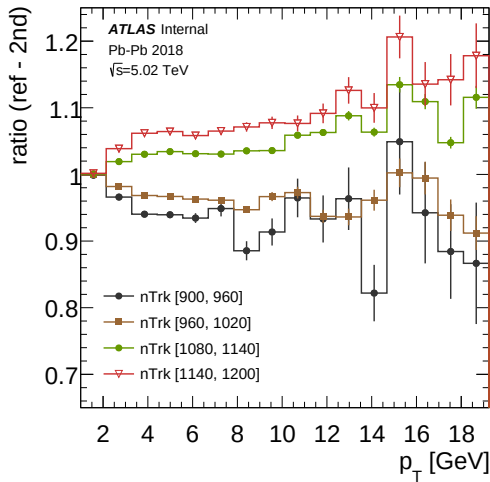


(a) linear x -axis

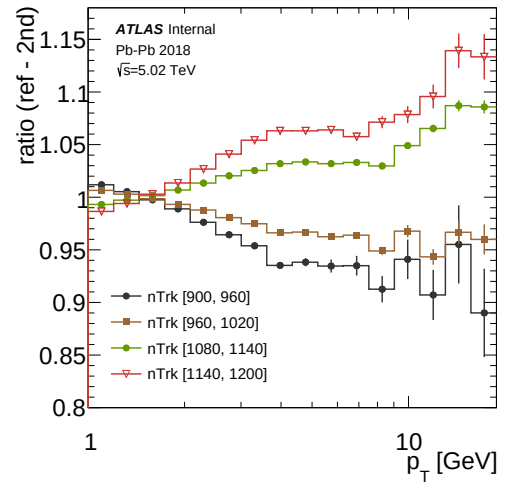


(b) logarithm x -axis

Figure D.1: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$, p_T spectrum normalized by the distribution integral



(a) linear x -axis



(b) logarithm x -axis

Figure D.2: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$, p_T spectrum normalized by the distribution integral

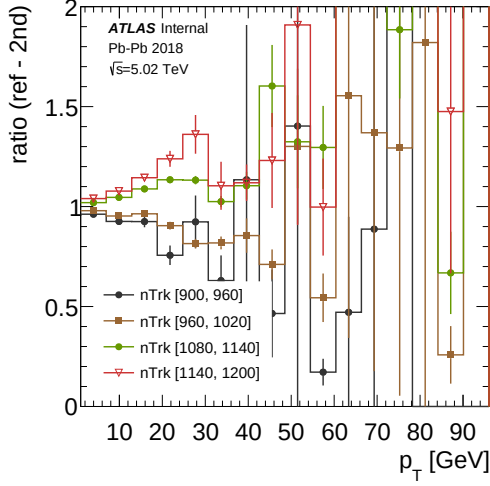
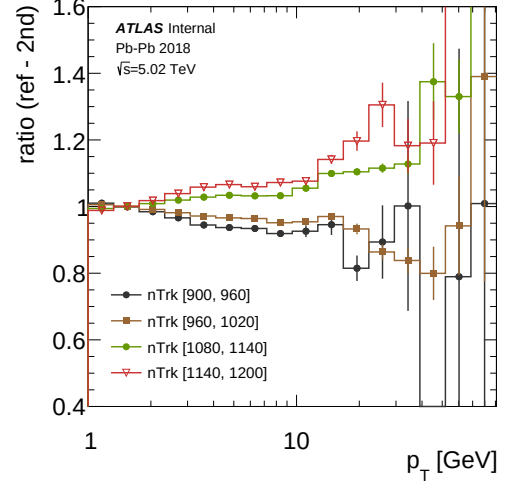

 (a) linear x -axis

 (b) logarithm x -axis

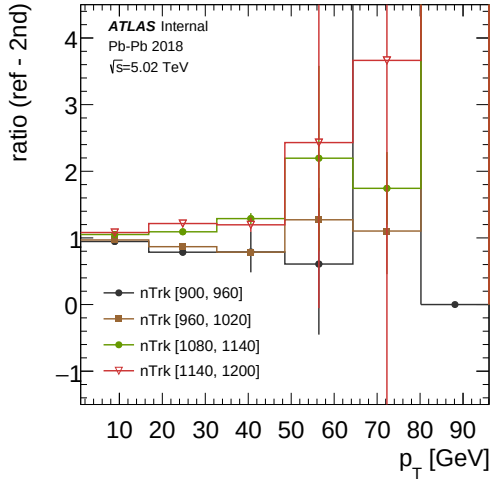
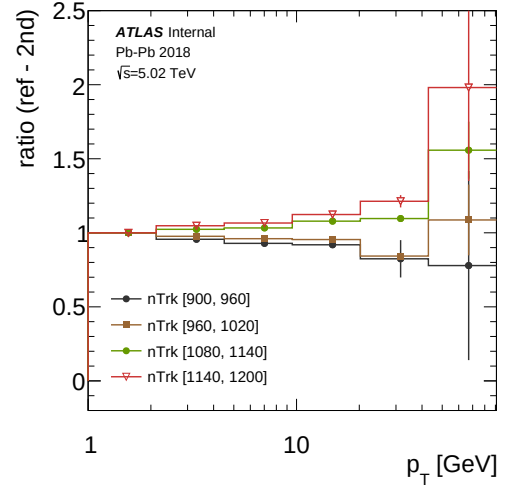
 Figure D.3: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, p_T spectrum normalized by the distribution integral

 (a) linear x -axis

 (b) logarithm x -axis

 Figure D.4: Transverse momentum distribution ratio for reference central bin – $\tilde{n}_{\text{trk}} \in [1020, 1080]$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, wider bins, p_T spectrum normalized by the distribution integral

B Floating reference bin

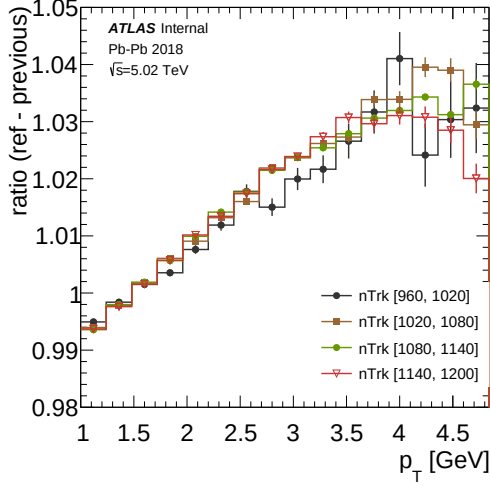
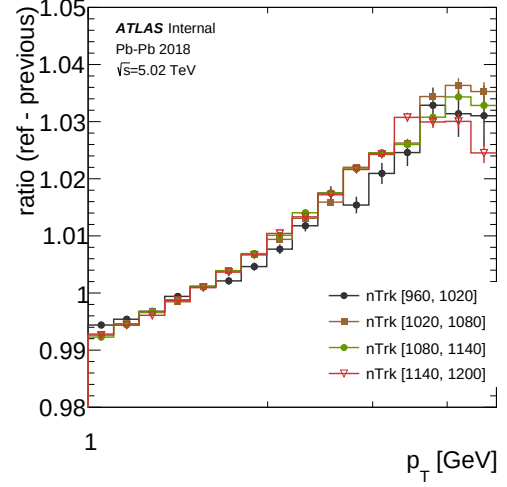
(a) linear x -axis(b) logarithm x -axis

Figure D.5: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 5 \text{ GeV}]$, p_T spectrum normalized by the distribution integral

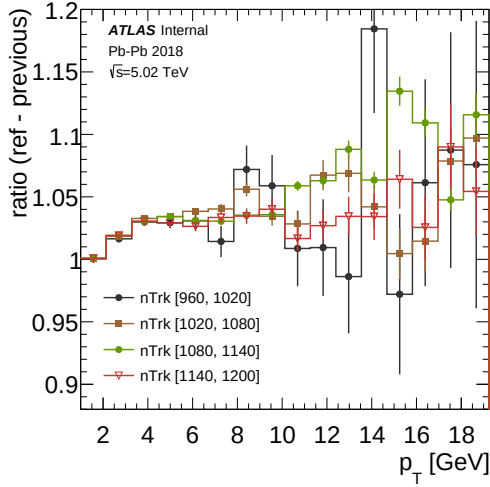
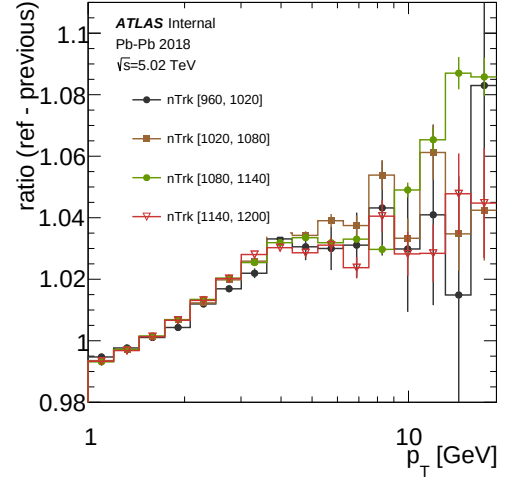
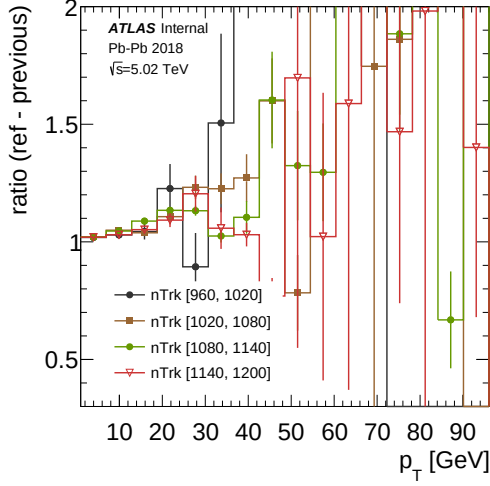
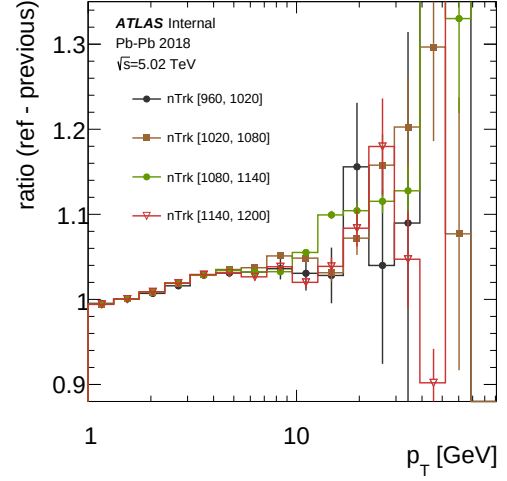
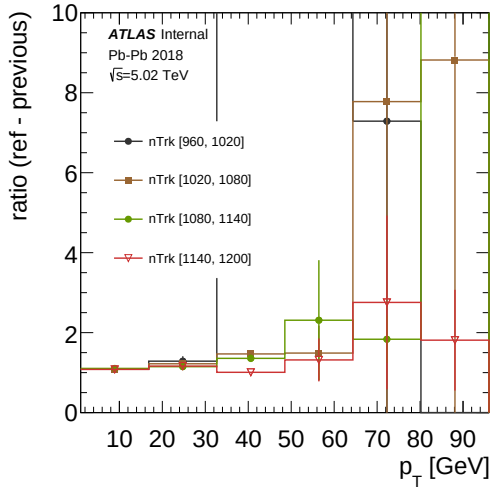
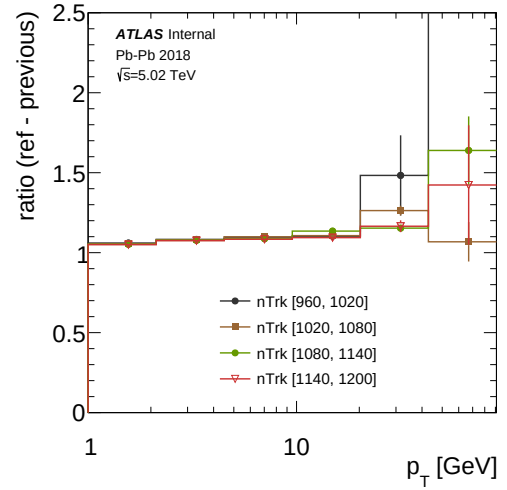
(a) linear x -axis(b) logarithm x -axis

Figure D.6: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 20 \text{ GeV}]$, p_T spectrum normalized by the distribution integral

(a) linear x -axis(b) logarithm x -axisFigure D.7: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, p_T spectrum normalized by the distribution integral(a) linear x -axis(b) logarithm x -axisFigure D.8: Transverse momentum distribution ratio for lower bin reference range – $p_T(i)/p_T(i-1)$, $p_T \in [1 \text{ GeV}, 100 \text{ GeV}]$, wider bins, p_T spectrum normalized by the distribution integral

E Linear and power function fit to track yield

Table E.1: Linear ($\sim x$) and power-law fits following [Equation 2.25](#) ($\sim x^{3/4}$) of the track yield for particles in a given p_T range, plotted against the track multiplicity – $\tilde{n}_{\text{trk}}$ of an event. All values are corrected by $\langle T_{AA} \rangle$

min p_T [GeV]	max p_T [GeV]	fit	intercept	coeff	χ^2
1	100	$\sim x$	8.89(61)	$2.631(58) \times 10^{-2}$	4.57
1	100	$\sim x^{3/4}$	$-4.1(81) \times 10^{-1}$	$2.003(44) \times 10^{-1}$	3.02
15	100	$\sim x$	$-1.37(12) \times 10^{-3}$	$2.33(11) \times 10^{-6}$	9.33
15	100	$\sim x^{3/4}$	$-2.19(15) \times 10^{-3}$	$1.774(80) \times 10^{-5}$	10.19
20	100	$\sim x$	$-5.77(56) \times 10^{-4}$	$8.18(53) \times 10^{-7}$	0.77
20	100	$\sim x^{3/4}$	$-8.64(75) \times 10^{-4}$	$6.22(40) \times 10^{-6}$	0.98
30	100	$\sim x$	$-1.39(26) \times 10^{-4}$	$1.94(25) \times 10^{-7}$	1.82
30	100	$\sim x^{3/4}$	$-2.08(35) \times 10^{-4}$	$1.48(19) \times 10^{-6}$	1.72

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