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**Study of the effect of the initial
geometry on elliptic flow and charged
hadron production in Pb-Pb collisions
with ALICE**

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Introduction

The aim of the ALICE experiment (A Large Ion Collider Experiment) [1, 2] at the LHC is the study of the nuclear matter under conditions of extreme energy density and temperature. Under these conditions the formation of a deconfined phase called Quark Gluon Plasma (QGP) is predicted by lattice QCD [3, 4]. In this phase, quarks and gluons are no longer confined to individual nucleons. A transition from the QGP state into a hadronic state should have occurred during the early stages of Universe, due to its expansion and to the consequent decrease of the temperature.

Collisions of heavy nucleons at relativistic energy create in the laboratory the conditions for the hot and dense environment required for the phase transition. The ALICE experiment is dedicated to the study of the deconfined state of strongly interacting matter.

Heavy-ions are extended object and the system created in central nucleus-nucleus collisions is different from the one created in peripheral collisions. In particular, for non-central collisions, in the plane perpendicular to the beam direction, the geometrical overlap region is highly anisotropic. This initial spatial asymmetry is converted via interactions into an anisotropy in the momentum space. Measurements of this modulation, known as anisotropic transverse flow [5], provide insight into the collective evolution and the early stages of a relativistic heavy-ion collision.

The QGP exhibits strong collectivity, behaving as a nearly perfect liquid as observed at RHIC [6, 7]. The collective properties of the system can be studied through the transverse momentum (p_T) distributions and the measurement of the anisotropy of the particle distributions. The p_T distributions allow to extract information about the collective transverse expansion (radial flow) and the temperature at the moment when the hadrons decouple from the system [8, 9]. On the other hand the magnitude of the anisotropic flow can be characterized by the

coefficients in the Fourier expansion of the azimuthal distribution of particles.

The dominant coefficient for non central collision is the second harmonic, v_2 , which is called elliptic flow. It has been observed and extensively studied in nuclear collisions from sub-relativistic energies on up to RHIC and LHC energies. For the collisions of two smooth spheres, one would expect all odd harmonics to vanish due to symmetry reasons. However, due to event-by-event fluctuations in the positions of the participating nucleons inside the nuclei, the shape of the initial energy density of the heavy-ion collision is, in general, not symmetric with respect to the reaction plane, defined by the beam direction and the impact parameter. This gives rise to non-zero odd harmonic coefficients [10–17].

In recent years the understanding of the initial geometry fluctuations and their role in the formation of final state anisotropic flow has significantly improved. Controlling the initial conditions in heavy-ion collisions would provide the possibility of detailed studies of the properties of the high density hot QCD matter. The Event Shape Engineering (ESE) technique allows the selection of different event shapes for a definite centrality and colliding system [18]. The event selection is based on the azimuthal distribution of produced particles, using the so-called flow vector. Recent Monte-Carlo studies show a strong correlation between the (final state) event shape selection and the (initial state) eccentricity of the collision [19]. This opens many new possibilities to study the properties of the system created in high energy nucleus-nucleus collisions, allowing to characterize events according to the initial geometry.

In particular the event shape selection allows investigating the non trivial correlation between elliptic and radial flow. In this thesis we present a measurement of the p_T distributions of primary particles in strongly or weakly anisotropic environments, at fixed impact parameter.

In the first chapter a brief introduction to the physics of the QGP is given, focusing on the global characteristics of heavy ion collisions and the time evolution of the created system. A brief overview of the most recent results at RHIC and LHC experiments is also presented.

In the second chapter we present a basic introduction to hydrodynamic models, which provide the theoretical framework, for the understanding the connection between initial condition dynamic and the hydrodynamic response of the system created in nucleus-nucleus collisions. Furthermore, recent measurements of a large set of flow observables associated with event-shape fluctuations and collective expansion in heavy ion collisions are discussed. The experimental results are presented and compared to theoretical calculations. New types of fluctuation measurements, that can further improve our understanding of the event-shape fluctuations and collective expansion dynamics, are discussed.

The third chapter is devoted to the description of the ALICE experiment.

After a general overview of the apparatus, the the ALICE particle identification capabilities are described.

In chapter 5 an approach to select the eccentricity of the event with the Event Shape Engineering is presented. The effect of this selection on the elliptic flow coefficient and identified particle spectra in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV center-of-mass energy are discussed in chapter 6 and 7, respectively.

The final results on the elliptic flow and the p_{T} distributions of charged hadrons in event shape selected events are discussed in chapter 8.

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Physics of the Quark Gluon Plasma

Quantum chromodynamics (QCD) is the fundamental theory that describes the elementary particles which interact via the strong force (quarks and gluons).

It predicts under conditions of extreme energy density and temperature a deconfined phase, in which quarks and gluons are no longer confined to individual hadrons, named the Quark Gluon Plasma (QGP). In the ultrarelativistic high energy collisions of heavy ions, currently performed at the BNLs Relativistic Heavy Ion Collider (RHIC) and the CERN's Large Hadron Collider (LHC), sufficiently large temperatures and energy densities, required for QGP formation, can be achieved.

The aim of this introduction is to give a brief overview of QGP physics and the most important physics observables for its studies.

1.1 The Quark Gluon Plasma - QGP

The Standard Model (SM) is at this moment the best description of all known elementary particles and the forces that act between them [1–3]. A particle is considered elementary if it has no known substructure. Elementary particles are divided into two groups (quarks and leptons) and 3 generations as illustrated in Fig. 1.1. In total there are 6 types of quarks: up (u) and down (d), charm (c) and strange (s), top (t) and bottom (b). The leptons are the electron (e), muon (μ), tau (τ) and their corresponding neutrinos (ν_e , ν_μ , ν_τ). The SM also describes the electromagnetic force, the weak force and the strong force.

The interactions between elementary particles are described by the exchange of “gauge bosons”. Mathematically, the SM is based on the non-abelian symmetry group $U(1) \times SU(2) \times SU(3)$ and has a total of twelve gauge bosons: the eight gluons mediate strong interactions, the W and Z mediate weak interactions and

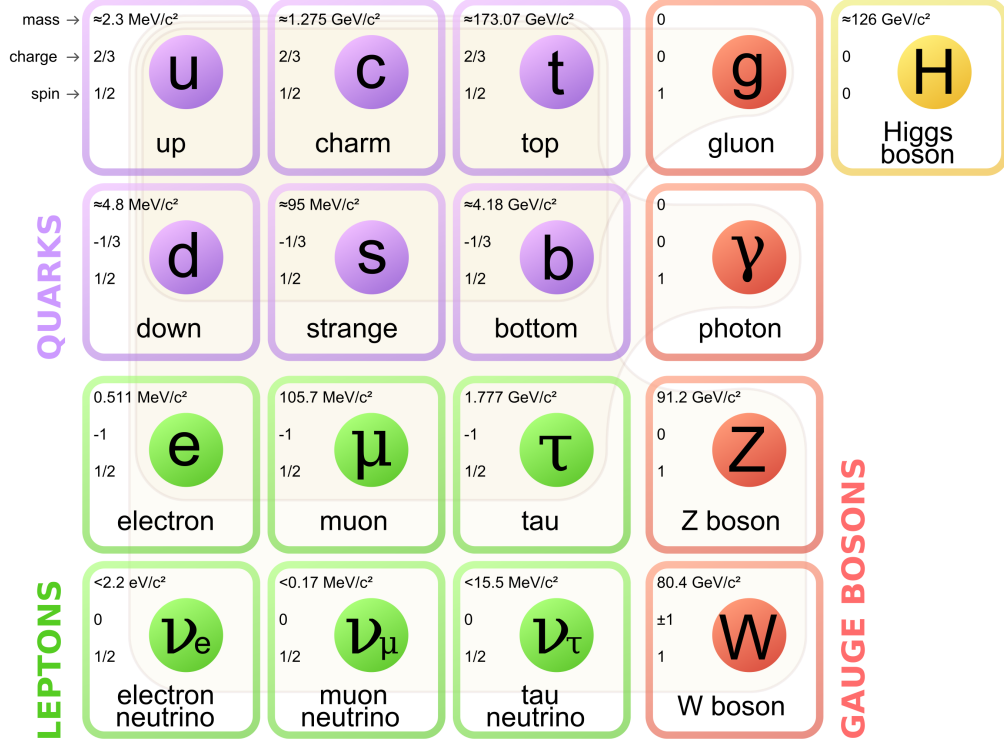


Figure 1.1: Fundamental constituents of the matter in the Standard Model description [4].

the photon mediates the electromagnetic interactions.

The strong interaction between quarks and gluons, responsible for binding hadrons together, is described by the fundamental non-Abelian theory known as Quantum Chromo-Dynamics (QCD). There are two key fundamental phenomena associated with QCD: *confinement* and *asymptotic freedom*.

- **Confinement:** it refers to the experimental observation that quarks and antiquarks cannot be found isolated in nature, but are instead bound inside hadrons. The strength of the interaction binding the quarks increases with the distance and it is characterized by a potential

$$V_{QCD} = -\frac{4}{3} \frac{\alpha_S(r) \hbar c}{r} + kr \quad (1.1)$$

where α_S is the strong coupling constant, r is the distance between the quarks and k a constant called *string tension*, $k \approx 1 \text{ GeV/fm}$. V_{QCD} is the sum of a Coulombian term due to the gluon exchange and another term called *confinement potential*. As the distance between quarks in hadrons increases,

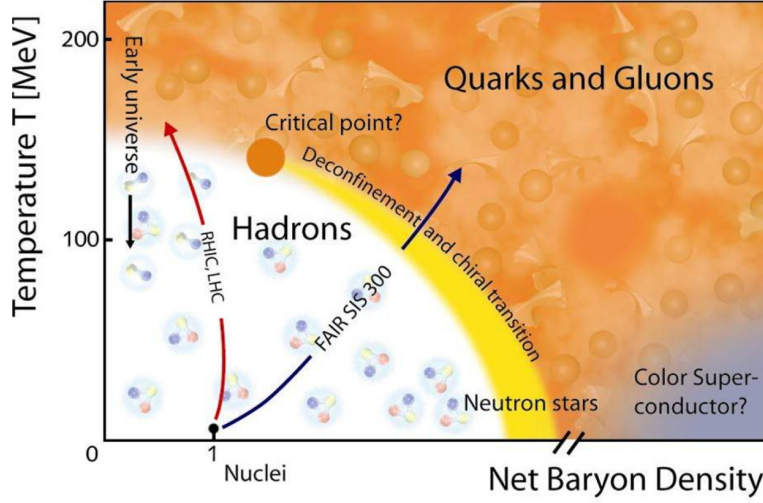


Figure 1.2: Schematic phase diagram of nuclear matter.

their interaction energy increases as well, which prevents the quarks to be separated.

- **Asymptotic freedom:** the coupling constant of the strong interactions α_S depends on the energy transfer in the interaction. At small distance between partons, α_S is smaller, leading to a weak coupling of quarks and gluons. Given the small value of α_S in the asymptotic freedom domain, the processes can be described via perturbative QCD (pQCD). For large values of α_S field equations are solved numerically on a discrete space-time grid using lattice QCD calculations.

QCD predicts that at very high temperature and/or baryon density, a phase transition from hadronic matter to a phase of deconfined quarks and gluons, called the Quark Gluon Plasma (QGP).

Thermodynamical properties of the strongly interacting matter are usually expressed in terms of phase diagram (Fig. 1.2), in the space of thermodynamic parameters (T, μ_B) ¹.

At low T , due to confinement, quarks and gluons are bound into hadrons.

¹In thermodynamics the chemical potential μ measures the amount of change of the system internal energy U for the introduction of an additional particle

$$\mu = \frac{\partial U}{\partial N} \quad (1.2)$$

The baryo-chemical potential μ_B measures the same quantity after introducing an additional baryon.

At small μ_B and high temperature (expected in Pb–Pb collisions at the LHC) several models and lattice QCD calculations indicate a smooth transition from hadrons to QGP, called *crossover*. Lattice QCD provides quantitative information on the QCD phase transition that is expected to occur at $T \sim 154(\pm 9)$ MeV [5, 6] for vanishing μ_B . The point in which the first order phase transition becomes a crossover is called critical point. In the crossover region the energy density varies in the range $\epsilon_c = (0.18 - 0.5)$ GeV/fm³ [6].

The phase transition between confined hadronic matter and the QGP is expected to be a first order phase transition at low temperatures and large μ_B [7]. In this region a colour superconductor state is also expected in some models [8].

Relativistic heavy-ion collisions are a unique tool to probe this phase diagram under controlled laboratory conditions. By colliding nuclei at extremely high energy it is possible to achieve an energy density high enough for the QGP phase transition to take place.

The matter created in heavy-ion collisions exhibits strong collectivity, behaving as a nearly perfect fluid, rather than a gas, as observed at RHIC [9–11] with a very short mean free paths of particles in it. The expansion of the thermalized system created in heavy ion collisions, is found to be well described by relativistic hydrodynamic models with very low viscosity [12].

The medium is opaque to energetic particles carrying a colour charge: the partons are expected to lose energy via interactions with the medium.

1.2 Heavy ion collision

Extreme energy density and temperature can be reached in the laboratory through heavy nucleus-nucleus collisions. The first heavy ion collisions were studied at the AGS at Brookhaven (Au–Au at $\sqrt{s} = 11.5$ GeV/ c) and at the SPS with center of mass energies of 17 GeV/ c in Pb–Pb collisions. At present, the properties of the deconfined state are thoroughly investigated in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV/ c at RHIC and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, collected at the LHC.

Nuclei are extended objects and the collisions between heavy ions can be categorized by their centrality, that is the transverse overlap area. In a heavy ion collision, the nucleons outside of the transverse overlap area continue essentially unperturbed along the beam direction, as observed by *zero degree calorimeter* measurements [13]. This permits to define a number of useful geometrical variables which characterize the collision. Theoretically, the centrality is characterized by the impact parameter $\mathbf{b}$ which is the distance between the centers of two colliding ions (Fig. 1.3 (a)).

The collision centrality can also be characterized by the number of participants

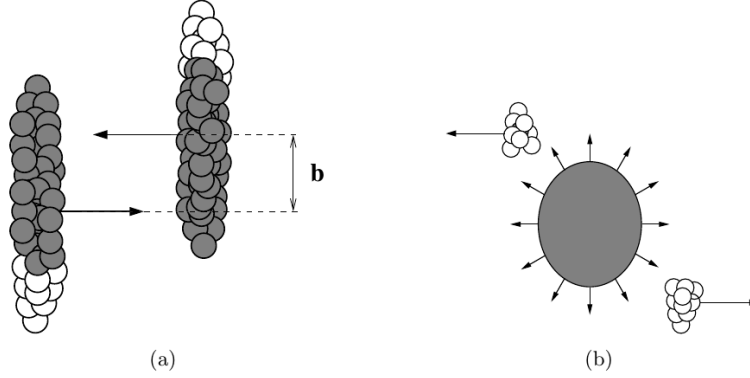


Figure 1.3: A heavy ion collision seen from the CM frame. (a) Impact parameter and (b) spectators (white) and participants (grey).

(N_{part}) and the number of binary collisions (N_{coll}) (see section 2.1 for details). N_{part} is the total number of nucleons which undergo at least one inelastic nucleon-nucleon collision (called wounded nucleons or participants), the nucleons outside the overlap region are known as spectators (Fig. 1.3(b)). N_{coll} is the total number of binary collisions. This quantity takes into account the fact that each nucleon could undergo multiple interactions, with different nucleons on its trajectory. Phenomenologically it is found that soft particle production scales roughly with the number of participating nucleons whereas hard processes scale with the number of binary collisions [14].

The centrality is usually expressed as the percentile of most central collisions with respect to the total cross section [13]. Head-on collisions are called “central”, while collisions with large impact parameters are called peripheral. In the following we will use expressions like “0-10% centrality” to indicate the class of 10% most central collisions.

In Fig. 1.4 a schematic view of the time evolution of A-A collisions in a 2-dimensional space-time is shown. We define $\tau=0$ as the time at which the system is created. Three dynamically distinct stages can be identified.

- $\tau \lesssim 10 \text{ fm}/c$: Before the formation of the QGP, heavy quarks and jets are produced.

The particles produced in the primary collisions mutually interact, giving rise to a region of high matter and energy density and creating the conditions for the formation of the QGP. After a short time, the system reaches thermal equilibrium and the thermodynamical description of the QGP is applicable.

Since the created medium is strongly interacting, then on top of the Brownian motion also collective behaviours can arise, generically called *collective flow*.

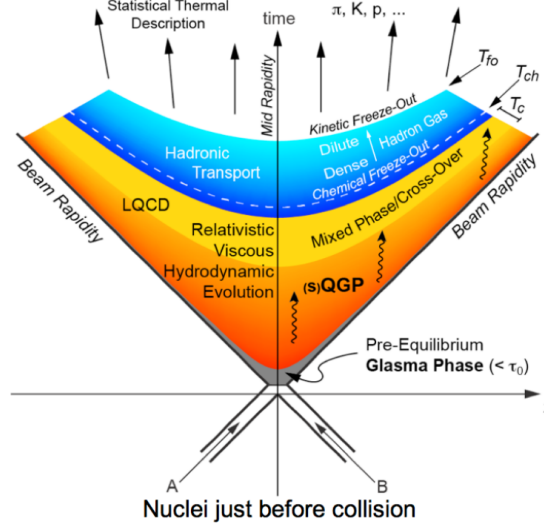


Figure 1.4: A schematic view of dynamics of a heavy ion collision along the collision axis [15].

Since a quark-gluon plasma is an (approximately) thermalized system of quarks and gluons, it has thermal pressure. This “fireball” is surrounded by the vacuum, this creates a pressure gradient which leads to a collective expansion of the system.

The standard approach for the description of collective flow is based on hydrodynamics which relies on the assumption that the system is thermalized and therefore it is possible to properly define a temperature and other thermodynamical variables (entropy, speed of sound in the medium and so on).

Collective flow can only appear in a strongly interacting system. The flow is established early in the collision, when the pressure gradients are strong, and its presence is one of the most compelling evidences of QGP creation. Models based on ideal hydrodynamics have been very successful in describing flow and they will be discussed in detail in chapter 2.

The QGP is a transient state and the fireball continues to expand and cool down, reaching the critical temperature T_{ch} . After this threshold the partons begin to hadronize and the fireball becomes a gas of hadrons and resonances, whose constituents still undergo scatterings but without enough energy to deconfine the partons.

The hydrodynamic stage of ultra-relativistic heavy-ion collisions is preceded by a short (0.2-1.5 fm/c) but very dense pre-equilibrium stage, named *Glasma* [16–20].

- $10 \lesssim \tau \lesssim 15 \text{ fm}/c$: The abundances of particle species are fixed when inelastic interactions cease. This is the so-called *chemical freeze-out*, the corresponding temperature is T_{ch} . Thermal fits on experimental data put this threshold at about 155-165 MeV [21–24]. As the system continues to expand, hadrons can still interact elastically without changing their relative abundances until the system reaches the temperature T_{kin} at which elastic interactions cease. This is the *kinetic freeze-out*: momentum distributions are fixed.

The kinetic freeze-out temperature T_{kin} is estimated [21–26] to be much lower than the hadronisation temperature (T_{ch}). Hadronic cascade models can be used to simulate these rescatterings, using everything that is known about hadron masses and cross sections [27].

- $\tau \gtrsim 15 \text{ fm}/c$: Elastic and inelastic interactions no longer play a significant role in the system evolution: the system is now made of free streaming particles that continue moving towards the detectors.

1.3 Small systems: proton-proton and proton-nucleus collisions

The interpretation of heavy-ion results depends on the comparison with results from smaller collision systems such as proton-proton (pp) or proton-nucleus (p-A). They provide the reference measurements for the nucleus-nucleus program and constitute a crucial component of the LHC heavy-ion program.

The characterization of the QCD matter created in heavy ion collisions needs to be benchmarked with elementary collision, in which final-state medium effects, such as collective phenomena, are largely absent.

Such benchmarking can be done with data from proton-proton collisions, where both initial and final state medium effects are absent. When observing modifications in between pp and A-A collisions, it is important to assess the effects of “cold nuclear” matter as well, i.e. the colliding nuclei, to be able to correctly disentangle the initial and final state modifications.

The absence of strong final state medium effects in proton-nucleus collisions offers unique possibilities to specific investigations of QCD physics: nuclear effects can also arise from presence of *cold* nuclear matter. However, proton-nucleus collisions are intermediate between proton-proton and nucleus-nucleus collisions in terms of system size and number of produced particles. Unexpected similarities have been recently observed. For instance, initial state effects as shadowing and anti-shadowing [28] or Cronin [29] effect have been observed in p-A or d-A collisions. Unexpected similarities in azimuthal correlations in p-A and A-A systems

challenge basic concepts of the heavy ion physics and may shed new light on the initial state properties of the collisions studied. d–Au at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}/c$ and p–Pb data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ GeV}/c$ have been collected from RHIC and LHC, respectively [30–32]. These observations suggest the formation of a collective medium already in high multiplicity p – A collisions.

By varying the collision system and energy, initial conditions can be tuned experimentally. Changing the collision system has provided important insights into the nature of the initial conditions. They help to separate collision geometry from effects due to event-by-event initial-condition fluctuations. Theoretical attempts to describe recent observations of collective dynamical behavior in p–Pb and d–Au collisions have highlighted the need for better understanding of event-by-event fluctuations in the initial condition.

1.4 Probes of QGP

Since the QGP only lives a few fm/ c , its properties cannot be studied directly, but need to be inferred from the final state hadrons measured in the detector. A number of QGP “signatures”, sensitive to different properties of the medium, have been proposed and studied in the past. They are divided in soft, hard and electromagnetic (EM) probes:

- *Soft probes*: light hadrons at low transverse momentum (p_{T}), produced during the hadronization stage of soft partons from the QGP, which are in thermal equilibrium in the deconfined phase, keep indirect information on the phase transition and on the QGP. These hadrons retain information about the bulk matter, allowing to constrain properties such as the expansion speed, the viscosity, the temperature at freezeout, the size of the system, etc. They are e.g. p_{T} spectra, anisotropic flow, particle correlations and fluctuations.
- *Hard probes*: energetic partons are produced in interactions with high momentum exchange at the early stages of the collisions. They propagate through the dense medium, suffering multiple scattering in the medium which will lead to transverse momentum broadening and parton energy loss. Heavy quarks play a special role because the heavy quark pairs experience the full evolution of the QGP phase and are subject to all the effects induced by the medium. They are e.g. jet production, high transverse momentum particles, open heavy quarks, quarkonia.

Hard probes offer the possibility to retrieve information about the parton energy loss in the medium. In particular, for open heavy flavour and quarkonia, a colour charge and a quark mass dependence is predicted by theoretical

models [33–36]. The measurement of quarkonia suppression gives information on properties of the stages of heavy ion collisions and the existence of the QGP [37]. Measuring the probability of different quarkonia states also allows us to estimate the temperature of the system [38]. These are calibrated probes of the QGP, and studying their modification provides information on the medium, in analogy with a Rutherford-like experiment.

- *Electromagnetic probes:* dileptons and direct photons are produced in each stage of the collision [39, 40], through thermal production and resonance decays. The interest in dileptons and photons stems from their relatively large mean free path. As a consequence, they can leave the interaction region without final state interaction, carrying information about the conditions and properties of the matter at the time of their production, providing a time-integrated picture of the collision dynamics [41].

The purpose of this section is not to give a detailed description of the all QGP probes, but rather to report about the most recent results obtained by RHIC and LHC experiments, showing, where available, results for the three colliding systems: proton-proton, proton-nucleus and nucleus-nucleus.

We start the discussion with the transverse momentum and azimuthal distributions of (identified) hadrons, as they are most relevant for the work presented in this thesis.

For a more exhaustive review of results from RHIC and SPS see [30, 42–47].

1.5 Soft probes

1.5.1 Identified primary hadron spectra and particle ratios

The transverse momentum distributions of produced hadron are the experimental tools to probe the properties of the fireball in its final stage, after the kinetic freeze-out, when all strong interactions cease, allowing to estimate the bulk properties of the event, such as the kinetic freeze-out temperature T_{kin} and the radial expansion velocity.

In heavy ion collisions the pressure gradients, originated from the density profile of the fireball in the transverse plane, boost all particles formed in the system, pushing them outwards. Particles move in a common velocity field. This collective radial expansion, called *radial flow*, modifies the (thermal) spectra of outgoing particles. Indeed, the radial velocity component results in an increase of the momentum which is proportional to the mass of the particle. Sometimes, this phenomenon is referred to as “blue shift”. The effect is stronger in central collision and decrease with the collision centrality [48].

Particle spectra in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV are reported in Fig. 1.5 for different centralities [25]. The radial expansion of the nuclear fireball results in a flattening of the p_{T} spectra with respect to pp collisions, more pronounced at low p_{T} and for heavier particles. This effect can be described quantitatively in the framework of relativistic hydrodynamics, as discussed in detail in the next chapter.

The kinetic freeze-out temperature T_{kin} and the average radial velocity $\langle\beta_{\text{T}}\rangle$ are extracted for different centralities using the Blast Wave (BW) model [49], which describes the shape of the p_{T} spectra in heavy-ion collisions, assuming a collective radial flow which modifies the thermal emission of the hadrons. The values reached for 5% of most central collisions are $T_{\text{kin}} \approx 95$ MeV and $\langle\beta_{\text{T}}\rangle \approx 0.65$, the latter being more than 10% above the RHIC value [50].

Particle spectra in p–Pb collisions measured with ALICE [31] are reported in Fig. 1.6 in several multiplicity bin. Spectra are flatter for heavy particles at low p_{T} , showing a surprisingly similar trend to the one observed in heavy-ion collisions. The transverse momentum distributions show a clear evolution with multiplicity, similar to the pattern observed in high-energy pp [51] and heavy-ion collisions [25], where in the latter case the effect is usually attributed to collective radial expansion.

The p/π and Λ/K_s^0 ratios as a function of transverse momentum are shown in Fig. 1.7 in Pb–Pb and in p–Pb collisions for two centrality classes. For central events, an increase of protons at intermediate p_{T} and a corresponding depletion at low p_{T} are evident for both systems, but the magnitude of the effect is much smaller in p–Pb collisions. In Pb–Pb collisions this effect is generally attributed to collective flow or quark recombination [25]. In the quark recombination models, hadrons are produced through the statistical recombination of quark-antiquark pairs in the medium. This idea would imply an enhanced production of baryons at mid-rapidity and was invoked to explain the p_{T} dependence of the baryon to meson ratios. Such an increase also occurs in hydro models as a consequence of the stronger push experienced by heavier particles.

The measurement of the ϕ/π ratio [52], however, suggests that is the mass, and hence the radial flow, which drives the spectra shapes at low and intermediate p_{T} and not the number of quarks. The baryon to meson ratio p/π has a very similar shape to the meson to meson ϕ/π ratio for $p_{\text{T}} \leq 3$ GeV/ c (1.8). This picture is consistent with the hydrodynamic models, which are able to reproduce the shape of the ϕ meson p_{T} distribution fairly well, but overestimate the ϕ yield) but it is contrary to the expectations from recombination mechanism.

At high $p_{\text{T}} > 10$ GeV/ c , the p/π and K/π ratios behave like those in pp Fig. 1.9, suggesting that fragmentation dominates the hadron production [53].

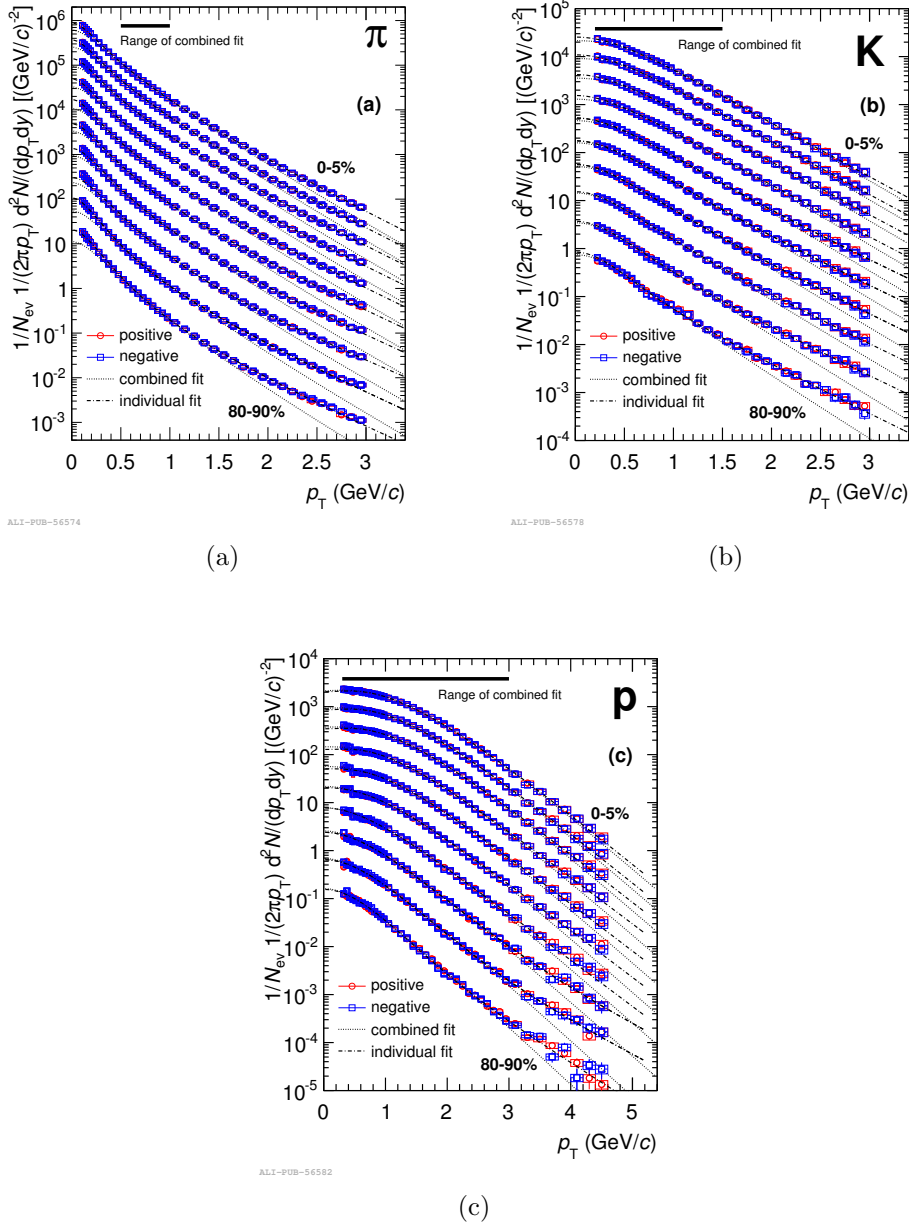


Figure 1.5: Transverse momentum (p_T) distribution of π , K, and p as a function of centrality, for positive (circles) and negative (squares) hadrons. Each panel shows central to peripheral data; spectra scaled by factors 2^n (peripheral data not scaled). Dashed curves: blast-wave fits to individual particles; dotted curves: combined blast-wave fits (see text for details). Statistical (error bars) and systematic (boxes) uncertainties plotted [25].

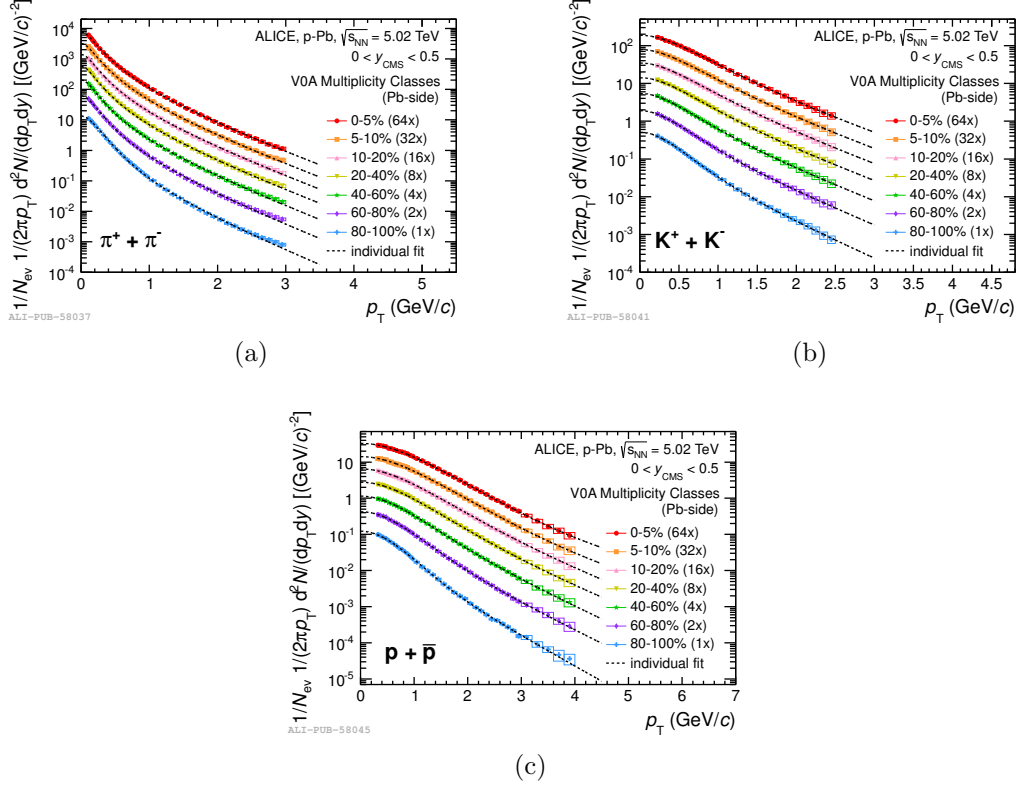


Figure 1.6: Invariant p_T -differential yields of $\pi^\pm$, $K^\pm$, $p(\bar{p})$ in different multiplicity classes measured in the rapidity interval $0 < y_{CMS} < 0.5$. Top to bottom: central to peripheral; data scaled by 2^n factors for better visibility. Statistical (bars) and full systematic (boxes) uncertainties are plotted. Dashed curves: blast-wave fits to each individual distribution [31].

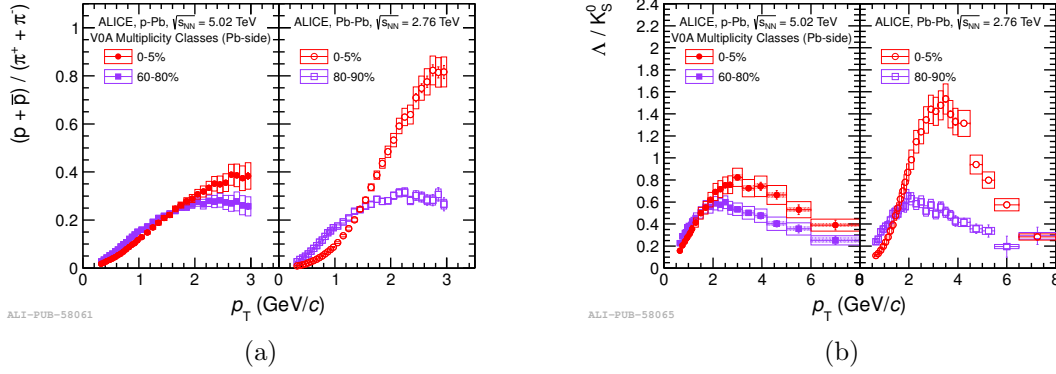


Figure 1.7: p/π and Λ/K_s^0 ratios as a function of p_T for p-Pb and Pb-Pb collisions. From [31].

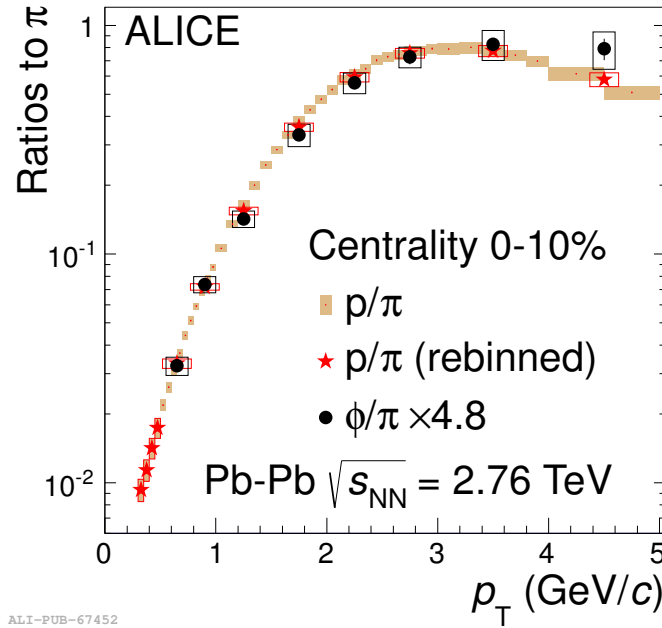


Figure 1.8: p/π and ϕ/π ratios as a function of p_T for central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [25]. The p/π ratio is presented using two p_T binning schemes: the ratio with its original measured bins is shown along with a recalculated version that uses the same bins as the ϕ meson p_T distribution for $0.5 < p_T < 5$ GeV/c. In order to show the similarity of the shapes of the two ratios the ratio has been scaled so that the ϕ and proton integrated yields are identical.

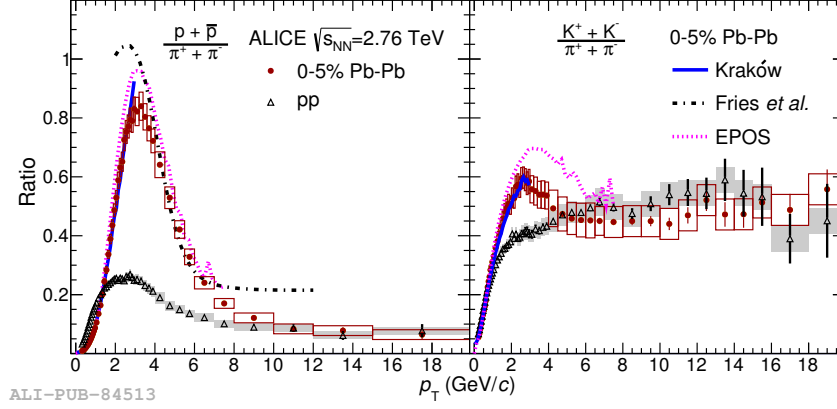


Figure 1.9: p/π and K/π particle ratios as a function of p_T measured in pp and the most central, 0-5%, Pb-Pb collisions. Statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively. The theoretical predictions refer to Pb-Pb collisions [53].

1.5.2 Azimuthal anisotropy

In non-central heavy-ion collisions the initial volume of the interacting system is anisotropic in the transverse plane. The highly Lorentz contracted nuclei intersect, assuming a characteristic almond shape (Fig. 1.10). This initial spatial asymmetry is converted by the collective expansion into an anisotropy in momentum space.

The impact parameter $\mathbf{b}$ and the beam axis z define the plane of symmetry of the event, called *reaction plane*, while the *reaction plane angle* is defined by the impact parameter vector in the transverse plane. Quantitatively, *anisotropic flow* [55] is characterized by the coefficients of a Fourier expansion of the azimuthal dependence of the invariant yield of particles relative to the reaction plane, the so-called flow harmonics v_n :

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T d\eta} \left(1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos[n(\phi - \psi_{RP})] \right) \quad (1.3)$$

where E is the energy of particle, p_T is the transverse momentum, ϕ is its azimuthal angle, y is the rapidity, and ψ_{RP} the reaction plane angle. The Fourier coefficients:

$$v_n(p_T, y) = \langle \cos[n(\phi - \psi_{RP})] \rangle \quad (1.4)$$

are called flow coefficients. Anisotropic flow analysis consists in the measurement of flow harmonics v_n . In particular, v_2 is called *elliptic flow* and represents the momentum anisotropy between particles emitted along the two axes of the initial

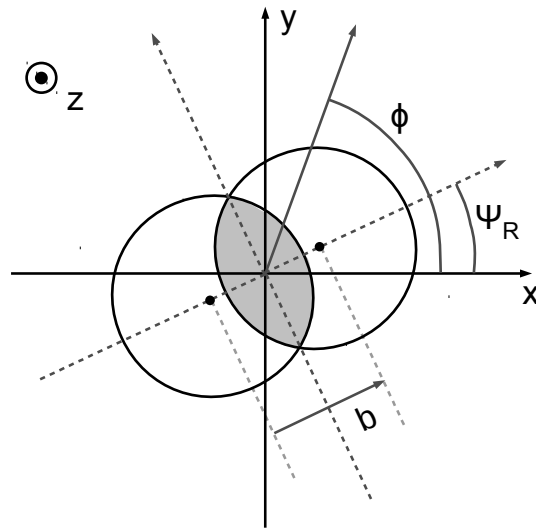


Figure 1.10: Almond shaped interaction region after a non-central collision of two nuclei. The spatial anisotropy with respect to the x - z plane (reaction plane) translates into a momentum anisotropy of the produced particles (anisotropic flow) [54].

almond shaped system. it is the dominant harmonic in non-central collisions, due to the approximately elliptical shape of the initial overlap region.

The anisotropic flow has become a key observable for the characterization of the properties and the evolution of the system created in a nucleus-nucleus collision, yielding to a precise evaluation of the QGP transport coefficients and reducing the model uncertainty in the initial shape of the thermalized fireball and its event-by-event fluctuations.

In Fig. 1.11, the p_T dependence of the harmonics v_2 , v_3 , v_4 and v_5 , measured by ALICE [56], are reported. The elliptic (v_2) and triangular (v_3) flow are compared to model calculations based both on ideal and viscous relativistic hydrodynamics with Glauber initial conditions (section 2.1), taking into account the role of event-by-event fluctuations of the initial state conditions [56].

At low p_T , the different p_T dependence of the v_2 and the v_3 is described by the hydrodynamic predictions. However, the magnitude of $v_2(p_T)$ is better described by the ratio of the shear viscosity to the entropy density $\eta/s = 0$ while for $v_3(p_T)$ $\eta/s = 0.08$ provides a better description. The details on the hydrodynamic models will be discussed in the next chapter, but it is already interesting to observe that the hydrodynamic can reproduce the trend of most coefficients and that the different combinations of initial conditions and transport coefficients (viscosity) produce different predictions, providing a handle to constrain the initial conditions models.

This result provides experimental information on the fluctuating event-by-event shape of the initial condition and will be discussed in detail in chapter 5.

Fig. 1.12(a) shows the p_T -differential v_2 for π , K, p, ϕ , Λ , Ξ and Ω . A clear mass ordering is observable for $p_T < 2$ GeV/ c , which is attributed to the presence of radial flow which boosts particles to higher momenta. The effect is larger for heavier particles resulting in a flattening of the transverse momentum spectra of heavy particles and in a decrease of v_2 at low p_T and a shift towards higher p_T of the rise of $v_2(p_T)$.

The same mass ordering and crossing is also observed in p-Pb collisions [32] (Fig. 1.12(b)). The trend it is qualitatively similar to the one in Pb-Pb collisions and this pattern is in agreement with the expectations from hydrodynamic models in p-Pb [58].

The elliptic flow is a key measurement to constrain the fundamental properties of the matter created in nucleus-nucleus collisions, in particular the the initial conditions of the collision, i.e. the spatial eccentricity (see chapter 5) and the transport properties.

1.5.3 Other soft probes

Charged-particle density and energy density One of the first measurements performed to characterize heavy ion collisions is the charged particle density

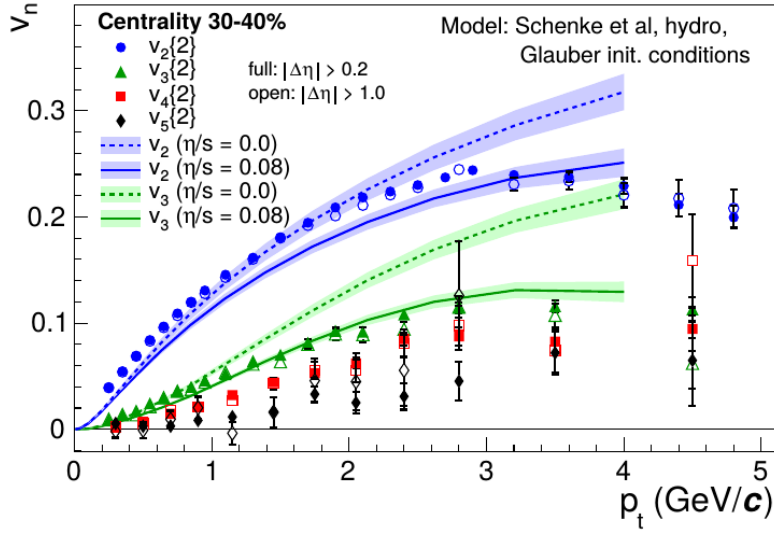
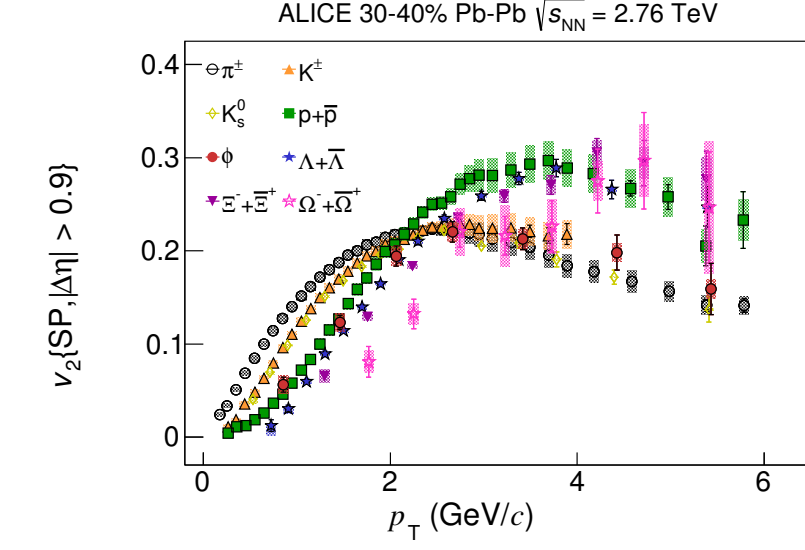


Figure 1.11: Comparison of transverse momentum dependence of measured anisotropic flow harmonic v_2 , v_3 , v_4 and v_5 with a particular theoretical model. This model fails to describe v_2 and v_3 simultaneously [56].

$dN_{\text{ch}}/d\eta$. It has been measured by all the three experiment participating in the LHC heavy-ion programme [59–62] in the mid-rapidity region $\eta < 0.5$. The results from the three experiments are in excellent agreement (Fig. 1.13), and they show an increase by more than factor of two, compared to the highest value observed at RHIC [63]. By extrapolation, the total charged-particle multiplicity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV for different centralities can be estimated, for example, in 5% of the most central events $(17.2 \pm 0.8) \cdot 10^3$ charged particles are created.

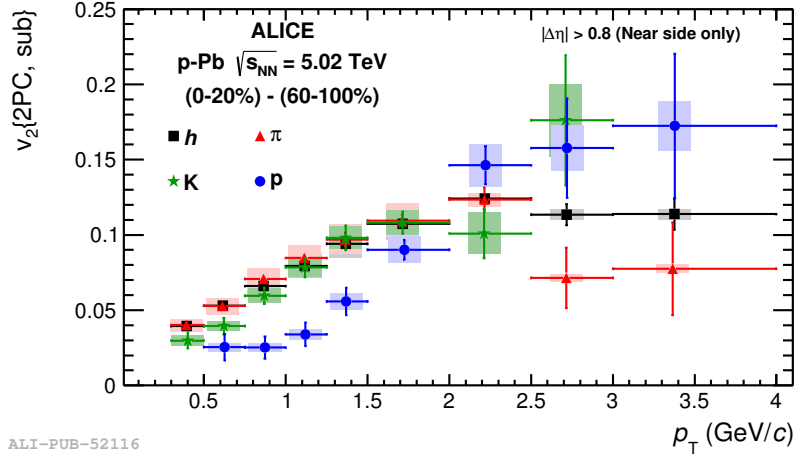
The energy distribution of all the produced particles is connected to the initial energy and entropy densities of the matter created in the collision. In order to estimate the energy density achieved in Pb–Pb collisions at the LHC, the transverse energy pseudorapidity density, $dE_T/d\eta$, has been measured by the CMS Collaboration for different pseudorapidities and centralities [64]. The transverse energy density per unit pseudorapidity ($dE_T/d\eta$) increases with the centrality of the collision. For the 5% most central collisions the energy density per unit volume is estimated to be about 14 GeV/fm^3 at a time of $1 \text{ fm}/c$ after the collision, i.e. the time when the initial thermalization was likely established.

Strange particle production The enhancement of strangeness in heavy-ion collisions was one of the earliest proposed signals for the QGP [65–67]. In high temperature QCD matter a partial chiral symmetry restoration is expected. There-



ALI-PUB-82670

(a)



ALI-PUB-52116

(b)

Figure 1.12: (a) Elliptic-flow coefficient $v_2\{\text{SP}\}$ as a function of p_T for π (black open circles), K (orange upward-pointing triangles), $p + \bar{p}$ (green squares), ϕ (red filled circles), Λ (blue filled stars), Ξ (violet downward-pointing triangles) and Ω (pink open stars) measured in central 30-40% Pb-Pb collisions [57]. (b) The Fourier coefficient $v_2\{2\text{PC}, \text{sub}\}$ for hadrons (black squares), pions (red triangles), kaons (green stars) and protons (blue circles) as a function of p_T from the correlation in the 0-20% multiplicity class after subtraction of the correlation from the 60-100% multiplicity class (see [32] for details).

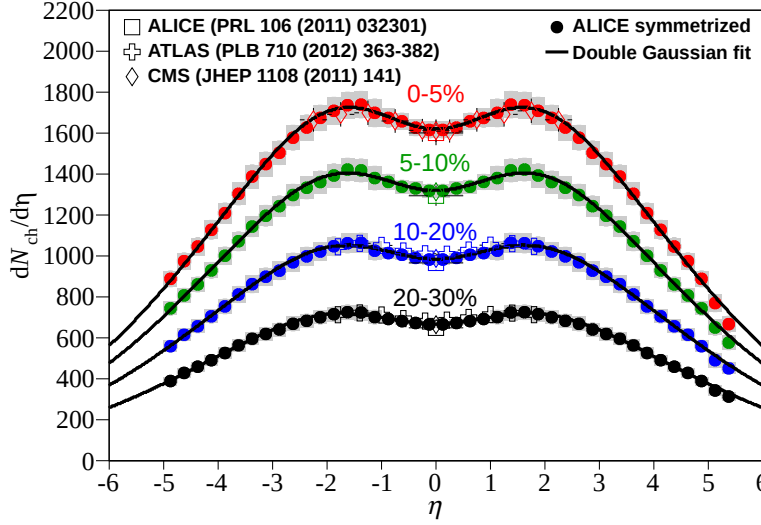


Figure 1.13: Charged-particle pseudorapidity density distribution for various centrality classes, comparison among the LHC experiments [59].

fore, the relevant quark masses drop from their constituent to their bare values and then the strange quark mass becomes comparable to the temperature, consequently the production rates for different light quarks tend to equalize.

Strangeness enhancement has been observed at SPS [68–71], RHIC [72] and LHC [73, 74] and it is measured as the ratio of the yield per participant in AA collisions to that in pp (or pA) collisions. The abundances are found to reflect athermal equilibrium distribution, and are studied with the “thermal models” [21–23, 26].

Particle yields The particle yields at mid-rapidity are obtained by integration of the p_T spectra fitted to the blast wave model [49], in order to extrapolate below the lowest measured p_T . They are studied with statistical hadronization models [21–23, 26]. The system is described in terms of the temperature T_{ch} , constrained by ratios of particles with a large mass difference, the baryon chemical potential μ_B , constrained by anti-baryon/baryon ratios (at LHC it is found $\mu_B \approx 0$), and the volume in thermal and chemical equilibrium, constrained by the most precisely measured species, typically pions.

The temperature extracted from a thermal analysis of the data $T_{ch} \approx 130$ –165 MeV [24, 75], is found to be very close to the critical (crossover) temperature estimated in lattice QCD, $T_c = 143$ –171 MeV [76].

Femtoscopy correlations Particle femtoscopy (also referred to as Hanbury-Brown Twiss (HBT) interferometry [77]) employs Bose-Einstein quantum statistics in order to measure the sizes of the particle emitting region. It is based on the idea that the $\vec{q} = \vec{p}_1 - \vec{p}_2$ measurement of identical bosons yields information on the average separation between emitters (HBT radius). The HBT radius $\vec{R}$ can be decomposed into three components (R_{out} , R_{side} , R_{long}), with the “out” axis pointing along the pair transverse momentum, the “side” axis perpendicular to it in the transverse plane, and the “long” axis along the beam [78]. The production of identical bosons, for instance pions, with close momenta will be enhanced by such an effect, and that of identical fermions (e.g. protons) will be suppressed.

The HBT radii are found to be significantly larger (by 10-35%) than those measured at RHIC [79].

Within a hydrodynamic scenario the decoupling time for hadrons, τ_f , corresponding to the kinetic freeze-out can be extracted from the k_T (one-half of the total pair transverse momentum) dependence of R_{long} [80]. The decoupling time, estimated this way for different collision energies reaches for most central LHC collisions a value by a factor 1.4 larger than was observed at RHIC [78]. Note that the estimate for τ_f has been done for an assumed kinetic freeze-out temperature $T_{kin} = 120$ MeV. Using the latest measured value (section 2.3), the decoupling time would increase to about 12 fm [24].

Angular correlations The angular correlations between two particles are widely used to study various phenomena of both non-flow and collective-flow origin. The two-particle correlation between pairs of particles [81] is measured as a function of the azimuthal difference and pseudorapidity difference. Various kinds of particle pairs are used: they can be all charged particles, pairs selected by charge (like sign, unlike sign), pairs when one particle (trigger) has given p_T or type while the second particle (associated) may have some other characteristics, etc.

An example of the two-dimensional two-particle correlation distribution is shown in Fig. 1.14 for central Pb–Pb collisions [82]. This is obtained for trigger-associated particle pairs, selected according their p_T as indicated in the figure. Some typical structures are apparent:

- the peak around $(\Delta\phi, \Delta\eta) = (0, 0)$ is due to (mini-)jets [83];
- the near-side ridge at $\Delta\phi = 0$ extending from the jet peak along the $\Delta\eta$ direction to larger $\Delta\eta$ values, this is presumably caused by the elliptic and higher-harmonic flows [82, 84];
- the away-side ridge at $\Delta\phi = 2\pi$ along the $\Delta\eta$ direction, where the recoil jet may appear (often quenched). In addition the flow azimuthal modulation also contributes here.

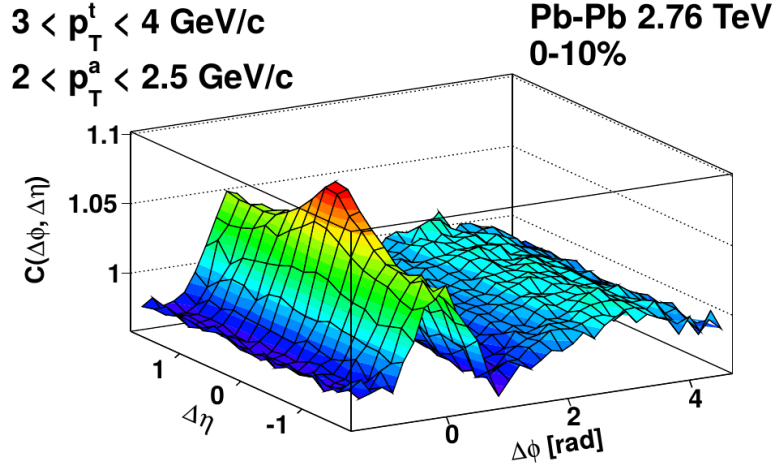


Figure 1.14: ALICE data showing the two-particle correlation function in $(\Delta\phi, \Delta\eta)$ for trigger and associated particle selected in p_T . The top 10% of most central Pb–Pb collisions are used [82].

In pp collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV the similar long-range ($2 < |\eta| < 4$) near-side ($\Delta\phi \approx 0$) correlations has been observed in events with significantly higher-than-average particle multiplicity [85]. The same structure in high-multiplicity p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [86] has been observed. Further measurements in p–Pb collisions employed a procedure for removing the jet contribution by subtracting the correlations extracted from low-multiplicity events, revealing essentially the same long-range structures on the away side in high-multiplicity events [87, 88].

The ridge structures in high-multiplicity pp and p–Pb events have been attributed to mechanisms that involve initial-state effects, such as gluon saturation and colour connections forming along the longitudinal direction [89–94] final-state effects, such as parton-induced interactions [95–97], and collective effects arising in a high-density system possibly formed in these collisions [98–105].

1.6 Hard probes

Suppression of charged particle production at large p_T To quantify nuclear medium effects at high p_T , the so called the *nuclear modification factor* - R_{AA} is used. It is defined as the ratio of the charged particle yield in Pb–Pb to that observed in pp collisions, scaled by the average number of binary nucleon-nucleon collisions N_{coll} :

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{A-A}/d\eta dp_T}{d^2 N_{p-p}/d\eta dp_T} \quad (1.5)$$

From this definition, if a nucleus-nucleus collision is an incoherent superposition of N_{coll} pp collisions, one would expect $R_{\text{AA}} = 1$, at high enough p_{T} , i.e. in the region where the hadron production is characterised by processes with large energy transfer. The scaling with the number of binary collision N_{coll} is a natural expectation for hard processes, because it expresses the effective luminosity seen by a given hadron. In Central collisions (0-5%) the yield of hadrons is most suppressed, due

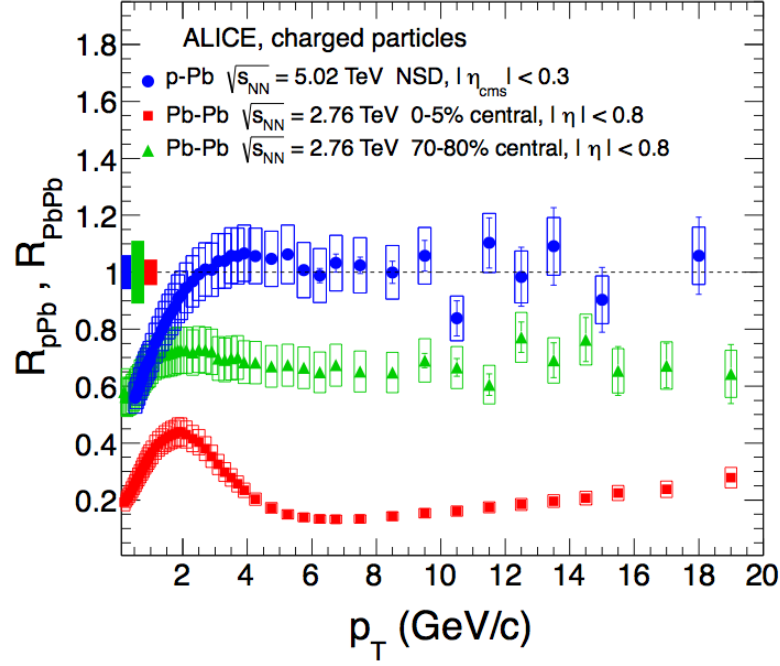


Figure 1.15: The nuclear modification factor of charged particles as a function of transverse momentum in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in $|\eta_{\text{cms}}| < 0.3$ [106], central (0-5% centrality) and peripheral (70-80%) Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [107].

to energy loss in the plasma, with a minimum at intermediate for $p_{\text{T}} = 6-7$ GeV/ c then the R_{AA} rises at higher p_{T} where production from hard processes is expected to dominate. In peripheral collision the R_{AA} still deviates from the unity but the suppression is significantly smaller than in central Pb–Pb collisions. Deviation of R_{AA} from unity for hard processes signals a nuclear effect. However, for soft processes, such as particle production at p_{T} below a few GeV, the scaling from pp to A–A is governed by N_{part} rather than by N_{coll} , leading naturally to an R_{AA} below unity in that p_{T} region, especially for central events.

In p–Pb the nuclear modification factor spectrum is observed to scale with N_{coll} at high p_{T} ($R_{\text{AA}} = 1$). The absence of suppression in p–Pb collisions supports the

interpretation of Pb–Pb results as a hot nuclear matter effect. Fig. 1.16 shows

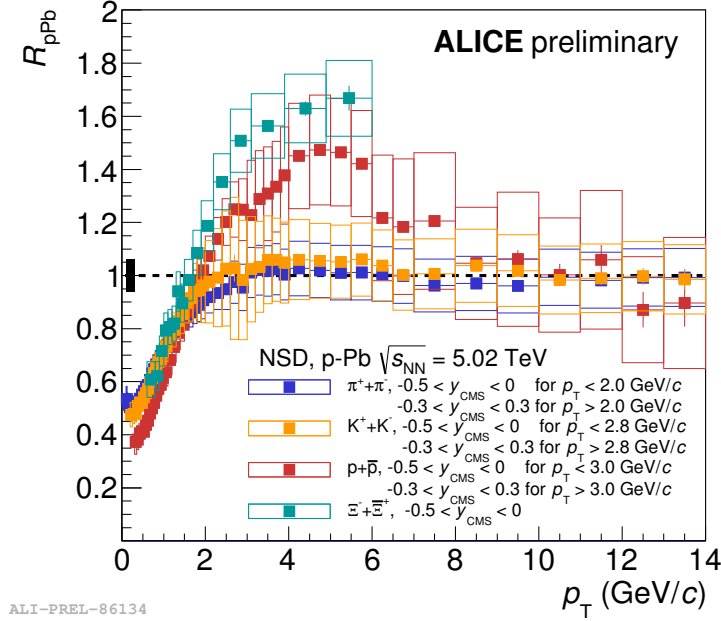


Figure 1.16: Nuclear modification factor R_{pPb} of primary charged π , K, p and Ξ at mid-rapidity measured p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

R_{pPb} for π , K, p up to $p_T = 14$ GeV/c and for Ξ up to 6 GeV/c. The nuclear modification factor of π and K, within the systematic uncertainties, does not differ from the charged particle result. At intermediate momenta of $2 < p_T < 6$ GeV/c a mass ordering is observed. In Pb–Pb collisions a similar behaviour is observed and attributed to radial flow. A notable Cronin peak is only observed for p and Ξ , suggesting that the small enhancement of R_{pPb} in Fig. 1.15 for charged particles is driven by the protons.

Jet quenching High p_T particles are produced in the initial hard scattering processes. Hard scattering and subsequent fragmentation of partons generates *jets* of correlated hadrons: a narrow cone of particles around the parton momentum direction. High p_T partons are produced in the early stages of the collisions and travel through the QGP interacting with the colour charged medium and losing energy by induced gluon radiation. This phenomenon is usually referred to as *jet quenching*. Partons energy loss may provide direct information on the colour charge density and the transport properties of the QGP since

Highly asymmetric dijets in central Pb–Pb collisions have been observed at the LHC. The azimuthal correlations and the momentum asymmetry between

the leading and subleading jets have been used to characterize the modification of dijet properties, relative to pp collisions [108]. The jet pairs are selected to be approximately back-to-back, with relative azimuthal angle $\Delta\phi_{1,2} = |\phi_1 - \phi_2| > \pi/2$ and their momentum asymmetry is characterized using

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \quad (1.6)$$

In Fig. 1.17 the dijet asymmetry and $\Delta\phi_{1,2}$ distributions for Pb–Pb data (solid markers) are shown in four bins of collision centrality. For peripheral events, the

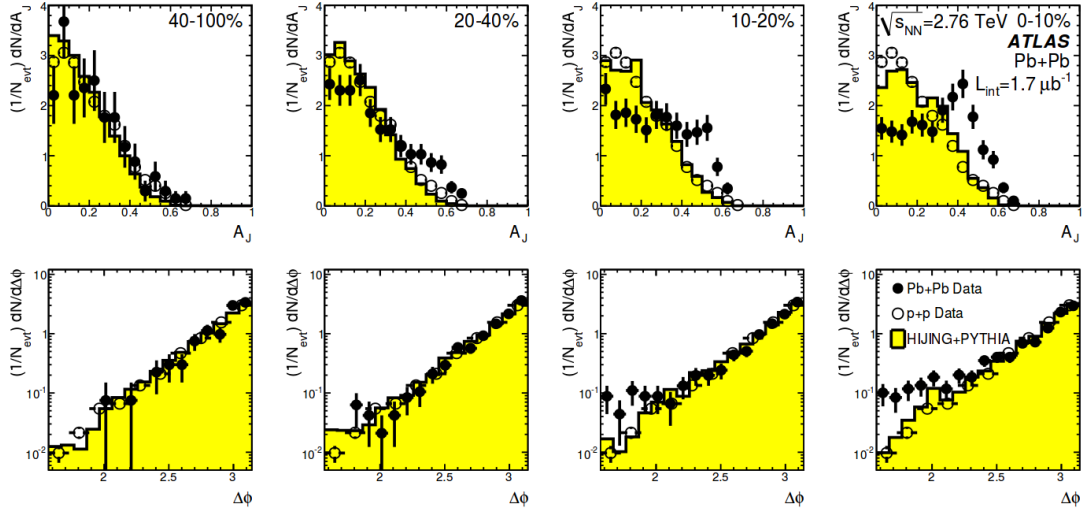


Figure 1.17: (Top) Dijet asymmetry distributions for data (points) and HIJING+PYTHIA simulations (solid yellow histograms), as a function of collision centrality. Protonproton data $\sqrt{s} = 7$ TeV is shown as open circles. (Bottom) Distribution $\Delta\phi_{1,2}$ between the two jets, for data and HIJING+PYTHIA, shown in four bins of centrality [108].

Pb–Pb dijet asymmetry is comparable to that seen in pp collisions. For central events the A_J distribution widens significantly, showing a large increase in unbalanced dijet events and a maximum far away from $A_J = 0$. This can be interpreted as due to different path lengths of the partons in the matter: the trigger jets is likely to come from the surface and loses significantly less energy than the other.

A complementary study to parton energy loss measurements using the jet nuclear modification factor R_{CP} , which is the ratio of jet p_T spectra in central and peripheral collisions, scaled to N_{coll} , assuming no QGP (or less extended in space-time) phase in peripheral nucleus-nucleus collisions. Figure 1.18 shows the R_{CP} distribution as a function of p_T measured by ATLAS (a) [109] and ALICE (b) [110] for different centrality bins in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

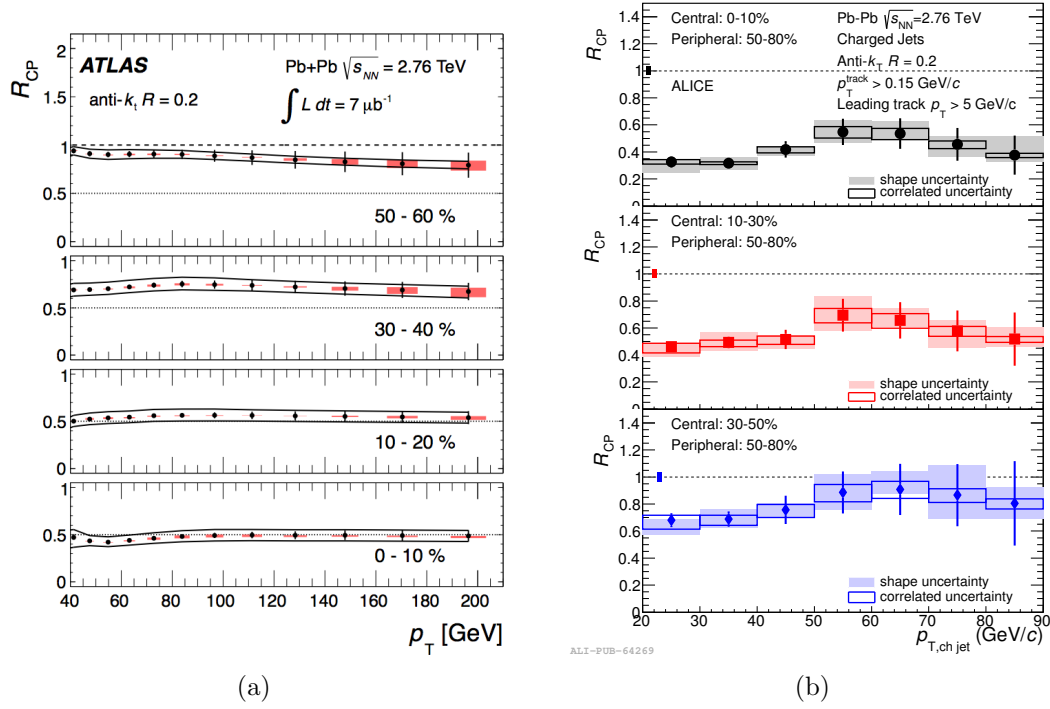


Figure 1.18: R_{CP} of reconstructed jets as a function of the jet p_T in four different centrality bins in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Jets are reconstructed using an anti- k_t algorithm with cone radius $R=0.2$. The R_{CP} measurements presented here use the 60-80% centrality bin as a common peripheral reference [109]. (b) Nuclear modification factor R_{CP} for charged jets with a leading charged particle with $p_T^{track} > 5$ GeV/c with $R=0.2$ and different centrality selections, using centrality class 50-80% as peripheral reference [111].

A strong jet suppression is observed for 0-10% central events, while more peripheral collisions are less suppressed. This is expected because energy loss increases with the density of the medium and with increasing path length of the parton in the medium.

In addition to characterize the energy loss of the fast partons as they traverse the medium, the modification of the fragmentation properties of the parton has been studied in [112].

Within uncertainties, the Pb-Pb data and pp based reference show the same fragmentation properties, for different jet imbalance in leading, as well as sub-leading, jets. After traversing the dense strongly interacting medium, partons produced in Pb-Pb collisions are reconstructed as jets with a significantly reduced momentum. However, the distribution of the remaining momentum within the jet cone into high- p_T particles corresponds to that observed for jets fragmenting in

vacuum, as seen in pp collisions.

Heavy flavour Charm and beauty quarks are good probes of the QGP due to their short formation time compared to the lifetime of the medium, coupled with the reduced energy loss caused by their high mass, which means they experience the full development history of the medium [113, 114].

Heavy flavour energy loss in the medium can again be quantified via R_{AA} measurements. The energy loss of heavy quarks is predicted to be different than that of light quarks [115, 116]. Figure 1.19(a) shows the average D meson R_{AA} (D^0 , D^* , D^{*+}) compared with charged hadrons R_{AA} and non-prompt J/ψ from B decays in 0-20% centrality class. The results for charged hadrons (mainly light flavour hadrons) and D meson are comparable, within the large uncertainties. The comparison with non-prompt J/ψ R_{AA} from CMS suggest that the c quarks are more affected by energy loss with respect to b quarks.

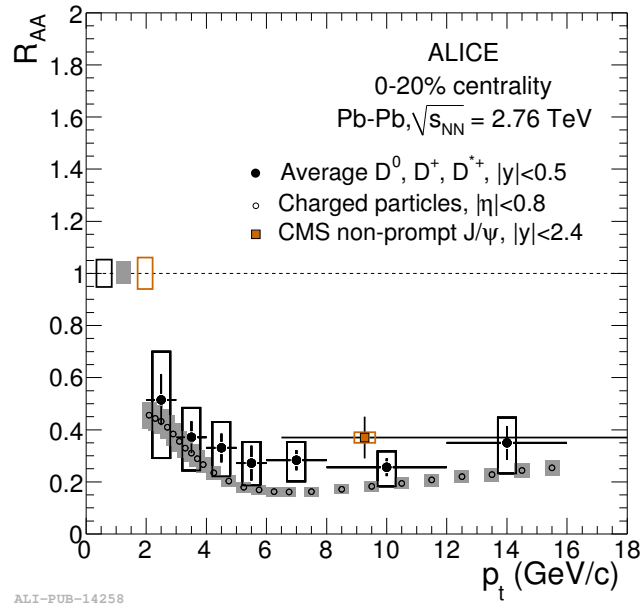
Fig. 1.19(b) shows the v_2 measurement as a function of the p_T in 30-50% centrality class [118]. The D meson v_2 is comparable to that of charged particles (dominated by light flavours), suggesting that charm quarks participation to the collective motion gives an important contribution to the D meson elliptic flow.

Quarkonia Quarkonia (a heavy quark and anti-quark bound states) are expected to be sensitive to the properties of the strongly interacting system formed in the early stages of heavy-ion collisions. The presence of the QGP reduces the distance at which each parton of the pair feels the interaction with the other quark because of the *Debye screening*, so that the two heavy quarks may not form a bound state [38].

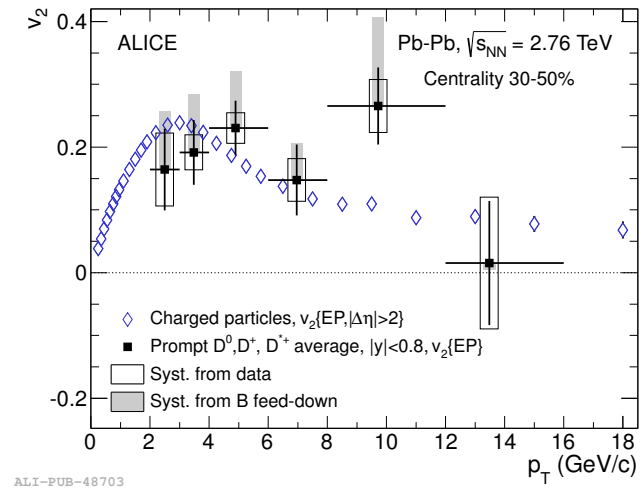
Fig. 1.20(a) shows R_{AA} for the 0-20% most central collisions. It exhibits a decrease indicating that high p_T J/ψ are more suppressed than low p_T ones. The data are compared to results obtained by PHENIX in 0-20% most central Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV, in the rapidity region $1.2 < |y| < 2.2$ [119]. At low p_T a striking difference between the J/ψ R_{AA} at LHC and RHIC can be observed. This can be interpreted as an increasing role of regeneration, that is the statistical recombination of quark-antiquark pairs in the medium, of at the LHC with respect to RHIC [120, 121].

J/ψ mesons produced by hard processes in the early stage of the collision are expected to be insensitive to collective phenomena. This aspect can be addressed in more details studying the flow of heavy flavor hadrons. On the contrary, for those produced by regeneration of charm quark pairs in the QGP phase a non-zero elliptic flow should be measured.

The p_T dependence of the J/ψ elliptic flow was studied by ALICE [122] up to 10 GeV/c for a large centrality bin 20-60% (Fig. 1.20(b)). The comparison with

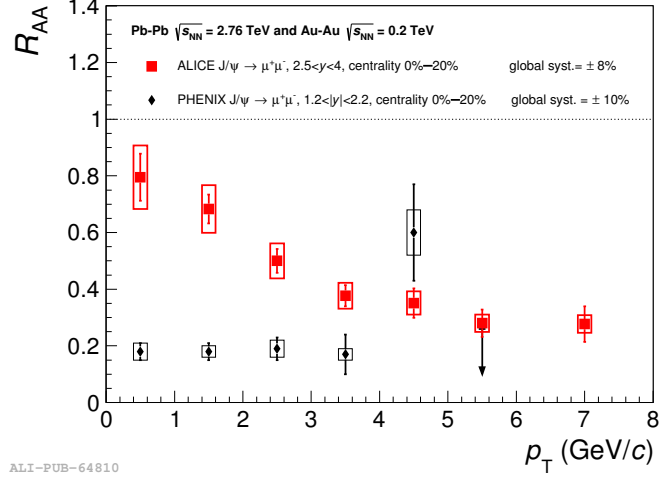


(a)

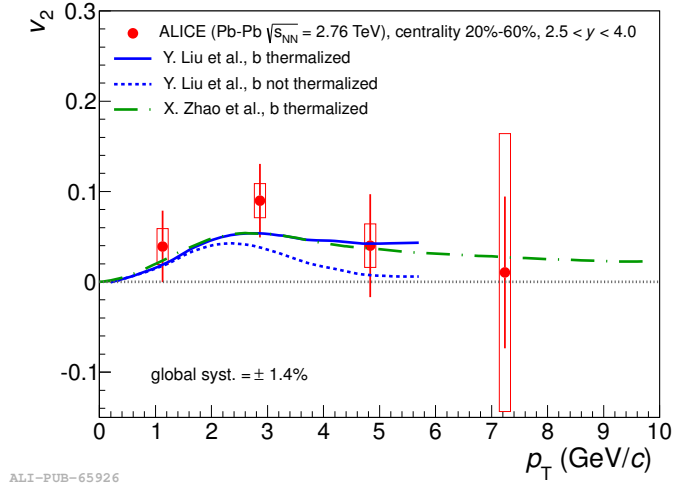


(b)

Figure 1.19: (a) Average D meson R_{AA} as a function of p_T in the 0-20% centrality class, compared to charged hadrons R_{AA} and to the nuclear modification factor of charged hadrons and non-prompt J/ψ from B decays in the same centrality class [117]. (b) Average of (D^0, D^*, D^{*+}) v_2 as a function of p_T compared to charged particle v_2 in 30-50% centrality class. [118].



(a)



(b)

Figure 1.20: (a) J/ψ R_{AA} as a function of momentum measured by ALICE in 0-20% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to PHENIX [119] results in the 0-20% most central Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. (b) J/ψ elliptic flow as a function of p_T in the centrality range 20-60% and in the rapidity range $2.5 < y < 4$. ALICE data are compared with a transport model prediction.

transport model calculation (including J/ψ regeneration component from deconfined charm quarks) is shown. A hint for non-zero v_2 is observed in the intermediate p_T range $2 < p_T < 6$ GeV/ c . Including statistical and systematic uncertainties the combined significance of a non-zero v_2 in this p_T range is 2.7σ . At lower and higher p_T the inclusive J/ψ v_2 is compatible with zero within uncertainties.

1.7 Electromagnetic probes

Dileptons Dileptons are a clean and penetrating probe for studying the properties of the QGP matter, such as the equation of state and the intrinsic chiral characteristics.

Dileptons emitted from the hadronic medium are governed by the coupling of vector mesons (e.g. ρ) to the medium and are expected to dominate the low-mass production ($M_{ll} < 1.1$ GeV/ c^2) [123]. Their vacuum mass spectra are determined by the spontaneously broken chiral symmetry. Vector meson in-medium properties can be studied through their dilepton decay, where modifications of mass and width of the spectral functions, may indicate the chiral symmetry restoration [40, 123, 124]. After freeze-out, long lived particles (π^0 , η , $D\bar{D}$, etc.) can decay to lepton pairs. The sum of these contributions, usually referred to as *hadronic cocktail*, can be calculated based on the measured or estimated yields.

Dileptons production at SPS [125–127] and RHIC [128, 129] energies has been measured.

The STAR Collaboration measured the dielectron production in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [129].

The dielectron yields in the ω and ϕ mass regions are well described by the hadronic cocktail model, while yields at higher mass (1-3 GeV/ c^2), can be understood from the decay leptons of charm pairs. In the 0.30-0.76 GeV/ c^2 region exists an excess over the hadronic cocktail, that cannot be explained by a pure vacuum ρ . Compared to the yields in the ω and ϕ regions, the excess in the ρ region exhibit stronger growth with more central collisions. Theoretical model calculations, that include a broadened ρ spectral function from interactions with the hadronic medium, can describe the STAR measured dielectron excess at the low-mass region [130, 131].

The dilepton spectra in the intermediate mass range ($1.1 < M_{ll} < 3$ GeV/ c^2) are directly related to the thermal radiation of the Quark-Gluon Plasma (QGP) [40, 123, 124]. However, the contributions from other sources have to be taken into account. Such contributions include background pairs from correlated open heavy flavor decays. NA60 presented the unprecedented excess dimuon mass spectrum in In+In collisions [127]. An excess of dimuons in the intermediate mass region is observed, interpreted in terms of thermal radiation from the fireball [127].

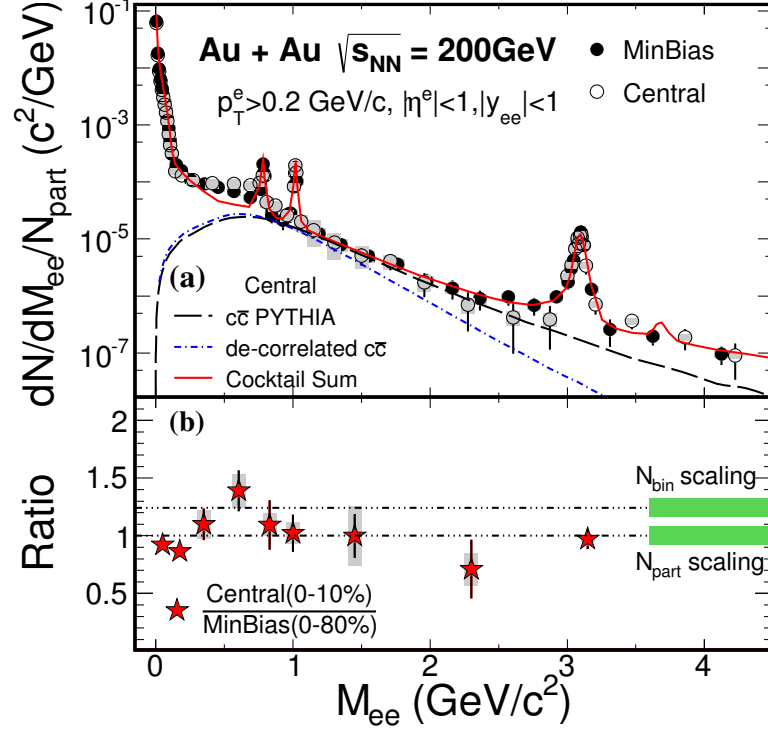


Figure 1.21: (a) Dielectron mass spectra scaled with N_{part} from minimum bias (0-80%) and central (0-10%) collisions. The solid line represents the hadronic cocktail for central collisions [129]. (b) The ratio of N_{part} scaled dielectron yields between the central and minimum bias collisions [129]. The grey boxes show the systematic uncertainties on the data.

Photons Direct photons are produced in various processes during the entire space-time evolution of the relativistic heavy ion collisions. Once created, most of them leave the collision region without appreciable further interaction, due to their small coupling.

At low p_T , ALICE performed a preliminary measurement of the spectrum of direct photons [132], in the 0-40% centrality interval. It is found a good agreement, above $p_T = 4$ GeV/ c , with scaled NLO calculation, at the Pb-Pb center-of-mass energy. Furthermore, an excess is observed below 4 GeV/ c . The exponential fit to the low momentum part of the spectrum gives an inverse slope parameter of $T_{LHC} = 304 \pm 51_{\text{syst.}+\text{stat.}}$ MeV. PHENIX [133] measured an inverse slope parameter of $T_{RHIC} = 221 \pm 19^{\text{stat.}} \pm 19^{\text{syst.}}$ MeV. In hydrodynamic models describing the PHENIX data, the inverse slope of 220 MeV indicates an initial temperature of the QGP above the critical temperature T_C for the transition to the QGP [133]. The ALICE result shows an expected increase in the extracted temperature.

CMS [134] and ATLAS [135] reported photon measurement in heavy ion and pp data. They are compared with NLO and pQCD calculation by scaling the calculation by the mean nuclear thickness function $\langle T_{AA} \rangle^2$ (which scales as the number of binary collisions). It is found that the NLO calculations agree with the pp and heavy ion data in all cases. The photon yields scale with the number of binary collisions.

PHENIX has measured the v_2 of π^0 , inclusive and direct photons in the $1 < p_T < 13$ GeV/ c range for minimum bias and selected centralities at $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions [136]. At higher p_T (>6 GeV/ c) the direct photon v_2 is consistent with zero at all centralities, as expected if the dominant source of photon production is initial hard scattering. In the thermal region ($p_T < 4$ GeV/ c), a positive direct photon v_2 is observed which is comparable in magnitude to the π^0 v_2 and consistent with early thermalization times and low viscosity, but its magnitude is larger than current theories predict [136].

In addition, ALICE reported that significant v_2 is observed for direct photons, though the systematic uncertainties are large [137].

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²The geometric nuclear overlap function $\langle T_{AA} \rangle$ is calculated as $\langle T_{AA} \rangle = N_{\text{coll}}/\sigma_{NN}^{\text{inel}}$, where $\sigma_{NN}^{\text{inel}}$ is the inelastic nucleon-nucleon cross section. $\langle T_{AA} \rangle$ represents the effective nucleon luminosity in the collision process.

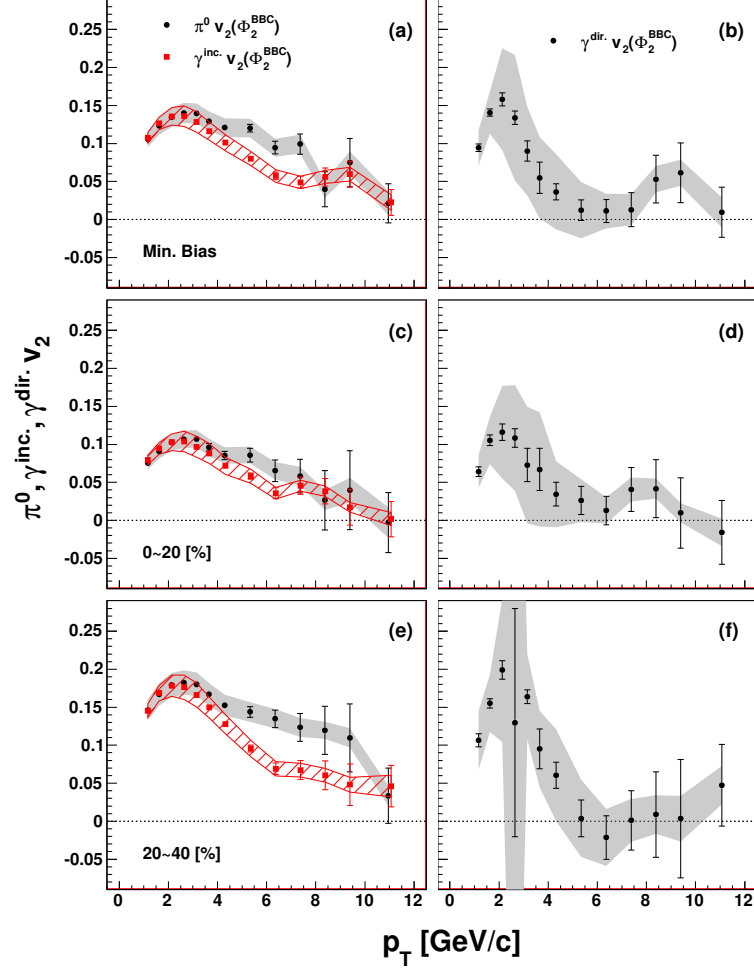


Figure 1.22: (a,c,e) Centrality dependence of v_2 for (solid black circles) π^0 , (solid red squares) inclusive photons, and (b,d,f) (solid black circles) direct photons measured with the BBC detector for (a,b) minimum bias (c,d) 0-20% centrality, and (e,f) 20-40% centrality [136]. The vertical error bars on each data point indicate statistical uncertainties and the shaded (gray) and hatched (red) areas around the data points indicate sizes of systematic uncertainties.

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Initial conditions dynamics and hydrodynamics

A first principle description of a nucleus nucleus collisions, based on the QCD lagrangian, is an intractable problem, due to the non-linearity of interactions of gluons, the strong coupling, the dynamical many body system and confinement. Several phenomenological approaches are used in the field. One of the most successful for the description of many soft observables is based on relativistic hydrodynamics.

The evolution of the system created in the collision is shown in Fig. 2.1. Ultra-relativistic heavy-ion collisions at RHIC and the LHC produce a fireball made of hot and dense matter. When the matter reaches approximately the local thermal equilibrium, due to the pressure gradients between the fireball center and the surrounding vacuum, the matter undergoes collective expansion.

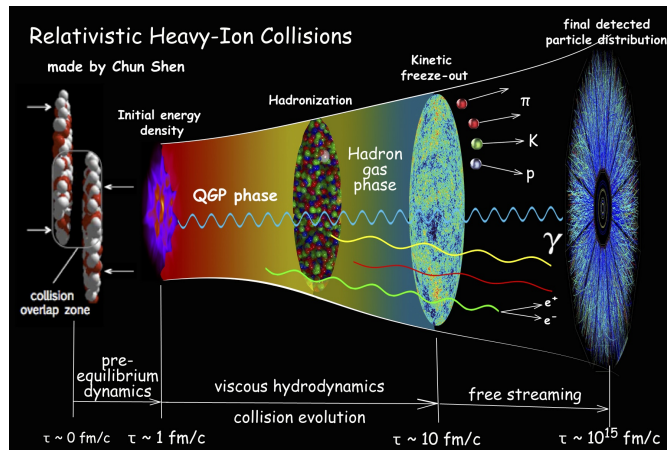


Figure 2.1: Schematic view of relativistic heavy ion collision evolution (credit: Paul Sorensen and Chun Shen).

The pressure generates a common velocity field of the outgoing particles, named *collective flow* and introduces space-momentum correlations [1]. A significant fraction of the collective flow builds up in the expansion of the fireball in the initial partonic phase [2]. In this picture, the system cools down rapidly as a consequence of the expansion and undergoes a phase transition from a partonic to a hadronic phase. The hadrons continue to interact, building up additional collective flow and potentially changing the relative abundances. Finally the matter fragments into free streaming hadrons whose energy and momentum distributions can be detected in the detectors set up around the collider rings.

Collective flow is sensitive to the equation of state of the hydrodynamically expanding system in all its different phases. The term collective flow encompasses common radial expansion, affecting the thermal spectra of outgoing particles, and an anisotropic expansion, affecting the azimuthal orientation of particles momenta.

The first component is called radial flow (section 2.3). Using thermodynamics to describe the evolution of the system, the measured transverse momentum spectra can be compared to the model predictions. The effect of different equations of state (EoS), which affect the radial flow through the pressure gradient, is more pronounced in the spectra of heavier particles, so that these measurements can be used to constrain the models [3–7].

The second component is called anisotropic flow (section 2.4). Most of the anisotropies in the transverse momentum distribution come from the early stage of the evolution of the system. By using hydrodynamics to describe the evolution of heavy ion collisions and comparing the measured data with different models, it is possible to introduce constraints on the medium properties such as the equation of state, the temperature and the order of the phase transition, transport coefficients and so on [3, 6, 8, 9].

At first order, measurements can be described assuming nuclei as perfectly smooth spheres and the QGP as a perfect liquid. However, in order to constrain quantitatively the properties of the QGP, we also need to understand the details. In particular it was realized in recent years that the interplay between fluctuating initial conditions and hydrodynamic evolution plays an important role in the understanding of many observations [10].

A detailed description of the different stages of the system evolution is reported in this chapter, with the models used to describe the system in such conditions. The effect of initial geometry fluctuation on collective flow, its anisotropies and event by event fluctuations are discussed.

2.1 Initial conditions and shape fluctuations

The shape and the structure of the initial energy density profile drive the anisotropies in the pressure gradient responsible for the development of the anisotropic flow. The energy density profile can be decomposed, in analogy with the flow Fourier coefficients (Eq. 1.3), in a set of *harmonic eccentricity coefficients* ϵ_n and associated angles Φ_n [10]:

$$\begin{aligned}\epsilon_1 e^{i\Phi_1} &\equiv -\frac{\int r dr d\phi r^3 e^{i\phi} e(r, \phi)}{\int r dr d\phi r^3 e(r, \phi)}, \\ \epsilon_n e^{in\Phi_n} &\equiv -\frac{\int r dr d\phi r^n e^{in\phi} e(r, \phi)}{\int r dr d\phi r^n e(r, \phi)} \quad (n > 1)\end{aligned}\tag{2.1}$$

where $e(r, \phi)$ is the initial energy density distribution in the plane transverse to the beam direction.

When, for colliding nuclei of the same species, the energy density is averaged over many events and ϕ is measured with respect to the impact parameter, all odd coefficients ϵ_n should vanish, due to the symmetry between ϕ and $-\phi$ as well as between ϕ and $\phi + \pi$. In an individual collision event, though, this is not valid anymore, since transverse positions of the nucleons inside the colliding nuclei and of the gluon density profiles inside those nucleons fluctuate from event to event, leading to non-zero ϵ_n and Φ_n and hence to non-zero anisotropic flow components of any order. The statistical distribution of ϵ_n and Φ_n , which control the statistical distribution of the final anisotropic coefficients v_n , depends on the internal structure of the colliding nuclei. Various theoretical approaches have been used to model the initial energy density profiles.

Monte Carlo Glauber In the Glauber model [11] the collision of two nuclei is modelled as a superimposition of individual interactions of constituent nucleons, with a random impact parameter $\mathbf{b}$. In the Monte Carlo approach, each nucleus is seen as a set of uncorrelated nucleons, sampled from the measured density distribution, which is usually parameterized with a Woods-Saxon distribution. The sampling procedure introduces event-by-event fluctuations of the nucleon positions. The nuclei collide if the distance between nucleons in the transverse plane is smaller than the radius ($\sqrt{\sigma_{inel}^{NN}}/\pi$) of the total inelastic nucleon-nucleon cross section.

Nucleons which undergo at least one inelastic interaction are called participants or wounded nucleons. The production of soft particles is expected to be proportional to the density of wounded nucleons. Within the Glauber model it is also possible to compute the number of binary nucleon-nucleon collisions N_{coll} . Hard processes scale with N_{coll} , quantity which takes into account the fact that each nucleon can have multiple interactions, with the different nucleons it encounters

on its trajectory. In other words, N_{coll} takes into account the interaction probability of two partons, i.e. the effective integrated pp luminosity due to the fact that there are many nucleons in a nucleus.

The initial energy density profile is usually considered proportional to the linear combination of the wounded nucleon density and of binary collision density, which are strongly fluctuating in the transverse plane and from event to event [11–13].

Some experimental data must be given as model inputs. The two most important are the nuclear charge densities and the energy dependence of the inelastic nucleon-nucleon cross section. The nucleon density is parameterized by a Woods-Saxon distribution with three parameters:

$$\rho(r) = \rho_0 \cdot \frac{1 + w(r/R)^2}{1 + \exp(\frac{r-R}{a})}. \quad (2.2)$$

The parameters are based on data from low energy electron-nucleus scattering experiments [14]. Protons and neutrons are assumed to have the same nuclear profile. The parameter ρ_0 is the nucleon density, which provides the overall normalization, not relevant for the Monte Carlo simulation, $R = (6.62 \pm 0.06)$ fm is the radius parameter of the ^{208}Pb nucleus and $a = (0.546 \pm 0.010)$ fm is the skin thickness of the nucleus, which indicates how quickly the nuclear density falls off near the edge of the nucleus. The parameter w is needed to describe nuclei whose maximum density is reached at radii $r > 0$ ($w = 0$ for Pb). In the Monte Carlo procedure the radial coordinate of a nucleon is randomly drawn from the distribution $4\pi r^2 \rho(r)$ and ρ_0 is determined by the overall normalization condition $\int \rho(r) d^3r = A$ [12].

For nuclear collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, $\sigma_{\text{NN}}^{\text{inel}} = (64 \pm 5)$ mb, estimated by interpolation [15] of pp data at different center-of-mass energies and from cosmic rays [16, 17], and subtracting the elastic scattering cross section from the total cross section. The interpolation is in good agreement with the ALICE measurement of the pp inelastic cross section at $\sqrt{s_{\text{NN}}} = 2.76$ TeV $\sigma_{\text{NN}}^{\text{inel}} = (62.8 \pm 2.4_{4.0}^{+1.2})$ mb [18], and with the measurements of ATLAS [19], CMS [20], and TOTEM [20] at $\sqrt{s_{\text{NN}}} = 7$ TeV, as shown in Fig. 2.2.

An illustration of a Glauber Monte Carlo event for a Au–Au collision with impact parameter $b = 6$ fm is shown in Fig. 2.3. The average number of participating nucleons and binary nucleon-nucleon collisions and other quantities are then determined by simulating many nucleus-nucleus collisions.

The azimuthal anisotropy of the initial collision region could be quantified by the eccentricity of the overlap region of the colliding nuclei. A *standard eccentricity* is determined by relating the impact parameter of the collision in the Glauber model to the eccentricity calculated assuming the x axis as the minor axis of the overlap ellipse along the impact parameter vector, and the y axis perpendicular to

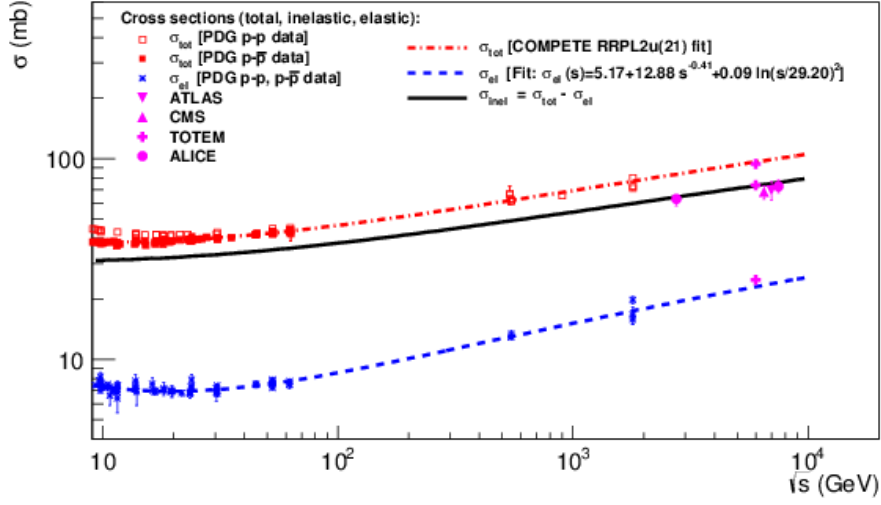


Figure 2.2: Compilation of total σ_{tot} , elastic σ_{el} and inelastic σ_{inel} cross sections of pp and p $\bar{p}$ collisions [15–17]. The σ_{tot} curve is a fit performed by the COMPETE Collaboration also available at [16, 17]. The pp data from ATLAS [19], CMS [20], TOTEM, [21] and ALICE [18] agree well with the interpolation for σ_{inel} .

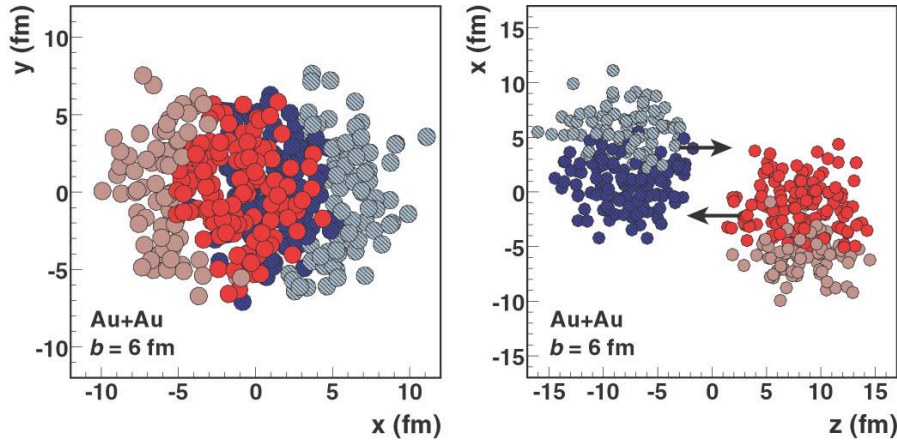


Figure 2.3: Glauber Monte Carlo event (Au–Au at $\sqrt{s_{NN}} = 200$ GeV with impact parameter $b = 6$ fm) viewed in the transverse plane (left panel) and along the beam axis (right panel). Darker disks represent participating nucleon.

that in the transverse plane. Thus the eccentricity is defined as:

$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \quad (2.3)$$

where σ_x and σ_y are the RMS widths of the participant nucleon distributions projected on the x and y axes, respectively.

Since the nucleon positions fluctuate event-by-event, the minor axis of the ellipse in the transverse plane formed by the participating nucleons is not along the impact parameter vector. To address this issue it is possible to make a principal axis transformation, rotating the x and y axes used in the eccentricity definition in the transverse plane to minimize σ_x . An alternative definition of eccentricity, called *participant eccentricity* is introduced to account for the nucleon position fluctuations. The participant eccentricity is calculated with respect to the minor axis of the ellipse defined by the distribution of participants. It can be written as:

$$\begin{aligned} \epsilon_{part} &\equiv \epsilon_2 = |\epsilon_2 e^{i2\Phi_2}| \\ &= \frac{\sqrt{\langle r^2 \cos 2\phi \rangle^2 + \langle r^2 \sin 2\phi \rangle^2}}{\langle r^2 \rangle} \\ &= \frac{\sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}}{(\sigma_x^2 + \sigma_y^2)} \end{aligned} \quad (2.4)$$

where σ_x^2 , σ_y^2 and σ_{xy}^2 are the variances and covariance of the nucleon distribution in a given event, respectively. Here $\langle \dots \rangle = \int dx dy (\dots) e(x, y)$ defines the average over the matter distribution $e(x, y)$ in a single collision event [22]. The participant eccentricity coefficients of order n can be also defined [23, 24], in analogy with the ϵ_n power spectrum (Eq. 2.1).

The initial azimuthal eccentricity of the system influences the value of the elliptic flow coefficient v_2 . Since $v_2 \propto \epsilon_2$ [25] and assuming this holds event-by-event, this condition would imply that

$$\frac{\sigma_{v_2}}{v_2} \propto \frac{\sigma_{\epsilon_2}}{\epsilon_2} \quad (2.5)$$

The RMS width over the mean of v_2 (σ_{v_2}/v_2) is sensitive to initial conditions [26]. The comparison with the MC-Glauber calculations of $\sigma_{\epsilon_2}/\epsilon_2$, reported in [26]: ϵ_{std} calculations are not able to reproduce the distribution of the relative width of the v_2 as a function of the mean impact parameter of the collisions, while the relative widths of the v_2 and ϵ_{part} distributions are consistent.

Color Glass Condensate The degrees of freedom involved in the early stages of a nucleus-nucleus collision at sufficiently high energy are partons, mostly gluons, whose density grows as the energy increases (i.e. when x , their momentum fraction, decreases). This growth in the number of gluons in the hadronic wave functions leads to a *saturation* of the gluon density number: when the gluon density increases the gluon recombination processes $g + g \rightarrow g$ are expected to gain importance and eventually balance gluon splitting $g \rightarrow g + g$ [27].

The dense, saturated system of partons in the hadronic wave functions at high energy is called *Color Glass Condensate (CGC)*. The CGC is colored since made of gluons carrying colour charge, it is a condensate because of the high occupation numbers and, finally, it behaves like a glass since, due to Lorentz time dilation, its internal dynamics is frozen over the natural time scales for high energy scattering (a glass is a disordered system which evolves very slowly relative to natural time scales: it is like a solid on short time scales and like a liquid on much longer time scales). There are different implementations of his idea, for instance the Monte Carlo Kharzeev-Levin-Nardi (MC-KLN) [28] model is based on CGC.

Pre-equilibrium dynamics: IP-Glasma model A short and dense preequilibrium stage precedes the hydrodynamic stage in heavy ion collisions. During this phase any interaction between system constituents in the fireball leads to non vanishing radial and anisotropic flow, because of the finite size and anisotropic shape of initial energy density distribution, which fluctuates event-by-event [29–33]. Hence the hydrodynamic stage begins with non-zero radial and anisotropic flow. At the same time, the pre-equilibrium stage reduces the initial space anisotropies, resulting in a decrease of the anisotropic pressure gradient that drive anisotropic flow during the hydrodynamic evolution of the system [34, 35].

Due to the difficulties in modelling the pre-equilibrium dynamic properly, most studies assume an early hydrodynamic starting time with non zero initial transverse flow velocity [36]. A different approach was developed during the last years with the IP-Glasma model [37], which includes fluctuations in the distributions of nucleons in the nuclear wavefunctions (generic to all models of quantum fluctuations) and fluctuations in the color charge distributions inside a nucleon. The model is based on the CGC framework. Initial nuclear color charge distributions are obtained from the IP-Sat (Impact Parameter dependent Saturation) parameterization constrained by HERA data [38], to generate finite deformed fluctuating initial gluon field configurations in the transverse plane, and then evolves them with classical Yang-Mills dynamics [29–33].

The energy density distribution in the transverse plane is shown in Fig. 2.4 for IP-GLASMA model, MC-KLN model and to an MC-Glauber model. The resulting initial energy densities differ significantly. In particular, fluctuations in

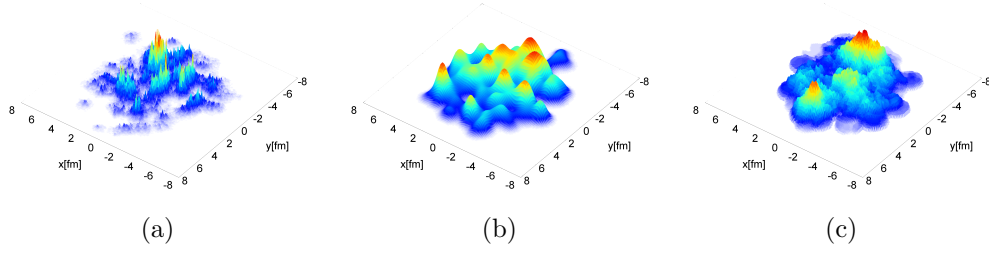


Figure 2.4: Initial energy density (arbitrary units) in the transverse plane in three different initial conditions model: IP-Glasma, MC-KLN and MC-Glauber models.

the IP-Glasma result into finer structures in the initial energy density relative to the other models [37].

Unlike the IP-Glasma model, both the MC-Glauber and the MC-KLN models do not account for fluctuations of the gluon fields inside the nucleons. The three models differ in their prediction on the eccentricity power spectrum and on the correlations between different eccentricity coefficients.

Figure 2.5 shows the $\langle \epsilon_n \rangle$ (Eq. 2.1) distribution computed using MC-Glauber, MC-KLN and IP-Glasma initial conditions. In central collisions (0-0.2% and 0-5%) ϵ_n are completely due to fluctuations and have the similar magnitude at every order. The strong ellipticity of the geometry in non-central collisions increases $\langle \epsilon_2 \rangle$, while the odd harmonics are still dominated by fluctuations.

There is a clear difference between the three models predictions. The extraction of the QGP transport coefficients is complicated by the uncertainties related to the initial conditions. A complete measurement of the flow power spectrum (Eq. 2.1) could constrain the theory to discriminate between different initial state model.

Flow coefficients v_2 and v_3 are, in good approximation, linearly proportional to ϵ_2 and ϵ_3 [25], while v_4 and v_5 are found to depend non-linearly on the initial harmonic eccentricity coefficients. Since the second and fourth order eccentricities ϵ_2 and ϵ_4 are strongly correlated by the collision geometry, the v_4 coefficient receives strong contributions even from a purely elliptical deformation of the final flow velocity distribution. Similar comments apply to the v_5 , which receives contributions from fluctuations (ϵ_3) and from the collision geometry (ϵ_2). Therefore, the response to the initial state fluctuations is characterized by mode-mixing of different order flow harmonics.

The (v_n, ϵ_n) correlation for $n=2, 3, 4, 5$, is shown in Fig. 2.6, obtained with fluctuating MC-KLN [28] events with non-zero ϵ_n values.

The elliptic flow v_2 coefficient is to a very good approximation linear with the initial ellipticity ϵ_2 of the collision, Fig. 2.6(a). At small and large ellipticity, (v_2, ϵ_2) correlation deviates from the line through the origin, indicating further

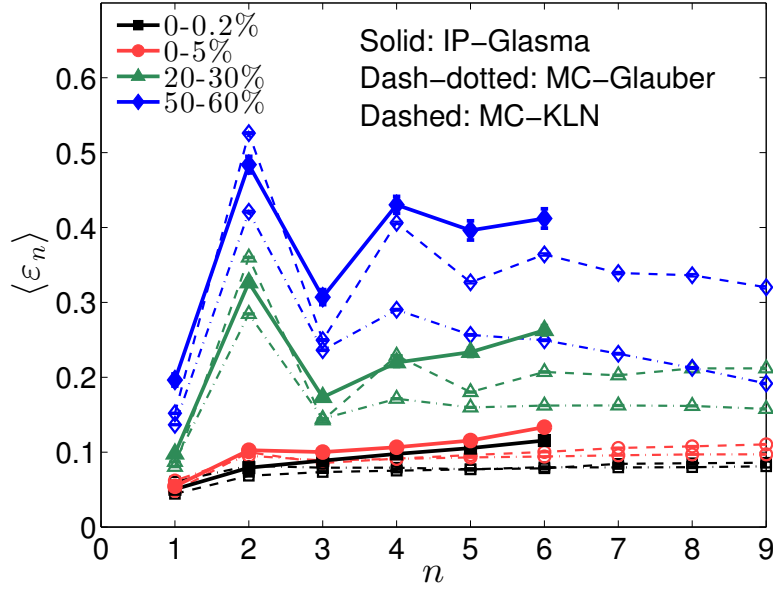


Figure 2.5: ϵ_n power spectrum in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, at different centralities, from three different initial-state models (IP-Glasma, MC-Glauber, MC-KLN).

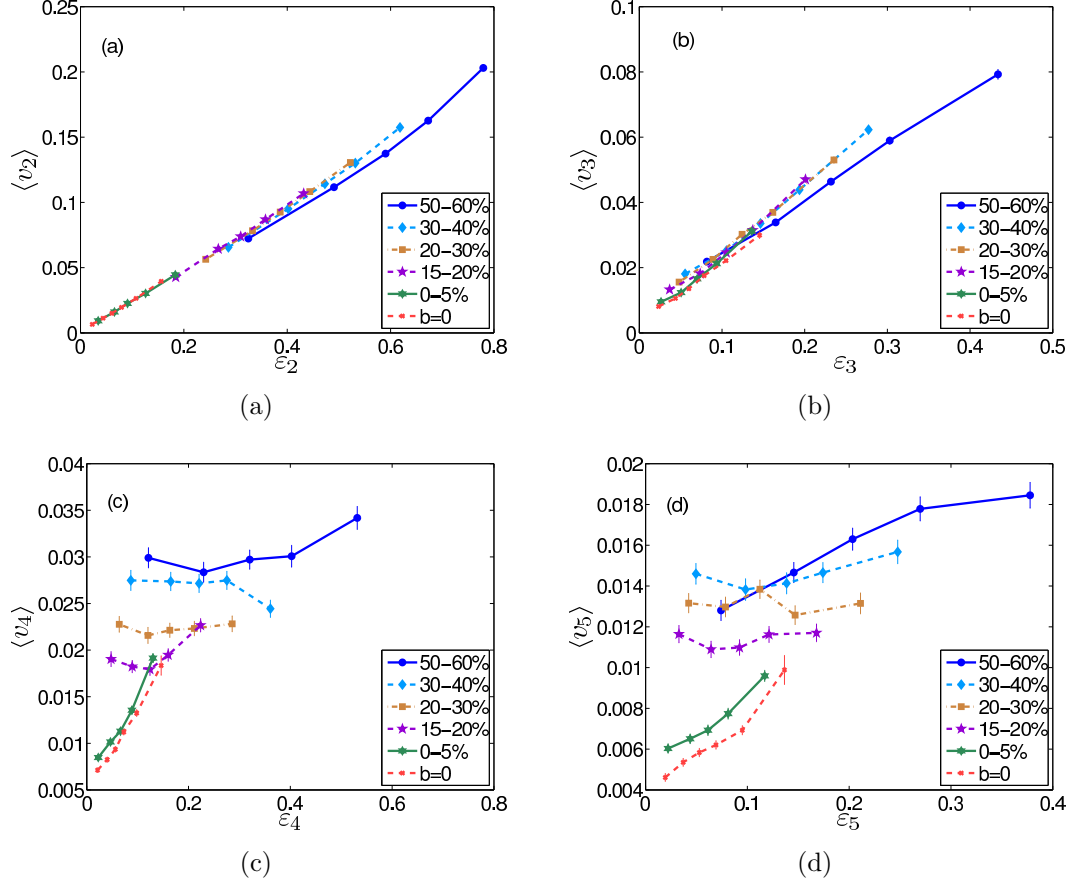
contributions to the elliptic flow. Indeed, even for zero ellipticity $\epsilon_2 = 0$ the average v_2 is not zero. These are events with typically large nonzero values for eccentricities of higher harmonic order which generate elliptic flow through mode-mixing (e.g. between ϵ_3 and ϵ_5). This happens at all centralities, even for $b = 0$, due to event-by-event fluctuations of the eccentricity coefficients. A similar dependence of v_3 from ϵ_3 is shown in fig. 2.6(b), even if stronger deviations are seen for v_3 , the overall the dependence is very close to linear. Non-linear mode-mixing effects appear to be minimal for the elliptic and triangular flow, while for v_4 and v_5 , shown in Fig. 2.6(c) and Fig. 2.6(d), mode-mixing effects are very strong, and the response of v_n from ϵ_n ($n = 4, 5$) is no more linear.

2.2 Hydrodynamic evolution

The initial conditions, discussed in the previous section, provide the input for the hydrodynamic evolution of the system at the thermalisation time, when the system is assumed to be in local thermodynamic equilibrium.

The basic hydrodynamical equations express energy-momentum conservation for a relativistic hydrodynamic fluid:

$$\partial_\mu T^{\mu\nu} = 0. \quad (2.6)$$

Figure 2.6: v_n vs ϵ_n correlation for $n = 2, 3, 4, 5$.

where $T^{\mu\nu}$ is the energy-momentum tensor, which for an inviscid fluid can be expressed as

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} \quad (2.7)$$

ϵ is the energy density, P is the hydrodynamic pressure, u^μ is the 4-velocity and $g^{\mu\nu} \equiv \text{diag}(1, -1, -1, -1)$ is the Minkovski metric tensor.

The hydrodynamic equations of motion can be obtained starting from the conservation laws of energy-momentum (Eq. 2.6) and baryon number:

$$\partial_\mu j_B^\mu = 0 \quad (2.8)$$

where j_B^μ is the baryon number current, defined as $j_B^\mu = n_B u^\mu$.

There are six variables: 3 component of the 4-velocity (it is a Lorentz scalar, so that $u^\mu u_\mu = 1$), the energy density ϵ , the pressure P and the baryon density n_B . The conservation laws Eq. (2.6) and Eq. (2.8) give five partial differential equations. Another equation is needed to close the system. This is obtained using the *Equation of State* (EoS) as input:

$$P = P(e, n_B) \quad (2.9)$$

which relate the pressure P to the energy density e and the baryon density n_B . It can be extracted from lattice QCD calculations [39] and match to the hadron resonance calculations gas [40] below $T_C \sim 155 - 160$ MeV [41], which is the critical temperature where free quarks and gluons combine into hadrons [42].

Since transverse flow builds in response to transverse pressure gradients in the initial state, we are interested in the relationship between the pressure P , whose gradients provide the accelerating forces, and the enthalpy $e + P$ which represents the inertia of the fluid. In the simplest case of an ideal fluid (neglecting viscous terms) the equation which relate the flow four-vector u^μ to the pressure gradients and energy density is [43]:

$$\dot{u}^\mu = \frac{\nabla^\mu P}{e + P} \quad (2.10)$$

where the $\dot{u}^\mu$ is the 4-velocity time derivative. From Eq. (2.10) is clear that the pressure gradients, quantified via $\nabla^\mu P$, accelerate the fluid element.

Hydrodynamics describes expansion and collective flow of matter but also provides complete information about the bulk properties of the QCD matter, such as local temperature or energy density for other observables. For instance, jet quenching studies need information of parton density or energy density along a trajectory of an energetic parton, the study of J/ψ production in heavy ion collisions need the local temperature at the position of J/ψ , etc. The understanding of the dynamical evolution of the fireball is a prerequisite for a quantitative description of heavy ion collisions.

Viscous hydrodynamic

The equations discussed in the previous section refer to ideal (i.e. inviscid) fluids. Despite the initial success of the ideal fluid approach in describing experimental data, with the improvement of experimental precision, the inclusion of dissipative effects became gradually more important.

In the case of viscous hydrodynamics additional transport coefficients such as shear viscosity η , the bulk viscosity ζ and the heat conductivity λ need to be included. For systems with baryon number approaching to zero, heat conductivity effects can be neglected [43]. Bulk and shear viscosities are usually characterized using the unitless specific viscosities ζ/s and η/s , respectively, where s is the entropy density.

The modified energy-momentum tensor (Eq. 2.7), which includes the viscous terms is:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \pi^{\mu\nu} + \Pi\Delta^{\mu\nu} \quad (2.11)$$

where $\pi^{\mu\nu}$ and $\Pi\Delta^{\mu\nu}$ are the stress corrections for shear and bulk viscosity respectively. The tensor $\Delta^{\mu\nu}$ is defined as $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$, where $g^{\mu\nu}$ is the Minkowski metric and u^μ the four velocity (for a complete discussion of this subject please refer to [44]).

Bulk viscosity causes local isotropic deviation from equilibrium, introducing the diagonal term $\Pi\Delta^{\mu\nu}$ to the energy-momentum tensor $T^{\mu\nu}$ in the local rest frame. The bulk viscous pressure counteracts the radial expansion of the fireball, reducing the radial flow development.

Shear viscosity causes local anisotropic deviation from equilibrium, creating a shear viscous pressure, $\pi^{\mu\nu}$, that favors the equalization of the expansion in all directions, by reducing longitudinal pressure and increasing the transverse one. The shear viscosity counteracts the build up of anisotropic flow: it increases the radial flow, but dampens the anisotropic flow.

The success of ideal hydrodynamic suggests a small value for the viscosities. From the comparison between hydrodynamic and experimental data from elliptic and triangular flow the average value of η/s is found to be small [45, 46], but that estimate depends on the model used for the initial conditions.

A lower bound on the η/s and ζ/s ratios has been proposed in [47, 48], through the so called *AdS/CFT* correspondence, which relates strongly coupled conformal field theories (CFT) to classical gravity in weakly curved Anti-de-Sitter (AdS) space-time geometries [49]:

$$\frac{\eta}{s} > \frac{\hbar}{4\pi}, \quad \frac{\zeta}{s} \sim 2 \left(\frac{1}{3} - c_s^2 \right) \quad (2.12)$$

where c_s is the speed of sound $c_s = \partial P / \partial e$. Shear viscous effects dominate over bulk viscous one. Experimentally it is not trivial to separate the two contribution

because both effects modify the spectra shape. Usually the bulk viscosity is ignored, since its contribution is estimated to be a factor 5-10 lower than the shear viscosity one [50].

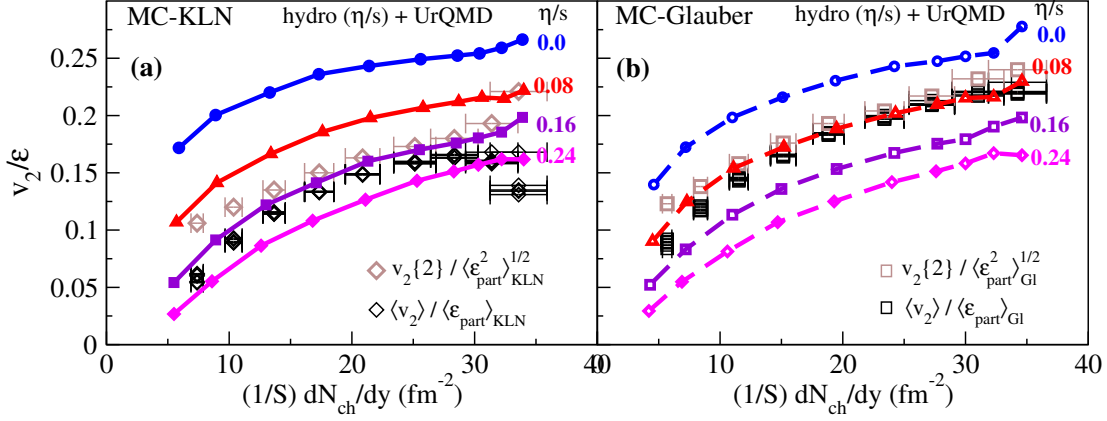


Figure 2.7: Eccentricity-scaled integrated elliptic flow (Au-Au collisions at RHIC) for charged hadrons as a function of total charged hadron multiplicity density per unit of overlap area. Both panels use the same sets of data, but different initial conditions from MC-Glauber and MC-KLN.

Fig. 2.7 shows the eccentricity-scaled v_2 distributions as a function of charged hadron multiplicity density per unit of overlap area, in Au-Au collisions at 200 GeV/c at RHIC, compared to hydro calculations, based on the VISHNU hybrid model [51]. Both panels use the same sets of data, but use different model to compute the normalization, average initial eccentricities ϵ_2 and overlap areas S (MC-Glauber and MC-KLN, respectively). The theoretical curves are obtained with the VISHNU hybrid model [51]. While with MC-KLN the extracted η/s is ≈ 0.16 , with MC-Glauber it is ≈ 0.08 . In both cases it is close to the theoretical limit, but this plot emphasizes the importance of additional experimental constraints to distinguish different initial conditions models and arrive to a precise characterization of the QGP transport properties.

2.3 Transverse momentum spectra and radial flow

Hadron spectra are sensitive to the effects of expansion from the beginning of the collision. In case of a static thermalized source of particles, the slope of the p_T distribution depends on the temperature of the source. For an expanding source, the thermal distribution is modified by the expansion. The collective component, in fact, is summed to the thermal contribution, which only depends

on the decoupling temperature T_{kin} , the final transverse momentum of the particles can be written, using non-relativistic kinematics in the low p_T region, as

$$p_T \sim p_T^{th} + m \langle \beta_T \rangle. \quad (2.13)$$

The radial flow causes a “blue-shift” of the transverse momentum of final emitted particles, due to the contribution of the collective radial expansion given by the average transverse flow velocity $\langle \beta_T \rangle$. This leads to a flatter p_T spectrum for heavier particles, in case of a spectrum emitted by an expanding thermalized source, as compared to a static source.

Figure 2.8(a) shows the identified primary hadron spectra in Pb–Pb collisions measured with ALICE in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [52]. The comparison with STAR and PHENIX results in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV/c is also shown. It can be seen that ALICE spectra are harder than RHIC ones and protons are flatter. This is interpreted as the effect of a stronger radial flow contribution.

Current state-of-the art hydrodynamic models reproduce well the p_T spectra: HKM [53] and MUSIC+UrQMD [54] are able to describe the data quite well. Both models include an explicit description of the late hadronic phase (“hadronic afterburner”). VISH2+1 [55] and Krakow [44], without a hadronic cascade afterburner, overpredict the proton yields, possibly because of ignoring baryon-antibaryon annihilation in the hadronic phase, but the shape of the spectra is reproduced.

The transverse flow velocity β_T , as well as the temperature of the system at decoupling T_{kin} , can be extracted from experimental data using the blast wave model [56], by fitting the hadron spectra in the low p_T region. This model, inspired by hydrodynamic, describes analytically the modifications of a thermal spectrum due to a collective expansion. As shown in Fig. 2.9, β_T increases with the energy of the collision and is higher in central collisions than in peripheral ones, while, on the contrary, T_{kin} decreases with the increasing centrality. This behaviour is compatible with a faster expansion and a longer QGP phase lifetime, due to higher initial fireball densities which results in a stronger radial flow.

Pion and protons spectra compared with Au–Au collisions at RHIC are shown in Fig. 2.10: p_T spectra cannot distinguish between different initial conditions and different values of the QGP shear viscosity. To correctly evaluate QGP transport coefficients the simultaneous investigation of the azimuthally averaged p_T spectra with their azimuthal anisotropies is needed.

2.4 Elliptic flow and higher flow harmonics

If the colliding system thermalises, its evolution follows the laws of hydrodynamics: the initial space anisotropy of the overlap region of the colliding nuclei,

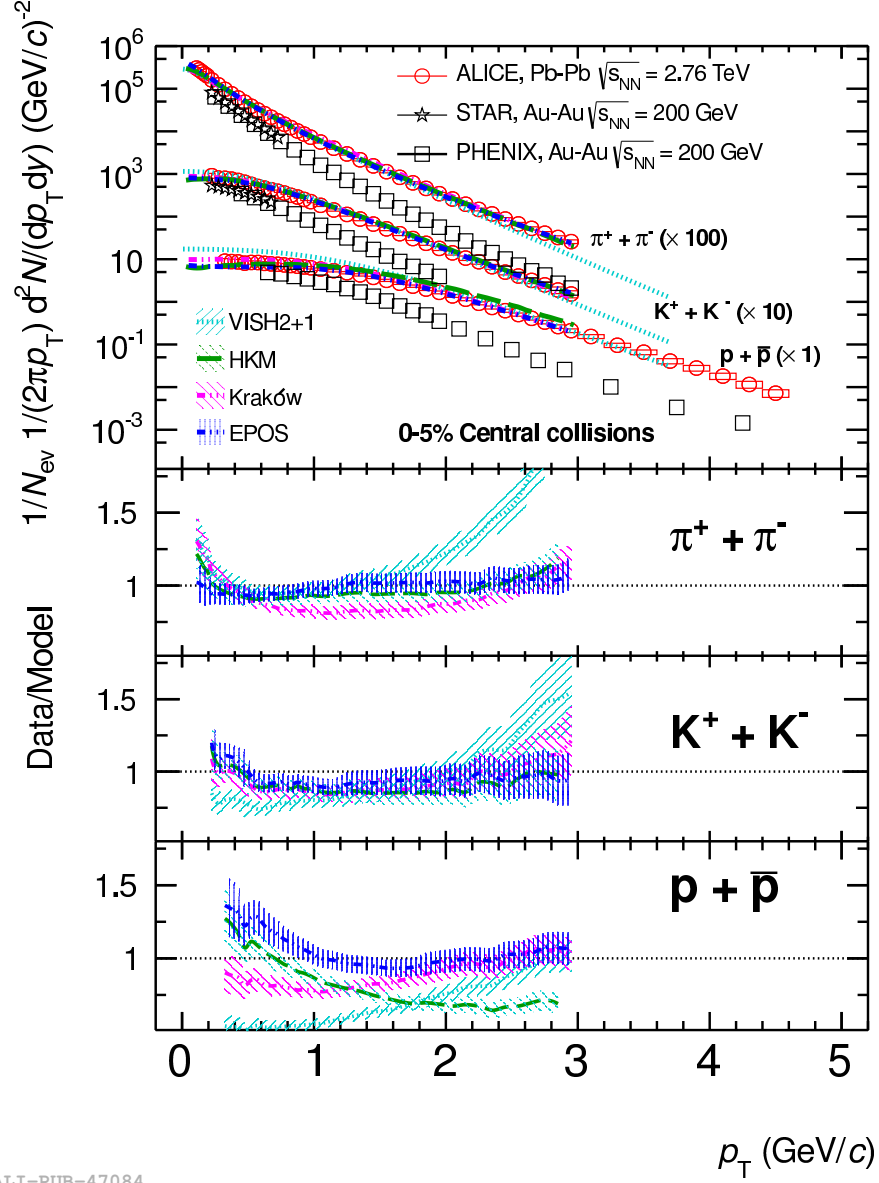


Figure 2.8: Pion, kaon and proton spectra of particles for summed charges in the centrality bin 0-5%, measured with ALICE at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, compared to hydrodynamical models and results from RHIC at $\sqrt{s_{\text{NN}}} = 200$ GeV/c [52].

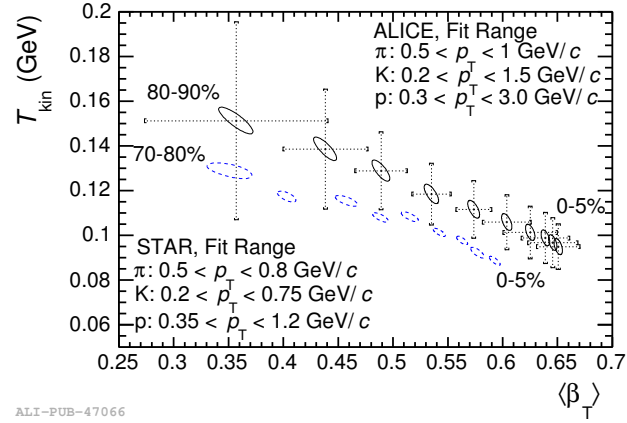


Figure 2.9: Results of blast-wave fits [56], compared to similar fits at RHIC energies [57]. The uncertainty contours include the effect of the bin-by-bin systematic uncertainties, the dashed error bars represents the full systematic uncertainty, the STAR contours include only statistical uncertainties [52].

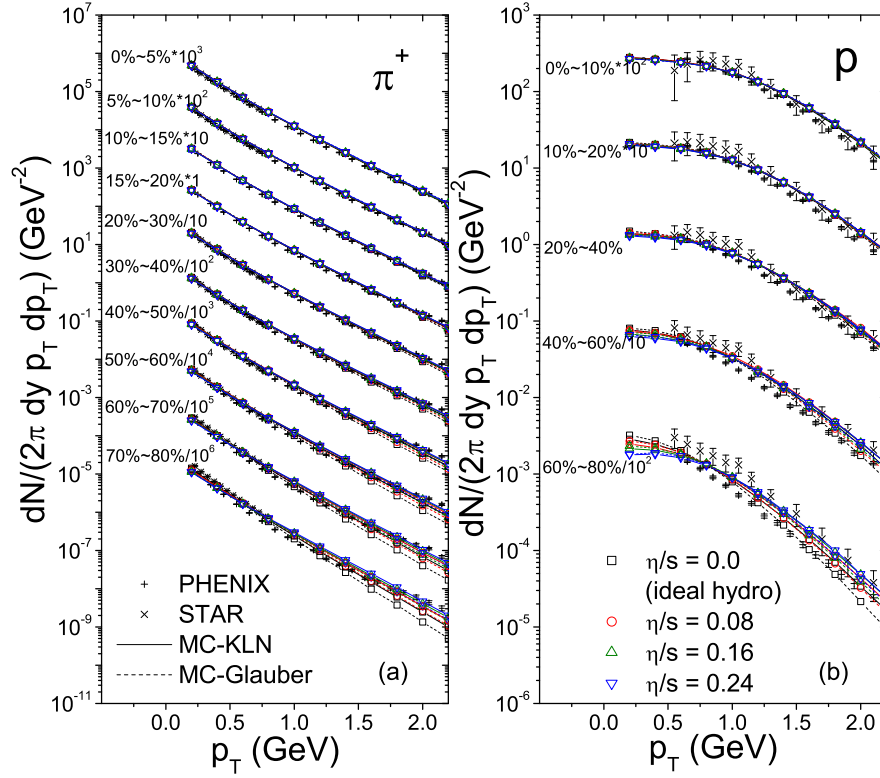


Figure 2.10: (a) Pion and (b) proton p_T spectra from Au–Au collisions at 200 GeV/c, for different collision centralities, compared with viscous hydrodynamic model predictions [4].

in particular in semi-central collisions, translates into an anisotropy in momentum space of the produced particles, due to the collective expansion under anisotropic pressure gradients.

The magnitude of the anisotropic flow is characterized by the coefficients of the Fourier expansion of the azimuthal distribution of particles with respect to the collision symmetry plane [58, 59]:

$$\frac{dN}{d\Phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos[n(\phi - \psi_n)] \quad (2.14)$$

$$v_n(p_T, \eta) = \langle \cos n(\phi - \psi_n) \rangle \quad (2.15)$$

where p_T , η , and ϕ are the particles transverse momentum, pseudo-rapidity, and the azimuthal angle, respectively, and ψ_n is the n -th harmonic symmetry plane angle¹ In case of smooth sphere the symmetry planes of all harmonics should coincide with the reaction plane². Symmetry consideration would suggest no odd harmonics. However due to event-by-event fluctuations in the positions of the participating nucleons inside the nuclei, the shape of the initial energy density of the heavy-ion collision is in general not symmetric with respect to the reaction plane and the ψ_n may deviate from the reaction plane. This implies significant observable consequences, in particular non-null odd harmonics flow coefficients (see section 2.1).

2.4.1 Methods

There exist several experimental method to evaluate the v_n coefficients (see for instance the discussion in [60] and in chapter 8 of this thesis).

Anisotropic flow measurements are based on an analysis of azimuthal correlations and might be biased by contributions from correlations unrelated to the azimuthal asymmetry in the initial geometry (non-flow). All analysis methods discussed in this chapter are based on the flow vector $\mathbf{Q}$:

$$\mathbf{Q}_n \equiv \sum_{i=1}^M e^{in\phi_i} \quad (2.16)$$

¹If the shape of Pb nuclei is approximated by the smooth Woods-Saxon function without fluctuations, ψ_n coincides with the azimuthal angle of the reaction plane defined by the beam axis and the impact parameter ψ_{RP} .

²The reaction plane is defined by the beam direction and the impact parameter.

Event plane method The most frequently used method in flow analysis is the *EventPlane* (EP) method [61], where the azimuthal angle of the reaction plane is estimated from the observed event plane angle for each harmonic n :

$$\psi_{EP} \equiv \frac{1}{n} \arctan \frac{\sum_i \sin(n\phi_i)}{\sum_i \cos(n\phi_i)} \quad (2.17)$$

Different ψ_{EP} can be calculated for different harmonics n . Since in each event there is a finite number of created particles, the result for ψ_{EP} will be affected by a limited resolution. This can be corrected for by estimating the event plane resolution from the correlations obtained via two or more independent subevents. The main issue of the event plane method is the fact that the event plane resolution is affected by non-flow contribution and this will introduce a bias in the flow estimates.

Scalar product method The scalar product method [62, 63] correlates particles to the flow vector and uses the length of the flow vector as a weight in the average over events. The method is based on the scalar product of a particle unit flow vector, $\mathbf{u} = e^{i2\phi}$, with the complex conjugate of the flow vector $\mathbf{Q}^*$:

$$v_n\{SP\} = \frac{\langle \mathbf{u}_{n,k} \mathbf{Q}_n^* / M \rangle}{\sqrt{\mathbf{Q}_n^a \mathbf{Q}_n^{b*} / M^a M^b}}. \quad (2.18)$$

The vectors Q_a and Q_b are two flow vectors constructed from two particle subsets, consisting of respectively M_a and M_b particles, called subevents. The two subevents are chosen in different pseudorapidity intervals, therefore, they do not overlap avoiding the autocorrelation the particles.

Two ad many particle correlation method The v_n coefficients can be determined studying the correlations between 2 or more particles.

In the *pair-wise correlation* method [64], all orders of v_n can be extracted without the need to evaluate ψ_n , using the pair density:

$$\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + 2 \sum_{i=1}^{\infty} 2v_n^2 \cos(n\Delta\phi) \quad (2.19)$$

where all pairs of particles in a given momentum region are correlated and $\Delta\phi$ is the angular difference between the two particles in a pair. The v_n coefficients are extracted by fitting the two-particle azimuthal distribution.

The *two-particle cumulant* method [65–67] calculates the coefficients directly as:

$$v_n\{2\}^2 = \langle \cos[n(\phi_1 - \phi_2)] \rangle = \langle u_{n,1} u_{n,2}^* \rangle \quad (2.20)$$

for all pairs of particles, where u_n is the particles unit flow vector. Flow coefficients measured with two particle correlation between final state particles, are denoted with $v_n\{2\}$, while v_n from four and six particles correlations, known as high order cumulants, are denoted with $v_n\{4\}$ and $v_n\{6\}$, respectively. The anisotropic flow is a correlation between each particle and the symmetry plane, on the other hand the non-flow correlations involve only few particles. This means that, if one considers many-particle correlations instead of just two-particle correlations, the relative contribution of non-flow effects (due to few particle clusters) should decrease.

In addition the higher order cumulants, which involve higher moments of the event-by-event v_n distribution, are sensitive differently on the variance σ_{v_n} of v_n distribution. The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to the width of the v_n distribution. Indeed if $(\sigma_{v_n} \ll \langle v_n \rangle)^2$:

$$v_n\{2\} \sim \langle v_n \rangle + \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}, \quad v_n\{4\} \sim \langle v_n \rangle - \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle} \quad (2.21)$$

This difference can be used to estimate the variance of the event-by-event flow fluctuations.

Finally the *Lee-Yang Zeros* (LYZ) method extracts the flow coefficients from the correlation among a large number of particles [68–70]. It is by design not sensitive to the contributions from correlations involving only few particles, therefore, from a theoretical point of view, it is the best method to perform anisotropic flow analysis. It is based on an analogy with the Lee-Yang theory of phase transitions [71]. The theoretical details of the LYZ method are rather sophisticated and will not be presented here, but the interested reader can consult [69, 70]. Automatic correction for non-uniform acceptance is built-in. However, in practice the LYZ method has one serious drawback, since it requires two passes over the data in order to get the differential flow.

q-distributions method The flow vector Q_n involves all the particles. In the absence of correlations, its length would grow as the square-root of the multiplicity M .

Thus, to reduce the effect of the multiplicity dependence, the reduced flow vector is defined [62] as

$$q_n = Q_n / \sqrt{M} \quad (2.22)$$

Indeed the relation of the length of q_n vector to the average correlation between all pairs of particles in a given event is given by:

$$q_n^2 = \frac{Q_n^2}{M} = \frac{1}{M} (M + M(M-1) \langle \cos[n(\phi_i - \phi_j)] \rangle_{i \neq j}) \quad (2.23)$$

where M is the particle multiplicity and ϕ_i are the particle azimuthal angles of particles.

The q_n distribution is very well described by the so-called Bessel-Gaussian (BG) distribution $BG(q; q_0, \sigma_{qx})$ [72, 73], defined as

$$BG(q; q_0; \sigma_{qx}) = \frac{q}{\sigma} I_0 \left(\frac{q_0 q}{\sigma^2} \right) \left(-\frac{q_0^2 + q^2}{2\sigma^2} \right) \quad (2.24)$$

which is a radial projection of 2-dimensional Gaussian distribution with width σ in each dimension and shifted off the origin by distance q_0 . I_0 is the modified Bessel function. For high multiplicities allows to extract parameters related to those of v_n distribution:

$$q_0 = \sqrt{M} v_0, \quad \sigma_{qx}^2 = \frac{1}{2} [1 + M(M-1)(2\sigma_{vx}^2 + \delta)] \quad (2.25)$$

where M is the multiplicity used to build the flow vector, and δ is a non-flow parameter which accounts for possible correlations not related to the initial geometry of the system. Assuming Bessel-Gaussian form for flow fluctuations to fit the q -distribution, is possible to find [72]:

$$v_2\{2\}^2 = \text{const} = v_0^2 + 2\sigma_{vx}^2 + \delta \quad v_n\{4\} = \text{const} = v_0 \quad (2.26)$$

Methods comparison Figure 2.11 shows the v_2 of charged hadron divided by the values for the event plane method $v_2\{\text{EP}\}$ in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV.

The results are grouped in two different bands. The upper one shows the two-particle correlation results, which are affected by non-flow and fluctuation contributions. The lower band shows the multi-particle correlation results, mostly free of non-flow and fluctuation contributions.

The event plane values are about 5% below most of the other two-particle results, being somewhere between $v_2\{2\}$ and $v_2\{4\}$, depending on the reaction plane resolution.

2.4.2 Event-by-event flow

On an event-by-event basis anisotropic flow fluctuates, leading to the v_2 distributions for charged hadrons showed in Fig. 2.12, in several centrality intervals. The shape of these distributions changes strongly with centrality. Event-by-event fluctuations in v_2 distributions, at fixed centrality, are evident.

Event-by-event fluctuations are evident in azimuthal two-particle correlation distributions. The system created in heavy ion collisions behaves as a fluid and converts the coordinate space distributions, characterized by ϵ_n , to long range correlations between produced particles, characterized by v_n . In fig. 2.13, the $\Delta\phi^3$

³difference in azimuthal angles between the two particles

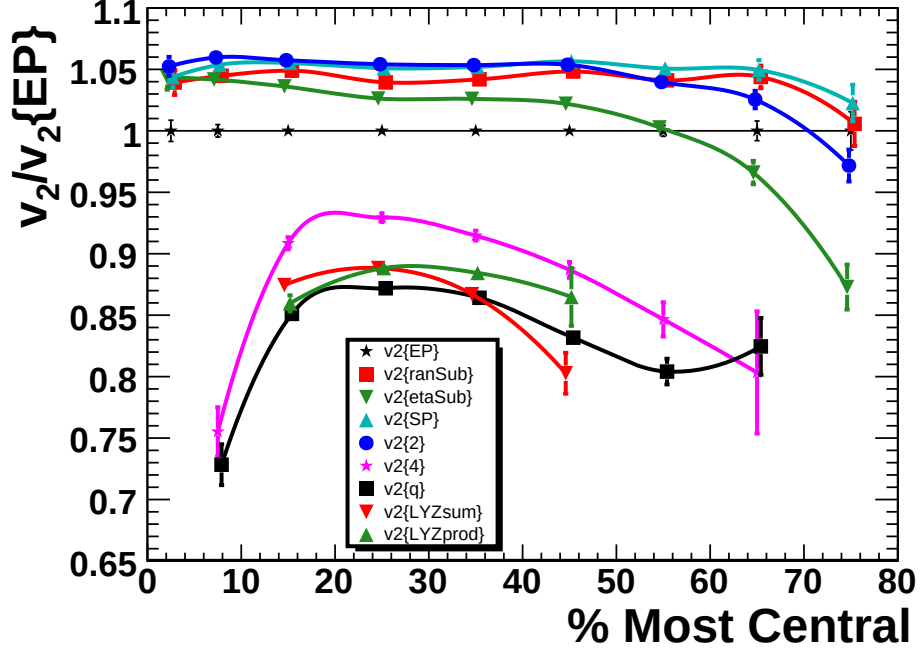


Figure 2.11: Charged hadron v_2 divided by $v_2\{\text{EP}\}$ as a function of geometrical cross section for $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au. Results are shown for the event plane method, random subevents, pseudorapidity subevents, scalar product, two-particle cumulants, four-particle cumulants, q-distribution, and Lee-Yang Zeros sum generating and product generating functions [60].

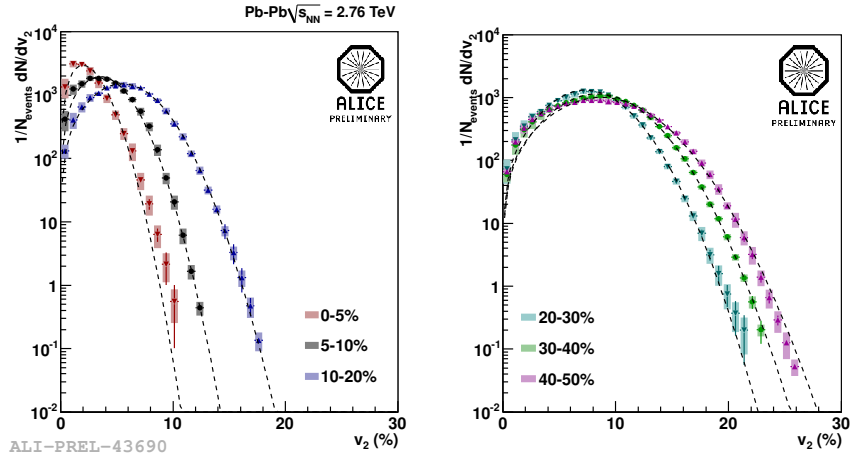


Figure 2.12: Unfolded v_2 distributions as a function of centrality, subject to a $\Delta\eta > 0.8$ gap.

distributions for two individual events are shown, for the same centrality class 4-5%. These events are completely dominated by elliptic ($n = 2$) and triangular ($n = 3$) flow, respectively.

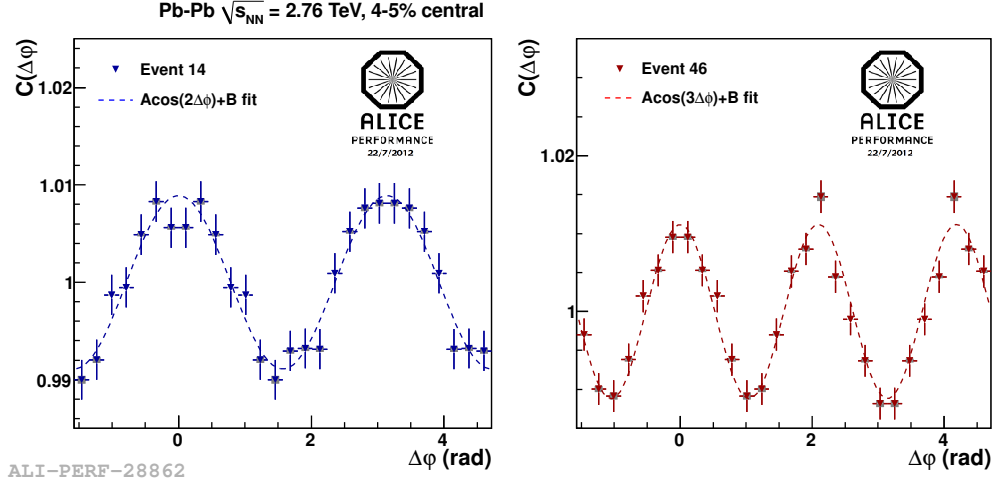


Figure 2.13: $\Delta\phi$ distributions in two individual events, dominated by the v_2 contribution (left) and v_3 contribution (right), respectively.

Figure 2.14 shows $\Delta\phi$ correlations in Pb-Pb collision in the 4-5% centrality class. A Fourier decomposition is performed and the Fourier series is shown by the black line. The first 5 terms are needed for a good description of the data and that the second harmonic contribution is larger than the third one. The distribution of the matter created in a collision is inhomogeneous, therefore there is a large range of non-null harmonics v_n .

2.4.3 Centrality dependence

Fig. 2.15 shows the v_n distribution as a function of centrality, in Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE. This is the so-called *flow power spectrum* and it is the response of the system to the *initial fluctuation power spectrum* shown in Fig. 2.5. Higher flow harmonics do not change much with the centrality, showing a similar behaviour to the eccentricity harmonic coefficients in Fig. 2.5.

Being dominated by event-by-event fluctuations, odd harmonics flow are more sensitive to the fluctuations in the initial positions of participating nucleons. Since the shear viscosity decreases anisotropic flow coefficients, more strongly for higher flow harmonics, v_n coefficients are sensitive to both initial conditions and viscosity. The IP-Glasma model, with $\eta/s = 0.2$, provides a good description of the data

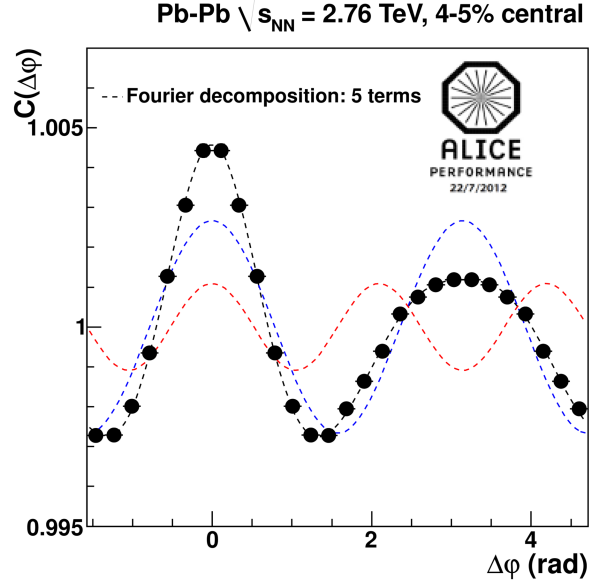


Figure 2.14: Event averaged $\Delta\phi$ distributions for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Up to 5 components of a Fourier decomposition are needed to describe the distribution, but only the 2 dominant ones are shown: v_2 (blue) and v_3 (red).

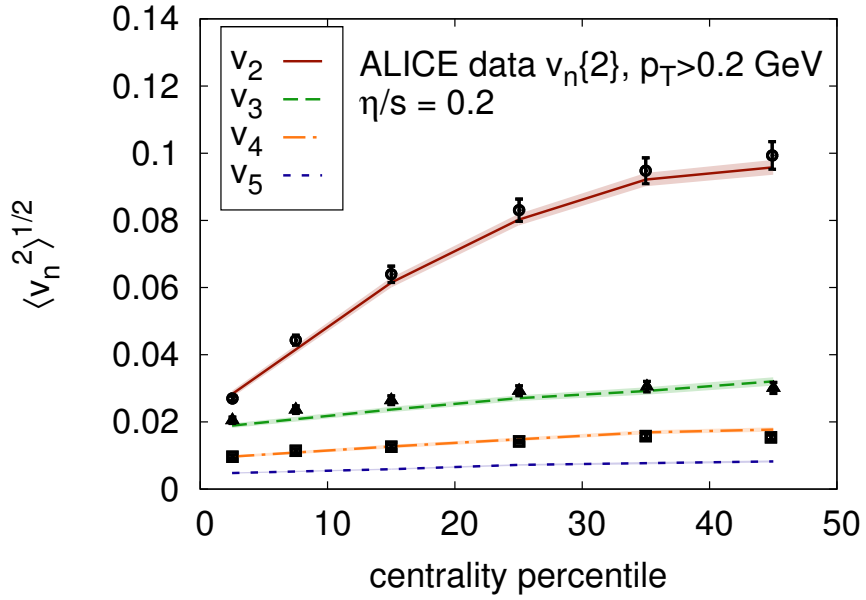


Figure 2.15: v_n as a function of centrality for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions measured by ALICE, compared to viscous hydrodynamic model calculation [8].

[8]: fluctuating initial conditions and viscous hydrodynamic can give a complete description of the centrality and p_T dependence of v_n power spectrum and their fluctuations.

In non-central heavy ion collisions the dominant harmonic is v_2 . A way to test the role of fluctuations in the measured v_2 is to study the normalized variance. Multi-particle correlations suppress of non-flow contribution, arising from resonance decays, jet fragmentation and Bose-Einstein correlations. In addition to being less sensitive to non-flow contributions, high order cumulants are sensitive to the width of v_n distribution [59, 66, 67], σ_{v_n} :

$$\begin{aligned}\bar{v}_n &\approx \sqrt{(v_n\{2\}^2 + v_n\{4\}^2)/2} \\ \bar{\sigma}_n &\approx \sqrt{(v_n\{2\}^2 - v_n\{4\}^2)/2}\end{aligned}\tag{2.27}$$

Since the magnitude of the elliptic flow is proportional to the eccentricity ϵ_2 , it is expected that the event-by-event fluctuation in v_2 should be proportional to that in ϵ_2 . The measured ratio $\sigma_{v_2}/\bar{v}_2$ is compared in Fig. 2.16 to the ratio $\sigma_{\epsilon_2}/\bar{\epsilon}_2$ calculated with Eq. 2.27 from a MC-KLN and MC-Glauber model, reported as black and red solid lines, respectively [74]. The normalized elliptic flow variance $\sigma_{v_2}/\bar{v}_2$ centrality dependence is similar to that extracted using MC-Glauber [11] and MC-KLN [28] initial conditions, though neither model is able to reproduce the data. Dash-dotted lines show the exact value of the ratio $\sigma_{\epsilon_2}/\bar{\epsilon}_2$. The difference between solid and dash-dotted lines gives an indication of the uncertainties related to the experimental extraction of the $\sigma_{v_2}/\bar{v}_2$.

2.4.4 Transverse momentum dependence

Figure 2.17 shows the p_T dependence of v_2 - v_6 for different centrality classes [75].

The flow coefficients v_n are measured using the event plane method ($v_n\{\text{EP}\}$ [60]). The elliptic flow v_2 show a strong centrality dependence. The coefficient v_3 originates entirely from fluctuations and it exhibits a weak centrality dependence with a magnitude significantly smaller than that of v_2 , except for the most central collisions. At high p_T the v_2 coefficient is non-zero, positive and approximately constant. The anisotropy is understood to result from the path-length dependent energy loss of jets as they traverse the medium, with more particles emitted in the direction of smallest path-length [76]. The overall magnitude of v_n also decreases with increasing n , except in the most central events where the v_3 is the largest.

Fig. 2.18 shows the elliptic flow distribution as a function of p_T , for pions and protons [77]. Data are compared to hydrodynamic models using two different equations of state: one of a hadron gas (dotted line) and one of a system with a phase transition from a QGP to a hadron gas (solid line), which gives a better

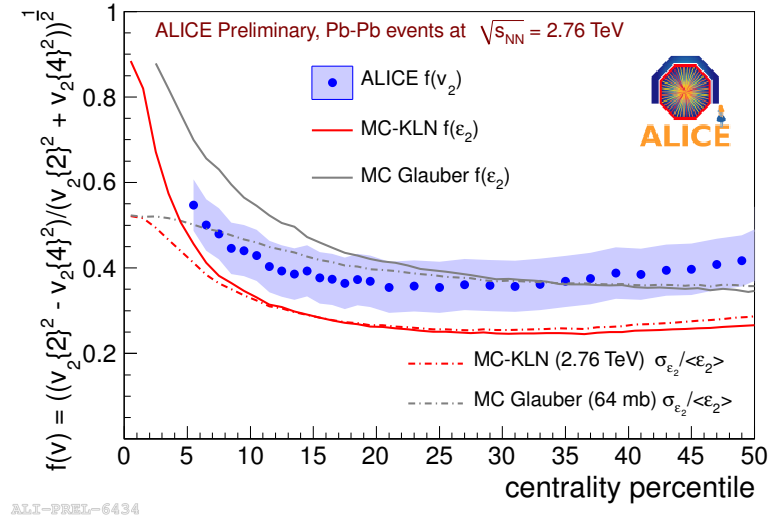


Figure 2.16: Normalized elliptic flow variance vs centrality measured by ALICE. Glauber-MC and MC-KLN predictions are reported as black and red lines, respectively (solid lines). Dash-dotted lines show the exact ratio $\sigma_{\epsilon_2}/\langle\epsilon_2\rangle$.

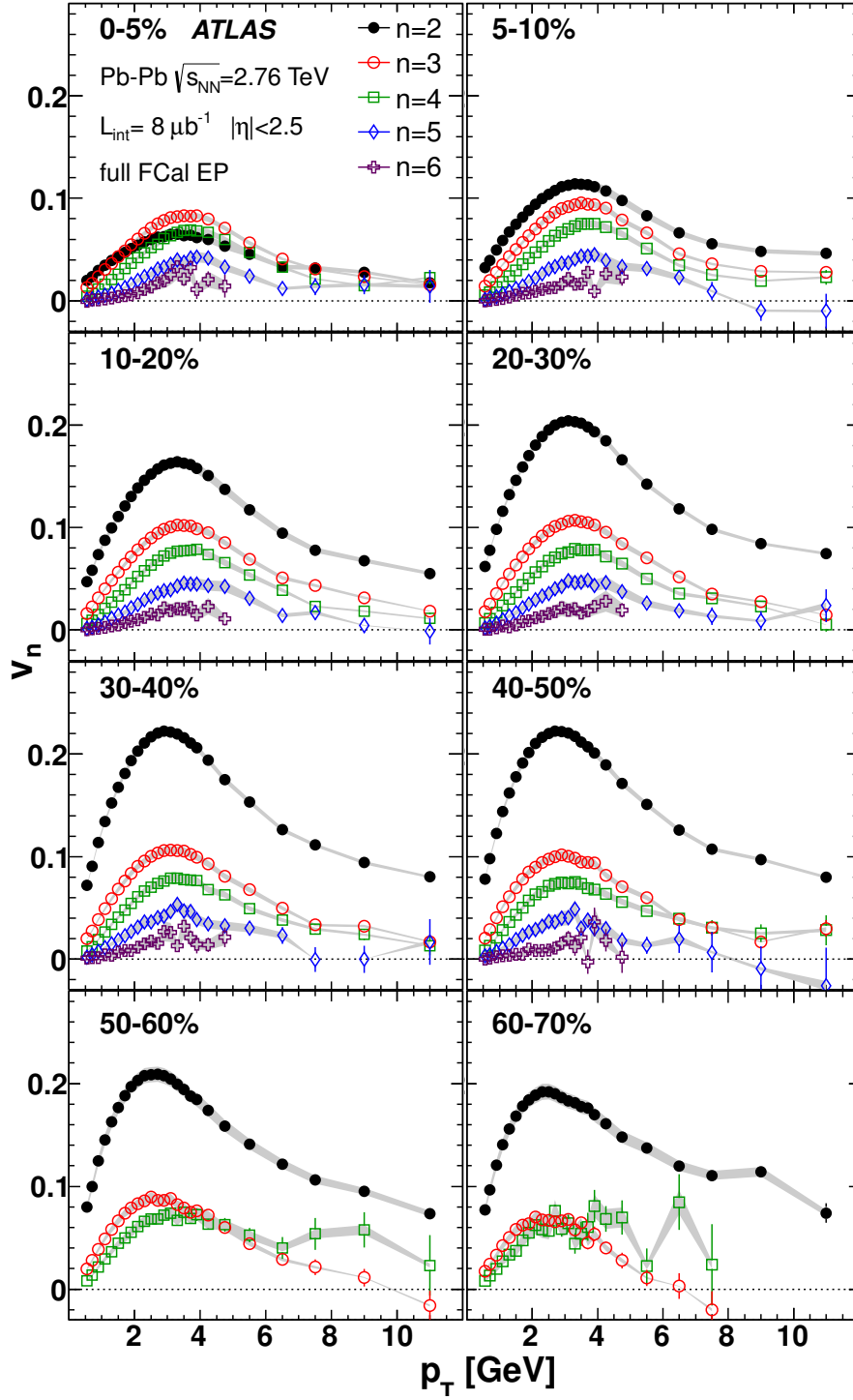


Figure 2.17: $v_n(p_T)$ distributions for several centrality intervals. The shaded bands indicate the systematic uncertainties [75].

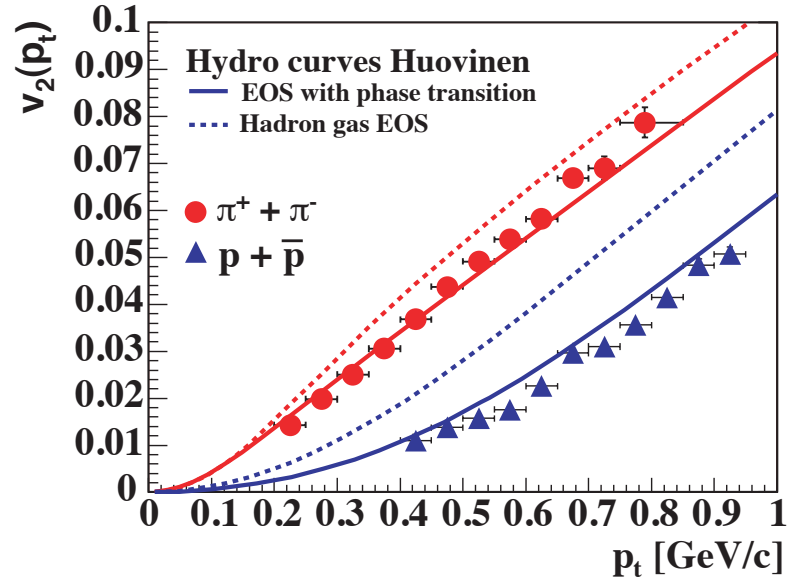


Figure 2.18: Elliptic flow of pions and protons as a function of p_T for Au-Au collisions at 130 GeV/ c , with hydrodynamic calculation using different equations of state [77].

description of data. The effect of the phase transition is stronger for protons, more influenced by the collective radial expansion which is sensitive to the equation of state.

In Fig. 2.20 the v_2 as a function of p_T for different centrality classes is reported for $\pi^\pm$, $K^\pm$, $p+\bar{p}$, $\Lambda + \bar{\Lambda}$, $\Omega + \bar{\Omega}$, $\Xi + \bar{\Xi}$ and ϕ [78]. The mass ordering observed in the low p_T region is attributed to an interplay between elliptic and radial flow. Radial flow tends to push particles at higher p_T , with a stronger radial push with increasing particle mass. In a system that exhibits azimuthal anisotropy, the effect is stronger in-plane than out-of-plane⁴, thus reducing the v_2 . The net result is that at a fixed value of p_T , heavier particles have a smaller v_2 value compared to lighter ones. A crossing between the v_2 of baryons and values of pions and kaons is observed depending on the particle species and centrality. The crossing point moves to higher p_T values for more central collisions, due to the effect of the common velocity field, which is stronger in central collisions [52].

At low p_T the v_2 of charged particles is well described by viscous hydrodynamic models, as shown in Fig. 2.19 where the elliptic flow of pions and protons measured at RHIC is compared with VISHNU calculations, for MC-Glauber or MC-KLN initial conditions, respectively [5].

2.5 Future perspectives

Heavy ion collisions studies at the RHIC and the LHC have already produced many results. Many of the measurements are relatively well understood in terms of a strongly coupled quark-gluon liquid, indicating the robustness of the hydrodynamic model expectations. At the same time there are still many open questions which need to be addressed to reach the goal of a quantitative reliable description of heavy-ion collisions.

Currently, the largest uncertainties in these calculations come from the initial density profile and its event-by-event fluctuation pattern: hydrodynamical model calculations can give a good description of the measurements, even though currently there is no simultaneous description of all the data with a single choice of initial conditions and η/s .

A simultaneous description of either p_T spectra and elliptic flow for charged hadrons and identified particles of all centralities provide a valuable consistency check for the viscous hydrodynamic approach and can help to constrain the spectrum of initial-state fluctuations. At present a purely hydrodynamic description does not produce enough radial flow in central collisions, although it qualitatively

⁴Particles escaping the collision in the azimuthal direction aligned with the reaction plane, in other words ($\phi_{particle} - \Psi_{RP} \approx 0$ or π rad), are said to be *in-plane*, while those away from the reaction plane, at $\phi_{particle} - \Psi_{RP} \approx 1/2\pi$ or $3/2\pi$ rad, are said to be *out-of-plane*.

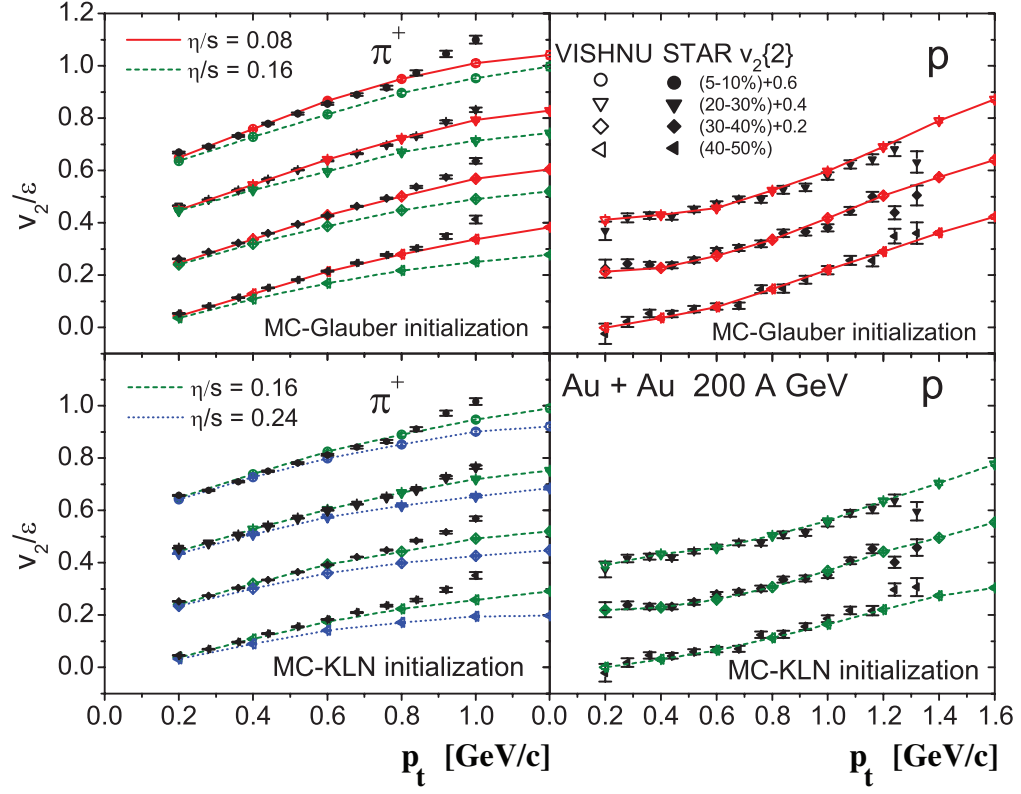
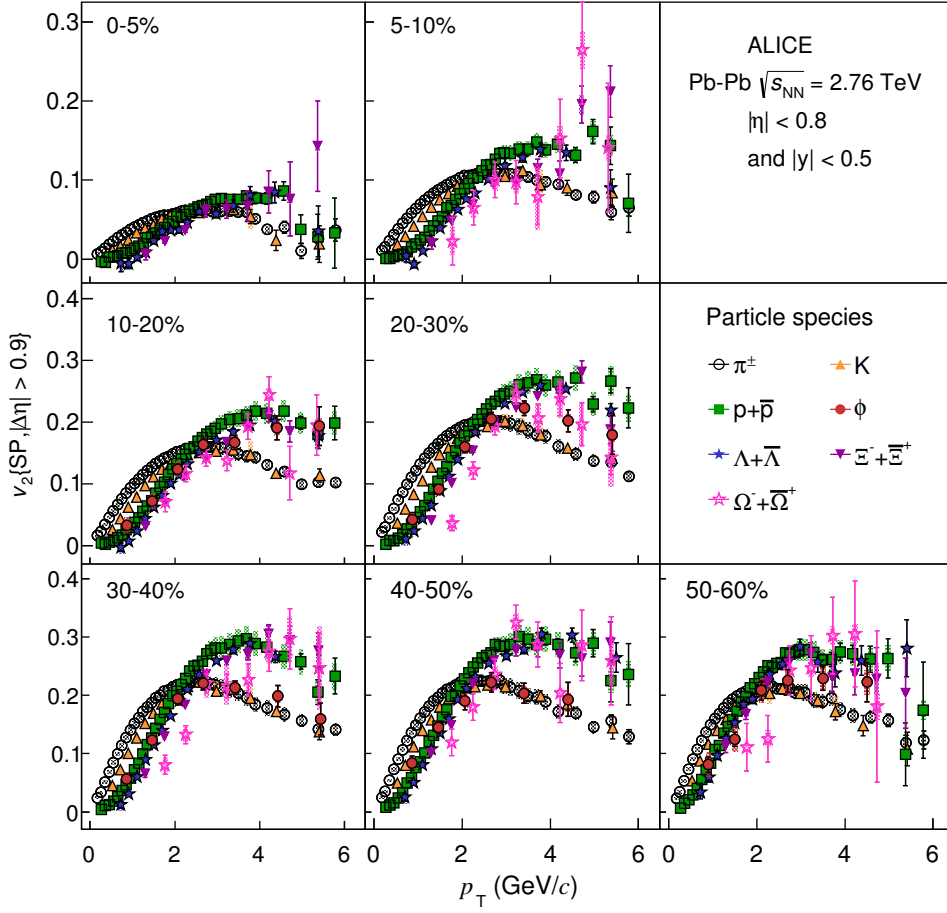


Figure 2.19: The $v_2(p_T)$ for pions and protons measured by STAR compared to hydrodynamic calculations with different eccentricities and η/s [5].



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Figure 2.20: p_T -differential v_2 for different particle species grouped by centrality class of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [78].

reproduces the larger mass splitting of the $v_2(p_T)$ due to stronger radial flow at LHC compared to RHIC. A hybrid approach (viscous hydro plus hadronic cascade) produces too much radial flow for protons in central collisions but, due to smaller cross sections, hyperons don't fully pick it up, yielding inverted mass-ordering (Λ - Ξ -p, instead of p- Λ - Ξ as experimentally measured) [79].

The IP-Glasma initial-state fluctuation model [37], which includes the pre-equilibrium dynamics of gluon fields, combined with viscous hydrodynamic evolution simultaneously correctly describe the mean $v_{2,3,4}$ coefficients at RHIC and LHC energies [25], their centrality and p_T dependence, as well as the detailed shape of their event-by-event distributions [8]. But the current models do not distinguish between a constant η/s of ≈ 0.2 or a temperature dependent η/s with a minimum

of $1/4\pi$. Moreover neither MC-Glauber nor MC-KLN is able to reproduce the correct initial power spectrum.

The final v_n power spectrum is affected by the viscosity in a different way for different harmonics: the same final state v_n can be obtained for different combinations of initial state ϵ_n and transport coefficients. These requires more differential measurements, as the one presented in this thesis.

A topic which currently gets a considerable theoretical attention is the contribution to the flow from the very early stage. Pre-equilibrium flow significantly affects the slope of the single-particle p_T -spectra; radial flow is created earlier, leaving less room for radial push from final hadronic rescattering [80]. In addition there are also still open questions about the contribution from the late hadronic stage and due to the particle production mechanism [81].

We want to emphasize that the event-by-event fluctuation of initial geometry is very large, and events with the same system size follow very different pathway during the collective expansion. A precise characterization of these events will give access to finer and more differential correlation measures, with the potential to further constrain the spectrum of initial conditions. Therefore, controlling the initial conditions in heavy-ion collisions is of the utmost importance to learn about the properties of high density hot QCD matter. This calls for more differential studies to constrain the different ingredients. The measurements presented in this paper constitute an attempt in this direction.

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Event shape engineering: an effective way to constrain the initial geometry

Initial conditions dynamic influences the hydrodynamic response of the system created in heavy ion collisions. In response to the pressure gradients due to the energy density profile of the fireball, collective flow builds up. Radial flow and anisotropic flow are strictly correlated. Since physics observables are affected by the combined effect of either radial and anisotropic flow, the individual contribution can't be easily disentangled. Moreover the initial spatial geometry is complex and possess odd harmonic symmetry planes because of the fluctuations in the initial density.

In fig. 2.13 we showed the $\Delta\phi$ distributions for for two individual events, dominated by elliptic ($n = 2$) and triangular ($n = 3$) flow. This suggests the possibility to characterize events dominated by different flow harmonics: some of the fundamental properties of the matter created in nucleus-nucleus collisions (such as the sound velocity, the shear viscosity and the spatial eccentricity) can be constrained by these differential flow measurements [1–3]. Since the v_2 distributions are expected to reflect the participant eccentricity distributions, this measurement suggests the intriguing possibility to select events with different initial shapes.

A strategy to select events with unusually large or small eccentricities, called *Event Shape Engineering* (ESE), is discussed in this chapter. It allows for unprecedented studies, with the selection of very large eccentricity even for central events, which typically have a more isotropic shapes. This technique allows the detailed study the effects of event-by-event fluctuations. In particular, the correlation between between anisotropic and radial flow can be studied by measuring p_T distributions of primary particles in strongly or weakly anisotropic environments, at fixed impact parameter.

3.1 The Event Shape Engineering technique

At present, the most common way to study the effect of the overlap geometry is to vary the collision centrality or collide different species. In this case, due to the large variety of possible overlap geometries, the interpretation of the results could be very complicated.

The Event Shape Engineering (ESE) technique, recently proposed in [4], allows us to bias the event sample through the selection of events characterized by a well defined initial geometry, by means of the *reduced flow vector* (also named *q-vector* in the following) evaluated from the azimuthal distribution of produced particles. The flow vector is defined as

$$\begin{aligned} Q_n &\equiv \sum_{i=1}^M e^{in\phi_i} \\ Q_{n,x} &= \sum_i^M \cos(n\phi_i), \quad Q_{n,y} = \sum_i^M \sin(n\phi_i) \\ q_n &= Q_n / \sqrt{M} \end{aligned} \tag{3.1}$$

where M is the particle multiplicity used to compute the flow vector and ϕ_i are particle azimuthal angles. In absence of correlations, the length of Q_n grows as $\sqrt{M}$: the reduced flow vector is introduced to remove the trivial part of the multiplicity dependence (see section 2.4.1 for details).

Monte Carlo (MC) simulations [4] show that anisotropic flow coefficients and the flow vector are strongly correlated. Moreover a strong positive correlation between the flow vector and the eccentricity of the collision has been observed [5]. These results suggest that the shape of the initial geometry can be constrained by using the flow vector in the final state.

Not all azimuthal correlations in the data are of collective origin. Other correlations exist between particles, but these typically only involve a few particles or are short range in η . Particles can be correlated because they are decay products of the same mother particle, because they belong to the same (mini)jet, because of momentum conservation or HBT correlations. These azimuthal correlations, not related to the reaction plane, are collectively known as non-flow. One should be careful in performing the event shape analysis, not to select events dominated by non-flow contribution. The characteristics of non-flow correlations cannot be calculated analytically as is done for flow correlations. Since non-flow correlations are expected to exist mostly between few particles that are close to each other in pseudorapidity, they can be distinguished from flow correlations which extend over all particles independent of pseudorapidity. Indeed, it is possible to avoid trivial bias from non-flow processes using a gap in η . The event selection (using

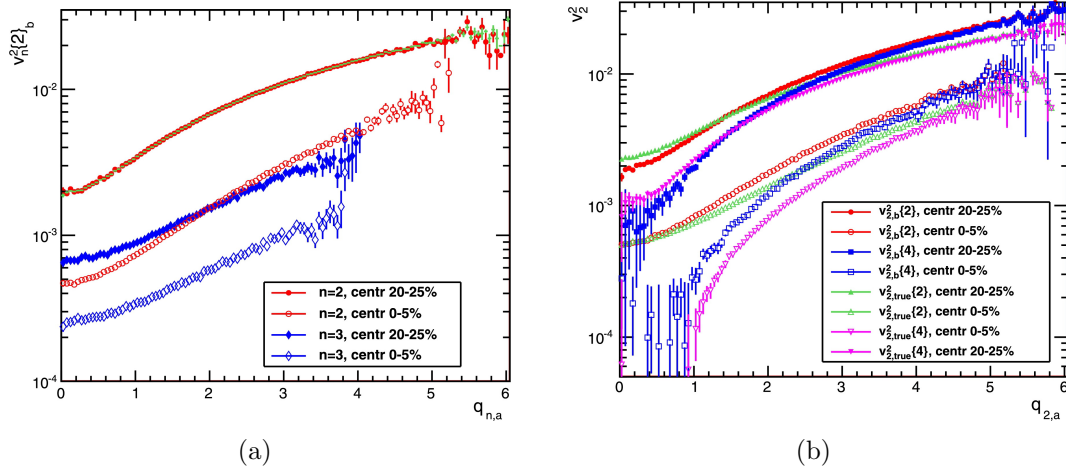


Figure 3.1: MC-Glauber simulation: (a) v_n^2 distribution as a function of q_n , measured in two different sub-events, for two centrality classes (0-5% and 20-25%) and for two harmonics $n = 2$ and $n = 3$. (b) Elliptic flow measured with 2 (red points) and 4-particle (blue) cumulant method as a function of the corresponding q_2 . The true (simulated) v_2 values are shown by green markers for 2-particle cumulant and by magenta for 4-particle cumulant results.

flow vector magnitude) is based on the information from one η window (sub-event a), while the physical analysis is performed in a different η region (sub-event b) which is expected to have small correlations via non-flow to the first one.

Figure 3.1(a) shows the average values of v_n^2 , calculated via the 2-particle correlation method [6], as function of the flow vector magnitude, in a simulation where all the correlations in the system are determined only by anisotropic flow. In this case the two sub-events (a and b) are statistically independent and are correlated only via common participant plane and flow values. Since there are no non-flow correlations, the $v_n^2\{2\}$ values coincide with the true values of $\langle v_n^2 \rangle$. The results demonstrate that, depending on q_2 , is possible to select events with average flow values varying more than a factor of two. Figure 3.2(a) shows the event-by-event v_n distribution in top 5%, bottom 5% and total of q_n events.

The results obtained by including non-flow correlations in the simulation are shown in Fig. 3.1(b). v_2 distributions, extracted by using 2 and 4 particle cumulant methods, as function of q_2 are compared with the expectations based on simulated flow. A significant bias due to non-flow is present, leading to overestimate the flow values in high q -vector selected events and to underestimate the flow values in the low q -vector selected events. The same bias in corresponding event-by-event v_n distributions is shown in Fig. 3.2(b).

The correlation between the (initial state) eccentricity and the (final state)

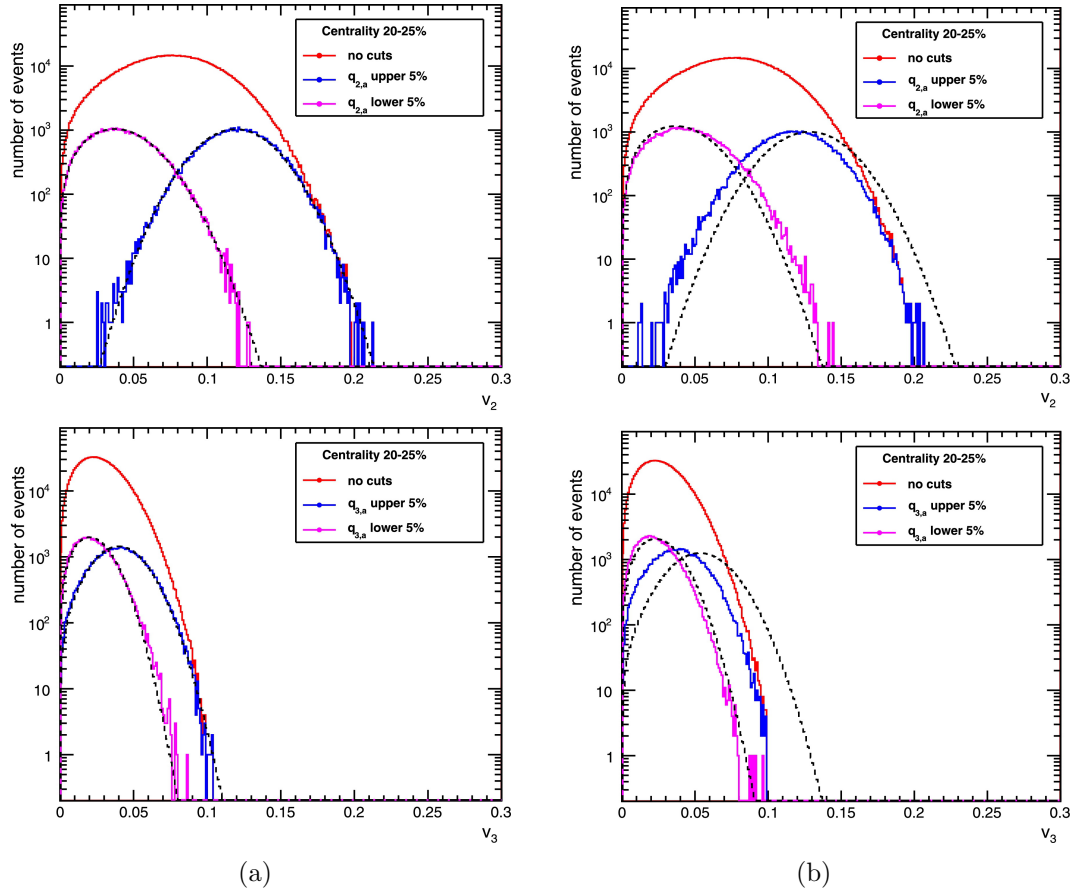


Figure 3.2: MC-Glauber simulation: true v_2 and v_3 distributions in the event samples selected by different cuts on the corresponding q_n vector magnitude, without (a) and with (b) non-flow contribution, compared to that extracted from the fits to $q_{n,b}$ distributions (dashed lines) [4].

anisotropic flow in event shape engineered events, has been recently further investigated in [5], using A Multi-Phase Transport model (AMPT) [7]. AMPT is frequently used to study the relation between higher-order v_n and ϵ_n of the initial geometry. It combines the initial fluctuating geometry based on Glauber model and final state interaction via a parton and hadron transport model. The collective flow in this model is driven mainly by the parton transport. AMPT was found to reproduce many flow related observables [7–9].

Figures 3.3(a-b) shows the performance of the event shape engineering in Pb–Pb collisions at LHC energy ($\sqrt{s_{NN}} = 2.76$ TeV), for $b = 8$ fm, corresponding to $\sim 30\%$ centrality. The figure clearly depict a strong positive correlation between the participant eccentricities ϵ_2 and ϵ_3 and the q-vectors q_2 and q_3 , respectively. Figures 3.3(e-f) demonstrate that, depending on q_n is possible to select events with average eccentricity values varying more than a factor 3 for $n=2$ and a factor 2 for $n = 3$. These results suggest that the shape of the initial geometry can be selected by using the q-vector in the final state. Figure 3.4 shows the correlations between of ϵ_n for $n \leq 4$, for the generated AMPT events. Significant correlations are observed between ϵ_2 and ϵ_3 , ϵ_1 and ϵ_3 . Since the hydrodynamic response is nearly linear for $n = 1 - 3$ (see section 2.1), these correlations are expected to survive into correlations between v_n of respective order. This is shown in Fig. 3.5 where v_3 values are observed to decrease with increasing q_2 , showing the same anti-correlation observed between ϵ_2 and ϵ_3 . The v_n dependence on q_2 reflects the correlation between ϵ_n and q_2 , implying that these correlations reveal mainly the intrinsic hydrodynamic response to the change in the selected initial geometry.

3.2 Initial conditions dynamic and radial flow

The shape of the overlap region of the collision influences the participant nucleons distribution. Indeed, even at fixed impact parameter, the number of individual nucleons participating in the collision as well as their positions in the transverse plane could fluctuate event-by-event.

This is clearly shown in Fig. 3.6 [10], for two Au-Au collisions. The figure shows two snapshots of typical configurations of sources in the transverse plane generated with a Glauber model calculation [11]. The dots indicate the positions of the wounded nucleons. Despite having equal numbers of wounded nucleons $N_w = 100$, the two distributions have rather different RMS radii and shape, which after the hydrodynamic expansion results in different transverse flows. To have a simple size measure, the RMS transverse size of the initial fireball is considered: the RMS radii differ by more than 40% in the two configurations. Even at precisely fixed centrality the radii fluctuates [10].

Event-by-event fluctuations in anisotropic flow are caused by the fluctuations of

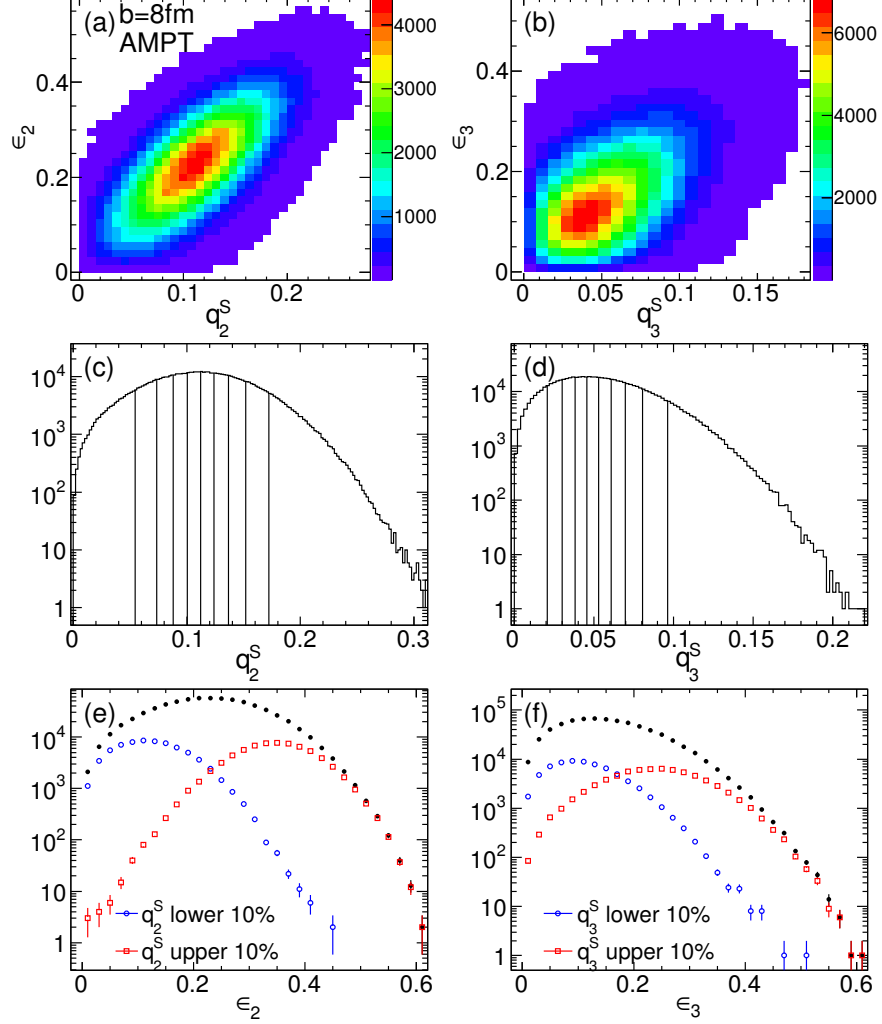


Figure 3.3: Correlation between ϵ_n and q_n . The results are calculated for $b = 8$ fm, for $n = 2$ and $n = 3$, and are shown in the left and right column, respectively [5]. In this simulation the sub-event used for for the event shape selection is labelled as S ($-6 < \eta < -2$). The particles in sub-event S are used only for this purpose and they are excluded explicitly for v_n and event plane correlation analysis.

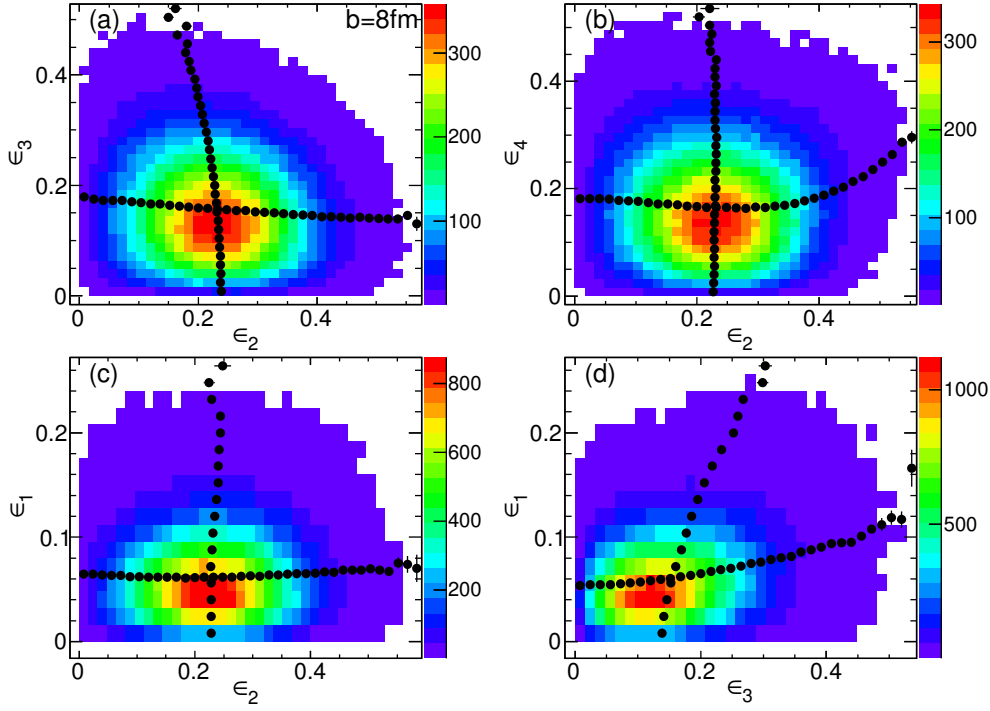


Figure 3.4: Correlations between ϵ_n of different order for Pb-Pb events generated at $b = 8$ fm [5].

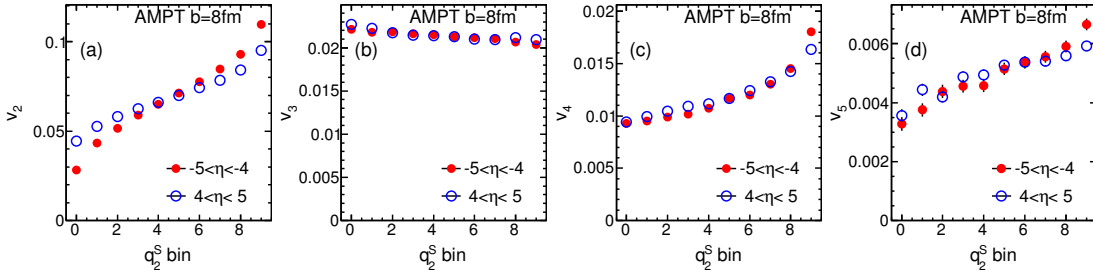


Figure 3.5: Dependence of the v_n on q_2 in a forward ($5 < \eta < 4$) and a backward ($4 < \eta < 5$) pseudorapidity [5]. In this simulation the sub-event used for for the event shape selection is labelled as S ($-6 < \eta < -2$). The particles in sub-event S are used only for this purpose and they are excluded explicitly for v_n and event plane correlation analysis.

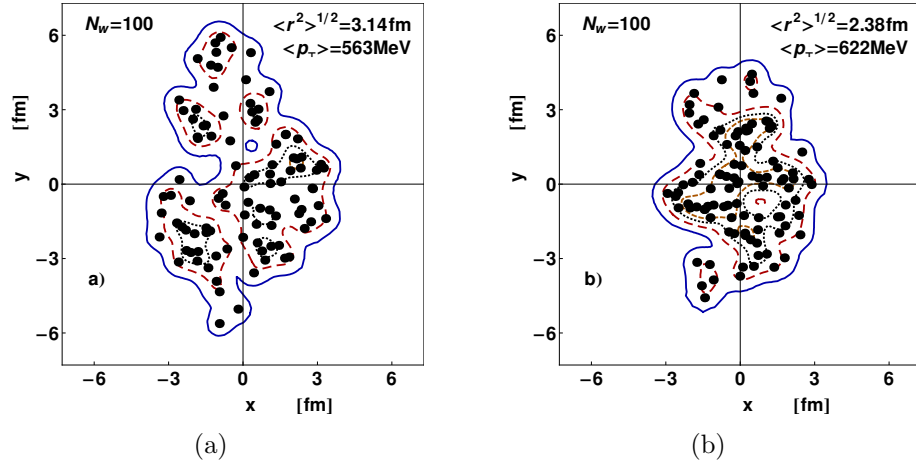


Figure 3.6: Two typical wounded nucleon configurations in the transverse plane for Au-Au collisions with $N_w = 100$ wounded nucleons, obtained using GLISSANDO [11] Monte Carlo code for the Glauber model [10].

the corresponding eccentricities of the initial density distribution. The anisotropy of the particle distribution in azimuthal angle ϕ is usually characterized by a Fourier series:

$$\frac{dN}{d\Phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)] \quad (3.2)$$

where v_n and ψ_n (symmetry plane) represent the magnitude and phase of the n^{th} -order harmonic flow. The magnitude and direction of each shape component can be estimated via a simple Glauber model from the transverse positions (r, ϕ) of the participating nucleons [12–14]:

$$\epsilon_n = \frac{\sqrt{\langle r^m \cos n\phi \rangle^2 + \langle r^m \sin n\phi \rangle^2}}{\langle r^m \rangle}, \quad (3.3)$$

$$\tan n\Phi_n^* = \frac{\langle r^m \sin n\phi \rangle}{\langle r^m \cos n\phi \rangle} + \frac{\pi}{n}, \quad m = 3 \text{ if } n = 1, \quad m = n \text{ if } n > 1 \quad (3.4)$$

with ϵ_n and Φ_n^* referred to as the eccentricity and participant plane, respectively. As seen in sec. 2.1 the hydrodynamic response to the shape component is linear for $n = 2, 3$, therefore $\psi_n \approx \Phi_n^{*1}$

For $n = 2$ the above definition corresponds to the one of *participant eccentricity* [12]:

$$\begin{aligned} \epsilon_{part} &= \frac{\sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}}{(\sigma_x^2 + \sigma_y^2)} \\ \sigma_x &= \langle x^2 \rangle - \langle x \rangle^2 \\ \sigma_y &= \langle y^2 \rangle - \langle y \rangle^2 \\ \sigma_{xy} &= \langle xy \rangle - \langle x \rangle \langle y \rangle \end{aligned} \quad (3.5)$$

where x and y are the transverse positions (x, y) of the participating nucleons and σ_x^2, σ_y^2 and σ_{xy}^2 are, respectively, the event-by-event variances and covariance of the participant nucleon distributions projected on the transverse axes x and y . With this definition the odd coefficients arise entirely due to statistical fluctuations [17]. Different shape components, corresponding to individual harmonics, are depicted in Fig. 3.7, for $n = 2, 3, 4, 5, 6$.

In order to study the correlation between the collision eccentricity and the spatial distribution of the participant nucleons, a Monte Carlo simulation has been performed, specifically for this thesis, using MC-Glauber initial conditions.

¹These simple relations are violated for higher-order harmonics, due to strong non-linear mode-mixing effects intrinsic in the collective expansion [13, 15, 16].

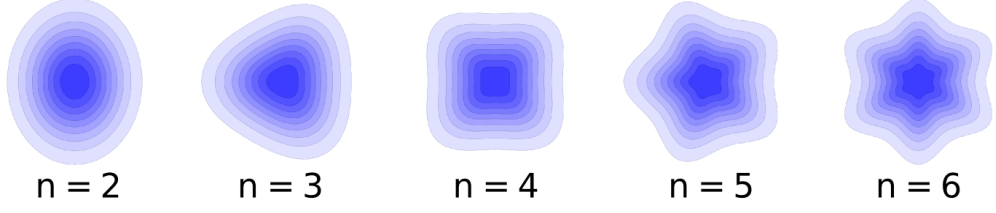


Figure 3.7: Different collision geometries for $n = 2, 3, 4, 5, 6$.

Figure 3.8 depicts the correlation between the participant eccentricity and the transverse effective area² of the collision, defined as

$$A = \pi \sqrt{\sigma_x \cdot \sigma_y}. \quad (3.6)$$

The MC-Glauber sample used in this study is generated for $8.55 < b < 9.88$ fm Pb-Pb collisions at LHC energy ($\sqrt{s_{NN}} = 2.76$ TeV), corresponding to the 30-40% centrality class [19]. The transverse area and eccentricity are anti-correlated. Even if the impact parameter is fixed, the distribution of wounded nucleons fluctuates on event-by-event basis, resulting in a variation of the effective area as a function of the fluctuating participant eccentricity of the collision. Due to the large centrality class used in this simulation (Fig. 3.8), the contribution from events with very different impact parameters could bias the distributions. To reduce this effect, Fig. 3.9 shows the same correlation in a thinner centrality bin, 39-40%. The effect is much more pronounced in peripheral collisions, where the overlap region is small and the randomness of binary processes dominates. In fact in the 0-1% centrality class the anti-correlation is still present, but it is much weaker.

It is clear that since initial state fluctuations affect not only the shape but also the size of the initial fireball, a modification of the shape of the p_T spectrum of the finally emitted hadrons could be observed.

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²The transverse area is related to the transverse particle density $1/A \cdot dN_{ch}/d\eta$, which is positively correlated to the eccentricity as shown in [18].

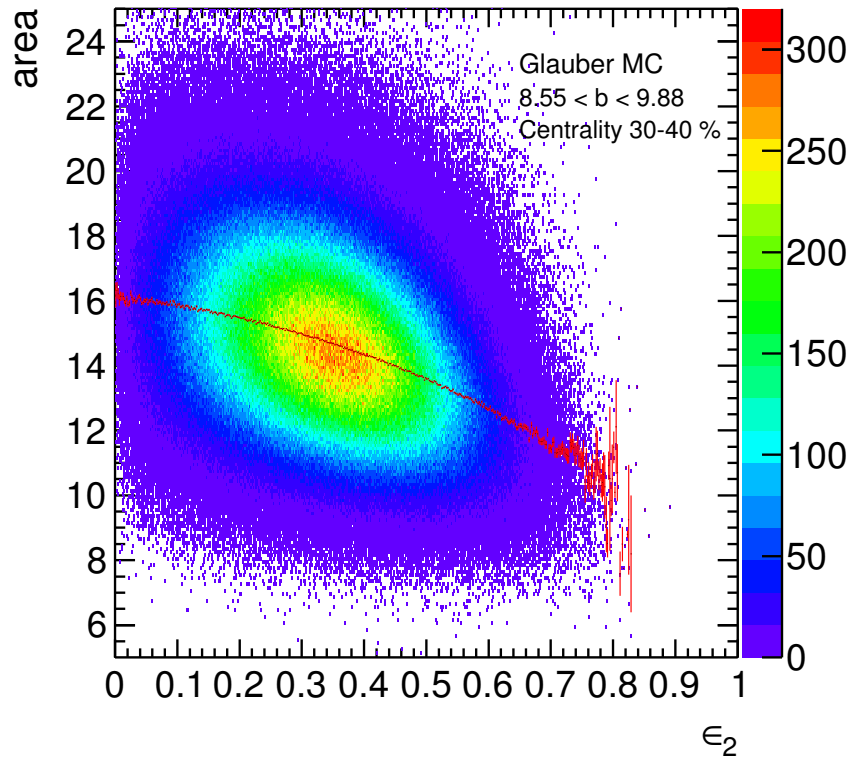
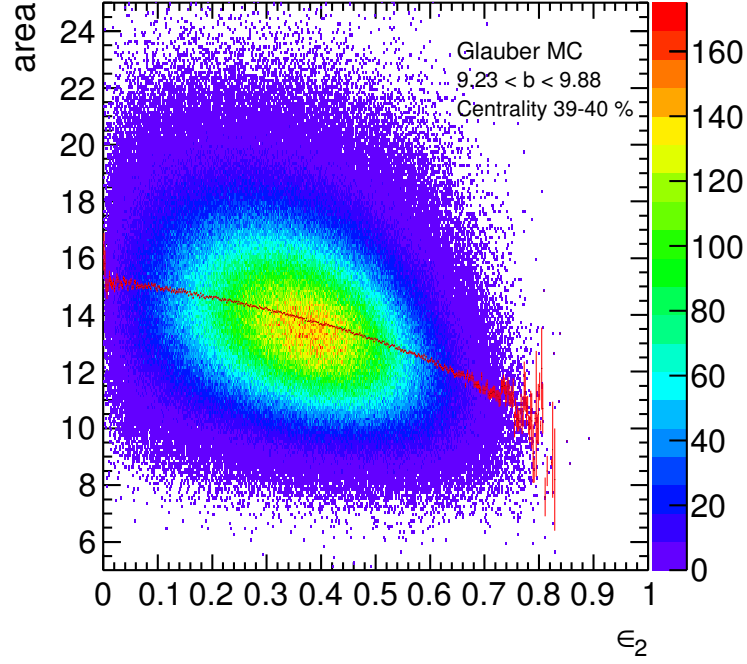
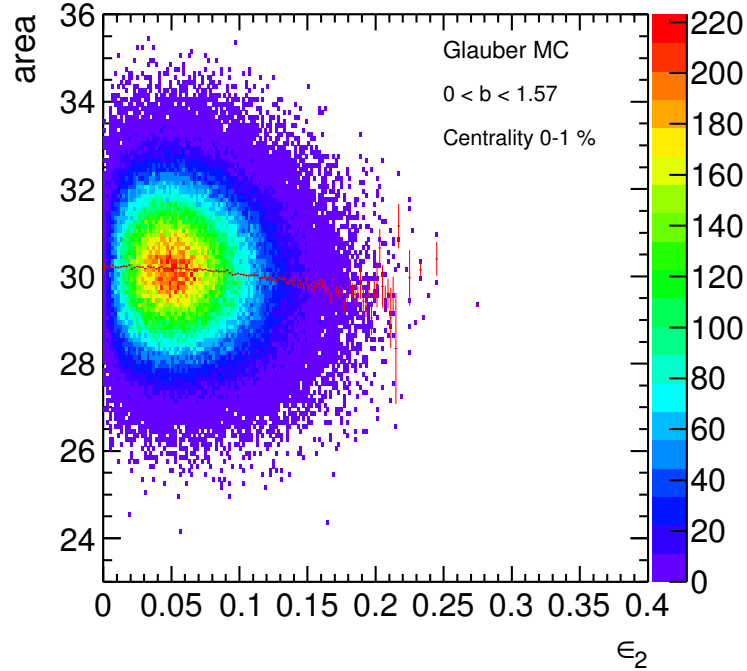


Figure 3.8: Transverse area distribution as a function of participant eccentricity in the 30-40% centrality class (MC-Glauber simulation). The red points show the average ϵ_{part} .



(a)



(b)

Figure 3.9: Transverse area distribution as a function of participant eccentricity in 39-40% (a) and 0-1% (b) centrality bin (MC-Glauber simulation). The red points show the average ϵ_{part} .

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The ALICE detector

ALICE (A Large Ion Collider Experiment) is a general purpose experiment at the CERN Large Hadron Collider (LHC) mainly devoted to the study of the strongly interacting matter and QGP physics through ultra-relativistic heavy ion collisions. Furthermore, ALICE studies proton-proton collisions, which on one hand serve as a baseline for heavy-ion measurements, on the other hand complements the measurements made by the other LHC experiments, thanks to the specific strengths of the ALICE detector (pid and low pt tracking). In this chapter the main features of the LHC are briefly presented. Then a short review of the ALICE detector, focusing mainly on the detectors used for this work, is presented in section 4.2. In particular, the combination of different detectors which use different PID techniques allows the identification over a broad range of transverse momentum. The ALICE PID strategy to identify pions, kaons and protons are described in section 7.2.

4.1 Introduction: the Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is the last ring of a complex chain of accelerators, depicted in Fig. 4.1, built by the European Organisation for Nuclear Research (CERN) [2]. The LHC is the world biggest particle accelerator, it lies in a tunnel 27 kilometres in circumference, at a depth ranging from 50 to 175 m underground.

The LHC has been designed to collide beams of either protons or nuclei. The maximum design energy for pp collisions is 7 TeV per beam (or 14 TeV centre-of-mass), while for Pb–Pb collisions the centre of mass energy is 5.5 TeV per nucleon pair. The design luminosity of the LHC is $10^{-34} \text{ cm}^{-2}\text{s}^{-1}$. The first pp collision at the LHC is dated November 23rd, 2009.

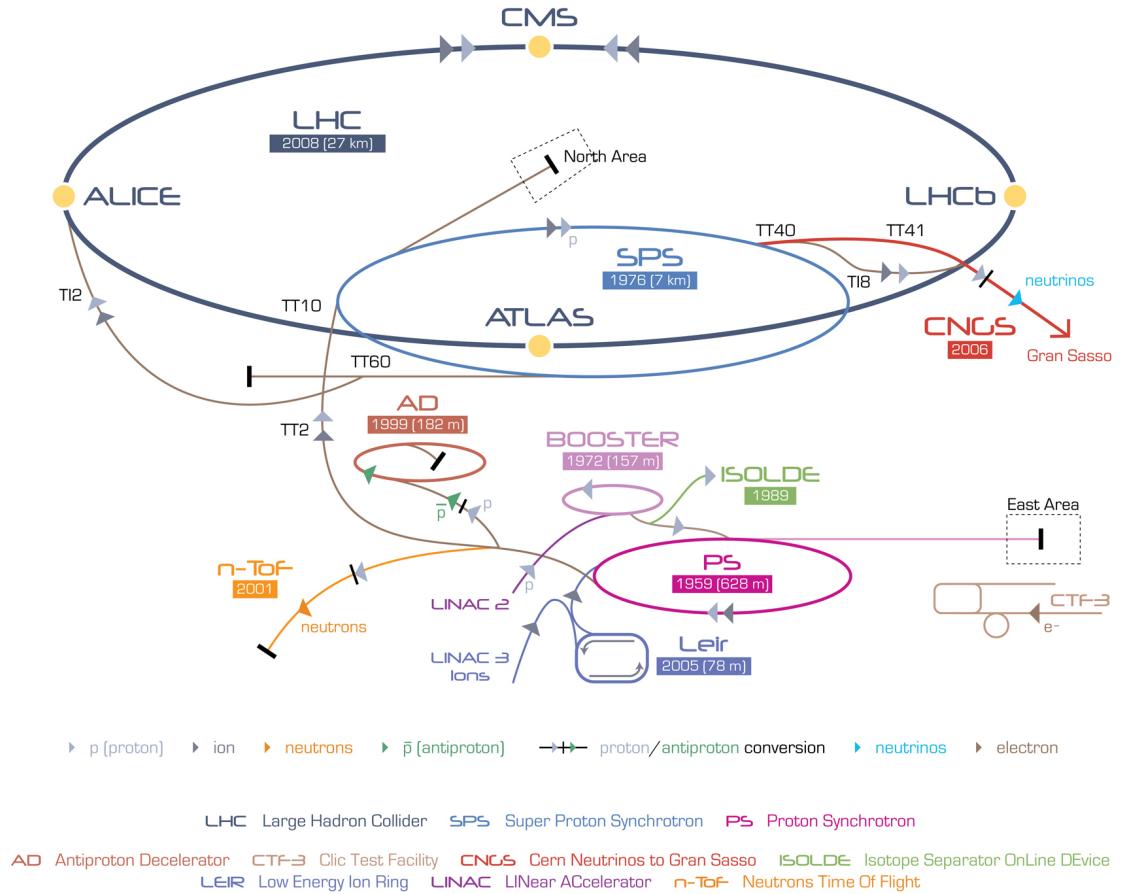


Figure 4.1: The CERN's Accelerator Complex [1].

	colliding system	CMS energy	Int. Luminosity (ALICE)
2009	pp	$\sqrt{s} = 900 \text{ GeV}$	-
2010	pp	$\sqrt{s} = 7 \text{ TeV}$	$\approx 48 \text{ pb}^{-1} (\approx 0.5 \text{ pb}^{-1})$
	Pb-Pb	$\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$	$\approx 10 \mu\text{b}^{-1} (\approx 10 \mu\text{b}^{-1})$
2011	pp	$\sqrt{s} = 7 \text{ TeV}$	$\approx 5.6 \text{ fb}^{-1} (\approx 2 \text{ pb}^{-1})$
	Pb-Pb	$\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$	$\approx 166 \mu\text{b}^{-1} (\approx 143.62 \mu\text{b}^{-1})$
2012	pp	$\sqrt{s} = 8 \text{ TeV}$	$\approx 23.3 \text{ fb}^{-1} (\approx 10 \text{ pb}^{-1})$
	p-Pb (pilot-run)	$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$	-
2013	p-Pb and Pb-p	$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$	$\approx 31.2 \text{ nb}^{-1} (\approx 31.2 \text{ nb}^{-1})$
	pp	$\sqrt{s} = 2.76 \text{ TeV}$	-

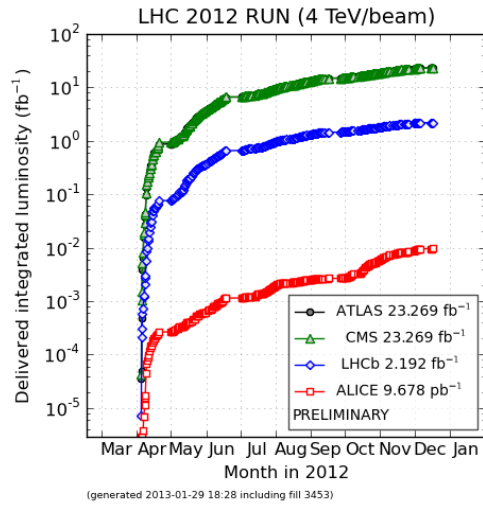
Table 4.1: LHC run 1 history.

The LHC delivered luminosity, as measured by the four experiments, is reported in Fig. 4.2, for pp, p-Pb and Pb-Pb collisions.

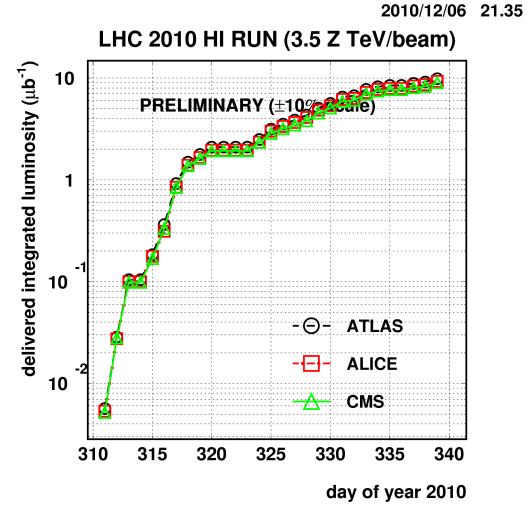
- In 2010 the integrated luminosity delivered by the LHC was $\approx 48 \text{ pb}^{-1}$ for pp collisions at $\sqrt{s_{\text{NN}}} = 7 \text{ TeV}$ ($\approx 0.5 \text{ pb}^{-1}$ in ALICE) and $\approx 10 \mu\text{b}^{-1}$ for Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ ($\approx 10 \mu\text{b}^{-1}$ in ALICE). The pp data have been collected by ALICE at reduced luminosity, due to the dead time of the slowest detectors, in order to keep the pile-up (multi event in a single colliding bunch) at an acceptable level. In Pb-Pb collisions the limit to the luminosity is imposed by the machine characteristics [3].
- In 2011 the beam energy was the same as in 2010 for both pp and Pb-Pb. The performance of the LHC improved in terms of luminosity with $\approx 5.6 \text{ fb}^{-1}$ for pp collisions ($\approx 2 \text{ pb}^{-1}$ in ALICE) and $\approx 166 \mu\text{b}^{-1}$ for Pb-Pb collisions ($\approx 143.62 \mu\text{b}^{-1}$ in ALICE).
- In the 2012 the centre-of-mass energy for pp collisions was 8 TeV and the integrated luminosity (up to October 2012) was $\approx 23.3 \text{ fb}^{-1}$ ($\approx 10 \text{ pb}^{-1}$ in ALICE). In addition to this LHC provided a pp run at $\sqrt{s_{\text{NN}}} = 900 \text{ GeV}$ on November 2009, a pp run at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ (the same energy as Pb-Pb) on March 2011 and a pilot p-Pb run at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ on September 2012.
- Finally on February 2013 p-Pb and Pb-p data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ have been collected, before the first Long Shutdown (LS1), with a delivered luminosity of 31.2 nb^{-1} .

A summary on LHC beam energies during run 1 is shown in table 4.1.

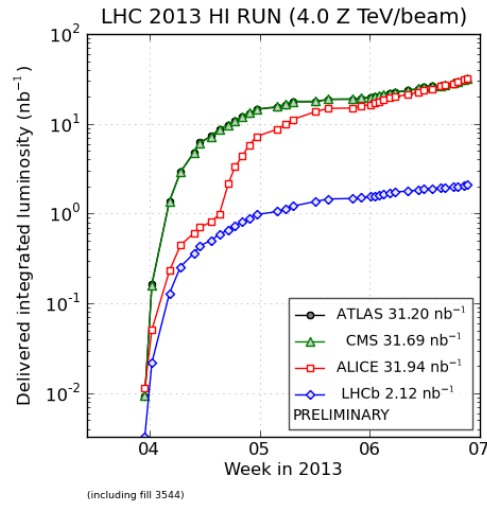
The LHC was built with the aim of testing the predictions of different theories of particle and high energy physics. The pp program at the LHC is expected to



(a)



(b)



(c)

Figure 4.2: Luminosity delivered by the LHC for pp (2012), p-Pb (2013) and Pb-Pb (2010) collisions.

shed new light on fundamental open questions in physics, in particular regarding the electroweak symmetry breaking, supersymmetry and CP violation.

The LHC heavy ion program is expected to extend the results obtained by previous experiments at the CERN's Super Proton Synchrotron (SPS) and Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). The heavy ion program is the main focus of the ALICE experiment, but the ATLAS and the CMS experiments also have a heavy ion study program. The main goal of these studies is to characterize the emergent behaviour and phases of strongly interacting matter, to understand its properties such as the equation of state (EoS), temperature and order of the phase transition, transport coefficients and so on, through the collision of lead (^{208}Pb) ions.

The LHC produces collisions in six interaction points in correspondence of which are located six detectors of different dimensions and with different goals:

ATLAS (A Toroidal LHC ApparatuS) [4] and *CMS (Compact Muon Solenoid)* [5] are general-purpose experiment, built to cover the widest possible range of physics at the LHC. The Higgs boson and physics beyond the Standard Model are the main research topic of this two experiments.

LHCb (The Large Hadron Collider beauty experiment) [6] is a dedicated experiment for the study of heavy flavour physics at the LHC. In particular the experiment has the primary goal of studying the difference between matter and anti-matter by studying the decays of b quark.

LHCf (Large Hadron Collider forward experiment) [7] is designed to measure neutral particles produced forward rapidity, to provide further understanding of high energy cosmic rays. The detector is placed at 140 metres either side of the ATLAS collision point.

TOTEM (TOTAl Elastic and diffractive cross-section Measurement) [8] measures the total proton-proton cross-section, elastic scattering, and diffractive processes. The detector is placed at about 147 m and 220 m from the CMS interaction point.

ALICE (A Large Ion Collider Experiment) is devoted to the study of the nature and properties of the QGP, believed to have existed in the early universe. The layout and subsystems of the ALICE detector are the main subjects of this chapter and will be discussed in details in the following.

4.2 The ALICE experiment

The ALICE physics program covers the study of many physics observables in heavy ion collisions, e.g. photons and soft particles, jets, heavy quarks, etc. This lead to the construction of a multi purpose apparatus combining different detection techniques.

The main experimental challenge for a heavy-ion experiment is to cope with the high multiplicity of nucleus-nucleus collisions, several thousands particles per unit of rapidity in central collisions [9] (see for instance the event display in Fig. 4.3). The detector acceptance must be sufficiently large to enable the study of the

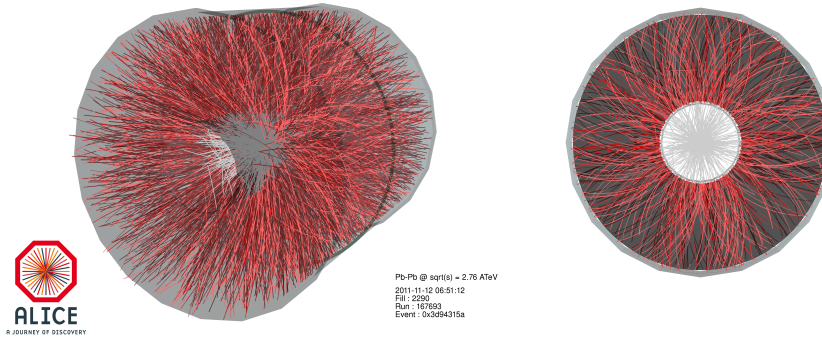


Figure 4.3: Pb–Pb collision recorded by ALICE detector in 2011.

different QGP probes presented in chapter 1. ALICE consists of two main parts: a central barrel and a forward muon arm [10]. It also has forward detectors which are used mainly as trigger detectors and in multiplicity measurements. The central barrel has an acceptance of $|\eta| < 0.9$ and provides full azimuthal coverage. It is optimized for precise tracking over a broad transverse momentum region (from 100 MeV/c to 100 GeV/c) in a high multiplicity environment, good resolution of primary vertex reconstruction and particle identification over a broad momentum region. Moreover, the material budget, kept very low through the usage of light materials in thin layers, especially for the inner detectors. A remarkably low value of 13% X0 (radiation length) is obtained from the primary vertex to the outer edge of the Time Projection Chamber. This minimizes the effects of Coulomb multiple scattering, which spoil the low- p_T measurements.

Detectors in the central barrel are embedded in a 0.5 T magnetic field provided by the solenoid magnet previously used in the L3 experiment of the Large Electron-Positron (LEP) collider. A large warm dipole magnet (0.7 T) with resistive coils and a horizontal field perpendicular to the beam axis is used for the muon spectrometer.

In the ALICE coordinate system the x-axis is perpendicular to the beam direction, aligned with the local horizontal direction and points to the accelerator centre. The y-axis points upward and is perpendicular to the x axis and to the beam direction. Finally, the z -axis is parallel to the beam direction and points in the opposite direction to the muon arm. The point of origin is the nominal interaction point.

The ALICE experiment is depicted in Fig. 4.5. A detailed description of the detectors and their performance can be found in [3, 11, 12].

4.2.1 Central detectors

Inneter Tracking System - ITS

The ITS [13] is built out of three different silicon detector technologies, each of which contributes with two detector layers (Fig.4.4). The six layers are arranged around the beam pipe with radii ranging from 3.7 cm, for the innermost layer, to about 44 cm for the outermost one. The first two layers are made of fast and high-granularity Silicon Pixel Detector (SPD), based on hybrid silicon pixels, consisting of silicon detector diodes with a thickness of $200\ \mu\text{m}$, coupled to a $300\ \mu\text{m}$ readout chip. The two intermediate layers are the Silicon Drift Detector (SDD), with a $300\ \mu\text{m}$ thick layer of homogeneous high-resistivity silicon. Finally, the two outermost layers, the Silicon Strip Detector (SSD), are composed of double-sided microstrip silicon sensors, 40 mm long and with a pitch of $95\ \mu\text{m}$. The six layers cover the pseudorapidity region $|\eta| < 0.9$ and have full azimuthal coverage. The

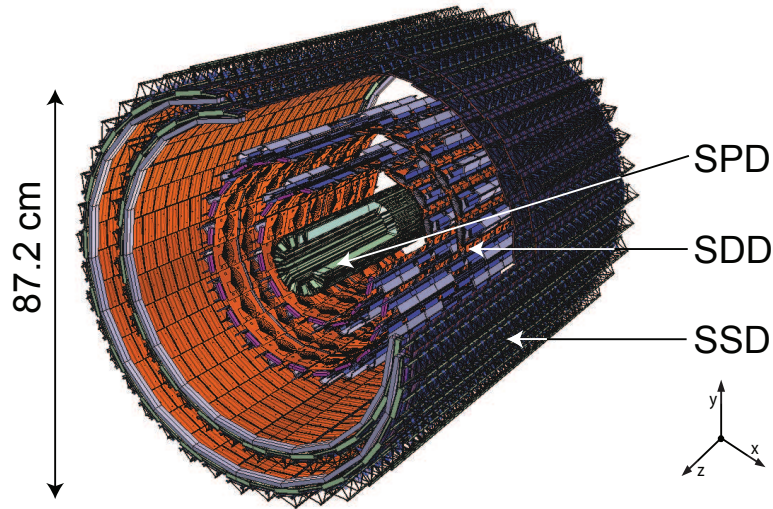


Figure 4.4: 3D view of the ITS detector.

ITS can reconstruct the primary vertex with resolution of $12\ \mu\text{m}$ in the transverse plane and $100\ \mu\text{m}$ along the beam axis and the secondary vertices from the decays of hyperons, D and B mesons. It is able to track and identify particles with momentum $\leq 0.6\ \text{GeV}/c$, to improve the momentum and angle resolution for particles reconstructed by the Time Projection Chamber (TPC) and to reconstruct particles traversing dead regions of the TPC.

The ITS is able to identify particles through the measurement the specific energy deposit (dE/dx) in the $1/\beta^2$ region of Bethe-Bloch curve (in SDD and SSD subsystems), the dE/dx resolution is about 10%. This makes the identification of π , K, and p possible down to respectively 0.1, 0.2, 0.3 GeV/c in p_T . The energy loss signal in the ITS is shown in Fig. 4.6. The expected energy loss distribution is shown for the pion, kaon and proton mass hypothesis in Fig. 4.6 on top of the measured dE/dx , with the parameters of the Bethe-Bloch extracted from a fit to this distribution.

Time Projection Chamber - TPC

The TPC [14] is the main tracking detector in the central barrel (Fig. 4.7). It provides charged particle momentum measurements with good two-track separation, particle identification, and vertex determination. The pseudorapidity coverage of tracks with full radial track length is $|\eta| < 0.9$. The detector is made of a large cylindrical field cage, filled with a gas mixture of 90 Ne / 10 CO₂. The primary electrons are transported over a distance of up to 2.5 m on either side of the central electrode to the end plates and are detected by multi-wire proportional chambers at each end-plate, with cathode pad readout.

The TPC identifies particles via the specific energy loss in the gas: up to 159 clusters can be measured. A truncated mean, using only 60% of the available clusters, is employed in the analysis. This leads to a Gaussian (and hence symmetric) response function. The resolution is $\approx 5\%$ in peripheral and $\approx 6.5\%$ in central collisions.

Because of its good dE/dx resolution, the TPC can identify particles with $p_T < 1\ \text{GeV}/c$ on a track-by-track basis. The specific energy loss in the TPC as a function of momentum is shown in Fig. 4.8. The different characteristic bands for $e^\pm, \mu^\pm, \pi^\pm, K^\pm$ and $(\bar{p})p$ are clearly visible. The continuous curves represent the Bethe-Bloch parametrization obtained from a fit to the dE/dx distribution. The TPC allows the identification of hadrons and nuclei over a wide p_T range. The relativistic rise of the dE/dx at high p ($> 4\ \text{GeV}/c$) can also be used to identify π , K and p at high p_T in a statistical basis.

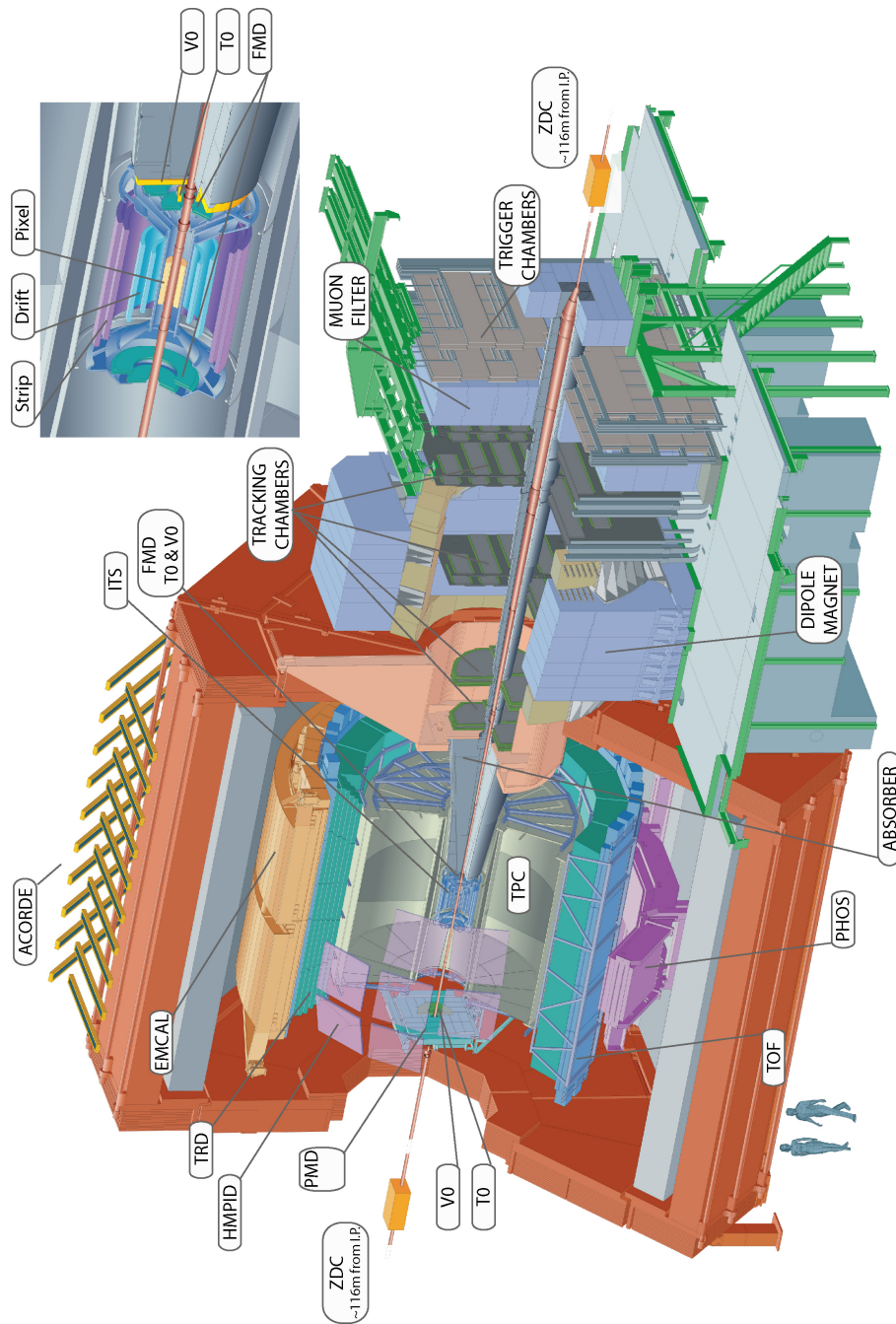


Figure 4.5: A Large Ion Collider Experiment - ALICE [11].

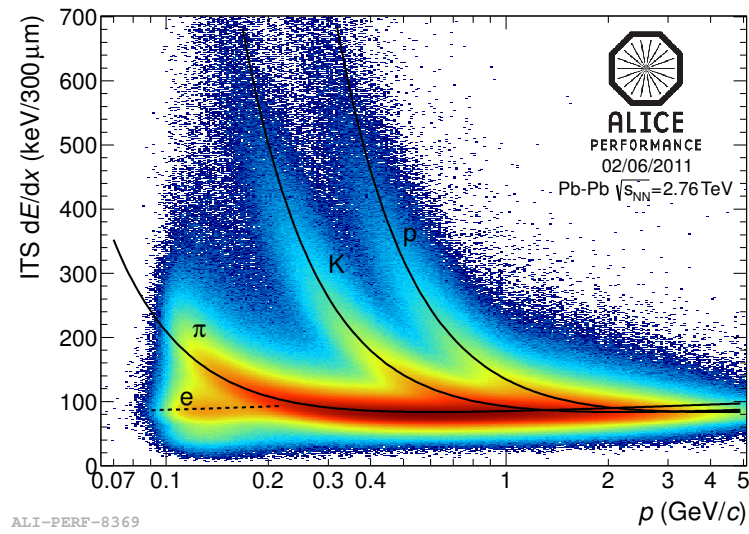


Figure 4.6: dE/dx as a function of p measurement in the ITS.

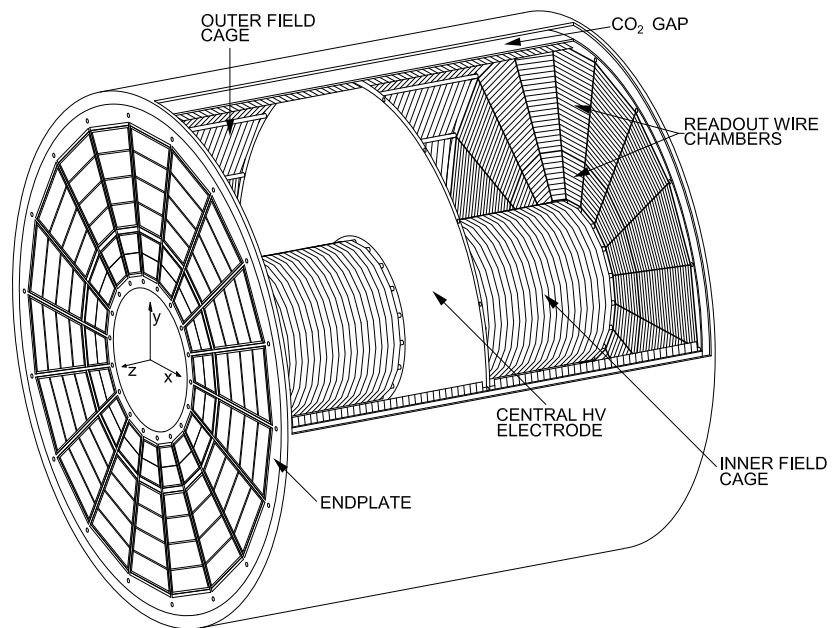
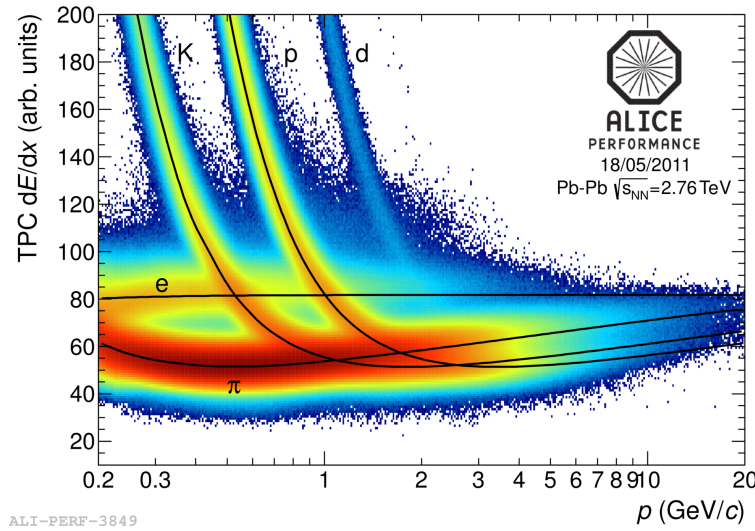


Figure 4.7: 3D view of the TPC detector.

Figure 4.8: dE/dx measurement in the ALICE TPC.

Time Of Flight detector - TOF

The main goal of the TOF detector [15] is the identification of charged particles produced at central rapidity in momentum regions where it is no longer possible to exploit the dE/dx measurements, i.e. above momenta of about 1 GeV/ c . It is used for PID in the intermediate momentum range, up to 3 GeV/ c for pions and kaons, up to 4 GeV/ c for protons. The total time resolution is about 85 ps and it is determined by three contributions: the intrinsic timing resolution of the detector and associated electronics, the tracking and the start time. The whole device is inside a cylindrical shell with an internal radius of 370 cm and an external one of 399. The pseudorapidity coverage is $|\eta| < 0.9$ as for ITS and TPC.

The TOF detector consists of a large area array of Multi-gap Resistive-Plate Chambers (MRPC). The basic unit of the system is a 10-gap double-stack Multi-gap Resistive Plate Chamber (MRPCs), 122 cm long and 13 cm wide, with an active area of $120 \times 7.4 \text{ cm}^2$ subdivided into two rows of 48 pads. It has a modular structure corresponding to 18 sectors in ϕ and to 5 segments in z direction, shown in Fig. 4.9. The β - p TOF performance plot for the 2011 Pb-Pb run is reported in Fig. 4.10.

Transition Radiation Detector - TRD

The main purpose of the TRD [16] is to provide electron (and positron) identification in the central barrel for momenta above 1 GeV/ c , by detecting the transition radiation emitted from these particles when crossing the detector. Each detector

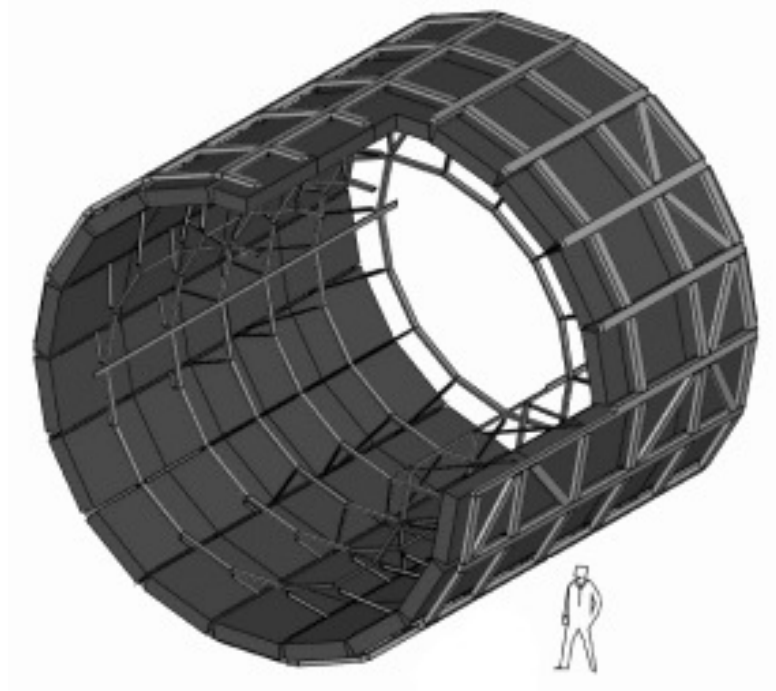
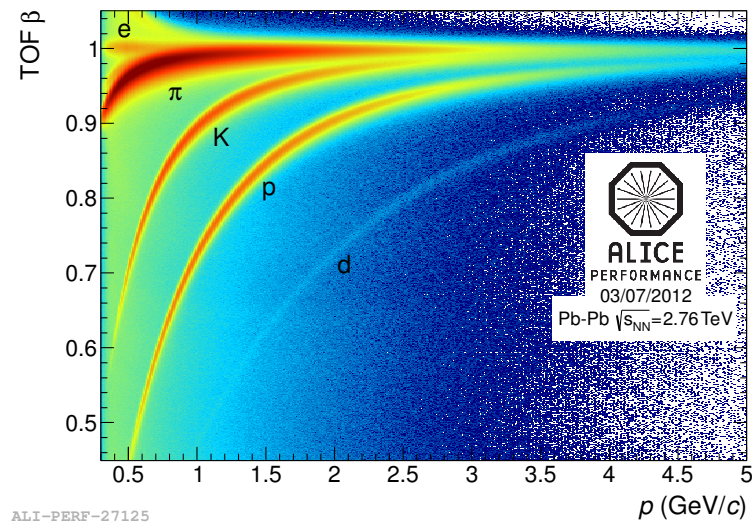


Figure 4.9: 3D view of the TOF detector.

Figure 4.10: TOF β -p performance plot in the 2011 Pb-Pb run.

element consists of a 4.8 cm thick radiator, a drift section of 30 mm thickness and a multiwire proportional chamber with pad readout. It consists of 540 individual readout detector modules. It is positioned at $2.9 < r < 3.68$ m and the nominal pseudorapidity coverage is $|\eta| < 0.84$. During the data taking in 2010 (used in this work) the TRD was not fully installed. The TRD tracking information, if present, is used to track charged particles and constrain the extrapolation to the TOF.

High Momentum Particle IDentification detector - HMPID

The HMPID [17] (Fig. 4.11) enhances the track-by-track identification capabilities of ALICE, extending the momentum range accessible with energy loss (ITS and TPC) and time of flight measurements (in TOF). It is based on the Cherenkov effect and allows the identification, of pions and kaons up to 3 GeV/ c and protons up to 5 GeV/ c .

It consists of seven identical proximity focusing Ring Imaging Cherenkov (RICH) counters, covering the 5% of the TPC acceptance. Charged particles, traversing the liquid radiator C_6F_{14} (with refractive index of $n = 1.2989$ at $\lambda = 175$ nm), produce Cherenkov photons. Photons and charged particles detection is performed with a Multi Wire Proportional Chamber (MWPC) coupled to a pad segmented CsI coated photocathode.

The reconstructed Cherenkov angle is shown in Fig. 4.12 as a function of the track momentum, in case of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV data. Three bands are visible, they correspond to pion, kaon and proton signals. The experimental values are in good agreement with the theoretical calculations showed as black curves.

PHOton Spectrometer - PHOS

The PHOS [18] is a high-resolution electromagnetic spectrometer covering a limited acceptance domain at central rapidity ($|\eta| < 0.12$ and $220^\circ < \phi < 320^\circ$). High energy resolution and granularity are obtained by using dense scintillator crystals ($PbWO_4$) of $20 X_0$ with high photo-electron yield. It allows, for instance, the measurement of direct photon and the study of jet quenching through the measurement of high p_T π^0 and γ -jet correlations.

ElectroMagnetic Calorimeter - EMCal

The jet quenching phenomenon can be further studied by the EMCal [19]. It is a lead scintillator sampling calorimeter that covers $|\eta| \leq 0.7$ and $\Delta\phi = 107^\circ$ at a radial distance of about 4.5 metres from the beam pipe.

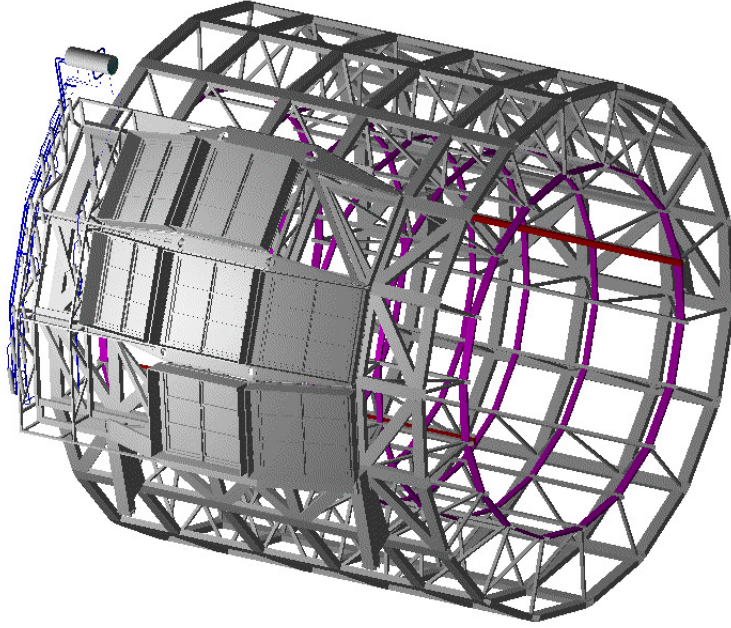
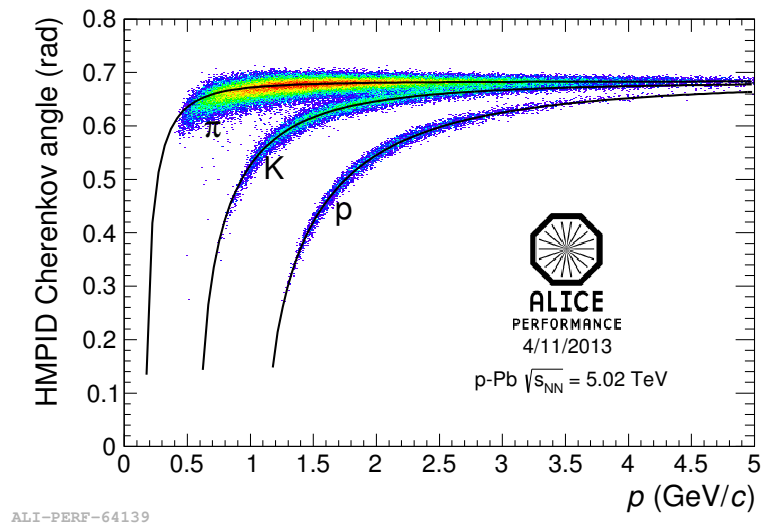


Figure 4.11: 3D view of the HMPID detector.

Figure 4.12: Cherenkov angle distribution as a function of p_T in p-Pb collisions.

4.2.2 VZERO detector

The V0 detector [20] is a small-angle detector, consisting of two arrays of scintillator counters, called V0A and V0C, which are installed on either side of the ALICE interaction point. They cover the pseudo-rapidity ranges $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C) and are segmented into 32 individual counters each distributed in four rings. The V0A and V0C scheme is reported in Fig. 4.13. This detector is devoted to trigger minimum bias events and to reject the beam-gas

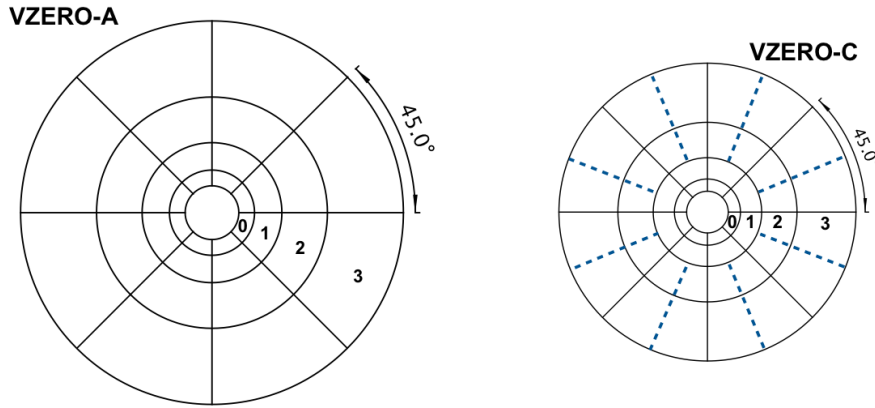


Figure 4.13: V0A and V0C arrays scheme, showing their segmentation [20].

background.

The V0 is also used to measure global event characteristics. The centrality of the collisions can be estimated via the multiplicity recorded in the event. It is evaluated by fitting the distribution of the summed amplitudes in the V0 with a Monte Carlo Glauber model study [21]. Finally, as described in section 5.2, it can be used to calculate the flow vector Q_2 on an event-by-event basis.

4.2.3 Others forward detectors

Placed in the high pseudo-rapidity region (small angles with respect to the beam pipe) they are small and specialized detector systems used for trigger purpose or to measure global event characteristics.

- The Time Zero (T0) [22] detector is used to generate a start time for the TOF detector, with precision of the order of tens of picoseconds. The detector consists of two arrays of Cherenkov counters placed at -72.7 cm and 375 cm from the nominal interaction point. The corresponding pseudorapidity range is $-3.28 < \eta < -2.97$ and $4.61 < \eta < 4.92$.

- The Forward Multiplicity Detector (FMD) [22] provides the charged particle multiplicity information over a large fraction of the solid angle ($-3.4 < \eta < -1.7$ and $1.7 < \eta < 5$). It is composed of three rings of silicon strips sensors placed at 320 cm, 75.2 cm and -62.8 cm from the interaction point, respectively.
- The Photon Multiplicity Detector (PMD) [23] measures the multiplicity and the spatial distribution of photons on an event-by-event basis in the $2.3 < \eta < 3.7$ region. It consists of a large array of gas proportional counters in a honeycomb cellular structure.
- The Zero Degree Calorimeter (ZDC) [24] is used to measure and trigger on the impact parameter. ZDC consists of two sets of hadronic ZDCs are located at 116 m on either side of the interaction point. In addition, two small electromagnetic calorimeters (ZEM) are placed at about 7 m from the interaction point, on both sides of the LHC beam pipe, opposite to the muon arm.

4.3 ALICE Particle IDentification

The ALICE experiment is capable of discriminating different particle species produced at central rapidity over a broad p_T range, from a few hundred MeV/ c up to ≈ 20 GeV/ c , by using various detectors, which exploit all known PID techniques.

The PID performance of the central barrel detectors is reported in Figure 4.14. The separation power between π -K (K-p) is reported for each detector in the upper left (right) panel of the figure. The p_T ranges in which the separation is $> 2\sigma$ are reported in the bottom panels. Identification and measurement of muons in ALICE are performed in the Muon Arm, covering the pseudo-rapidity region $2.5 < \eta < 4$.

Several different strategies can be pursued for the actual particle identification, with the combination of different detectors. For the studies discussed in this thesis the $n\sigma$ cut and the bayesian approach are here discussed. More performance studies are presented in chapter 7.

4.3.1 PID selection with $n\sigma$ cut

A robust and straightforward strategy for particle identification is given by simple $n\sigma$ -cuts, defined, for each track, as the difference between the value of the measured PID signal and the expected theoretical one, in units of the detector resolution.

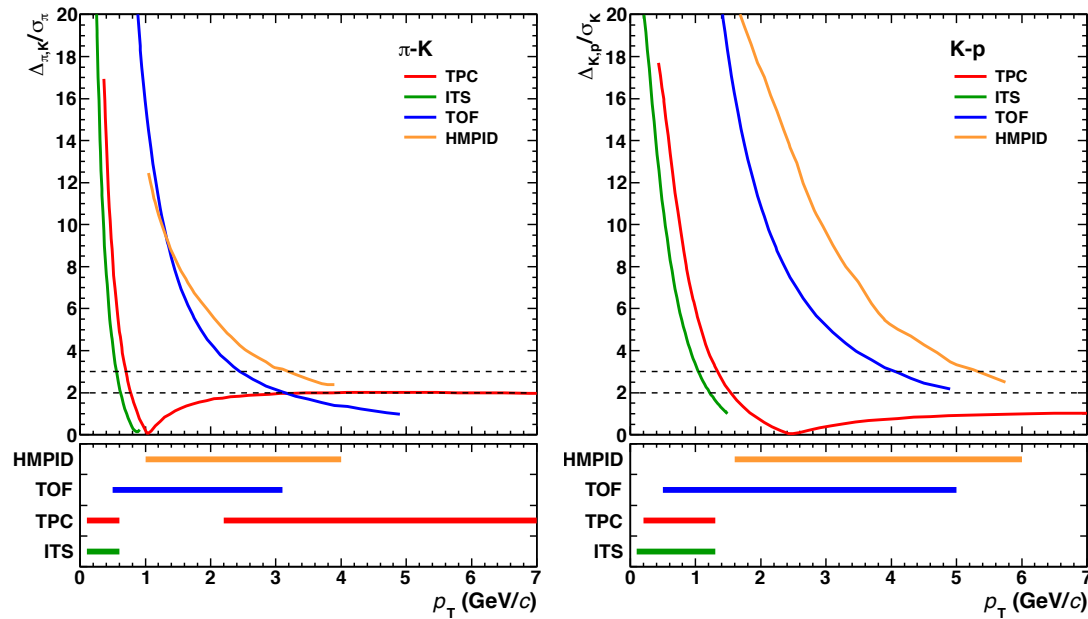


Figure 4.14: Upper left (right) panel: separation power between π -K (K-p). The p_T ranges in which the separation is $> 2\sigma$ are reported in the bottom panels.

Fig. 4.15 shows the correlation between the number of standard deviations for 3 mass hypotheses (π , K, p left to right), in the momentum window $3.6 < p_T < 3.8$ GeV/c, from the expected signal of the TPC and the TOF detector, in Pb-Pb collisions. With a 3σ compatibility cut (i.e. related to the dE/dx and TOF resolutions), particles can be cleanly identified over a wide momentum range without loss of efficiency, up to 4 GeV/c with contamination less than 1% for pions, up to 3 GeV/c with a contamination less than 20% for kaons and up to 4 GeV/c with a contamination less than 10% for protons.

If the same track is compatible with more than one mass hypothesis, the one associated to the smallest $n\sigma$ value is selected. It is also possible to associate the same track to more than one mass hypothesis, “double counting” the track. This procedure results in a better efficiency of identification, but also in a bigger contamination of the sample of identified particles from other species.

4.3.2 PID selection with bayesian approach

The Bayesian approach is based on the probability that a given signal corresponds to a given species. The probability P of a particle to belong to a certain

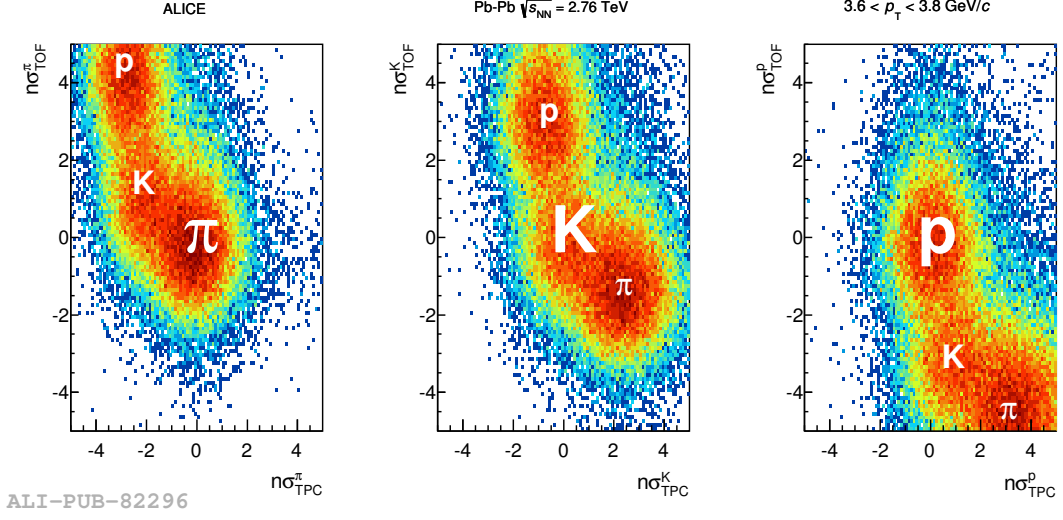


Figure 4.15: The correlation between the number of standard deviations from the expected signal of the TPC and the TOF detectors using the three different mass hypotheses (π , K, p, left to right) for $3.6 < p_T < 3.8$ GeV/ c in the 5% most central Pb–Pb collisions [25].

species i can be defined for a single detector as:

$$P_{det}^i = \frac{C^i W_{det}^i}{R} \quad \text{with} \quad R = \sum_{i=0}^{allspecies} C^i W_{det}^i \quad (4.1)$$

where C^i express the a priori relative concentrations of particles and are known as *priors*, W_{det}^i the detector probability to register the measured signal for a given mass hypothesis, and R is the normalization factor to guarantee the sum of the probability is one.

The obtained probabilities P^i can contribute to a combined Bayesian approach of PID. The overall detector response probability P_{tot}^i , under the assumption of independent measurements, is the product of several single detector response probabilities:

$$P_{tot}^i = P_{TPC}^i \cdot P_{TOF}^i \cdot \dots \quad (4.2)$$

A standard set of priors is provided by the AliRoot¹ [26] framework based on an iterative procedure explained in [27], computed for Pb–Pb data, using LHC10h data sample, as a function of transverse momentum.

¹AliRoot is the offline framework, for simulation, alignment, calibration, reconstruction, visualization, quality assurance, and analysis of experimental and simulated data.

4.3.3 Statistical unfolding

If a track-by-track particle identification is not needed, particle identification can be performed via statistical unfolding. In a given p_T -bin particle are identified by fitting the distribution with a superposition of several functions (typically Gaussians) and the corresponding yields are extracted. This procedure allows the extension of the p_T coverage [28].

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Event selection with ALICE

In the following the procedure that we developed to select shaped events in ALICE, according to the magnitude of the second order reduced flow vector q_2 , is described. This selection constrains the initial second-order eccentricity, as suggested by Monte Carlo simulations and Glauber model reported in chapter 3. Then we proceed in the characterization of the selected sample with the measurement of the elliptic flow (chapter 6) and the transverse momentum distributions of charged hadrons (chapter 7) in different ESE-selected events.

5.1 Data sample and track selection

In this section the data, the event, and the track selections used in the data analysis are described.

The data used for this analysis were collected during the December 2010 Pb–Pb run. The full sample consists of about $29 \cdot 10^6$ events, characterized by good performance of the detectors and good running conditions (e.g. low level of beam induced background).

The purpose of the event selection is to tag hadronic interactions with the highest possible efficiency, while rejecting the machine-induced and physical backgrounds. The ALICE minimum bias trigger used for this analysis is defined by the following requirements.

On-line trigger selection

The trigger logic requires a combination of the following conditions:

- At least 2 chips hit in the outer layer of the SPD,
- A signal in the V0A,

- A signal in the V0C.

According to the period, the trigger implemented one of following requirements:

- 2 out of 3 of the above conditions,
- “AND” of the V0 signal on the A and C side,
- 3 out of 3 of the above conditions.

In addition to the previous conditions, a further coincidence with two beam bunch crossing in the ALICE interaction point is requested. ALICE has been equipped with two Beam Pickup for Timing of eXperiments (BPTX) to monitor the timing of the LHC machine [1].

Control triggers were also collected with the same trigger logic, in coincidence with only one beam crossing the ALICE interaction point (from either the A or the C side) or with no beam at all (“empty”). No events were observed in the present sample for the empty triggers, meaning that the noise from the triggering detectors is negligible.

Off-line selection

• Machine-Induced Background (MIB)

Two different sources of machine-induced background can be identified.

The beam ions interacting with the residual gas in the beam pipe (beam-gas) and the ions in the halo of the beam interacting with mechanical structures in the machine constitute the first MIB source. To remove this background at the analysis level, the timing information of the V0 (coincidence of the V0A and V0C signals) was used. MIB events caused by one of the beam, happen upstream of the V0 and thus produce an *early* signal as compared to the time corresponding to a collision in the nominal interaction point. This is illustrated in Fig. 5.1(a). The time difference between the ZDC signal on either side, corresponding to the vertex position of the event, is also a powerful cut to reject the MIB in Pb–Pb collisions. The MIB contamination amounts to about 25%.

The second source of background is due to parasitic collisions from debunched ions. The radio-frequency (RF) structure of the LHC is such that there are 10 RF “buckets” within a 25 ns bunch, spaced by 2.5 ns. Only one of them should be populated by ions [2]. However, it is possible that the ions populate one of the neighbouring buckets. This causes a displacement in the vertex position of $2.5 \text{ ns}/2 \cdot c = 37.5 \text{ cm}$, outside to the fiducial region $|V_z| \lesssim 10 \text{ cm}$.

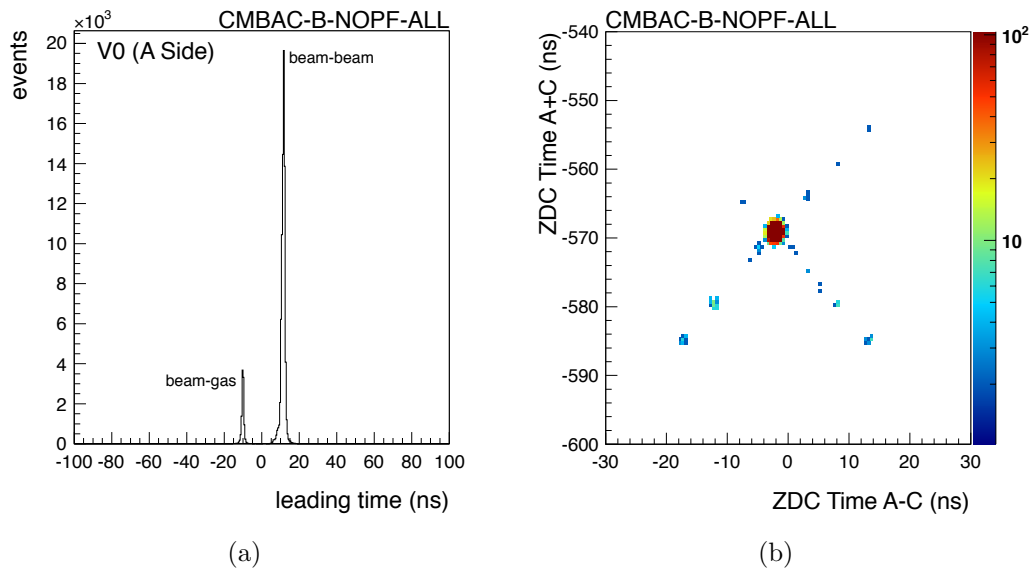


Figure 5.1: Machine-induced backgrounds. (a) Time distribution of the V0 signals on the A side. The peaks corresponding to beam-beam and to beam-gas events are clearly visible (Pb–Pb). (b) Correlation between the sum and the difference of times recorded by the neutron ZDCs on either side (Pb–Pb). The big cluster in the middle corresponds to collisions between ions in the nominal RF bucket on both sides, while the small clusters along the diagonals (spaced by 2.5 ns in the time difference) correspond to collisions in which at least one of the ions is displaced by one or more RF buckets.

These events are rejected using the correlation between the sum and the difference of times measured in the ZDC¹, as shown in Fig. 5.1(b).

- **Physical background**

At LHC energies, the strong electromagnetic fields generated by the heavy ions moving at relativistic velocity lead to large cross sections for QED processes [3]. This is the main physical background and needs to be rejected to isolate hadronic interactions. These events can be classified into several processes: QED pairs (lepton pairs produced via QED processes), nuclear dissociation (one (single) or both (mutual) nuclei break up as a consequence of the EM interaction) and photo-production (one photon from the EM field of one of the nuclei interacts with the other nucleus, possibly fluctuating to a vector meson). These processes are characterised by production of soft particles and low multiplicity at mid-rapidity.

Some of them, e.g single photo-production or single EM dissociation, are characterized by a strong asymmetry around mid-rapidity event-by-event. They can thus be rejected by requiring an energy deposit above 500 GeV in both neutron ZDC calorimeters. The symmetric ones still survive, but they are negligible in the 90% most central events, as demonstrated by the study of dedicated simulation of the EM background [3], by data-driven checks based on the comparison of the measured distribution of SPD clusters, V0 amplitude or tracks with different selections and by the comparison to the Glauber fits [4].

- **Centrality selection**

In order to classify the collisions in percentiles of the hadronic cross section corresponding to the particle multiplicity, the distribution of the V0 amplitude is fitted with a model inspired by the Glauber description of nuclear collision combined with a simple model for particle production based on a negative binomial distribution. To avoid the region of the most peripheral collisions, characterized by high trigger inefficiency and strong contamination by electromagnetic processes, the fit is restricted to amplitudes above a value corresponding to 90% of the hadronic cross section. Centrality classes are determined by integrating the measured distribution above the cut, as shown in Fig. 5.2. The Glauber model is used to find the amplitude of the V0 detector equivalent to 90% of the hadronic cross section, named *anchor point*, which determines the absolute scale of the centrality and hence the

¹The sum of times changes because the start time is always referred to the nominal time for a good collision.

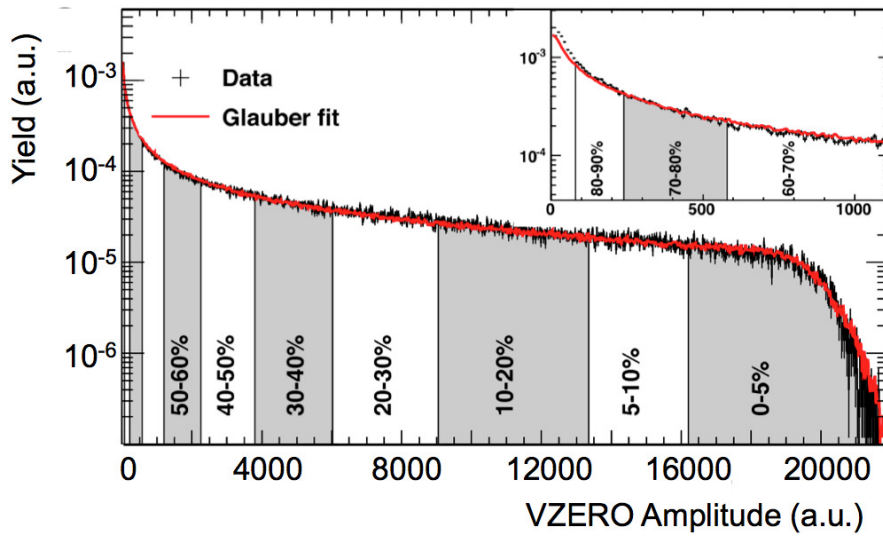


Figure 5.2: Distribution of the summed amplitudes in the V0 scintillator tiles (histogram); inset shows the low amplitude part of the distribution. The curve shows the result of the Glauber model fit to the measurement. The vertical lines separate the centrality classes [5].

0-90% most central events. The centrality resolution ranges from 0.5% in the most central to 2% in peripheral collisions [5].

Further off-line selections have been applied. The determination of the position of the primary vertex of the collision is done by correlating hit pairs, called tracklets, in the two layers of the SPD. As these are also the ITS innermost layers, they provide most of the resolution on the vertex position. The ITS vertex resolution in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV as a function of half of the tracklets multiplicity of the event is reported in Fig. 5.3. The resolution is extrapolated for the events in the 0-5% centrality class (orange box) [6]. The extrapolated resolution is better than $10 \mu\text{m}$ for the 5% most central events.

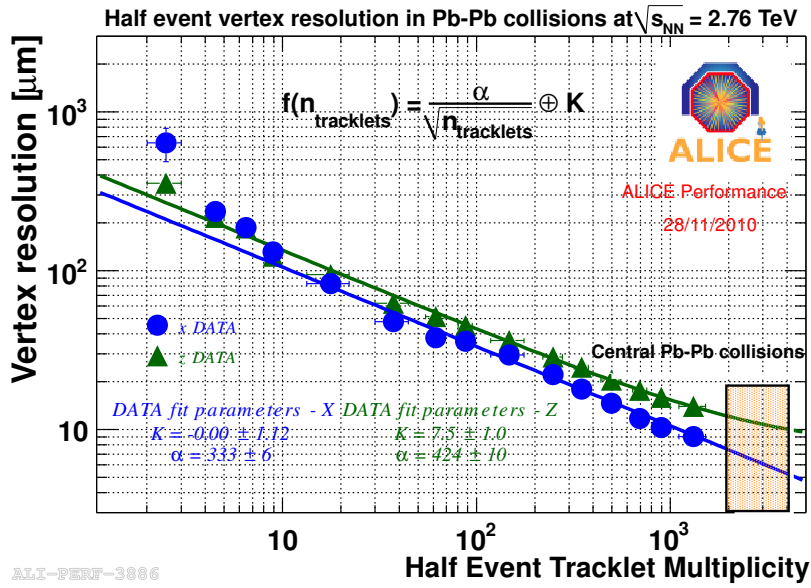


Figure 5.3: Primary vertex reconstructed with tracks in Pb–Pb data at $\sqrt{s_{\text{NN}}} = 2.76$ TeV per nucleon pair. The track sample is randomly divided into two. The primary vertex is reconstructed for each sub-samples. The residual distribution of the 2 vertices is fitted with a Gaussian and $\sigma/\sqrt{2}$ is taken as the vertex resolution. The resolution is extrapolated for most central (0-5%) Pb–Pb collisions (orange box) [6].

The ALICE reconstruction software produces tracks based either on the information of the TPC alone (TPC-only tracks) or on the combined information of the ITS, TPC and TRD (global tracks). The former have the advantage of an essentially flat azimuthal acceptance. The latter provide better track parameters. However, due to the geometry of the ITS and TRD and to missing or inefficient regions in those detectors, their acceptance and efficiency are not flat in azimuth.

TPC-only tracks can also be constrained to the primary vertex (reconstructed also using the ITS information) to provide better momentum resolution. Only events with a primary vertex position within the fiducial region of $|V_z| < 10$ cm from the center of the detector along the beam line were selected. This ensures good rapidity coverage and uniformity for the particle reconstruction efficiency in the ITS and TPC tracking volume.

The final sample in the 0-80% centrality range corresponds to approximately $17 \cdot 10^6$ Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

5.2 Analysis technique

The ESE approach described below uses two sub-events separated in pseudorapidity: one of the sub-events is used for the event selection, while the observables of interest are studied in another pseudo-rapidity window. The event shape selection is (mostly) based on the reduced flow vector magnitude measured in one of the V0 detectors, while the analysis is performed using the TPC, as shown in Fig. 5.4. Those detectors are separated by about two units of pseudorapidity which greatly suppresses non-flow correlations between the two. As a cross check, we will also discuss cases where the rapidity gap between the two sub events is reduced, and the q_2 is computed in the TPC.

The shape of the event is selected, by default, using the distributions measured in the V0A, in order to maximize the pseudorapidity separation with respect to the central barrel. The reduced flow-vector q_2 [7, 8] is computed as:

$$\begin{aligned}
 q_2 &= \frac{|Q_2|}{\sqrt{M}} \\
 Q_2 &= Q_{2,x} + iQ_{2,y} \\
 Q_{2,x} &= \sum_i w_i \cos(n\phi_i), \quad Q_{2,y} = \sum_i w_i \sin(n\phi_i)
 \end{aligned} \tag{5.1}$$

where the sum i runs over all the 32 azimuthal sectors of the V0 detector, w_i is the signal amplitude in sector i and ϕ_i is azimuthal angle of the centre of sector i and M is the total amplitude measured in the V0.

V0 calibration procedure

A gain equalization procedure [9] is performed prior on the V0 signals, to account for fluctuations induced by the performance of the hardware and by different conditions of the LHC for each data taking period. Furthermore, to remove acceptance correlations due to the detector non-uniformities, one must make the

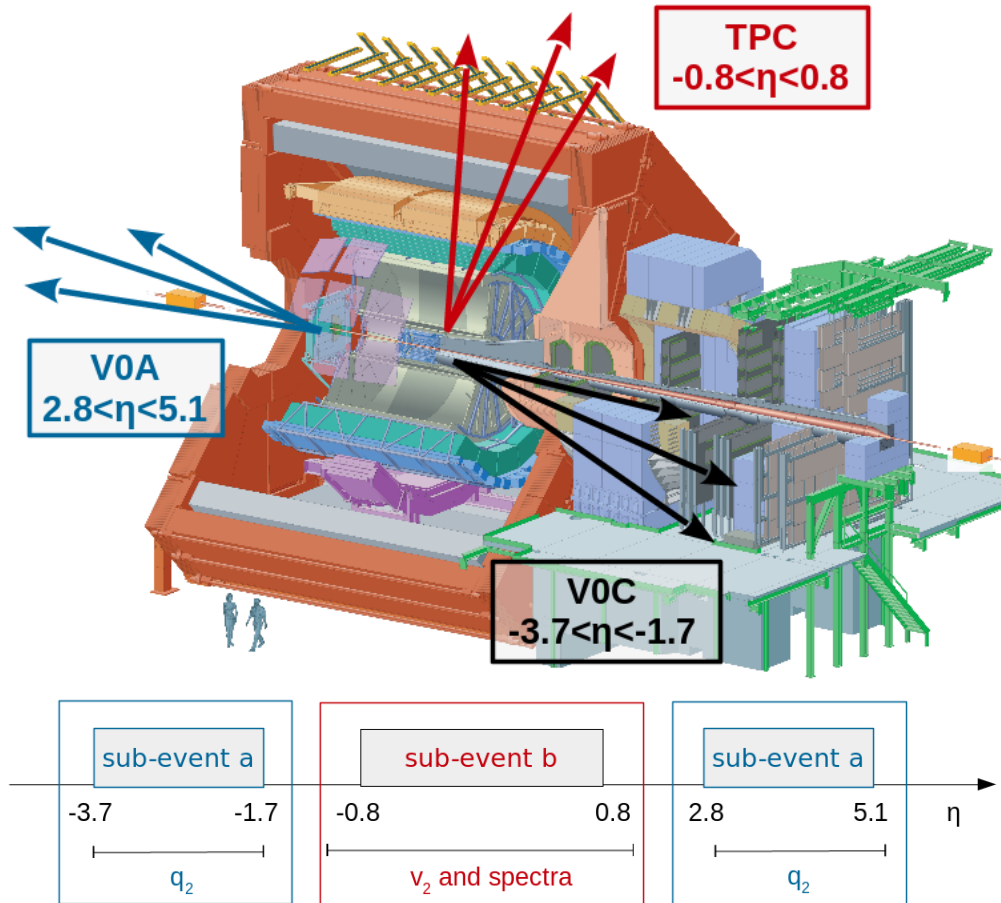


Figure 5.4: Pseudo-rapidity gap between the region at mid-rapidity where the elliptic flow and the spectra are measured and the forward rapidity regions where the flow vector q_2 is calculated.

Q-vector in Eq. 5.1 isotropic in the laboratory. For this purpose the Q-vector *recentering* method [10] has been used.

The V0 gain has been equalized ring by ring, separately for V0A and V0C, according to the formula

$$M_i^{corr} = M_i / \langle M_i \rangle \times M \quad (5.2)$$

where M_i is the multiplicity (amplitude) of the channel i in the analysed event, $\langle M_i \rangle$ is the mean multiplicity of the channel i and M is a gain factor obtained by fitting with a zero degree polynomial the mean multiplicity distribution of V0A/V0C.

Figure 5.5 shows the multiplicity distribution of V0 detectors before (left) and after (right) the gain equalization together with the mean multiplicity as a function of channel number. The RMS of the multiplicity distribution before and after the gain equalization is presented in Fig. 5.6: the gain equalization also flattens the RMS. Each of the V0 arrays is segmented in four rings in the radial direction, and each ring is divided in eight sectors in the azimuthal direction. Channels numbered from 0 to 31 correspond to V0C, channels numbered from 32 to 63 correspond to V0A. Since the calibration has been done ring by ring, the procedure equalizes the multiplicity distribution in each ring, as show in Fig. 5.5 (right panel).

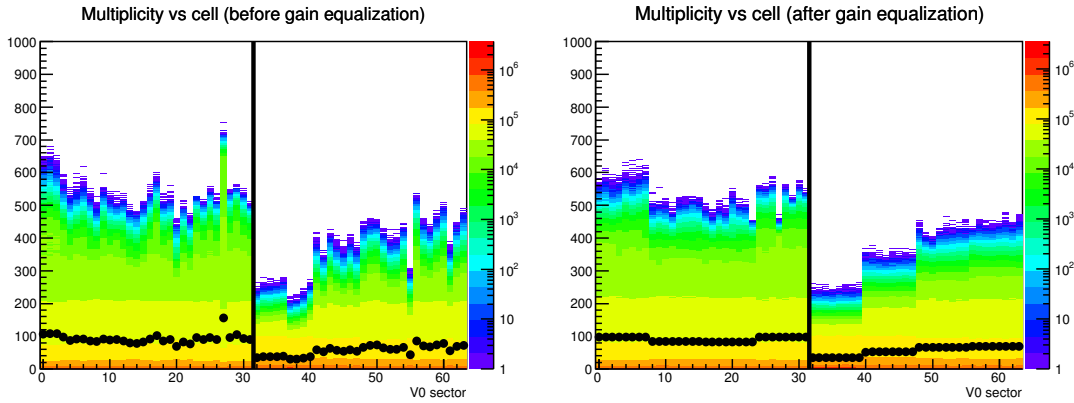


Figure 5.5: VZERO multiplicity before (left) and after (right) gain equalization. The black points indicate the mean multiplicity in each V0 channel. Channels numbered from 0 to 31 correspond to V0C, channels numbered from 32 to 63 correspond to V0A.

The *recentering* procedure consists in the subtraction of the average centroid position, $\langle Q_n \rangle$, of each V0 sector [11]. This has to be done for every centrality bin according to the formula

$$Q_{n,x}^{corr} = \frac{Q_{n,x} - \langle Q_{n,x} \rangle}{\sigma_{n,x}}, \quad Q_{n,y}^{corr} = \frac{Q_{n,y} - \langle Q_{n,y} \rangle}{\sigma_{n,y}} \quad (5.3)$$

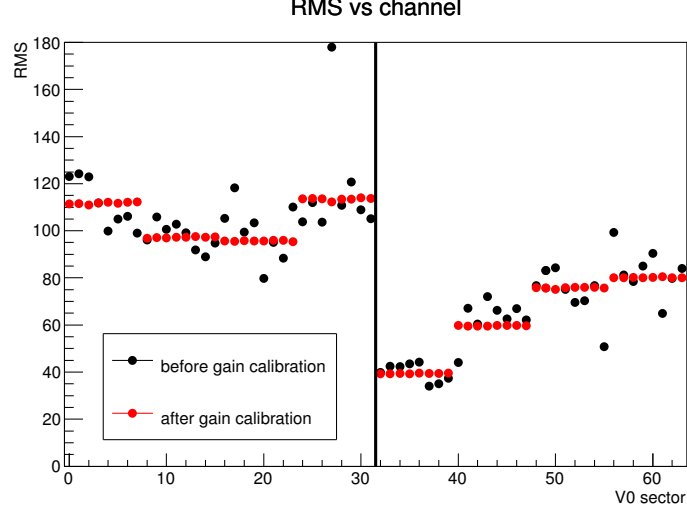


Figure 5.6: RMS of the V0 multiplicity distribution before (black) and after (red) gain equalization. Channels numbered from 0 to 31 correspond to V0C, channels numbered from 32 to 63 correspond to V0A.

where Q_n and σ_n are the mean value and the width of the $Q_x(Q_y)$ distribution, respectively and n is the harmonic number.

The distributions of the flow vector, after the calibration procedure, as a function of centrality are shown in Fig. 5.7, for V0A and V0C. The projection for the centrality bin 0-1% and 30-31% is shown in the bottom panel. This procedure ensures a correct evaluation of the q-vector, with flat event-plane angle distribution [7], shown in Fig. 5.8 for V0A and V0C. The q_2 size follows the v_2 distribution as a function of centrality, with higher values for semi-central collisions with respect to central ones. This is due to the residual multiplicity dependence of the reduced q-vector (see section 2.4.1 for details). The q_2 from V0A and from V0C, labelled as q_2^{V0A} and q_2^{V0C} , have different lengths, since V0A and V0C have different η coverage, i.e. different flow sensitivity and multiplicities (both flow and $dN/d\eta$ are smaller at forward rapidity [12, 13]).

The q_2 integrated distribution, shown in Fig. 5.9 for V0A and V0C, allows to select the samples with the 10% highest and 10% lowest q_2 . In the following, we refer to these two classes of events as “large- q_2 ” and “small- q_2 ” or, generically, as ESE-selected events. For instance, in Fig. 5.10 the q_2 distribution in the 30-40% centrality bin for the large- q_2 ($q_2 > 3.8$) sample is reported in green, while the small- q_2 ($q_2 < 0.8$) is in blue.

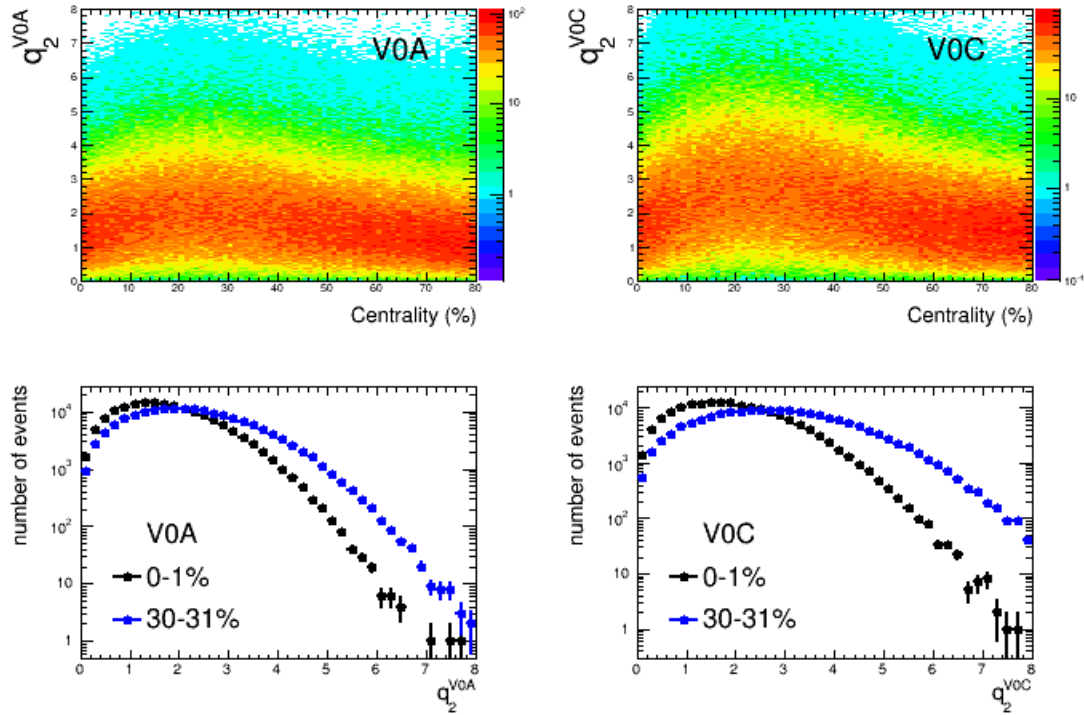


Figure 5.7: q-vector as a function of centrality (top), q-vector projection for centrality bin 0-1% and 30-31% (bottom) for V0A (left) and V0C (right).

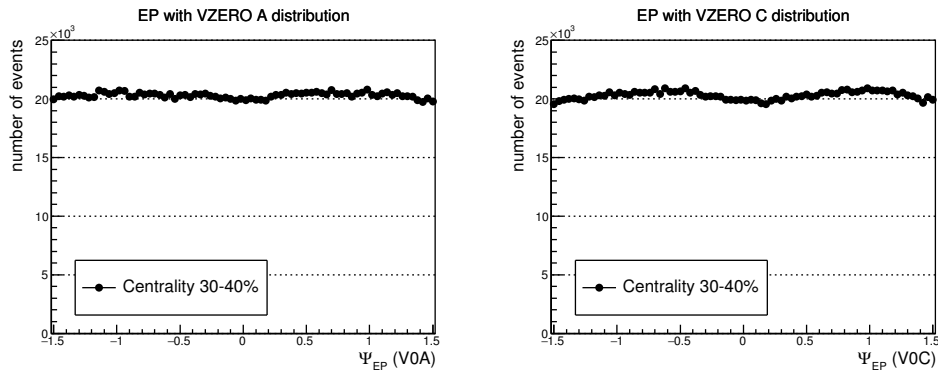


Figure 5.8: Event-plane angle distribution for V0A (left) and V0C (right) after calibration in the 30-40% centrality class.

Multiplicity bias

A selection based on the absolute q_2 value in a large centrality class can introduce a multiplicity bias, due to the q_2 multiplicity dependence. The largest bias

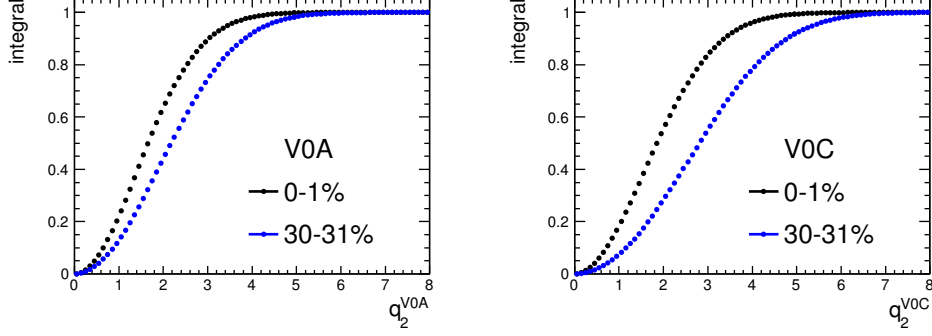


Figure 5.9: q_2 integrated distribution for centrality bins 0-1% and 30-31% for V0A (left) and V0C (right).

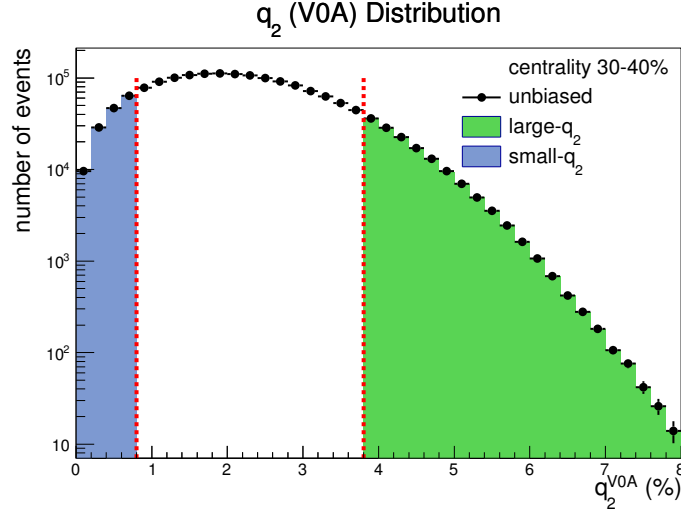


Figure 5.10: q_2 distribution with 10% large (green) and 10% small (blue) sample, in 30-40%. $q_2 < 0.8$ correspond to 10% small- q_2 events, with $q_2 > 3.8$ corresponds to 10% large- q_2 events.

has been observed in 30-40%, therefore we refer to this centrality class in the study discussed below.

The elliptic flow increases with decreasing centrality (Fig. 5.11) up to centrality $\approx 40\%$, then the trend is inverted. On the other hand, the q_2 depends both on multiplicity and flow, so it peaks at a different centrality ($\sim 20\%$, Fig. 5.7 top). When selecting events with a large value of q_2 , using an absolute cut on the value of q_2 , we would expect to bias the sample towards the maximum of the q_2 vs centrality distribution, that is towards smaller multiplicities for events below centrality $\approx 20\%$ and larger multiplicities above $\approx 20\%$.

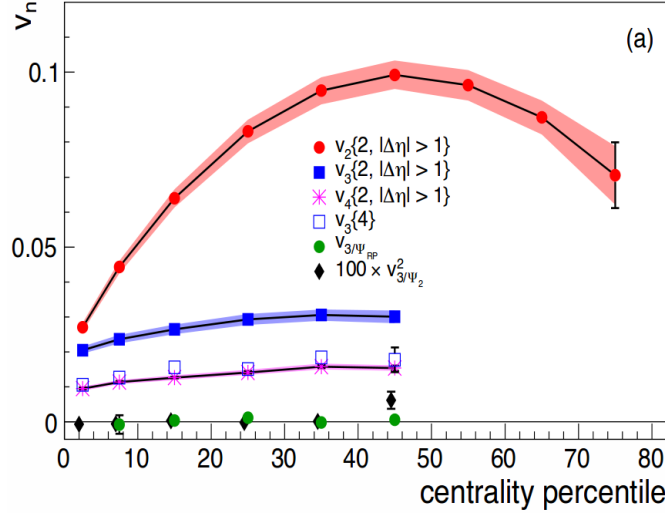
Figure 5.11: v_2 distribution from [14].

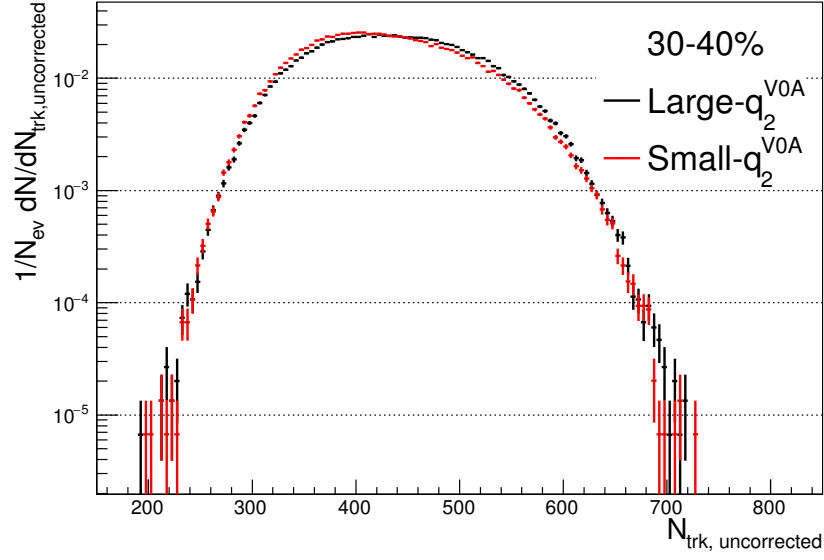
Figure 5.12(a) shows the distribution of the raw number of charged tracks in the TPC ($|\eta| < 0.8$), $N_{trk,uncorrected}$, for large- q_2 and small- q_2 events sample in the 30-40% centrality bin, while the ratio between events in the large- q_2 sample to the unbiased sample is shown in Fig. 5.12(b). The $N_{trk,uncorrected}$ distribution for large- q_2 is shifted towards large multiplicity, as expected from the q_2 centrality dependence.

Fig. 5.13 shows the raw $dN/d\eta$ (or charged tracks multiplicity) measured in the TPC ($|\eta| < 0.8$) distribution as a function of the flow vector, here reported normalized so that $dN/d\eta = 1$ for $q_2 = 0.1$. The yield is seen to decrease for large q_2 as shown for 0-5%, where the v_2 is smaller and is essentially dominated by fluctuations. The yield is almost flat for 20-30% and it increases with the q_2 in 30-40%, following the q_2 centrality dependence.

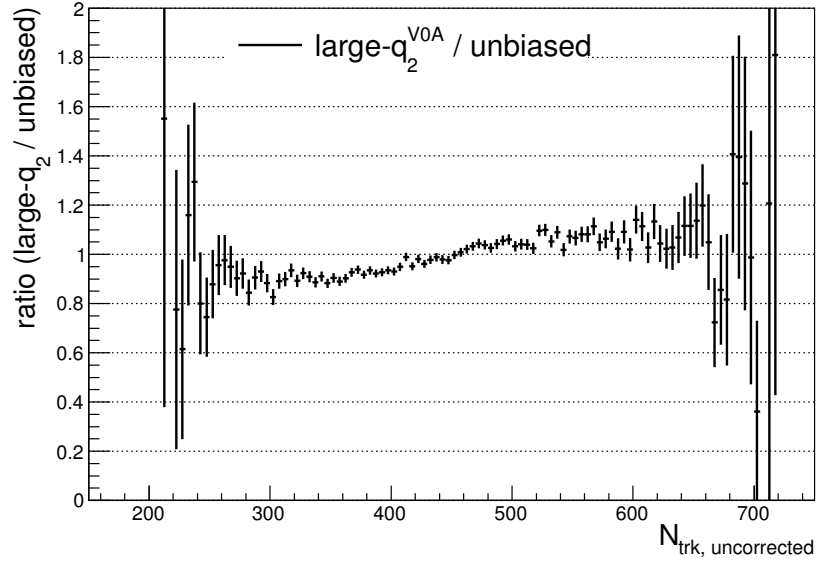
A cut on a fixed q_2 value doesn't correspond on cutting on the same q quantile in a large centrality bin (e.g. 30-40%). Since as we will see, the effect on spectra which we want to measure is small, this small multiplicity bias has the potential to spoil the genuine effect due to the q -vector selection

To avoid this bias and to flatten the q_2 centrality dependence, the q_2 selection has been calibrated in fine centrality bins. The integrated q_2 distribution has been obtained for every 1% wide centrality bin (between 0% to 80%). The integrated distribution as a function of centrality, for V0A and V0C, is shown in Fig. 5.14 (top).

Then each slice is fitted with a spline interpolation [15], as shown in Fig. 5.14 (bottom). This procedure allows us to cut on a well-defined q_2 quantile, rather than on an absolute value, thus removing the trivial multiplicity bias.



(a)



(b)

Figure 5.12: (a) Raw $N_{\text{trk,uncorrected}}$ distribution in the TPC ($|\eta| < 0.8$) for the large- q_2 and small- q_2 sample. (b) $N_{\text{trk,uncorrected}}$ ratio large- q_2 to unbiased sample.

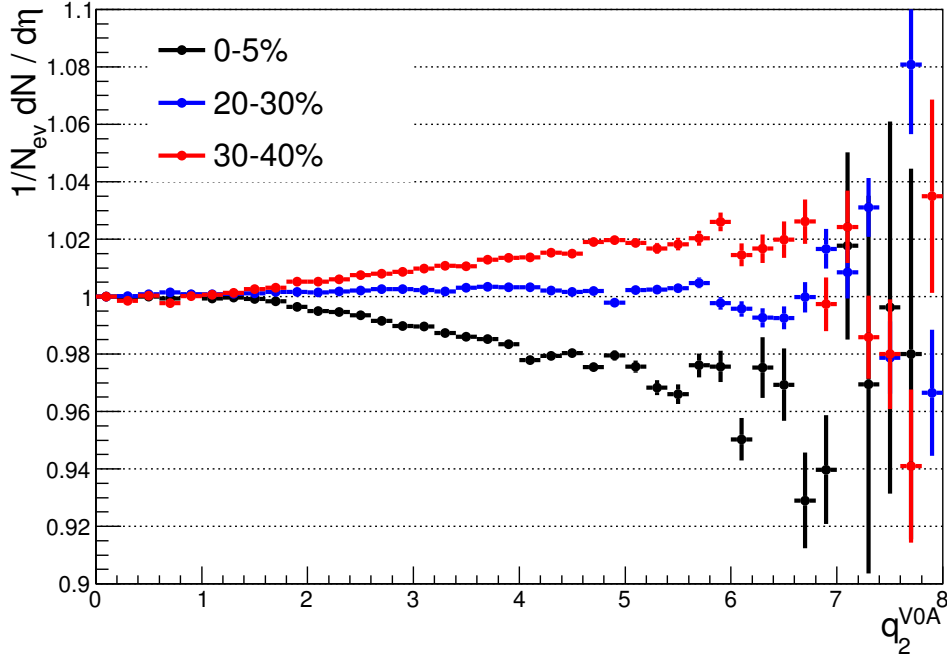


Figure 5.13: $dN/d\eta$ ($|\eta| < 0.8$) distribution as a function of q_2^{V0A} normalized so that $dN/d\eta = 1$ for $q_2^{V0A} = 0.1$, for three centrality bins: 0-5%, 20-30%, 30-40%.

The resulting distribution for V0A and V0C of the q_2 percentile is shown in Fig. 5.15. The distribution is flat, both for V0A and V0C.

As a further test of the calibration procedure, in the 30-40% centrality bin, the $N_{\text{trk,uncorrected}}$ distribution and the yields have been evaluated in large- q_2 and small- q_2 events. Figure 5.16 show the $N_{\text{trk,uncorrected}}$ distribution for large (black) and small (red) q_2 events, obtained after the calibration procedure. The ratio between events in the large- q_2 sample to the unbiased sample is reported Fig. 5.17. The ratio distribution is essentially flat, with only a minor shift towards small multiplicities. Figure 5.18(a) shows the yield $dN/d\eta$ as a function of the q_2 percentile, for two centralities 0-5% and 30-40%, normalized to the mean (obtained by fitting with a degree 0 polynomial the distribution in the q-vector range 20-60%): the distribution is almost flat. The check has been repeated in 1% wide centrality bins, for the 30-40% interval, and it is shown in Fig. 5.18(b). The yields are independent of q_2 for all the centrality bins. Therefore we can conclude that after this calibration, any residual multiplicity bias is negligible.

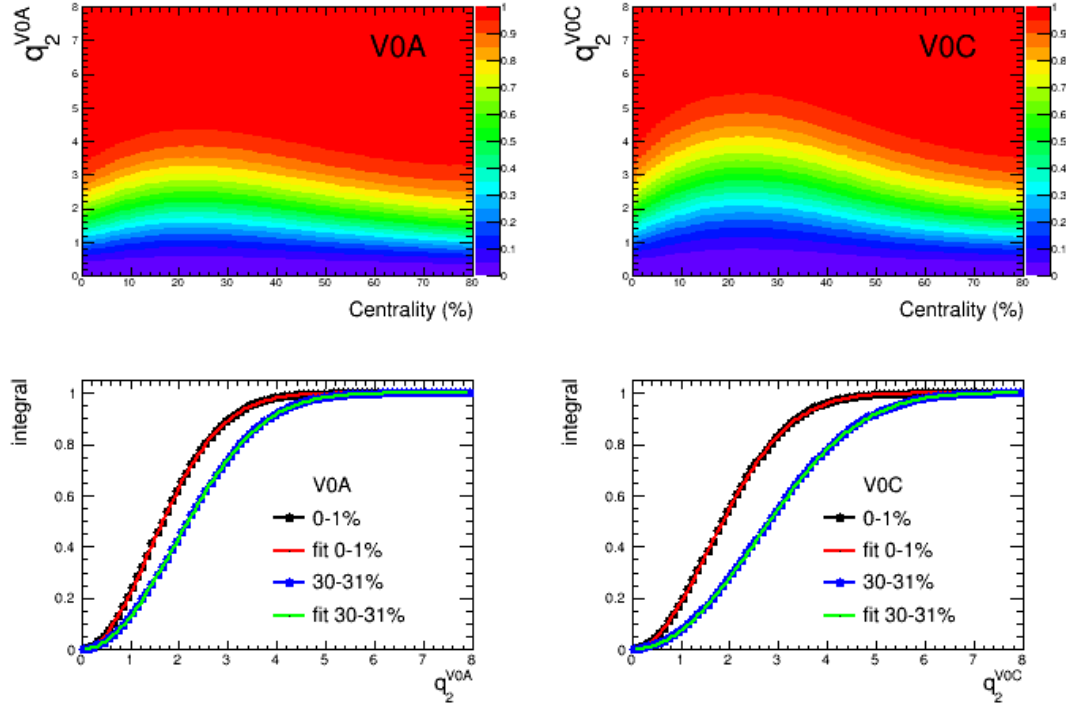


Figure 5.14: q_2 integrated distribution as a function of centrality for V0A (left). and the integrated distribution (right) fitted with a spline interpolation (red) in the centrality bin 30-31%.

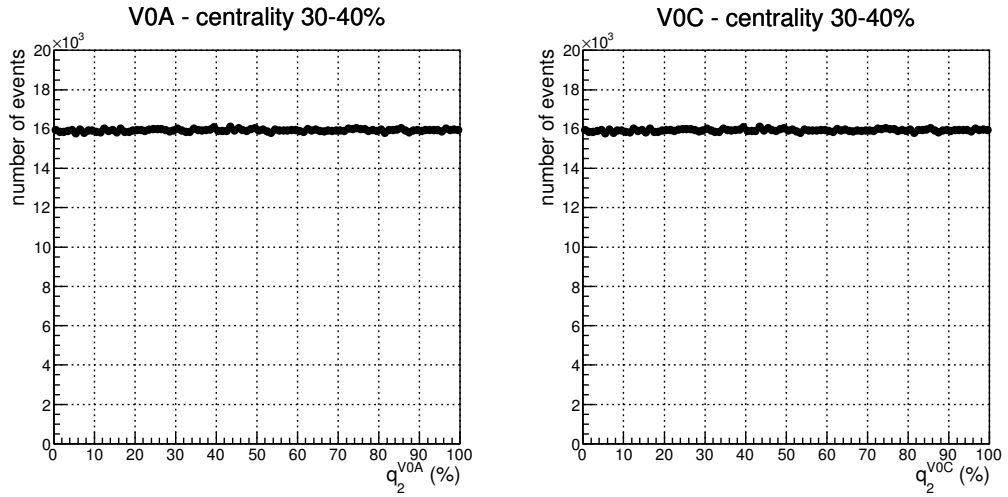


Figure 5.15: q_2 percentile distribution for V0A and V0C for centrality 30-40%.

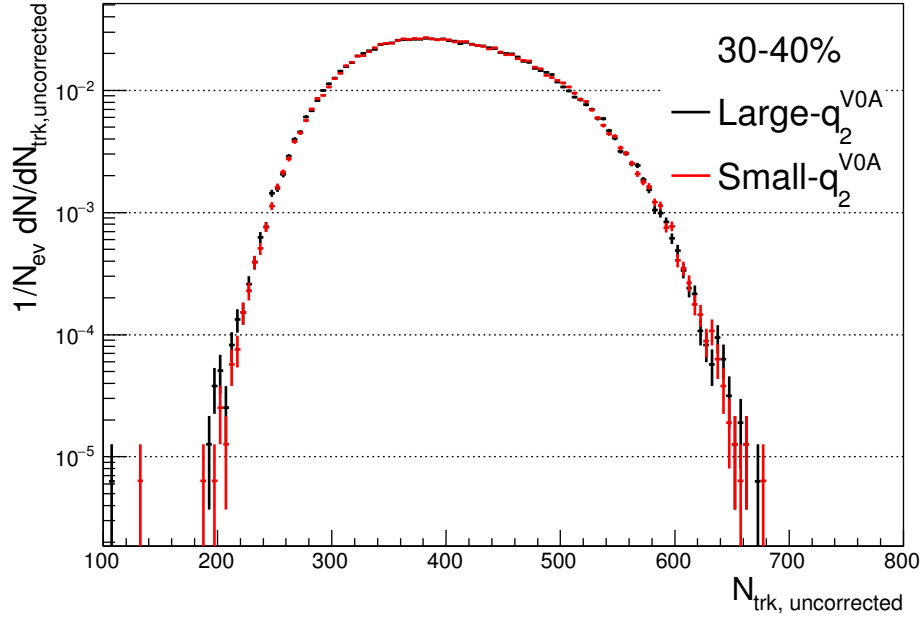


Figure 5.16: Raw $N_{\text{trk,uncorrected}}$ distribution in the TPC ($|\eta| < 0.8$) for the small- q_2 and the large- q_2 sample, for 30-40% centrality class.

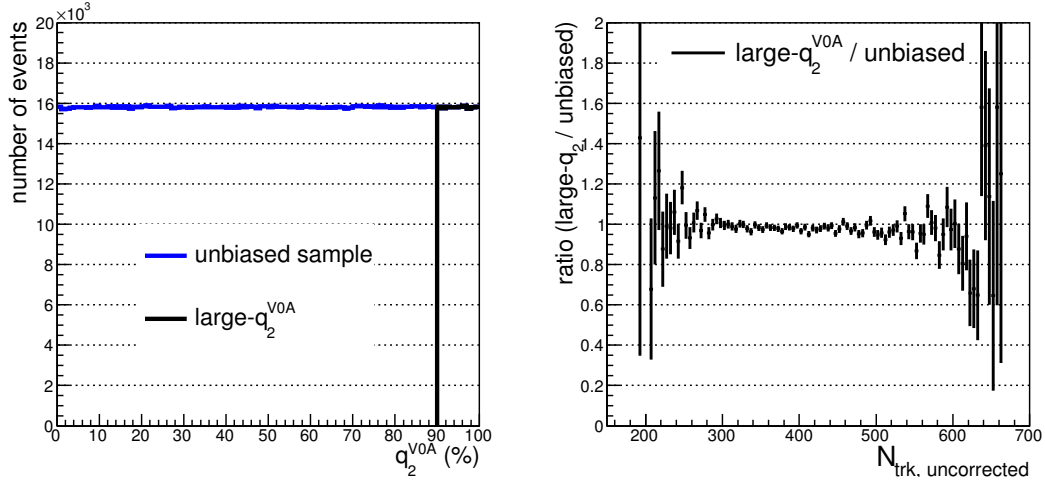


Figure 5.17: $N_{\text{trk,uncorrected}}$ ratio between large- q_2 sample and unbiased sample.

TPC q -vector Two main aspects define the performance of the event shape selection: the pseudorapidity coverage of the detector and the non-flow correlations between subevents involved in event selection. The latter can be studied mea-

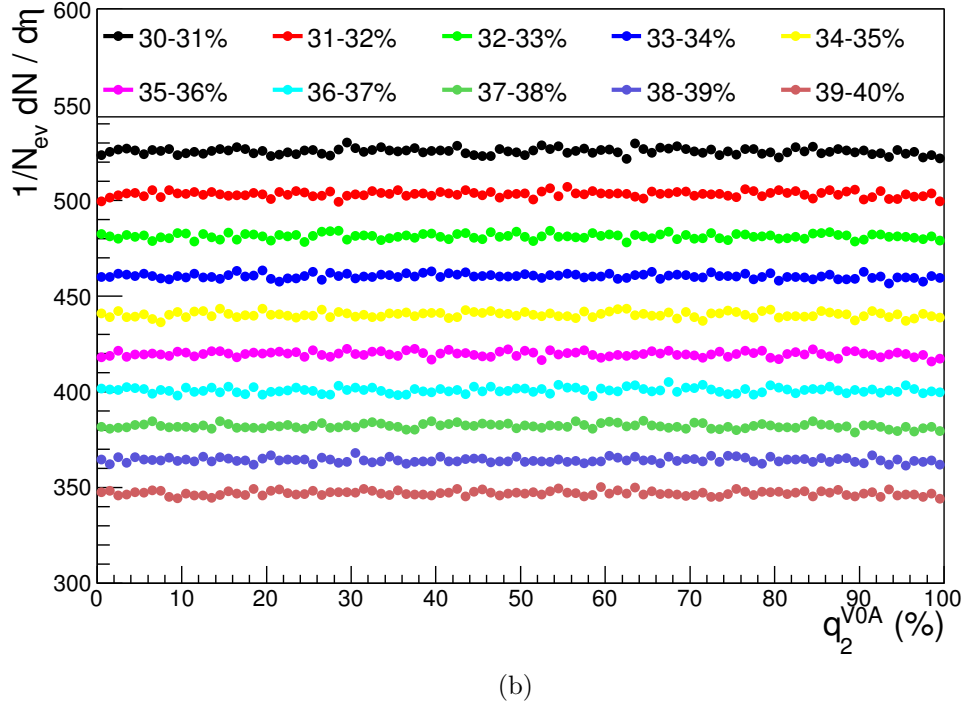
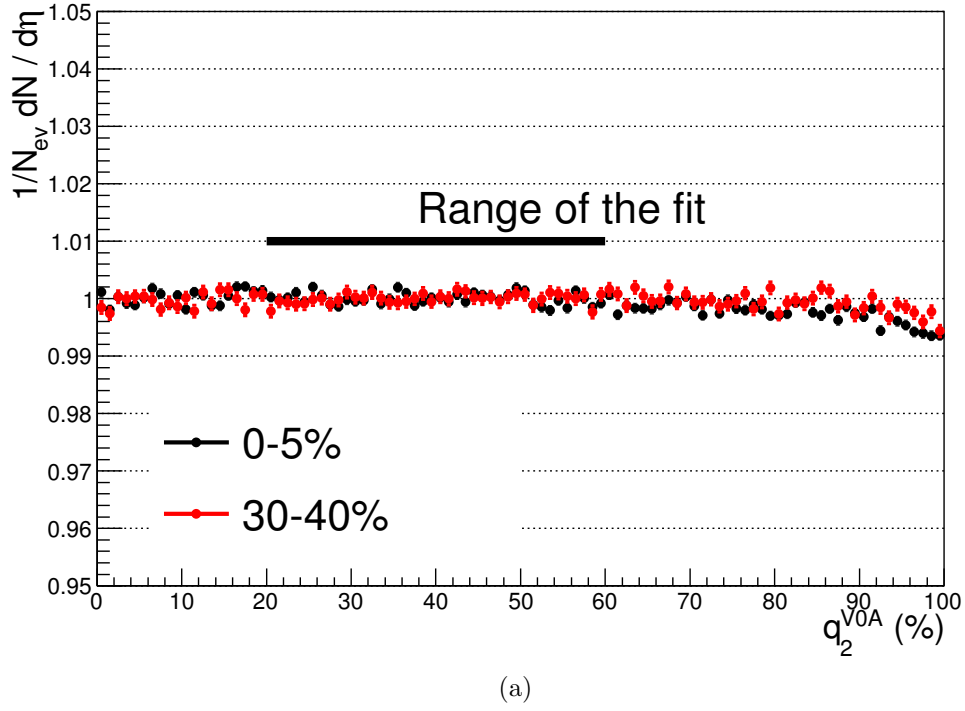


Figure 5.18: (a) $dN/d\eta$ as a function of the q_2 percentile for 0-5% and 30-40%, normalized to the mean retrieved by fitting with a 0 degree polynomial the distribution in the q_2 range 20-60%. (b) $dN/d\eta$ as a function of q_2^{V0A} in 1% wide centrality bin from 30% to 40%.

asuring physics observables in the same pseudorapidity window of the event shape selection.

Therefore, the q_2 percentile has been computed using TPC tracks (q_2^{TPC}) within $-0.5 < \eta < 0.5$, with the same procedure used for the q_2 from V0s. The result of this procedure is shown in Fig. 5.19 and Fig. 5.20. Also in this case the q_2 percentile distribution is flat.

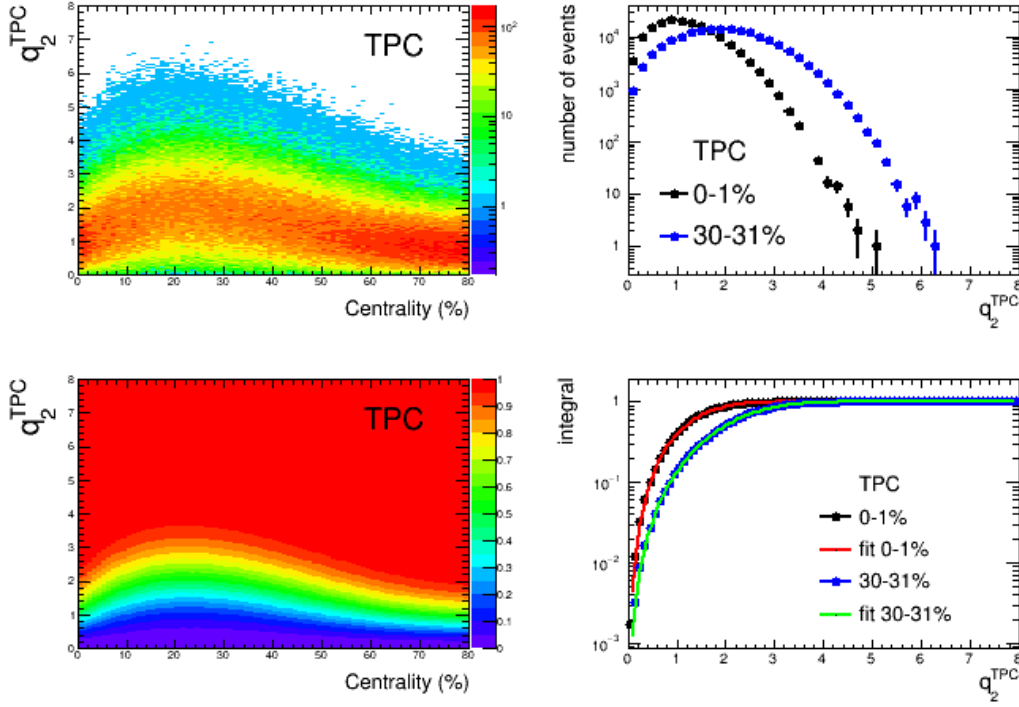


Figure 5.19: (top-left) q_2^{TPC} calibration procedure: q_2 vs centrality, (top-right) q_2^{V0C} distribution in 0-1% and 30-31% centrality bin, (bottom-left) q_2 integral distribution as a function of centrality, (bottom-right) q_2^{TPC} integral distribution in 0-1% and 30-31%.

5.2.1 Flow vector studies in AMPT model

AMPT (A Multi-Phase Transport model) [16–18] is an event generator, which includes both an initial partonic phase and final hadronic scattering. The multi-phase design of AMPT makes it well suited for studies of collective phenomena, e.g. anisotropic transverse v_n .

It uses the HIJING model [19] for the generation of initial conditions while changing the treatment of the resulting collision evolution. It takes the hard mini

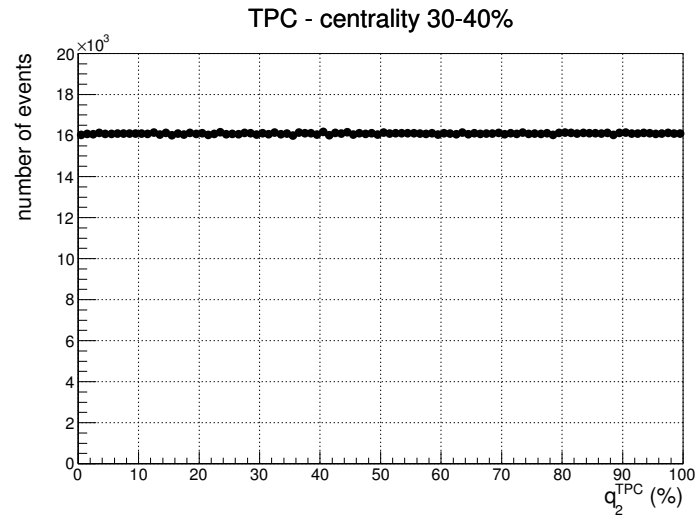
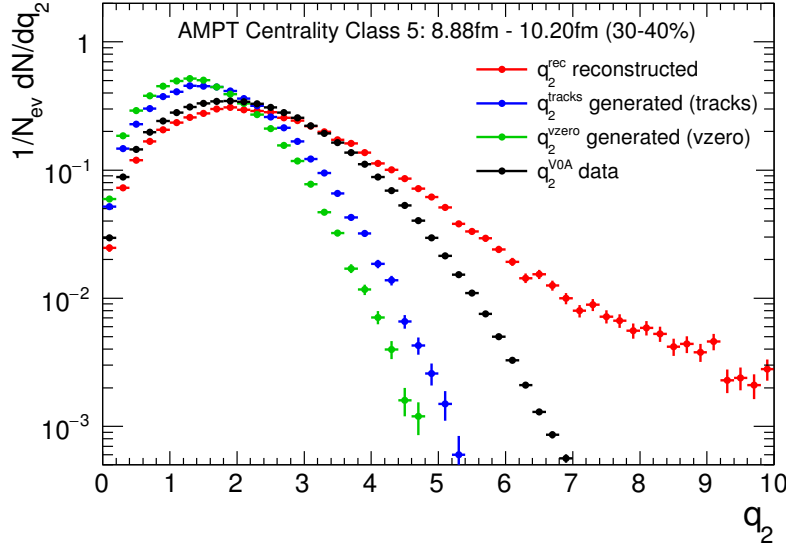


Figure 5.20: q_2 percentile distribution for TPC for centrality 30-40%.

Figure 5.21: q_2 distribution in AMPT.

jets and soft strings from HIJING to generate the initial conditions. Then the Zhang's Parton Cascade Model (ZPC) is used for partonic (quarks and gluons) scatterings and A Relativistic Transport Model (ART) is used for the hadronic scatterings after the phase transition. By combining all of these models AMPT is able to describe heavy ion data reasonably well.

AMPT has been used to study the systematic uncertainties in large- q_2 and small- q_2 event samples. The Monte Carlo production used in the present study has been tuned to reproduce the charged tracks multiplicity of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the 30-40% centrality bin.

The q_2 has been evaluated by using simulated V0s signals in AMPT, q_2^{rec} in the following. It is shown in Fig. 5.21, compared to the q_2^{V0A} from data. The q_2 has been also evaluated at generator level, taking into account all the tracks in the V0s acceptance. It is labelled as q_2^{tracks} in Fig. 5.21. Moreover, the V0s segmentation has been taken into account by assigning to each generated track the azimuthal angle ϕ of the corresponding V0 sector and weighting each one for the V0 reconstruction efficiency. It is labelled as q_2^{vzero} in Fig. 5.21. The VZERO signal is not well reproduced in the Monte Carlo simulation and show a tail in the q_2 distribution, which is not seen in the data. On the other hand the q_2 from the generated tracks shows a smaller dynamic range, with respect to data.

In order to study the elliptic flow and p_T spectra in AMPT ESE-selected events, the same flow vector calibration used for the data has been applied. The result of

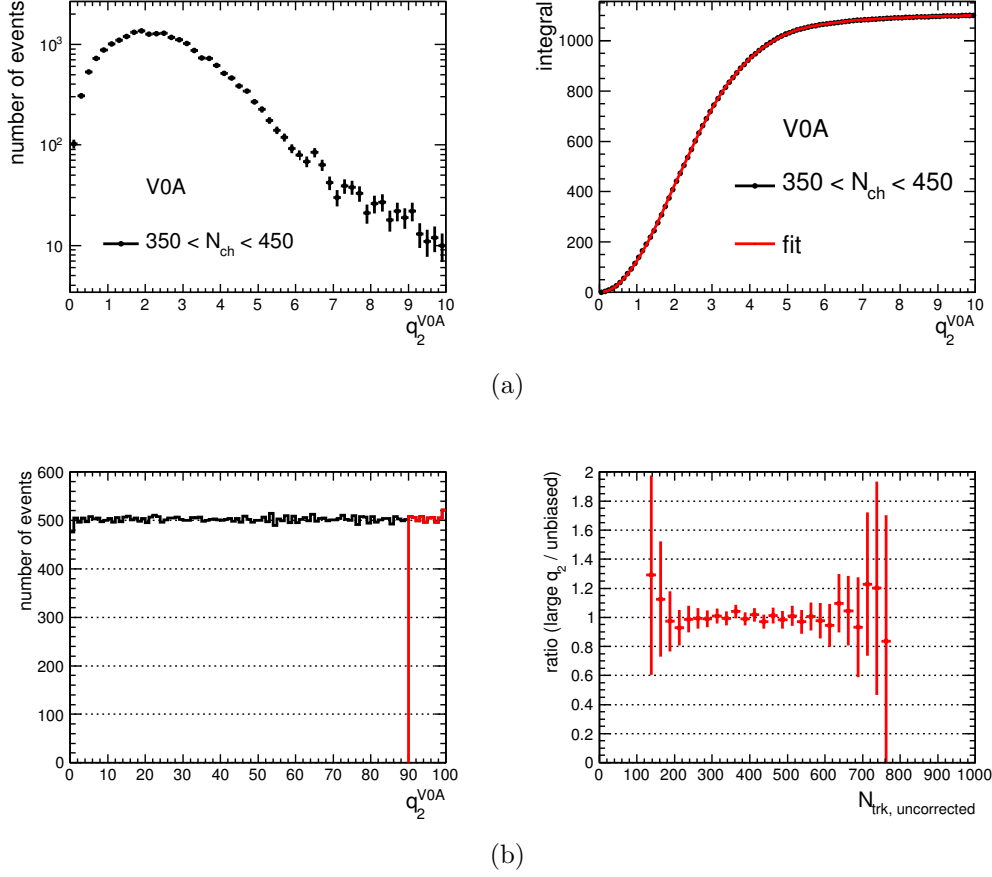


Figure 5.22: (a) q_2 distribution for $350 < N_{ch} < 450$ (left) and q_2 integral distribution in the same multiplicity bin (right). (b) q -vector percentile distribution for unbiased and large- q_2 sample (left). N_{ch} ratio large- q_2 to unbiased sample (right).

this procedure is shown in Fig. 5.22(a): q_2 distribution is shown for $350 < N_{ch} < 450$, while the corresponding integral distribution is shown on the right.

Finally a flat q_2 distribution can be obtained by using the fit of the integral distribution, obtained via spline interpolation: the distribution, shown in 5.22(b), is flat. The ratio between the N_{ch} distribution in large- q_2 and unbiased events is reported on the left as a function of N_{ch} : the ratio is close to unity and it doesn't depend on N_{ch} , ensuring that also in AMPT the multiplicity bias is negligible.

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Elliptic flow in ESE selected events

In this chapter analysis method for the measurement of elliptic flow coefficient v_2 for inclusive charged particles (h) in event-shape-selected events, in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV is discussed. The v_2 has been measured for primary particles, defined as particles produced directly in the collision or in the decay of short-lived resonances or muons and not particles from the weak decays of strange hadrons or from interactions with material.

The results are obtained with the *Scalar Product* method, a two-particle correlation technique, using a pseudo-rapidity gap of $|\Delta\eta| > 1$ between the hadron under study and the reference particles. The v_2 is reported for the pseudo-rapidity range $|\eta| < 0.8$ as a function of transverse momentum p_T .

The aim of this section is to give a detailed description of the v_2 analysis in event shaped events and of the systematic uncertainties associated to this measurement. The discussion on the interpretation of these results will be presented in detail in chapter 8.

6.1 Track selection

The events which pass the basic selection described in sec. 5.1 are used to evaluate the elliptic flow coefficient.

The analysis has been performed using tracks measured only with the TPC constrained to SPD vertex. The track quality cuts are applied to minimize contamination from secondary charged particles and fake tracks [1]. Tracks are required to have at least 70 TPC clusters out of 159 and a $\chi^2 \leq 4$ per TPC cluster. Tracks with a transverse Distance of Closest Approach to the vertex $\text{DCA}_{xy} > 2.4$ cm and a longitudinal distance of closest approach $\text{DCA}_z > 3.2$ cm are rejected to reduce the contamination from secondary tracks. Tracks are selected within the pseudo-

rapidity range $|\eta| < 0.8$, and in the transverse momentum region $0.2 < p_T < 20$ GeV/c.

6.2 Scalar product method

The v_n coefficients can be extracted directly from the reconstructed tracks [2–9] using the Scalar Product (SP) method [10, 11], extensively used in ALICE flow analysis ([12, 13]):

$$v_n\{SP\} = \frac{\langle \mathbf{u}_{n,k} \mathbf{Q}_n^* / M \rangle}{\sqrt{\mathbf{Q}_n^a \mathbf{Q}_n^{b*} / M^a M^b}} \quad (6.1)$$

where ϕ_k is the angle of the Particle Of Interest (POI) k , $\mathbf{u}_{n,k} = \exp(in\phi_k)$ is the unit vector of the particle k , $\mathbf{Q}_n = \sum_l \exp(in\phi_l)$ is the event flow vector, where the sum runs over all azimuthal particle angles, M is the event multiplicity, and n is the harmonic number. The full event is divided into two independent sub-events a and b based on different pseudorapidity intervals with flow vectors $\mathbf{Q}_n^a$ and $\mathbf{Q}_n^b$ and multiplicities M_a and M_b . The angle brackets denote an average over all particles in all events.

Each POI is correlated with all other unidentified particles, named Reference Particles (RPs), used to determine $\mathbf{Q}_n$. A gap in pseudorapidity ($|\Delta\eta| > 1$) between POI and RPs is used to reduce non-flow correlations. The two sub-events a and b are defined within the pseudorapidity range $-0.8 < \eta < -0.5$ and $0.5 < \eta < 0.8$, respectively. If the POI is taken from the sub-event a , the RP is taken from the sub-event b (and vice-versa).

This method weights events with the magnitude of the $\mathbf{Q}_n$ vector. If $\mathbf{Q}_n$ is replaced by its unit vector, the above reduces to $\langle \cos n(\phi - \Psi_{RP}) \rangle$, i.e. the conventional Event Plane (EP) method [2, 10].

In general, the event-plane method yields a result which depends on the reaction plane resolution: in the limit of perfect resolution $v_n\{EP\}$ does indeed measure the event-averaged mean $\langle v_n \rangle$. In reality, the resolution is not perfect and in the low resolution limit $\langle v_n \rangle$ yields a root-mean-square value $\sqrt{\langle v_n^2 \rangle}$. In general, the event-plane method yields a result which is between these two limits. The scalar product method gives a well-defined measurement, since it always yields the root-mean-square of v_n , regardless of the details of the analysis [10, 11]. In addition, it is very simple to implement.

The $v_2\{SP\}$ results for charged particles are compared with the results obtained using the two-particle correlation method ($v_2\{2\}$) and already published by the ALICE Collaboration in [1] in Fig. 6.1. A good agreement ($< 5\%$) is observed in the most central event class (0-5%) and for semicentral collisions (30-40%). The residual discrepancy is due to the different data processing step used for the published data and those used in this analysis.

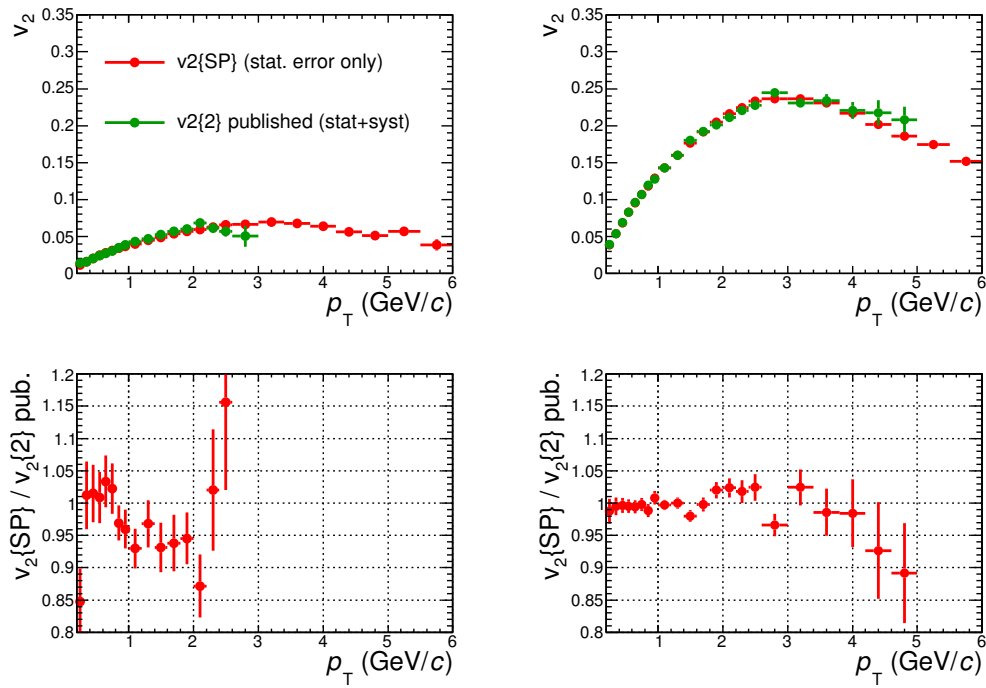


Figure 6.1: Comparison between the published results and the this analysis in PbPb 0-5% and 30-40% centrality.

TPC non uniformities could affect the v_2 measurement with the contribution of additional terms, e.g. proportional to $\langle \sin(2\phi) \rangle$ and $\langle \cos(2\phi) \rangle$, that for a detector with full uniform azimuthal coverage are identical to zero (see appendix A). To test the uniformity of the ϕ acceptance the $\langle \sin(2\phi) \rangle$ and $\langle \cos(2\phi) \rangle$ as a function of p_T were checked, in each centrality bin. Fig. 6.2-6.3 show the distributions for $\langle \sin(2\phi) \rangle$ and $\langle \cos(2\phi) \rangle$ in 30-40%, fitted with a zero-degree polynomial. The distributions are compatible with zero and the systematic errors associated to the non uniform acceptance of the detector are negligible, with respect to the systematic error obtained by varying the track selection (see section 6.3).

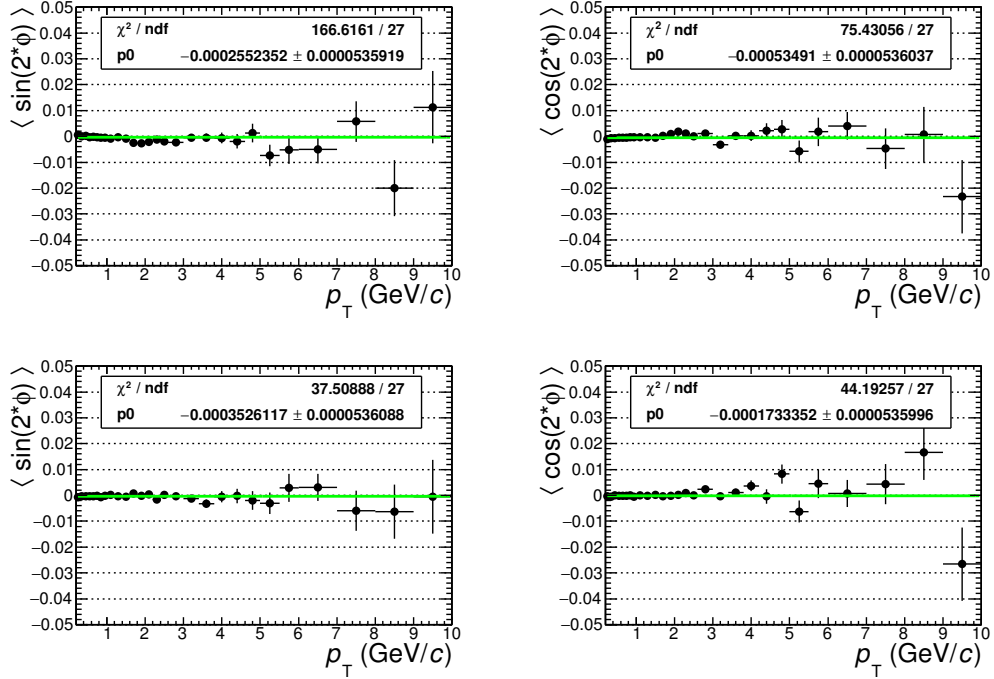


Figure 6.2: $\langle \sin(2\phi) \rangle$ and $\langle \cos(2\phi) \rangle$ for the reference particles in 30-40% centrality bin.

6.3 Study of systematic uncertainties in the v_2 measurement

Systematic uncertainties for the elliptic flow measurement are here discussed for $v_2\{\text{SP}\}$ in large- q_2 , small- q_2 and unbiased events and for the ratios large- q_2 (small- q_2) to unbiased events.

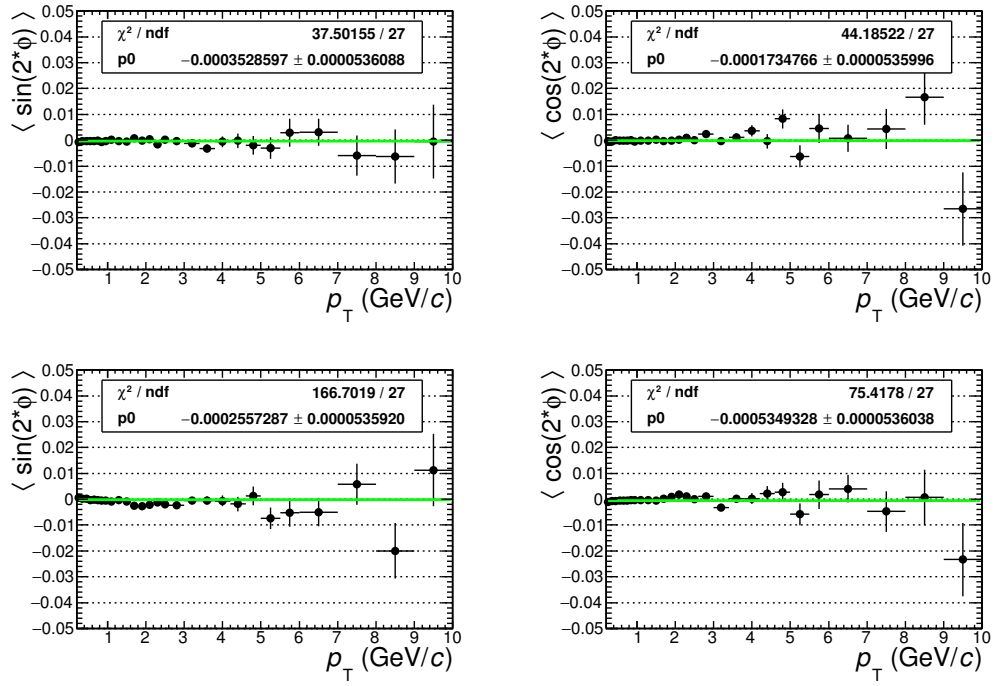


Figure 6.3: $\langle \sin(2\phi) \rangle$ and $\langle \cos(2\phi) \rangle$ for the particles of interest in 30-40% centrality bin.

Various systematic studies have been used to estimate the systematic uncertainties, for instance variations of track cuts or the study of the detector response with Monte-Carlo (MC) simulations. The different sources, described below, are estimated for every centrality separately.

The difference between the result obtained for a given track variation and the main result extracted using the default selection criteria is computed. This variation is considered significant only if it is larger than the expected statistical uncertainty between the two samples and the variation is added as systematic uncertainty. The significance is estimated using the procedure described in [14] and reported in the appendix B. If the variation is found negligible, no systematic error is assigned. Each contribution is divided by $\sqrt{2}$ to estimate the Root Mean Square (RMS) deviation of the values from the mean, under the assumption of a gaussian distributed sample of measurements [14, 15]. The total systematic uncertainty is calculated as the quadratic sum of these individual contributions.

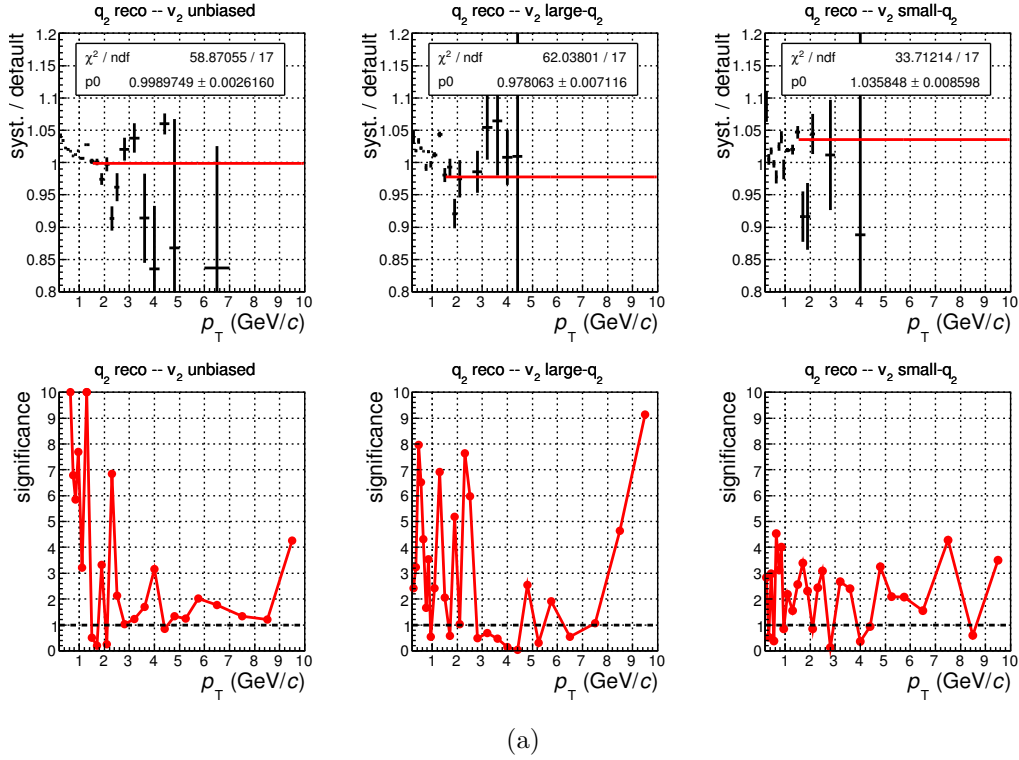
The v_2 measurement is done under the assumption that effects such as detector efficiency and secondary particles contamination do not affect $v_2\{\text{SP}\}$. This assumption is tested by applying the same analysis procedure to AMPT events (see section 5.2.1), comparing the $v_2\{\text{SP}\}$ with the values extracted from Monte Carlo particles. The results are presented in Fig. 6.4 for the 30-40% centrality class. The discrepancy between reconstructed v_2 values and true results from AMPT is found to be $\approx 0.1\%$, for $p_T > 1$ GeV/c. For $p_T < 1$ GeV/c the discrepancy increases up to 4%, mainly due to secondary contamination. This is due to the fact that TPC-only track are used, which have loose DCA cuts. The alternative use of global tracks would introduce even larger uncertainties due to non uniformity of the detector.

The uncertainty on the tracking efficiency has been studied using pure TPC tracks (not constrained to the primary vertex) and varying the minimum number of TPC clusters required in the analysis. This uncertainty obtained by varying the track cuts is found to be of the order of 0.3%.

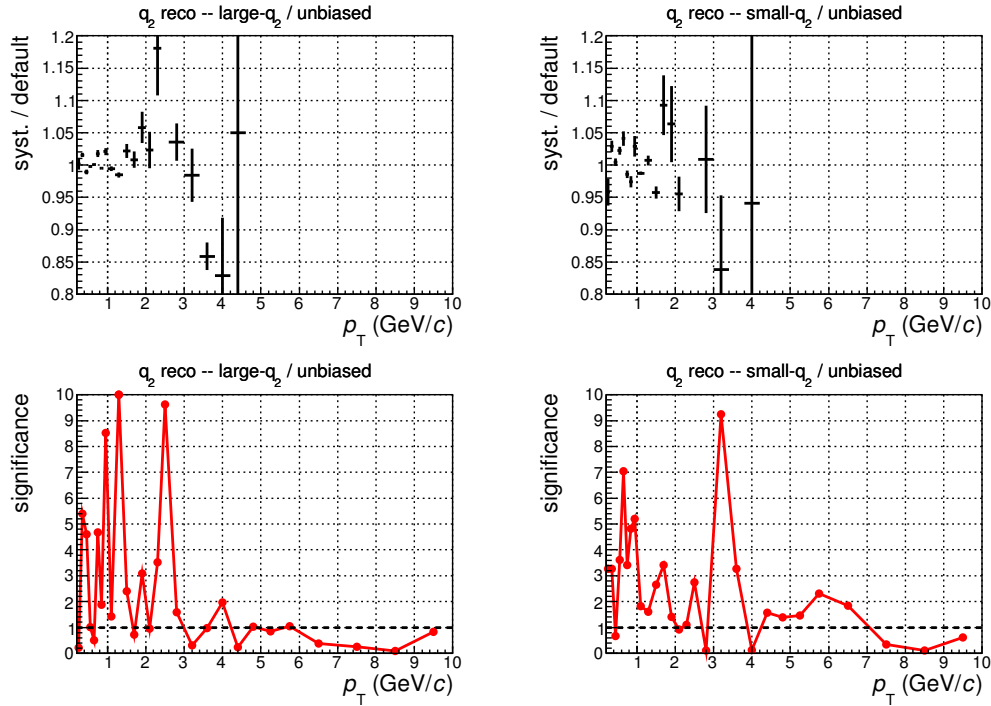
The effect of the tracking efficiency on v_2 coefficient in event shaped events has been also tested applying track-by-track weights corresponding to the tracking efficiency. It is defined as

$$\epsilon_{\text{tracking}} = \frac{\text{reconstructed primary tracks}}{\text{generated primary tracks}} \quad (6.2)$$

and it has been determined from MC for inclusive charged particles for different centrality classes (Fig. 6.5). The tracking efficiency inverse has been used as weight in the $\mathbf{u}$ and $\mathbf{Q}$ vectors determination from Eq. (6.1). A good agreement is found between efficiency uncorrected and corrected $v_2(p_T)$ in large- q_2 , small- q_2 and unbiased events for different centrality classes for charged hadrons, with differences within 0.5%.



(a)



(b)

Figure 6.4: Ratio between reconstructed and Monte Carlo truth $v_2(p_T)$ for charged hadrons in unbiased, large- q_2 and small- q_2 events (a) and for the ratios large- q_2 (small- q_2) to unbiased. The significance of the systematic check is reported in the bottom panels.

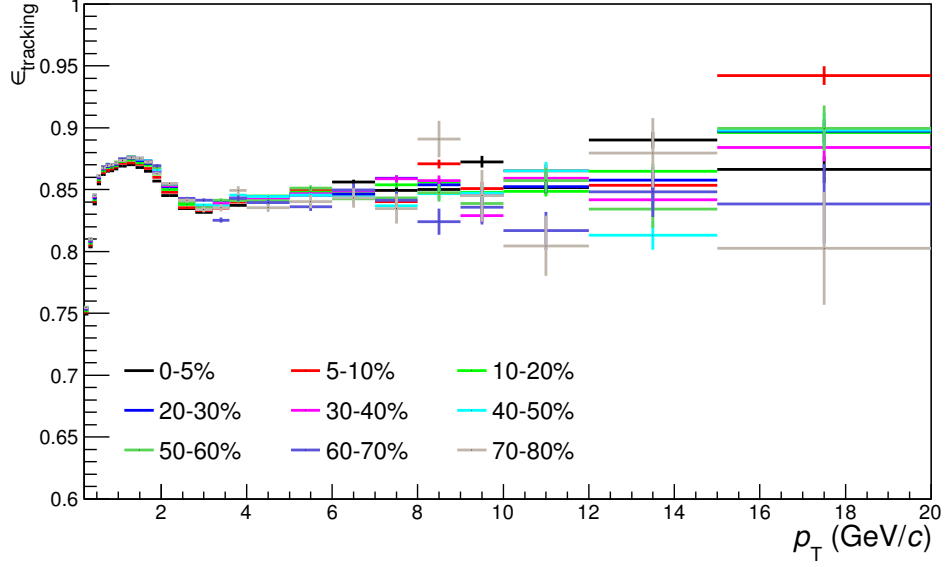


Figure 6.5: Tracking efficiency in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, evaluated in Monte Carlo.

The Glauber procedure used to estimate the centrality in Pb–Pb collisions with V0 detectors leads to a 1% uncertainty on the definition of the classes [16]. In order to propagate this uncertainty to the results here presented the measurement is repeated by shifting the centrality percentiles by 1%. This uncertainty is found to be 0.5%. The centrality estimator was changed, using tracks multiplicity in the TPC instead of V0 amplitude to evaluate the centrality percentile. The related uncertainty is of the order of 0.8%.

As a further systematic check the results from events collected with different magnetic field polarities, from positive and negative particles separately did not exhibit any systematic change for any centrality. The analysis has been repeated changing the cut on the position of the primary vertex along the beam axis (V_z) from ± 10 cm to $-10 < V_z < 0$ and $0 < V_z < 10$. Also in this case the differences are negligible.

Summary of systematic error

The different sources of systematic error are summarized in Tab. 6.1 and Tab. 6.2.

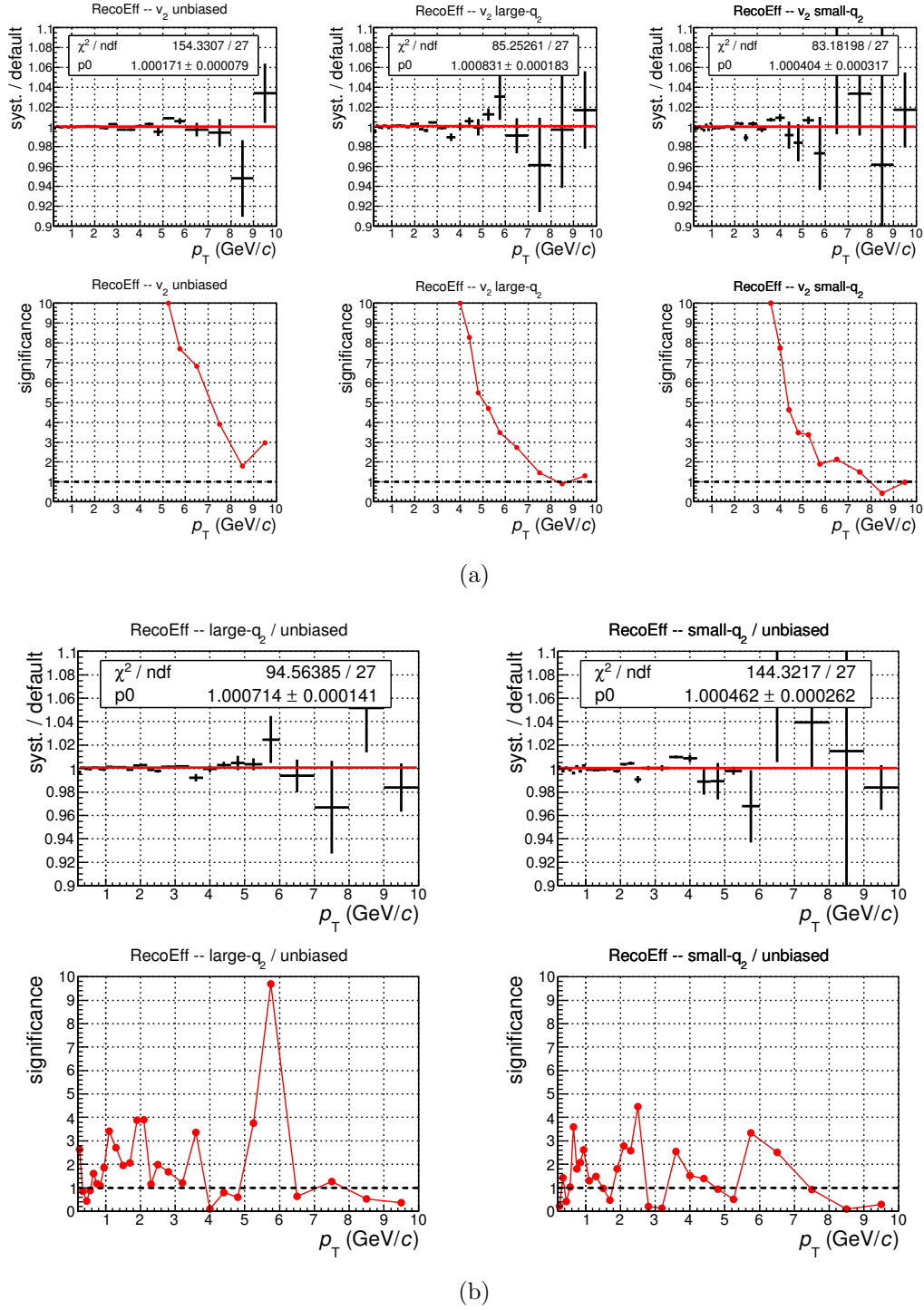


Figure 6.6: Ratio between efficiency uncorrected and corrected $v_2(p_T)$ for inclusive charged particles in the 30-40% centrality class (top panel) and significance distribution as a function of p_T in large- q_2 , small- q_2 and unbiased events (a) and the ratios large- q_2 (small- q_2) over unbiased event sample (b).

effect	$v_2\{\text{SP}\}$	$v_2\{\text{SP}\}$ large- q_2	$v_2\{\text{SP}\}$ small- q_2
magnetic Field	NS	NS	NS
charge	NS	NS	NS
vertex	NS	NS	NS
track reconstruction	negligible	0.1%	0.2%
centrality resolution	0.2%	0.35%	0.35%
centrality estimator	0.6%	0.50%	0.60%
tracking efficiency	0.07%	0.35%	0.15 %
MC closure	2.85%	2.85%	2.85%
	$(p_T = 0.2 \text{ GeV}/c)$	$(p_T = 0.2 \text{ GeV}/c)$	$(p_T = 0.2 \text{ GeV}/c)$
	0.7%	0.7%	0.7%
	$(p_T = 1.5 \text{ GeV}/c)$	$(p_T = 1.5 \text{ GeV}/c)$	$(p_T = 1.5 \text{ GeV}/c)$

Table 6.1: Summary of systematic errors on $v_2\{\text{SP}\}$ measurement. NS = Not Significant.

effect	$v_2\{\text{SP}\}$ large- q_2 /unbiased	$v_2\{\text{SP}\}$ small- q_2 /unbiased
magnetic Field	NS	NS
charge	NS	NS
vertex	NS	NS
track reconstruction	0.1%	0.15%
centrality resolution	0.15%	0.2%
centrality estimator	0.15%	0.1%
tracking efficiency	0.35 %	0.2%
MC closure	2.85%	2.85%
	$(p_T = 0.2 \text{ GeV}/c)$	$(p_T = 0.2 \text{ GeV}/c)$
	0.7%	0.7%
	$(p_T = 1.5 \text{ GeV}/c)$	$(p_T = 1.5 \text{ GeV}/c)$

Table 6.2: Summary of systematic errors on the ratios large- q_2 (small- q_2) over unbiased. NS = Not Significant.

6.3.1 $v_2\{SP\}$ in shape selected events

The $v_2(p_T)$ distributions of charged hadrons in 10% highest and 10% lowest q_2 events are presented in this section. The q_2 has been computed using different estimator: V0A, V0C and TPC. The results will be discussed in chapter 8.

The V0 calibration after the 60% centrality class is not accurate due to the limited statistics available. Therefore, the results are presented up to 60% centrality class.

Fig. 6.7(a) shows the $v_2(p_T)$ distributions, different centrality classes, in 10% large- q_2 events (red), 10% small- q_2 events and for unbiased events (black). The elliptic flow coefficient exhibits a strong centrality dependence, increasing from central to peripheral collisions, up to the 40-50% centrality interval.

The ratios between large- q_2 (small- q_2) and the unbiased sample are shown in Fig. 6.7(b). The event shape selection results in a change in the value of the v_2 of $\approx 20\%$ for large- q_2 and $\approx 10\%$ for the small- q_2 . The ratios are flat up to ≈ 4 GeV/c.

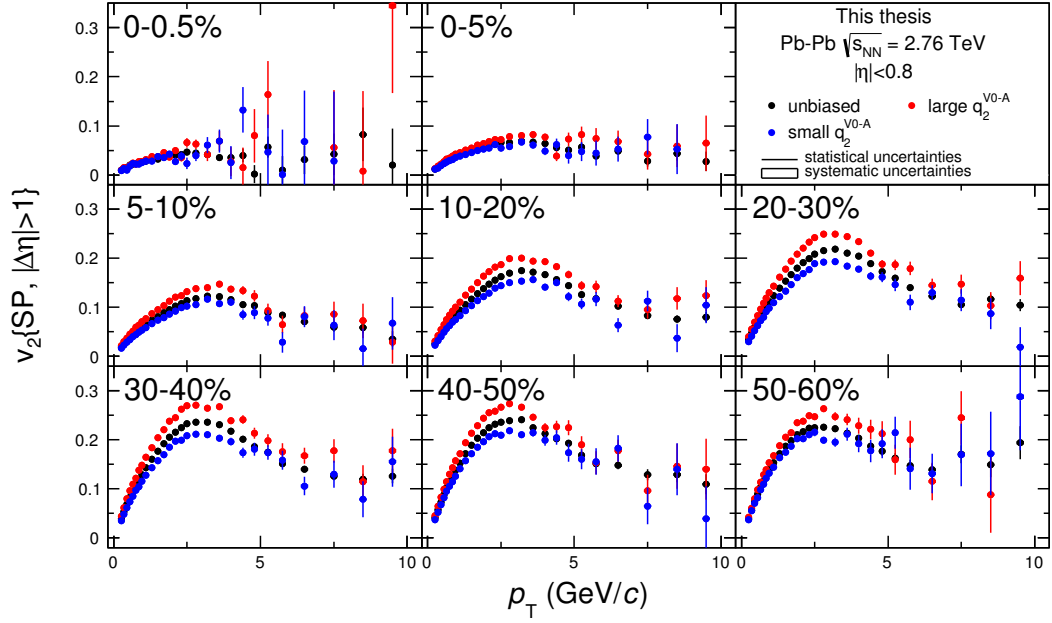
Fig. 6.8(a) shows the $v_2(p_T)$ in large and small q_2 sample and the unbiased sample, determined by using the V0C to estimate the q_2 . The ratios large- q_2 (small- q_2) to the unbiased sample are shown in Fig. 6.8(b). Using the q_2^{V0C} to bias the event sample results in a stronger modification of the elliptic flow coefficient with respect to the results obtained using the q_2^{V0A} .

Finally Fig. 6.9(a-b) shows the $v_2(p_T)$ for large and small q_2 sample, determined using the TPC and the ratios to the unbiased sample. To avoid autocorrelation v_2 and q_2^{V0C} have been evaluated in two different pseudorapidity windows, without any η gap: q_2^{V0C} is in $0.5 < \eta < 0.5$ while we measured the v_2 in $-0.8 < \eta < -0.5$ and $0.5 < \eta < 0.8$, as for the other q_2 selections. We obtained a stronger modification of the v_2 using the q_2^{TPC} for the ESE selection, $\approx 50\%$ for either large- q_2 and small- q_2 events.

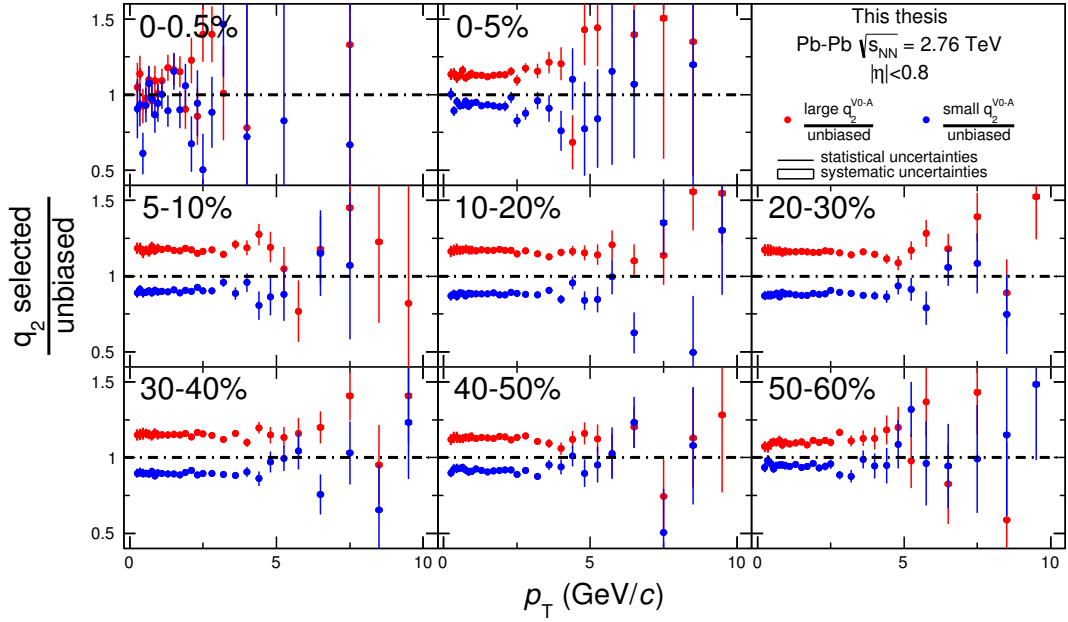
The results obtained using the q_2 from V0A have been directly compared with those obtained using V0C and TPC in Fig. 6.10, varying the cut so that similar v_2 is found at midrapidity. The selections are consistent up to the 60% centrality bin, as shown in Fig. 6.10. To match the v_2 values in 10% large- q_2^{V0A} events, one should take 23% large- q_2^{V0C} events and 50% large- q_2^{TPC} . Moreover similar results to the v_2 values in 10% small- q_2^{V0A} events are obtained with 50% small- q_2^{V0C} events and 75% small- q_2^{TPC} events.

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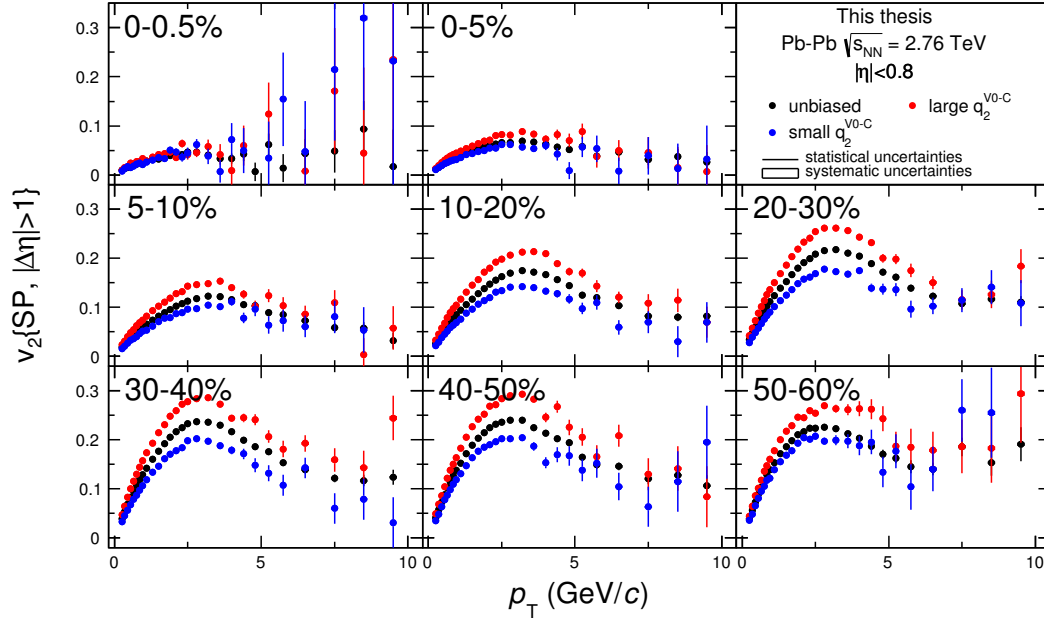


(a)

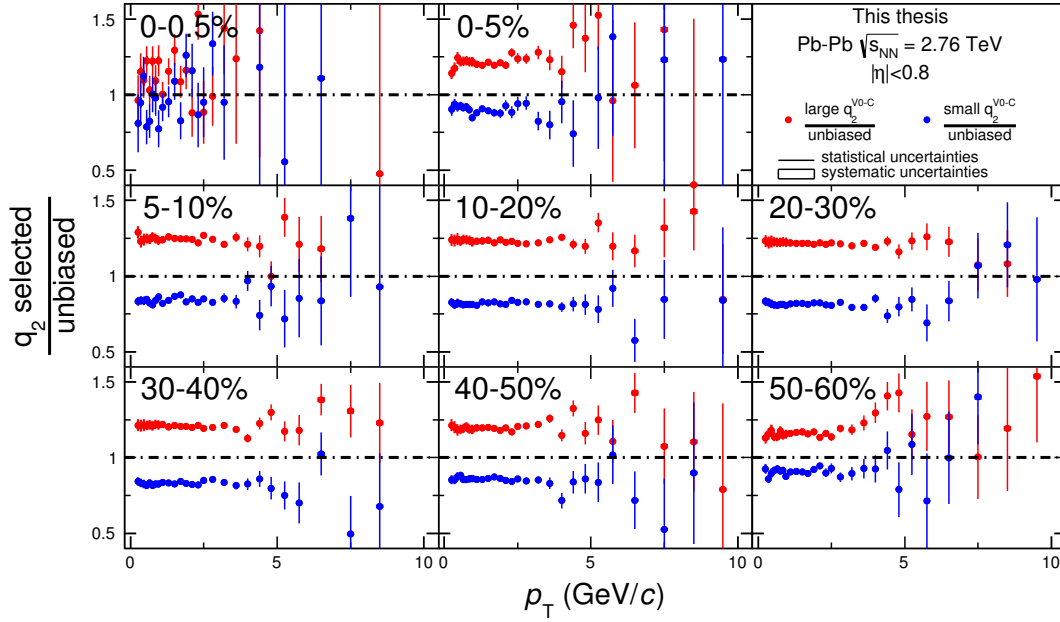


(b)

Figure 6.7: (a) $v_2(p_T)$ for charged particles for 10% large- q_2^{V0A} events (red), 10% small- q_2^{V0A} events (blue) and for the unbiased sample (black). (b) Unidentified charged particle ratios between the 10% large (small) q_2^{V0A} and to unbiased events for different centrality classes.

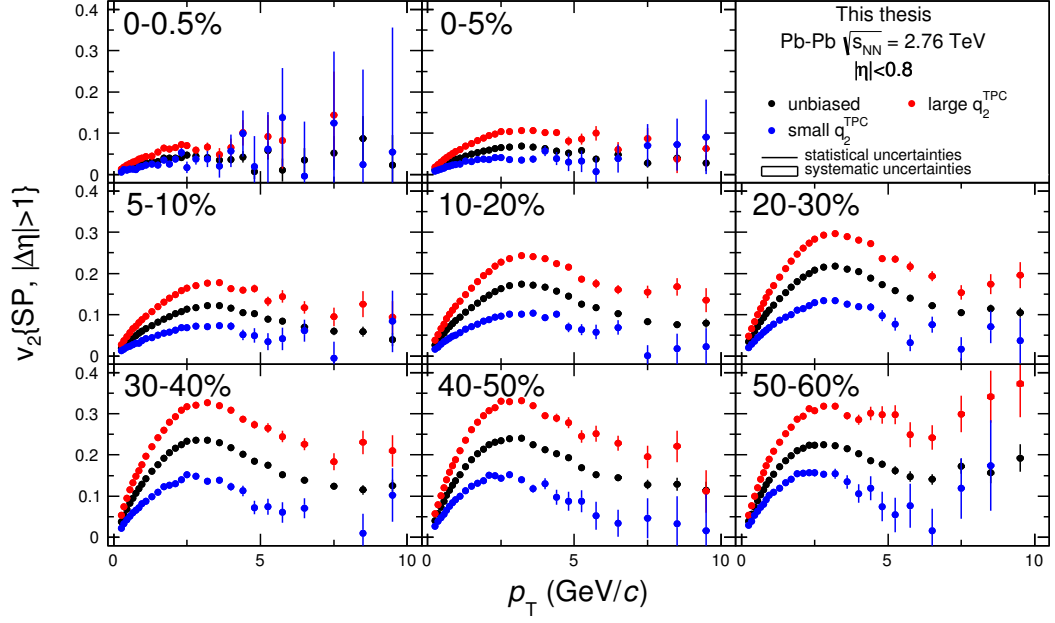


(a)

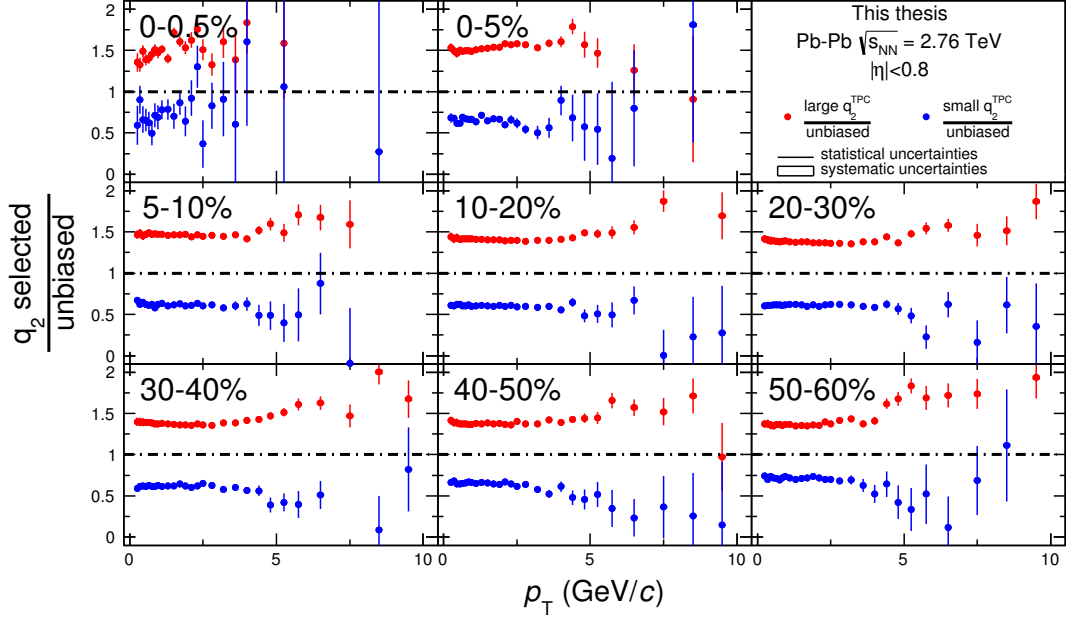


(b)

Figure 6.8: (a) $v_2(p_T)$ for charged particles for 10% large- q_2^{V0C} events (red), 10% small- q_2^{V0C} events (blue) and for the unbiased sample (black). (b) Unidentified charged particle ratios between the 10% large (small) q_2^{V0C} and to unbiased events for different centrality classes.

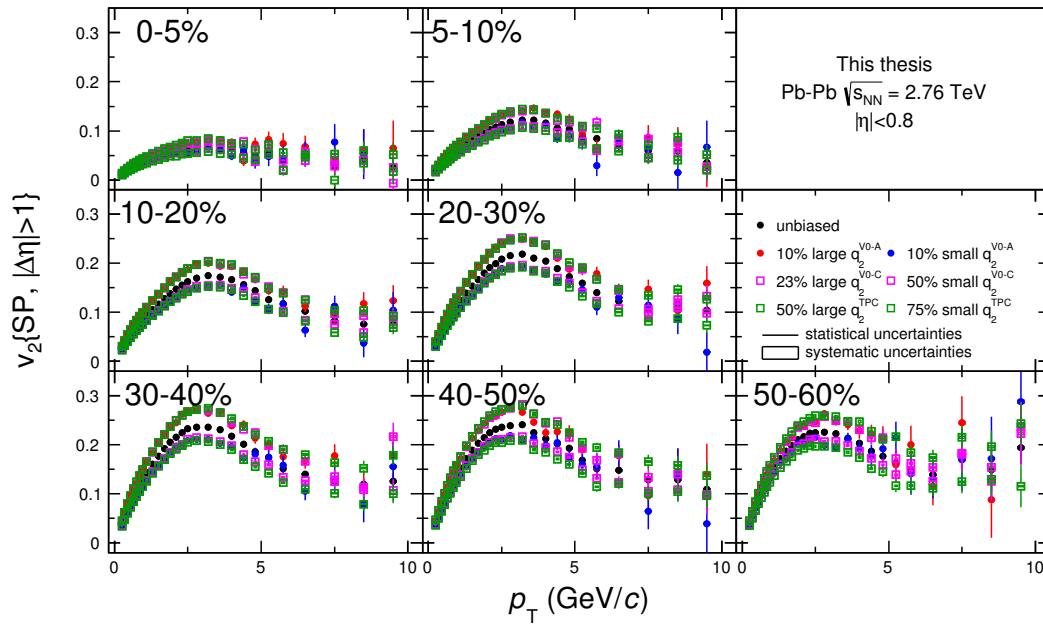


(a)

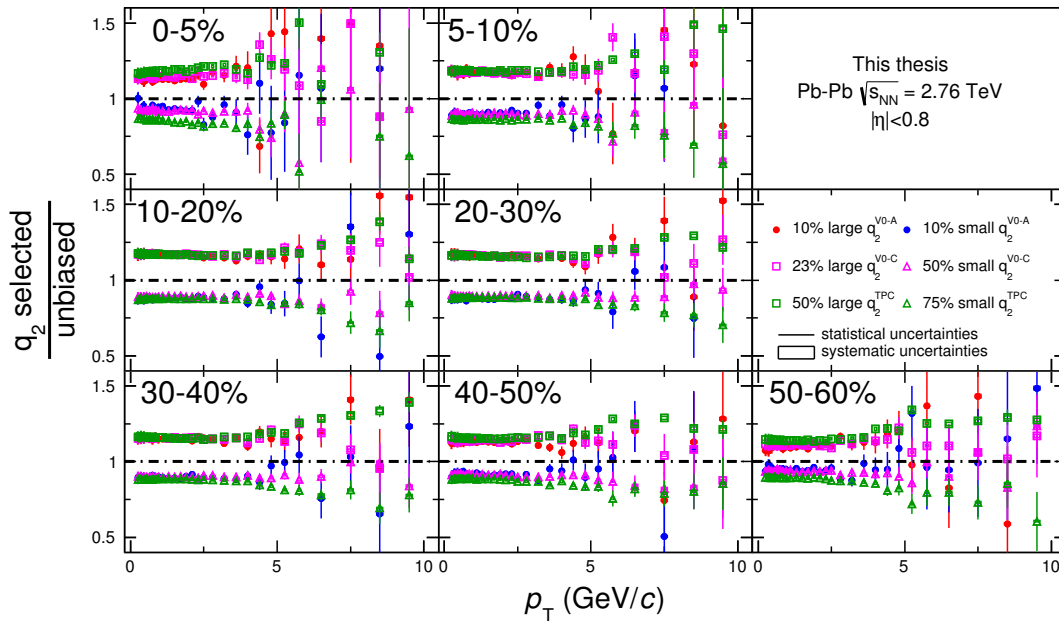


(b)

Figure 6.9: (a) $v_2(p_T)$ for charged particles for 10% large- q_2^{TPC} events (red), 10% small- q_2^{TPC} events (blue) and for the unbiased sample (black). (b) Unidentified charged particle ratios between the 10% large (small) q_2^{TPC} and to unbiased events for different centrality classes.



(a)



(b)

Figure 6.10: (a) $v_2(p_T)$ for charged particles in large- q_2 events from V0A (10%), V0C (23%) and TPC (50%) and small- q_2 events from V0A (10%), V0C (50%) and TPC (75%). (b) Unidentified charged particle v_2 ratios in large- q_2 and the unbiased from V0A (10%), V0C (23%) and TPC (50%) and small- q_2 events from V0A (10%), V0C (50%) and TPC (75%).

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p_T distributions in ESE selected events

We further proceed in the characterization of the event shape selected sample with a measurement of transverse momentum spectra. The measurement of p_T distributions of unidentified primary particles, pions, kaons and protons in ESE-selected events allows us the study of the correlation between anisotropic and radial flow.

The final results consist in the ratio of spectra measured in an ESE-selected sample over the unbiased sample. Most of the corrections discussed in this chapter cancel out in these ratios, allowing for a precise measurement of the effect of the event shape selection on p_T spectra. The discussion in this section has mainly the purpose of showing that the analysis procedure, and in particular the PID technique, is robust, by comparing to the ALICE published p_T spectra results in [1]. Since in this work a track-by-track identification is needed, the PID techniques used are different from that one used in [1].

7.1 Event and track Selection

The measurement of p_T spectra uses global tracks, which provide good resolution in the transverse distance of closest approach to the vertex, DCA_{xy} , and hence good separation of primary and secondary particles. The track selection requires at least 70 clusters in the TPC and at least 2 points in the ITS, out of which at least one must be in the first two layers, to improve the DCA_{xy} resolution. To further reduce the contamination from secondary particles, tracks are rejected from the final sample if their distance of closest approach to the reconstructed vertex in longitudinal and radial direction, DCA_z and DCA_{xy} respectively, satisfies $DCA_z > 2$ cm and $DCA_{xy} > 0.018$ cm + 0.035 cm $\cdot p_T^{-1.01}$, the latter corresponding to about 7σ the resolution of the DCA in the transverse plane [2]. Tracks with

a χ^2 per point larger than 36 in the ITS and larger than 4 in the TPC are rejected. Finally, to further reduce the contamination from fake tracks, a consistency cut between the track parameters of TPC and global tracks was applied. For each reconstructed TPC track, the χ^2 -difference between the track parameters computed using the only the TPC information constrained to the vertex and the associated global track is computed and required to be less than 36 [3]. Charged tracks are studied at midrapidity, $|\eta| < 0.8$.

The measured p_T distributions are first of all normalised to the number of events passing the event selection criteria described in sec. 5.1. In Pb–Pb collisions, for the centrality selection considered in this work, the vertexing [4, 5] and event selections [6] are 100% efficient, so that the number of events after selection corresponds to the total number of collisions in the corresponding centrality interval.

7.2 Particle IDentification procedure

Particles are identified using the specific energy loss in the TPC and their arrival time in the TOF. The information from the TPC alone is used between $0.2 < p_T < 0.5$ GeV/ c , while above 0.5 GeV/ c the PID signals from both TPC and TOF are used.

Two PID techniques have been explored:

- $n\sigma$ PID
- bayesian PID

The $n\sigma$ approach has been described in sec. 4.3.1. A track is identified as either a pion, a kaon or a proton based on the distance, in the detector resolution units, from the expected energy loss ($n\sigma_{\text{TPC}}$) or time of flight ($n\sigma_{\text{TOF}}$) for each particle species.

Once the $n\sigma$ is computed for all the three mass hypotheses (π , K, p), the identity is assigned to the track if the number of sigma is smaller than 3. If this condition is satisfied by more than one mass hypothesis, the identity is assigned to the hypothesis with smaller $n\sigma$. It can be discarded and no identity is assigned (*$n\sigma$ exclusive*) or the track can be associated more than one mass hypothesis (*double counting*).

Below $p_T = 0.5$ GeV/ c , where only the TPC information is used, the particles are required to be within $3\sigma_{\text{TPC}}$ of the expected energy loss for π , K or p¹. For larger p_T , the TPC and TOF information are combined using a geometrical mean:

$$n\sigma_{\text{combined}} = \sqrt{\frac{n\sigma_{\text{TPC}}^2 + n\sigma_{\text{TOF}}^2}{2}}. \quad (7.1)$$

¹Both charge states are considered.

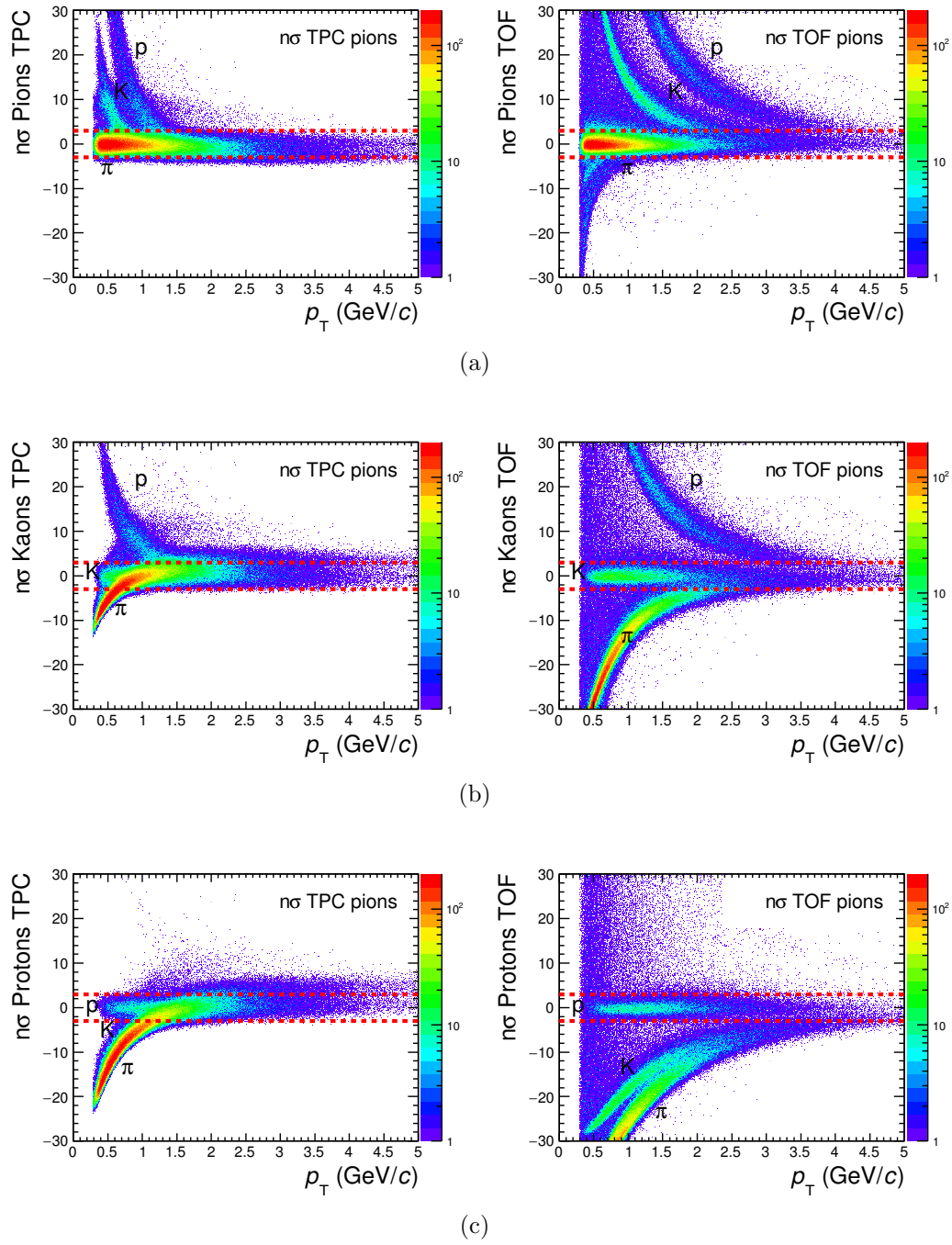
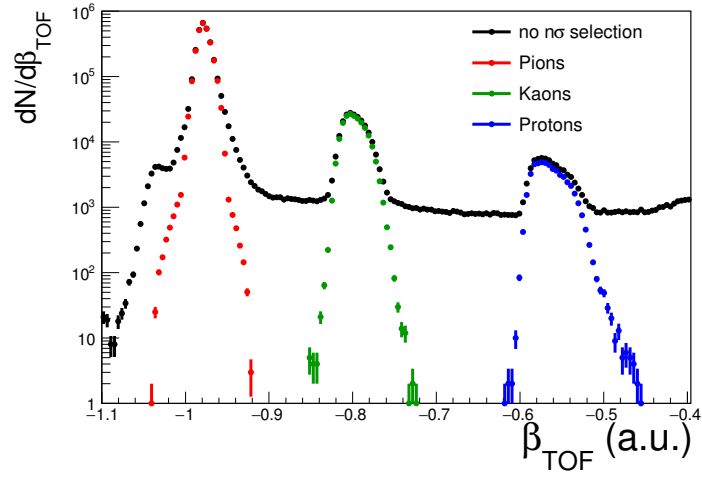
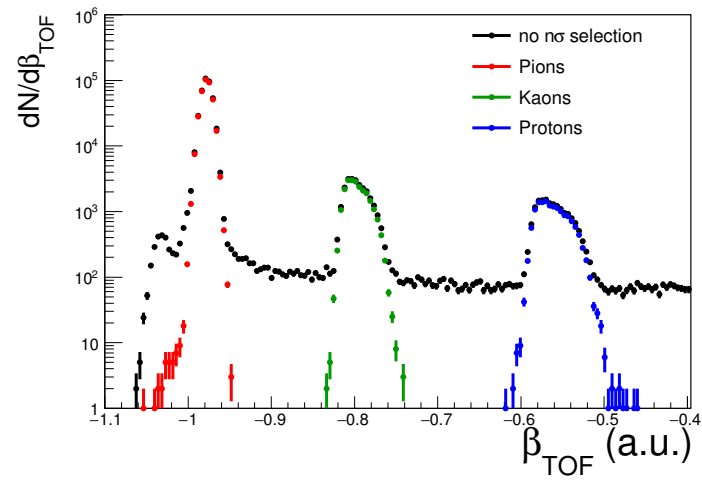


Figure 7.1: Distribution of the number of σ , for TPC (left) and TOF (right), for pions (a), kaons (b) and protons (c).



(a)



(b)

Figure 7.2: β_{TOF} in data (a) and Monte Carlo (b) for $0.6 < p_T < 0.7$ GeV/c. The selection for pions (red), kaons (green) and protons (blue) obtained from a $n\sigma < 3$ cut is shown.

Tracks are required to be within 3σ to be identified as π , K or p. This technique gives a clean track-by-track identification in the following p_T ranges: $0.2 < p_T < 4$ GeV/ c for π , $0.3 < p_T < 3.2$ GeV/ c for K, $0.5 < p_T < 4$ GeV/ c for p. The results for the identified particles are provided in the rapidity range $|y| < 0.5$. In Fig. 7.1 the $n\sigma$ distribution for the pions, kaons and protons mass hypothesis is shown as a function of transverse momentum. The horizontal bands centered at zero, which the red lines show, correspond to the tracks with the correct mass hypothesis. At low p_T the three bands from the three particle species are clearly distinguishable, while as p_T increases, they start to overlap due to the decreasing separation power of the TPC and TOF detector with the increasing transverse momentum. The β_{TOF} distribution is shown in Fig. 7.2 for particles in the range $0.6 < p_T < 0.7$ GeV/ c , for data and Monte Carlo. Pions, kaons and protons selected based on the combined $n\sigma$ are depicted in red, green and blue, respectively. The combined PID selection rejects those tracks which are associated to a wrong hit in the TOF (mismatch)². As shown in Fig. 7.2 the mismatch contribution is different in data and Monte Carlo. However this is not a problem in this analysis due to the combined PID procedure.

The bayesian probability, described in sec. 4.3.2 provides a pure sample of pions ($0.2 < p_T < 4$ GeV/ c), kaons ($0.5 < p_T < 3$ GeV/ c) and protons ($0.5 < p_T < 4$ GeV/ c). The probability is computed for each mass hypothesis. Tracks identified as a pion, a kaon or a proton are required to have a probability larger than 80%. Below $p_T = 0.5$ GeV/ c the probability is computed using only the TPC information, while at larger p_T the combined information from TPC and TOF is used. A further $n\sigma < 5$ cut is applied when using the bayesian approach, to remove the residual contamination due to the mismatched tracks.

The PID efficiency of the selection and the purity of the obtained sample are depicted in Fig. 7.3, for positive pions, kaons and protons. The PID efficiency ϵ_{PID} and the purity $p(i)$ are here defined as:

$$\epsilon_{PID}(i) = \frac{N_{id}^t(i)}{N(i)} \quad p(i) = \frac{N_{id}^t(i)}{N_{id}(i)} \quad (7.2)$$

where $N_{id}^t(i)$ is the number of tracks correctly identified as type i , $N(i)$ is the number of tracks of type i in the sample under study and $N_{id}(i)$ is the number of particles identified as type i whether the identification is correct or not, with

²During the tracking procedure, the tracks are extrapolated to the TOF sensitive layer and a track matching window (on the TOF layer) of 3 cm in Pb–Pb interactions and 10 cm in pp collisions is open around this crossing point. All TOF clusters inside the track matching window are collected and the one closest to the crossing point between the track prolongation and the TOF sensitive layer is associated to the track. The difference between the two window sizes is related to the different track multiplicity in pp and Pb–Pb collisions. At this moment, the time-of-flight measured by the TOF detector is associated to the track.

$i = \pi, K, p$. In other words, $N(i)$ and $N_{id}(i)$ are the number of the primary tracks reconstructed by TPC, matched with TOF in $|y| < 0.5$, with true and reconstructed identity, respectively. As expected the $n\sigma$ selection with double counting leads to a higher PID efficiency and to lower purity of the sample. The bayesian approach, on the other hand, ensures a good PID efficiency with high purity. However, the stringent cut used to obtain these results reduces the available statistic.

7.3 Efficiencies studies

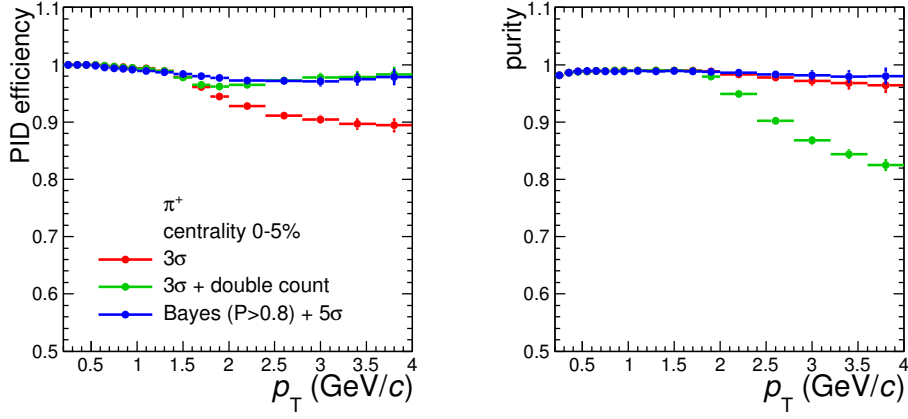
The data are corrected for efficiency and contamination from other species using a Monte Carlo simulation. The basic correction factor is computed by dividing the number of tracks reconstructed for particle species i (regardless of the true identity of the track) by the total number of generated primary particles of specie i :

$$correction\ factor_{MC} = \frac{N_{id}(i)}{N_{gen}^{primary}(i)} \quad (7.3)$$

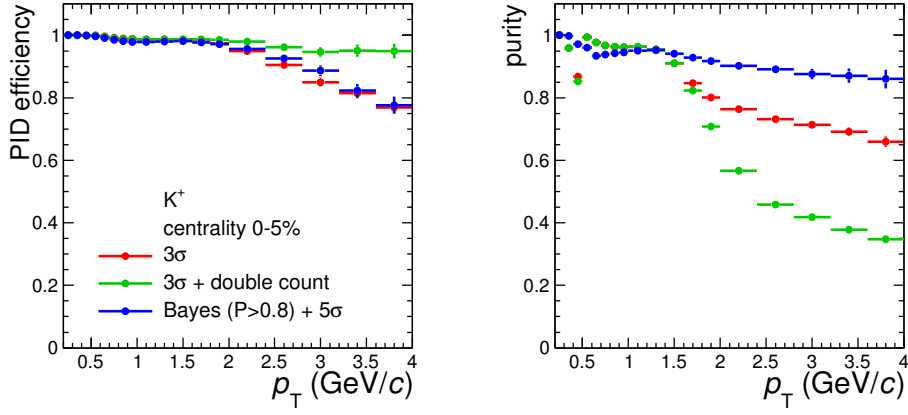
This correction automatically removes secondaries and contamination from other species. It is shown in Fig. 7.4 for unidentified particles up to 15 GeV/ c , and for pions, kaons and protons up to 4 GeV/ c .

Eq. 7.3 assumes a perfect Monte Carlo simulation. Since the Monte Carlo production studied can't reproduce perfectly real data, the differences between data and Monte Carlo coming from the TPC-TOF matching efficiency, secondary particle contribution and the contribution from mis-indentification need to be taken into account. The additional corrections, applied to account for the differences between data and Monte Carlo, are discussed in the following.

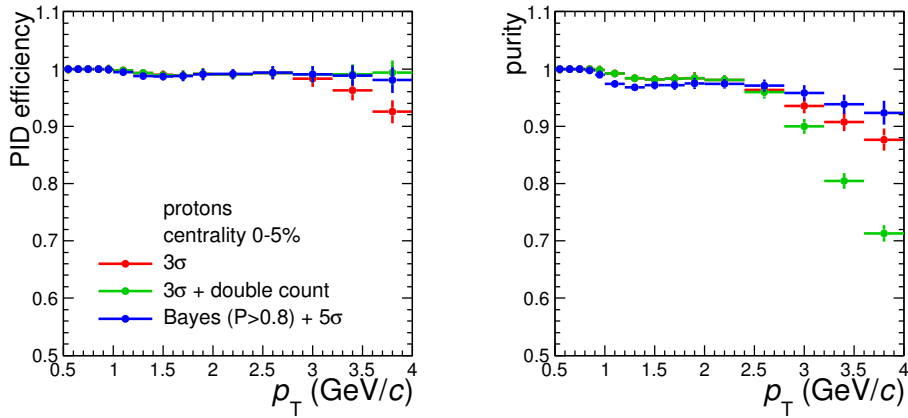
The correction factor allows to correct for the *tracking efficiency*, due to the fact that only a fraction of the primary tracks produced in the collisions are reconstructed as global tracks, and for the *PID efficiency*, if the PID information is used. Furthermore, at $p_T \geq 0.5$ GeV/ c , where the information from TOF starts to be required, it takes into account that only a fraction of the reconstructed primary tracks are matched with a hit on the TOF detector (*matching efficiency*). The latter explains the drop in the correction factor from ≈ 0.75 to ≈ 0.4 , for pions, then it saturates. A similar behaviour is seen for kaons. Protons are identified with combined TPC-TOF information in the whole p_T range ($0.5 < p_T < 4$ GeV/ c). The procedure was tested by applying the same correction factor to raw Monte Carlo data, corrected using the correction factor and compared to the values extracted from Monte Carlo truth, showing perfect agreement. This checks ensures that there are no trivial mistakes in the procedure.



(a)



(b)



(c)

Figure 7.3: PID efficiency and purity for pions (a), kaons (b) and protons (c), identified using $n\sigma$ approach, with and without double counting, and bayesian probability.

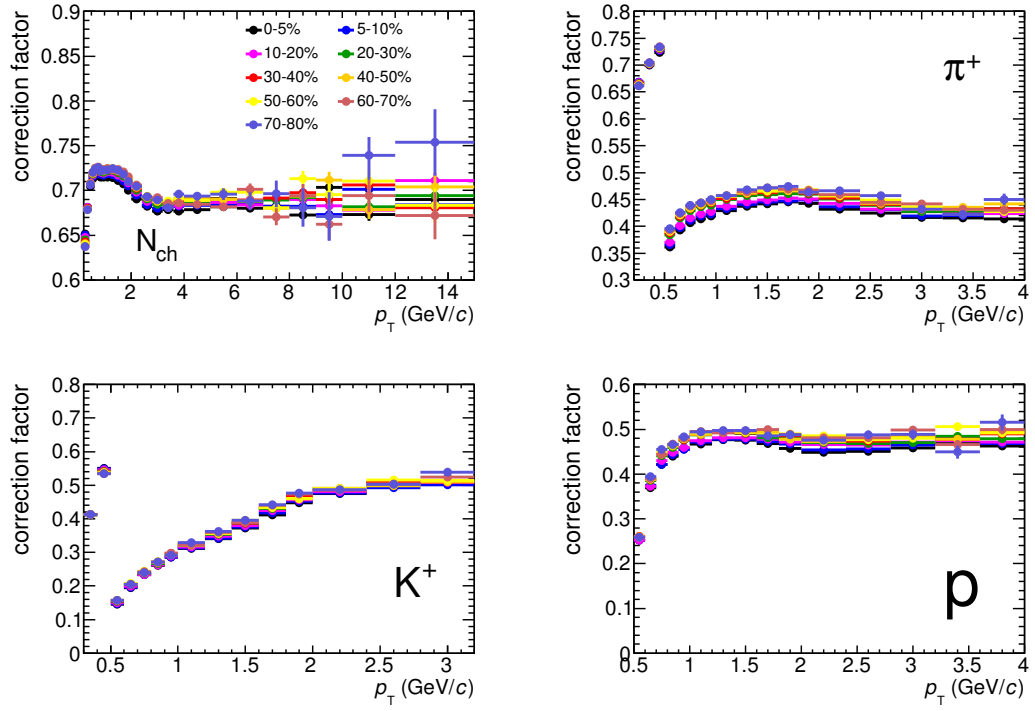


Figure 7.4: Correction factor for unidentified charged particles, pions and protons as a function of p_T in several centrality classes.

7.3.1 TOF Matching efficiency: data-driven correction

The matching efficiency accounts for the fraction of tracks that are lost during the propagation from TPC to TOF due to the geometrical acceptance, the decays and the interactions with the material. In addition it includes the probability to match a track reaching the TOF with a TOF hit. This depends on the TOF intrinsic detector efficiency, on the effect of dead channels and on the efficiency of the track-TOF signal matching algorithm. The *matching efficiency* is defined as follows:

$$\epsilon_{match} = \frac{N^{match}(i)}{N_{reco}^{select}(i)} \quad (7.4)$$

i.e. the number of tracks matched with TOF over the number of tracks reconstructed by the TPC for specie i . Figure 7.5(a) shows the matching efficiency for charged hadrons in data and Monte Carlo evaluated as the fraction of the reconstructed and selected primary tracks that have been successfully matched with a TOF signal. A p_T -dependent discrepancy of $\approx 2\%$ has been found, as shown by the ratio of ϵ_{match} in data and Monte Carlo in Fig. 7.5(b).

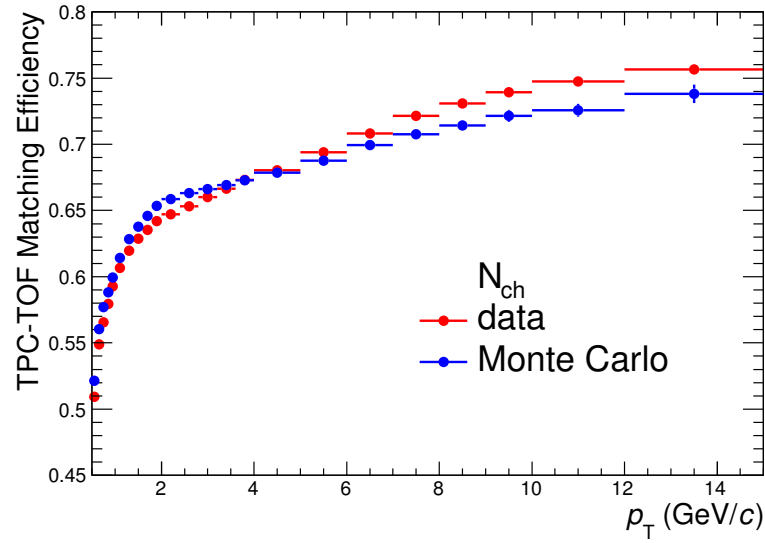
Monte Carlo simulation shows that the matching efficiency is different for pions, kaons and protons, as reported in Fig. 7.6. To account for this difference, the TOF matching efficiency for π , K and p is extracted from data, using a tight $n\sigma$ cut in the TPC. This approach allows the matching efficiency of identified particles to be estimated in a data-driven way, using TPC tracks as reference. π , K and p are selected using a symmetric cut at 1σ in the TPC. The purity of the selected sample is very high at low p_T where the difference between the matching efficiency of the different particles species is large. At high- p_T some contamination can be accepted since the difference between π , K and p becomes significantly smaller, as reported in Fig. 7.6. The effect of the contamination is estimated by varying the selection in the TPC to $\pm 2\sigma$ and by selecting only particles in the lower band. No significant deviation of the correction is observed for pions and protons, while the contamination is not negligible for kaons and the corrections cannot be applied.

The same procedure is applied on the Monte Carlo and data and the matching efficiencies are reported in Fig. 7.7 for positive and negative identified particles.

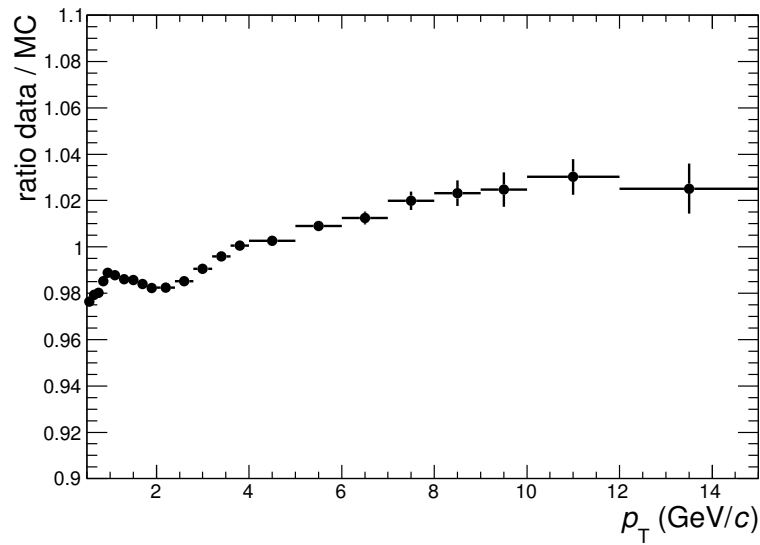
For the comparison of data and MC only the centrality 50-90% is considered in order to reduce the contribution from mismatched tracks, since the mismatching is not well reproduced in the MC. The contribution of the mismatch is very small in peripheral Pb-Pb collisions, due to the small particle multiplicity with respect to the central collisions.

The spectra are corrected for the ratio:

$$\frac{matching\ eff.\ data}{matching\ eff.\ MC} \quad (7.5)$$



(a)



(b)

Figure 7.5: (a) TOF matching efficiency for unidentified charged particles in Pb–Pb collisions, for data and Monte Carlo. (b) Ratio of the matching efficiency in data over the one in Monte Carlo.

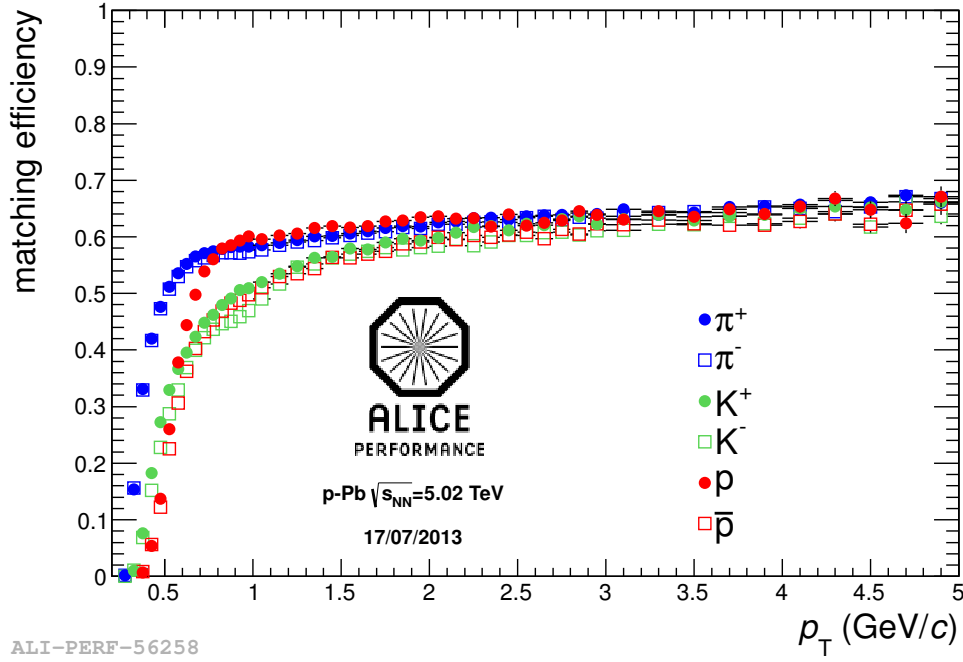


Figure 7.6: TOF matching efficiency for pions, kaons and protons in p-Pb collisions.

The ratio is reported in Figure 7.7(b) for positive (left) and negative particles (right).

For anti-protons part of the difference between data and Monte Carlo comes from the cross section of absorption in the material which is not properly reproduced in the simulation, as described in sec. 7.5. Therefore the correction for protons is also used for anti-protons.

7.4 Secondary particles contribution

The contamination from secondary particles produced by weak decays or interaction with the material is mostly relevant for pions and (anti)protons. Since strangeness production is typically underestimated in current event generators and the low p_T interactions with the material are not modeled perfectly in transport codes, the contamination is extracted from data.

Weak-decay feed-down corrections to protons, antiprotons and pions as well as corrections for protons coming from the detector material are obtained by fitting the DCA_{xy} distributions measured in the data, in p_T bins, with three distributions

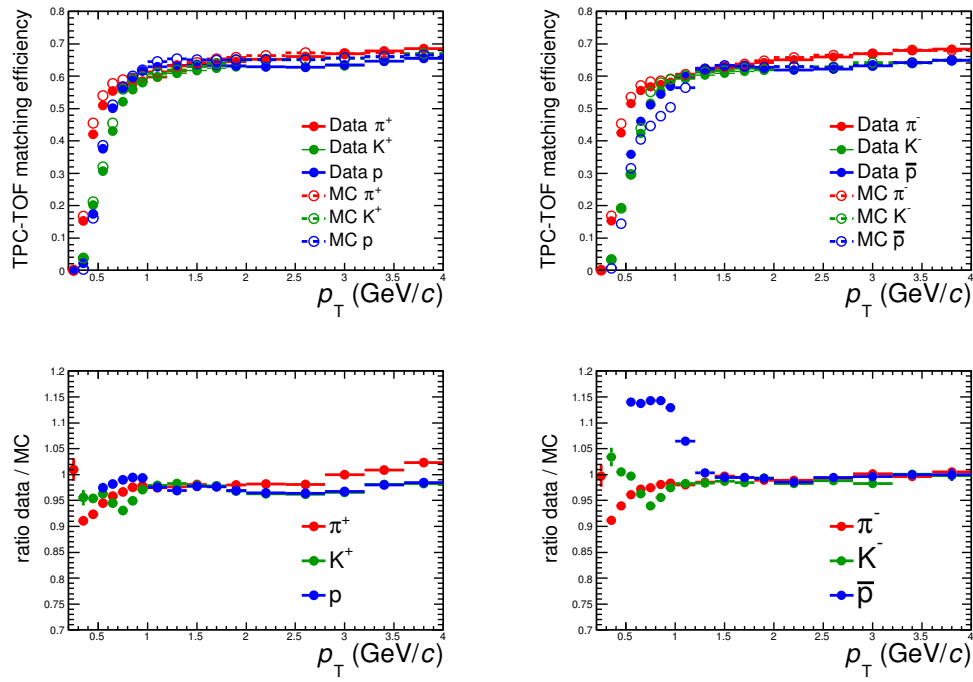


Figure 7.7: TOF matching efficiency correction for positive (left) and negative particles (right). Top: matching efficiency. Bottom: Ratio of the matching efficiency data to Monte Carlo, for pions, kaons and protons.

(*templates* in the following) corresponding to the expected shapes for primary particles, secondaries from material and secondaries from weak decays, as extracted from Monte Carlo.

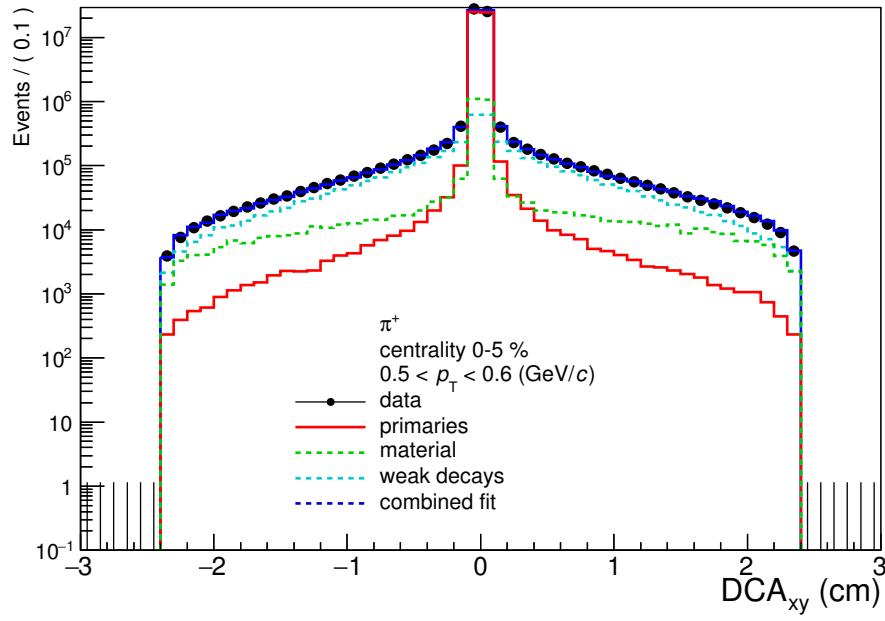
The DCA_{xy} distributions are obtained from the data selecting pions and protons using a narrow $n\sigma < 2$ cut. Only tracks that pass the primary-track selection cuts, with loose DCA cuts ($DCA_{xy} = 2.4$ cm, $DCA_z = 3.2$ cm), are used. Monte Carlo templates of the DCA_{xy} distributions are obtained using a detailed simulation of the ALICE detector. The particle identity as well as the track origin (primary particle, weak-decay daughter, material knock-out particle) is known using the Monte Carlo information. The expected shapes (templates) DCA_{xy} distribution corresponding to primary particles, weak-decay daughters and material knock-out particles are used to perform a 3-component global fit to the measured DCA_{xy} distribution of π^+ , π^- , p and $\bar{p}$. For negative particles, only the primaries and weak decay templates have been used, since the probability to extract anti-particles from material is very low. The results of this procedure, the DCA_{xy} distributions, templates and fits are shown in Fig. 7.8 in the momentum window $0.5 < p_T < 0.6$ GeV/ c for positive pions (a) and protons (b). The fractions of primary, weak-decay and material particles over the total can be obtained from the fit, for both the inclusive sample (loose DCA cut applied) and for the tracks that pass the DCA_{xy} cut. The results are shown in Fig. 7.9 for positive pions and protons, respectively.

The fraction of secondaries has been subtracted directly by the raw count and the correction factor (Eq. 7.3) has been changed accordingly, dividing the number of primary tracks reconstructed for particle specie i (regardless of the true identity of the track) by the total number of generated primary particles of specie i , to avoid double corrections:

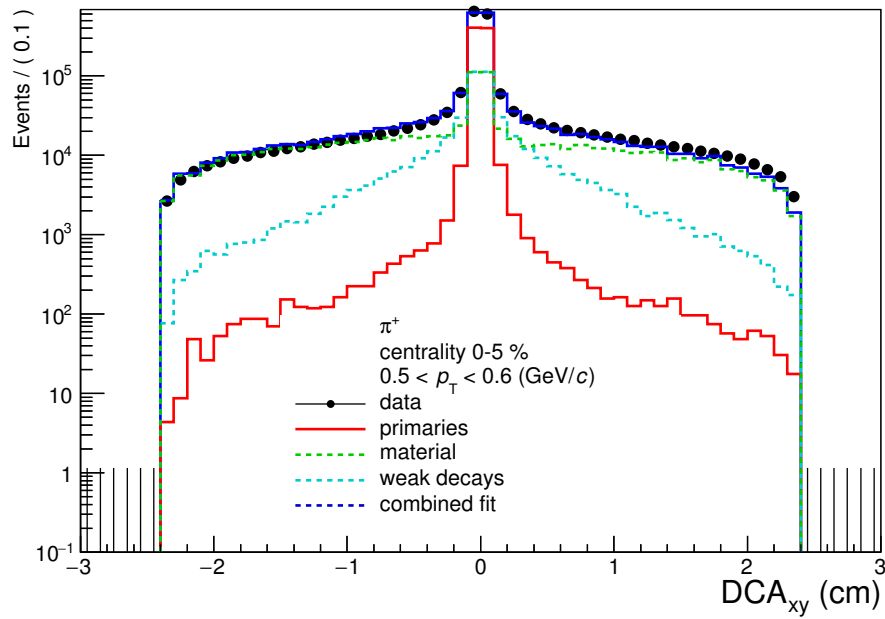
$$correction\ factor_{PRIM} = \frac{N_{id}^{primary}(i)}{N_{gen}^{primary}(i)} \quad (7.6)$$

Feed down corrections in event shaped events The shape of the p_T distribution changes in a mass-dependent way with centrality (as the transverse expansion velocity $\langle\beta_T\rangle$ changes). This could lead to a different p_T -shape of the feed-down correction at different centralities. To quantify this effect, the feed-down correction for protons in different centrality classes have been considered (Fig. 7.10).

Figure 7.11 shows the dependence of the feed-down correction on the centrality (i.e. $\langle\beta_T\rangle$) for each p_T bin, where the values of $\langle\beta_T\rangle$ for each centrality come from Ref. [1]. Especially at low p_T , there is a small dependence of the feed-down correction on the $\langle\beta_T\rangle$. A linear interpolation has been used to fit the data in different p_T ranges (Fig. 7.11). In order to estimate the effect in the ESE analysis the blast wave model was used [7]. As it will be discussed in the section 7.8, the q_2

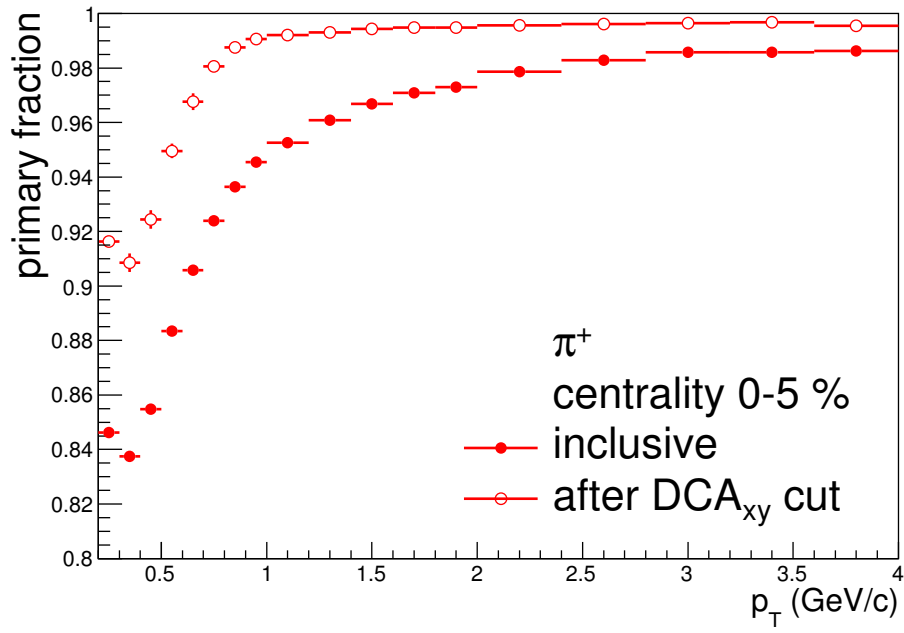


(a)

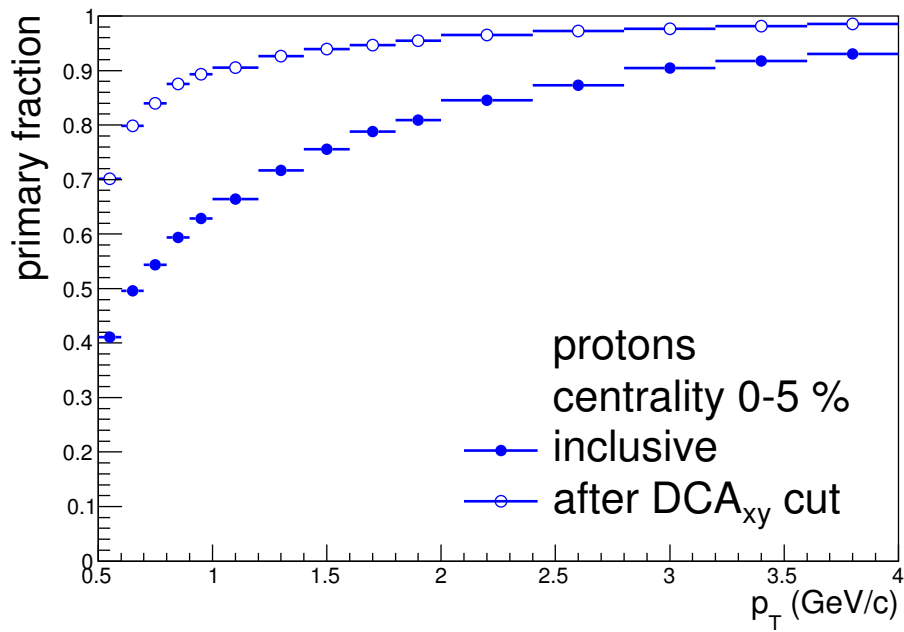


(b)

Figure 7.8: Pion (a) and proton (b) DCA_{xy} distribution measured in 0-5% central Pb–Pb collisions shown together with the resulting global fit and the corresponding components: primaries (red), material (green), weak decay (cyan). The global fit is reported in blue.



(a)



(b)

Figure 7.9: Fraction of primary pions (a) and protons (b) obtained from the DCA_{xy} fits to the data.

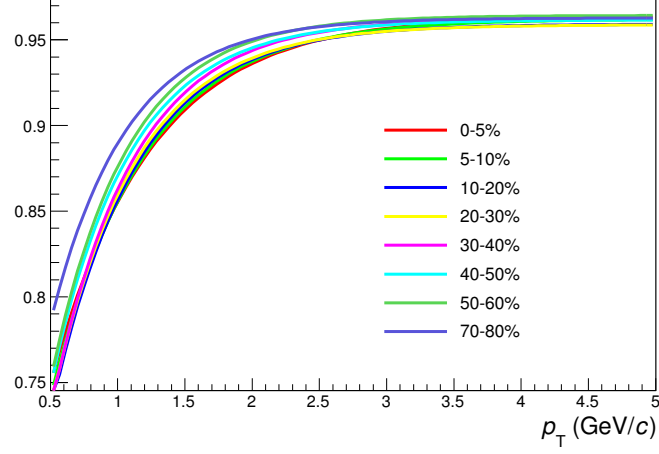
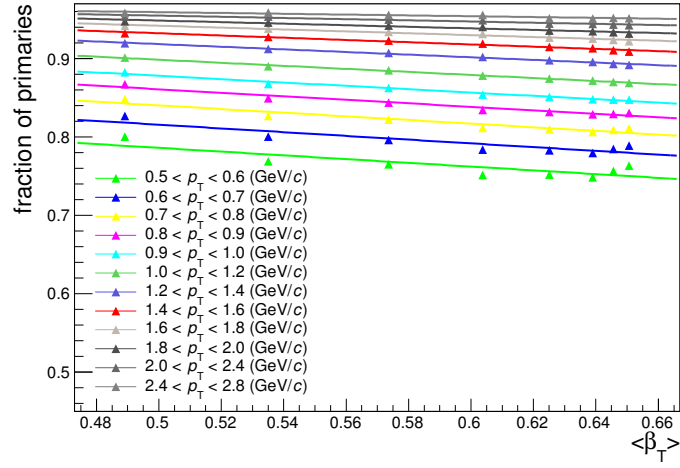


Figure 7.10: Feed-down corrections for different centrality classes.

Figure 7.11: Feed-down corrections as a function of $\langle\beta_T\rangle$ for different p_T bins.

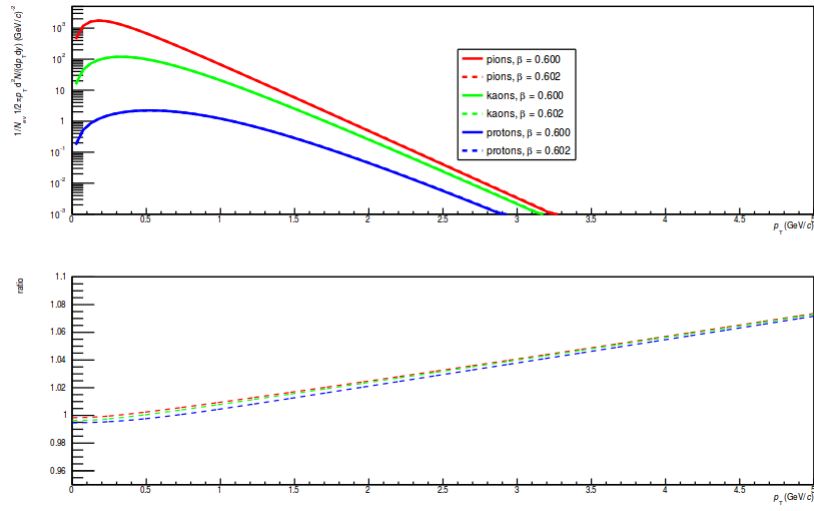


Figure 7.12: Blast wave for pions, kaons and protons for $\langle\beta_T\rangle \sim 0.6$ and ~ 0.602 .

selection leads to a change in p_T shape similar to the one which would be obtained with a few per-mil change in $\langle\beta_T\rangle$. The class 30-40% has a $\langle\beta_T\rangle \sim 0.6$. In order to see a similar effect as in the data the beta value has to be increased to ~ 0.602 , as shown in fig. 7.12.

The ratio between the corrections with $\langle\beta_T\rangle \sim 0.602$ and $\langle\beta_T\rangle \sim 0.6$ is reported in fig. 7.13: the difference is negligible.

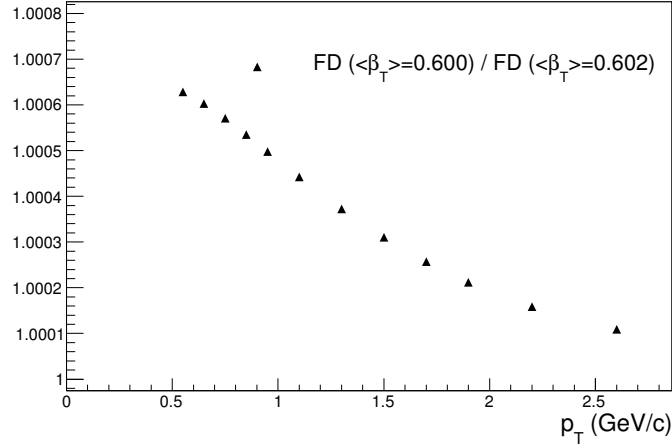


Figure 7.13: Feed-down corrections ratio between $\langle\beta_T\rangle \sim 0.6$ and ~ 0.602 .

To further check the dependence of the corrections on β the feed-down contribution with different q -vector cut has been evaluated in large- q_2 and small- q_2 events. Feed-down correction ratios between large- q_2 (small- q_2) events to unbiased events, for π^+ , π^- , p and $\bar{p}$ are shown in Fig 7.14 and 7.15. The dependence of the correction on the q_2 selection is negligible.

7.5 Other corrections

As already mentioned, the main correction factor has been evaluated in Monte Carlo. However, since the simulation does not reproduce perfectly the data, two additional data-driven corrections have been applied.

Mis-identification correction The Monte Carlo used to correct the spectra does not reproduce particles abundances, therefore a correction for the mis-identification is needed. Fig. 7.16 shows the fraction of kaons with respect to all charged particles in 0-5% centrality class in data and Monte Carlo. In the data the particles are identified with the $n\sigma$ approach. The Monte Carlo underestimates

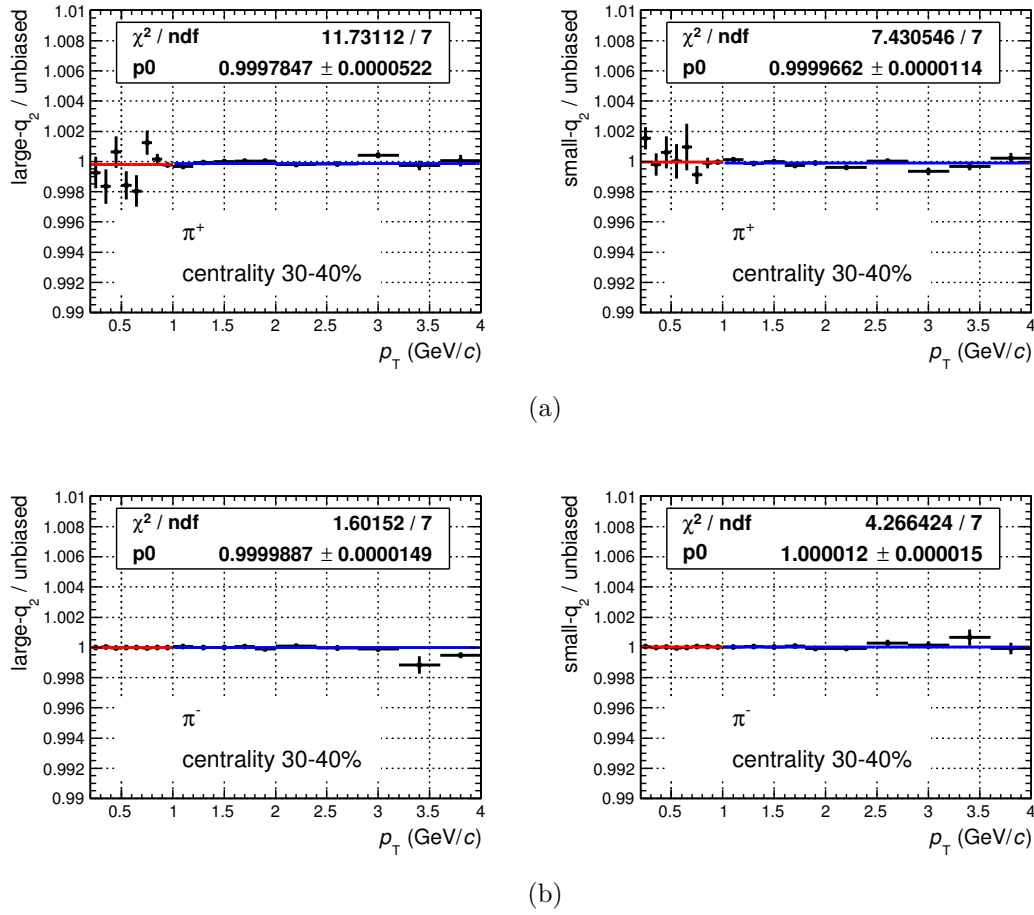


Figure 7.14: Feed-down correction ratios for large- q_2 (left) and small- q_2 (right) to unbiased, for positive pions (a) and for negative pions (b), in 30-40% centrality class.

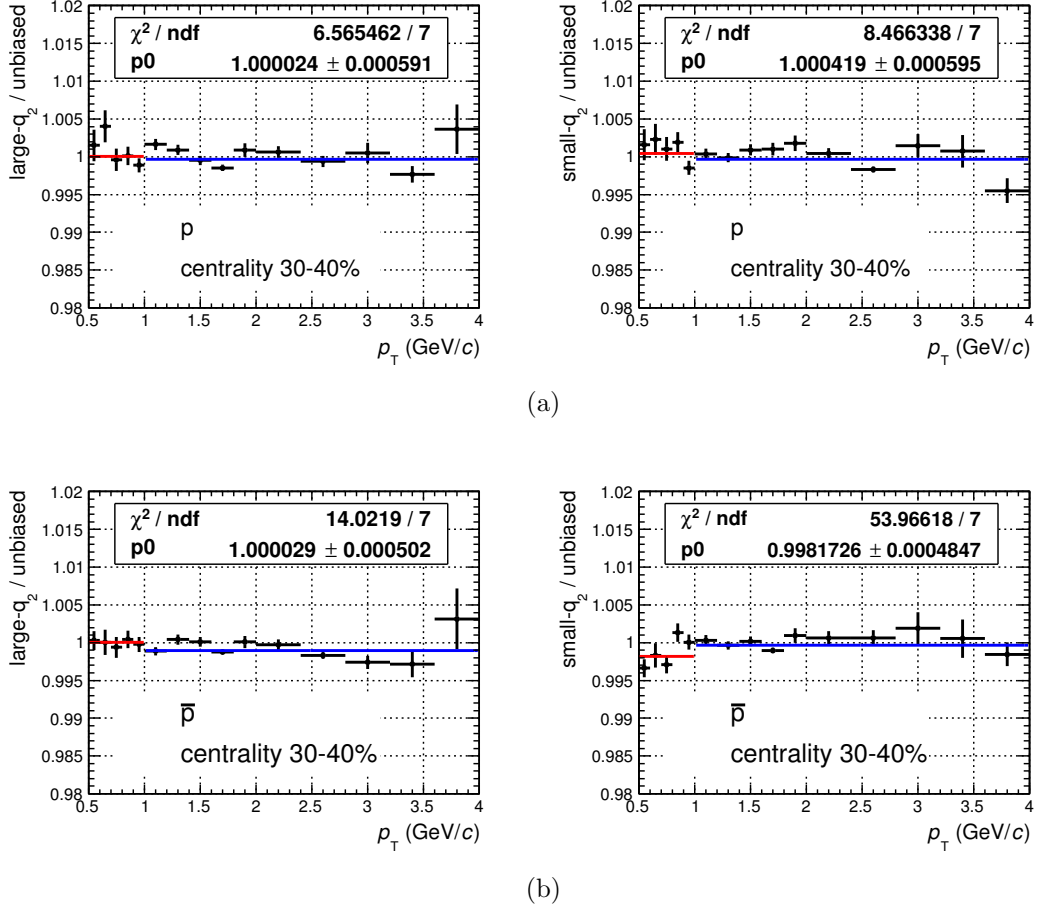


Figure 7.15: Feed-down correction ratios for large- q_2 (left) and small- q_2 (right) to unbiased, for protons (a) and for anti-protons (b), in 30-40% centrality class.

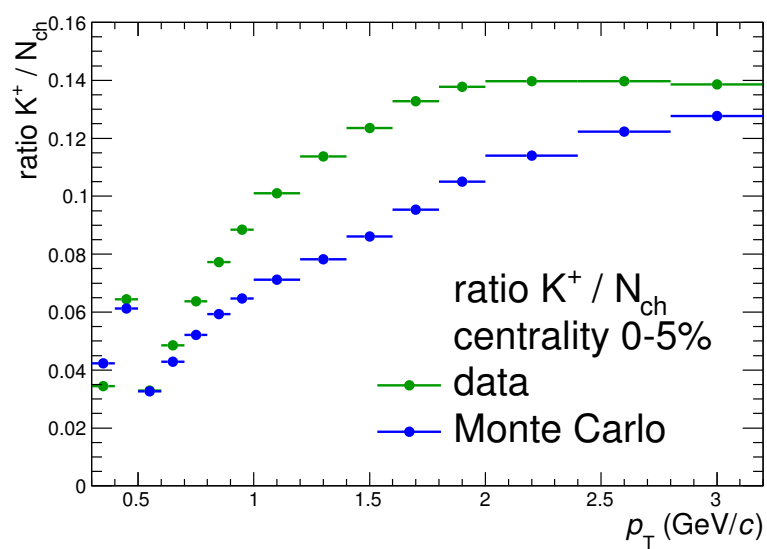


Figure 7.16: Number of kaons with respect to all charged particles in data and Monte Carlo in the 0-5% centrality bin.

the kaon fraction in the sample for $p_T > 0.5$ GeV/ c , while at very low p_T the situation is inverted and it overestimates the number of kaons. Since the bayesian PID takes into accounts the particle abundances by means of the priors, the correction for mis-identification is needed only when using the $n\sigma$ cut.

Following the same approach used for the secondary particles correction, the contamination from mis-identified particles has been subtracted from the raw count. The contamination, computed using Monte Carlo, is defined as:

$$c_i = \frac{N_{id}^W(i)}{N_{id}(i)} \quad i = \pi, K, p \quad (7.7)$$

where $N_{id}(i)$ is the number of particles identified as type i and $N_{id}^W(i)$ the number of non-type i particles identified as particles of type i . This factor is further rescaled by the double ratio f_i^{MC}/f_i^{Data} , which takes into account the different relative abundances in data and MC, being f_i is the fraction of particles of type i with respect to all charged. The correction factor, defined in Eq. 7.3, corrects the p_T distributions for the contamination from wrongly identified particles. Then to avoid double corrections, it has to be defined as:

$$correction\ factor = \frac{N_{id}^{t,primary}(i)}{N_{gen}^{primary}(i)} \quad (7.8)$$

obtained dividing the number of primary tracks correctly reconstructed for particle specie i , by the total number of generated primary particles of specie i .

Geant-Fluka Correction The transport code used in the Monte Carlo production is Geant 3.11. It is well known that the cross-section for the interaction of negative particles with material in Geant3 are larger than in nature, leading to an over-correction when the efficiency is computed. The Fluka Monte Carlo is known to have a description of cross section closer to reality (as illustrated in Fig. 7.17 [8]). The ratio between the efficiency computed in a Fluka simulation and the default one, computed with Geant 3.11, was used as a correction factor, as illustrated in Fig. 7.18 for the tracking (a) and the matching efficiency (b).

7.6 Comparison with the published analysis

The transverse momentum distribution of charged particles are reported in Fig. 7.19 for unidentified charged particles, pions, kaons and protons identified using the $n\sigma$ -cut approach. The distributions of positive and negative particles are compatible within uncertainties at all p_T , as expected at LHC energies. The change of shapes with centrality is clear: the spectra get harder with increasing centrality.

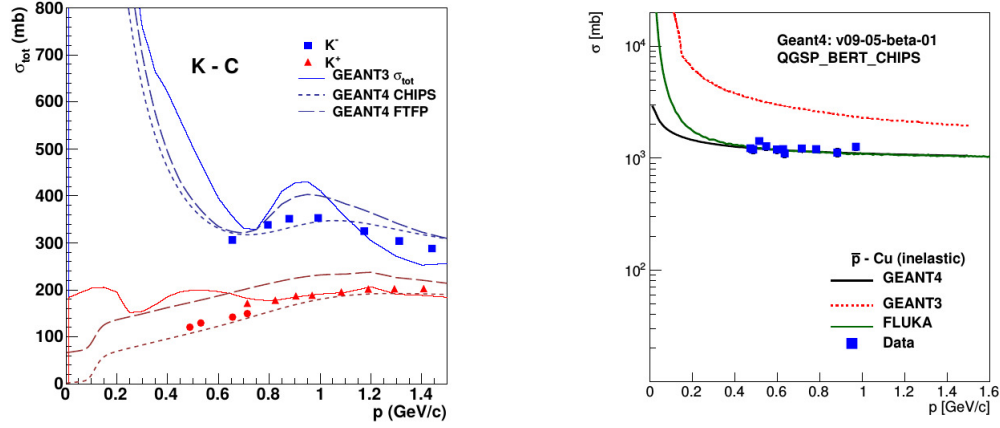


Figure 7.17: Comparison of K-C (left) and $\bar{p}$ -Cu (right) cross sections, transport codes compared to data.

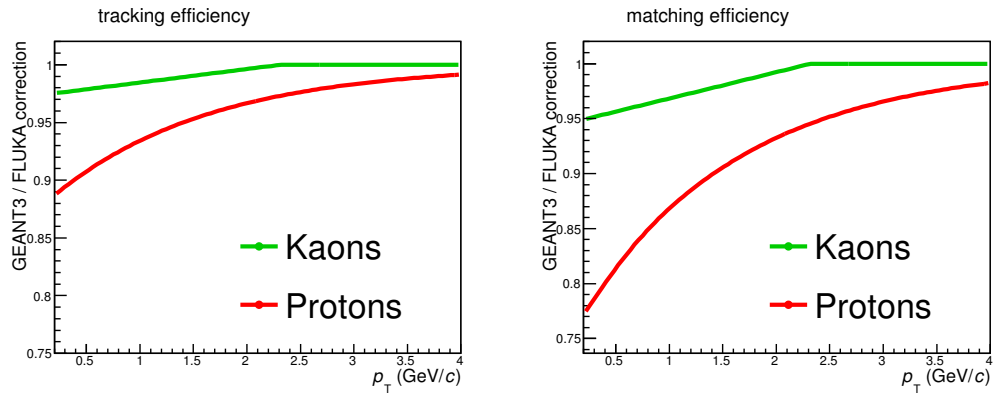


Figure 7.18: Geant 3/Fluka correction factor for Matching efficiency and tracking efficiency.

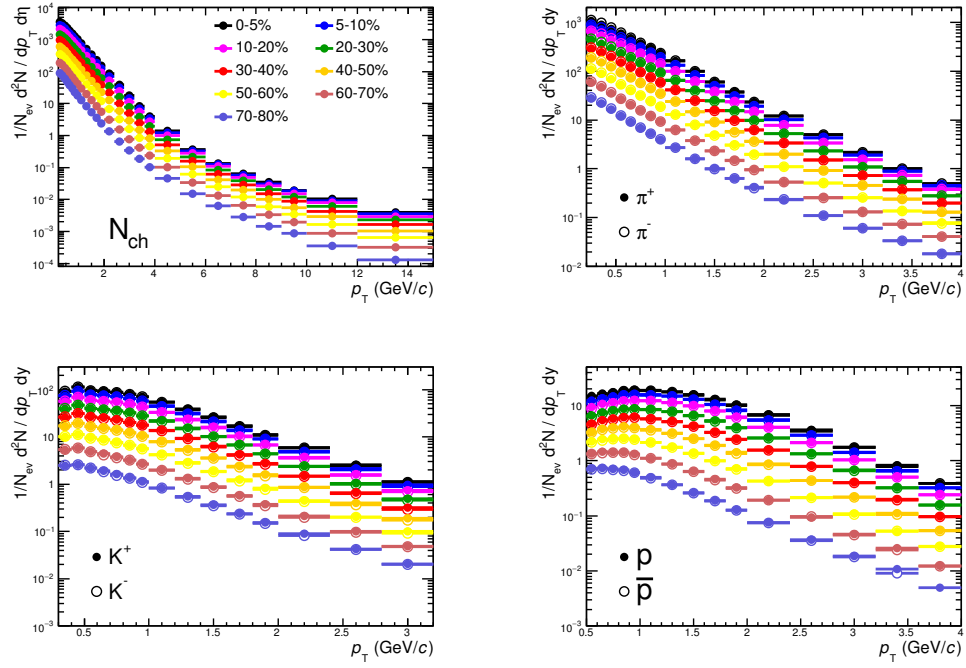


Figure 7.19: Transverse momentum (p_T) distributions of charged particles, π , K, and p as a function of centrality, for positive (open circles) and negative (closed circles) hadrons. Each panel shows central to peripheral data.

A flattening of the spectra, more pronounced at low p_T and for heavier particles, is expected in the hydrodynamical models as a consequence of the blue-shift induced by the collective expansion. In central collisions the p_T shape is mainly exponential, also for identified particles up to 1.5 GeV/ c for pions, 2.5 GeV/ c for kaons and 3 GeV/ c for protons. Then, in more peripheral collisions, the onset of the pQCD power-law tail, typical of pp collisions [9], starts to be visible.

The comparison with ALICE published spectra [1, 10] is shown in the following. Since the published results have a different p_T -binning with respect to this analysis, they are fitted with a Blast-Wave function (BW) [7]. The p_T spectra of the particles are well described by this model which makes the simple assumption that particles are locally thermalized at a kinetic freeze-out temperature T_{kin} and are moving with a common collective transverse radial flow velocity field β_T . The blast wave function is defined as

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right), \quad (7.9)$$

where the dependence on the velocity profile is described by

$$\rho = \tanh^{-1} \left(\left(\frac{r}{R} \right)^n \beta_t \right). \quad (7.10)$$

where $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, I_0 and K_1 the modified Bessel functions, r is the radial distance in the transverse plane, R is the radius of the fireball, β_T is the transverse expansion velocity and β_s is the transverse expansion velocity at the surface. The freeze-out temperature T_{kin} , the average transverse velocity $\langle \beta_T \rangle$ and the exponent of the velocity profile n are the free parameters in this fit. The p_T ranges used in the fit are 0.1-4 GeV/ c , 0.2-4 GeV/ c , 0.3-4 GeV/ c for π , K and p, respectively. This function is found to describe very well all particle species over the whole measured p_T range.

The comparison in 0-5% and 30-40% is reported for unidentified particles (Fig. 7.20), pions (Fig. 7.21), kaons (Fig. 7.22) and protons (Fig. 7.23). A good agreement, within 5%, is found for unidentified charged particles pions and protons. The results are found to be in agreement within the errors for the kaons. However, the missing correction of the matching efficiency to account of the discrepancy between data and Monte Carlo and the discrepancies in the particle abundances, in the dE/dx and β_{TOF} distributions in data and Monte Carlo lead to the worse agreement for the kaons.

In order to extrapolate to zero p_T for the extraction of p_T -integrated yields, the spectra were fitted individually with a blast-wave function [7] (Eq. 7.9). It should be noted that from an individual fit to a single particle no physical meaning can

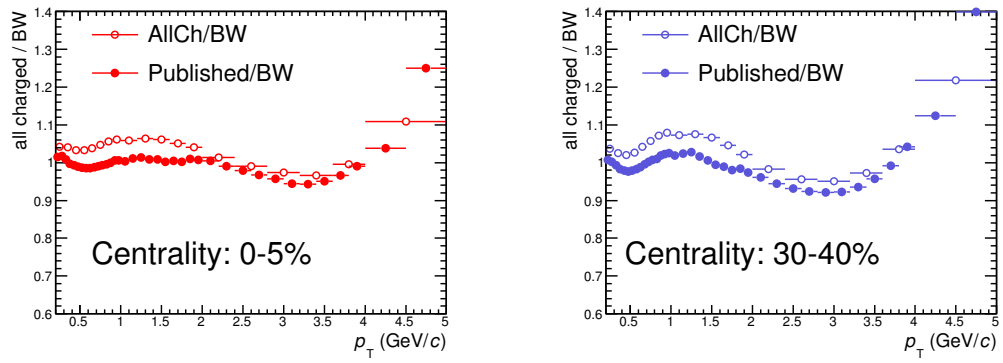


Figure 7.20: Comparison between ALICE published charged particles spectra and this analysis in Pb-Pb 0-5% (left) 30-40% (right) centrality class. The error bars are smaller than the markers.

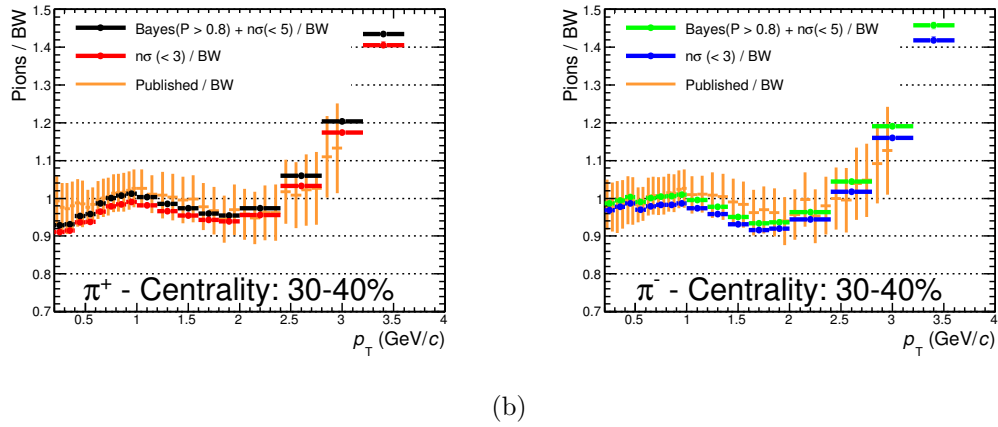
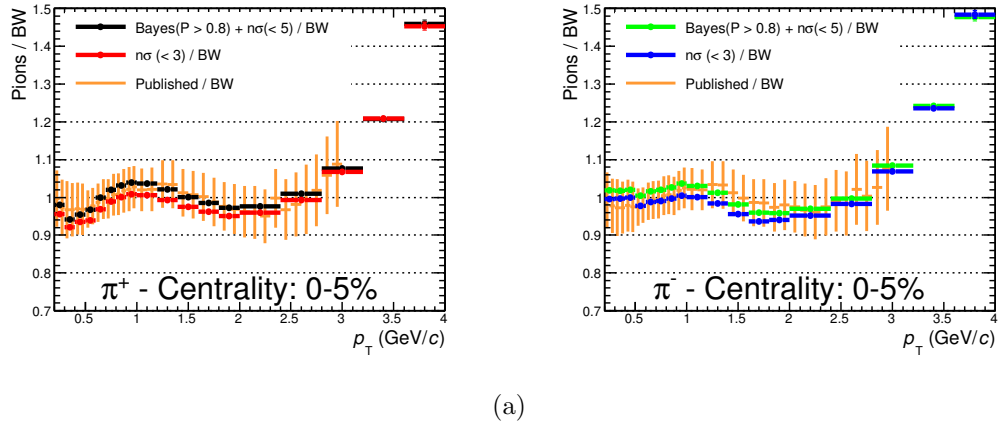


Figure 7.21: Comparison between ALICE published pion spectra and this analysis in Pb–Pb: π^+ and π^- in 0-5% (a) and 30-40% (b) centrality class.

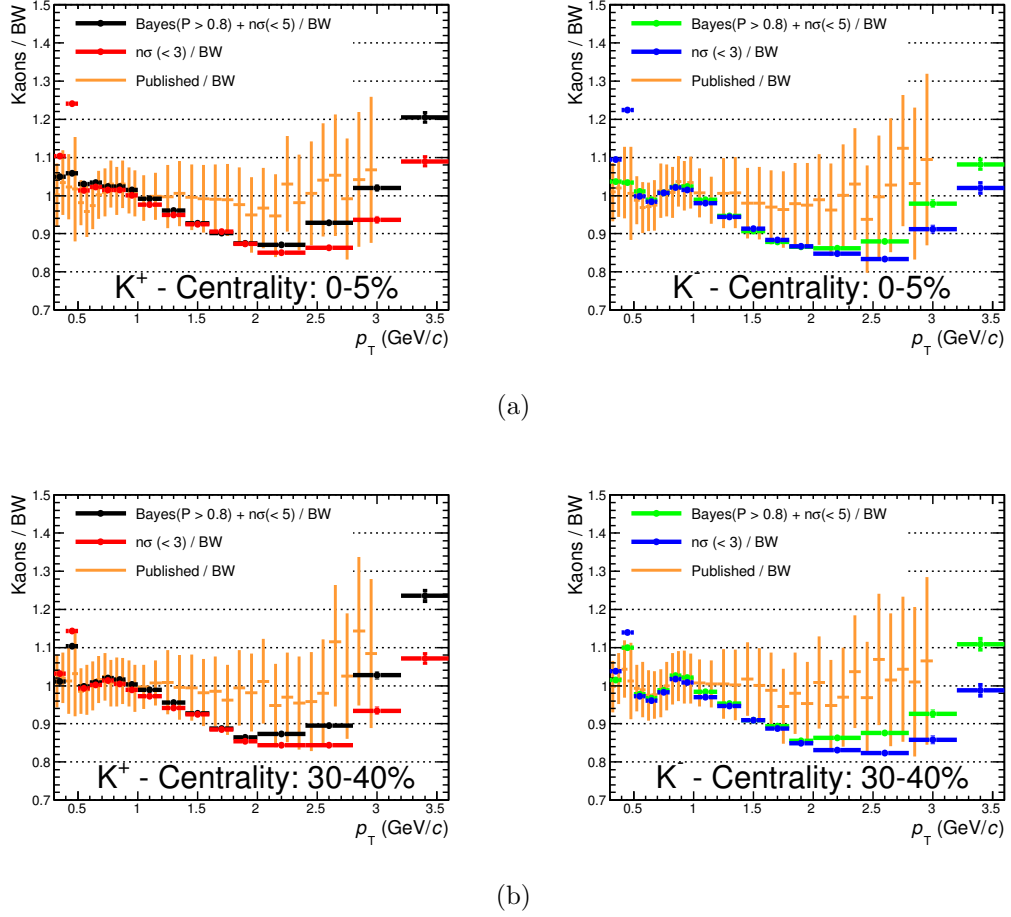


Figure 7.22: Comparison between ALICE published kaons spectra and this analysis in Pb-Pb: K^+ and K^- in 0-5% (a) and 30-40% (b) centrality class.

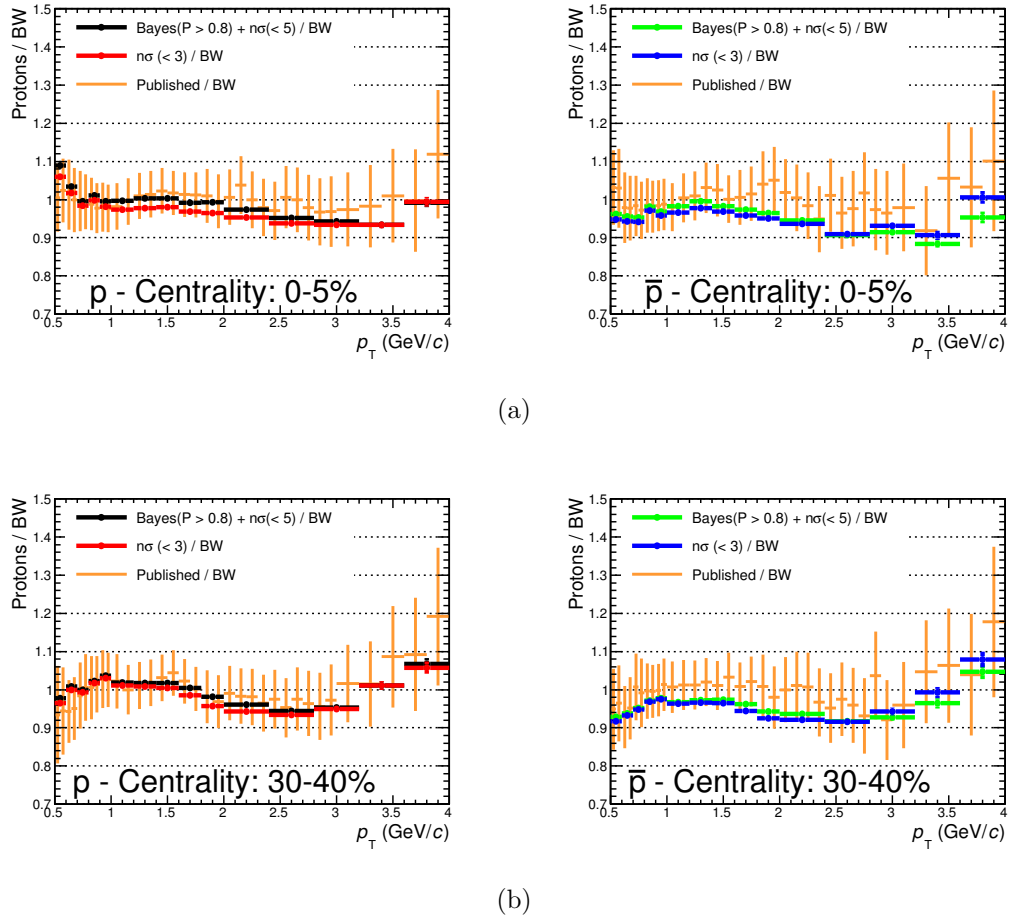


Figure 7.23: Comparison between ALICE published proton spectra and this analysis in Pb-Pb: p and $\bar{p}$ in 0-5% and 30-40% (b) centrality class.

centrality	π^+	π^-	p	$\bar{p}$	p/π
0-5%	710.963	740.093	33.6651	31.8528	0.045
5-10%	576.454	601.029	27.7681	26.3569	0.046
10-20%	432.021	451.183	21.1122	20.2221	0.047
20-30%	286.211	300.705	14.3376	13.8009	0.048
30-40%	183.848	195.812	9.57156	9.23353	0.0498
40-50%	112.543	120.808	6.11482	5.92144	0.052
50-60%	64.7846	69.1956	3.6495	3.5335	0.054
60-70%	33.6376	36.0448	1.96909	1.91306	0.0557
70-80%	15.7527	16.6261	0.934347	0.896759	0.057

Table 7.1: Mid-rapidity particle yields dN_i/dy and π/p ratio measured in this analysis.

centrality	π^+	π^-	p	$\bar{p}$	p/π published
0-5%	733 $\pm$ 54	732 $\pm$ 52	34 $\pm$ 3	33 $\pm$ 3	0.048
5-10%	606 $\pm$ 42	604 $\pm$ 42	28 $\pm$ 2	28 $\pm$ 2	0.048
10-20%	455 $\pm$ 31	453 $\pm$ 31	21 $\pm$ 1.7	21.1 $\pm$ 1.8	0.046
20-30%	307 $\pm$ 20	306 $\pm$ 20	14.4 $\pm$ 1.2	14.5 $\pm$ 1.2	0.047
30-40%	201 $\pm$ 13	200 $\pm$ 13	9.6 $\pm$ 0.8	9.7 $\pm$ 0.8	0.048
40-50%	124 $\pm$ 8	123 $\pm$ 8	6.1 $\pm$ 0.5	6.2 $\pm$ 0.5	0.048
50-60%	71 $\pm$ 5	71 $\pm$ 4	3.6 $\pm$ 0.3	3.7 $\pm$ 0.3	0.0514
60-70%	37 $\pm$ 2	37 $\pm$ 2	1.9 $\pm$ 0.2	2.0 $\pm$ 0.2	0.053
70-80%	17 $\pm$ 1.1	17 $\pm$ 1.1	0.9 $\pm$ 0.08	0.93 $\pm$ 0.09	0.054

Table 7.2: Mid-rapidity particle yields dN_i/dy and π/p ratio measured by ALICE [1].

be attached to the blast wave parameters, due to the strong correlations between them. The particle yields of pions and protons, at mid-rapidity, are reported in table 7.1 for this analysis and in table 7.2 for the ALICE published results [1]. The errors are dominated by the systematic uncertainties, reported for the published analysis in table 7.2. The integrated yields and the ratios π/p of the two analysis are compatible within the systematic uncertainties.

The comparison with the published spectra validates the PID procedure. Each correction has been studied in large- q_2 and small- q_2 events and the q_2 dependence has been to be negligible. Therefore for the final results, the ratios of raw spectra are used.

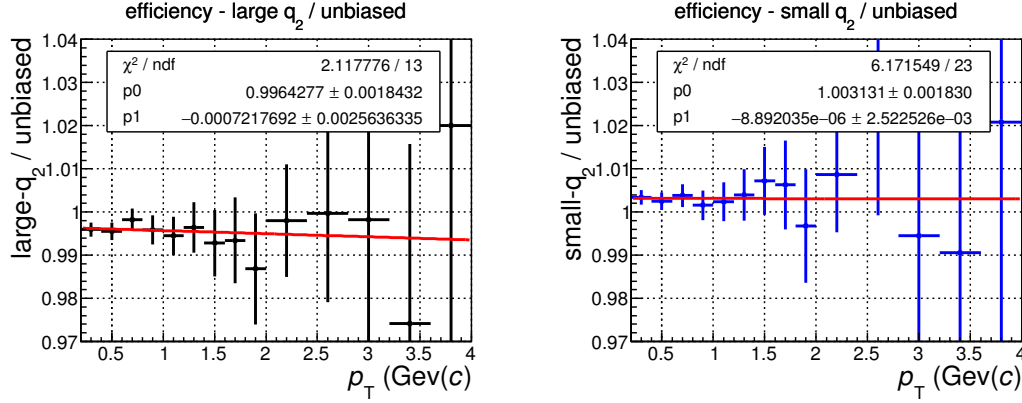


Figure 7.24: Systematic error from efficiency in AMPT Monte Carlo production.

7.6.1 Monte Carlo study

In order to estimate the dependence of the efficiency on the event shape selection a study on AMPT Monte Carlo production has been done.

The aim of this study is to check the dependence of the efficiency on the local occupancy, that can be larger in high elliptic flow events. The ratios of the correction factor, Eq. (7.3), evaluated in large- q_2 and small- q_2 samples with respect to the unbiased sample are reported in Fig. 7.24. It is possible to conclude that the Monte Carlo correction factor is weakly dependent on the flow vector selection applied. It should be noted that for this analysis global tracks are used. The tracking efficiency for global tracks depends only weakly on the multiplicity of the event, thanks to the large number of points available for reconstruction in the TPC.

Since the AMPT model is not able to reproduce the p_T spectra perfectly, it is not possible to use this Monte Carlo production to correct the data. For this reason the ratio has been fitted with a straight line and the discrepancy from unity is taken as a systematic error. The contribution assigned is about 0.2% with a normalization uncertainty³ of 0.4% for large- q_2 events while for small- q_2 events the systematic error is about 0.3% with a normalization uncertainty of 0.3%. Since the efficiency dependence on the q_2 selection is weak, it is possible to estimate the spectrum modification as a function of the q_2 only looking at raw yields (only statistical error from data).

³ p_T -independent uncertainties, which affect only the overall normalization of the spectra

7.7 Study of systematic uncertainties

The results for the spectra in shape selected events are presented in terms of ratios between events in the large- q_2 (small- q_2) sample to the unbiased sample.

The corrections for negative and positive particles are different. These corrections, however, do not change as a function of the event shape. Indeed, the analysis has been repeated using the raw p_T spectra and the corrected p_T spectra to obtain the ratios in the large- q_2 (small- q_2) sample to the unbiased sample. No deviation from the unity, as shown in Fig. 7.25 (a-c), has been observed. Therefore ratios of raw yields, without any charge selection, can be used to evaluate the systematic uncertainties.

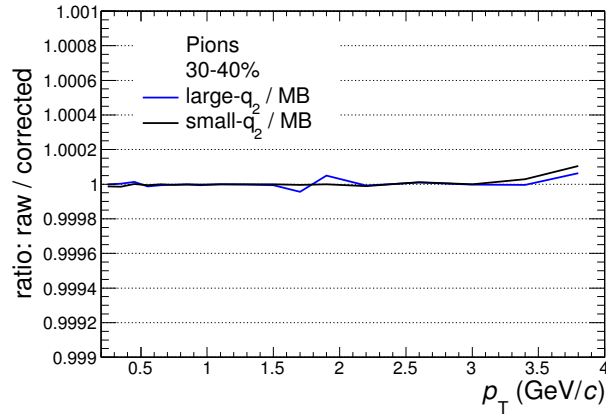
The systematic uncertainties studies are presented as ratio between the results obtained with the default set of cuts and those obtained with cuts variations. The significance of the systematic uncertainties has been also evaluated and is reported, as already done for the elliptic flow analysis (see appendix B for details).

The uncertainties on the tracking efficiency are estimated analysing event samples collected with different magnetic polarities and studying separately samples produced at different vertex position. Events produced at different longitudinal positions cross different portions of the detector, with different inefficiencies. The samples of events produced with $-10 < V_z < 0$ cm and $0 < V_z < 10$ cm have been studied separately. Only the contribution related to the vertex cut has been found significant (0.07%). The systematic uncertainty related to the tracking is also estimated by varying the tracks selection, requiring also that the track candidates in the TPC have hits in at least 120 (out of a maximum of 159) pad-rows and that the fraction of shared clusters in the TPC, i.e. the ratio of the clusters shared between two tracks candidates and the total number of clusters in the TPC, is < 0.4 . The related uncertainty is negligible for the unidentified charged particles and it is 0.07% for pions, kaons and protons.

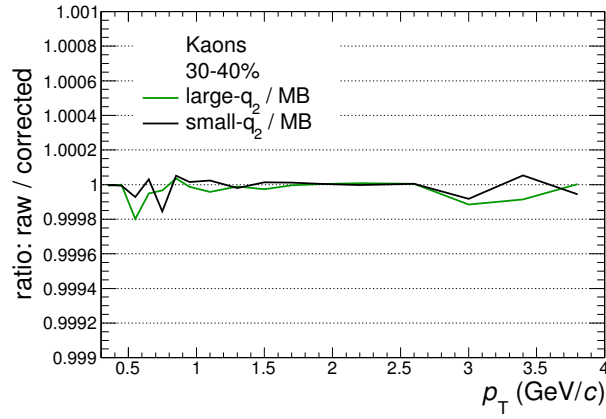
The uncertainty on the centrality is estimated varying the definitions of centrality classes by 1% and using tracks as the centrality estimator (as done for the v_2). This check leads to an uncertainty in the ratios of spectra of about 0.1% and 0.35%, for large- q_2 and small- q_2 samples, respectively.

In order to estimate the contribution from the PID procedure, different PID methods were used: bayesian PID, 3σ with double counting, 2σ and 3σ exclusive cut. The results are reported in Fig. 7.26-7.27-7.28 (by default, the 3σ method is used). The uncertainty related to the particle identification strategy is less than 0.1%.

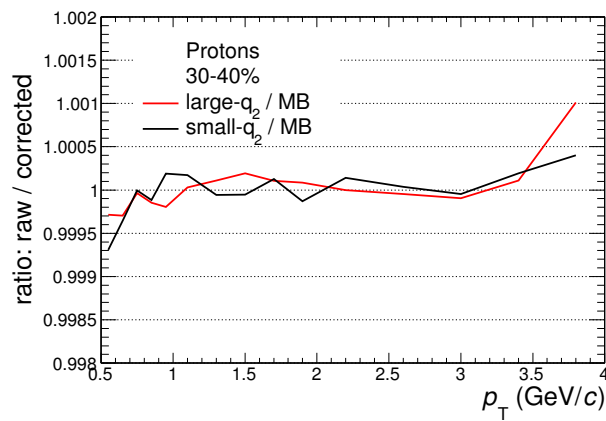
The different sources of systematic error are summarized in table 7.3 and 7.4 for the large- q_2 and small- q_2 sample, respectively.



(a)



(b)



(c)

Figure 7.25: Double ratios large- q_2 to unbiased (left), small- q_2 to unbiased (right), evaluated using raw and corrected spectra for pions (a), kaons (b) and protons (c).

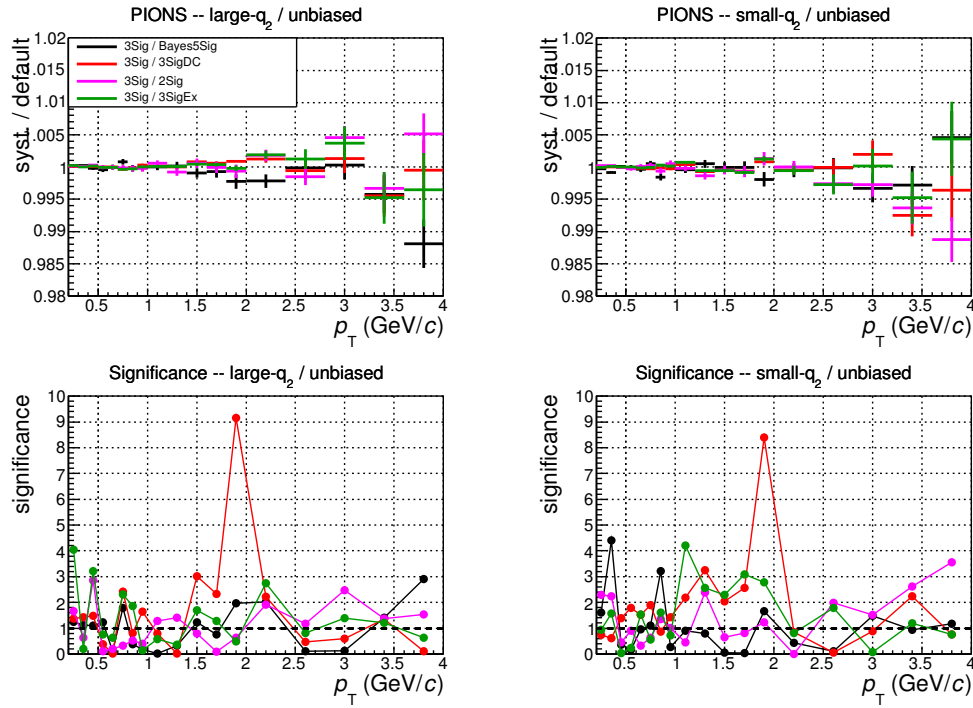


Figure 7.26: Systematic error related to PID procedure for pions (30-40%).

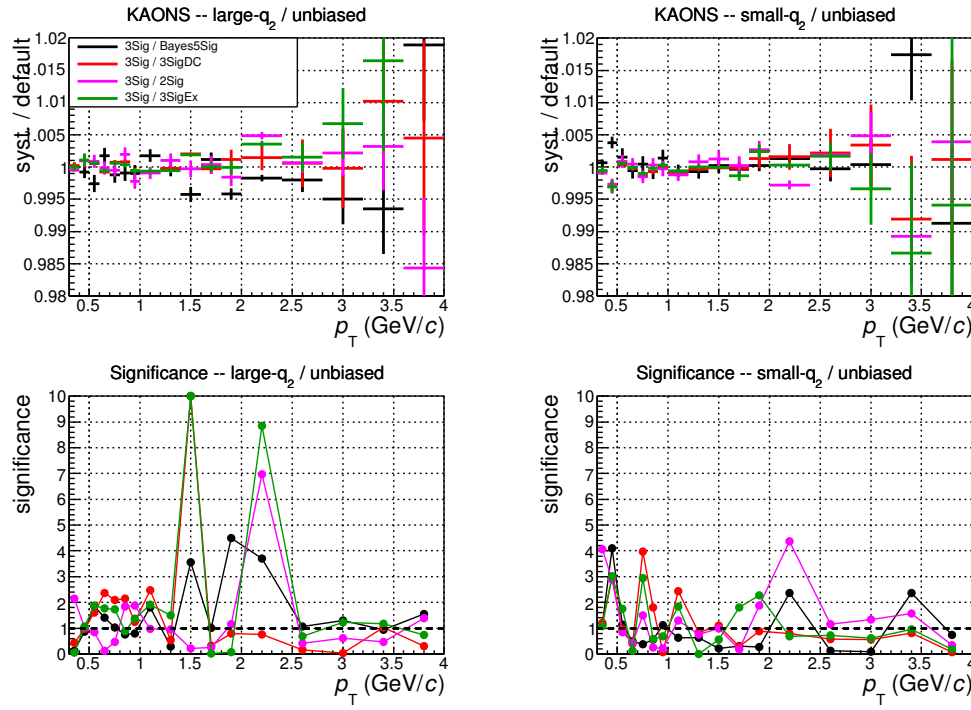


Figure 7.27: Systematic error related to PID procedure for kaons (30-40%).

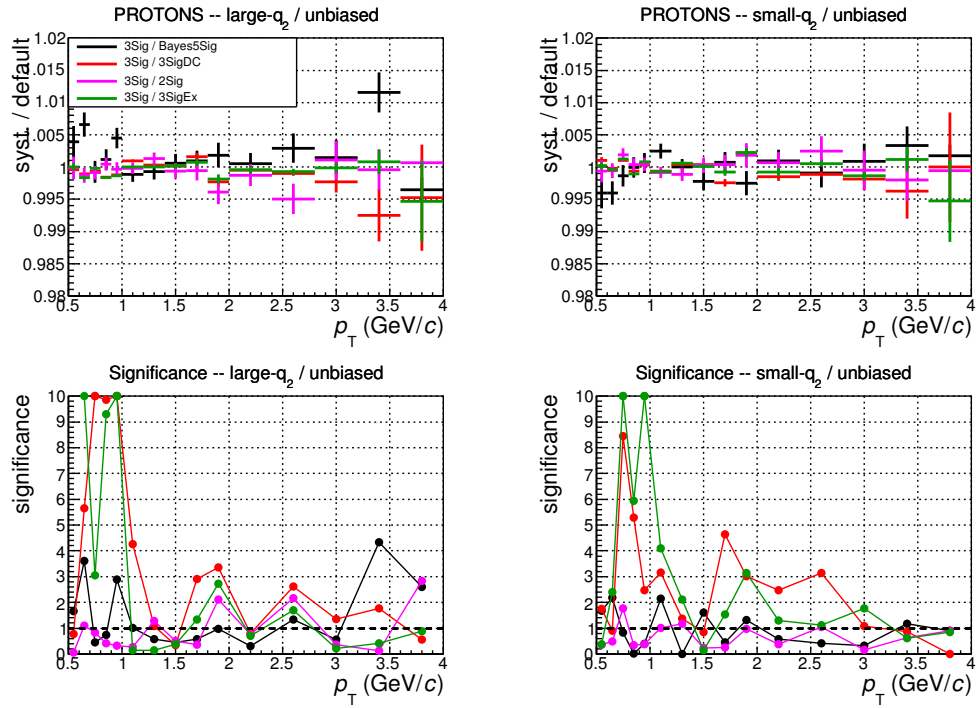


Figure 7.28: Systematic error related to PID procedure for protons (30-40%).

effect	N_{ch}	$\pi^\pm$	$K^\pm$	p and $\bar{p}$
magnetic field	NS	NS	NS	NS
charge	negligible	negligible	negligible	negligible
vertex	0.07%	0.07%	0.07%	0.07%
PID	-	0.07%	0.07%	0.07%
$(p_T > 1.5 \text{ GeV}/c)$				
track reconstruction	negligible	0.07%	0.07%	0.07%
centrality resolution	0.07%	0.07%	0.14%	0.07%
	$(p_T > 1.5 \text{ GeV}/c)$	$(p_T > 1.5 \text{ GeV}/c)$	0.14%	0.07%
centrality estimator	0.35%	0.35%	0.35%	0.35%
efficiency	0.21%	0.21%	0.21%	0.21%
normalization	0.4%	0.4%	0.4%	0.4%

Table 7.3: Summary of systematic errors for the ratio between large- q_2 and unbiased events.

effect	N_{ch}	$\pi^\pm$	$K^\pm$	p and $\bar{p}$
magnetic field	NS	NS	NS	NS
charge	negligible	negligible	negligible	negligible
vertex	0.07%	0.07%	0.07%	0.07%
PID	-	0.07%	0.07%	0.07%
$(p_T > 1.5 \text{ GeV}/c)$				
track reconstruction	negligible	0.07%	0.07%	0.07%
centrality resolution	0.07%	0.07%	0.14%	0.07%
	$(p_T > 1.5 \text{ GeV}/c)$	$(p_T > 1.5 \text{ GeV}/c)$	0.14%	0.07%
centrality estimator	0.35%	0.35%	0.35%	0.35%
efficiency	0.28%	0.28%	0.28%	0.28%
normalization	0.3%	0.3%	0.3%	0.3%

Table 7.4: Summary of systematic errors for the ratio between small- q_2 and unbiased events.

7.8 p_T spectra in ESE selected events

The effect of the event shape selection on p_T distributions is reported for two event shape classes, corresponding to the 10% of the events having the top (bottom) values of q_2 . The results are presented terms of ratios between p_T -spectra in 10% large (small)- q_2 and the unbiased sample. The V0A ($2.8 < \eta < 5.1$) is used as the default q_2 estimator, since it provides the largest η gap with respect to the central barrel. The ratios between large- q_2 (small- q_2) and unbiased sample are reported in Fig. 7.29 as red (blue) markers, for several centrality classes. A modification in the p_T spectra shape is observed at intermediate p_T : the spectra are harder in large- q_2 events, while softer spectra are observed in small- q_2 events. This modification is larger in semicentral collisions. At high p_T the modification vanishes.

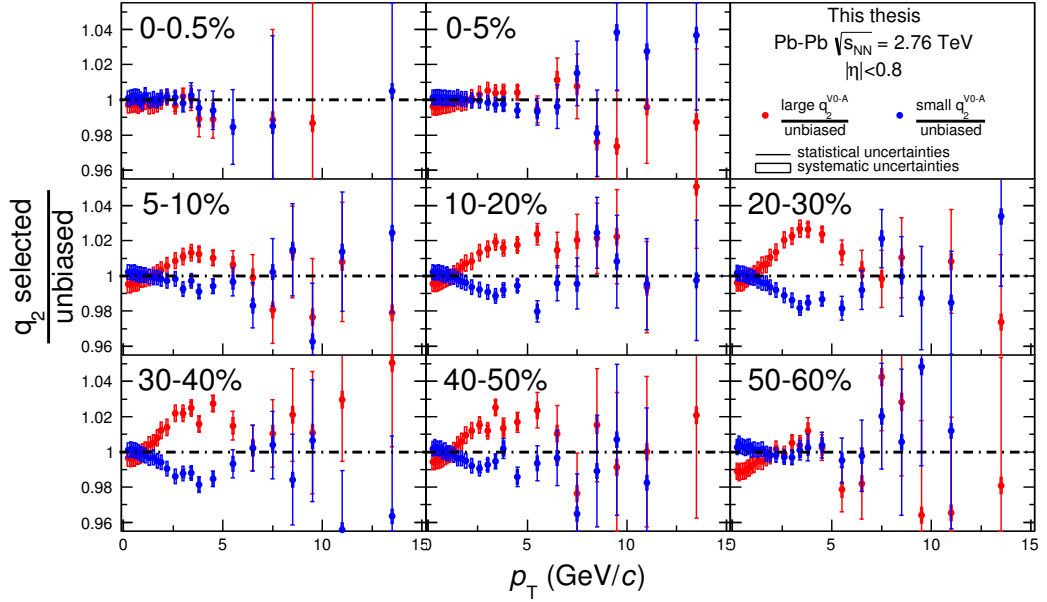


Figure 7.29: Ratios of the p_T spectra for charged hadrons in the large- q_2 or small- q_2 samples to the unbiased sample ($q_2^{\text{V0-A}}$ selection). Statistical (error bars) and systematic (boxes) uncertainties plotted.

To study the effect of the detector resolution and the non-flow contribution the analysis has been repeated using the V0C ($-3.7 < \eta < -1.7$) and the TPC ($-0.8 < \eta < 0.8$) to evaluate the q_2 . When the TPC is used to evaluate the flow vector in the range $-0.5 < |\eta| < 0.5$, spectra are measured in the range $-0.8 < |\eta| < -0.5$ and $0.5 < |\eta| < 0.8$, to avoid autocorrelations between the tracks.

The results are shown in Fig. 7.30 and Fig. 7.30 for q_2^{V0C} and q_2^{TPC} , respectively. The modification is larger when q_2^{V0C} and q_2^{TPC} are used to select the 10% large- q_2 and the 10% small- q_2 event samples.

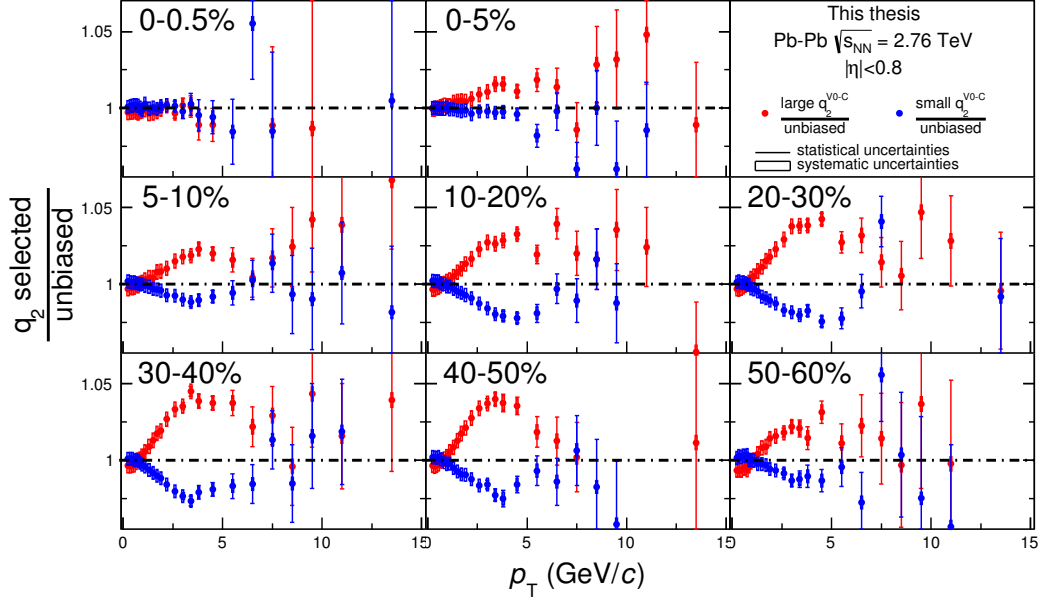


Figure 7.30: Ratios of the p_T spectra for charged hadrons in the large- q_2 or small- q_2 samples to the unbiased sample (q_2^{V0-C} selection). Statistical (error bars) and systematic (boxes) uncertainties plotted.

A normalization bias is observable for the 50-60% centrality class when the V0A is used to compute the q_2 . The bias is smaller when the V0C or the TPC are used, which indicates that this could be due to the detector resolution effect.

The analysis has been repeated with V0C and TPC, varying the cut so that a similar change in $v_2(p_T)$ is found at midrapidity (Fig. 6.10).

Similar modification of the p_T distributions can be obtained selecting 10% large- q_2^{V0-A} , 23% large- q_2^{V0-C} , 50% large- q_2^{TPC} and 10% small- q_2^{V0-A} , 50% small- q_2^{V0-C} , 75% small- q_2^{TPC} , as shown in Fig. 7.32. The three selections are consistent up to 50% centrality bin.

7.9 Contamination from non-flow processes

The selection based on q_2 could be biased by hard processes: one event could have a particularly large q_2 because of a jet produced in the acceptance of the detector used for the q_2 measurement.

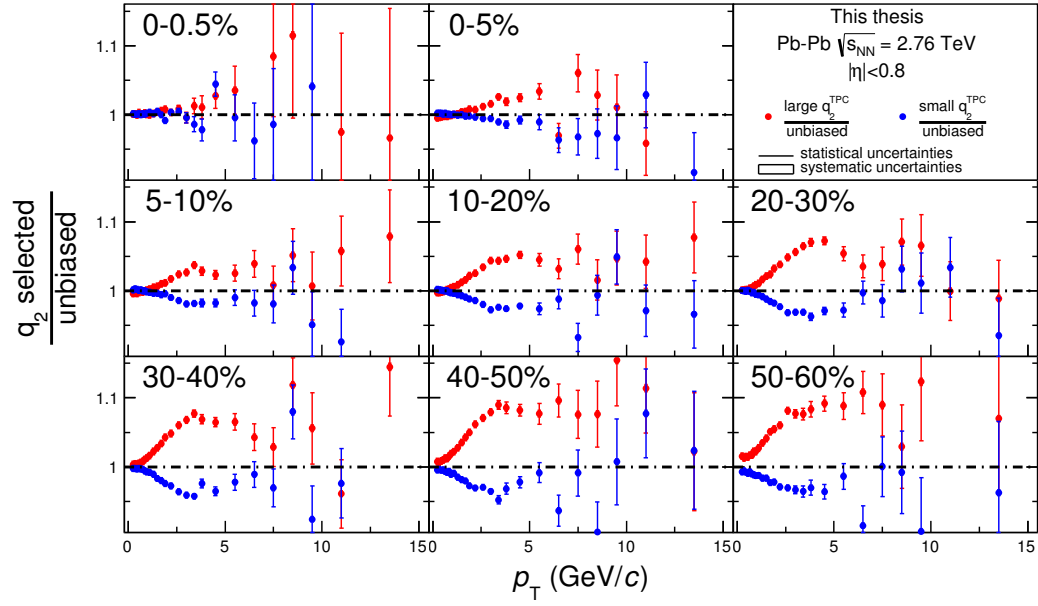


Figure 7.31: Ratios of the p_T spectra for charged hadrons in the large- q_2 or small- q_2 samples to the unbiased sample (q_2^{TPC} selection). Statistical (error bars) and systematic (boxes) uncertainties plotted.

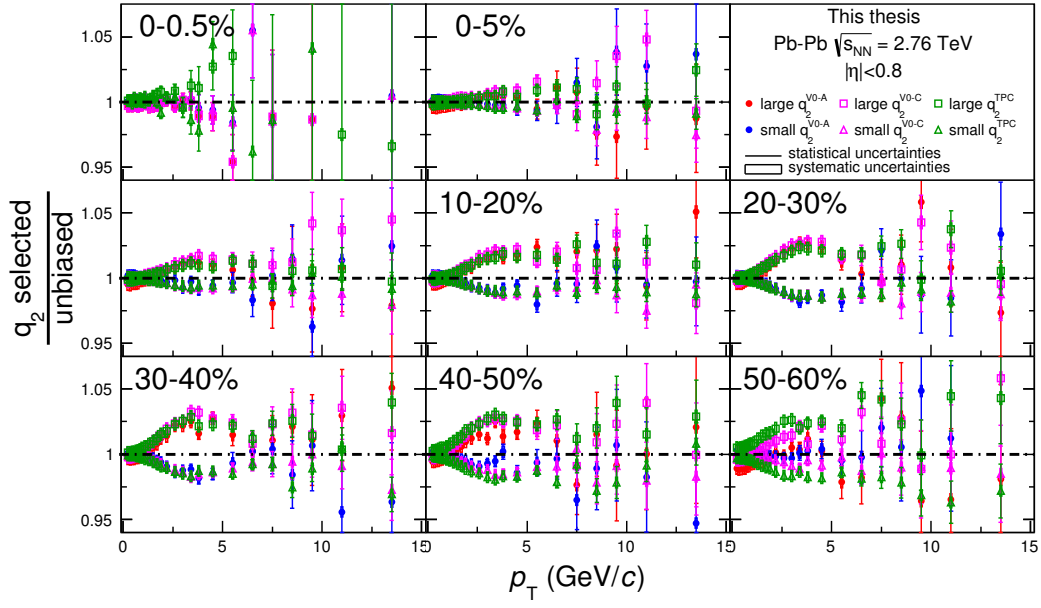


Figure 7.32: Ratios of the p_T spectra for charged hadrons in the 10% large (10% small) q_2^{V0-A} , 50% large (23% small) q_2^{V0-A} , 50% large (75% small) q_2^{TPC} . Statistical (error bars) and systematic (boxes) uncertainties plotted.

This effect can be studied varying the η -gap between the q_2 selection and the spectra measurement. In particular, a strong non-flow effect can be expected in case of overlapping η region.

We select events according to the magnitude of the q_2 . The selection is not properly calibrated (as done with the V0s and the full TPC), therefore, a bias in the multiplicity distribution is still present. This is not a problem in this study, since we want to evaluate the η dependence of p_T spectra in the same class of events. Half of the TPC is used to calculate the q_2 , while the p_T spectra are measured in the other half. We label the q_2 computed in $-0.8 < \eta < 0$ as q_{neg} and the one computed in $0 < \eta < 0.8$ as q_{pos} .

The ratio of the spectra in large- q_{pos} events to the unbiased sample, in the same η region, is reported in Fig. 7.33(a). The left panel shows the large- q_2 selection and the right one the small- q_2 selection. At high- p_T the ratio does not go to zero as it does with the standard q_2 selection. The bias is much larger in the region where the track selection and the event selection overlap (the positive TPC side in this case), due to the autocorrelation of the tracks. The ESE selection has been also performed using the q_{neg} and measuring the spectra in the positive side of the TPC ($0 < \eta < 0.8$). The results are presented in Fig. 7.33(b)). Also in this case the bias is larger with respect to the default q_2 selection based on the V0A.

As a further check we report in Fig. 7.34 the ratio ESE-selected events to unbiased events up to 50 GeV/c in the 30-40% centrality class. The ratio at high p_T is found to be close to 1, indicating that the jet-bias is negligible.

Figure 7.35 shows the ratios of the spectra in large- q_2 and small- q_2 events for the 70-80% centrality class, using q_{pos} (a) and q_{neg} (b). In peripheral collisions the non-flow contribution is dominant and the effect of the bias is stronger than in the 30-40% centrality bin.

To further check the influence of a potential non-flow bias in the event shape engineered events, the study, with events selected based on the q_2^{V0A} , is repeated using the two sides of the TPC to calculate the particle spectra. The result in the region $\eta > 0$ is compared with the one obtained in $\eta < 0$. This corresponds to different η gaps between the event selection and the measurement of the spectra, which is sensitive to non-flow effects, as described in this section.

All these observations confirm that no significant jet-related effect is observed in the data.

Bibliography

- [1] ALICE Collaboration. Centrality dependence of π , K, p Production in Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. C* **88** 044910, 2013.

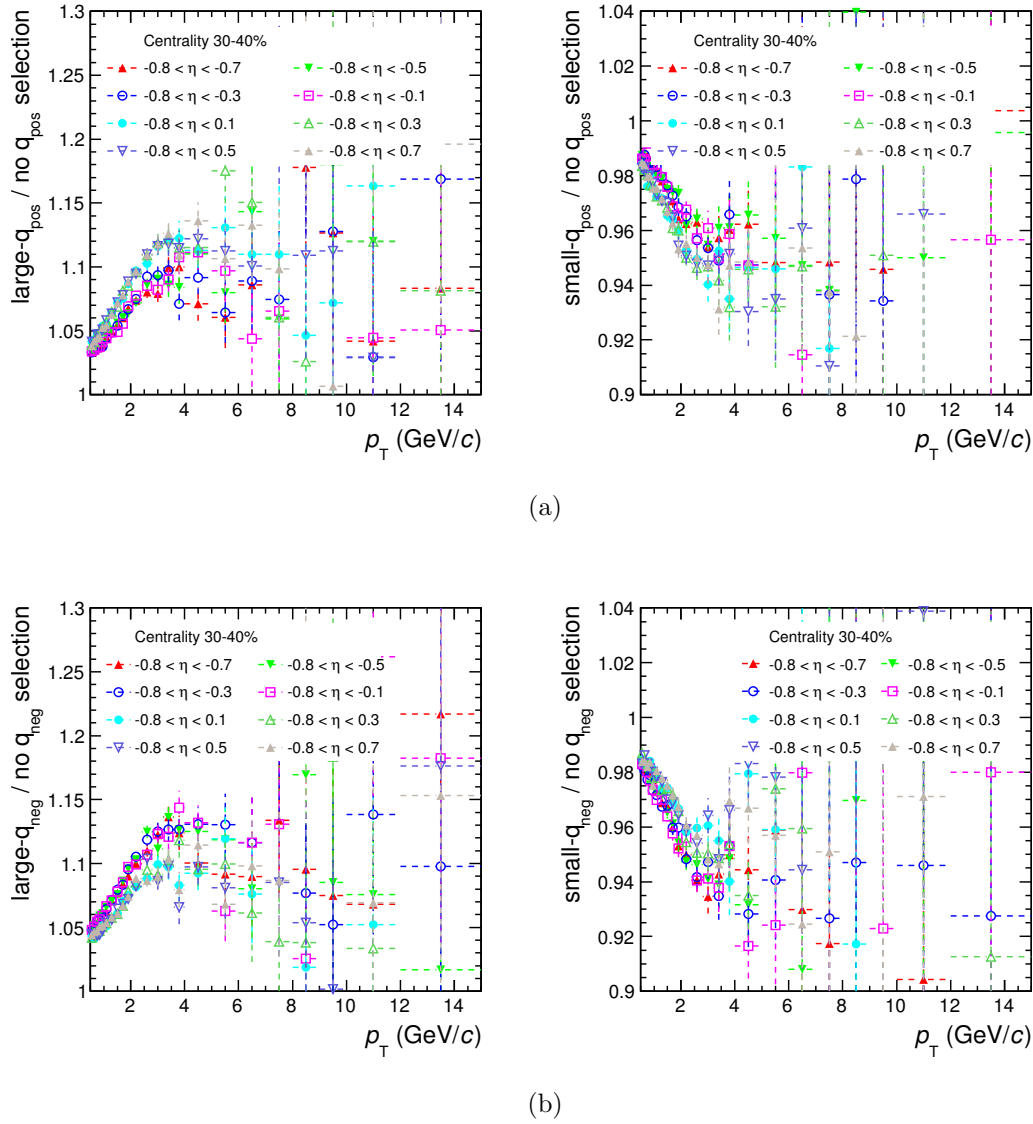


Figure 7.33: Ratio with respect to the unbiased spectra are reported for different η regions for the events selected using the q_2 calculated in the positive (a) and negative (b) side of the TPC (q_{pos}). Left corresponds to large- q_2 selection and right to small- q_2 selection. Centrality: 30-40%.

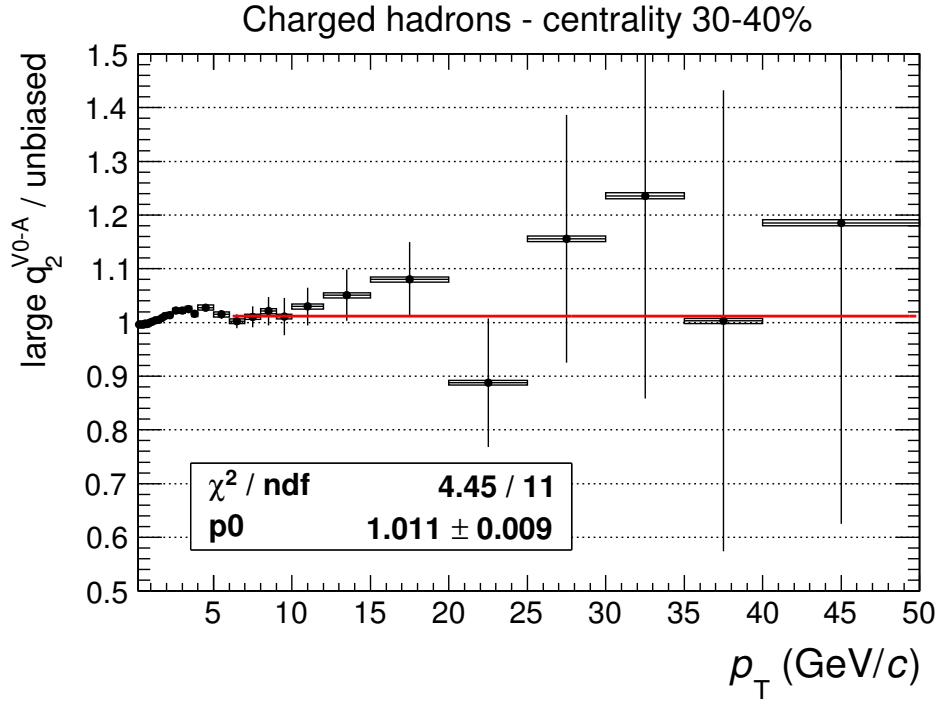


Figure 7.34: Ratio of p_T spectra in large- q_2 events to unbiased events up to 50 GeV/ c in 30-40%.

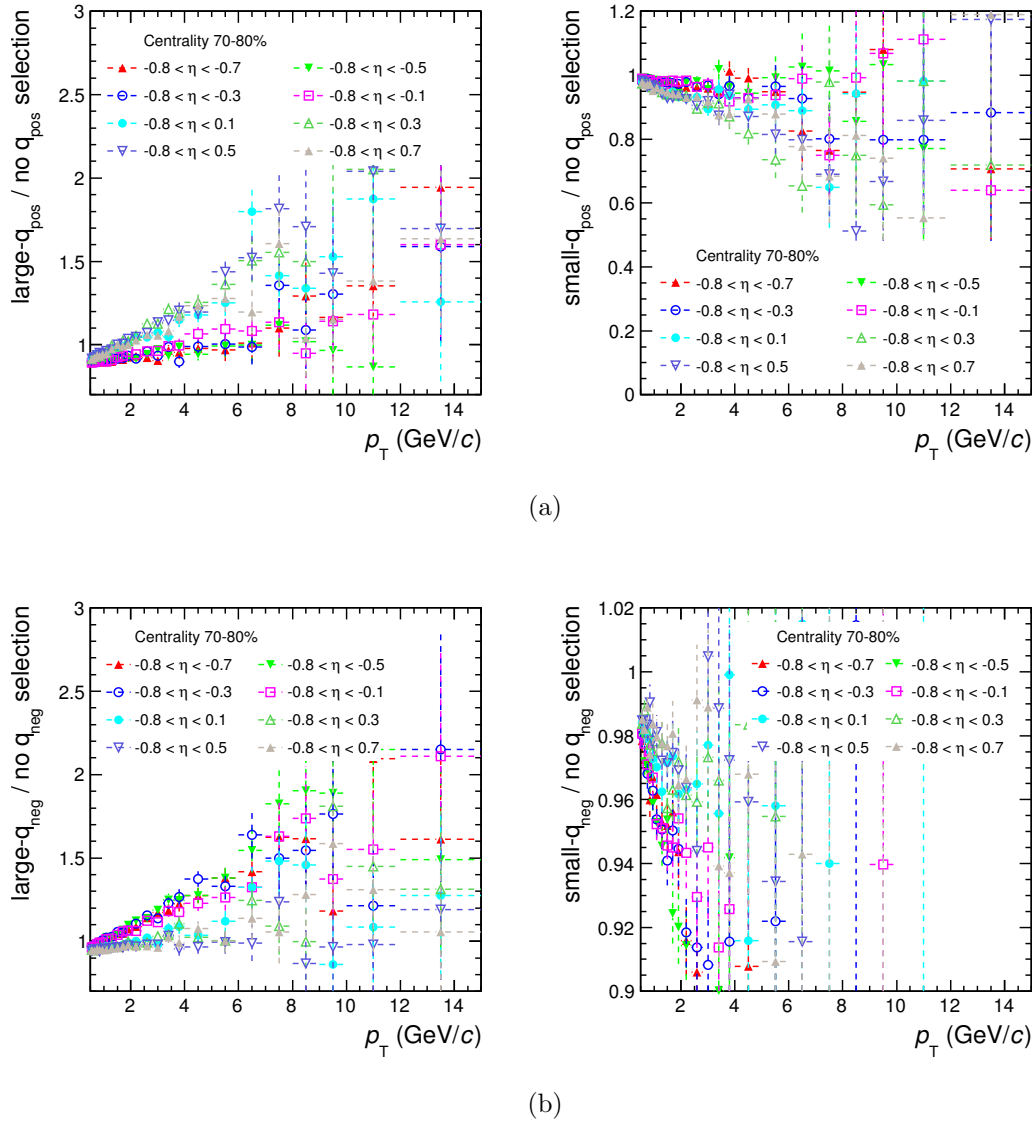


Figure 7.35: Ratio with respect to the unbiased spectra are reported for different η regions for the events selected using the q_2 calculated in the positive (a) and negative (b) side of the TPC (q_{pos}). Left corresponds to large- q_2 selection and right to small- q_2 selection. Centrality: 70-80%.

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In this chapter we discuss the results of the event shape selection on elliptic flow and p_T spectra measurement with the ALICE detector in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. We start by outlining the results of elliptic flow in event shape selected events. The analysis procedure has been discussed in chapter 6. Then we show the effect of the ESE-selection on p_T distributions for unidentified charged particles, pions, kaons and protons. The analysis procedure has been described in chapter 7. We conclude the chapter with the comparison to the models.

The results presented in the next sections are obtained for two event shape classes, corresponding to 10% highest and 10% lowest q_2 values, which will be referred to as large- q_2 and small- q_2 in the following. The V0A is used as the default q_2 estimator. The distribution of the flow vector as a function of centrality is shown in Fig. 8.1, on the left. The dashed line and the dash-dotted line indicate the large- q_2 and small- q_2 event classes, respectively. On the right the q_2 distribution in the two centrality classes, 0-1% and 30-31%, are shown. The measurement is also reported using V0C and TPC for the q_2 evaluation, to estimate the effect of non-flow. To avoid ambiguities, when necessary, we indicate the q_2 as q_2^{V0-A} , q_2^{V0-C} and q_2^{TPC} , clarifying the detector used to compute it.

For centralities larger than 60% centrality the V0s calibration, due to the low statistics available, is not accurate. Therefore we present results up to the 50-60% centrality class.

8.1 Elliptic flow results

The effect of the V0A event shape selection on q_2^{TPC} distribution in 30-40% centrality class in large- q_2^{V0-A} and small- q_2^{V0-A} events is shown in Fig. 8.2. The average q_2^{TPC} value changes by about 12% (8%) in large- q_2 (small- q_2) events. The q_2 distribution is very well described by the *Bessel-Gaussian* (BG) distribu-

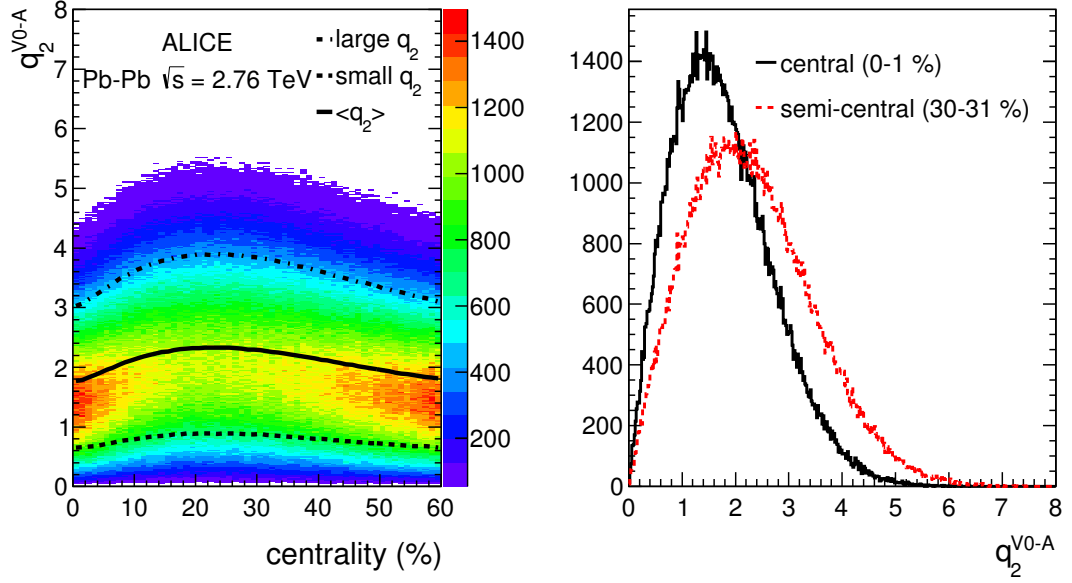


Figure 8.1: q_2^{V0-A} vector distribution as a function of centrality (left) and projection for 2 centrality classes (right).

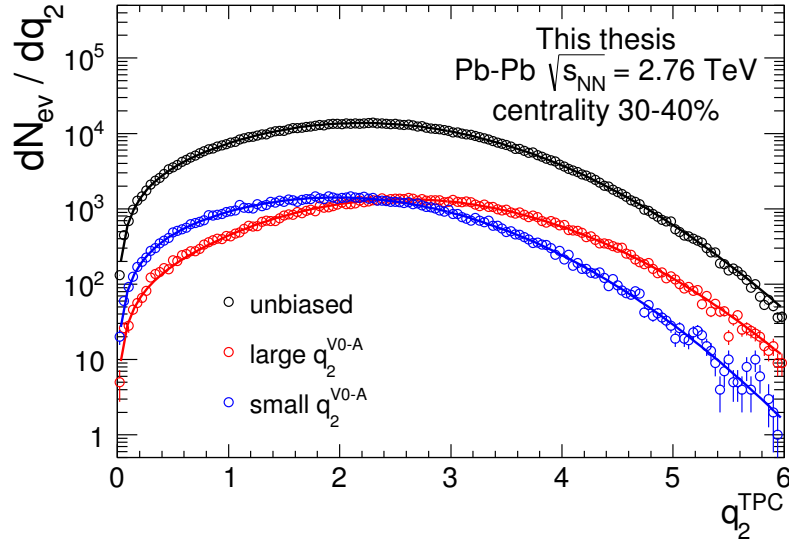


Figure 8.2: Distribution of q_2^{TPC} in the unbiased, large- q_2 and small- q_2 samples, selected using q_2^{V0-A} .

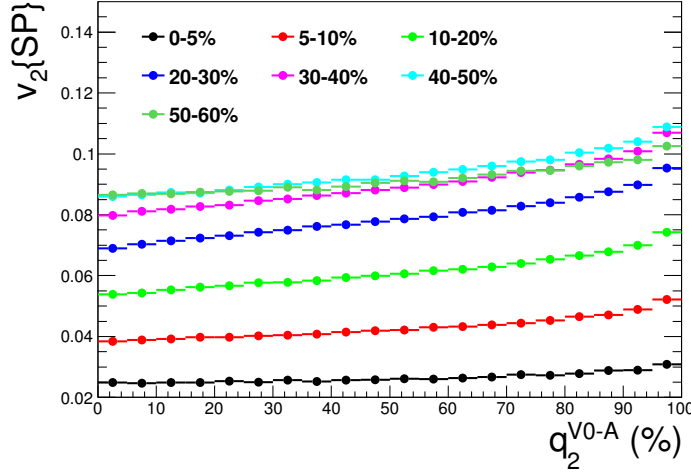


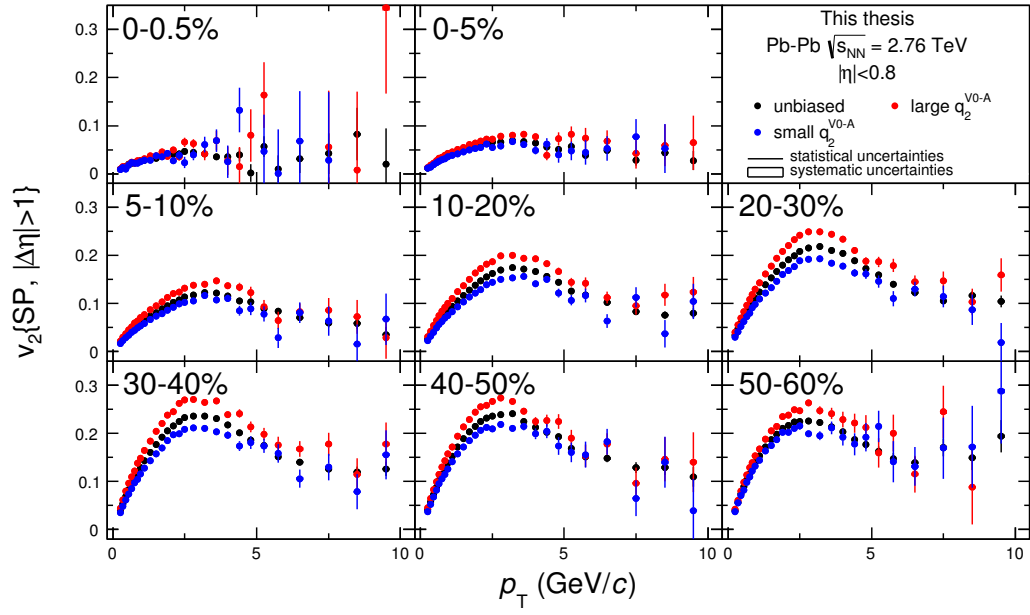
Figure 8.3: Integrated $v_2\{\text{SP}\}$ as a function of q_2^{V0-A} .

tion $\text{BG}(q; q_0; \sigma_{qx})$ [1, 2] that for high multiplicities allows to extract the $v_2\{2\}$ and $v_2\{4\}$ coefficients (see section 2.4.1 for details). The extracted elliptic flow coefficient $v_2\{4\}$, which is essentially insensitive to non-flow, is found to increase of $\approx 20\%$ in the large- q_2 events and to decrease of $\approx 10\%$ in small- q_2 events.

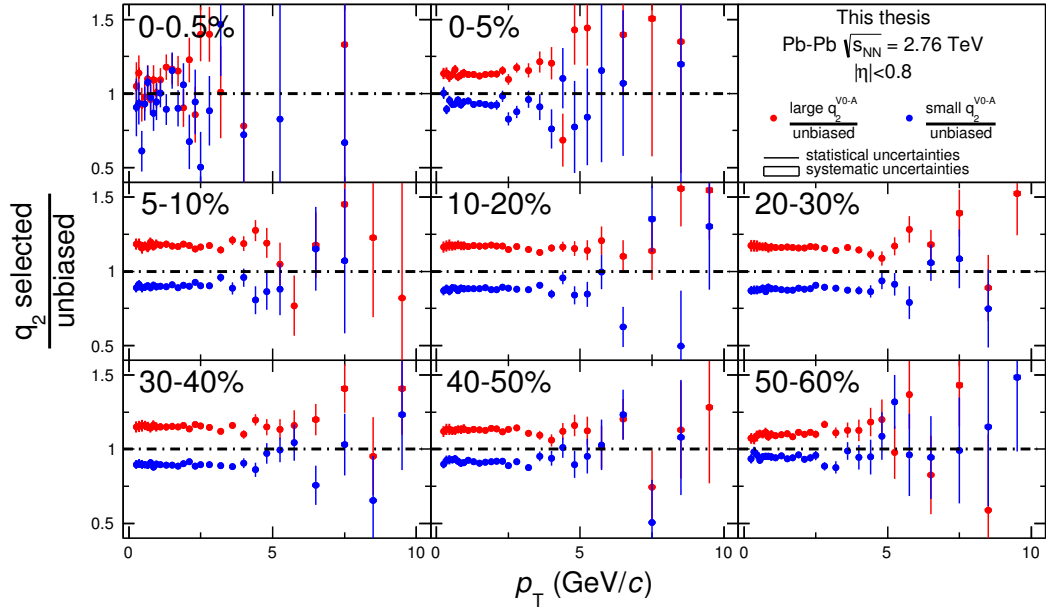
The $v_2\{\text{SP}\}$ integrated distribution as a function of q_2^{V0-A} is shown in Fig. 8.3, for different centralities. As expected, v_2 increases as a function of q_2 . The effect is stronger for semicentral events, in particular, in the centrality class 20-30% the $v_2\{\text{SP}\}$ is found to increase of $\approx 15\%$ in large- q_2 events and to decrease $\approx 10\%$ in small- q_2 events.

Figure 8.4(a) presents the $v_2(p_T)$ distributions, with different panels representing different centralities. The top left plot presents results for the 0.5% most central Pb-Pb collisions, while the most peripheral interval (50-60% centrality class) is shown in the bottom right plot. The value of v_2 increases from central to peripheral collisions up to the 40-50% centrality class. In the hydrodynamic model, this can be interpreted as a consequence of the increase of the initial state eccentricity towards peripheral collisions. For more peripheral events (i.e. 50-60%), the v_2 does not change significantly as compared to the previous centrality interval. This might originate from different effects such as the smaller lifetime of the fireball in peripheral compared to more central collisions, which does not allow v_2 to further develop, the smaller contribution of eccentricity fluctuations or to final state hadronic effects (compared to more central events) [3].

The increase of the v_2 as a function of the transverse momentum is almost linear up to 2-3 GeV/ c . This initial rise is followed by a saturation and then a decrease is observed for all centralities. For $p_T > 8$ GeV/ c , where particle production is



(a)



(b)

Figure 8.4: (a) $v_2\{\text{SP}\}$ as a function of centrality, for no $q_2^{\text{V0-A}}$ selection and for the 10% highest (smallest) q_2 . (b) Ratio of $v_2\{\text{SP}\}$ estimated in the large- q_2 and small- q_2 samples to unbiased sample.

dominated by fragmentation of hard partons, the v_2 of charged particles is positive and weakly dependent on transverse momentum, over the full centrality range studied in this work. The $v_2(p_T)$ distributions show a similar pattern in large- q_2 and small- q_2 events.

Figure 8.4(b) shows the ratio between the large- q_2 (small- q_2) selection and the unbiased sample. The selection of the 10% highest (lowest) q_2 events results in a change of 10-20% of the $v_2\{\text{SP}\}$ measured at mid-rapidity. Ratios are constant up to $p_T \approx 4$ GeV/ c , suggesting a common origin of flow fluctuations up to 4 GeV/ c . This suggests that the q_2 selects a global property of the event, likely related to the initial shape of the overlap region. For $p_T > 4$ GeV/ c , the elliptic flow coefficient do not seem to depend on the q_2 selection, indicating a smaller effect of flow fluctuations, even if large statistical uncertainties do not allow to make any firm conclusion. More data are needed to study this regime in more detail.

This picture is in agreement with the conclusions in [4], which indicates a common origin for flow fluctuations, based on the relative difference of the $v_2\{\text{EP}\}$ and four-particle cumulant $v_n\{4\}$ measurement. This is usually associated with fluctuations of the initial collision geometry, at least up to the regime where hard scattering and jet energy loss are expected to dominate.

The average $v_2\{\text{SP}\}$ change for each centrality class has been evaluated fitting the ratios up to 4 GeV/ c with a constant. The result is shown in Fig. 8.5. The modification is stronger in semicentral collisions, as expected, since the q_2 covers a larger dynamic range in semicentral collisions, as shown in Fig. 8.1. The event shape technique is more efficient in selecting elliptic events than isotropic events. This results in a larger modification in high q_2 events with respect to low q_2 events, as it is seen in Fig. 8.5.

The detector resolution effects on the v_2 results and the contribution of non-flow processes have been studied using different q_2 estimators: V0A, V0C and TPC. We discuss here only the results for the 30-40% centrality class, referring the reader to the section 6.3.1 for the other centrality classes.

Figure 8.6 shows the results obtained using the V0C and the TPC to compute the q_2 .

The results from the V0C ($-2.7 < \eta < -1.7$) are similar to the ones obtained using the V0A. The small difference can be attributed to the smaller η gap introduced when using the V0C. In case of the TPC-based selection, we used the central region $|\eta| < 0.5$ to determine the q_2 while $v_2\{\text{SP}\}$ is still computed in the region $-0.8 < \eta < -0.5$ and $0.5 < \eta < 0.8$. The modification of the v_2 is larger with respect to the case of the event selection based on $q_2^{\text{V0-A}}$ and $q_2^{\text{V0-C}}$. The ratio large- q_2 (small- q_2) over unbiased approaches 1.5 (0.5) in several centrality classes.

The selectiveness of the ESE cut depends on the range of the q_2 and on the

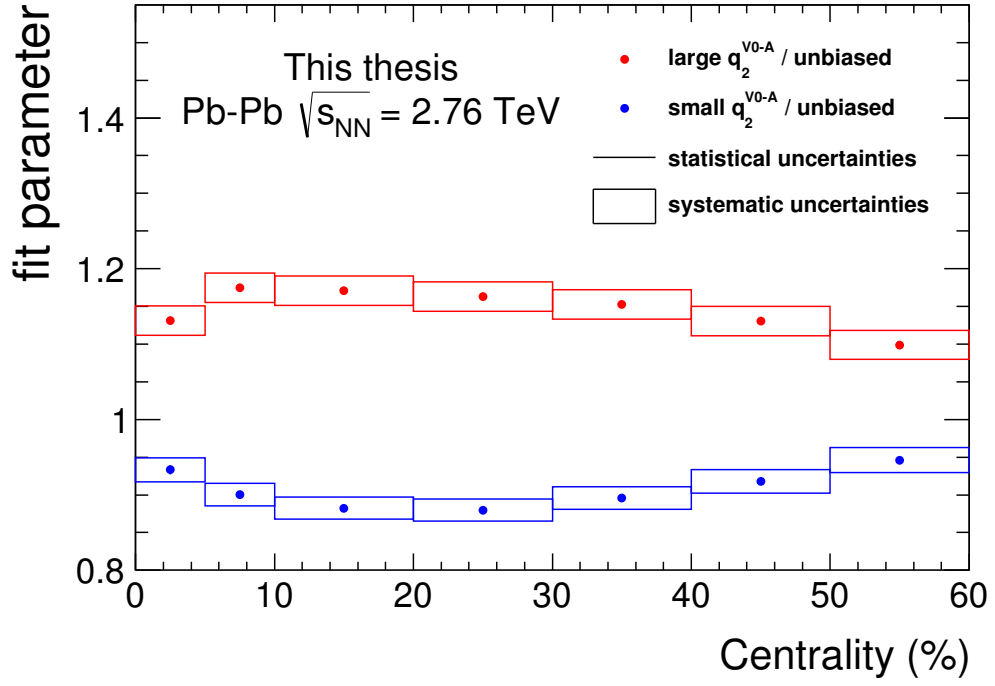


Figure 8.5: Centrality dependence of the average $v_2\{\text{SP}\}$ variation with the event shape selection based on q_2^{V0-A} .

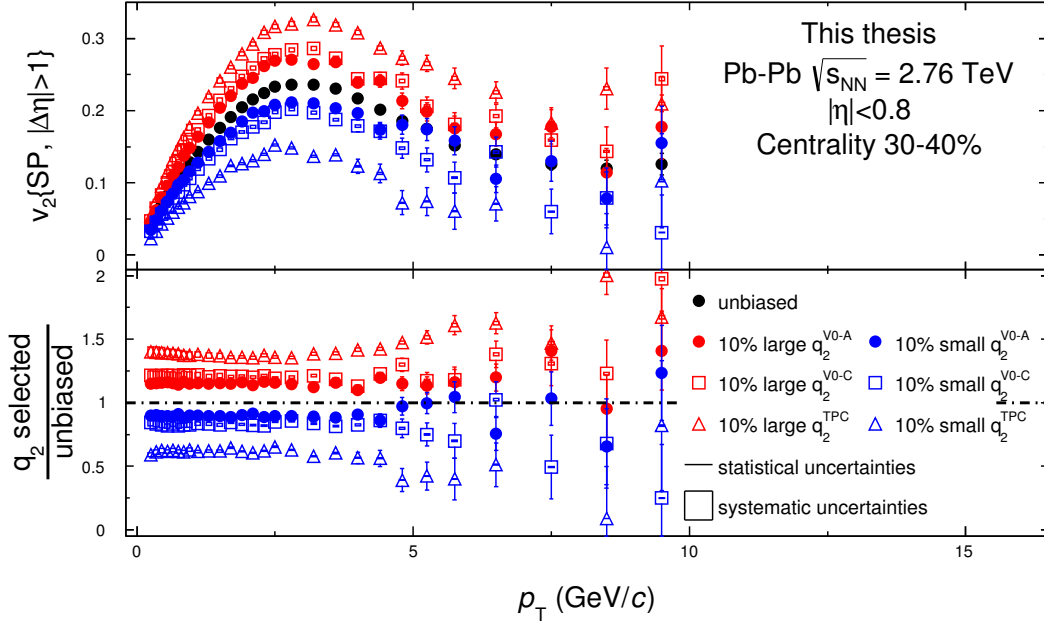


Figure 8.6: $v_2\{\text{SP}\}$ in the 30-40% centrality class, for no q_2 selection and for the 10% highest (smallest), $q_2^{\text{V0-A}}$, $q_2^{\text{V0-C}}$ and q_2^{TPC} selections.

resolution of the estimator used to compute the q_2 . The latter depends on the flow [5] and on the multiplicity [6], which are reduced at forward rapidity. Moreover, since the V0 segmentation is coarse with respect to the high granularity of the TPC, we expect that the selection based on the V0A is the less sensitive among those we have used. Therefore, the stronger increase is expected when the TPC is used, due to the larger multiplicity, flow and detector resolution for charged particles measured at mid-rapidity. This leads to a stronger sensitivity on ESE selection when the q_2 cut is performed. This is expected since the same hierarchy in the event-plane [7] resolution measurement for V0A, V0C and TPC has been observed, as shown in Ref. [8].

For a fair comparisons between different estimators, we need to change the cut so that the average change in v_2 is the same, as shown in Fig. 8.7.

In order to reproduce the behaviour observed in the 10% highest (10% smallest) $q_2^{\text{V0-A}}$ one needs to select 23% large (50% small) $q_2^{\text{V0-C}}$ and the 50% large (75% small) q_2^{TPC} events. The p_T dependence is rather flat in all classes: this suggests that the stronger effect seen in TPC is not (only) due to non flow, but the cut is also much more effective, opening up the possibility for future studies. For $p_T > 7$ GeV/c the ratio is not flat as in the selection with $q_2^{\text{V0-A}}$ and $q_2^{\text{V0-C}}$ and develops a momentum dependence starting at high p_T . This could be interpreted

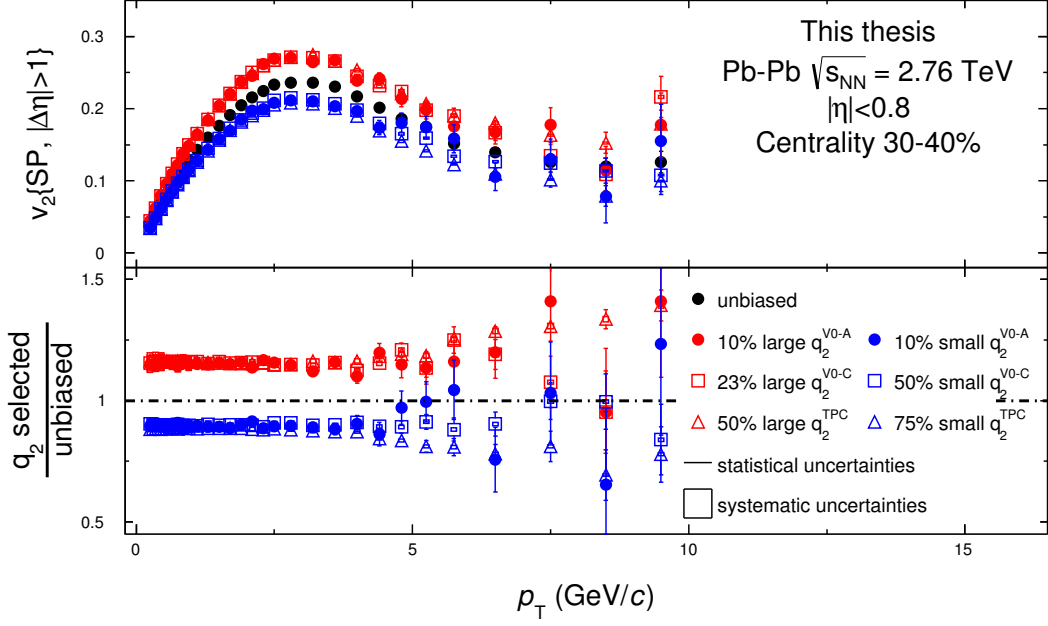


Figure 8.7: $v_2\{\text{SP}\}$ in the 30-40% centrality class, for no q_2 selection and for different selections in $q_2^{\text{V0-A}}$, $q_2^{\text{V0-C}}$ and q_2^{TPC} .

as a consequence of the contamination from high- p_T jets, which leads to larger q_2 , biasing the selection. The reduced η gap between the measurement of $v_2\{\text{SP}\}$ and the q_2 based selection could enhance this effect.

The $v_2(p_T)$ distributions, shown in Fig. 8.4, demonstrate that event shape selection based on the azimuthal asymmetry of the event can be used to select event samples with elliptic flow significantly larger or smaller than the average. The ratios in Fig. 8.4 and Fig. 8.6 indicate that the q_2 selection allows to select event based on the initial shape of the collision and not on a local multiplicity fluctuations.

8.2 Spectra results

The results for the spectra in event-shape-selected events are presented in terms of ratios between events in the large- q_2 (small- q_2) sample to unbiased sample. As already discussed in chapter 7, since the corrections do not show any dependence on the event shape, they cancel out in the ratios allowing for a very precise measurement.

The effect of the ESE selection on the p_T distributions of charged hadrons is re-

ported in Fig. 8.8. A modification of the p_T -spectra is observed for $p_T \leq 5$ GeV/ c : in the large- q_2 sample the p_T distribution is harder than the unbiased, while the opposite happens in small- q_2 sample, where softer p_T spectra are observed. The modification vanishes at high p_T , at the limit of applicability of the hydrodynamical picture.

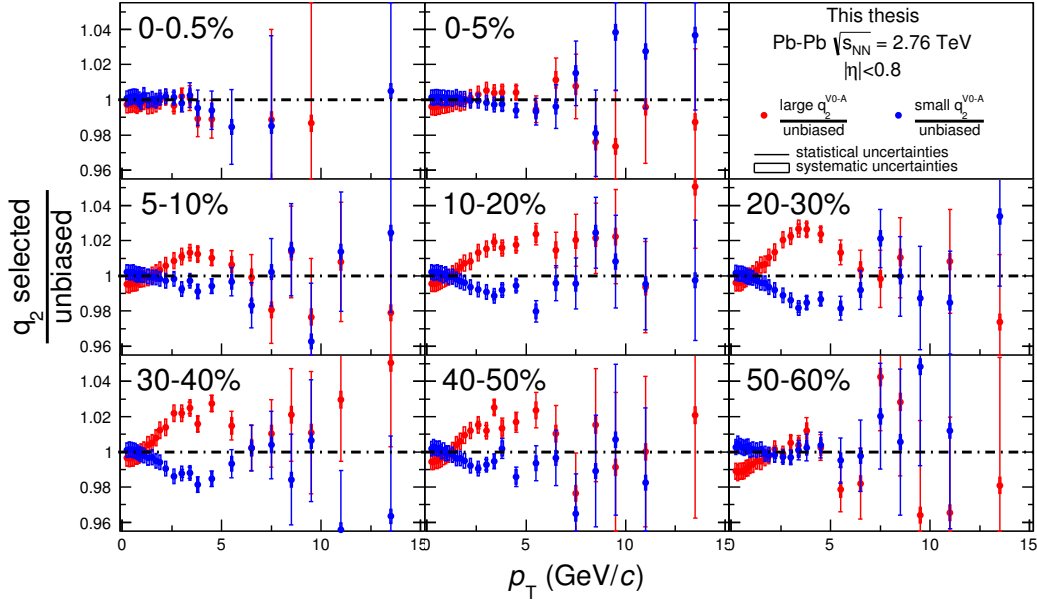


Figure 8.8: Ratios of the p_T spectra for charged hadrons in the large- q_2 or small- q_2 samples to the unbiased sample (q_2^{V0-A} selection). Statistical (error bars) and systematic (boxes) uncertainties plotted.

To evaluate the potential bias related to hard processes, the analysis has been repeated using q_2^{V0-C} and q_2^{TPC} as in the case of $v_2\{SP\}$.

The ratios large- q_2 (small- q_2) to unbiased events are shown in Fig. 8.9, in the 30-40% centrality class (see section 7.8 for all the centrality classes). Using the V0C or the TPC to estimate the q_2 leads to a larger modification of the spectra, than in the case of the event selection based on q_2^{V0-A} . As discussed for $v_2\{SP\}$, this could be due to the larger multiplicity, flow and detector resolution of the V0C and the TPC.

Similar results obtained with 10% highest q_2^{V0-A} have been obtained by cutting at 23% in V0C and 50% in the TPC, while to have a modification of the spectra shape similar to the one obtained by selecting the 10% smallest q_2^{V0-A} , we have to select the 50% small- q_2^{V0-C} and the 75% small- q_2^{TPC} events, as shown in Fig. 8.10. At high- p_T the ratios seem to be not close to the unity, which could indicate some

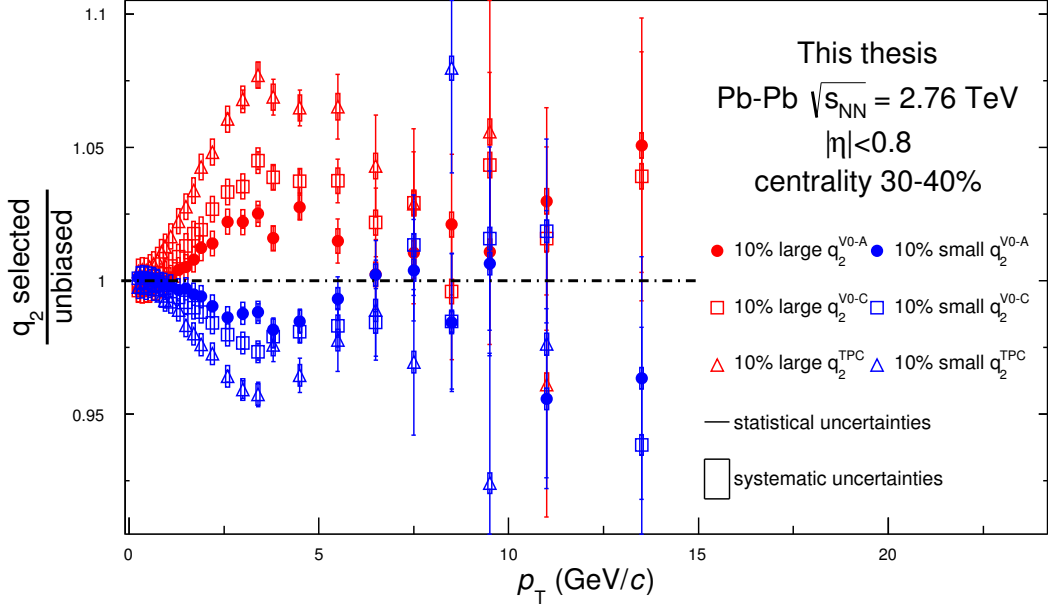


Figure 8.9: Ratios of the p_T spectra for charged hadrons in the 30-40% centrality class, for the 10% highest (smallest), q_2^{V0-A} , q_2^{V0-C} and q_2^{TPC} selections.

non-flow contribution, not completely removed even for the largest η gap available with the measurement of q_2^{TPC} , but negligible if the q_2 is computed using the V0A.

The modification on the spectra for identified pions, kaons and protons is reported in Fig. 8.11 for different centrality classes. The same pattern observed in the case of unidentified hadrons is seen for pions, kaons and protons. Furthermore an indication of mass ordering is observable in the transverse momentum range $p_T \leq 3$ GeV/c suggesting a stronger (weaker) radial flow in the large (small)- q_2 event sample. Indeed, an increase of the radial flow would produce a similar effect as shown in Fig. 8.12, for 20-30% centrality class. The effect of radial flow was investigated with a blast wave model. The parameters have been initially taken from [9] and tuned to describe the spectra of pions, kaons and protons. Then, the $\langle\beta_T\rangle$ parameter (the average transverse expansion speed in the model) has been increased (decreased) by a factor 0.1%, and a ratio to a function with the standard parameters has been taken. This ratio is compared to the measurement in Fig. 8.12: this small change in $\langle\beta_T\rangle$ can reproduce the observed modification.

The modification of the p_T spectrum increases from central to semi-central events (up to 40-50%). Then it decreases for more peripheral collisions. This is due to the fact that the selectivity of the event shape selection deteriorates

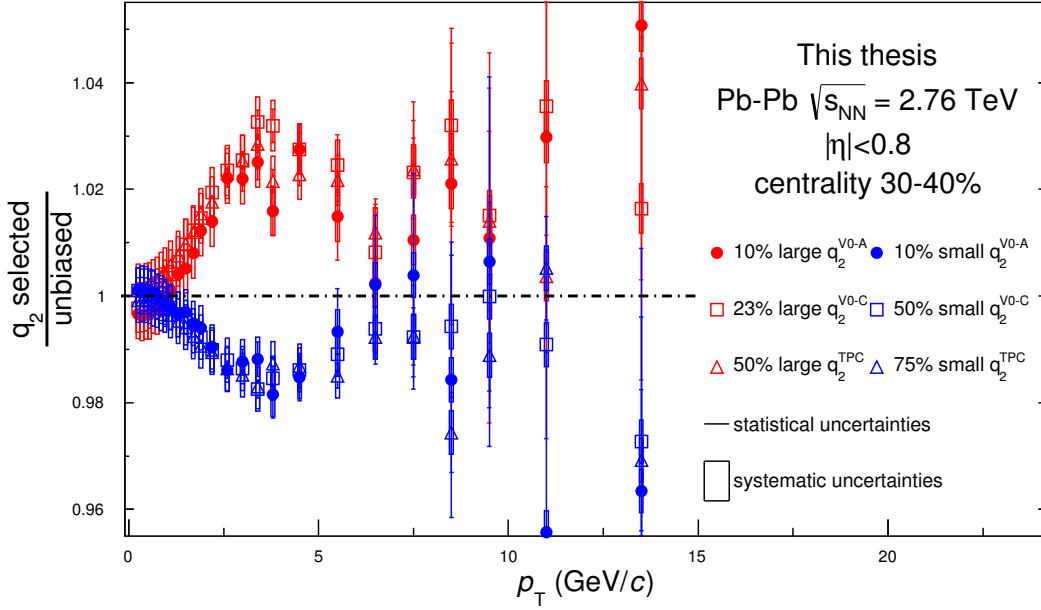


Figure 8.10: Ratios of the p_T spectra for charged hadrons in the 30-40% centrality class, for different selections in q_2^{V0-A} , q_2^{V0-C} and q_2^{TPC} .

for peripheral collisions due to small multiplicity and reduced magnitude of flow vector, whose length is maximal for semi-central collisions. This makes the event shape selection more efficient in the 30-50% centrality range.

8.3 Discussion

The correlation between radial and elliptic flow, observed in the analysis, could be introduced in the initial stage, depending on the fluctuations of the energy density profile of the fireball or in hydrodynamic evolution of the system created in the collision.

Since the effect of the event shape selection on the p_T spectra is closely related with to the physics underlying the initial collision geometry, we performed a study based on the Glauber model.

A Glauber Monte Carlo simulation has been performed to estimate the correlation between the initial eccentricity of the overlap region and the pressure gradients that originate from the initial anisotropies of the system. The multiplicity of charged particle in the acceptance of the V0 detector is computed following [10]. In the Glauber Monte Carlo, event by event fluctuating N_{part} and N_{coll} are

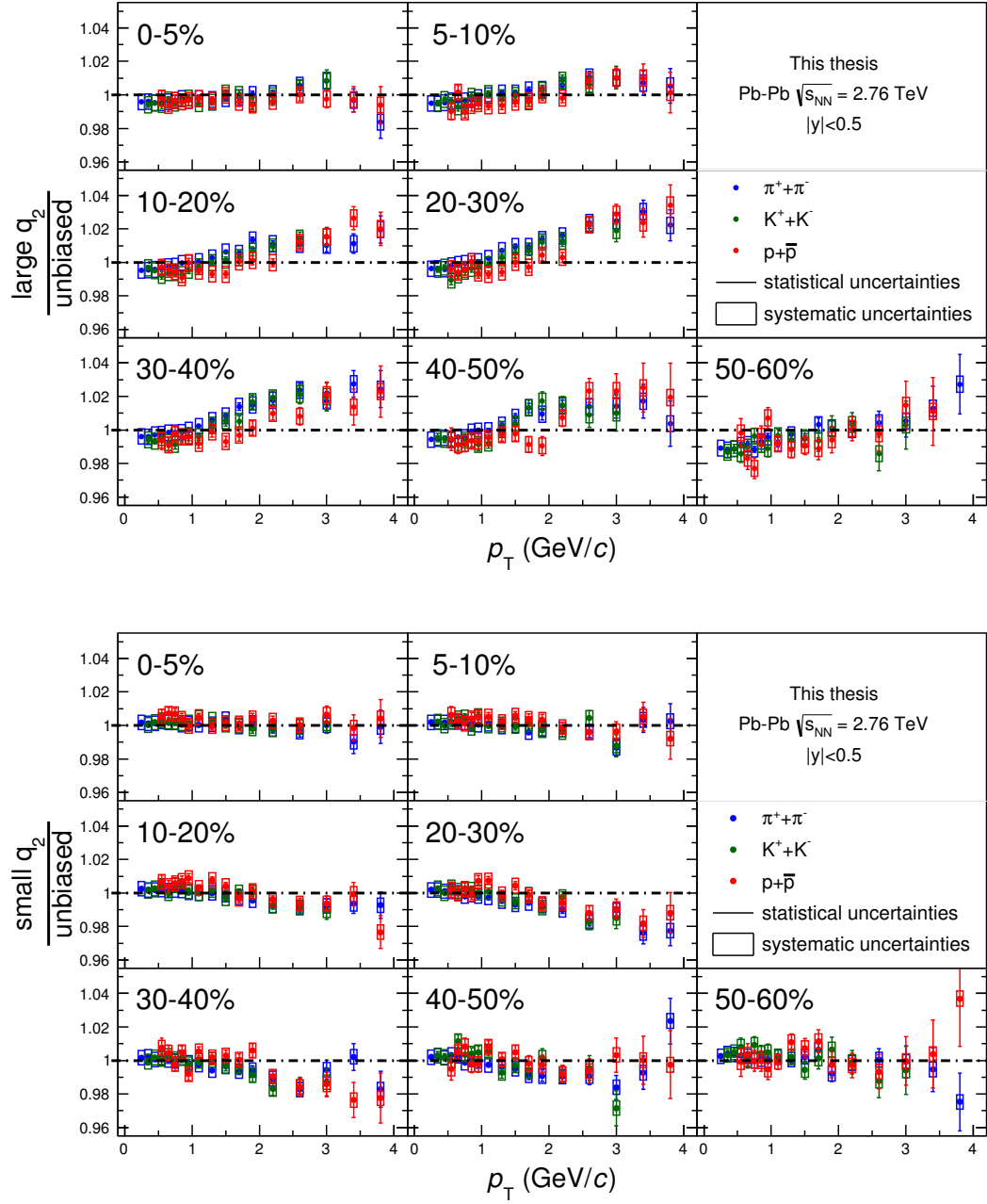


Figure 8.11: Ratios of the p_T spectra for charged hadrons in the large- q_2 (top) and small- q_2 (bottom) samples to the unbiased sample (q_2^{V0-A} selection).

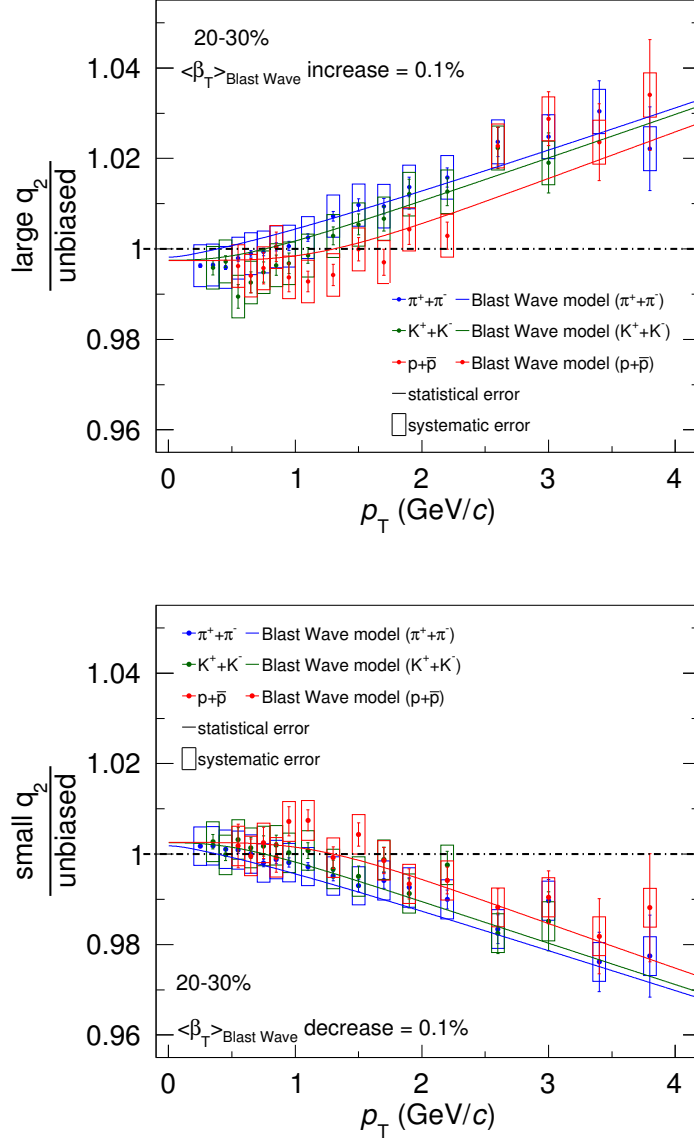


Figure 8.12: Ratios of the p_T spectra for charged hadrons in the large- q_2 (top) and small- q_2 (bottom) samples to the unbiased sample ($q_2^{\text{V0-A}}$ selection), in 20-30% centrality class. Lines: ratio of the Blast Wave parametrization, with a 0.1% change in the $\langle\beta_T\rangle$ parameter (see text for details).

generated based on the nuclei density profiles and a the impact parameter $\mathbf{b}$.

To compute the multiplicity in an event collision, with a given N_{part} and N_{coll} value, the concept of *ancestors*, i.e. independently emitting sources of particles, is introduced. The number of ancestors $N_{\text{ancestors}}$ can be parameterized as $N_{\text{ancestors}} = f \cdot N_{\text{part}} + (1 - f) \cdot N_{\text{coll}}$. This is inspired by two-component models, which decompose nucleus-nucleus collisions into soft and hard interactions, where the soft interactions produce particles with an average multiplicity proportional to N_{part} , and the probability for hard interactions to occur is proportional to N_{coll} .

Earlier in this work we introduced the *participant eccentricity* (Eq. 3.5) and the *transverse area* (Eq. 3.6) to describe the geometry of the overlap region. We define here the participant density as $\frac{N_{\text{part}}}{\text{area}}$ and the binary collision density calculated as $\frac{N_{\text{coll}}}{\text{area}}$, which correspond to a different energy deposition hypothesis. These quantities are related to the pressure gradients that drive the development of the radial flow in the hydrodynamic phase. The correlation with the participant eccentricity is shown in Fig. 8.13 for two narrow centrality bins, obtained by cutting on the charged particle multiplicity distribution, corresponding to the centrality intervals 0-2% (central) and 30-32% (semi-central). Figure 8.13 shows a correlation between the densities and the eccentricity qualitatively similar to the one observed in the spectra measurement. However different initial state models could lead to different prediction and the correlation could be modified by the hydrodynamic phase. Indeed, the shear viscosity counteracts the build up of anisotropic flow, increasing the radial flow and decreasing the anisotropic flow [11]. The bulk viscous pressure counteracts the radial expansion of the fireball, reducing the radial flow development, even if this effect is negligible with respect to the shear viscosity one [11]. For this reason a quantitative comparison would require full hydrodynamic calculation.

To further understand the effect, it is interesting to study both elliptic flow and spectra in ESE-selected events by using the AMPT model. The flow vector has been evaluated by using reconstructed V0A signals in AMPT, labelled as q_2^{rec} in the following. Figure 8.14 show $v_2(p_T)$ distributions (a) and spectra ratios large- q_2 to unbiased events(b), in 30-40% centrality class. Red lines represents AMPT predictions. The agreement is quite good, even though AMPT is not able to reproduce correctly particle spectra.

To study the effect of the V0 detector resolution on the ESE analysis the flow vector, q_2^{tracks} in the following, has been evaluated using all generated tracks in V0A acceptance ($2.8 < \eta < 5.1$), including both primary and secondary particles. Finally the effect of V0 segmentation is taken into account using generated tracks multiplicity in each V0A sector to compute q_2^{vzero} (see section 5.2.1 for details).

The effect of the event shape selection, using either q_2^{tracks} (blue) or q_2^{vzero} (green), results in a stronger increase of the elliptic flow, as shown in Fig. 8.14(a)

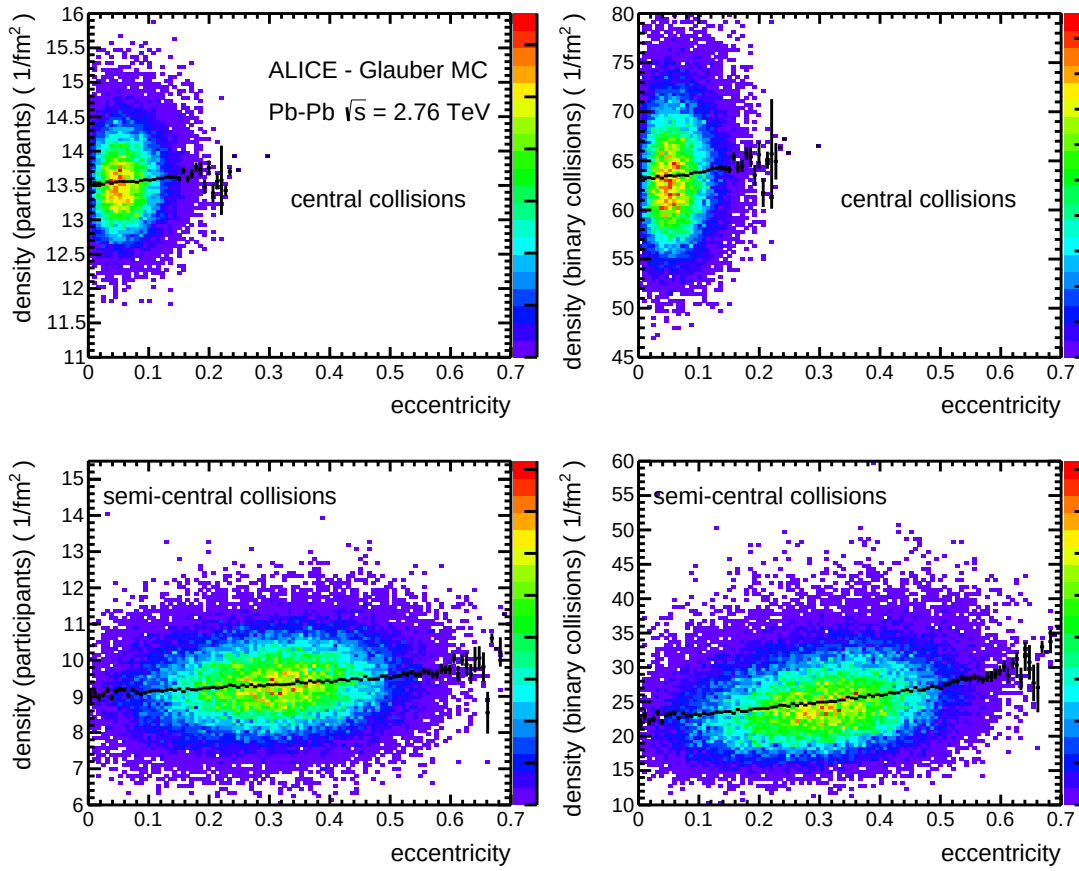
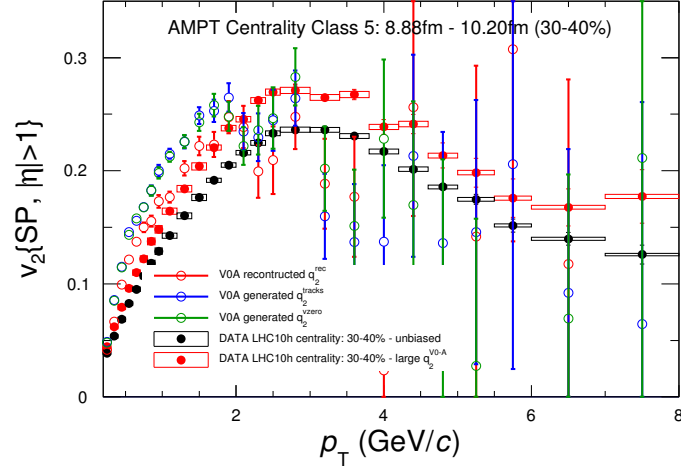


Figure 8.13: Correlation between the density (participants or binary collisions) and the participant eccentricity estimated in a Glauber Monte Carlo model for central (top) and semi-central (bottom) collisions.

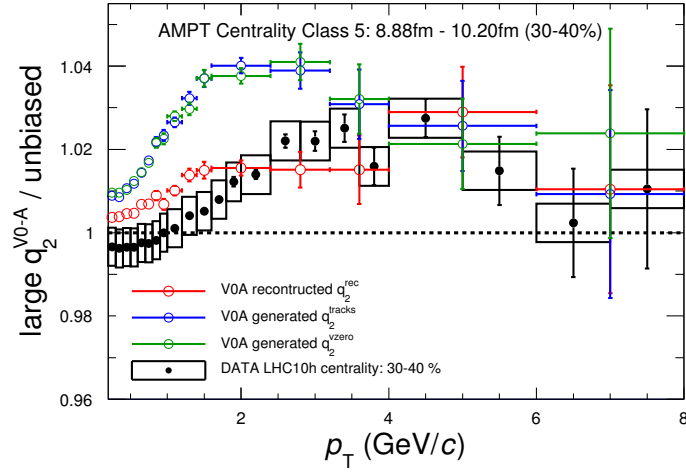
and a stronger modification of the spectra shape shown in Fig. 8.14(b). This suggests that the cut on the flow vector depends on the V0 resolution. When the selection is based on the q_2 computed using the V0 the effect is similar for data and AMPT. On the other hand when the sample is biased using the q_2 from generated tracks, the increase in the elliptic flow is higher, leading a larger modification in the spectra shape. This study shows the importance of η coverage and detector resolution in ESE selectiveness.

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(a)



(b)

Figure 8.14: (a) $v_2(p_T)$ distribution in large- q_2 -events in AMPT. (b) large- q_2 events to unbiased sample ratio in AMPT. Statistical (error bars) and systematic (boxes) uncertainties plotted.

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Conclusions

In this thesis the first application of the Event Shape Engineering (ESE) technique to the analysis of ALICE Pb–Pb data has been presented.

Strong event-by-event fluctuations in the energy density of heavy-ion collisions have been observed, with the measurement of non-zero odd harmonic anisotropic flow coefficients. The pattern of flow coefficients is understood in terms of hydrodynamics plus fluctuating initial conditions [1, 2]. Following this observation the ESE technique was proposed to study events with specific initial shapes, selecting events characterized by a well defined initial geometry, by means of the flow vector evaluated from the azimuthal distribution of produced particles. This technique allows for unprecedented studies.

The experimental method developed to perform the event shape engineering within the ALICE framework has been presented in chapter 5, using the V0 detector to evaluate the flow vector. To avoid trivial bias from non-flow processes (e.g. resonance decays, jet fragmentation and Bose-Einstein correlations) two sub-events, with large η -gap, have to be considered. For instance, the flow vector is evaluated from the V0A ($2.8 < \eta < 5.1$), while the experimental observables are measured in the TPC ($-0.8 < \eta < 0.8$). This ensures a large $|\Delta\eta|$ separation between the detectors involved in the analysis, leading to non-flow suppression. Since the length of q_2 shows a pronounced centrality dependence, a cut at a fixed value of q_2 , in a large centrality bin, would introduce a dependence on multiplicity that would bias the effect of the event shape. For this reason a calibration procedure has been devised. The data sample have been divided in 1%-wide centrality bins and for each of these bins the q_2 value corresponding to the event quantile, for large and small q_2 samples, have been found.

The effect of the event shape engineering technique on $v_2\{\text{SP}\}$ and p_T spectra in Pb–Pb collisions at center of mass energy of 2.76 TeV per nucleon pair has been

reported.

The event shape selection results in a change in the value of the $v_2\{\text{SP}\}$ of 15% for large- q_2 and 10% for the small- q_2 . Ratios are constant up to $p_T = 4 \text{ GeV}/c$, suggesting that the effect of flow fluctuations on particle production at different transverse momenta is very similar up to $4 \text{ GeV}/c$. For $p_T > 4 \text{ GeV}/c$ the ratios seem to approach to one, indicating a smaller effect of flow fluctuations, even if large statistical uncertainties do not allow to make a firm conclusion. The results on the $v_2\{\text{SP}\}$ measurement suggest that the ESE technique indeed selects a global property of the collision.

The selection induces a change in the p_T spectra, which are found to be harder in events with larger v_2 , while smaller v_2 leads to softer spectra. This can be interpreted as a modification of radial flow and this conclusion is supported by the mass dependence observed in identified particles. The effect is more pronounced in semi-central collisions where a higher elliptic flow has been observed. The trend is similar for pions, kaons and protons. An indication of mass ordering is observable in the transverse momentum range $p_T \leq 3 \text{ GeV}/c$ suggesting a stronger (weaker) radial flow in the large (small) q_2 event sample. In order to quantify the variation of radial flow induced by the event shape selection the blast wave model has been used. Data are reasonably reproduced by an increase (decrease) of radial flow of 0.1%. The effect vanishes at high p_T , showing a behaviour similar to that observed for the elliptic flow in shape selected events. These measurements suggest that the origin of the effect is related with the hydrodynamic response of the system to the initial geometry rather than with hard processes. A Glauber Monte Carlo simulation has been performed to gain some insight on the effect of the initial eccentricity of the overlap region on the spectra. The number of wounded nucleons (number of binary collisions) per unit of participant area shows a positive correlation with the participant eccentricity of the collisions, qualitatively similar to that observed in the spectra measurement.

The ESE technique has been suggested in [3], to study in detail the properties of high density hot QCD matter. This thesis presents a first application, which confirm that the shape of the initial geometry can be selected using the flow vector in the final state.

The observations and methods discussed here pave the road for further studies such as azimuthally sensitive HBT, to relate shape and flow, double differential studies to investigate the path dependence of jet suppression, flow fluctuations with higher order cumulates and the development of the ESE technique itself, with the investigations of other detectors for the selection.

The first result presented in this work reveals somewhat unexpected correlations and put very stringent constraints on initial conditions and hydro models, providing a tool which may allow to constrain the transport properties of QGP.

The analysis will be published in an ALICE paper. The related draft is currently at the first stages of the ALICE Collaboration review.

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2-particle azimuthal correlations

In this appendix we summarize the main formulas to obtain the exact expressions for 2-particle azimuthal correlations [1]. The generalization to azimuthal correlations involving more particles is straightforward.

The single-event average 2-particle azimuthal correlations is defined as:

$$\langle 2 \rangle \equiv \langle e^{in(\phi_1 - \phi_2)} \rangle \equiv \frac{1}{P_{M,2}} \sum_{i \neq j} e^{in(\phi_i - \phi_j)} \quad (\text{A.1})$$

where $P_{n,m} = n!/(n-m)!$, M is the number of particles and n is the azimuthal angle. Then average over all events is:

$$\langle \langle 2 \rangle \rangle \equiv \langle \langle e^{in(\phi_1 - \phi_2)} \rangle \rangle \equiv \frac{\sum_{events} (W_{\langle 2 \rangle})_i \langle 2 \rangle}{\sum_{events} (W_{\langle 2 \rangle})_i} \quad (\text{A.2})$$

where by double brackets denote the average first over all particles and then over all events.

W_2 are the event weights, which are used to minimize the effect of multiplicity variations in the event sample on the estimates of 2-particle correlations. In general, the choice of weights is determined by the multiplicity dependence of v_n . However, if we assume that the v_n is independent of multiplicity

$$W_2 \equiv M(M-1) \quad (\text{A.3})$$

This choice takes into account the number of different 2-particle combinations in an event with multiplicity M .

Following the formalism of cumulants introduced in [2, 3] the second order cumulant is the average of 2-particle correlation defined in A.2 is:

$$c_n\{2\} = \langle \langle 2 \rangle \rangle. \quad (\text{A.4})$$

Different order cumulants provide independent estimates for the same v_n harmonic. In particular

$$v_n\{2\} = \sqrt{c_2} = \sqrt{\langle\langle 2 \rangle\rangle} \quad (\text{A.5})$$

where $v_n\{2\}$ is used to denote the reference flow v_n from the second order cumulant.

2- particle azimuthal correlation could be obtained by separating diagonal and off-diagonal terms in $|Q_n|^2$ 3.1:

$$|Q_n|^2 = \sum_{i,j=1}^M e^{in(\phi_i - \phi_j)} = M + \sum_{i \neq j} e^{in(\phi_i - \phi_j)} \quad (\text{A.6})$$

which give:

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)} \quad (\text{A.7})$$

In this way is possible to estimate the flow harmonic v_n . These equations are applicable for an analysis with a detector with full azimuthal coverage. In a non-ideal case one need to take into account the acceptance corrections, which could come from [1, 4, 5]

- contributions from additional terms, e.g. proportional to $\langle\langle \sin(n\phi) \rangle\rangle$ and $\langle\langle \cos(n\phi) \rangle\rangle$, that for a detector with full uniform azimuthal coverage are identical to zero,
- contributions from other flow harmonics.

A more general equation of A.8 which takes into account the terms due to non uniformities is:

$$c_n\{2\} = \langle\langle 2 \rangle\rangle - [\langle\langle \cos(n\phi) \rangle\rangle^2 \langle\langle \sin(n\phi) \rangle\rangle^2] \quad (\text{A.8})$$

The correction terms can be expressed in terms of the real and imaginary part of the Q-vector Q_n :

$$\langle\langle \cos(n\phi) \rangle\rangle = \frac{\sum_{i=1}^N (\Re |Q_n|)_i}{\sum_{i=1}^N M_i}, \quad (\text{A.9})$$

$$\langle\langle \sin(n\phi) \rangle\rangle = \frac{\sum_{i=1}^N (\Im |Q_n|)_i}{\sum_{i=1}^N M_i}. \quad (\text{A.10})$$

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Significance of a systematic check

The significance of a systematic check is estimated as in [1]. The relevant section is reported here. A check which consists of a different analysis of the data (for example, using different track cuts or different PID techniques) involves comparing the two results. The difference between these results will not be zero (as the techniques are different, after all, or the event samples can be slightly different) but should be ‘small’. Here ‘small’ needs to be compared to the expected statistical fluctuations within the 2 samples, which however will be significantly correlated, as the results use (almost) the same data. The statistical error for the difference of the two results has to lie in the interval:

$$\left| \sqrt{\sigma_1^2 - \sigma_0^2} - \sqrt{\sigma_2^2 - \sigma_0^2} \right| \leq \sigma_{diff} \leq \sqrt{\sigma_1^2 - \sigma_0^2} + \sqrt{\sigma_2^2 - \sigma_0^2} \quad (\text{B.1})$$

Where σ_1 is the largest of the two errors, σ_2 is the smallest, and σ_0 is the Minimum Variance Bound (MVB). If the better technique saturates the Minimum Variance Bound then Eq. B.1 the range decreases to nothing and $\sigma_{diff}^2 = \sigma_1^2 - \sigma_0^2$.

We assume in our analysis that our best estimation satisfies the MVB, then we calculate the error on the difference as

$$\sigma_{diff}^2 = \sigma_{systematic}^2 - \sigma_{default}^2 \quad (\text{B.2})$$

where $\sigma_{default}$ and $\sigma_{systematic}$ are the statistical errors associated to the default analysis and to the systematic check, respectively.

The *significance* of a given systematic check is hence evaluated by comparing the difference between the two results and the corresponding error on the difference. If the ratio:

$$significance = \frac{|val_{default \text{ analysis}} - val_{systematic \text{ check}}|}{\sigma_{diff}} > 1 \quad (\text{B.3})$$

the variation is considered significant and it is considered in the systematic error estimation.

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