Study of global observables in p-p and A-A collisions with ALICE at LHC

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Introduction

The Large Hadron Collider (LHC) is the biggest particle accelerator worldwide, built at CERN (European Organization for Nuclear Research) near Geneva and placed in the same underground tunnel previously hosting the Large Electron–Positron collider (LEP) at an average depth of 100 m. This challenging project and the related experiments are designed to address fundamental questions about matter and the origin of the Universe. The LHC can collide both proton and heavy-ion beams with a centre-of-mass energy never reached before. In particular it can recreate the conditions just after the Big Bang by colliding heavy-ion beams head-on at extremely high energy. Six experiments detect the results from these collisions. Data, collected in the whole range of the LHC energy, should confirm the established knowledge of the Standard Model particle physics and explore new physics beyond it. LHC circulated its first beams (protons) on September 10th 2008, but suffered a serious malfunction nine days later. A failure in an electrical connection led to serious damage and CERN has spent over a year repairing and consolidating the machine. On November 20th 2009 proton beams circulated again. First proton–proton collisions took place on November 23rd 2009 and during the following three weeks the six LHC experiments recorded over a million proton–proton collisions, which have been spread for analysis around the world on the LHC computing grid. The LHC has now been put into standby mode and will be restarted in February 2010 to provide higher energy collisions. The CERN Director General Rolf Heuer said: “It’s a great achievement
to have come this far in so short a time, but we need to keep a sense of perspective — there is still much to do before we can start the LHC physics programme."

The ALICE experiment (A Large Ion Collider Experiment) is the only dedicated heavy-ion detector at LHC. The main physics goal of the project is to study nuclear matter under extreme conditions, namely compressed and heated well over the predicted limits to undergo a phase transition to Quark–Gluon Plasma. This is a phase of matter in which the protons and the neutrons melt, freeing the quarks from their bonds with the gluons. Such a state should have existed in the first microseconds of the Universe’s life, just after the Big Bang. ALICE will also study proton–proton collisions, both as baseline sample to thoroughly understand and interpret the physics of Pb-Pb collisions and to carry out genuine proton–proton physics studies in the areas where it is competitive with the other LHC experiments.

This thesis is focused on basic and fundamental measurements that have always been the starting point for event characterization both in hadron and in heavy-ion interactions. These studies have been carried out using data provided by the innermost detector of the ALICE experimental apparatus: the Silicon Pixel Detector (SPD). Besides its key role in event triggering and in the reconstruction of primary and secondary vertices, the SPD reconstructed points can be also used for a first reconstruction of the charged tracks that traverse its two highly-segmented layers. The fast and simple alignment and calibration procedures allow physics results to be extracted from the very first available data. The analysis tools and procedures developed and described in this thesis have been indeed applied to the first proton–proton data collected by the ALICE detector November 23rd 2009 to reconstruct the pseudorapidity density distribution of charged particles. The thesis is organized as follows: in Chapter 1 the main points of the ALICE physics and experimental programme are illustrated; in Chapter 2 the experimental apparatus and the offline framework developed within the ALICE Collaboration are described.
and in Chapter 3 theoretical concepts related to the main global variables for the event characterization are introduced together with the main results from previous experiments. Chapter 4 is the heart of this thesis, where the analysis developed for the pseudorapidity density distribution and multiplicity measurements is described: it contains the study for the optimization of the algorithm to reconstruct pseudo-tracks with data provided by the SPD and the analysis to measure the charged-particle pseudorapidity density and the multiplicity both in p-p and Pb-Pb collision, applied to Monte Carlo samples. In the last chapter this analysis is applied to the first real proton–proton data, in particular for the pseudorapidity density distribution measurement. The pseudorapidity density distribution of charged particles measured by the ALICE experiment has also been the subject of the first physics paper of the LHC.
Chapter 1

Physics with ALICE at LHC

1.1 Introduction

The most relevant topics related to the physics that the ALICE experiment at the LHC will investigate, both in proton–proton and heavy-ion collisions, are outlined in this chapter. An overview of the physics programme and the relevant experimental running conditions both for proton–proton and for heavy-ion physics are also presented.

The main goal of the ALICE experiment is to study the physics of strongly interacting matter and the properties of the Quark–Gluon Plasma formed in nucleus–nucleus collisions at the LHC. The ALICE detector has been designed and optimized for charged-particle multiplicities up to \( dN_{ch}/dy \approx 8000 \), corresponding to a safe factor of two or more with respect to the present expectations for the most central Pb-Pb collisions at the LHC energy. Collisions between lower mass ions and protons will be also used in order to establish the benchmark processes under the same experimental conditions of Pb-Pb. In addition, measurements with proton-induced reactions will also allow a genuine p-p physics programme to be carried out.
1.1.1 Overview of the LHC programme

The Large Hadron Collider (LHC) [1], schematically shown in Fig. 1.1, is the biggest and most powerful particle accelerator in the world. The LHC is designed to collide two counter-rotating beams of protons or heavy ions and is currently accelerating proton beams. The maximum energy for proton beams is 7 TeV ($\sqrt{s} = 14$ TeV) and the maximum luminosity is $10^{34}$ cm$^{-2}$ s$^{-1}$, which is 100 times greater than the LEP or Tevatron luminosity. As a heavy-ion collider it will collide lead nuclei at a centre-of-mass energy of 5.5 TeV per nucleon pair and a luminosity of $10^{27}$ cm$^{-2}$ s$^{-1}$. It is located in the 27 km circular tunnel buried around 50 to 175 m underground (previously hosting the LEP) on the French-Swiss border near Geneva. The beams move around the LHC ring inside a continuous vacuum guided by superconducting magnets. The magnets are cooled by a huge cryogenic system.

The LHC with its high energy and luminosity offers the opportunity for a very rich physics programme. The four main experiments at the LHC (ATLAS, CMS, ALICE, LHCb) will each focus on rather different topics from the completion of the experimental evidence for the Standard Model to the study and characterization of new phenomena and search for unexpected physics signals.

One of the central problems addressed at the LHC is the connection between phase transitions involving elementary quantum fields, fundamental symmetries of nature and the origin of mass. The theory makes a clear distinction between symmetries of the dynamical laws of nature (symmetries and particle content of the Lagrangian) and symmetries of the physical state with respect to which these laws are evaluated (i.e. symmetries of the vacuum or of an excited thermal state). The experiments at LHC will cover both aspects of the symmetry-breaking mechanism.

ATLAS and CMS, which have been designed as general-purpose p-p experiments, will search for the Higgs boson over the full range of allowed masses. The Higgs boson is the particle that generates the bare masses of elementary fermions and the masses
of electroweak gauge bosons, through the spontaneous breaking of the electroweak gauge symmetry. Those experiments will also search for supersymmetric partners of bosons and fermions, which are particles with inverted statistic with respect to their corresponding particles (i.e. non supersymmetric) in the Standard Model. That arises from the broken intrinsic symmetry between fermions and bosons in extensions of the Standard Model.

LHCb will focus on precise measurements of the CP-symmetry violation in the B meson system. This measures the misalignment between gauge and mass eigenstates which is a natural consequence of electroweak symmetry-breaking via the Higgs mechanism.

Through its heavy-ion physics programme, ALICE will exploit the unique physics potential of nucleus–nucleus interactions at LHC energies to study in detail the strongly interacting nuclear matter under extreme conditions and fully understand and characterize the deconfined (Quark–Gluon Plasma) phase [2].
There are also two experiments, TOTEM and LHCf, much smaller in size, designed to focus on forward particles (protons or heavy ions) that brush each other rather than meeting head-on as the beams collide. The TOTEM experiment studies physics that is not accessible to the general-purpose experiments. Among a range of studies, it will measure, in effect, the size of the proton, it will measure the total elastic and diffractive cross section and also monitor accurately the LHC’s luminosity. It consists of detectors housed in specially designed vacuum chambers, called Roman pots, which are connected to the beam pipes in the LHC, placed near the collision point of the CMS experiment. Although the two experiments are scientifically independent, TOTEM will complement the results obtained by the CMS detector and by the other LHC experiments overall. LHCf is aimed at studying forward production of neutral particles in proton–proton collisions at extremely low angles, using two small calorimeters placed on either side 140 meters away from the ATLAS interaction point. The results will provide invaluable inputs to the many air-shower Monte Carlo codes currently used for modeling cosmic rays interactions in the Earth atmosphere, covering an energy range up to and beyond the “knee” of the cosmic ray spectrum.

1.1.2 ALICE experimental programme

One of the main physics aims of the ALICE experiment is to detect and study the phase transition from nuclear matter to a deconfined state in which quarks and gluons are free, the so-called “Quark–Gluon Plasma” (QGP) phase. ALICE will fully characterize and study the QGP properties: the existence of such a phase and its properties are key issues in QCD for the understanding of the confinement and chiral-symmetry restoration. It will study the chiral-symmetry role in the generation of mass in composite particles (hadrons) using heavy-ion collisions to attain sufficiently high energy density over a large time and space scale. ALICE will also study equilibrium and non-equilibrium physics of strongly interacting matter.
in the energy density regime $\epsilon \approx 1$-1000 GeV/fm$^3$. In addition, the aim is to gain insight into the physics of parton densities close to phase space saturation, and their collective dynamical evolution towards hadronization (confinement) in a dense nuclear environment. In this way one also expects to gain further insight into the structure of the QCD phase diagram and the properties of the QCD phase.

In general, to establish experimentally the collective properties of the hot and dense matter created in nucleus–nucleus collisions, both systematics- and luminosity-dominated questions have to be answered at LHC. Thus, the ALICE programme for heavy-ion collisions is firstly to accumulate enough integrated luminosity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, to measure rare processes. Data from different colliding systems than Pb-Pb, that is lighter nuclei, proton–proton and proton-nucleus collisions, are needed as reference data to measure the same observables under the same conditions to spot effects of the formation of the hot medium.

Proton–proton studies of unique interest, complementary to the ones performed by the other p-p dedicated experiments, will also be carried out as explained in Section 1.3.

1.2 Heavy-ion physics at the LHC

The aim of ultra-relativistic heavy-ion physics is to apply and extend the Standard Model to complex and dynamically evolving systems of finite size to study and understand how collective phenomena and macroscopic properties emerge from elementary particle physics.

Phase transitions at certain energy densities are among the collective bulk phenomena predicted by the Standard Model. Phase transitions are strictly connected to the breaking of fundamental symmetries of nature and thus to the origin of
mass. In general, intrinsic symmetries that are valid at high-energy densities are broken under critical energy densities: particle contents and masses originate as a direct consequence of the symmetry-breaking mechanism. Lattice calculation of QCD predicts a phase transition at a critical temperature of \( \approx 170 \text{ MeV} \), corresponding to an energy density \( \epsilon_c \approx 1 \text{ GeV} \text{ fm}^3 \): nuclear matter would undergo a phase transition to the QGP. This transition is the only one that can be recreated in laboratory experiments. In the QGP phase, the chiral symmetry is approximately restored and the quark masses are reduced from their large effective values to their small bare ones.

Energy densities higher than the critical density can be reached only in ultra-relativistic heavy-ion collisions: the main objective of heavy-ion physics is then to explore the QCD phase diagram and study the phase transition and the physics of the QGP state.

Experimental difficulties and theoretical challenges in detecting and studying the QGP have to be faced. Experimentally the biggest challenge in colliding heavy nuclei (\( A \approx 200 \)) at high centre-of-mass energies \( \sqrt{s_{NN}} = 20 \) up to 5500 GeV is to observe the QGP through specific probes since the system created in heavy-ion collisions evolves rapidly from the extreme initial conditions (energy density attained up to 30 times that of ordinary nuclear matter) to the final hadronic state: it extends in a small region (\( \approx 10^{-14} \text{ m} \)) for a short time (\( \approx 10^{-23} \text{ s} \)). Probes have to be sensitive to the presence of the QGP and to the occurrence of the QCD phase transition. A direct link between the predictions of the Standard Model and experimental observables in heavy-ion collisions exists only for a limited number of observables: calculations from truly first principles are impossible due to the complexity of the scattering dynamics and the non-perturbative features of the produced matter. Different approaches are currently used, from idealized (macroscopic) models based on hydrodynamics to the (microscopic) theoretical approach of lattice QCD Monte Carlo simulations.
1.2.1 Hot and dense partonic matter

1.2.1.1 Quantum Chromodynamics and phase diagram

The Quantum Chromodynamics (QCD) is the fundamental theory describing the mutual strong interactions of quarks, gluons and antiquarks. The QCD is an example of “gauge theory”, i.e. a quantum field theory that has a local symmetry described by a symmetry (or gauge) group: in particular it is the SU(3) gauge symmetric part of the Standard Model of particle physics. The fundamental properties of the QCD cannot be directly tested, but a wealth of indirect evidence supports this theory. The two peculiar features of QCD are the following:

- asymptotic freedom: at high energy or very short distance \( Q^2 \gg \Lambda^2 \), quarks and gluons interact weakly

\[
\alpha_s(Q^2) \approx \frac{12\pi}{(33 - 2n_{flavour}) \ln \frac{Q^2}{\Lambda^2}}
\]

where \( \Lambda \approx 200 \text{ MeV} \);

- confinement: the interaction of quarks and gluons becomes stronger at large distance or low energy, which means that they cannot be separated (typical scale: 1 fm or 200 MeV) as the potential energy between the quarks increases with the distance

\[
V(r) = -\frac{A(r)}{r} + Kr
\]

where \( K \approx 1 \text{ GeV/fm} \). Once the energy is above the threshold for \( q\bar{q} \)-pair production, such a pair is created and rapidly forms colour singlet bound states (hadrons).

The situation radically changes, however, if sufficiently high number of partons are made to scatter simultaneously into the same volume element: a dense medium of partons is formed, where the interactions of quarks, antiquarks and gluons are
effectively screened, so that the formation of bound states is inhibited. This is the only way to observe the behaviour of free quarks and gluons. This kind of strongly interacting dense matter where the quarks, antiquarks and gluons behave collectively as free, deconfined particles, is the QGP. The coupling constant at short distances is small, thus leading to only weak coupling between the quarks and gluons. Since the QCD interaction is typically strong, perturbative approximations often fail: this is the reason why very few precise predictions can be made directly from the theory. This led to the introduction of a non-perturbative approximation based on discretizing four-dimensional space-time onto a lattice of points, giving a theory called lattice QCD, which can be simulated on a computer. QCD thermodynamics on lattice aims for quantitative studies and predictions about the phase transition onto the QGP.

The phase transition was indeed foreseen, for the first time in 1975 [3], and confirmed by lattice calculations at high temperature or high baryochemical potential $\mu_B$. The critical temperature and the order of the transition depend on the number of flavours and the value of the quark masses. Calculations indicate that for $\mu_B \approx 0$ the transition is a rapid crossover in a narrow temperature interval around $T_c \approx 170$ MeV ($\approx 2 \times 10^{12}$ K) and an energy density $\epsilon_c \approx 1$ GeV/$fm^3$. Recent calculations have found crossover temperatures $T_c = 151$ MeV [4] and $T_c = 190$ MeV [5]. The QCD phase diagram is shown in Fig. 1.2. The region of hadronic matter, the one of the QGP and the hadronization (chemical freeze-out) points, measured by various experiments, are indicated. QGP is expected to have existed few tens of microseconds after the Big Bang, in the early stages of the evolution of the Universe: then from an initial state of extreme energy density, traversing a series of phase transitions predicted by the Standard Model, matter got to its present state after a rapid expansion and cooling. By colliding ultra-relativistic heavy ions, protons and neutrons, hence quarks and gluons, are compressed and heated beyond the critical temperature: in this scenario the interaction system should be large enough to effectively free
the coloured constituents over a region which is much larger than a hadron. The deconfined (QGP) phase is however transient: within a short time, of the order of $10^{-22}$-$10^{-23}$ s, it expands, cools and hadronizes. After the hadronization two phases can be distinguished: the chemical freeze-out, when inelastic interactions among the collision products cease and the abundances of particles are fixed and the thermal freeze-out, when elastic interactions also cease and momentum spectra are fixed.

The QCD lagrangian has an exact global symmetry only in the case of vanishing quark masses (chiral symmetry) that means the QCD lagrangian is symmetric with respect to left/right handed quarks. Confinement results in a large dynamical mass of quarks (constituent mass) and the chiral symmetry is then broken (or hidden) in the
ordinary hadronic phase. When the transition to a deconfined phase takes place, the quark masses become small (current masses) and the chiral symmetry gets partially restored.

1.2.1.2 Deconfinement and experimental evidences

A series of heavy-ion experiments have already created hot and very dense nuclear matter (up to 10 times ordinary nuclear matter density). The first claims of formation of the QGP came from the fixed target experiments at the Super Proton Synchrotron (SPS) accelerator at CERN in February 2000: NA44, NA45, NA49, NA50, NA52, WA97/NA57 and WA98 collaborations took Pb-Pb and Pb-Au data up to $E_{\text{beam}} = 158$ AGeV ($\sqrt{s_{NN}} = 17$ GeV) from 1986 to 2003, as well as proton-induced collision data at the same energy for comparison. The estimated maximum temperature attained at SPS is 250 MeV. The analysis of several observables from independent measurements suggested that there were indications of the existence of the QGP in central Pb-Pb collisions. For instance, evidence for deconfinement of quarks and gluons from the $J/\Psi$ suppression pattern measured in Pb-Pb collisions has been reported by the NA50 experiment [6], while the enhancement of multistrange hyperon production observed by WA97/NA57 [7] proves that strangeness is equilibrated on a very short timescale, according to the behaviour expected in the case of transition to a deconfined state. All the experiments agreed in concluding that, at least in central Pb-Pb interactions, a state with many of the characteristics of the theoretically predicted QGP was created [8].

Since July 2000, the properties of the QGP have been explored in colliding-beam experiments at the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory (USA). The collider has been designed to search for signatures of the QGP and enhance the understanding of the behaviour of strongly interacting matter under extreme conditions. RHIC, as the first dedicated heavy-ion collider
facility, can collide Au-Au beams at a centre-of-mass energy of $\sqrt{s_{NN}} = 56$ up to 200 GeV, thus achieving energy densities higher than any previous heavy-ion physics programme. The estimated maximum temperature attained is $T \approx 350$ MeV. Four experiments have been constructed: BRAHMS, PHENIX, PHOBOS, STAR. There is good evidence that QGP has been also produced at RHIC [9, 10, 11, 12]. Striking effects have been observed in central Au-Au collisions, complemented by data collected at lower energies and with lighter nuclei: among the most prominent, the suppression of high-$p_t$ particles [13, 14, 15] and the suppression of back-to-back correlations [16]. These results show that the jet structure and jet pair correlations are strongly modified in dense matter, consistent with expectations from perturbative QCD calculations of partonic energy loss via induced gluon radiation.

1.2.2 Heavy-ion observables in ALICE

To observe the properties of the created QCD matter and relate them to the predicted transition to the QGP, good probes are needed. Good probes are those whose behaviour and characteristics are well understood in p-p collisions and possibly strongly affected by the deconfined QCD medium. The proposed experimental probes are sensitive to different stages of the matter as it rapidly expands and evolves back to normal matter.

The most useful probes can be divided into three groups:

- hadron radiation: it gives direct information about the hadronization stage of the plasma and allows the thermodynamical state at the stage when hadrons cease interactions and decouple to be determined. Enhanced production of strange particles was predicted to be a signature of QGP formation [17]. In addition, collective features (e.g. flow) of the hadron emission also give information on the pre-hadronic stage: the QGP seems to behave as a nearly
ideal fluid when it expands.

- electromagnetic radiation: even in a transient plasma, there should be electromagnetic processes involving quarks and gluons at thermal equilibrium leading to emission of photons and lepton pairs, which leave the plasma unaffected. The main problem in this case is to subtract the background of photons and leptons from post-hadronization decays.

- hard probes: these are mainly heavy quarks and quarkonia, jets and hard photons. Their common feature is that they are well controlled both theoretically and experimentally: they are produced early in the interaction before thermalization of the medium, calculable in perturbative QCD and easily comparable to production in p-p and p-A interactions. In particular charmonium states (J/Ψ, Ψ′, Xc) are predicted to be suppressed [18] when compared to p-p reference measurements. These states, produced at the early stage of the collision, before the plasma is formed, interact with the medium and may be dissociated since their binding energy is comparable to the mean energy of the plasma. According to physical considerations and confirmed by lattice QCD, they dissolve sequentially in the plasma, at different temperatures: the more loosely bound the state, the lower the dissociation temperature. Jet suppression (quenching) is also expected: unlike in p-p interactions, high-p_t jets can be produced in a medium. Parton radiative energy loss through multiple gluon radiation of the produced hard parton is induced by the dense QCD medium: energy loss is flavour dependent and is determined by the density of the medium, increasing with the temperature.

A theoretical overview of some of the observables and probes that ALICE can measure and that are relevant to the physics goals of the experiment is presented in the following.
**Charged-particle multiplicity** The charged-particle multiplicity and in particular the average number of charged particles, on the theoretical side, fixes a global property of the medium produced in the collision. It is related to the energy density reached in the collision and features in the calculation of many other observables. On the experimental side, the charged-particle multiplicity per unit rapidity largely determines the accuracy with which many observables can be measured. This variable is not derivable in any way from the QCD lagrangian since it is dominated by soft non-perturbative QCD and the relevant processes must be modelled using the new, large-scale, $R_A \approx A^{1/3}$ fm. Chapter 3 will cover the charged-particle multiplicity extensively.

**Particle spectra** The bulk of the particles emitted in a heavy-ion collision consists of soft hadrons, which decouple from the collision region in the late hadronic freeze-out stage of the evolution. They provide information on the freeze-out temperature and chemical potential. In addition, parameters characterizing the freeze-out distributions constrain the dynamical evolution and thus provide indirect information about the early stage of the collision. Theoretical arguments also show that different aspects of the measured final hadronic momentum distributions are determined at different times.

**Jets** Jets are clusters of hadrons and they are defined with dedicated algorithms. They are formed by a hard parton produced in the hadronic collision that further produces a shower of hadrons. The definition of a jet strongly depends on the algorithm used and the background from the underlying event: this is produced in the soft scattering of the incoming hadrons, and is quite large in particular for heavy-ion collisions, making the reconstruction a challenge for all experiments and requiring the development of proper techniques for its subtraction. At the LHC, high rates are for the first time expected for energies at which jets can be fully reconstructed against the high background from the underlying nucleus–nucleus event. Jet study will have much
higher sensitivity to the medium properties with respect to the nuclear modification factor $R_{AA}$\textsuperscript{1}. Jets in p-p interaction are fairly well understood and described by Monte Carlo models based on perturbative QCD in a wide kinematical range. In A-A interactions, fragmentation is strongly modified by medium at $p_t \approx 1$\text{-}5 GeV/c even for the highest energy jets. High-$p_t$ partons mainly lose energy through a radiative effect called gluon rescattering. Recent studies concluded that this loss grows quadratically with the in-medium path length, thus being very sensitive to the geometry of the collision region. The same parameter determines the $p_t$ broadening and energy loss of jets. This leads to a jet quenching effect, that sensitively depends on the scattering properties of the medium.

**Direct photons** Studies in p-p collisions are still necessary, even though direct photon production has been studied for years: there is indeed no good agreement between theory and experimental results. In A-A collisions prompt photons from the colliding hadron can probe the medium at the time of their production as they do not interact with the medium afterwards. However, several contributions to the photon production add to the initial production in different temporal stages of the collision (e.g. background from $\pi^0 \rightarrow \gamma\gamma$ which can be, of course, subtracted). Thermal photons are produced in the plasma till the freeze-out. These thermal effects can be disentangled from QCD effects (p-p interactions) and nuclear effects (p-A interactions): in p-p interactions there are no thermal effects, in p-A interactions there are only nuclear effects and no thermal effects and in nucleus–nucleus collisions both nuclear and thermal effects are present.

**Dileptons** Lepton pairs are produced throughout the evolution of the system: these come from prompt production in nucleon–nucleon collisions, thermal radiation

\textsuperscript{1}This quantity is defined as the ratio between particle yield in nucleus–nucleus collisions, normalized to the number of binary collisions given by the Glauber model calculation, to the corresponding yield in p-p collisions. If there is no medium effect, the yield should scale with the number of binary collisions and the ratio is 1.
from the QGP and hot hadronic phase and final state meson decays after freeze-out. Each of these contributions will dominate the continuum in the dilepton mass range in different regions. Since leptons and dileptons, once produced, are not affected by later stages of the collision, their production is an important tool for measuring the temperature and the dynamical evolution of the system.

**Heavy-quark and quarkonium production** Heavy quarks (charm and bottom) provide sensitive probes of the collision dynamics both at short and long timescales: their production takes place on the timescale of $1/m_Q$, where $m_Q$ is the mass of the quark, and their lifetimes are long enough to let them go through the thermalization phase of the plasma so that they can be affected by its presence. Production of heavy-quark pairs can also take place: these pairs can form quarkonium states that can very likely dissolve since their binding energy is comparable to the mean energy of the plasma (color screening of the $c\bar{c}$ potential by the surrounding color charges). As a result, open heavy flavours emerge in the final state. Therefore quarkonium states should be suppressed and open heavy flavour enhanced. However, at high $p_t$ open heavy flavours are expected to be suppressed due to the parton energy loss through the medium. To extract information about the QGP phase from the features of heavy-quark and quarkonium production, a deep knowledge in p-p and p-A collision is mandatory. In particular the measurement of the total cross-sections both in p-p and A-A is necessary, as no measurements were possible at Tevatron and the theoretical uncertainties on them are great. The typical variables to be studied are the total production rates, transverse momentum distributions and kinematical correlations between the quark and the antiquark.

1.2.2.1 Novel aspects of heavy-ion physics at the LHC

The heavy-ion programme of the LHC will push the energy density to a much higher limit, using Pb-Pb beams at energy 5.5 TeV per nucleon pair, exceeding the
maximum energy available at RHIC by a factor about 30: in ALICE at the LHC energies, extreme heating of an essentially baryon free central region will dominate. The estimated maximum temperature attainable is $T \approx 750$ MeV. This energy allows a new physics realm to be opened, entering a qualitatively new regime as well. Indeed a novel range of the Bjorken-x values will be accessible, corresponding to a regime where strong nuclear gluon shadowing is expected.

Hard processes will contribute significantly to the total cross-section. In particular very hard strongly interacting probes (quarkonia, open heavy flavours and jets), whose attenuation can be used to study the early stage of the collision, will be produced at a high rate. Weakly interacting hard probes will become accessible, like direct photons produced in hard processes that will provide information about nuclear parton distributions at very high $Q^2$. In addition the ratio between the lifetime of the QGP and the thermalization time will be higher by an order of magnitude than at RHIC, so the parton dynamics will dominate the fireball expansion and the collective features at the hadronic final state.

Access to new signatures of the QGP will be possible (higher $p_t$, charm and bottom physics). The experiments and analyses are going to be a challenging issue: state-of-the-art technology and an advanced computing environment will be used.

1.2.2.2 ALICE first heavy-ion physics

The first heavy-ion run is scheduled for $\sqrt{s_{NN}} = 5.5$ TeV Pb-Pb collisions at a luminosity $L \approx 5 \times 10^{25}$ cm$^{-2}$ s$^{-1}$, reduced to 1/20 of the design luminosity. Running for $10^6$ s should be enough to collect $10^7$ minimum-bias and another $10^7$ 5 % most central collisions. For this data taking a fully commissioned detector is expected: in particular alignment and calibrations will be available from the previously collected cosmics and p-p samples. Data quality and statistics should already allow, with this pilot run, a quite rich physics spectrum to be explored.
The initial $10^5$ events, collected in one day, will provide information about global event properties such as multiplicity, pseudorapidity density and elliptic flow. Indeed the very first measurement in the ALICE heavy-ion physics programme will be the charged-particle pseudorapidity density at mid-rapidity, followed by its behaviour along the $\eta$ range covered by the apparatus.

With 10 times higher statistics ($10^6$ events collected in one week), particle spectra, resonances, differential flow and interferometry analyses will be reasonably accessible. Essential measurements, such as the particle composition and the transverse momentum distributions of identified particles, will be addressed with the copious multiplicity of produced particles. As an example, ALICE will have reconstruction rates of 13, 0.1 and 0.01 per event for the $\Lambda$, $\Xi$ and $\Omega$ hyperons respectively. The excellent performance in terms of tracking, vertexing and particle identification capabilities will be key factors.

Statistically significant samples of only $10^6$ events will provide freeze-out temperature and collective motion of the particle-emitting source. This will also allow the thermal models, which have successfully described hadron production up to RHIC energies [19], to be verified. In addition, bulk properties of the medium (jet quenching), heavy-flavours and charmonia production will also be achieved with a full sample of $10^7$ events from such a first Pb-Pb pilot run.

### 1.3 Proton–proton physics with ALICE

ALICE will take and study proton–proton data at a centre-of-mass energy up to 14 TeV both as a benchmark for the understanding of heavy-ion data and to explore p-p physics in a new energy domain. The apparatus has several features that makes it an important contributor to genuine p-p physics studies as well. Indeed, ALICE can identify particles over a broad momentum range, it has powerful tracking
with good two-track resolution (from 100 MeV/c up to 100 GeV/c) and an excellent
determination of secondary vertices. The low material budget (≤ 10 % $X_0$ in the
full tracking volume) and rather weak magnetic field (0.5 T) will provide a unique
capability of detecting low-\(p_t\) phenomena in p-p at the LHC. This will allow several
basic QCD measurements to be performed, as described in the following. In addition,
it will also contribute to understanding the underlying events and minimum-bias event
properties. These events constitute the background for the high-\(p_t\) rare processes of
interest for the other dedicated p-p experiments at the LHC.

1.3.1 Benchmark for heavy-ion physics

Studying p-p collisions and measuring the same observables at the same specific
energy is needed to identify genuine collective phenomena in A-A collisions (i.e. not
present in a superimposition of p-p collisions). Some of the observables useful to this
extent are listed below.

- Particle multiplicities: differences in particle multiplicities between p-p and
  A-A collisions are related to the features of parton distributions in the nucleon
  with respect to parton distributions in nuclei and to the onset of saturation
  phenomena occurring at small x.

- Jet fragmentation functions: these are predicted to be modified from
calculations of medium-induced parton-energy loss.

- Slopes of transverse-mass distribution: the comparison will allow collective
effects such as transverse flow, present in A-A and absent in p-p, to be spotted.

- Particles yields and ratios: these are indicative of the achieved chemical
equilibration in A-A collisions and should be compared to those in p-p collisions.
• Ratios of momentum spectra: at high momenta these allow the differentiation of partonic energy-losses of quarks and gluons.

• Strangeness enhancement: strangeness production shows a very regular behaviour in p-p collisions from 10 up to 1800 GeV with an almost constant ratio between newly produced s and u quarks, while a strangeness enhancement is observed in heavy-ion collisions between 2 and 10 GeV. Changes in this ratio indicate new production mechanisms, as provided, for example, by new collective effects or by the significant contributions of jet fragments to total multiplicity.

• Heavy-quark and quarkonium production cross section: possible suppressions or enhancement, as well as parton energy-loss, have to be estimated and compared to the p-p yields. In addition more precise measurements of these yields are needed.

• Dilepton spectra: dileptons from resonance decays carry information about in-medium modifications in A-A collisions.

• Photon spectra: in p-p this measurement is needed to calibrate photon production in order to estimate the background to the thermal photon production in heavy-ion collisions. Reference values for the $\gamma$-jet cross sections in p-p are also important.

Measurements with the same detector set-up have also the advantage of minimizing systematic effects in the comparison.

1.3.2 Genuine proton–proton physics with ALICE

As already mentioned above, ALICE interest in the p-p LHC programme goes beyond the need to provide reference data for Pb-Pb. Its unique detection capabilities
will allow a number of important studies within p-p physics to be addressed. The most interesting aspects of specific p-p studies are connected to the exploration of a new energy domain and the access to the region of low Bjorken-x values. In the study of some observables ALICE has a unique capability, or at least is competitive with the other LHC experiments: this is particularly true for the low-\(p_t\) domain (below 1 GeV/c) for which the detector has been optimized. Indeed the p-p ALICE physics programme aims to study non-perturbative strong-coupling phenomena related to confinement and hadronic structure since the main contribution to the cross-section relevant for these studies is in the low-\(p_t\) region.

Some specific issues in p-p physics are outlined and briefly discussed in the following.

**Charged-particle multiplicity** Measuring multiplicity will allow the \(dN_{ch}/d\eta\) dependence on the centre-of-mass energy to be studied (see Chapter 3). Measurements of multiplicity will allow comparisons with the KNO scaling and the predictions from other models. Search for substructures, in a model-independent way, would be important to distinguish between soft and semi-hard components in the minimum-bias p-p interactions. Studies in the high multiplicity region (e.g. multiplicities above 10 times the average in minimum-bias collisions) are also very interesting: these events can give access to initial states where new physics, such as high density effects and saturation phenomena, sets in.

**Charged-particle spectra** Charged-particle spectra, both inclusive and for identified species, will be measured in rapidity and transverse momentum. Correlations between mean \(p_t\) and multiplicity are of great interest, for example studied for each particle specie, since at Tevatron different correlations were found. This will be relevant, in particular, in issues related to strangeness production.

**Baryon-number transfer in rapidity** The mechanism by which the baryon number is transported to the central rapidity region in hadronic collisions is an
open question: there are models explaining the transfer with different mechanisms (quark–diquark string breaking) and estimates. ALICE will measure with abundant statistic baryons in several channels in the central-rapidity region to clarify this issue. The baryon-number asymmetry will be studied for identified baryons (protons, Λs, Ξs and Ωs) at low $p_t$ and as a function of particle multiplicity.

**Two-particle correlations** In particular, studying two-particle correlations will allow the energy dependence and the dependence on particle type of the two-particle pseudorapidity correlations to be determined.

**Heavy-flavour production** Measuring heavy-quark production cross sections will help in understanding discrepancies found between theoretical predictions and measurements at SPS, Tevatron, HERA and LEP. The measurements will be extended to very low $p_t$, improving the precision with respect to existing results.

**Jets** In p-p collisions the main interest is in characterizing events with several jets at relatively low $p_t$. ALICE will be also able to study jet fragmentation as it can measure and identify particles in a highly dense environment, this being crucial for the reconstruction of jet topology.

**Diffractive physics** The interest in diffractive physics ranges from understanding Pomeron exchange in Regge theory to small-x phenomena. In particular ALICE should be able to observe large rapidity gaps, due to its wide coverage in central and forward pseudorapidity, as well as for low-x phenomena (down to $10^{-6}$). Diffractive processes will have a sizeable effect since single and double-diffractive dissociation cross-sections are predicted to increase at the LHC. Investigation of the hadronic structure of the final state produced in diffractive processes can provide, as well as particle identification, important information on the mechanism of high-energy hadronic interactions.

**Double-parton collisions** Increasing the energy of p-p collisions, multi-parton collisions become increasingly important since the parton flux increases. Such a
measurement has already been performed at Tevatron showing that the structure of the proton is much richer than the independent superposition of single-parton distribution functions accessible by deep-inelastic scattering. At the LHC a significant cross-section is estimated for double-parton collisions into final states with four jets and three jets and one photon.

1.3.2.1 ALICE first physics programme

The first proton–proton data-taking scenario (approximately 10 months, starting at the end of 2009) is mostly based on collisions at \( \sqrt{s} = 7 \) TeV with a luminosity of about \( 10^{30} \) cm\(^{-2}\) s\(^{-1}\): in such conditions statistics from a few times \( 10^8 \) to \( 10^9 \) minimum-bias events is expected to be collected.

Collisions at 0.9 TeV have been produced (with a reduced luminosity up to a few times \( 10^{27} \) cm\(^{-2}\) s\(^{-1}\)): this is very useful to compare with existing measurements and estimate systematic uncertainties.

Firstly ALICE will study global observables for event characterization. In particular the \( dN_{ch}/d\eta \) and the multiplicity distributions are currently being studied (see Chapter 4 and 5): this is possible with data taken in the first few days with a statistics of a few \( 10^4 \) events for the pseudorapidity density distribution and a few \( 10^5 \) events for the multiplicity distribution, where the multiplicity reaches up to 5 times the mean multiplicity. Then the inclusive charged-particle transverse momentum differential yield (\( d^2N/d\eta dp_t \) distribution) and the correlations between the mean transverse momentum and charged-particle multiplicity will follow. These first measurements are meant first of all to test ALICE performance. At \( \sqrt{s} = 900 \) GeV these results will be compared to results obtained at the same centre-of-mass energy in p-\( \overline{p} \) collisions at the SppS at CERN and to Monte Carlo models. At new energies these measurements will allow the Monte Carlo generators to be tuned and these will be used as reference data for heavy-ion data. Moreover, the measurement of the
charged-particle pseudorapidity density in the central rapidity region will extend the existing energy dependence pattern. These topics will also be the subject of the first physics papers that ALICE plans to publish.

Besides these very first measurements, $p_t$ spectra of both all charged and identified particles, baryon number transport and strangeness production ($K^\pm$, $K^0$, $\Lambda$ and $\bar{\Lambda}$) analyses will also be carried out within the p-p first physics programme.

### 1.4 LHC running conditions for ALICE

#### 1.4.1 Global running strategy

ALICE will take data with p-p collisions first, because the LHC will be first commissioned and then operated with proton beams for the first physics run. In the general schedule the proton runs will last several months each year followed by several weeks of heavy-ion runs for an effective time of $10^7$ s and $10^6$ s respectively. This is the same yearly running schedule usually applied for the SPS operation.

Heavy-ion runs will start with the largest available nuclei at the highest energy. Runs of different colliding systems at different energies will then be necessary. Decisions about the colliding systems to be run and the beam energy, as too many of them are possible, will be made and changed continuously as data become available according to priorities. In the first phase, priorities are set based on the current understanding of the results from SPS and RHIC. Subsequently, priorities will be set based on the results obtained analysing data from the first phase.

For proton runs, during the first year of operation a progressive increase of beam energy from the injection energy ($\sqrt{s} = 900$ GeV) up to $\sqrt{s} = 7-10$ TeV is foreseen. In the commissioning phase, p-p will be first helpful to complete the commissioning and the fine calibration of the detectors. Subsequently they will be used for the p-p
physics studies as previously discussed.

During the first years, the heavy-ion programme is scheduled according to the following:

- Pb-Pb physics pilot run that will allow global event properties and large cross sections observables to be measured;
- 1-2 years of Pb-Pb runs at the highest possible luminosity to provide sufficient statistics for low cross-section observables;
- 1 year of pPb-like collisions (like p-Pb, d-Pb or α-Pb);
- 1-2 years of Ar-Ar runs.

For the later phase the following runs are desirable:

- p-p runs at $\sqrt{s} = 5.5$ TeV;
- additional intermediate-mass ion runs for a more complete energy density scan;
- another p-A (d-A, α-A) system to study the A-dependence;
- lower energy Pb-Pb runs to connect to the RHIC results;
- further Pb-Pb high energy runs to increase the statistics of rare events.

1.4.2 Luminosity and beam size in A-A versus p-p collisions

Limitations on luminosity are imposed by both detectors and the accelerator. In Pb-Pb collisions, the Time Projection Chamber and the muon spectrometer place restrictions on the luminosity (the TPC has a drift time of 88 $\mu$s and the muon spectrometer has a maximum acceptable illumination for its trigger chambers). The probability of pile-up events during the TPC drift time has to stay below reasonable
limits: at $10^{27}$ cm$^{-2}$s$^{-1}$, such probability is estimated to be 76% for an hadronic interaction cross-section of 8 b: since the average particle multiplicity is only about 20% of the maximum multiplicity for which ALICE has been optimized and since only partial events overlap, such value is acceptable. The muon spectrometer requires limitations imposed by the maximum acceptable illumination of the trigger chambers (Resistive-Plate Chambers) of 50-100 Hz cm$^{-2}$: this results in a maximum usable luminosity $2-4 \times 10^{28}$ cm$^{-2}$s$^{-1}$.

However, stronger limitations come from the accelerator. From the machine side the problem is the luminosity lifetime since the electromagnetic cross-section for removing Pb ions from the beam is high. It will also depend on how many experiments are active during the ion run. Currently the maximum luminosity assumed for Pb-Pb runs ranges from $0.5 \times 10^{27}$ cm$^{-2}$s$^{-1}$.

In p-p runs luminosity of beams will be reduced at the Interaction Point 2 (IP2 where ALICE is placed) compared to the luminosity for the other experiments. On the detector side it is necessary to keep pile-up in the Time Projection Chamber and in the Silicon Drift Detector at an acceptable level, thus a luminosity of about $5 \times 10^{30}$ cm$^{-2}$s$^{-1}$, that corresponds to an interaction rate of approximately 200 kHz, is advisable. To eliminate pile-up the luminosity should be $10^{29}$ cm$^{-2}$s$^{-1}$. A higher limit would be imposed by the muon spectrometer ($5 \times 10^{31}$ cm$^{-2}$s$^{-1}$). In conclusion, the foreseen luminosity at IP2 for p-p runs will be about $5 \times 10^{30}$ cm$^{-2}$s$^{-1}$ in order to maximize integrated luminosity for rare processes. Furthermore, to collect statistics for large cross section observables and global event properties, runs with luminosity of about $10^{29}$ cm$^{-2}$s$^{-1}$ will take place. The luminosity will be reduced acting on the optics in the p-p collision mode and displacing the two beam centres.

In the approximation of Gaussian distributed bunches, the size of the luminous
region in which the interaction vertex will be spread is given by

\[\sigma_{\text{vertex}} = \frac{\sigma_{\text{bunch}}}{\sqrt{2}} F\]  \hspace{1cm} (1.3)

where the factor F takes into account the finite crossing angle of the two colliding beams and depends on the ratio between the longitudinal and transverse beam sizes (nominal values are F = 0.81 for Pb-Pb and F = 0.99 for p-p). The main machine parameters at \(\sqrt{s} = 7\) TeV for p-p and at top collision energy for Pb-Pb runs at the ALICE intersection point are summarized in Chapter 4.
Chapter 2

The ALICE experiment

2.1 Introduction

ALICE is the only general-purpose detector of the LHC designed to cope with the high particle multiplicity produced in central heavy-ion collisions [2, 20]. Very different optimization criteria than those applied to the other p-p dedicated experiments at the LHC have been adopted for ALICE: the detector has to track and identify particles in a broad momentum range, from very low (≈ 100 MeV/c) to fairly high (≈ 100 GeV/c) transverse momentum, with high-momentum resolution in an environment with large charged-particle multiplicity. The low interaction rate expected in Pb-Pb collisions allows rather slow but high granularity detectors to be used, such as the time-projection chamber and the silicon drift detectors. Besides that, specific features of the apparatus, such as those mentioned above, make it an important contributor to specific aspects of p-p physics at the LHC: as already discussed in the previous chapter, the aim of the ALICE p-p physics programme is not only to provide a reference to understand and interpret heavy-ion data but also to carry out genuine proton–proton physics studies, for the most part complementary to those that will be realized by the other dedicated experiments at LHC.
The complexity and dimension of the experiment have also required a wide effort to develop and operate a complete and stable framework for data processing together with proper management and control of the computing resources.

In the first part of the chapter the main detector subsystems and their performance will be described. The last section contains an overview of the offline framework, developed to simulate Monte Carlo samples and to reconstruct and analyze both simulated and real data.

### 2.2 ALICE detector

The ALICE experimental area is located at the Intersection Point (IP) 2 of the LHC. The detector is placed in an underground cavern with its central axis (beam line) at 44 m below ground level. The main parts of the apparatus are the central barrel detectors and the forward detectors, in addition to structures which support and carry services and cables to the detectors. Two magnets are employed: the solenoid magnet (nominal field of 0.5 T), constructed for the L3 experiment at LEP and now enclosing the central part of the ALICE detector, and the dipole magnet for the muon spectrometer (field integral in the forward direction of 3 T m).

The beam pipe at IP2 is a beryllium tube 0.8 mm thick and 3.5 m and 0.4 m long on the two sides of the IP respectively. Outside this region it is made of copper and stainless-steel. Its outer diameter is 59.6 mm.

Four suspended counting rooms house the electronics for the ALICE detectors below ground level, separated from the experimental cavern by a shielding plug (Fig. 2.1). At ground level the experimental area has a control room for remote control, supervision and operation of the detectors and service buildings to distribute electricity, cooling and ventilation and for the gas supply.
2.2.1 Global detector layout and design considerations

The ALICE experimental apparatus consists of 14 detector subsystems whose technology and design have been chosen considering both physics requirements and experimental conditions expected in the most central Pb-Pb collisions at the LHC. They can be divided in two sets according to their main functions and position. The first set is composed of tracking and particle identification detectors, placed inside the solenoidal magnet, to constitute the central system. From the innermost, they are as follows:

- an Inner Tracking System (ITS);
- a Time-Projection Chamber (TPC);
- a Time-Of-Flight detector (TOF);
• a High-Momentum Particle Identification Detector (HMPID);

• a Transition Radiation Detector (TRD);

• a Photon Spectrometer (PHOS);

• an ElectroMagnetic Calorimeter (EMCal).

Except the PHOS, the HMPID and the EMCal, all these detectors cover the full azimuthal range. The tracking system in the ALICE central barrel (ITS, TPC and partly TRD) covers a pseudorapidity window corresponding to $|\eta| < 0.9$. It has been designed to cope with the highest charged-particle densities originally expected in central Pb-Pb collisions ($dN_{ch}/d\eta \approx 8000$) and its performance has been checked up to 6000 charged particles per rapidity unit at mid-rapidity. The most recent estimates, extrapolating from RHIC data, predict values in the range 1500-4000 but the extrapolation is so large (the RICH top energy per nucleon–nucleon pair is still 30 times less than the LHC energy) that both the hardware and software of ALICE had to be designed to cope with the highest predicted multiplicity. The tracking was made particularly safe and robust using mostly three-dimensional hit information with up to 150 points in a moderate magnetic field. For the momentum measurement a very low material thickness is used to reduce effects of multiple scattering at low $p_t$. The tracking system will track and also identify hadrons, electrons and photons by measuring their specific energy loss $dE/dx$. All the other detectors in the central barrel will perform particle identification employing different PID techniques: time-of-flight, transition and Cherenkov radiation, electromagnetic calorimetry, muon filters and topological decay reconstruction.

To complete the central detection system, there are additional detectors at large rapidity (rapidity range within $-3.4 \leq \eta \leq 5.1$), one of which is devoted to identifying muons. Other smaller detectors are devoted to triggering events and providing for event characterization. These are as follows:
- a muon spectrometer;
- a Forward Multiplicity Detector (FMD);
- the V0 and T0 detectors;
- a Photon Multiplicity Detector (PMD);
- Zero-Degree Calorimeters (ZDC).

An array of scintillators (ACORDE) is placed on top of the L3 magnet to trigger cosmic rays: besides the study of cosmic-ray physics, it is also useful to collect data for alignment and calibration purposes.

All the central system detectors in the L3 magnet and the muon spectrometer are shown in Fig. 2.2. ALICE will concentrate on physics at or close to mid-rapidity where the lowest baryon density and the maximum energy density is reached. Therefore detectors are mainly concentrated around mid-rapidity, covering about two units in rapidity, while 1.5 units of rapidity at small angles with respect to the beam line is the coverage of the muon spectrometer.

The ALICE global coordinate system [21] is a right-handed orthogonal Cartesian system with the origin \( x, y, z = 0 \) at the nominal interaction point. The three Cartesian axes are defined as follows: the \( x \) axis pointing towards the centre of the LHC, the \( y \) axis pointing upward and the \( z \) axis parallel to the local mean beam line and pointing in the direction opposite to the muon spectrometer. The azimuthal angle increases counter-clockwise from the positive \( x \) axis (\( \varphi = 0 \)) to the positive \( y \) axis (\( \varphi = \pi/2 \)) with the observer standing at positive \( z \) and looking at negative \( z \); the polar angle increases from the positive \( z \) axis (\( \theta = 0 \)) to the \( x-y \) plane (\( \theta = \pi/2 \)) and to the negative \( z \) axis (\( \theta = \pi \)).
2.2.2 Central detectors: the tracking system

2.2.2.1 Inner Tracking System (ITS)

The ITS [22] consists of the following six cylindrical layers of silicon detectors:

- two layers of Silicon Pixel Detectors (SPD);
- two layers of Silicon Drift Detectors (SDD);
- two layers of Silicon Strip Detectors (SSD).

A schematic layout is reported in Fig. 2.3. The pseudorapidity coverage corresponds to $|\eta| < 0.9$ for particles originating within the length of the interaction diamond. The
number, the position and the segmentation of the layers are optimized for efficient track finding and high impact parameter resolution. The inner radius is the minimum allowed by the radius of the beam pipe, while the outer radius is determined by the requirement of a good matching of ITS standalone tracks with tracks reconstructed in the TPC. The high track density expected (up to 50 per cm$^2$ for the first layer) has determined the choice of detectors with increasing granularity towards the beam line. Only the pixels have a digital readout, the other detector planes have analogue readout for particle identification via dE/dx measurement in the non-relativistic region. This will give to the ITS stand-alone capability as a spectrometer to identify low-$p_t$ particles. All layers have their own cooling systems. The main parameters of the three detectors are summarized in Table 2.1 and 2.2.

The main tasks of the ITS are as follows:

- to contribute with the TPC to the global tracking of ALICE by improving the angle and momentum resolution;
- to reconstruct the position of the primary interaction vertex;
- to reconstruct secondary vertices from decays of heavy-flavour and strange
particle decays;

- to track and identify particles with momentum below 100 MeV/c;

- to improve the momentum, impact parameter and angle resolution for the measurement of high-$p_t$ particles performed with the TPC;

- to reconstruct particles traversing dead regions of the TPC.

The amount of the material in the active region has been reduced to minimize the effect of multiple scattering for particles that have a small transverse momentum. The spatial resolution is of the order of a few tens of $\mu$m with the best precision for the detectors closest to the primary vertex (12 $\mu$m).

The SPD will be described in a dedicated section since the analysis discussed in the last two chapters of this thesis rely heavily on data provided by this detector.

The SDD consists of two cylindrical layers at average radii of 15.0 and 23.9 cm and covers the region $|\eta| < 0.9$. It is composed of 260 sensors (84 in the inner layer and 176 in the outer layer). Each sensor, 300 $\mu$m thick, is made of Neutron Transmutation Doped (NTD) silicon, with an internal voltage divider providing a drift field of 500 V/cm and MOS charge injectors that allow measuring the drift speed via dedicated calibration triggers. The charge signal of each of the 133 000 collection anodes, arranged with a pitch of 294 $\mu$m, is sampled every 50 ns by an ADC in the

---

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>$r$ (cm)</th>
<th>$\pm z$ (cm)</th>
<th>Area (m²)</th>
<th>Ladders</th>
<th>Channels</th>
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<tbody>
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<td>Pixel</td>
<td>3.9</td>
<td>14.1</td>
<td>0.07</td>
<td>80</td>
<td>3 276 800</td>
</tr>
<tr>
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<td>Pixel</td>
<td>7.6</td>
<td>14.1</td>
<td>0.14</td>
<td>160</td>
<td>6 553 600</td>
</tr>
<tr>
<td>3</td>
<td>Drift</td>
<td>15.0</td>
<td>22.2</td>
<td>0.42</td>
<td>14</td>
<td>43 008</td>
</tr>
<tr>
<td>4</td>
<td>Drift</td>
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<td>29.7</td>
<td>0.89</td>
<td>22</td>
<td>90 112</td>
</tr>
<tr>
<td>5</td>
<td>Strip</td>
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<td>43.1</td>
<td>2.20</td>
<td>34</td>
<td>1 148 928</td>
</tr>
<tr>
<td>6</td>
<td>Strip</td>
<td>43.0</td>
<td>48.9</td>
<td>2.80</td>
<td>38</td>
<td>1 459 200</td>
</tr>
</tbody>
</table>

**Table 2.1:** Dimensions of the ITS detectors (active areas).

---


Table 2.2: Parameters of the various ITS detector types. A module represents a single sensor element.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Silicon pixel</th>
<th>Silicon drift</th>
<th>Silicon strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial precision $r_\phi$ ($\mu$m)</td>
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<td>38</td>
<td>20</td>
</tr>
<tr>
<td>Spatial precision $z$ ($\mu$m)</td>
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<td>25</td>
<td>830</td>
</tr>
<tr>
<td>Two track resolution $r_\phi$ ($\mu$m)</td>
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<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Two track resolution $z$ ($\mu$m)</td>
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<td>600</td>
<td>2400</td>
</tr>
<tr>
<td>Cell size ($\mu$m$^2$)</td>
<td>$50 \times 425$</td>
<td>$202 \times 294$</td>
<td>$95 \times 40000$</td>
</tr>
<tr>
<td>Active area per module (mm$^2$)</td>
<td>$12.8 \times 69.6$</td>
<td>$72.5 \times 75.3$</td>
<td>$73 \times 40$</td>
</tr>
<tr>
<td>Readout channels per module</td>
<td>40,960</td>
<td>2 $\times$ 256</td>
<td>2 $\times$ 768</td>
</tr>
<tr>
<td>Total number of modules</td>
<td>240</td>
<td>260</td>
<td>1,608</td>
</tr>
<tr>
<td>Total number of readout channels (k)</td>
<td>9,835</td>
<td>133</td>
<td>2,608</td>
</tr>
<tr>
<td>Total number of cells (M)</td>
<td>9.84</td>
<td>23</td>
<td>2.6</td>
</tr>
<tr>
<td>Average occupancy (inner layer) (%)</td>
<td>2.1</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>Average occupancy (outer layer) (%)</td>
<td>0.6</td>
<td>1.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Power dissipation in barrel (W)</td>
<td>1,350</td>
<td>1,060</td>
<td>850</td>
</tr>
<tr>
<td>Power dissipation end-cap (W)</td>
<td>30</td>
<td>1,750</td>
<td>1,150</td>
</tr>
</tbody>
</table>

front-end electronics. The total thickness of the SDD layers (including mechanical supports and front-end electronics) amounts to 2.4 % of a radiation length.

The two layers of the double-sided SSD are located at average radii of 38 and 43 cm respectively, covering the pseudorapidity range $|\eta| < 0.97$. The SSD consists of 1698 sensors with a strip pitch of 95 $\mu$m and a stereo angle of 35 mrad. Each module consists of one sensor, 300 $\mu$m thick, connected to two hybrids with six chips each. Each sensor has 768 strips per side. Modules are assembled on ladders along the beam direction (25 modules per ladder). For both the inner and the outer layers of the SSD and the SDD, ladders are mounted at two different radii to obtain a full azimuthal coverage. The position resolution is better than 20 $\mu$m in the $r$-$\phi$ direction and about 0.8 mm in the direction along the beam line. The thickness of the SSD, including support and services, corresponds to about 2.2 % of a radiation length. These layers are crucial for ITS-TPC track-matching and both provide a
two-dimensional measurement of the track position.

2.2.2.1 Silicon Pixel Detector ( SPD) The SPD is ALICE’s innermost detector and has a central role in reconstructing the primary vertex and in measuring the impact parameter of secondary tracks, in particular particles from heavy-flavour and strange particle decays. The expected density of charged particles, in the region where the SPD is placed, is about 50 cm$^{-2}$ for central Pb-Pb collision and the integrated level of total dose and fluence are estimated to be 2.7 kGy and 3.5×10$^{12}$ n/cm$^2$ respectively. Therefore a pixel detector was selected: it has two-dimensional readout, high granularity, high precision and double-hit resolution and radiation hardness. It also has a high speed readout and is rather easy to calibrate and align. In addition, the high segmentation leads naturally to a low individual diode capacitance, resulting in an excellent signal-to-noise ratio.

It consists of two cylindrical layers with average radii of 3.9 and 7.6 cm and has about 9.8 million pixels for a total area of 0.24 m$^2$. The two layers cover the pseudorapidity ranges $|\eta|<2$ (inner layer) and $|\eta|<1.4$ (outer layer) respectively, for particles originating at the centre of the detector. The effective acceptance is larger due to the longitudinal spread of the position of the interaction vertex. The total thickness of the SPD amounts to about 2.3 % of a radiation length.

The inner and outer layers consist of 40 and 80 basic modules (half-staves) respectively. In Fig. 2.4 the two layers of the detector are depicted with one half-stave highlighted. Each half-stave (Fig. 2.5) is about 140 mm long and consists of two silicon sensors (two ladders) bump-bonded directly to 10 custom-designed ASICs readout chips, a grounding foil made of kapton and aluminium, a multi-layer bus and a controller, the Multi Chip Module (MCM). In Fig. 2.6 one half-stave and its components are shown. Details on the complex assembly procedure can be found in [23].
Figure 2.4: Schema of the SPD inner and outer layer: the basic module (half-stave) is highlighted.

A ladder is a 200 $\mu$m thick high resistivity n-type silicon sensor matrix, bump-bonded to five front-end chips. The matrix consists of $256 \times 160$ cells, measuring 50 $\mu$m and 425 $\mu$m in the r-$\phi$ and z direction respectively. Each detector cell is a reverse-biased diode whose nominal operating voltage is 50 V.

Each readout chip contains the electronics to read out 8192 detector cells, organized in 256 rows and 32 columns. The chip is a mixed signal ASIC developed in an IBM 0.25 $\mu$m CMOS process with radiation tolerant layout design: the physical size of the detector and the radiation levels did not allow the application of commercial components. It is 150 $\mu$m thick and 14 mm large and its nominal setting for the power supply is 1.8 V. Each pixel cell consists of an analog and a digital section (Fig. 2.7). The analog circuitry contains a preamplifier-shaper with leakage current compensation, followed by a discriminator. The readout is digital: a threshold is set for the pre-amplified and shaped signal and each cell output is a binary 1 if the threshold is exceeded. The logical 1 is propagated through one of the two delay lines.
during the second level trigger signal L1 (Level 1) latency (approximately 6 $\mu$s). The read-out is organized in 2 trigger levels. A four-hit-deep multi-event buffer in each cell de-randomizes the event arrival times. Upon the arrival of the L1 trigger, the logical level present at the end of the delay line is stored in the first available buffer location, where the data wait for the last level trigger signal L2 (Level 2) decision (latency approximately 100 $\mu$s) to be read out via a 32-bit parallel data bus or they are discarded. The chip clock frequency is 10 MHz. A detailed description of the chip architecture can be found in [24, 25].

Each chip generates a digital signal (Fast-Or) whenever at least one of its pixel cells is fired (at least one particle traversing the chip). It is used for self-triggering the front-end in test mode and to implement physics triggers, as described for example
in Chapter 4 for the minimum-bias trigger in p-p collisions. This signal is available 300 ns after the particle hits the detector: the response is fast since the signal does not undergo any processing in the electronics. The 10 Fast-Or bits of each half-stave are continuously transmitted on the output optical link by the MCM to the control room, with a clock frequency of 10 MHz (bunch crossing frequency in heavy-ion operation). The Pixel Trigger (PIT) [26] unit has to extract and process all the 1200 Fast-Or signals in order to be able to deliver an input signal for the Level 0 trigger decision in the ALICE Central Trigger Processor (CTP). Indeed, the Fast-Or can contribute to the first level trigger signal L0 (Level 0) of the experiment, since it can be generated quickly enough to arrive at the central trigger processor (CTP) in time for the L0 trigger decision, whose latency is 1.2 $\mu$sec. Being synchronous with the clock of the chip, the Fast-Or signals produced are integrated over 100 ns, that is 4 bunch-crossing periods (if the bunch spacing is 25 ns). Therefore it is not possible to identify the bunch crossing in which the Fast-Or have been generated. The ambiguity can be solved requiring a logic and coincidence with signals from the V0 or the T0 detector (see Chapter 4).

The readout of the two ladders on each half-stave is controlled by the three ASICs:
the digital PILOT, the analog PILOT and the gigabit optical link driver GOL, that constitute the MCM located at the end of each half-stave and which is connected to the pixel bus. The digital PILOT receives serial trigger, configuration data and clock signals from the off-detector electronics. It also initiates the pixel chip read-out, performs data multiplexing and sends the data to the GOL that will convert and send them to the control room. The analog PILOT reads the temperature and the voltage of the sensors and provides power to the front-end chips.

The data/control lines and the power/ground planes are implemented in an aluminium/polyimide multi-layer flex: the pixel bus. It is 240 µm thick and consists of five layers step-wise receded to make room for the wire bonding pads and to allow connections to the power and ground planes without using vias. The bus is glued to the sensors and wire-bonded to the readout chips.

Two independent flexible copper/polyimide laminates, called power extenders, provide power to the pixel bus and to the MCM. The MCMs are connected to the remote readout electronics (Router) in the counting rooms through optical fibres.

The inner layer modules are tangent to two cylindrical surfaces of different radii that allow for a full azimuthal coverage (Fig. 2.8). The outer layer half-staves make an angle of about 22° with the tangent to a cylindrical surface centred on the beam line. All modules overlap in ϕ for a total amount of about 2% of the SPD area. The half-staves are glued on a carbon-fibre support structure with an embedded cooling system. Two half-staves are placed along the z direction to form a stave. Each sector supports two staves in the inner layer and 4 staves in the outer layer. Ten of these structures are mounted together around the beam pipe to close the full barrel. The cooling system lines keep the temperature on the back plane of the front-end chip at the operating value of about 25°C. It has to be very efficient since the power density is quite high and the mass of the detector is small.

The SPD (Fig. 2.9 and Fig. 2.10) has been aligned using cosmic-ray tracks collected
Figure 2.8: Sketch of two adjacent sectors on which the SPD half-staves are glued. The cooling system is represented in blue.

during 2008 [27]: the residual misalignment has been estimated to be below 10 \( \mu \text{m} \) for most of the modules, except those located on the sides. Those modules are likely to be affected by larger residual misalignment since quite poor statistics of muon tracks were available in this case.

2.2.2.2 Time Projection Chamber (TPC)

The TPC is the main tracking detector of the ALICE apparatus. It covers a pseudorapidity range of \( |\eta| < 0.9 \) for tracks with full radial track length and up to \( \eta = 1.5 \) for reduced track length. It covers the full azimuth (except dead zones). The inner radius is determined by the maximum acceptable hit density and is about 85 cm, the outer radius is 250 cm and is determined by the length required to have a \( \text{dE/dx} \) resolution better than 5-7 \%. The length along the beam direction is 500 cm. It has a conventional design in overall structure but is innovative in many aspects. It consists of a large cylindrical field cage, filled with 90 \( m^3 \) of \( \text{Ne/CO}_2/\text{N}_2 \) (90/10/5), in which 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. Multi-wire proportional chambers with cathode pad readout are mounted into 18 trapezoidal sectors at each end plate. The
field cage is operated at high voltage gradients because of the gas mixture used, with a high voltage of 100 kV at the central electrode that results in a maximum drift time of about 90 $\mu$s.

The TPC together with others detectors of the central barrel has to provide charged-particle momentum measurements with good two-track separation, particle identification and vertex determination. The TPC has been optimized for Pb-Pb expected luminosity and the initially foreseen charged-particle multiplicity density $dN_{ch}/d\eta = 8000$, that means about 20000 primary and secondary particles in the TPC acceptance. These extreme multiplicities, unprecedented for a time-projection...
chamber, required a careful optimization of the TPC design.

For p-p collisions the limiting factor for the luminosity is the memory time of the TPC due to its 90 $\mu$s drift time. Tracks from pile-up events can be eliminated since they point to a wrong vertex.

With its resolution the TPC can also identify particles in the region of the relativistic rise momenta, up to 50 GeV/c. Despite its data volume and speed, only such a tracking detector can guarantee the desirable performance at the order of 20 000 particles within the acceptance.

2.2.3 The Particle Identification system

2.2.3.1 Transition Radiation Detector (TRD)

The TRD is segmented in 18 super modules in $\phi$, each containing 30 modules arranged in 5 stacks along z and 6 layers in radius. Each detector element consists of a radiator, a drift section and a multi-wire proportional chamber section with pad readout. The layers are placed at a distance of $2.90 \text{ m} < r < 3.68 \text{ m}$ from the beam line; they cover the full azimuth and a pseudorapidity range $|\eta| < 0.84$.

It will identify electrons with momentum above 1 GeV/c in the central barrel, where the pion rejection capability of the TPC is no longer sufficient. This information, in addition to that provided by ITS and TPC, will allow production rates of quarkonia near mid-rapidity, as well as the dilepton continuum in Pb-Pb and in p-p, to be measured. With the impact parameter determination provided by ITS, it will also be possible to measure open charm and beauty in semi-leptonic decays.

With its six layers, the TRD will contribute to the global tracking through the central barrel improving the $p_t$ resolution at high momentum.
2.2.3.2 Time-Of-Flight detector (TOF)

The TOF is a large area array of Multi-gap Resistive-Plate Chambers, a new type of gas detector developed to fulfil the requirements of having a large number of channels to keep the occupancy low, an affordable system and a time resolution better than 100 ps. It is positioned on a cylindrical surface that covers the central barrel ($|\eta| < 0.9$) over an area of $140 \text{ m}^2$ with 160,000 individual cells at a radius of about 4 m.

It has to identify hadrons in the intermediate momentum range: below 2.5 GeV/c for pions and kaons, up to 4 GeV/c for protons, with a $\pi$/K and K/p separation better than $3\sigma$. It will provide, together with the tracking system, event-by-event identification of large samples of pions, kaons and protons. In addition, identified kaons will allow invariant mass studies, in particular the detection of open-heavy flavour states and vector-meson resonances.

2.2.3.3 High-Momentum Particle Identification Detector (HMPID)

It is a single-arm, 10 $\text{ m}^2$ array of proximity-focusing ring imaging Cherenkov counters with a liquid radiator and a solid CsI photocathode, evaporated on the segmented cathode of multiwire proportional chambers. It consists of 7 modules of $1.5 \times 1.5 \text{ m}^2$. It is placed at 5 m from the beam line at the 2 o’clock position and has a coverage in pseudorapidity of $|\eta| \leq 0.6$, while the azimuthal coverage is $1.2^\circ \leq \varphi \leq 58.8^\circ$, that results in an acceptance 5 % of the central barrel phase space.

It extends the inclusive measurement of identified hadrons of the ALICE detector towards momenta $p_t > 1 \text{ GeV/c}$ and the PID capability to particles with momenta beyond the momenta measurable through energy loss (in TPC and ITS) and time-of-flight measurements (TOF). The detector was optimized to extend the useful range for $\pi$/K and K/p discrimination, on track-by-track basis, up to 3 GeV/c and
5 GeV/c respectively. The geometry of the detector has been optimized with respect to particle yields at high \( p_t \) in p-p and heavy-ion collisions at the LHC energies and with respect to the large opening angle required for two-particle correlation measurements.

### 2.2.3.4 Electromagnetic calorimeters: PHOS and EMCal

The PHOS is a single-arm high-resolution and high-granularity electromagnetic spectrometer consisting of a highly segmented electromagnetic calorimeter and a charged-particle veto detector. It is made up of five modules and is placed on the bottom of the ALICE apparatus at a distance of 460 cm from the beam line. It will cover approximately a quarter of a unit of pseudorapidity \((|\eta| \leq 0.12)\) and 100° in \( \varphi \). It is made of dense scintillating crystals in order to cope with large particle density. The scintillator material employed allows a good resolution even at the lowest energies. Charged particles are vetoed by a set of multi-wire chambers in front of the PHOS.

It has to measure photons, spanning from the range of thermal emission to hard QCD processes, and neutral mesons. Its main goals are the following:

- to test thermal and dynamical properties of the initial phase of the collision, in particular the initial temperature and space-time dimensions of the hot zone, through measurement of direct single-photon and di-photon spectra and Bose-Einstein correlations of direct photons;

- to investigate jet quenching as probe of deconfinement through the measurement of high-\( p_t \) \( \pi^0 \) spectrum, and identifying jets through \( \gamma \)-jet and jet-jet correlation measurements.

The main requirements are to detect and discriminate between direct and decay photons, as well as to discriminate photons against charged hadrons and to
perform momentum measurements over a wide dynamic range with high energy and spatial resolution. Discrimination criteria such as topology analysis of the shower, time-of-flight measurements and the veto detector will be used.

The EMCal is a Pb-scintillator sampling calorimeter with cylindrical geometry, placed adjacent to the L3 magnet coil at a radius of about 4.5 m from the beam line. It covers the pseudorapidity region $|\eta| < 0.7$ and $\Delta \varphi = 107^\circ$ and is positioned approximately opposite to the PHOS in the azimuthal direction. Limitations on the weight and size of the detector were required. It is much larger than PHOS but with lower granularity and energy resolution.

The EMCal has to explore aspects related to the physics of jet and in particular of jet quenching, an effect due to the interaction of energetic partons with dense matter, relevant to the study of energy loss and interaction of high energy partons in a dense medium. It widens the electromagnetic calorimeter coverage of ALICE, provides fast and efficient trigger (L0, L1) for hard jets, photons and electrons and also measures the neutral component of jets allowing the full reconstruction of jets in all collisions systems. It has, together with the TPC, a good jet energy resolution and an excellent sensitivity to the full range of jet-quenching effects expected at the LHC.

### 2.2.4 Forward detectors

#### 2.2.4.1 Muon spectrometer

It consists of a system of absorbers, a high-granularity tracking system of 10 planes, a large dipole magnet and four planes of trigger chambers. Its pseudorapidity coverage is $-4.0 \leq \eta \leq -2.5$. The five tracking chambers are cathode pad chambers placed one before, one inside and two after the dipole. Each chamber has two cathode planes to provide two-dimensional information. The granularity of readout pads decreases at larger radii. The trigger system performs a $p_t$ selection on muons.
using Resistive Plate Chambers. The system of absorbers has to absorb hadrons and photons from the interaction vertex, to shield primary and secondary particles produced at large rapidities in the beam pipe and to protect the trigger chambers.

The muon spectrometer has to detect and identify muons and in particular has to measure the production of heavy-quark vector-meson resonances ($J/\Psi,\Psi',\Upsilon,\Upsilon'$, $\Upsilon''$), as well as the $\phi$ meson, in the $\mu^+\mu^-$ decay channel with a sufficient mass resolution to separate all states. Measuring all states with the same detector will allow their production rate, as a function of different parameters such as the transverse momentum and the centrality of the collision, to be compared. The detection of heavy-quarkonia states is very important since these are good probes for the early stage of the collision. Furthermore it will be possible to study the production of open flavours measuring the $e-\mu$ coincidences, where the muon is detected by the muon spectrometer and the electron is detected by the TRD. The trigger systems have to reject events in which only low-$p_t$ muons from $\pi$ and $K$ decays and no high-$p_t$ muons, from heavy quarkonia decays or from a semi-leptonic decay of open charm and beauty, are produced.

2.2.4.2 Zero-Degree Calorimeter (ZDC)

The ZDC consists of two sets of two compact calorimeters (neutron and proton calorimeters) placed at 116 m from the IP on both sides in the machine tunnel. The spectator neutrons and protons are spatially separated by the magnetic elements of the LHC beam line, therefore the neutron calorimeter is placed in between the two beam pipes at $0^\circ$ with respect to the LHC beam line, and the proton calorimeter is placed externally on the side where positive particles are deflected. In addition, two small electromagnetic calorimeters (ZEM), placed on one side of the interaction point, opposite to the muon arm, at 7 m from the vertex will improve the centrality selection, as explained in Chapter 3. They cover the pseudorapidity region $-4.8 \leq \eta \leq 5.7$. The
hadronic calorimeters are quartz fibres sampling calorimeters: the shower generated by incident particles in a dense absorber produces Cherenkov radiation in quartz fibres interspersed in the absorber. This technique gives the ZDC compactness, radiation hardness and fast response. The ZDCs are indeed very compact, especially the neutron calorimeter, due to the limited space available. A similar detection technique is adopted for the ZEMs: the main difference is that the fibres are oriented at 45° with respect to the beam line to maximize the efficiency since the Cherenkov light produced has a peak around 45°.

It will measure and trigger on the impact parameter of the collision and, being position-sensitive, can give an estimate of the reaction plane in nuclear collisions. The ZDC will measure the energy carried by non-interacting (spectator) nucleons in the forward direction (zero degree with respect to the beam line) in heavy-ion collisions. This measurement gives an estimate of the number of participants nucleons $N_{\text{part}}$: the observable most directly related to the geometry of the collision. This energy decreases increasing the centrality and consequently the number of participants nucleons. Not all the spectators are detected at a collider so the number of participants cannot be estimated with the simple relations

$$E_{\text{ZDC}}(\text{TeV}) = 2.76 \times N_{\text{spec}}$$

$$N_{\text{part}} = A - N_{\text{spectators}}$$

where 2.76 TeV is the energy per nucleon. A good resolution on the number of spectators detected is necessary to have a reliable estimate of the centrality variables. The resolution on the measure of the impact parameter has been estimated to be of the order of 1 fm.

The electromagnetic calorimeter will help in discriminating central event and peripheral events. Indeed, in peripheral events a significant number of spectators is bound in fragments that stay in the beam pipe and therefore cannot be detected
by the two ZDCs. This has to be distinguished from the case of central collisions in which the number of spectators detected is also small. The ZEMs will measure the energy of particles at forward rapidity that increases with centrality; this additional measurement can help in classifying the event centrality.

The ZDC will provide three L1 centrality triggers: central, semi-central and minimum-bias.

2.2.4.3 Photon Multiplicity Detector (PMD)

The PMD is placed at 364 cm from the IP and consists of two identical planes of high granularity gas proportional counters (of 24 modules each) with a honeycomb cellular structure. A $3X_0$ thick lead converter is in between the two planes. One plane has to provide a veto for charged particles and the plane behind the converter is a preshower plane. The preshower method is used to detect photons since calorimetric techniques are not feasible in the forward region because of the large particle density. The cell occupancy is 13% for the veto plane and 28% for preshower plane. The granularity of the counters and the thickness of the converter have been chosen in order to minimize the overlaps between photon showers. The pseudorapidity coverage is $2.3 \leq \eta \leq 3.7$.

The PMD will measure the multiplicity and the spatial ($\eta$-$\phi$) distribution of photons on an event-by-event basis in the forward pseudorapidity region. Providing these pieces of information, the PMD will be employed for event-by-event studies as, for example, fluctuations and flow, the estimate of the reaction plane and of transverse electromagnetic energy.

2.2.4.4 Forward Multiplicity Detector (FMD)

The FMD consists of 51,200 silicon strip channels distributed on five ring counters of two different designs (inner and outer rings): three rings are placed on the right
of the IP, two on the left; each with 20 or 40 sectors in the azimuthal angle. The rings are located at three different positions along the beam pipe and the design and position of the rings is constrained by the beam pipe and the layout of other detectors (ITS, T0).

The FMD will measure the charged-particle multiplicity in the pseudorapidity regions $-3.4 \leq \eta \leq -1.7$ and $1.7 \leq \eta \leq 5.1$, counting particles in the rings of silicon strip. It will complete the multiplicity measurement together with the SPD, enlarging the accessible pseudorapidity coverage and a cross check of results is possible in the region where it overlaps with the inner layer of the pixels. The high radial segmentation of the FMD will allow multiplicity fluctuations on an event-by-event basis to be studied, while the azimuthal segmentation allows the reaction plane for each event to be determined and to carry out flow analysis within the pseudorapidity range covered. The occupancy is of one charged particle per strip in central events. However, considering the contribution of secondary particles, this number increases up to 3 charged particles per strip. Peripheral and p-p collisions have a significantly hit density and each strip allows up to 20 minimum-ionizing particles before saturation. The FMD cannot provide triggered signals because of its readout time.

2.2.4.5 V0

The V0 detector consists of two segmented arrays of plastic scintillator counters, placed around the beam-pipe on either side of the IP: one at $z = 90$ cm (in front of the absorber), covering the pseudorapidity range $-3.7 \leq \eta \leq -1.7$, and the other at $z = -340$ cm, covering the pseudorapidity range $2.8 \leq \eta \leq 5.1$. They consist of 32 counters distributed in four rings, each divided in eight $45^\circ$ sectors. Each counter is made of scintillator material embedded with WaveLength Shifting fibres. Clear fibres collect and transport the signal to photomultipliers 3-5 m far from the detector, inside the L3 magnet. The counters have a time resolution better than 1 ns. Its response is
recorded in a time window of 25 ns around the nominal beam crossing time.

The V0 is a trigger detector that will provide minimum-bias trigger for all colliding systems to the central barrel detectors and three centrality triggers in Pb-Pb collisions (multiplicity, central and semi-central). It has an important role in rejecting background from beam-gas collisions exploiting the relative time-of-flight measurement between the two arrays: when the beam–gas collision takes place outside the region between the two arrays, particles arrive 6 ns before or after the time of a beam–beam collision. If the beam–gas collision takes place in between the two arrays it is not possible to reject it and an offline trigger has to be employed. It will also participate in the measurement of luminosity in p-p collisions with a fairly good precision (about 10 %).

2.2.4.6 T0

The T0 detector consists of two arrays of 12 Cherekov counters each, mounted around the beam-pipe. One array is placed at -72.7 cm from the IP, the distance imposed by the layout and position of the muon spectrometer and of the other forward detectors, and has a pseudorapidity coverage of $-3.28 \leq \eta \leq -2.97$. The other array is placed at 375 cm on the opposite side of the IP, grouped together with other forward detectors, and has a pseudorapidity coverage of $4.61 \leq \eta \leq 4.92$. In the radial direction they are placed as close as possible to the beam pipe to maximize the trigger efficiency.

The T0 detector, together with the V0, will provide fast trigger signals. The main goals of the T0 are as follow:

- to measure the event time with a precision better than 25 ps;

- to provide the TOF with a start time signal, that is the real time of the collision plus a fixed delay and is independent of the position of the primary vertex;
to measure the interaction vertex position with a precision of ± 1.5 cm and
to provide a L0 trigger when the position is within a predefined window to
discriminate against beam-gas interactions;

• to provide a wake-up signal to the TRD, prior the L0 trigger;

• to generate minimum-bias and multiplicity trigger signal (based on threshold
  on multiplicity in heavy-ion collisions).

It will contribute to the L0 trigger of the experiment so its dead time has to be less
than the bunch-crossing period in p-p collisions (25 ns).

2.3 ALICE offline framework

In this section the software and the main tools developed to process and analyse
data will be reviewed. First the ALICE offline framework will be introduced, then a
short description of the simulation, reconstruction and analysis architecture will be
given. Finally the tools for distributed analysis will be listed. Details can be found
in [28].

2.3.1 AliRoot framework

The ALICE offline framework, AliRoot [29], is shown schematically in Fig. 2.11.
Its implementation is based on Object Oriented design and C++ programming
by multiple authors, with some external programs (hidden to the user) still in
FORTRAN. It is based on the ROOT system [30] and completed by the ALICE
interface to the Grid: AliEn. It has been developed since 1998. This framework is
used for simulation, alignment, calibration, reconstruction, visualization and analysis
of the experimental data. Initially it was used to carry out simulation studies in order
to optimize the design of the ALICE subsystems, then it has been used to study the physics performance of the full ALICE detector and to assess the functionality of the framework towards the final goal of extracting physics results from the data.

The processing steps performed with the AliRoot framework starting from Monte Carlo data or from real raw data is shown in Fig. 2.12. Simulated data are produced using Monte Carlo generators and contain the full information about the generated particles (particle identification and momentum); then the generated tracks are transported through the detector geometry using simulation packages such as GEANT 3, FLUKA and GEANT 4, and the energy deposition at a given point and time is stored in the so called hits for each detector. This information is complemented by

Figure 2.11: Schema of the AliRoot framework.
the so-called “track references”, corresponding to the location where the particles are crossing user-defined reference planes. Hits are then transformed into an ideal detector response and subsequently into the real detector response: digits are produced taking into account the electronic manipulation of the signal performed by detectors and their electronics, including digitization. Finally the digits are stored in the specific hardware format of each detector as raw data. From this point on, simulated and real raw data data undergo the same processing steps: the local reconstruction such as clusterization and tracking. To evaluate the detector and software performance, simulated data are processed throughout the full chain and the final reconstructed particles are compared to the Monte Carlo ones. Users can develop and run their
own analysis in this framework-driven cycle, using I/O and user interfaces.

Re-usability and modularity are the basic features of the AliRoot framework. Modularity allows parts of the code to be replaced, with minimum or no impact on the rest (for example change the event generator, the transport Monte Carlo or reconstruction algorithms). This is achieved implementing abstract interfaces. In addition codes for each detector subsystem are independent modules with their specific code for simulation and reconstruction and the code can be developed concurrently with the minimum interference. Re-usability is meant to maintain the maximum amount of backward compatibility as the system evolves.

The central module of the AliRoot framework is STEER which provides several common functions such as:

- steering of program execution for simulation, reconstruction and analysis;
- general run management, creation and destruction of data structures, initialization and termination of program phases;
- base classes for simulation, event generation, reconstruction, detectors elements.

Virtual interfaces are provided to access different Monte Carlo event generators and to detectors to perform response simulation using different transport codes.

Since the framework is continuously evolving, a specific release policy has been adopted. In addition, being developed by multiple authors, to keep the code uniform, readable and understandable, a set of coding and programming rules has been adopted. The compliance of the code with these rules is performed by a code-analysis tool and violations are published.
2.3.2 Event simulation and reconstruction

2.3.2.1 Generators

The offline framework was developed for efficient simulation of different colliding systems, that is proton–proton, nucleus–nucleus and proton–nucleus collisions. External generators (for example HIJING\cite{31} for nucleus–nucleus interactions, PYTHIA\cite{32} and PhoJet\cite{33} for p-p interactions) can be employed, using the abstract generator interface \texttt{AliGenerator}: this base class, responsible of generating primary particles of an event can delegate the task to an external generator, for example PYTHIA, through the generic \texttt{TGenerator} interface. This class allows FORTRAN code, then accessible and usable from the AliRoot classes, to be wrapped. However, since existing generators give different predictions at the same energy or do not reproduce most of the physics signals and do not correctly simulate some features, the ALICE offline framework provides a number of options for efficient simulation, listed below:

- simple generators based on parametrized $\eta$ and $p_t$ distributions that can provide a signal-free event with multiplicity as a parameter;
- a tool to merge events from different signal generators;
- tools for merging underlying events and signal events on the primary particle level (cocktail) or on the digit level (merging);
- afterburners to introduce particle correlations in a controlled way.

In addition, since simulation of small cross-section observables would require long campaigns to simulate a number of events sufficient to their study and comparable to the statistics that will be collected in the experiment, rare signals can be generated using the interface to external generators or simple parameterizations of transverse momentum and rapidity spectra, defined in independent libraries.
2.3.2.2 Detector response

To simulate the detector response, particles generated by a Monte Carlo generator have to be transported in the materials of the detector simulating their interaction and the energy deposition that generates the detector response, ideal and real as explained before.

Three transport Monte Carlo packages exist to simulate the detector response: GEANT 3 [34], GEANT 4 [35] and FLUKA [36]. They have a very different user interface to define signals and geometry. Virtual interfaces have been developed to use them for the simulation of the ALICE geometry within the AliRoot framework. In addition, their native geometry modellers have been replaced by TGeo, the geometry modeller provided by ROOT. Therefore it is enough to instantiate the appropriate class in the simulation configuration file to simulate ALICE with any of these three codes. The ALICE detector is described in the simulation in great detail, including services and support structures, absorbers, beam pipe, flanges and pumps.

2.3.2.3 Reconstruction

The reconstruction code has a modular design that allows it to be compiled into separate libraries and executed independently of the other parts of AliRoot. The input consists of the digits together with some additional information like for example module number, readout channel number. The reconstruction can use both digits in special ROOT format (for development and debugging purposes) and digits in the form of RAW DATA, as they are produced by the real detectors or by special-format output of the simulation: a schematic view of the interplay between the reconstruction and the rest of Aliroot is illustrated in Fig. 2.13.

The output of the reconstruction is stored in the Event Summary Data (ESD) and contains the reconstructed charged-particle tracks together with the particle

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identification information, the reconstructed primary vertex, decays and $V^0$, kink and cascade topologies and particles reconstructed in the calorimeters.

**AliReconstruction** is the main steering reconstruction class: it provides the user with a simple interface to configure reconstruction procedure, include or exclude a detector from the run and ensure the correct sequence of the reconstruction steps (local reconstruction for each detector, primary vertex reconstruction, track reconstruction and particle identification and secondary vertex reconstruction).
2.3.3 Data analysis

2.3.3.1 Tools for distributed analysis

The computing resources required to store, reconstruct and analyse the present and foreseen amount of data (both real and simulated) is such that they cannot be concentrated in a single computing centre. Therefore data processing and storage is distributed onto several computing centres located worldwide. The Grid middleware allows treatment of these heterogeneous collection of resources as an integrated computing centre. This is one of the main areas in which the ALICE Offline Project operates.

2.3.3.1.1 The Parallel ROOT Facility

PROOF (Parallel ROOT Facility) allows interactive parallel analysis on a local cluster to process large amounts of data minimizing the response time. Interactive means that users can see the results without waiting for the job to finish; parallel means that several nodes process subsets of data at the same time. PROOF itself is not related to Grid but can be used in the Grid. Using PROOF is aimed to be transparent, so users can execute the same analysis code locally and on a PROOF system, provided they follow certain rules.

The CERN Analysis Facility (CAF) is a cluster at CERN running PROOF for ALICE. Simulated data and measured data are available on the CAF. It can be used to perform analysis (p-p data, pilot analysis on Pb-Pb data), calibration and alignment (both for p-p and Pb-Pb) during the day and as a batch queue to run Grid jobs during the night. The aim of the CAF is conceptually different from analysis on the Grid: due to the limited disk space not all data taken by ALICE will be accessible on the CAF, however it gives much faster feedback than the Grid, thus allowing very fast development cycles. This is crucial to analyse the first real data for an early and prompt discovery of important features of data. The design goal for the CAF is a
system with 500 CPUs. At least 50 TB of selected data will be available. The CAF will also interface with the CERN Castor 2 disk cache to retrieve raw data or ESDs selected for analysis.

2.3.3.1.2 AliEn interface to the Grid The ALICE interface to the Grid is AliEn (Alice Environment) [37]. This framework has been developed to offer the ALICE user community a simplified and transparent but functional access to the computing resources distributed worldwide through a single interface, shielding the user from the underlying complexity and heterogeneity of the Grid world. The AliEn system is built around common Open Source components and on top of the latest Internet standards for information exchange and authentication. AliEn provides a virtual file catalogue that allows transparent access to distributed data sets and a number of collaborating Web services which implement the authentication, job execution, file transport, performance monitor and event logging. A detailed description of the architecture and the components of the AliEn system can be found in [38]. It has been tested in productions for several years, showing its capability to implement the ALICE Computing Model for simulation and reconstruction described in [28]. The AliEn capability to run analysis has been being exercised and is now the part of the more rapidly evolving framework.

2.3.3.1.3 Organization of data analysis Analysis is the last step performed on data to extract physics results. In the ALICE computing model the analysis starts from the Event Summary Data (ESD), where the output of the reconstruction process is stored and its size is about one order of magnitude lower than the corresponding raw data. Analysis performed on the ESD produces Analysis Object Data (AOD). Further analysis steps can start from condensed AODs.

Analyses can be scheduled (or ordered) or chaotic. Scheduled analysis will be
performed in a way that is sometimes indicated as “freight train”. The ALICE
generic analysis framework attaches a number of official algorithms and carries them
through data. The advantage is that each event is read only once and the different
algorithms are applied to it. This kind of scheduled analysis has a predictable resource
consumption and data access pattern as opposed to chaotic analysis. Chaotic analysis
is usually performed during the phase of development and testing of the code, on
local systems with a limited amount of data and then, once it has been finalized,
submitted to the Grid or on local clusters running PROOF on a larger amount of data.
In the ALICE offline framework, a general analysis framework has been developed:
AliAnalysis. Its scheme has to be employed by users to perform scheduled and
chaotic analyses. It has been developed such as the user code is independent of the
computing system used (local, PROOF, Grid). It also allows Monte Carlo truth to
be used for acceptance and efficiency correction studies and calculation.
Chapter 3

Global observables and event characterization

3.1 Introduction

The event characterization aims to investigate and understand the dynamics of the collision and the way the initial centre-of-mass energy is redistributed in the accessible phase space. Indeed it allows the validity of models for particle production to be tested comparing their predictions to measured values and to place important constraints on fundamental properties of particle production. It requires the study of a number of global observables of the final state, such as the charged-particle multiplicity, the charged-particle pseudorapidity density and the transverse momentum. These observables can be measured in the early phase of data taking and do not require particle identification.

In nucleus–nucleus collisions the event characterization is based on the determination of the initial geometry of the collision, i.e. estimation of the centrality of the collision, which is an essential prerequisite to study any other physical observable.
Global event properties in p-p(\overline{p}) collisions have been studied at collider experiments at CERN and Fermilab over about two orders of magnitudes, from \( \sqrt{s} = 23.6 \) GeV to 1.8 TeV. Concerning nucleus–nucleus collisions, at CERN (fixed target experiments) and Brookhaven National Laboratory (both collider and fixed target experiments) the study of global variables has been performed up to a maximum energy of \( \sqrt{s_{NN}} = 200 \) GeV.

At LHC, the ALICE experiment, with the features of soft-particle designed detector, even though design for heavy-ion physics, will be very effective in the study of global properties of minimum-bias p-p events as well. The energy domain accessible at LHC will be extended by about one order of magnitude compared to the highest energy reached so far. A large transverse momentum range will be covered, ALICE being sensitive to very low \( p_t \) (from about 100 MeV/c up to 100 GeV/c).

In this chapter, the most relevant global observables for the event characterization will be reviewed: existing measurements from collider experiments will be recalled and the expected techniques and performances for ALICE will be described. Particle multiplicity, centrality and transverse momentum will be discussed.

### 3.2 Hadron and heavy-ion colliders before LHC

In this section the colliders, whose results will be used in the following paragraphs, will be listed with some of their detector facilities.

The Intersecting Storage Ring (ISR), built at CERN, has been the first hadron collider in the world, operating from January 1971 for 13 years. It had a diameter of 300 m and accelerated beams with a maximum centre-of-mass energy of 63 GeV. The ISR later produced the first proton–antiproton collisions in 1981, followed by the Super Proton Synchrotron (SPS). The main detector at ISR was the Split-Field-Magnet detector.
The CERN Super Proton Synchrotron (SPS) was conceived as a proton accelerator with a beam energy of 300 GeV providing beams to two large experimental areas (North Area and West Area). Its circumference is about 7 km. It was operated first in 1976 and later, from 1981 to 1984, it was made running as a two-beam proton–antiproton collider (and at that time called SppS): its beams provided data for the UA1 and UA2 experiments, which resulted in the discovery of the W and Z bosons (Nobel Prize for Rubbia and van der Meer in 1984). The SPS has been used to accelerate protons and antiprotons, electrons and positrons (injector for the Large Electron–Positron Collider, LEP), and heavy ions. It operates now at 450 GeV beam energy as the last part of the accelerator chain that provides beams to the LHC. One of the main detectors at the SppS was UA5 (Underground Area 5). It was dedicated to the study of soft inelastic processes. It took data also in a test run at the ISR: data in a wide range of the centre-of-mass energy from 53 to 900 GeV are available. It was a multiparticle detector, based on two large and very long (6 m long) streamer chambers placed below and above the beam pipe. The chambers were triggered by two sets of scintillation hodoscopes placed at each end of the streamer chambers themselves. Each chamber was viewed by three cameras, recording stereoscopic pairs of views which allowed a three-dimensional reconstruction of the events. Charged tracks were observed down to 3-4°, and hence over most of the pseudorapidity range $|\eta| < 5.0$, resulting in a wide range of pseudorapidity coverage.

The Tevatron, built at Fermi National Accelerator Laboratory (Fermilab, Illinois), is the second most powerful proton–antiproton collider in the world after the LHC. The Tevatron is a synchrotron that accelerates protons and antiprotons in a 6.4 km ring to energies of up to 1 TeV, hence the name. The Tevatron operated first in 1983. Two main detector facilities collect data at Tevatron: the Collider Detector at Fermilab (CDF) and D0.

At the Brookhaven National Laboratory (BNL, Long Island, New York) the first
machine in the world capable of colliding heavy ions has been built: the Relativistic Heavy Ion collider (RHIC). It is 3.8 km long in circumference and has been taking data successfully since 2000, mainly Au-Au collisions at $\sqrt{s} = 200$ GeV, complemented by data collected at lower energies and with lighter nuclei. The aim is to study the QGP properties and the structure of protons as well. The six interaction points are at the middle of the six relatively straight sections, where the two rings cross: the four intersection points currently in use host the detector facilities for the STAR, PHENIX, PHOBOS, and BRAHMS experiments, while two interaction points are unused and left for further expansion. The main colliding systems at RHIC are p-p, d-Au, Cu-Cu and Au-Au. For p-p collision, the latest run achieved a centre-of-mass energy of 500 GeV in February 2009.

### 3.3 Centrality determination in A-A collisions

The first parameter to be determined in nucleus–nucleus collisions is the centrality. Estimating the centrality, results of measurements from various experiments can be compared and studies of the dependence of some variables from the centrality can be carried out. In addition, provided there is a signal sensitive to centrality, it can help to locate the onset of the phase transition (for example strangeness enhancement and $J/\Psi$ suppression).

The centrality of a nucleus–nucleus collision is defined according to the value of the impact parameter and provides a geometrical scale of the overlapping region between the colliding nuclei: a collision will be defined from central to peripheral, as the impact parameter increases. The collision centrality relates to geometrical quantities such as the number of participant nucleons $N_{part}$\(^1\) and the number of binary collisions between two nucleons $N_{coll}$. It is not directly available and must be deduced from a

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\(^{1}\)The number of participants $N_{part}$ (sometimes called wounded nucleons) is defined as the number of nucleons in the target and projectile which have at least one inelastic collision.
combination of experimentally measured quantities and Monte Carlo simulations.

There are a number of centrality estimators that can be measured. The charged-particle multiplicity $N_{ch}$ and the transverse energy $E_t$ measured around mid-rapidity are the measurable quantities related to the energy deposited in the interaction region; therefore these are related to $N_{part}$. These variables increase significantly increasing the centrality of the collisions. Another measurable quantity to estimate the centrality is the zero-degree energy $E_{ZDC}$, namely the energy carried by spectator nucleons $N_{spec} = E_{ZDC}/E_A = A - N_{part}$, $E_A$ being the beam energy per nucleon. It has been shown that the measurement of projectile spectators in a ZDC is well correlated with the other centrality estimators mentioned above. Both techniques have been successfully adopted by several SPS heavy-ion experiments (examples can be found in [39, 40]). For an accurate determination of the centrality of the collision through the measurement of these estimators, the detector-related effects have to be taken into account.

The approach to calculate the centrality of the collision from measured quantities can be either using the Glauber model or an event generator to simulate the experimental spectra as a function of the impact parameter.

The Glauber model [41, 42] uses a semi-classical approach: the nucleus–nucleus collision is assumed to be the incoherent superimposition of $N$ elementary nucleon–nucleon collisions. The main parameters of the model are the inelastic nucleon–nucleon collision cross-section $\sigma_n$ and the nuclear density distribution $\rho(r)$. The model gives the relation between the impact parameter $b$ and the number of participants $N_{part}$ (or $N_{coll}$) (Fig. 3.1) and allows $d\sigma/db$ and $d\sigma/dN_{part}$ to be estimated. The relation between $N_{part}$ and any of the measurable quantities $E_{ZDC}$, $E_t$, $N_{ch}$ being known, the $d\sigma/dE_{ZDC}$, $d\sigma/dE_t$ and $d\sigma/dN_{ch}$ can be calculated. These calculated distributions can then be compared to the measured distributions which are usually well reproduced. In practice, the measured distributions are often fitted
with analytical functions of $N_{\text{part}}$. The experimental distribution can be divided in classes with sharp cuts on $E_{ZDC}$, $E_t$, $N_{ch}$, which will correspond to well defined intervals of centrality. The number of classes that can be defined depends on the resolution achievable on that variable. The Glauber model can be implemented in Monte Carlo simulations.

![Glauber Monte Carlo simulations of geometrical quantities for Au-Au collisions at the highest RHIC energy: $N_{\text{part}}$ and $N_{col}$ as a function of the impact parameter.](image)

Figure 3.1: Glauber Monte Carlo simulations of geometrical quantities for Au-Au collisions at the highest RHIC energy: $N_{\text{part}}$ and $N_{\text{col}}$ as a function of the impact parameter.

In ALICE both multiplicity and forward energy will be measured. If the particle production mechanism is soft, the relation between $N_{\text{part}}$ and $N_{ch}$ is linear. This is valid up to SPS energies but not at LHC energies since the production mechanism around mid-rapidity will probably be dominated by hard processes, which scale with the number of nucleon–nucleon collisions $N_{\text{coll}}$. This change of behaviour has already been observed at RHIC energies [43]. The zero-degree energy is not affected by the onset of hard processes, but its measurement has the disadvantage that some spectators will be bound into fragments escaping from detection, leading to a non-linear relation between $E_{ZDC}$ and $N_{\text{part}}$, that exhibits two branches (left panel.
of Fig. 3.2). If another quantity with a monotonic relation with $N_{\text{part}}$ can be correlated to $E_{\text{ZDC}}$, different classes of events, corresponding to given fractions of the total Pb-Pb cross-section, can be defined along this correlation. The $N_{\text{part}}$ range corresponding to such fractions can be calculated using either the Glauber model or an event generator.

In [44] two different methods to determine either $N_{\text{part}}$ or $b$ are described. One method relies on HIJING simulations and the combination of the information from the energy measured in the two hadronic calorimeters and the energy measured in the electromagnetic calorimeters. The information from the forward electromagnetic calorimeters (ZEMs), described in Chapter 2, removes the ambiguity due to the two branches in the $E_{\text{ZDC}}$-$N_{\text{spec}}$ correlation: indeed there is a monotonic correlation between the number of spectators and the energy detected in the ZEMs (right panel of Fig. 3.2). The value of $E_{\text{ZEM}}$, corresponding to $N_{\text{spec}}$, where the two branches in the $E_{\text{ZDC}}$-$N_{\text{spec}}$ correlation meet, can be calculated and can be set as a threshold for discriminating between the two branches at fixed $E_{\text{ZDC}}$. Sharp cuts on the generated
impact parameter or on the generated $N_{\text{part}}$ are set to define centrality classes for the generated events. The corresponding cuts in the reconstructed variables can then be easily obtained. It has been verified that this method does not introduce any significant bias in the centrality determination and the overlap between adjacent centrality classes is rather limited both using $N_{\text{part}}$ and $b$. The other method is based on measured quantities only, that is the correlation between $E_{ZDC}$ and $E_{ZEM}$. Centrality classes are defined by means of cuts perpendicular to the $E_{ZDC}$ versus $E_{ZEM}$ (Fig. 3.3) correlations so that these correspond to well-defined fractions of the inelastic nucleus–nucleus cross-section.

RHIC experiments measure the centrality on the basis of either the total charged-particle multiplicity or the zero-degree energy [45].
3.3.1 Centrality determination from multiplicity

The charged-particle multiplicity at mid-rapidity can be used to determine the centrality of the event and to estimate the number of participants defined as the number of wounded nucleons [46], i.e. nucleons suffering at least one primary inelastic collision. The procedure to extract the average number of wounded nucleons is based on a best fit of the multiplicity distribution with a generalized Wounded Nucleon Model, where $N_{ch}$ is assumed to be proportional to a power of the number of wounded nucleons, i.e. $\langle N_{ch} \rangle \propto N_{wound}^\alpha$. The number of wounded nucleons is estimated from a geometrical (Glauber) model of the A-A collisions. The method has been applied for example by the WA97 and NA57 heavy-ion experiments at SPS, as described in [47] and illustrated in Fig. 3.4.

![NA57 definition of centrality classes based on multiplicity measurement. Left panel: multiplicity distribution of charged particles measured in Pb-Pb collisions at 158 A GeV/c where five centrality classes are defined. Right panel: distributions of $N_{part}$ for the five centrality classes.](image)

3.4 Charged-particle multiplicity

The multiplicity of charged particles produced in an interaction is the most fundamental and basic measurement for the event characterization and features in
the calculation of many other observables. Multiplicity related measurements are important since they allow models that describe particle production, which are the basis of Monte Carlo generators, to be constrained. These models are based on QCD but, the production mechanisms being dominated by soft processes, a phenomenological approach is also used.

The two observables related to the multiplicity are the pseudorapidity density distribution of primary charged particles and the multiplicity distribution. The pseudorapidity \( \eta \) is a variable related to the polar angle \( \theta \) with respect to the beam axis with which a particle is emitted from the interaction vertex. The pseudorapidity can also be expressed as a function of the momentum

\[
\eta = -\ln[\tan(\theta/2)] = (1/2) \ln[p + p_l/(p - p_l)]
\]

(3.1)

where \( p \) and \( p_l \) are the total momentum and longitudinal momentum of the emitted particle respectively. It is easier to measure than the rapidity \( y \)

\[
y = (1/2) \ln[(E + p_l)/(E - p_l)]
\]

(3.2)

since it does not require particle identification and momentum measurements. The pseudorapidity density distribution of primary charged particles is the average number of primary charged particles produced in an interaction per pseudorapidity unit \( (dN_{ch}/d\eta) \). The multiplicity distribution represents the probability distribution \( P(n) \) to have an interaction in which \( n \) primary charged particles have been produced. The measured multiplicity can be limited to a certain range of pseudorapidity according to the coverage of the detector used. The multiplicity related observables cannot be derived in any way from the QCD Lagrangian since the dominant processes are soft non-perturbative interactions for which the strong coupling constant is large and perturbative methods are difficult to apply.

When measuring the total multiplicity of charged particles, its distribution in pseudorapidity space and, for nucleus–nucleus interaction, its dependence on collision
centrality and energy, important information about the collision can be obtained: the redistribution of the incoming energy into particle production and kinetic energy can be studied.

Measurements of multiplicity in hadron interactions are usually reported for inelastic interactions and/or for the subsample of non single-diffractive interactions. Indeed, inelastic interactions are usually classified as diffractive and non-diffractive. In the theoretical context, diffraction means that the initial and final states in the scattering process have the same quantum numbers. The traditional theoretical framework for diffraction [48] is the Regge theory, that describes hadronic reactions at high energies in terms of the exchange of objects called Regge trajectories or “Reggeons”; the Reggeon with vacuum quantum numbers, which dominates in diffractive processes, is the so-called Pomeron. Diffractive processes are generally classified as single-diffractive and double-diffractive, in which one or two Pomerons are exchanged: one or both incident hadrons are excited and form a system of particles that carries the same quantum numbers of the incident hadron. Diffractive reactions are characterized by a large rapidity gap in the final state. Single-diffractive events are asymmetric since particles are produced at high rapidity from the break-up of one of the colliding hadrons only on one side, while the other colliding hadron is found at a rapidity close to that of the beam. In double-diffractive interactions there are particles at high rapidities, both positive and negative, produced in the break-up of the two colliding hadrons. In non-diffractive events the two incident hadrons break apart and no rapidity gap is observed. The event class to which the measurement is referred is determined by the trigger efficiency of the experiment in selecting a certain event class. The UA5 experiment, for example, was able to separate the contribution of double-diffractive events using a “2-arm” trigger (requiring two hits in the counters at both ends of the detector in coincidence with a beam crossing) to select mainly non single-diffractive events and a “1-arm trigger” (requiring a hit in
one set only of the two trigger counters) to select highly asymmetric events, such as single-diffractive events. ALICE will not be able to distinguish the physics processes event-by-event but different trigger algorithms that maximize the overall efficiency in selecting inelastic and non single-diffractive events can be defined combining signals from several detectors (forward and central detectors).

In the following a review of the main theoretical concepts related to multiplicity and physics motivations to measure and study multiplicity, in particular as a function of the centre-of-mass energy and centrality for nucleus–nucleus interactions, will be presented together with the main results and conclusions from previous experiments, both in p-p and in A-A interactions.

### 3.4.1 The multiplicity distribution

The multiplicity distribution would be described by a Poisson distribution, if the mechanisms of particle production were uncorrelated. As the measured distributions do not follow such a distribution there are correlations in the production of primary particles.

Several attempts have been made to reproduce the shape of the measured multiplicity distributions at different centre-of-mass energies using analytical expressions and requiring scaling properties or varying parameters as a function of $\sqrt{s}$.

In 1972 the Koba-Nielsen-Olesen scaling was introduced [49] and was found to be a useful phenomenological framework to describe and predict the multiplicity distributions in hadron interactions at a given energy. It is based on the Feynman scaling (which will be described in the next section). The original formulation of KNO scaling states that at asymptotic energies the following relation holds:

$$P_n = \frac{1}{\langle n \rangle} \Psi \left( \frac{n}{\langle n \rangle} \right)$$  \hspace{1cm} (3.3)
\[ \langle n \rangle = \sum_n n P_n \]

where \( n \) is the number of particles produced in an inelastic interactions, \( P_n \) is the probability of producing \( n \) particles in a final state, and \( \Psi \) is an universal energy-independent function. This means that multiplicity distributions at all energies must fall onto the same curve when plotted as a function of \( n/\langle n \rangle \):

\[ \Psi \left( \frac{n}{\langle n \rangle} \right) = \langle n \rangle P_n(n/\langle n \rangle) \quad (3.4) \]

The function \( \Psi(n/\langle n \rangle) \) can be different according to the type of reaction and to the type of measured particles. The KNO scaling validity can be tested examining the energy dependence of the moments of the distribution. Exact KNO scaling would indeed yield constant values for the normalized standard moments

\[ C_k = \frac{\langle n^k \rangle}{\langle n \rangle^k} \quad (3.5) \]

and for the \( D_2/\langle n \rangle \), where \( D_2 \) is the dispersion and the D-moments are defined as

\[ D_k = \langle (n - \langle n \rangle)^k \rangle^{1/k} \quad (3.6) \]

However, it turned out that the multiplicity distribution follows a universal function only approximately [50] with the consequence that the normalized factorial moments

\[ F_k = \frac{\langle n(n-1)...(n-k+1) \rangle^k}{\langle n \rangle^k} \quad (3.7) \]

are required to be constant instead of the standard ones. Indeed, there was never a perfect agreement in comparing data to KNO predictions, in particular at \( \sqrt{s} = 900 \) GeV and higher energies, and the shape of the scaling function had to be changed considerably with the energy in order to obtain the best fit to the data. A great effort was undertaken to generalize the KNO scaling or to find a way of enabling description of the multiplicity data in a full energy range by a single scaling function.
A single Negative Binomial Distribution (NBD) was found to describe fairly well the overall features of the measured multiplicity distributions of hadrons, first in cosmic rays observations in the sixties [51] and later confirmed in p-p collisions (see next paragraph), as well as in other types of interactions (p-p, p-\(\bar{p}\), e\(^+\)-e\(^-\), A-A), in different ranges of rapidity and in a wide interval of energies. The NBD

\[
P(n; \langle n \rangle, k) = \binom{n + k - 1}{k - 1} \left( \frac{\langle n \rangle / k}{1 + \langle n \rangle / k} \right)^n \frac{1}{(1 + \langle n \rangle / k)^k}
\]

(3.8)

has two energy dependent parameters: \(\langle n \rangle\) and \(k\) that increase and decrease with the centre-of-mass energy respectively. The parameter \(k\) determines the width of the distribution and measures the deviation of the variance from the Poisson shape

\[
1/k + 1/\langle n \rangle = D^2_{\text{2}}/\langle n \rangle^2
\]

(3.9)

that reduces to a Poisson distribution for \(k \rightarrow \infty\).

With higher energy data, a shoulder structure in the multiplicity distribution appeared that could not be reproduced with a single NBD. Combinations of two or more NBDs have provided a useful parameterization of multiplicity distributions in p-p(\(\bar{p}\)) collisions, as well as in various other systems, including e\(^+\)-e\(^-\), \(\mu-p\) and central nucleus–nucleus collisions. This parameterization explains the shape of the distribution in a multi-component scenario, by assuming that particle production has an increased contribution from hard processes (jets and minijets production) with increasing energy. Multiplicity distributions are fitted to a weighted superimposition of NBDs corresponding to different classes of events (soft and semi-hard).

3.4.1.1 Physics motivations

In p-p collisions the shape of the inclusive multiplicity distribution can hint at transition from perturbative to non-perturbative regimes. Analysing the moments of the distribution can point out patterns and correlations in the final state.
Measurements of the multiplicity distribution in p-p collisions have been carried out at ISR up to $\sqrt{s} = 63$ GeV finding that the KNO scaling is fulfilled. At ISR multiplicity distributions have been measured in full phase space at four energies $\sqrt{s} = 30.4$, 44.5, 52.6 and 62.2 GeV with the SFM detector [52]. Studying the moments of the distribution the conclusions are as follows:

- the energy dependence of the mean multiplicity can be described by a polynomial of second order in $\ln s$ and the simple dependence in $\ln s$ is excluded;

- the KNO scaling holds only for non single-diffractive events (Fig. 3.5).

At energies higher than the ISR energies KNO scaling is violated: this was first shown in p-$\overline{p}$ data from the UA5 experiment at $\sqrt{s} = 540$ GeV [53, 54] (Fig. 3.6) and
Figure 3.6: Multiplicity distributions in the KNO scaling variable \( n/\langle n \rangle \): UA5 data \( (\sqrt{s} = 540 \text{ GeV}) \) compared to data from ISR \( (\sqrt{s} = 64 \text{ GeV}) \) and to Fermilab data at lower energy \( (\sqrt{s} = 10 \text{ GeV}) \).

then later confirmed with measurements at \( \sqrt{s} = 200 \) and 900 GeV [55].

The NBD parameterization was found to well describe data up to \( \sqrt{s} = 540 \) GeV [54] and also ISR data at lower energy. The empirical formulas found for the NBD confirm a polynomial of second order in \( \ln s \) for the mean multiplicity dependence on the centre-of-mass energy.

However deviations were found at \( \sqrt{s} = 900 \) GeV where the distribution exhibits a shoulder structure (Fig. 3.7) [55]. The two-component approach was introduced and explained in terms of the weighted superposition of different classes of events: events with and without mini-jets (called semi-hard and soft, respectively) [56, 57]. This parameterization has also been used to extrapolate the multiplicity distribution in the TeV energy domain covered by Tevatron and LHC: the soft component satisfies KNO scaling, while the semi-hard one violates it strongly. These predictions are in agreement with Tevatron data at \( \sqrt{s} = 1.8 \) TeV from the CDF and the E735 experiments: it was found that by subdividing the CDF minimum-bias sample into
two groups, characterized respectively by the absence or the presence of minijets, the soft component satisfies KNO scaling while the hard one does not [58] (Fig. 3.8).

As already stated, in the new energy domain of LHC this measurement will allow models for particle production based on wrong assumption to be rejected, improving the understanding in particle production mechanism. Several predictions exist, based on different models, that agree at low energy and not at the LHC energy. Extrapolations to high energy of the mean multiplicity and to full phase space for distributions measured in limited rapidity intervals in p-p collisions are quite uncertain and affected by rather big inaccuracies.

3.4.2 Pseudorapidity density distribution

A simple scaling law in hadron interactions for the $\sqrt{s}$ dependence of the average charged-particle multiplicity at mid-rapidity was derived by Feynman in 1969, based on the assumption that the function $f_s(p_t, p_l/(\sqrt{s}/2))$ describing the distribution of particles, is independent of the collision energy at high energy. This scaling function
can be used to write the invariant cross-section. The assumption is known as Feynman scaling [59]. This leads to predict a logarithmic increase of the average particle multiplicity with $\sqrt{s}$

$$\langle N_{ch} \rangle \propto \ln \sqrt{s}$$  \hspace{1cm} (3.10)

Since the maximum rapidity in a collision increases with $\ln \sqrt{s}$, it follows that the rapidity density $dN/dy$ is constant, so the height of the flat region of the distribution around mid-rapidity, called plateau, does not depend on the energy. Considering the relation between the rapidity and the pseudorapidity, that depends on $m_t = \sqrt{m^2 + p_t^2}$, only a weak dependence on the energy is introduced and a dip in the distribution appears at $\eta \approx 0$. It can be concluded that the pseudorapidity density at $\eta = 0$ is approximately constant.

However, the best fit to p-p and p-Pb data for the $dN_{ch}/d\eta$ at $\eta \approx 0$ and for $\langle N_{ch} \rangle$ is given by a quadratic polynomial in $\ln s$, suggesting that the Feynman scaling was only approximately valid (see next section for experimental evidence).
The energy dependence of the charged-particle density in hadronic interactions can be obtained within the framework of models for soft interactions, like for example those from the large class of string models (Dual Parton Model [60], Quark–Gluon String Model [61]), based on Regge theory and the parton structure of hadrons. These models relate the energy dependence of the total cross section to that of the multiplicity production using a small number of parameters, and are the basis for several Monte Carlo event generators describing soft hadron collisions [33, 62, 63]. The Quark–Gluon String Model (QGSM) is a phenomenological model that makes use of very few parameters and gives a very good description of many aspects of high-energy hadronic interactions, such as diffractive processes, multiplicity distributions, correlations and inclusive spectra of different particles in a broad energy region. In this model, the total cross-section \( \frac{d\sigma_{ch}}{d\eta} \) increases at very high energies and at \( \eta \approx 0 \) as a power-law \( \approx (s/s_0)^\Delta \), where \( s_0 = 1 \text{ GeV}^2 \) and \( \Delta = \alpha_P - 1 \), \( \alpha_P \) being the intercept of the Pomeron Regge trajectory. Indeed, with the value \( \Delta = 0.12 \pm 0.02 \) [64] obtained from the analysis of \( \sigma^{tot}(s) \), the QGSM model successfully reproduces the observed growth of pseudorapidity distributions with energy [65]. Furthermore, the increase with energy of the charged-particle density, as well as the bulk properties of minimum-bias events and of the underlying events in hard processes, are successfully reproduced (up to Tevatron energy) by models that assume the occurrence of multiple parton interactions in the same p-p collision. Such models, extending the QCD perturbative picture to the soft regime, are implemented in the general purpose Monte Carlo programmes, e. g. PYTHIA which contains several parameters that must be tuned to reproduce experimental data.

In nucleus–nucleus collisions, combining perturbative QCD with the idea of parton saturation in the Gluon Saturation Model [66, 67], the multiplicity production and its dependence on centrality and centre-of-mass energy can be calculated: a theoretical interpretation of experimental data and predictions can be made in this framework.
It has been found to well describe RHIC data [67] and in particular the multiplicity dependence on centrality. That suggests that high density QCD effects play a relevant role in determining the global characteristics of events at RHIC energies.

The pseudorapidity density distribution of charged particles has a nearly flat region near mid-rapidity followed by an almost linear fall-off region toward larger values of $|\eta|$. In Fig. 3.9 an example of $dN_{ch}/d\eta$ distribution is shown, measured in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHOBOS experiment.

Particles emitted in the angular region $45^\circ < \theta < 135^\circ$ corresponding to $|\eta| < 0.88$ are most likely to represent a thermalized region of phase space, so the height of the mid-rapidity plateau is a relevant value. Actually, however, the angular distribution of the produced primary charged particles is far from being isotropic, having a minimum at $\theta = 90^\circ$ and being very forward peaked.

The fall-off region of the $dN_{ch}/d\eta$ corresponds to the fragmentation region of the colliding nuclei where particles with $p_t \gg p_l$ are produced at angles $\theta \approx 0^\circ$ and $180^\circ$.

Figure 3.9: Distributions for charged particles measured in 0-6 % central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV by PHOBOS. The shaded regions indicate the angular region where the transverse momentum $p_t$ exceeds the longitudinal momentum $p_l$. Panel a: $dN_{ch}/d\eta$ distribution. Panel b: $dN_{ch}/d\theta$ distribution. Panel c: $dN_{ch}/d\Omega$ distribution.
At mid-rapidity the $dN_{ch}/d\eta$ depends on the centre-of-mass energy and, in nucleus–nucleus collisions, on centrality. To study the dependence on centrality the following variables are introduced:

$$\frac{dN_{ch}(\eta = 0)/d\eta}{N_{part}/2} \quad (3.11)$$

$$\frac{N_{ch}}{N_{part}/2}$$

that are the pseudorapidity density at mid-rapidity and the total multiplicity per participant pairs. These variables are useful to verify the validity of scaling properties with $N_{part}$, since if the number of produced particles scales with $N_{part}$, these variables should be constant as a function of centrality. In addition, the comparison with results in p-p interaction, where $N_{part} = 2$, is more straightforward.

### 3.4.2.1 Physics motivations

The pseudorapidity density at mid-rapidity has traditionally been among the first measurements performed by all experiments exploring a new energy domain. The measurement of the pseudorapidity density distribution is important since it gives general indications on the interplay between hard and soft processes in the overall particle production mechanisms. For example the relative contribution of hard parton–parton scattering processes, governed by perturbative QCD, and soft processes, that can be described using phenomenological non-perturbative approaches, can be estimated. In the central pseudorapidity region the hadroproduction mechanism dominates, while in the forward region the effects of the fragmentation of the projectile and target can be studied. Furthermore determining the $\sqrt{s}$ dependence of charged-particle pseudorapidity density is also important since it allows particle-production models to be constrained and to tune the Monte Carlo generators based on these models as well, as already pointed out.
Indeed the various models provide estimates of the pseudorapidity density produced at the LHC energies that are widely different.

In nucleus–nucleus collisions in particular, the pseudorapidity density also reflects the properties of the hot and dense system formed in the overlap region between the two incoming nuclei. Even without more detailed and differential measurements of the emitted particles, important information about the collisions can be obtained: it is related to the energy density attained in the first stage of a collision. Bjorken proposed a method to calculate the energy density from the density of charged particles produced at mid-rapidity [68], based on the total energy of particles emitted at mid-rapidity

$$\varepsilon_{Bj} = \frac{\langle m_t \rangle}{S \tau_0} \left( \frac{dN_{ch}}{dy} \right)_{y=0}$$

(3.12)

where $\langle m_t \rangle$ is the average transverse mass of the produced particles, $S$ is the transverse overlapping area in the collision of the two nuclei, $\tau_0$ is the proper time, which can be estimated around 1 fm/c. For example, at RHIC energies, using this relation and values measured by the BRAHMS and PHOBOS experiment [69], an energy density of $\varepsilon_0 \approx 5$ GeV/fm$^3$ is found, which is well above the predicted threshold for the phase transition obtained from lattice QCD calculations ($\varepsilon_0 \approx 0.7-1.0$ GeV/fm$^3$). Having $\langle m_t \rangle = 0.57$ GeV, much of the available energy is carried off by particles emitted in forward-backward directions associated with lower energy density, which gives rise to pseudorapidity distributions that are substantially broader than expected for an isotropic source. The pseudorapidity distribution is therefore intimately connected to the energy density of the emitting source and provides an important input for validating theoretical models attempting to describe the conditions in the early phases of the collision.

The characteristics of the shape of the $dN_{ch}/d\eta$ distribution for different values of the energy and the centrality of heavy-ion collisions can be observed in Fig. 3.10 where results from the PHOBOS experiment are shown and can be summarized as
Figure 3.10: $dN_{ch}/d\eta$ distributions measured by PHOBOS (solid and open points) for five centrality bins representing the 45% of the total cross section for $\sqrt{s_{NN}} = 19.6$ GeV Au-Au collisions and for six centrality bins for $\sqrt{s_{NN}} = 130$ and 200 GeV corresponding to the 55% of the cross section. The shaded bands represent the estimated systematic errors.

follows:

- the width and the height of the mid-rapidity plateau increase with the centre-of-mass energy;

- the extent of the fall-off regions increases with energy, but the slope is almost independent of the energy, due to limiting fragmentation scaling [70] (behaviour observed first in p-\bar{p} collisions [71]);

- the height of the plateau increases with centrality.

Similar results at $\sqrt{s_{NN}} = 130$ and 200 GeV have been obtained by the BRAHMS collaboration [72, 73]. Quantitatively, increasing the collision energy by an order of magnitude results in only a factor two in the mid-rapidity height of the plateau. This can be explained considering that the energy of particles has the $\eta$ dependence $E = \sqrt{m_0^2 + p_t^2 \cosh^2 \eta}$. This means that a particle with a certain $p_t$, emitted with an $\eta$ value at the half maximum of the distributions at the two energies, will have
higher energy for $\sqrt{s_{NN}} = 200$ GeV. So the additional energy is mostly consumed in increasing the width of the plateau. Calculations in the Gluon Saturation Model framework satisfactorily reproduce the measured distributions.

As for the energy dependence of the $dN_{ch}/d\eta$ at mid-rapidity for participant pair, using RICH data and measurements at fixed target experiments at AGS and SPS, a roughly logarithmic increase with collisions energy is found. In Fig. 3.11 these data points are shown together with the grey bars representing the models predictions prior to 2000; most of them significantly differ from the measured value at RHIC. After the measurements at RHIC these models have been strongly revised and others discarded. Even though none of the present models reproduced this dependence, consistency with the trend of the Gluon Saturation Model above $\sqrt{s_{NN}} = 20$ GeV is
observed (Fig. 3.12). In addition, in Fig. 3.12 it can be observed that the trend of this dependency is different in p-p(\(\overline{p}\)) collisions and the particle production in heavy-ion collisions (solid symbols) is substantially higher than in p-p [74] or p-\(\overline{p}\) [71, 75] collisions (open symbols) when normalized to colliding nucleon–nucleon pairs. The same can be concluded for the total multiplicity per participant pair. One possible interpretation of this difference is that a large fraction (\(\sim 50\%\)) of the available energy is carried off by leading hadrons in p-p and p-\(\overline{p}\) collisions, whereas this effect is absent in heavy-ion collisions because these hadrons suffer subsequent collisions leading to particle production in the heavy-ion collision environment [76].

The expected values from extrapolations at \(\sqrt{s_{NN}} = 5.5\) TeV for the \(dN_{ch}/d\eta\) plateau level range from 1200 to 2600 (for most central 5% collisions) and from
Figure 3.13: $dN_{ch}/d\eta$ at mid-rapidity scaled to the number of participant pairs measured by PHOBOS and shown as a function of centrality for $\sqrt{s_{NN}} = 200$ GeV (left panel) and $\sqrt{s_{NN}} = 19.6$ GeV (right panel). The solid squares (diamonds) represent the $p$$-\bar{p}$ ($p$$-p$) values at 200 (19.6) GeV. The solid curves show the scaling with the number of collisions obtained by the Glauber model using nucleon-nucleon cross sections of 42 mb and 33 mb for 200 and 19.6 GeV, respectively. The dashed line represents the level seen in $p$$-\bar{p}$ collisions at $\sqrt{s} = 200$ GeV and in $p$$-p$ at $\sqrt{s} = 19.6$ GeV.

25 000 to 30 000 for the total multiplicity, substantially lower than the ALICE design value.

As for the centrality dependence, at RHIC it has been observed for the first time that the $dN_{ch}/d\eta$ at mid-rapidity per participant pair increases with $N_{part}$, whereas scaling with the number of participants would lead to a flat dependence as found at SPS. In Fig. 3.13 this dependency is shown for two energies 19.6 and 200 GeV in Au-Au collisions from the PHOBOS experiment: a 25 % rise in the multiplicity per participant pair between peripheral and central events in Au-Au
collisions at $\sqrt{s_{NN}} = 200$ GeV [43] has been observed. The dashed line represents the level seen in p-\(\bar{p}\) collisions at $\sqrt{s} = 200$ GeV [71] and in p-p at $\sqrt{s} = 19.6$ GeV (extrapolated) [74]. The observed dependence is, however, much weaker than a scaling with the number of nucleon–nucleon collisions would suggest (obtained from Glauber model simulations), as shown by the solid curves in Fig. 3.13. This dependence can be explained in terms of the more frequent occurrence of hard processes in the production mechanism. Theoretical models have been developed in order to explain these features. A phenomenological approach has been developed by Kharzeev and Nardi [66] that can be used to extract from the data the fraction of the total multiplicity of particles produced in hard processes.

Concerning the total charged-particle multiplicity scaled by the number of participant pairs, it is found that it is essentially constant as a function of centrality, but at a level of about 40 % higher than for nucleon–nucleon (Fig. 3.14).

In p-p and p-\(\bar{p}\) collisions, the dN$_{ch}$/d\(\eta\) distribution has been measured at the ISR.
with the Split-Field-Magnet detector at centre-of-mass energies ranging from 23.6 to 62.8 GeV [74], at SpS with the UA5 and UA1 detectors from $\sqrt{s} = 53$ GeV to $\sqrt{s} = 900$ GeV and at the Tevatron with the CDF detector at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV. As already pointed out, the best fit to the p-p and p-$\bar{p}$ data follows a quadratic polynomial in ln $s$ dependence showing that the Feynman scaling is broken. It should be noted that the difference in charged-particle densities between p-p and p-$\bar{p}$ interactions is predicted to decrease as $1/\sqrt{s}$ at high energies [77]. This difference was last measured at the the ISR to be in the range 1.5-3 % [78] at $\sqrt{s} = 53$ GeV. Extrapolating these values to $\sqrt{s} = 900$ GeV, one obtains a very small difference of about 0.1-0.2 %.

According to the models that describe multi-particle production in soft processes, it is expected that the charged-particle density increases by a factor 1.7 and 1.9 when raising the LHC centre-of-mass energy from 900 GeV to 7 and 14 TeV respectively (i.e. intermediate and nominal LHC energies). At $\sqrt{s} = 14$ TeV the $dN_{ch}/d\eta$ at mid-rapidity is expected to be about 6 for non single-diffractive interactions.

3.4.2.2 Multiplicity and pseudorapidity determination in ALICE

The measurement of charged-particle multiplicity can be performed with various detectors of the ALICE apparatus that cover different pseudorapidity ranges, over 8 units of pseudorapidity.

The first measurement of the multiplicity and of the $dN_{ch}/d\eta$ distributions around mid-rapidity can be performed by counting correlated clusters (tracklets) in the two layers of the SPD (in the pseudorapidity region $|\eta| < 1.5$), with an algorithm that is extensively described in the next chapter, and by counting tracks in the TPC. The measurement can be done with very few events ($10^4$ events will give a statistical error of 2 % for the $dN_{ch}/d\eta$ and $10^5$ events are good to measure the multiplicity distribution). Once the fully reconstructed tracks in the ITS and TPC are available
a more precise measurement can be obtained in the pseudorapidity region $|\eta| < 0.9$. In addition, the measurement of the pseudorapidity density distribution can also be performed in the forward region ($-3.4 < |\eta| < -1.7$ and $1.7 < |\eta| < 5.1$) with the Forward Multiplicity Detector, based on the measurement of the energy deposition in the pads of FMD. In this case a complete understanding of secondary processes, which are dominant at low angles, is required. Experimentally, the physical multiplicity distribution is extracted using unfolding methods [79, 80, 81].

ALICE multiplicity measurements will reach a value of about 120 ($|\eta| < 0.9$) during the first physics runs ($10^7$ minimum-bias triggered events). However, an sample rich in high-multiplicity events in the range above 60-70 (i.e. ten times the mean multiplicity at mid-rapidity) can be collected by using a high-multiplicity trigger based on the SPD Fast-OR trigger circuit. This class of events may give access to initial states where new physics, such as high-density effects and saturation phenomena, sets in.

### 3.5 Transverse momentum distributions

The transverse momentum distribution of particles produced in heavy-ion interactions characterizes the freeze out phase of the collision and allows information about the dynamical evolution of the system created to be extracted. There are theoretical arguments that show that several characteristics of the final momentum distributions are determined at different times of the collision. In particular these distributions provide information about the freeze out temperature and chemical potential, radial-flow velocity, direct and elliptic-flow velocity.

The bulk of the particles produced in hadron and heavy-ion collisions are soft and their $dN_{ch}/dp_t$ distributions decrease exponentially with a weak dependence on the centre-of-mass energy ($p_t < 1\text{ GeV/c}$); particles produced in hard processed
Figure 3.15: Transverse momentum distributions of particles produced in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV in different centrality ranges.

$(p_t \gg 1$ GeV/c) determine a change in the slope of the distribution that follows a power law (Fig. 3.15). High $p_t$ particles constitute a very low fraction of the whole spectrum (e.g. at RHIC 0.1 % of the particles has $p_t > 4$ GeV).

Collider data on charged-particle $p_t$ spectra have shown that the high $p_t$ yield rises dramatically with the collision energy, due to the increase of the hard processes cross-sections. At high $p_t$ the transverse momentum spectra are well described by Leading Order (LO) or Next to Leading Order (NLO) pQCD calculations, but involving several phenomenological parameters and functions (K-factor, parton distribution functions and fragmentation functions) which need an experimental input to be determined. At lower $p_t$, where perturbative QCD calculations cannot be performed, theoretical foundations of different models are even more insecure. Therefore, early measurements of $p_t$ spectrum are important for the tuning of the model parameters and for the understanding of the background in the experimental study of rare processes. In p-p collisions, the measurement of high-$p_t$ observables also requires good understanding of the characteristics of the underlying event and backgrounds which are dominated by soft $p_t$ spectra. Moreover the measurement of the $p_t$ spectrum is necessary to perform high-$p_t$ hadron suppression studies in
heavy-ion collisions, where the proton–proton data are used as reference.

In ALICE the transverse momentum of charged particles will be measured using the full tracking system (ITS and TPC) and the TRD within the pseudorapidity range $|\eta| < 0.9$. First, track finding and fitting in the TPC are performed from outside inward by means of a Kalman filtering algorithm. In the next step, tracks reconstructed in the TPC are matched to the outermost ITS layer and followed in the ITS down to the innermost pixel layer. As a last step, reconstructed tracks can be back-propagated outward in the ITS and in the TPC up to the TRD innermost layer and then followed in the six TRD layers, in order to improve the momentum resolution. The resolution will be optimal in the range $|\eta| < 0.9$, however the measure could be performed in the range $|\eta| < 1.5$ when analysing tracks with reduced track length, hence with reduced momentum resolution. The $p_t$ spectrum is measured by counting the number of tracks in each $p_t$ bin and then correcting for the detector and reconstruction inefficiencies (as a function of the $z$-position of the primary vertex and of $p_t$). Finally, the $p_t$ distribution is normalized to the number of collisions and corrected for the effect of vertex reconstruction inefficiency and trigger bias. With a sample of $10^7$ events that could be collected in the first runs, ALICE could reach $p_t > 40$ GeV/c.

3.5.1 Mean $p_t$ dependence on multiplicity

A correlation between $(p_t)^2$ and the charged multiplicity has been first observed by UA1 [82]. This correlation has been studied subsequently at ISR [83] and Tevatron [84, 58] energies. The increase of $p_t$ as a function of multiplicity has been also suggested by cosmic ray measurements [85]. This correlation describes the balance between particle production and transverse energy and has been attributed to the onset of gluon radiation and explained in terms of jet and minijet production

$(p_t)$ is the arithmetic mean of the $p_t$ of all the reconstructed charged tracks.
increasing with energy [86]. Since these processes should become dominant at the LHC energies, this correlation is expected to disappear. However, CDF has shown an interesting feature [87] by subdividing the minimum-bias sample in the two classes, as explained in the previous section: data have shown that the rise of \( \langle p_t \rangle \) with multiplicity is also present in events without jets (soft events), but the soft subsample was seen to start to saturate, pointing to different particle production mechanisms. In Fig. 3.16 it can be also noted that the \( \langle p_t \rangle \) dependence on multiplicity in soft events is independent of collision energy from RHIC to Tevatron and the minimum-bias and hard events show a stronger dependence. These results confirm that the dynamical mechanism of inelastic multi-particle production in soft interactions from RHIC to Tevatron energy, is invariant with centre-of-mass energy, and the properties of the final state are determined only by the number of (charged) particles. This behaviour is not yet satisfactorily explained by any theoretical or phenomenological model. In soft events, the \( \langle p_t \rangle \) increases even for small multiplicity, which indicates that minijet production is not the only cause of \( \langle p_t \rangle \) increasing with multiplicity. This kind of analysis could be repeated also in ALICE, after the development of some tools to
select event samples enriched in hard interactions, for example via algorithms of cluster finding (charged tracks in TPC or towers in the electromagnetic calorimeter).

The expected $\langle p_t \rangle$ from PYTHIA simulations is of the order of 0.6 GeV/c, a momentum where CMS is essentially blind and ATLAS is reaching its lower limit, while ALICE has a good resolution down to 100 MeV/c. In ALICE it will be relatively straightforward to obtain the correlation between $\langle p_t \rangle$ and the charged particle multiplicity, once the multiplicity distribution and the $p_t$ spectra have been measured. The $p_t$ cut-off imposed by the detector (100 MeV/c for pions and 300 MeV/c for protons) introduces a rather large systematic uncertainty on the $\langle p_t \rangle$ estimate. Detailed measurements of $\langle p_t \rangle$ versus multiplicity (eventually in different regions in $\eta-\phi$ relative to leading-jet direction, as in CDF analyses) will give an insight to jet fragmentation processes and to the general underlying event structure. Another interesting subject for ALICE, due to its powerful particle identification system at low and high $p_t$, will be the correlation between $\langle p_t \rangle$ and multiplicity studied separately for pions, kaons and proton/antiprotons to further investigate the differences observed at Tevatron. The data collected at Tevatron by the E735 experiment [84] indicate that the correlation has rather different behaviour for the three types of particles, especially as regards the proton and antiproton $\langle p_t \rangle$, that do not appear to saturate at high multiplicity as pions (and maybe also kaons, within experimental uncertainties). This is not yet understood in terms of the available hadronic models.
Chapter 4

Multiplicity and pseudorapidity density measurements

4.1 Introduction

The charged-particle pseudorapidity density and multiplicity distributions are the first measurements foreseen to be carried out with the ALICE detector both in p-p and in Pb-Pb collisions. Indeed, the charged-particle pseudorapidity density has already been measured with the first available low energy p-p data sample (see Chapter 5). The key role of these measurements in the global event characterization has been illustrated in Chapter 3: they will allow the hadroproduction models used to make estimates extrapolating from existing results to be constrained, the Monte Carlo generators to be correctly configured and the energy dependence of the charged-particle density in the realm of LHC energies to be determined. At low energy $\sqrt{s} = 900$ GeV (LHC injection energy), these measurements will be compared to p-p existing results.

The reconstruction of the multiplicity and pseudorapidity density distribution in the central $\eta$ region can be performed using only data provided by the two SPD
layers. Compared to the measurement based on the fully reconstructed tracks (using combined measurements from the ITS and the TPC) the charged-particle multiplicity reconstructed only with pixels has some basic advantages: a larger acceptance coverage both in pseudorapidity and $p_t$ (down to 35 MeV/$c$) and a much smaller reliance on alignment and calibration procedures. This makes the measurement with SPD tracklets suitable to extract results from the very first available data from the LHC.

In this chapter the reconstruction procedure and the correction method developed for both the pseudorapidity density distribution measurement and for an event-by-event multiplicity estimation will be described. Data produced in the SPD only are used for multiplicity reconstruction. The results of this analysis, based on Monte Carlo samples, will be shown both for p-p and Pb-Pb events. In the last section the systematic uncertainties will be listed and some of them will be estimated for the $dN_{ch}/d\eta$ measurement in p-p collisions.

### 4.2 Monte Carlo data samples used in the analysis

Several samples have been used to carry out the study on $dN_{ch}/d\eta$ and multiplicity. Three samples have been generated on the Bari computer farm to study and improve the performance of the reconstruction algorithm. These are as follows:

- 10 000 PYTHIA minimum-bias p-p events at $\sqrt{s} = 14$ TeV;
- 5 000 HIJING minimum-bias Pb-Pb events at $\sqrt{s}_{NN} = 5.5$ TeV;
- 1 000 HIJING 5% most central Pb-Pb events at $\sqrt{s}_{NN} = 5.5$ TeV.

The magnetic field has been assumed at the nominal ALICE value of 0.5 T. The central Pb-Pb event sample has also been used to carry out the $dN_{ch}/d\eta$ analysis illustrated in this chapter.
The results of the analysis for p-p interactions, that will be shown here, have been obtained using the First Physics official Monte Carlo productions of the Physics Data Challenge 2009 (PDC09) available on the CERN Analysis Facility (CAF) and produced with the most updated version of the simulation and reconstruction code. In particular, the following minimum-bias p-p samples at $\sqrt{s} = 7$ TeV have been employed to compute the corrections for the $dN_{ch}/d\eta$ distribution and some of the associated systematic errors:

- 275 000 PYTHIA events with magnetic field $B = 0$ T;
- 59 000 PYTHIA events with magnetic field $B = 0.5$ T;
- 175 000 PhoJet events with magnetic field $B = 0$ T;
- 217 000 PhoJet events with magnetic field $B = 0.5$ T.

All the results that will be shown for the $dN_{ch}/d\eta$ in the next sections will refer to the PYTHIA sample with magnetic field $B = 0.5$ T, unless otherwise specified. In addition, the results for the estimate of the multiplicity in p-p collisions will be shown for a larger official Monte Carlo p-p sample of about 400 000 events, generated at $\sqrt{s} = 900$ GeV with PYTHIA and magnetic field $B = 0.5$ T.

All these samples have been reconstructed considering a given map of dead pixels (in the real case corresponding to disconnected and/or noisy parts of the detector). This map consists of the following parts: known dead pixels since detector construction (6 488 pixels), one half of a chip (4 096 pixels) and 15 half-staves (6 in the inner layer and 9 in the outer layer). Dead pixels make up 13 % of the SPD: 10 % in side A and 15 % in side C, hence the distribution is not symmetric in $\eta$. This appears clearly in the plots of the cluster occupancy for both the SPD layers shown in Fig. 4.1.
4.3 Sample selection

In this section the selection criteria used in the data acquisition to trigger minimum-bias events will be described. Events usable for the analysis are selected in two phases: the trigger selection and the analysis-level selection.

For p-p events, this selection will be performed exploiting the capability of both the V0 and the SPD sub-detectors, complementary in the geometrical acceptance, in selecting inelastic collisions with very high efficiency, rejecting almost all the events coming from collisions of the proton beam with the residual gas in the beam pipe (beam-gas interactions).

In Pb-Pb collisions, the ZDC will provide for a trigger signal to select minimum-bias events, as well as for two centrality triggers (central and semi-central). These triggers will essentially be based on a threshold imposed on the energy deposited in the calorimeters.

A further selection is performed at the level of the analysis, since triggered events usable to estimate the charged-particle multiplicity must have a reconstructed primary vertex: the vertex position cannot be assumed to be known, as it will have a spread around the nominal interaction point in the ALICE global reference system. Indeed the proton beams will have a nominal spread; the LHC machine parameters at
the ALICE intersection point for p-p and Pb-Pb beams at different energies and luminosity values are quoted in Table 4.1 [1, 2, 88]. The spread of the interaction region and consequently of the vertex can be calculated from the bunch spread as the convolution of the particle distribution in the two intersecting bunches

\[ \sigma_{\text{vertex}}^{x,y,z} = \sigma_{\text{bunch}}^{x,y,z} / \sqrt{2} \]  

(4.1)

where the particles in the bunch can be assumed to have a Gaussian distribution with dispersion \( \sigma_{\text{bunch}} \). This formula applies on the supposition of a zero crossing angle. The vertex reconstruction procedure will be described in Section 4.5.1.

The measured distributions have to be properly corrected to take into account the bias produced with these selections on the sample analysed.

### 4.3.1 Minimum-bias trigger in p-p

The minimum-bias trigger has to select inelastic p-p events with the highest efficiency and the lowest beam background contamination (beam-gas and beam-halo contributions). The minimum-bias trigger is a Level 0 (L0) trigger whose latency is 1.2 \( \mu s \). The main detector designed to contribute to the minimum-bias trigger is the V0. The SPD also contributes to this trigger with its digital Fast-Or signal. In particular the use of the V0 as a trigger detector is based on the fact that the

<table>
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<th>Pb-Pb</th>
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<td>Luminosity [cm(^{-2}) * s(^{-1})]</td>
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<td>( 1.0 \times 10^{37} )</td>
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<td>5.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Table 4.1: Nominal LHC parameters at the IP2 at different energies for proton and Pb beams at peak luminosity. Longitudinal dimensions of the beams are given for Gaussian distribution, even though the real beam will not have a Gaussian distribution.
arrival time of particles at each of the two arrays will be different in beam–beam and beam–gas interactions with respect to the time $t_0$ in which the two bunches, coming from opposite directions, cross the nominal interaction point. Particles originated in a beam–beam collision will arrive at the two V0 counters after the $t_0$, while particles originating in beam–gas interactions, that occur outside the region in between the two V0 counters, will arrive before the $t_0$ at least in one of the two counters (see [89] for a detailed description).

Combinations of the signals produced by the two detectors are expected to be effective in selecting inelastic collisions with very high efficiency, due to their complementarity in geometrical acceptance. The condition of requiring at least a Fast-Or signal in the whole SPD (GlobalFO) has shown a good performance. Several combinations of the signals from the V0 and the Fast-Or have been investigated [89]. The two most efficient algorithms are MB1 and MB2. They are defined as follows:

\begin{align*}
\text{MB1} & \equiv (\text{V0OR})\cdot\text{or}\cdot(\text{GlobalFO})\cdot\text{and}\cdot\text{notBG} \\
\text{MB2} & \equiv (\text{V0OR})\cdot\text{and}\cdot(\text{GlobalFO})\cdot\text{and}\cdot\text{notBG}
\end{align*}

that is the presence of at least one Fast-Or signal in the whole SPD (GlobalFO) or/and at least one hit on either one of the two V0 scintillators arrays at a time of a beam–beam (V0OR) interaction are required. The condition \text{notBG} allows beam-gas events to be rejected: it is a veto signal from the V0 detector based on the definition of time windows around the time corresponding to beam-gas interactions. In Table 4.2 the efficiencies for the two minimum-bias trigger algorithms and for different event classes, calculated using the PhoJet sample at $\sqrt{s} = 7$ TeV and magnetic field on, are quoted, while in the left panel of Fig. 4.2 the MB1 trigger efficiency is shown as a function of the generated Monte Carlo multiplicity.

In the following the MB1 trigger algorithm is used to select events. For the first data taking, since a constant trigger rate, based on bunch-crossing signals, is foreseen,
Table 4.2: Efficiencies for the MB1 and MB2 trigger algorithms for different event classes (inelastic, non single-diffractive NSD, non-diffractive ND, single-diffractive SD and double-diffractive DD events). The percentages are quoted for the assumed distribution of the SPD dead channels (about 13%) and for the PhoJet sample at $\sqrt{s} = 7$ TeV with magnetic field on. The values obtained with PYTHIA are lower.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Inelastic</th>
<th>NSD</th>
<th>ND</th>
<th>SD</th>
<th>DD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB1</td>
<td>95.5</td>
<td>99.1</td>
<td>99.9</td>
<td>72.7</td>
<td>89.6</td>
</tr>
<tr>
<td>MB2</td>
<td>91.2</td>
<td>96.8</td>
<td>99.2</td>
<td>56.4</td>
<td>69.0</td>
</tr>
</tbody>
</table>

Figure 4.2: Efficiency of the MB1 trigger (left panel) and of the vertex reconstruction in triggered events (right panel) as a function of the multiplicity for different event classes.

trigger conditions equivalent to the ones described here can be applied to data offline.

4.4 The tracklet reconstruction algorithm

In this section the algorithm to estimate the charged-particle multiplicity using data from the SPD only, namely the tracklet algorithm, is described. This algorithm was used for the ALICE Physics Performance Report [44] and is extensively described in [90]. The performance of this algorithm has been studied both for p-p and Pb-Pb events concluding that the algorithm can be optimized, as illustrated in the next sections.
Figure 4.3: Sketch of the two differences calculated for each combination of clusters in the two SPD layers and used to define tracklets: the transverse plane view of the detector (left panel) illustrates how the $\Delta \phi$ is calculated and the z-y plane view (right panel) illustrates how the $\Delta z_{\text{projected}}$ is calculated (approximation of the prediction of the straight line in the outer layer).

The reconstructed points of the SPD (clusters\(^1\)) and the reconstructed main vertex position are needed to build tracklets. The primary vertex is reconstructed using SPD clusters as well, exploiting their correlation as described in [91, 92].

A straight line from the vertex to each cluster in the inner layer is considered. For each cluster in the inner layer two differences are computed using the reconstructed vertex as the origin: the difference in the azimuthal angles ($\Delta \phi$) between this cluster and each cluster in the outer layer and the difference between the longitudinal coordinate of the prediction from the straight line in the outer layer and the longitudinal coordinate of each cluster in the outer layer ($\Delta z_{\text{projected}}$). The differences are schematically shown in Fig. 4.3. Regarding the $\Delta z_{\text{projected}}$, it is sufficient to use an approximation for the prediction on the outer layer (Fig. 4.3). This difference is not constant as $\theta$ varies, keeping $\Delta \theta$ constant: it is bigger if the pseudorapidity $|\eta|$ of the cluster in the outer layer increases. For each pair the following elliptical cut is

\(^1\)A cluster is made up of one or more adjacent pixels fired by a particle.
applied

\[ \frac{(\Delta z_{\text{projected}})^2}{\Delta z_{\text{cut}}^2} + \frac{(\Delta \phi)^2}{\Delta \phi_{\text{cut}}^2} < 1 \]  

(4.2)

and, if the pair satisfies the window requirement, it is labeled as “tracklet”. The default widths of the cut windows for p-p events are \( \Delta \phi_{\text{cut}} = 0.08 \) rad and \( \Delta z_{\text{cut}} = 1 \) cm respectively. The cut imposed in the azimuthal angle corresponds to a transverse-momentum cut-off of about 35 MeV/c (for pions). If more than one cluster in the outer layer matches the window requirement with the same cluster in the inner layer, the one with the minimum distance is associated to the cluster in the inner layer. The procedure is repeated for each cluster in the inner layer so that each cluster can be associated only once. Clusters in the outer layer can either be used in one tracklet only or in more than one. In the first case the reconstructed tracklets are biased by the cluster ordering. The possibility to interpolate starting from the clusters on the outer layer has also been considered: due to the larger background fraction on that layer, the number of fake tracklets is larger in this case, especially for Pb-Pb events.

The pseudorapidity \( \eta \) is evaluated by considering a straight line from the main vertex to the position of the cluster in the inner layer. The multiplicity of charged particles is estimated counting the number of tracklets.

The tracklet-based method for multiplicity studies is a proven technique used in the PHOBOS experiment at RHIC [93]. The tracklet method allows a better rejection of the background (detector noise, secondary particles, residual beam-gas contamination) than a method simply based on cluster counting [90].

---

2The ITS clusters are ordered according to the increasing number of the module to which they belong and in the module according to the increasing \( z \) and \( \phi \).
4.4.1 Optimization of the cuts

Studies on the performance of the tracklet algorithm as a function of the selected fiducial windows and the adopted combination strategy will be presented in this and in the next section.

The widths of the cuts applied have to be optimized with respect to the efficiency in reconstructing primary particles and the background contamination. A performance study has been carried out varying the cuts applied both for p-p and Pb-Pb events (minimum-bias and central). The Monte Carlo particle labels stored in the reconstruction process for the two clusters that made up each tracklet are used for this purpose. In order to choose a reasonable set of cuts, the signal, i.e. pairs of clusters produced both by the same primary particle, has been plotted in the $\Delta \varphi - \Delta z_{\text{projected}}$ plane both for p-p and for Pb-Pb events. In Fig. 4.4 the result for central Pb-Pb events is shown, where the two peaks in $\Delta \varphi$ are due to the curvature in opposite directions of positive and negative charged particles when the magnetic field is active.

The efficiency has been evaluated as the ratio between all the reconstructed primaries, i.e. primaries that have an associated tracklet, and all the primaries that produced at least one cluster in each layer. In order not to include in this...
Table 4.3: Efficiency of the tracklet algorithm and tracklet composition varying the cuts to reconstruct tracklets for the Monte Carlo p-p sample. In brackets the results allowing multiple association of clusters in the outer layer are quoted.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{cut}$ (rad)</th>
<th>$\Delta z_{cut}$ (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0800</td>
<td>1.00</td>
<td>97.4 (98.8)</td>
<td>89.9 (88.5)</td>
<td>5.9 (5.8)</td>
<td>4.2 (5.7)</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.50</td>
<td>98.2 (98.6)</td>
<td>92.4 (91.8)</td>
<td>5.4 (5.4)</td>
<td>2.2 (2.8)</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.30</td>
<td>98.2 (98.5)</td>
<td>93.5 (93.1)</td>
<td>4.8 (4.9)</td>
<td>1.6 (2.0)</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.20</td>
<td>98.0 (98.2)</td>
<td>94.3 (94.0)</td>
<td>4.4 (4.4)</td>
<td>1.3 (1.6)</td>
</tr>
<tr>
<td>0.0600</td>
<td>0.20</td>
<td>97.7 (97.9)</td>
<td>94.7 (94.5)</td>
<td>4.1 (4.1)</td>
<td>1.2 (1.4)</td>
</tr>
<tr>
<td>0.0400</td>
<td>0.10</td>
<td>95.6 (95.6)</td>
<td>96.2 (96.1)</td>
<td>3.1 (3.1)</td>
<td>0.7 (0.8)</td>
</tr>
<tr>
<td>0.0200</td>
<td>0.05</td>
<td>84.8 (84.8)</td>
<td>97.5 (97.4)</td>
<td>2.1 (2.1)</td>
<td>0.4 (0.5)</td>
</tr>
<tr>
<td>0.0150</td>
<td>0.03</td>
<td>69.8 (69.8)</td>
<td>97.9 (97.8)</td>
<td>1.7 (1.8)</td>
<td>0.4 (0.4)</td>
</tr>
<tr>
<td>0.0100</td>
<td>0.02</td>
<td>51.1 (51.1)</td>
<td>98.1 (98.1)</td>
<td>1.6 (1.6)</td>
<td>0.3 (0.3)</td>
</tr>
<tr>
<td>0.0075</td>
<td>0.01</td>
<td>27.8 (27.8)</td>
<td>98.2 (98.3)</td>
<td>1.4 (1.4)</td>
<td>0.4 (0.3)</td>
</tr>
</tbody>
</table>

efficiency the effect of the vertex reconstruction quality, events with a reconstructed vertex in $|z_{vtx}| < 10$ cm are selected. Indeed, events with a bad reconstructed vertex lower the efficiency since the two clusters produced may not be well aligned with the vertex within the fiducial windows. In addition, the reconstructed tracklets have been classified as primary, secondary or combinatorial tracklets. The fractions of tracklets for these classes will be indicated as PP, SS and Combinatorial respectively. The efficiencies and the percentages in the tracklet composition are shown in Table 4.3 for p-p events. The results allowing multiple association of clusters in the outer layer are quoted in brackets.

Preventing multiple associations, the efficiency increases and then decreases as the cuts become tighter. Allowing multiple association the efficiency has the expected trend and is higher due to the fact that the order does not prevent the algorithm from sorting the best association. However, the results obtained with the two options do not differ as the cuts become tighter. The order dependence can be clearly seen in Fig. 4.5, where the comparison between the $\Delta \varphi$ distribution of tracklets obtained preventing and allowing multiple association of clusters in the outer layer is shown. The order
dependence of the results has been confirmed performing the reconstruction reversing the order of the clusters: the asymmetry in the $\phi$ distributions is also reversed (more tracklets at negative $\Delta \phi$).

In Table 4.4 and Table 4.5, the efficiencies and tracklet compositions are quoted for minimum-bias and central Pb-Pb events respectively. For Pb-Pb events the maximum achievable efficiency is quite low and the background fraction is high, in particular for central events where the maximum efficiency is about 60% and half of the reconstructed tracklets are combinatorial.

All these features suggested that there was room for improving the algorithm performance.

### 4.4.2 Optimization of the tracklet algorithm

In principle, the best algorithm should associate the pair with the minimum distance over all the possible combinations of clusters in the inner layer with clusters in the outer layer. A naive implementation of such an algorithm scales as $O(N^3)$, $N$ being the number of particles, which is very time-consuming. Alternatively, an
Table 4.4: Efficiency of the tracklet algorithm and tracklet composition varying the cuts for tracklet reconstruction of the minimum-bias Pb-Pb sample. The results allowing multiple association of clusters in the outer layer are quoted in brackets.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta z_{\text{cut}}$ (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0800</td>
<td>1.000</td>
<td>51.5 (74.3)</td>
<td>39.0 (48.6)</td>
<td>1.7 (1.7)</td>
<td>59.3 (49.7)</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.200</td>
<td>63.3 (74.6)</td>
<td>54.0 (61.6)</td>
<td>2.1 (2.1)</td>
<td>43.9 (36.3)</td>
</tr>
<tr>
<td>0.0150</td>
<td>0.030</td>
<td>60.2 (61.1)</td>
<td>86.4 (85.1)</td>
<td>1.7 (1.7)</td>
<td>11.9 (13.2)</td>
</tr>
<tr>
<td>0.0125</td>
<td>0.025</td>
<td>52.5 (53.2)</td>
<td>87.7 (86.5)</td>
<td>1.6 (1.6)</td>
<td>10.7 (11.9)</td>
</tr>
<tr>
<td>0.0100</td>
<td>0.020</td>
<td>42.1 (42.5)</td>
<td>88.6 (87.8)</td>
<td>1.5 (1.5)</td>
<td>9.9 (10.7)</td>
</tr>
<tr>
<td>0.0075</td>
<td>0.015</td>
<td>28.6 (28.7)</td>
<td>89.1 (88.6)</td>
<td>1.4 (1.4)</td>
<td>9.5 (10.0)</td>
</tr>
<tr>
<td>0.0060</td>
<td>0.005</td>
<td>9.9 (9.9)</td>
<td>89.8 (89.6)</td>
<td>1.3 (1.3)</td>
<td>8.9 (9.1)</td>
</tr>
</tbody>
</table>

Table 4.5: Efficiency of the tracklet algorithm and tracklet composition varying the cuts for the sample of central Pb-Pb events. The results allowing multiple association of clusters in the outer layer are quoted in brackets.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta z_{\text{cut}}$ (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0800</td>
<td>1.000</td>
<td>42.0 (63.4)</td>
<td>31.9 (42.3)</td>
<td>1.1 (1.2)</td>
<td>67.0 (56.5)</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.200</td>
<td>50.3 (63.5)</td>
<td>42.2 (53.0)</td>
<td>1.4 (1.4)</td>
<td>56.4 (45.5)</td>
</tr>
<tr>
<td>0.0150</td>
<td>0.030</td>
<td>55.8 (57.1)</td>
<td>79.2 (77.4)</td>
<td>1.5 (1.5)</td>
<td>19.3 (21.1)</td>
</tr>
<tr>
<td>0.0125</td>
<td>0.025</td>
<td>49.1 (50.1)</td>
<td>81.0 (79.5)</td>
<td>1.5 (1.4)</td>
<td>17.5 (19.1)</td>
</tr>
<tr>
<td>0.0100</td>
<td>0.020</td>
<td>39.6 (40.3)</td>
<td>82.5 (81.3)</td>
<td>1.4 (1.4)</td>
<td>16.1 (17.3)</td>
</tr>
<tr>
<td>0.0075</td>
<td>0.015</td>
<td>27.0 (27.3)</td>
<td>83.1 (82.4)</td>
<td>1.3 (1.3)</td>
<td>15.6 (16.3)</td>
</tr>
<tr>
<td>0.0060</td>
<td>0.005</td>
<td>9.2 (9.3)</td>
<td>84.2 (83.8)</td>
<td>1.3 (1.3)</td>
<td>14.5 (14.9)</td>
</tr>
</tbody>
</table>

iterative procedure, starting from the basic algorithm, can be implemented. The first step is basically the old algorithm allowing multiple use of clusters in the outer layer. At the end of the loop on clusters in the inner layer, each cluster in the outer layer, that is associated to more than one cluster in the inner layer, is associated to the cluster in the inner layer with which it has the minimum distance. This step is repeated using all the clusters not associated in the previous step. The iterations stop when no more tracklets are found.

Concerning the cut variables, the cut in $\Delta z_{\text{projected}}$ is replaced by a cut in $\Delta \theta$, which is constant varying $\theta$ (Fig. 4.6). As for the cut in $\Delta \varphi$, it should be noted
Figure 4.6: Sketch of the two differences calculated for each combination of clusters in the two SPD layers and used in the optimized tracklet algorithm to select tracklet candidates: the transverse plane view of the detector (left panel) illustrates how the $\Delta \phi$ is calculated and the $z$-$y$ plane view (right panel) illustrates how the $\Delta \theta$ is calculated.

that, when the magnetic field is active, tracklets have the same peak structure in the $\Delta \phi$ distribution as that of pairs of clusters produced by the same primary particle. As previously explained, this is due to the charge of the reconstructed particles. In Fig. 4.7 an example of $\Delta \phi$ distributions of tracklets reconstructed with and without magnetic field are shown. Thus, according to the value of the magnetic field, a shift can be added in the calculation of the $\Delta \phi$. A linear $\Delta \phi$ dependence on the magnetic field has been assumed. The elliptical cut applied is then

$$\frac{\Delta \theta^2}{\Delta \theta_{\text{cut}}^2} + \frac{(|\Delta \phi| - |\Delta \phi_{\text{shift}}|)^2}{\Delta \phi_{\text{cut}}^2} < 1 \quad (4.3)$$

This procedure shows better performance than the basic algorithm, in particular in reconstructing Pb-Pb events: the efficiency is higher and the background contamination markedly decreases. The improvement is basically due to the iterative procedure. In the next two paragraphs the results of the study to optimize the cuts to define tracklets will be discussed for p-p and Pb-Pb events.
4.4.2.1 Tuning of the reconstruction in p-p events

The optimized algorithm has been tested varying the cuts applied to define tracklets.

In Fig. 4.8 the signal in the $\Delta \phi$-$\Delta \theta$ plane for p-p events is shown, while in Table 4.6 the optimized algorithm efficiencies are quoted for five sets of cuts.

As previously explained, the efficiencies and the background contaminations have been calculated using events with a vertex reconstructed in $|z_{vtx}| < 10$ cm. The $\Delta \theta_{cut} = 0.15$ rad corresponds roughly to the $\Delta z_{cut} = 1$ cm at $\theta = \pi/2$ rad. The
Table 4.6: *Efficiency of the optimized tracklet algorithm and tracklet composition varying the cuts to reconstruct the p-p event sample.*

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta \theta_{\text{cut}}$ (rad)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.150</td>
<td>98.7</td>
<td>91.3</td>
<td>6.0</td>
<td>2.7</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>98.7</td>
<td>93.6</td>
<td>5.1</td>
<td>1.3</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>98.2</td>
<td>94.8</td>
<td>4.3</td>
<td>0.9</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>85.0</td>
<td>97.2</td>
<td>2.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>79.3</td>
<td>97.7</td>
<td>1.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Efficiency is not much higher than with the old algorithm because of the low SPD occupancy in p-p events, whereas the background fraction is a few percent lower. Tightening the applied cuts to $\Delta \theta_{\text{cut}} = 0.025$ rad and $\Delta \varphi_{\text{cut}} = 0.08$ rad, the efficiency decreases by 0.5 % and the background fraction (secondary tracklets and combinatorial) is 3.5 % lower. A lower background fraction is preferable to higher efficiency: indeed the background amount can depend on multiplicity, hence on the Monte Carlo generator. The efficiency, on the other hand, only depends on the cuts applied and can be easily taken into account in the correction to the multiplicity and pseudorapidity density distribution.

The cuts used by default in the following are $\Delta \varphi_{\text{cut}} = 0.08$ rad and $\Delta \theta_{\text{cut}} = 0.025$ rad. Tighter cuts can be applied in the analysis since the $\Delta \varphi$ and the $\Delta \theta$ will be saved in the ESDs for each reconstructed tracklet but then they must both be scaled proportionally.

### 4.4.2.2 Tuning of the reconstruction in Pb-Pb events

As previously seen, the reconstruction of Pb-Pb events is very critical since the cluster occupancy in the SPD and the background are quite high. In particular in the 5 % most central collisions, the mean number of clusters is about 21 000 and 24 000 in the SPD inner and outer layer respectively and roughly 10 % are produced by
Figure 4.9: $\Delta \varphi$ and $\Delta \theta$ calculated for pairs of clusters produced by the same primary particle in central Pb-Pb events.

Table 4.7: Efficiency of the optimized tracklet algorithm and tracklet composition varying the cuts to reconstruct the minimum-bias Pb-Pb event sample.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta \theta_{\text{cut}}$ (rad)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.150</td>
<td>71.2</td>
<td>56.1</td>
<td>2.1</td>
<td>41.8</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>81.2</td>
<td>68.2</td>
<td>2.6</td>
<td>29.2</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>83.2</td>
<td>72.8</td>
<td>2.6</td>
<td>24.6</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>73.6</td>
<td>82.3</td>
<td>2.1</td>
<td>15.6</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>70.0</td>
<td>86.5</td>
<td>1.9</td>
<td>11.6</td>
</tr>
</tbody>
</table>

secondary particles. In Fig. 4.9 the signal in the $\Delta \varphi$-$\Delta \theta$ plane is shown for central events. A similar plot has been obtained for minimum-bias events. In Table 4.7 and Table 4.8 the efficiencies and the tracklet composition for all the cuts used in the minimum-bias and central Pb-Pb events respectively are shown.

The efficiency increases and then decreases as the fiducial cuts become tighter because the larger windows used do not follow the elliptical correlation in the plane where the distance is computed (Fig. 4.9) and wrong associations of clusters can have a smaller distance than the correct combination. This does not happen for p-p events (efficiency decreases tightening the cuts) because the SPD cluster occupancy is low.
and, even using a large cut window, the probability to make wrong associations is low. A good choice for the cuts is clearly $\Delta \phi = 0.08$ rad and $\Delta \theta = 0.025$ rad and this will be used to reconstruct tracklets for the analysis that follows. As stated for the p-p case, tighter cuts can be applied later in the analysis, provided these both scale proportionally.

### 4.4.3 Study on the reconstruction in the SPD overlap regions

Due to the SPD geometry design (Fig. 4.10), particles crossing the overlap regions in $\varphi$ between modules can produce two clusters in each layer so that the track could be reconstructed twice. Using the ideal geometry of the detector, that happens

![Figure 4.10: View of the geometry of two SPD sectors in the r-$\varphi$ plane: the overlap regions between adjacent modules in $\varphi$ are clearly visible for both layers.](image)

Table 4.8: Efficiency of the optimized tracklet algorithm and tracklet composition varying the cuts to reconstruct the central Pb-Pb event sample.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta \theta_{\text{cut}}$ (rad)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Combinatorial (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.150</td>
<td>59.3</td>
<td>47.4</td>
<td>1.4</td>
<td>51.2</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>71.9</td>
<td>60.3</td>
<td>1.8</td>
<td>37.9</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>74.7</td>
<td>64.5</td>
<td>1.9</td>
<td>33.6</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>67.2</td>
<td>73.7</td>
<td>1.8</td>
<td>24.5</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>64.8</td>
<td>79.4</td>
<td>1.7</td>
<td>18.9</td>
</tr>
</tbody>
</table>
Figure 4.11: $\varphi$ distributions for clusters in the inner layer (left panel) and in the outer layer (right panel): the spikes are due to overlaps between two SPD modules adjacent in $\varphi$. The spikes are higher for the inner layer mainly due to the larger acceptance in $\eta$.

Figure 4.12: $\varphi$ distributions for tracklets: the spikes are due to tracklets reconstructed in regions where there are overlaps between adjacent modules both in the inner layer and in the outer layer at the same $\varphi$.

more likely when the overlap regions crossed are in the same sector, while when the overlapping modules belong to adjacent sectors, the probability is smaller because the overlapping areas are smaller. The effect of the overlaps between the SPD modules in $\varphi$ can be clearly seen in Fig. 4.11 for clusters, where the higher spikes are due to the overlap between modules in the same sector and the lower ones to the overlap between modules in adjacent sectors. In Fig. 4.12 the $\varphi$ distribution for tracklets is shown as well. This feature can be useful to check the alignment with first data since the overlaps are approximately 2% of the whole SPD. However, for physics
analysis the multiple reconstruction of tracks should be avoided: a procedure has been implemented to reduce as much as possible multiple reconstructed tracklets.

The basic idea is, for each cluster, to look for close clusters in the adjacent module. These should be flagged to avoid their use in tracklet building. However, for practical reasons, this selection is made on clusters once the tracklets have been reconstructed. After the tracklet reconstruction, a loop over the tracklets is performed. For each of the two clusters in the tracklet the check on the distance previously described is carried out: if the distance is within a fiducial elliptical window, those clusters are flagged. These flags will then be checked for the clusters in the following reconstructed tracklets: if at least one of the two clusters has been flagged, the tracklet is eliminated and is not stored.

The distance between clusters on adjacent modules is calculated in the $\Delta \phi$-$\Delta z$ plane. The $z$ coordinate of the clusters is calculated at the mean radius between the maximum and the minimum radii in the $x$-$y$ plane for two modules in the overlap region.

In order to fix the width of the windows in $\Delta z$ and $\Delta \phi$, the distributions in $\Delta \phi$ and in $\Delta z$ of clusters, produced by the same primary that crosses two adjacent modules in each layer, have been produced (Fig. 4.13). These have been compared to the same distributions for all pairs of clusters on adjacent modules: the region around zero has the same entries as the plot for all pairs of clusters. Therefore, cutting on the distance between clusters in adjacent modules is effective to select clusters produced by the same particle. Two sets of cuts to flag the clusters in the SPD overlaps have been used to reconstruct tracklets varying the cuts for the reconstruction itself as well.

In Table 4.9 the efficiencies and the tracklet composition are quoted for p-p events. In p-p events the result does not change widening the cuts to eliminate tracklets in the SPD overlaps and both the efficiency and the tracklet composition remain constant compared to the efficiency of the algorithm without this option (Table 4.6).
Figure 4.13: Distance in the $\Delta \varphi - \Delta z$ plane between two clusters produced by the same primary particles in two adjacent modules in the same SPD layer (outer layer). The two projections are also shown. The projection on one variable is done cutting on the other variable. For each variable the dotted line represents the cut applied in projecting the other variable.
Table 4.9: Efficiency of the optimized tracklet algorithm and tracklet composition for the p-p event sample cutting the clusters in the overlap regions of the SPD. Two different windows have been used to flag clusters, each of them for three different sets of the cuts for the tracklet reconstruction.

<table>
<thead>
<tr>
<th>(\Delta \phi_{\text{cut}}) (rad)</th>
<th>(\Delta \theta_{\text{cut}}) (rad)</th>
<th>(\Delta \phi_{\text{SPDoverlaps}}) (rad)</th>
<th>(\Delta z_{\text{SPDoverlaps}}) (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Comb. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.005</td>
<td>0.05</td>
<td>98.6</td>
<td>93.7</td>
<td>5.1</td>
<td>1.2</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.015</td>
<td>0.2</td>
<td>98.6</td>
<td>93.7</td>
<td>5.1</td>
<td>1.2</td>
</tr>
<tr>
<td>0.08</td>
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<td>0.005</td>
<td>0.05</td>
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<td>94.8</td>
<td>4.3</td>
<td>0.9</td>
</tr>
<tr>
<td>0.08</td>
<td>0.015</td>
<td>0.015</td>
<td>0.2</td>
<td>98.2</td>
<td>94.8</td>
<td>4.3</td>
<td>0.9</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.005</td>
<td>0.05</td>
<td>85.0</td>
<td>97.2</td>
<td>2.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.015</td>
<td>0.2</td>
<td>85.0</td>
<td>97.2</td>
<td>2.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 4.10: Efficiency of the optimized tracklet algorithm and tracklet composition for the minimum-bias Pb-Pb event sample cutting the clusters in the overlap regions of the SPD.

<table>
<thead>
<tr>
<th>(\Delta \phi_{\text{cut}}) (rad)</th>
<th>(\Delta \theta_{\text{cut}}) (rad)</th>
<th>(\Delta \phi_{\text{SPDoverlaps}}) (rad)</th>
<th>(\Delta z_{\text{SPDoverlaps}}) (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Comb. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.005</td>
<td>0.05</td>
<td>80.4</td>
<td>68.8</td>
<td>2.8</td>
<td>28.4</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.010</td>
<td>0.15</td>
<td>79.6</td>
<td>68.4</td>
<td>2.7</td>
<td>28.9</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>0.005</td>
<td>0.05</td>
<td>82.7</td>
<td>73.3</td>
<td>2.8</td>
<td>23.9</td>
</tr>
<tr>
<td>0.08</td>
<td>0.010</td>
<td>0.015</td>
<td>0.15</td>
<td>82.2</td>
<td>73.1</td>
<td>2.7</td>
<td>24.2</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.005</td>
<td>0.05</td>
<td>73.8</td>
<td>82.8</td>
<td>2.1</td>
<td>15.1</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.010</td>
<td>0.15</td>
<td>73.4</td>
<td>82.6</td>
<td>2.1</td>
<td>15.3</td>
</tr>
</tbody>
</table>

In Table 4.10 and Table 4.11 the efficiencies and the tracklet composition are quoted for Pb-Pb events. Comparing the reconstruction efficiency between the two sets of cuts, it can be concluded that the loss of efficiency is less than 1%. In this case the efficiencies are also slightly lower than the efficiencies quoted in Table 4.7 and Table 4.8, i.e. without using the option for the tracklet removal. In addition, looking at the \(\phi\) distributions of tracklets, removing tracklets in the overlaps with both cuts, it can be concluded that the best choice for the cut widths is \(\Delta \phi_{\text{SPDoverlaps}} = 0.01\) rad and \(\Delta z_{\text{SPDoverlaps}} = 0.15\) cm for Pb-Pb events: in Fig. 4.14 the comparison of the \(\phi\) distributions obtained keeping and eliminating tracklets in the SPD overlaps,
Table 4.11: Efficiency of the optimized tracklet algorithm and tracklet composition for the central Pb-Pb event sample cutting the clusters in the overlap regions of the SPD.

<table>
<thead>
<tr>
<th>$\Delta \varphi_{\text{cut}}$ (rad)</th>
<th>$\Delta \theta_{\text{cut}}$ (rad)</th>
<th>$\Delta \varphi_{\text{SPD overlaps}}$ (rad)</th>
<th>$\Delta z_{\text{SPD overlaps}}$ (cm)</th>
<th>Efficiency (%)</th>
<th>PP (%)</th>
<th>SS (%)</th>
<th>Comb. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.005</td>
<td>0.05</td>
<td>71.2</td>
<td>61.0</td>
<td>1.9</td>
<td>37.1</td>
</tr>
<tr>
<td>0.08</td>
<td>0.050</td>
<td>0.010</td>
<td>0.15</td>
<td>70.7</td>
<td>61.1</td>
<td>1.9</td>
<td>36.9</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>0.005</td>
<td>0.05</td>
<td>74.2</td>
<td>65.2</td>
<td>2.0</td>
<td>32.8</td>
</tr>
<tr>
<td>0.08</td>
<td>0.025</td>
<td>0.010</td>
<td>0.15</td>
<td>73.6</td>
<td>65.3</td>
<td>2.0</td>
<td>32.6</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.005</td>
<td>0.05</td>
<td>67.5</td>
<td>74.7</td>
<td>1.8</td>
<td>23.5</td>
</tr>
<tr>
<td>0.04</td>
<td>0.005</td>
<td>0.010</td>
<td>0.15</td>
<td>67.0</td>
<td>74.7</td>
<td>1.8</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Figure 4.14: Comparison between the $\varphi$ distribution for tracklets (left panel) and the same distribution obtained removing clusters in overlapping modules (right panel).

respectively, is shown for central Pb-Pb events. Using the tighter window, there are still residuals of the peaks left. In the p-p case the tighter window can be used since there is almost no difference enlarging the window. The flagging of clusters in the overlap regions of the SPD can be optionally switched on in the reconstruction.

The main features of the tracklet algorithm are described in an internal note of the ALICE Collaboration [94].
4.5 General reconstruction procedure

The reconstructed distributions have to be corrected for several effects to
obtain the physical distributions of primary charged particles. Primary particles are
defined as particles produced by the event generator and particles originated from
electromagnetic and strong decays. The products of weak decays and particles from
feed-down are excluded. Two event classes will be considered in this study: inelastic
and non single-diffractive events. The following effects, which affect the reconstructed
distribution, will be considered:

- background from secondary particles;
- algorithm and detector efficiency;
- detector acceptance;
- particles that do not reach the sensitive layers of the detector;
- vertex reconstruction efficiency;
- minimum-bias trigger efficiency.

These effects and the corresponding corrections have been studied both at the tracklet
and at the event level for the pseudorapidity density distribution. Regarding the
multiplicity, the same corrections have been studied and computed at the event level.
To calculate them, information from both reconstruction and Monte Carlo is needed.

In this paragraph the corrections and their calculation will be described. Finally,
the procedure to apply them to obtain the physical distributions will be illustrated.

4.5.1 Vertex reconstruction algorithm

The position of the primary vertex used in the present analysis has been estimated
exploiting the correlation between the reconstructed clusters in both SPD layers as
Two different strategies have been developed for p-p and Pb-Pb data. For p-p events the VertexerSPD3D algorithm tries to find the three coordinates of the primary vertex is called. If this algorithm fails, which happens mainly in events with very low multiplicity, the VertexerSPDz algorithm tries to calculate only the z-coordinate of the vertex. In Pb-Pb events only the VertexerSPDz algorithm is called since the first one would be time-consuming. In addition, in Pb-Pb events there is no need to calculate the x and y coordinates since the beams are not defocused or displaced. The run-by-run information on the position and spread of the interaction region (diamond), if available from the Offline Condition Database (OCDB), is used by the two algorithms. It is calculated quasi-online with a detector algorithm based on VertexerSPD3D with the purpose of monitoring the position and the size of the diamond during the run.

The two algorithms use all the possible associations of clusters (pairs or associations in the following) in the inner SPD layer to clusters in the SPD outer layer and apply several cuts. The VertexerSPDz algorithm imposes a cut on $\Delta \varphi < 0.01$ rad for each pair to exclude the contributions of low $p_t$ tracks: the pairs selected very likely correspond to high momentum tracks (straight lines in the bending plane). For all these pairs the intersection with the z axis is calculated ($z_i$). A region of interest (ROI) around the peak of the $z_i$ is defined and the mean of the $z_i$, weighted with the errors given by the pixels, is calculated. The ROI is then centred on the calculated mean and the steps are redone every time centering the ROI on the new mean till this region becomes symmetric. This allows possible biases due to asymmetries in the tails of the distributions of the $z_i$ to be minimized. If the vertex is not found the procedure can be redone enlarging the azimuthal window. By default the procedure is redone three times enlarging the $\Delta \varphi$ window up to 0.2 rad.

The VertexerSPD3D algorithm consists of several selection steps. First a selection
of pairs is made in a cylindrical fiducial region where the interaction point is expected to be located (the region is centred on the average beam position provided by the quasi-online detector algorithm): two cuts are imposed on the $\Delta \varphi$ and on the distance of each pair from the centre of the fiducial region. Then a further selection of pairs of associations is made considering their mutual distance of closest approach and applying a cut on that distance. The crossing point of each pair is calculated and further cuts are applied. Finally the coordinates of the vertex are given by finding the point of minimum distance among the pairs that passed the three selection steps. The procedure is redone tightening all the cuts applied and considering the position of the vertex found in the first iteration.

The knowledge of the transverse position of the beam is used in the two algorithm to properly centre the fiducial region in which the pairs of clusters are selected.

The main factors that affect the efficiency and the resolution of the vertex finding are the multiplicity of particles in the event, the position of the vertex along the z axis and the strength of the magnetic field. The efficiency decreases significantly when the vertex approaches the physical limit of the SPD coverage in z: the SPD acceptance is limited in z to $\pm 14$ cm. The efficiency of the vertex finding as a function of the Monte Carlo multiplicity in $|\eta| < 1.4$ is shown in the right panel of Fig. 4.2 for events that fulfil the MB1 trigger condition.

The resolution decreases increasing the number of pairs that contribute to the vertex determination and is about 0.1-0.3 mm in the longitudinal direction and 0.2-0.5 mm in the transverse directions.

In the analysis only events with the z coordinate of the reconstructed vertex $|z_{SPDvtx}| < 10$ cm will be used, since the efficiency and reliability decreases for larger values because the vertex finding is biased by SPD acceptance effects.
4.5.2 Pseudorapidity density distribution

4.5.2.1 Description of the method

The reconstructed data needs two types of corrections in order to reconstruct the distribution of primary charged particles: at the tracklet level to correct the number of tracklets in pseudorapidity bins and at the event level to correct the number of events to obtain the proper normalization factor in each pseudorapidity bin. At the tracklet level the corrections depend on the longitudinal vertex position and in the pseudorapidity, but in principle they can also be multiplicity dependent. At the event level the corrections still depend on the longitudinal vertex position and on the multiplicity. For these reasons, data are stored in two-dimensional histograms both at the track and event level. Two classes of events in the data have to be considered to apply the corrections, as will be clear in the next sections: triggered events and triggered events in which a vertex has been found. In the latter, only events with the $z$-coordinate of the reconstructed vertex in $|z_{SPD_{vtx}}| < 10$ cm and at least one tracklet reconstructed ($\text{mult}_{SPD} > 0$) are considered (reconstructed events in the following). These two conditions are required since the efficiency of the vertex reconstruction decreases for larger values due to SPD acceptance and also because the efficiency and the quality of the vertex decreases with the multiplicity. Reconstructed events will be indicated in the text as trigVtxEvts and triggered events as trigEvts. A histogram, to which corrections tracklet by tracklet will be applied, is filled for each reconstructed event with the reconstructed vertex position $z_{SPD_{vtx}}$ and the pseudorapidity $\eta_{SPD}$ of each tracklet

$$\text{tracklets}(\eta_{SPD}, z_{SPD_{vtx}})$$

(4.4)

At the event level two histograms are filled with the reconstructed vertex and the tracklet multiplicity for the proper event class:

$$\text{trigVtxEvts}(\text{mult}_{SPD}, z_{SPD_{vtx}})$$

(4.5)
one for reconstructed events and the other for triggered events only. The
zero-multiplicity bin will be empty for the first histograms since these events are
not considered in the definition of that event class and, for the second one, the
zero-multiplicity bin will be always filled with $z_{SPD_{vtx}} = 0$ cm since, even if
determined, this value is not reliable. Indeed, it has been verified on Monte Carlo
simulations that if events with zero tracklet multiplicity have a reconstructed vertex
(1% of the events), this vertex can be several centimetres apart from the Monte
Carlo vertex. The three histograms mentioned above can be filled in both for real
and simulated events and will be used to apply the corrections.

For the simulated events only, two-dimensional histograms are used to calculate
and store the multiplicative factors to correct the data both at the tracklet and at
the event level:

$$TLC_i(\eta, z_{vtx}) \quad ELC_j(mult_{SPD}, z_{MC_{vtx}})$$

(4.7)

where the indices $i$ and $j$ indicate that there are several of these matrix for each effect
to be corrected. The data and the correction histograms have the same binning which
can be set appropriately.

The products of data matrices and corrections are stored in independent
histograms to have the result at each correction step. The pseudorapidity
distributions are obtained from the projection of these product histograms on the $\eta$
axis. The $dN_{ch}/d\eta$ distributions will result from the ratio between the pseudorapidity
distributions and the proper normalization histograms or factors, which will be
described later. The event level corrections enter in the calculation of these
normalization factors. Therefore the final distribution in each pseudorapidity bin
is given by

$$\frac{dN}{d\eta}(\eta) = \frac{\int_{\eta} tracklets(\eta, z) * \prod_i TLC_i(\eta, z) \, dz}{\int_{z_1}^{z_2} \sum_m trigVtxEvts(m, z) * trigEvts(m, z) * \prod_j ELC_j(m, z) \, dz}$$

(4.8)
where $z_1$ and $z_2$ are the minimum and the maximum values of the vertex position that gives that $\eta$ value in the SPD acceptance. Finally, the number of pseudorapidity bins per unit of pseudorapidity multiplies the content of each bin. The products over the corrections can be limited to a subset of corrections to obtain the distribution at intermediate phases of the correction process.

The correction procedure is also described in an internal note of the ALICE Collaboration [95]. In the next paragraph each correction and the computing method are described.

4.5.2.2 Tracklet level corrections

The corrections at the track level are calculated as a function of the pseudorapidity $\eta$ and the $z$-coordinate of the primary vertex and are stored in two-dimensional histograms. The binning of those histograms in the analysis shown in this chapter is 2 cm in $z$ and 0.1 in $\eta$. The corrections needed at the track level are the following:

- background from secondary particles;
- algorithm and detector efficiency;
- detector acceptance;
- particles that do not reach the sensitive layers;
- vertex reconstruction efficiency;
- minimum-bias trigger efficiency.

To calculate them, the following information produced in the reconstruction is retrieved from the ESDs files:

- the reconstructed vertex position $z_{\text{SPDvtx}}$.
• the tracklet pseudorapidity $\eta_{SPD}$;

• the two Monte Carlo particle labels of the clusters in the tracklet.

Furthermore the following Monte Carlo variables allow the calculation to be completed:

• the vertex position $z_{MC_{ext}}$;

• the pseudorapidity $\eta_{MC}$ of primary particles;

• particle indices;

• the track references produced during particle transport through the detector;

• the event type.

Using this information, the generated primary particles can be subdivided into the following subsets:

• **reconstructed**: primaries that have a tracklet associated;

• **reconstructable**: primaries that cross sensitive regions of the two SPD layers and might then produce at least one cluster in each layer;

• **detectable**: primaries crossing the two SPD layers.

**Background from secondaries** Because of the presence of particles produced in secondary interactions and decays, a certain amount of background tracklets will be reconstructed. These are tracklets that cannot be associated to a primary particle because the two clusters that compose the tracklet have been produced either by two different particles (combinatorial) or by the same secondary particle. A correction factor is needed to subtract the contribution of background tracklets.
Background tracklets have been identified by means of the labels each cluster has that record the particle or particles which generated it. Each cluster has at most three labels and for each tracklet two labels are stored: if the two clusters associated have at least one equal label, the tracklet takes that label for each of the two clusters, otherwise the first label for each cluster is stored. These labels allow primaries that have been reconstructed to be selected: for each primary if a tracklet is found having both labels matching with this primary, it is labeled as reconstructed. For each reconstructed primary particle a two dimensional histogram is filled using the values of the generated pseudorapidity $\eta_{MC}$ and the generated vertex position $z_{MCvtx}$. For all reconstructed tracklets, both primary and background tracklets, another two dimensional histogram is filled with reconstructed pseudorapidity $\eta_{SPD}$ and the reconstructed vertex position $z_{SPDvtx}$. The correction is the ratio between the two histograms:

$$T_{C_{Bkg}}(\eta, z_{vtx}) = \frac{\sum_{trigVtxEvts} #reconstructedPrimitives(\eta_{MC}, z_{MCvtx})}{\sum_{trigVtxEvts} #tracklets(\eta_{rec}, z_{SPDvtx})}$$ (4.9)

This correction will depend on the cuts applied in the reconstruction: the larger the windows, the higher the background fraction. The cuts for the tracklet reconstruction have to balance the background fraction and the reconstruction efficiency. However a lower background percentage is preferable to a higher efficiency as, in principle, the background might depend on the multiplicity and then will depend on the model used to simulate the sample on which corrections are calculated.

**Tracklets reconstruction efficiency**

The algorithm is inefficient if it fails to associate the clusters produced by the same primary particle in each of the two SPD layers. Two effects can cause the failure: either the wrong association of the cluster in the outer layer to make up a combinatorial tracklet or the width of the fiducial window.
All the primaries producing at least one cluster on both the SPD layers should be defined as \textbf{reconstructable} primaries. However, since the clusters are not available in the ESDs, the track references are used for this purpose. For most of the detectors, for each primary particle a track reference is stored if the particle crosses a sensitive region of the detector. This approximation is quite good: the presence of a track reference does not correspond to the presence of a cluster mainly for tracks with high pseudorapidity that might not produce a signal over the threshold. Thus, the presence of at least one track reference in each SPD layer is required. A two-dimensional histogram is filled for each reconstructable particle. The ratio between the histogram of the reconstructable particles and the reconstructed particles is the correction that takes into account the tracklet algorithm efficiency

\[ TC_{\text{Eff}}(\eta, z_{\text{vtx}}) = \frac{\sum_{\text{trigVtxEvents}} \#\text{reconstructablePrimitives}(\eta_{\text{MC}}, z_{\text{MCvtx}})}{\sum_{\text{trigVtxEvents}} \#\text{reconstructedPrimitives}(\eta_{\text{MC}}, z_{\text{MCvtx}})} \] (4.10)

and represents for each bin the inverse of the algorithm efficiency. On the other hand, the correction for the tracklet algorithm efficiency only depends on the cut window widths.

\textbf{Detector efficiency}

A cluster from a primary could be missing due to the presence of dead or noisy channels (ladders, chips and pixels). This will cause a primary particle not to be reconstructed and a correction for such loss has to be added. This contribution is evaluated including in the simulation a dead channel map for the detector.

It should be noticed that such a condition implies that this correction is automatically included in the one previously described: the reconstructable particles, whose definition relies on the presence of track references, are not affected by the presence of dead channels as the reconstructed particles are.
Geometrical acceptance

This correction can be calculated once and for all for each layer and for tracklets, provided the detector geometry is fixed. The calculation is carried out selecting the detectable primaries, namely primaries which have reached and crossed the region in which the detector is placed. Those particles might or might not have produced a signal in the detector according to whether the traversed volume is sensitive or not. The selection of the detectable primaries can be performed using the track references. As already mentioned, for each primary Monte Carlo particle a number of track references is stored during the transport through the ALICE geometry if the particle crosses the sensitive region of a detector, each detector being identified with a numerical label. A track reference with the numerical label = -1 is saved when the particle disappears somewhere in the geometry (detector material or empty space). A particle to be labeled as detectable for a specific detector (both SPD layers in the present case) has to satisfy one of the following conditions:

- it has no track references at all or it does not have a track reference with label equal to -1, which means it did not disappear in the ALICE geometry;
- it has a track reference with label equal to -1 and with a radius greater than the maximum radius of the track references of the detector, that means the particle disappeared after the detector;
- it has at least one track reference with radius in the range of the radii of the detector, that means the particle crossed a sensitive region of the detector.

As a consequence of the previous definition, particles outside the acceptance of the detector could be labeled as detectable as well, but without affecting the correction calculation since the correction will not be used outside the acceptance region of the detector. A two-dimensional histogram is filled for each detectable primary. The
Figure 4.15: Acceptance correction for the SPD inner (left panel) and outer (right panel) layer.

generational acceptance correction for each bin is the ratio between the histogram of detectable primaries and the histogram of reconstructable primaries

\[
Acc = \frac{1}{TC_{Acc}(\eta, z_{vtx})} = \frac{\sum_{\text{trigVtxEvts}} \text{#detectablePrimitives}(\eta_{MC}, z_{MC_{vtx}})}{\sum_{\text{trigVtxEvts}} \text{#reconstructablePrimitives}(\eta_{MC}, z_{MC_{vtx}})}
\] (4.11)

In Fig. 4.15 the correction is shown as a function of \(z_{MC_{vtx}}\) and \(\eta_{MC}\) for both the SPD layers. The same map for tracklets is shown in Fig. 4.16. It can be noted that the pseudorapidity range covered depends on the vertex position and that for \(z_{vtx} = 0\) cm (primary vertex in the center of the detector) the main losses come from three “holes” corresponding to the three junctions between ladders: for the inner layer at \(\eta = -1.35\), \(\eta = 0\) and \(\eta = 1.35\), for the outer layer at \(\eta = -0.86\), \(\eta = 0\) and \(\eta = 0.86\). For tracklets (Fig. 4.16) the acceptance contains the combination of all the holes in both layers.

The effect of the acceptance also has to be taken into account at the event level to calculate the correct normalization factors for each bin of the pseudorapidity distribution once corrected for the acceptance. Indeed, due to the limited dimension in \(z\) of the detector and to the spread of the vertex position, not all the reconstructed events will contribute to each \(\eta\) bin of the corrected distribution but for each \(\eta\) bin a range \(z_1 < z_{SPD_{vtx}} < z_2\) of the reconstructed vertex distribution will be considered to fill the normalization histogram. For a pseudorapidity bin \(\eta'\) this range is defined
requiring $TC_{Acc}(\eta', z) > 0$.

**Particles not reaching the sensitive layers**

A fraction of primary particles does not reach the sensitive layers of the detector because particles decay, undergo secondary interactions or are below the $p_t$ cut-off to reach the SPD outer layer. This correction is calculated as the ratio between all primary particles produced by the generator in events triggered with vertex and the detectable primaries.

The two histograms needed to calculate this correction are the one of the detectable primaries and the one of all the primaries generated in reconstructed events. The correction corresponds to the inverse fraction of primary particles which traverse the SPD.

$$TC_{Decays}(\eta, z_{vtx}) = \frac{\sum_{\text{trigVtxEvts}} \#Primaries(\eta_{MC}, z_{vtxMC})}{\sum_{\text{trigVtxEvts}} \#detectable Primaries(\eta_{MC}, z_{vtxMC})}$$  \hspace{1cm} (4.12)

**Vertex reconstruction efficiency and minimum-bias trigger acceptance**

A fraction of the triggered events may not have a vertex reconstructed so it is necessary to add at this stage the contribution of the missing events both at the
event level and at the tracklet level.

At the tracklet level, this correction is calculated as the ratio between the primary charged particles produced by the generator in triggered events and the primary charged particle found in reconstructed events

\[
TC_{Vertex}(\eta_{MC}, z_{MC_{vtx}}) = \frac{\sum_{\text{trigEvts}} \# Primaries(\eta_{MC}, z_{MC_{vtx}})}{\sum_{\text{trigVtxEvts}} \# Primaries(\eta_{MC}, z_{MC_{vtx}})} \quad (4.13)
\]

Similarly, the ratio between the primaries in all the generated events for a certain event class (inelastic or non single-diffractive) and the primaries in triggered events is the correction needed to take into account the primaries missed due to the minimum-bias trigger selection.

\[
TC_{Trigger}(\eta_{MC}, z_{MC_{vtx}}) = \frac{\sum_{\text{allEvts}} \# Primaries(\eta_{MC}, z_{MC_{vtx}})}{\sum_{\text{trigEvts}} \# Primaries(\eta_{MC}, z_{MC_{vtx}})} \quad (4.14)
\]

Two distinct corrections for inelastic and non single-diffractive events have been calculated. Events contributing to these two corrections are low multiplicity events in the central \( \eta \) region, so the correction is very low (at the level of few per mill for inelastic events) and does not show any dependence on \( \eta \) and \( z \).

### 4.5.2.3 Event level corrections

The corrections needed at the event level are calculated as a function of the reconstructed multiplicity \( \text{mult}_{SPD} \) (i.e. the number of reconstructed tracklets) and the position of the Monte Carlo primary vertex \( z_{MC_{vtx}} \). They are the following:

- vertex reconstruction efficiency;
- minimum-bias trigger efficiency.

These allow the normalization factors for the corresponding corrected pseudorapidity distributions to be calculated to obtain the \( dN_{ch}/d\eta \) distributions. To calculate them,
besides the information used for the track level correction calculation, the tracklet multiplicity is used.

**Vertex reconstruction efficiency** The vertex reconstruction efficiency correction is the ratio between all triggered events and all the reconstructed events in each bin

\[
EC_{\text{vertex}}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}}) = \frac{\sum_{\text{trigEvts}} \#\text{events}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}})}{\sum_{\text{trigVtxEvts}} \#\text{events}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}})} \quad (4.15)
\]

This correction is equal to one everywhere by construction and zero in the zero-multiplicity bin since events with zero tracklet multiplicity are not considered in the sample of reconstructed events, as explained for the data histograms.

**Minimum-bias trigger efficiency** The trigger efficiency correction is calculated as the ratio between two-dimensional matrices: one filled for all the events generated in a certain event class and the other filled for all triggered events

\[
EC_{\text{trigger}}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}}) = \frac{\sum_{\text{allEvts}} \#\text{events}_{\text{evtClass}}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}})}{\sum_{\text{trigEvts}} \#\text{events}(\text{mult}_{\text{SPD}}, z_{\text{MCvtx}})} \quad (4.16)
\]

### 4.5.3 Statistical errors on the corrections

The statistical error per bin for those corrections which are defined as efficiencies, as for example the acceptance correction, has been calculated using the binomial distribution. In the following the calculation is illustrated for the acceptance correction.

For each bin the acceptance is the ratio between M successes (detected) over N identical and independent trials (detectable). The variable M follows a binomial distribution, the true acceptance being the probability p of success. The mean and variance of the binomial distribution are \( \mu = Np \) and \( \sigma^2 = Np(1-p) \). The variance of \( \text{Acc} = M/N \) is \( \sigma^2_{\text{Acc}} = p(1-p)/N \). The error on the acceptance is then
\[ \sigma_{Acc} = \sqrt{Acc(1 - Acc)/N}, \] which are binomial errors. This is valid in the limit of large N, where Acc can be taken as an estimate of p.

This applies to all corrections, except the background correction and the trigger non single-diffractive event corrections as they do not represent efficiencies: these both have to subtract a fraction to each bin.

However they can be written as the sum of an efficiency and a part whose numerator and denominator are not independent. For the background correction for example one has the following, omitting the summations for the sake of simplicity:

\[
\frac{1}{TC_{Bkg}(\eta, z_{vtx})} = \frac{tracklets(\eta_{rec}, z_{SPD_{vtx}})}{reconstructedPrimitives(\eta_{MC}, z_{MC_{vtx}})} = \frac{primTracklets}{reconstructedPrimitives} + \frac{bkgTracklets + ovelapTracklets}{reconstructedPrimitives} = efficiency + \frac{bkgTracklets + ovelapTracklets}{reconstructedPrimitives}
\]

(4.17)

The first term has a binomial error (however in the background case this efficiency term is equal to one); on the second term the error can be estimated as an upper limit, that is the ratio between the square root of the numerator and the denominator.

The errors on the trigger corrections for the non single-diffractive events are computed likewise.

4.5.4 Preliminary reconstruction of the multiplicity distribution

A study has been carried out to develop an event-by-event method to correct the charged-particle multiplicity measured counting tracklets in a certain pseudorapidity range. The multiplicity distribution can also be obtained using these corrected values of the multiplicity and further correcting for the number of events missing due to vertex and trigger efficiency. With this method a value of the measured multiplicity
μ_{meas} in an event with vertex z will always give the same value for the corrected multiplicity μ_{corr}. Further development of this procedure can be useful for studies in which an event-by-event estimation of the multiplicity is necessary, as for example to study the correlation between multiplicity and centrality in heavy-ion interactions.

The proper method to correct the multiplicity distribution in reconstructed events is using unfolding methods as explained in Chapter 3. The unfolding problem applies when a distribution f(x) of a kinematic variable x has to be measured. There are three main issues in measuring this distribution:

- the limited detector acceptance, that is the probability to observe a given event;
- the transformation of the measured variable: y is measured instead of x, even though these are related;
- the finite detector resolution: y is also smeared out due to the finite detector resolution or to the limited accuracy of the method.

The unfolding allows the true distribution f(x) of the true variable x to be obtained starting from the measured distribution g(y) of the measured quantity y. To solve this problem requires the knowledge of the resolution function A(y,x) that represents the effects of the detector. The detector response matrix, i.e. the probability that a certain true multiplicity gives a certain measured multiplicity, can be obtained from detector simulation studies. Using this, the true multiplicity spectrum can be estimated from the measured spectrum using different unfolding techniques. The procedure of measuring the multiplicity distribution with the ALICE detector (using the Silicon Pixel Detector of the ITS, as well as the full tracking based on the TPC), is thoroughly described in [96] The unfolding, however, does not allow the multiplicity to be obtained event-by-event.

The event-by-event correction method described in the following uses the same information obtained from the reconstruction process and Monte Carlo simulation to
correct the dN_{ch}/d\eta distribution: the selection of reconstructed, reconstructable and detectable primaries and the same subsets of event samples (i.e. trigVtxEvts and trigEvts for the data sample, inelastic and non single-diffractive for the Monte Carlo sample). This information is properly used to calculate corrections as a function of the tracklets multiplicity (\text{multSPD}) and of the position of the Monte Carlo primary vertex. The pseudorapidity range |\eta| < 1.4 has been chosen to calculate the reconstructed tracklet multiplicity and the multiplicity calculated in this range will be indicated as \text{multSPD}_{\text{EtaCut}}. All the multiplicities reported in the following are calculated in this pseudorapidity range if not otherwise stated.

The measured multiplicity and the measured vertex (data) are stored in a two-dimensional histogram for each reconstructed event

$$ \text{data}(\text{multSPD}_{\text{EtaCut}}, z_{\text{SPDvtx}}) $$

(4.18)

The following matrices, where the index \(i\) indicates that different values are obtained according to the number of corrections applied, will be filled with the corrected multiplicities \(\text{corrMult}_{\text{EtaCut},i}\)

$$ \text{corrData}_i(\text{corrMult}_{\text{EtaCut},i}, z_{\text{SPDvtx}}) $$

(4.19)

To correct the measured tracklet multiplicity \text{multSPD}_{\text{EtaCut}} the following corrections are needed:

- background subtraction;
- efficiency correction;
- acceptance correction;
- correction for decays and low \(p_t\) particles.
Each correction is stored in a two-dimensional matrix

\[ MC_i(multSPD_{EtaCut}, z_{MC_{vtx}}) \]  \hspace{1cm} (4.20)

For each event the ratio between the multiplicity of reconstructed primaries and the tracklet multiplicity is computed. The background correction is then evaluated in each bin as the mean value of these ratios over all the events contributing to that bin:

\[ MC_{Bkg}(multSPD_{EtaCut}, z_{MC_{vtx}}) = \langle \frac{ReconstructedMult}{TrackletMult} \rangle \]  \hspace{1cm} (4.21)

The efficiency correction is defined similarly as the ratio between the reconstructed primaries and the reconstructable primaries:

\[ MC_{Eff}(multSPD_{EtaCut}, z_{MC_{vtx}}) = \langle \frac{ReconstructableMult}{ReconstructedMult} \rangle \]  \hspace{1cm} (4.22)

The global acceptance correction for the tracklet multiplicity only depends on the longitudinal position of the vertex. To calculate the correction factor as a function of the vertex position, the acceptance correction Acc(\(\eta, z\)) is considered (Section 4.5.2). The following assumption is made to calculate the global acceptance: the number of primaries corrected for acceptance does not depend on the pseudorapidity. Indeed the pseudorapidity distribution is almost flat in the pseudorapidity range considered. The mean value of the acceptance is calculated then for each vertex over the whole pseudorapidity range chosen for the analysis.

\[ MC_{Acc}(z_{MC_{vtx}}) = \langle Acc(\eta, z) \rangle_{|\eta|<\text{EtaCut}} \]  \hspace{1cm} (4.23)

This assumption allows the multiplicity to be measured in regions where the detector also has no acceptance coverage.

Taking into account the contribution to the multiplicity of primary charged particles that do not reach the outer layer of the SPD detector, the following correction is calculated:

\[ MC_{Decays}(multSPD_{EtaCut}, z_{MC_{vtx}}) = \langle PrimMult \rangle_{DetectableMult} \]  \hspace{1cm} (4.24)
Applying all these corrections to each measured tracklet multiplicity value allows the corrected multiplicity $\text{correctedMult}_{\text{EtaCut}}$ to be obtained in the event with the reconstructed vertex $z = z_{MC\text{vtx}}$

$$\text{correctedMult}_{\text{EtaCut}} = \text{multSPD}_{\text{EtaCut}} \cdot \prod_i MC_i(\text{multSPD}_{\text{EtaCut}}, z_{MC\text{vtx}}) \quad (4.25)$$

The multiplicity distribution in the reconstructed events is then obtained using these corrected values. At this stage, to obtain the distribution in triggered events and in all events for the inelastic and non single-diffractive p-p interactions, two corrections $\text{MEC}_i(\text{MCmult}_{\text{EtaCut}}, z_{MC\text{vtx}})$ have to be applied to the distribution of corrected multiplicities. The corrections for vertex finding efficiency and trigger bias and efficiency are calculated as a function of the Monte Carlo multiplicity and the Monte Carlo vertex

$$\text{MEC}_{\text{vertex}}(\text{MCmult}_{\text{EtaCut}}, z_{MC\text{vtx}}) = \frac{\sum_{\text{trigEvts}} \#\text{events}}{\sum_{\text{trigVtxEvts}} \#\text{events}} \quad (4.26)$$

$$\text{MEC}_{\text{trigger}}(\text{MCmult}_{\text{EtaCut}}, z_{MC\text{vtx}}) = \frac{\sum_{\text{allEvts}} \#\text{events}}{\sum_{\text{trigEvts}} \#\text{events}} \quad (4.27)$$

These corrections are applied to the two-dimensional matrix of the corrected multiplicities in Eq. 4.19. The final multiplicity distribution is obtained by projecting this two-dimensional matrix product on the multiplicity axis.

## 4.6 Reconstruction in p-p collisions

In this section the corrections calculated for the pseudorapidity density distribution and for the multiplicity, which have been previously described, will be shown using p-p Monte Carlo samples available on the CAF. The results from the application of the corrections to Monte Carlo reconstructed data will be also shown.
4.6.1 Calculating and applying corrections

4.6.1.1 Pseudorapidity density

In Fig. 4.17 the reconstructed and the Monte Carlo primary charged particle $dN_{ch}/d\eta$ distributions are shown. The reconstructed distribution is obtained counting tracklets in each pseudorapidity bin and dividing the distribution by the number of the reconstructed events. The effect of the detector acceptance can be seen in particular for $|\eta| > 1$: this effect will be corrected at the event level with a proper normalization factor that takes into account only events that contribute to each $\eta$ bin.

The background correction is shown in Fig. 4.18. The background fraction is about 6 % in the central pseudorapidity region and increases up to 10 % with the pseudorapidity due to the longer distance and the amount of material budget crossed. The overall background fraction with the default cuts used in tracklet reconstruction is about 5 %.
Figure 4.18: *Background correction: ratio between the reconstructed primaries and all the tracklet reconstructed for each bin.*

The correction for the algorithm and the detector efficiency is shown in Fig. 4.19. The dominant effect is that of the detector dead channels that also produces the asymmetry in the map since the dead channels map in not symmetric in $\eta$. The effect of the overall algorithm efficiency with the default cuts used in the reconstruction as been evaluated to be about 2 %.

The correction for primary charged particles, which do not reach the sensitive layers of the detector is shown in Fig. 4.20. It is about 3 % in the central region and larger increasing $|\eta|$ due to the longer distance that particles have to cover to reach the detector.

The combined correction for vertex finding and minimum-bias trigger efficiency at the tracklet level is less than 0.5 % since both events that do not fulfil the trigger condition and triggered events without a vertex are very low multiplicity events. This correction does not show any particular dependence on the pseudorapidity and the
The event level correction for vertex efficiency is one by construction everywhere and zero in the zero-multiplicity bin, since events with zero tracklet multiplicity are not considered in the sample of reconstructed events, as previously explained.

In Fig. 4.21 the correction for the trigger bias and efficiency is shown both for inelastic and non single-diffractive events. For inelastic events it is equal to one for $\text{mult}_{SPD} > 0$ and greater than one in the zero-multiplicity bin since it must correct for events that have not been triggered. The correction for non single-diffractive events is less than one since it mainly reduces single-diffractive events from the selected sample: this reduction is stronger (correction factor lower) at low multiplicity, since single-diffractive events are events with low multiplicity in the central pseudorapidity region.

To apply the correction to the reconstructed data the following procedure is
adopted. The tracklet data matrix will be multiplied by the correction matrices, adding one correction at a time to show the effect of each correction on the $dN_{ch}/d\eta$ distribution.

$$tracklets(\eta, z_{vtx}) \times \prod_{i} TLM_{i}(\eta, z_{vtx})$$  \hspace{1cm} (4.28)

The projections on the $\eta$ axis are normalized as follows:

- with the number of reconstructed events for each bin, if the distribution is not corrected for acceptance;

- with a different factor for each bin, as calculated using the acceptance map, if the distribution is corrected for the SPD acceptance.

In Fig. 4.22 the results applying one correction at a time are shown. The distribution after background subtraction has about 5% less tracklets than the reconstructed distribution, as expected. The efficiency correction is quite high and makes the
distribution symmetric. To correct for the acceptance, the track level map is not enough: a normalization histogram has to be filled as previously illustrated. Looking at the distribution corrected also for acceptance, the effect of the proper normalization is noticeable for $|\eta| > 1$. The higher distribution is the distribution in the reconstructed events.

To obtain the distribution in the triggered events and in the whole sample of events for the two event classes, the corrections for vertex and trigger efficiency are applied both at the tracklet and at the event level. At the event level the corrections are applied as follows from the following remarks. The vertex correction is unity except in the zero-multiplicity bin where it is zero. This implies that the vertex correction cannot correct the number of events in the zero-multiplicity bin. However, the number of triggered events and its distribution in multiplicity are known. What is not known is their vertex distribution in the zero-multiplicity bin, since triggered events with zero tracklet multiplicity do not have a reconstructed vertex. This prevents from calculating the normalization histogram for the vertex efficiency corrected distribution and afterwards to apply the trigger correction at the event level, which is vertex dependent. The vertex distribution of triggered events in the zero multiplicity bin
can be assumed from the Monte Carlo simulation or, alternatively, can be inferred from data. The only information available from data is the vertex distribution of reconstructed events. Assuming that the vertex distribution is independent of multiplicity, the fractions of reconstructed events for each vertex bin can be calculated. The triggered events with zero tracklet multiplicity will be distributed in vertex bins using these fractions. However these fractions are calculated on triggered events which have a vertex so the hypothesis that the vertex distribution is not dependent on multiplicity is not true and introduces a bias the calculation. These fractions will be then corrected using the Monte Carlo simulation: the correction will take into account how the fractions of triggered events with zero multiplicity are distributed in vertex bins with respect to the fractions of reconstructed events. These correction factors are less than 15%. In Fig. 4.23 the distributions obtained applying these corrections at the track and event level are shown.

In Fig. 4.24 the final results are compared to the Monte Carlo distributions for the
two event classes. The ratios between the Monte Carlo and the corrected distributions are also shown: it is clear that the Monte Carlo distribution is well reproduced that means all the contributions are properly considered in the correction process.

### 4.6.1.1.1 Method verification

A verification of the method can be performed using the same sample both to calculate corrections and to fill the data matrices, processing only primary particles (the background correction is unity) and using the Monte Carlo values for the pseudorapidity and the vertex position. The Monte Carlo distribution in the SPD acceptance has to be obtained if the method is correct. In Fig. 4.25 the ratio between the generated distribution in the SPD acceptance and the corrected distribution is shown.
Figure 4.24: Corrected \( dN_{ch}/d\eta \) distribution in inelastic and non single-diffractive events (squares) compared to the Monte Carlo distributions (lines) (top panel) and their ratios (lower panels).

4.6.1.2 Event by event multiplicity

The corrections illustrated in Section 4.5.4 will be applied to the tracklet multiplicity in this paragraph. The corrected distributions will also be shown. These results have been obtained using a Monte Carlo sample at \( \sqrt{s} = 900 \) GeV generated with PYTHIA (see Section 4.2). The reconstructed and the Monte Carlo multiplicity distributions and their correlation are shown in Fig. 4.26.

In Fig. 4.27 the corrections for the measured multiplicity are shown. The efficiency correction has a strong dependence on the vertex due to the asymmetry of the position of dead modules in pseudorapidity.
Figure 4.25: *Ratio between the Monte Carlo dN_{ch}/d\eta distribution in inelastic events in the SPD acceptance and the corrected distribution obtained processing only primary particles and using the Monte Carlo values for the pseudorapidity and the primary vertex. The ratio is unity in the SPD acceptance that confirms that the method takes into account all the contributions properly.*

In Fig. 4.28 the corrections to obtain the multiplicity distribution in triggered events and in all (inelastic or non single-diffractive) events are shown. These factors correct the number of events in multiplicity bins.

In Fig. 4.29 the corrected distribution in the reconstructed events is shown together with the reconstructed and the Monte Carlo ones. The distribution is reproduced quite well except in the region of high multiplicity where the statistic limits the measurement. In the left panel of Fig. 4.30 the correlation between the corrected multiplicity at the first correction stage (only background correction applied) and the Monte Carlo multiplicity is shown and can be compared to the correlation in the right panel of Fig. 4.26 where the uncorrected multiplicity is plotted. The final correlation applying all the corrections to the tracklet multiplicity is shown in the right panel of Fig. 4.30: the correlation after the corrections is centred on the bisector, indicating that the true multiplicity in the pseudorapidity range covered by the detector can be obtained.

In Fig. 4.31 the corrected distributions for the sample of inelastic and non
Figure 4.26: Comparison between the generated and the reconstructed multiplicity.

single-diffractive events respectively are shown with the reconstructed and the Monte Carlo ones. The distributions have been obtained multiplying the two-dimensional matrix of the corrected multiplicities by the corrections for the trigger efficiency (inelastic and non single-diffractive).

4.7 Reconstruction in Pb-Pb collisions

In this section the dN_{ch}/d\eta analysis will be applied to the Pb-Pb Monte Carlo sample of central events. The selection on centrality is applied in the Monte Carlo simulation. In a further step, a centrality trigger condition can be implemented in the analysis to select on centrality classes.
Figure 4.27: Correction weights for the measured tracklet multiplicity as a function of the total reconstructed multiplicity and of the position of the primary vertex.
Figure 4.28: Correction weights to obtain the multiplicity distribution in triggered, all inelastic and non single-diffractive events.
Figure 4.29: Corrected multiplicity distribution in $|\eta| < 1.4$ in reconstructed events.

Figure 4.30: Correlations between the corrected tracklet multiplicity and the Monte Carlo multiplicity.
4.7.1 Calculating and applying corrections to the pseudorapidity density distribution

In this section the correction method described in Section 4.5.2 will be applied to central Pb-Pb events. The data and the corrections will be calculated on the same sample of events. Only corrections at the tracklet level are needed: in central events, due to the large number of clusters, a vertex is always reconstructed. In this analysis no trigger condition for event selection has been assumed. The corrections calculated for Pb-Pb central events at the tracklet level are shown in Fig. 4.32. The background correction is larger than in p-p events as expected from the study on the performance of the tracklet algorithm: the mean value of the correction is consistent with the background percentages extracted in the study to optimize the cuts for tracklet reconstruction (see Table 4.8).

Applying the corrections to reconstructed data, the distributions shown in Fig. 4.33 are obtained and compared to the Monte Carlo and the reconstructed distributions. The Monte Carlo distribution is well reproduced as it can be inferred from the ratio between the generated and the corrected distribution.

Figure 4.31: Corrected multiplicity distribution in $|\eta| < 1.4$ in inelastic events (left panel) and in non single-diffractive events (right panel).
Figure 4.32: Corrections at the tracklet level to obtain the $dN_{ch}/d\eta$ distribution, calculated for central Pb-Pb events.

Figure 4.33: Central Pb-Pb events: reconstructed, Monte Carlo and corrected $dN_{ch}/d\eta$ distributions at each correction step (left panel) and ratio between the Monte Carlo distribution and the fully corrected distribution (right panel).
4.8 Expected systematic uncertainties

In this paragraph the main sources of systematic error for the corrected $dN_{ch}/d\eta$ distribution will be listed and some of the associated systematic will be estimated for the p-p case only. These originate in the assumptions made in the simulation, i.e. the model and the parameters of the Monte Carlo generator, in the detector description, in the experimental conditions and in the parameters used in the analysis. The main sources of systematic uncertainties are listed below:

- uncertainty in the cross sections of the different processes;
- particle $p_t$ spectrum and particle composition;
- contribution of beam-gas events;
- presence of pile-up;
- uncertainty in the estimation of the material budget;
- uncertainty in the SPD residual misalignment;
- uncertainty in the efficiency of the detector;
- cuts used for tracklet definition.

The general procedure to evaluate each systematic is mainly the following. A Monte Carlo sample is modified, introducing changes in the parameters and variables whose effect has to be estimated. The modified sample is used to calculate corrections, while the unmodified sample is used both to fill data and correction matrices. The size of the systematics is evaluated here as the ratio between the distribution corrected using the unmodified sample and the distribution corrected using the modified sample.

An estimate of the systematic due to the combined effect of the assumptions in the event generator (fractions of different processes, particle spectrum and composition)
can be made using samples simulated with two different generators. The two generators used are PYTHIA for the sample to calculate the corrections and PhoJet to generate the data sample. In Fig. 4.34 the corrected distributions for inelastic and non single-diffractive events are shown. The ratios between the Monte Carlo distributions from the data sample (which is equivalent to use the corrected distributions obtained with the PhoJet sample both for data and corrections) and the distributions corrected using the correction sample (PYTHIA) are shown in Fig. 4.34 as well. It can be concluded that the systematic error is about 1 % for inelastic events and 4 % for non single-diffractive events at $\sqrt{s} = 7$ TeV. In particular in the two event generators the fractions of diffractive and non-diffractive processes differ as shown in Table 4.12 and the kinematic is also different. It is not possible to correct PYTHIA data using corrections calculated with PhoJet as the multiplicity reach with PhoJet is lower than with PYTHIA. All the systematic sources included can be also studied and estimated separately.

The systematic due to uncertainty on the cross sections of the different processes can be evaluated changing the relative fractions of diffractive and non-diffractive processes in the Monte Carlo sample. These fractions strongly affect the corrections for the trigger efficiency. The relative fractions of single and double diffractive processes have been changed from 0.50 up to 1.50 in the p-p PYTHIA Monte Carlo sample at $\sqrt{s} = 7$ TeV. In Fig. 4.35 the effect is shown for different sets of variations in the fractions. The systematic error is then about 8 % for non single-diffractive

<table>
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<th>Event type</th>
<th>Fractions</th>
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<tr>
<td></td>
<td>NSD</td>
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<tr>
<td>PYTHIA</td>
<td>0.809</td>
</tr>
<tr>
<td>PhoJet</td>
<td>0.860</td>
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Table 4.12: Fractions of different process types in the two samples generated with PYTHIA and PhoJet at $\sqrt{s} = 7$ TeV.
Figure 4.34: Corrected distribution for inelastic and non single-diffractive events superimposed to the Monte Carlo distributions (top panel): the data sample has been generated with PhoJet and corrected with a sample generated with PYTHIA. The Monte Carlo distributions are obtained from the data sample and indicate where the corrected distributions would have been placed if the same sample had been used to calculate corrections. The ratios that give an estimate of the systematics due to the different assumptions in the event generator are also shown (lower panels).
Figure 4.35: Ratios between the corrected $dN_{ch}/d\eta$ obtained from the unmodified sample and the corrected $dN_{ch}/d\eta$ obtained calculating the corrections with the modified sample. The modified fractions of single-diffractive and double-diffractive events are indicated in the legend, where SDfrac and DDfrac indicate the default PYTHIA values respectively.
Concerning effects related to the detector performance, the systematic due to a not well known SPD efficiency, can be estimated assuming in the filling of data matrices 1% of randomly distributed inefficient channels; if the inefficient zones are not correlated, this leads to an inefficiency in tracklet reconstruction of about 2%. The ratio between the corrected $dN_{ch}/d\eta$ and the corrected distribution in which the data sample is affected by an additional percentage of dead regions of the detector is shown in Fig. 4.36: the resulting error on the $dN_{ch}/d\eta$ is 2% both for the inelastic and the non single-diffractive measurement. This is an upper limit since the assumption of inefficient channels is put after the reconstruction (of clusters and tracklets) for the sake of simplicity.

A detailed description and the estimation of the main systematic errors on the $dN_{ch}/d\eta$ measurement in p-p collisions at $\sqrt{s} = 10$ TeV can be found in [96]. The
Some systematic errors on the $dN_{ch}/d\eta$ measurement estimated for \textit{p-p} events simulated with \textit{PYTHIA} and \textit{PhoJet} at $\sqrt{s} = 7$ TeV and magnetic field $B = 0.5$ T.

global systematic error stays at the level of few percent: about 2 % for inelastic events and 8 % for non single-diffractive events. It has been calculated as the sum in quadrature of the main contributions, even though there are correlations. Some of those errors can be better estimated once data will be available, such as misalignment, cross sections and beam-gas influence. The systematic errors evaluated here at $\sqrt{s} = 7$ TeV are summarized in 4.13 and in agreement with the corresponding values in [96].

<table>
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<tr>
<th>Systematic source</th>
<th>Inel</th>
<th>NSD</th>
</tr>
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<td>Relative cross sections</td>
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<td>8 %</td>
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<td>4 %</td>
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<td>SPD efficiency</td>
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Chapter 5

First ALICE p-p physics results and discussion

5.1 Introduction

During the early commissioning phase of the LHC, on the 20th of November 2009, two beams were injected in the LHC and circulated alternately in each direction at the injection energy of 450 GeV. The beam lifetime was gradually increased up to approximately 10 hours. On Monday afternoon, November 23rd 2009, two proton beams circulated together for the first time and collided at the injection energy \( \sqrt{s} = 900 \) GeV at the four Interaction Points. The four LHC experiments recorded a number of p-p collision candidates. After that, on the 29th of November the world record energy was also broken when one beam was accelerated reaching 1050 GeV and three hours later both LHC beams were successfully accelerated to 1.18 TeV. The previous world record of 0.98 TeV had been held by the US Fermi National Accelerator Laboratory’s Tevatron collider since 2001.

A concentrated commissioning phase is ongoing, aimed at increasing the beam intensity to provide meaningful proton–proton collision rates to deliver good
quantities of data to the experiments. The LHC is progressing towards the objective of first physics early in 2010, at a collision energy of $\sqrt{s} = 7 \text{ TeV}$.

Data collected by the ALICE detector on the 23rd of November have been used for the first measurement of the pseudorapidity density distribution of charged particles in the central pseudorapidity region using mainly data provided by the Silicon Pixel Detector [97]. In this chapter details about the data taking conditions and the first results from this data sample will be presented and discussed. Such results concern the $dN/d\eta$ reconstructed with pixel information and corrected using the method described in Chapter 4.

5.2 Data taking conditions

As previously mentioned, the first ALICE data taking with proton beams happened on the 23rd of November 2009. That day two proton bunches were circulated concurrently. The bunches used during the machine commissioning, so-called “pilot bunches”, have a low intensity (few $10^9$ protons per bunch and one pilot bunch per beam). They were brought into nominal position for collisions without any attempt to maximize the interaction rate. The first fill had pilot bunches in the buckets which crossed only in point 1 and 5, where ATLAS and CMS detectors are located respectively. A later fill was centred in Point 2 and within few seconds ALICE recorded the first collisions. The nominal r.m.s. size of the beams at the injection energy is 300 $\mu$m in the transverse direction and 10.5 cm in the longitudinal direction. As expected, at this early stage the size varied and deviated from these values. The bunch size has not been measured for the data used in this analysis. For the previous fill it was measured and resulted shorter than the nominal values, with a r.m.s. of about 8 cm. The ALICE solenoidal magnetic field was switched off in this data-taking phase.
Figure 5.1: Event display showing one of the first p-p collision candidates in the ALICE counting room: 3D, r-ϕ and r-z views of the detectors. Dimensions are shown in cm. The ellipse in the middle indicates the position of the reconstructed vertex, the blue dots correspond to reconstructed points in the six layers of the ITS, and the blue lines indicate tracks reconstructed in the ITS with loose quality cuts.

Only resistant detectors participated to this first data taking to avoid damage in case the beam would have been lost: the ITS detectors (SPD, SSD, SDD) and the V0.

About 83 % of the pixel detector channels and 77 % of the Fast-Or signals were operational during data taking. The High Level Trigger [98] computer farm reconstructed events online and real events were checked to come from a collision vertex almost centred in the middle of the experiment. In Fig. 5.1 one of the first events is shown, displayed in the ALICE counting room with the AliRoot software running in online mode.

ALICE triggered and recorded 284 real p-p collisions at 450+450 GeV in
coincidence with the two passing proton bunches. Events collected have been triggered by the SPD Fast-Or in coincidence with signals from the beam pickup detectors.

The trigger rate was measured just before collisions (which is basically background) with the same trigger condition. Without beams the measured rate was $3 \times 10^{-4}$ Hz (in coincidence with one bunch crossing interval per orbit); with one beam circulating, concurrently with the passage of the bunch, the rate was 0.006 Hz and as soon as the second beam was injected the rate increased significantly to 0.11 Hz. After 43 minutes, beams were dumped to proceed with the LHC commissioning phase. Data were promptly reconstructed and analysed.

5.2.1 Monte Carlo samples used for the analysis

Two official Monte Carlo minimum-bias p-p samples have been generated on the Grid with the most updated version of AliRoot at the same energy ($\sqrt{s} = 900$ GeV), magnetic field (B = 0 T) and detector configuration used for data taking. These are available on the CAF and are as follows:

- about 200 000 events generated with PYTHIA 6.4.14 [99], tune D6T [100];
- about 200 000 events generated with PhoJet.

Both samples have been used to evaluate trigger efficiencies and estimate systematic errors. The PYTHIA sample has been used to calculate the corrections for the $dN_{ch}/d\eta$ distribution. The two samples will be used in the analysis presented here for the same purposes.

In the calculation of the corrections using the PYTHIA sample, the fractions of the different processes (non-diffractive, single-diffractive and double-diffractive) have been scaled to obtain the same fractions measured by the UA5 experiment [101] at $\sqrt{s} = 900$ GeV and quoted in Table 5.1.
Table 5.1: Fractions of non-diffractive, single-diffractive and double-diffractive processes as measured by the UA5 experiment.

<table>
<thead>
<tr>
<th>$\sigma_{ND}/\sigma_{inel}$</th>
<th>$\sigma_{SD}/\sigma_{inel}$</th>
<th>$\sigma_{DD}/\sigma_{inel}$</th>
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<tbody>
<tr>
<td>0.767 ± 0.059</td>
<td>0.153 ± 0.031</td>
<td>0.08 ± 0.05</td>
</tr>
</tbody>
</table>

5.2.2 Event selection

The SPD has been used to trigger events. The required trigger condition was to have at least two Fast-Or signals within the whole detector. This condition was required in coincidence with the signals from the two beam pickup counter, confirming the passage of the two proton bunches. The trigger efficiencies for different event classes have been studied using the two samples listed in the previous section and are summarized in Table 5.2.

A further selection was performed offline to identify and remove beam-gas and beam-halo events (background events) [102]. The V0 and the other silicon layers of the ITS (SDD, SSD) were used for this purpose. The ratio between the number of tracklets and the number of the reconstructed points in the whole ITS is smaller for background events (as measured in the previous fill, triggering on the passage of one bunch from one side) than for collisions: cutting on this ratio background events were eliminated. The timing information from the V0 was used as well: events

<table>
<thead>
<tr>
<th>Event type</th>
<th>Trigger efficiencies (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PYTHIA 6.4.14 (tune D6T)</td>
</tr>
<tr>
<td>ND</td>
<td>98</td>
</tr>
<tr>
<td>SD</td>
<td>48</td>
</tr>
<tr>
<td>DD</td>
<td>53</td>
</tr>
<tr>
<td>Inel</td>
<td>87</td>
</tr>
<tr>
<td>NSD</td>
<td>94</td>
</tr>
</tbody>
</table>

Table 5.2: Efficiencies in selecting different event types requiring at least two Fast-Or signals per event in the whole SPD, for simulated p-p events at $\sqrt{s} = 900$ GeV for two different event generators.
with negative arrival times were removed. Indeed, the two V0 counters (described in Chapter 2) are fired by particles at a positive time with respect to the beam-crossing time (time zero), if the particles are produced in the collision. Particles arriving earlier than the time zero are particles produced in beam-gas or beam-halo collisions, outside the region between the two V0 counters. The arrival time of particles in the two V0 counters are shown in Fig. 5.2 for the collected data sample. The majority of the signals are clearly produced after the time zero, at the correct arrival time for collisions taking place around the nominal interaction vertex. A crosscheck campaign with the visual scan was carried out to confirm the quality of the events in the whole sample. Within this test, 29 events were classified as background events (10 % as expected from the previous fills) and 2 events were classified as cosmic events by scanning. The contamination from cosmic events is in agreement with the expectations.

5.2.3 First data samples

The sample consists of 284 events: out of these, 31 events have been eliminated since identified as background events and 15 events do not have a reconstructed vertex (so the vertex finding efficiency is 94 % for this sample). The vertex has been
reconstructed exploiting correlations between clusters produced in both layers of the SPD as described in the previous chapter. Out of all the events with a reconstructed vertex, 79% have been reconstructed with the Vertexer3D algorithm and 21% with the VertexerZ algorithm. The vertex distributions are shown in Fig. 5.3 for the transverse coordinates x and y, and the longitudinal coordinate z, separately.

The distributions in the transverse plane are very narrow and include the effect of detector resolution and residual misalignment. In the longitudinal direction the spread is as expected. In the three directions the vertex is well positioned with respect

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Figure 5.3: Reconstructed primary vertex distributions in the three coordinates, z in the longitudinal direction, x and y in the transverse direction. A Gaussian fit to the z distribution is shown (r.m.s. of about 4 cm).
to the centre of the detector, just slightly shifted. The small shifts of the vertex in the three directions have been used to generate the main interaction vertex position in the two Monte Carlo samples used for data analysis.

From the full available statistic of the selected events 227 events will be used for the analysis as these have a vertex in $|z_{\text{vertex}}| < 10$ cm and at least one tracklet.

Tracklets have been reconstructed using the SPD clusters and the reconstructed vertex. The cuts used for the tracklet definition are the default values defined in the previous chapter, namely $\Delta \varphi = 0.08$ rad and $\Delta \theta = 0.025$ rad.

### 5.3 Data analysis

The reconstructed $dN_{\text{ch}}/d\eta$ distribution is shown in Fig. 5.4. It has been obtained counting tracklets in each pseudorapidity bin, normalizing the distribution to the total number of selected events and finally multiplying the distribution by the number of bins per unit pseudorapidity (the same as for simulated data).

The distributions have been extracted for two event classes in order to compare these results with those of the UA5 experiment: all inelastic events (INEL) and non
single-diffractive events (NSD).

The corrections described in the previous chapter have been calculated on an official Monte Carlo sample generated for this purpose and available on the CAF. There is one main difference in the correction method as compared to the method described in the previous chapter. The vertex distribution of triggered events in the zero multiplicity bin has been assumed from the Monte Carlo, since the recorded sample is too small and does not have enough statistics. Of course it has been scaled properly according to the number of triggered events with vertex from data. The trigger condition applied for the data taking is also applied to the simulated data. Applying the corrections to the two-dimensional matrix of data shown in the right panel of Fig. 5.5 and calculating the proper normalization factors as described in the previous chapter, the distributions for all inelastic events and for non single-diffractive events have been produced and are shown in Fig. 5.5.

Figure 5.5: Tracklets pseudorapidity vs z vertex position in the events selected for the analysis (left panel). Applying the corrections at the tracklet level to this histogram and the corrections at the event level, the $dN_{ch}/d\eta$ distributions for the inelastic and non single-diffractive event classes have been obtained (right panel).
5.4 Results and discussion

The $dN_{ch}/d\eta$ distributions have been published as in Fig. 5.6 [97] and have been compared to the UA5 measurements. The values of the pseudorapidity density of charged particles obtained in the central pseudorapidity region ($|\eta| < 0.5$) are $3.10 \pm 0.13(stat.) \pm 0.22(syst.)$ for all inelastic interactions and $3.51 \pm 0.15(stat.) \pm 0.25(syst.)$ for inelastic non single-diffractive interactions. In Table 5.3 these values are quoted together with the UA5 measurements and the values obtained from the PYTHIA and PhoJet generators. The systematic errors have been calculated as described in [97] and partially illustrated also in the previous chapter, that is by repeating the analysis changing parameters related to the systematic source to be estimated. The estimated systematic uncertainties are quoted in Table 5.4.

Among these, for the SPD efficiency a safe value of 4 % has been assigned since the statistic used so far to determine the efficiency of the SPD modules is limited. The SPD efficiency in active areas was measured in test beams to be higher than 99.8 % [103, 104]. This was crosschecked with cosmic data, but only...
Table 5.3: Pseudorapidity density of charged particles measured at $\sqrt{s} = 900$ GeV by ALICE and UA5 in p-p and p-$\bar{p}$ interactions respectively, compared to the values obtained from two Monte Carlo generators. The tune of PYTHIA is the one indicated in Section 5.2.1. The errors are statistical and systematic respectively for ALICE and statistical only for UA5.

<table>
<thead>
<tr>
<th>Measurement/Generator</th>
<th>ALICE</th>
<th>UA5 (p-$\bar{p}$)</th>
<th>PYTHIA</th>
<th>PhoJet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic</td>
<td>$3.10 \pm 0.13 \pm 0.22$</td>
<td>$3.09 \pm 0.05$</td>
<td>$2.33$</td>
<td>$3.14$</td>
</tr>
<tr>
<td>Non single-diffractive</td>
<td>$3.51 \pm 0.15 \pm 0.25$</td>
<td>$3.43 \pm 0.05$</td>
<td>$2.83$</td>
<td>$3.61$</td>
</tr>
</tbody>
</table>

Table 5.4: Systematic errors estimated for the $dN_{ch}/d\eta$ measurement [97].

over a limited area and with limited statistics. The triggering efficiency of the SPD was estimated from the data itself, using the trigger information recorded in the data stream for events with more than one tracklet. The efficiency was found to be very close to 100 %, with an error of about 2 % due to the limited statistics. It can be concluded that the largest contribution comes from uncertainties in cross sections of diffractive processes and their kinematic simulation. In Fig. 5.7 the centre-of-mass energy dependence of the pseudorapidity density is shown for different measurements in $|\eta| < 0.5$. The dashed and the solid lines (inelastic and non single-diffractive interactions respectively) are obtained fitting data with a power-law dependence on energy. Using this parameterization, the estimates at the nominal LHC energy $\sqrt{s} = 14$ TeV are $dN_{ch}/d\eta = 5.5$ and $dN_{ch}/d\eta = 5.9$ for inelastic and
Figure 5.7: Charged-particle pseudorapidity density in the central pseudorapidity region measured by several experiments in p-p and p-$p$ collisions as a function of the centre-of-mass energy. The dashed and the solid lines represent a fit using a power-law dependence on energy.

These results are consistent with previous measurements in proton–antiproton interactions performed with the UA5 detector at the same centre-of-mass energy at the CERN Sp$S$ collider. These can be directly compared since the predicted difference between p-p and p-$p$ is well below the uncertainties on the measurements. These results will be used, together with the forthcoming measurements at higher energies, to determine the energy dependence of the charged-particles pseudorapidity density. Furthermore, in this early start-up and commissioning phase, they also illustrate the rapid progress of the LHC accelerator and its excellent functioning and are a measure of the readiness of both the hardware and software of the ALICE experiment.
Conclusions

Two of the most fundamental global variables for event characterization in hadron and heavy-ion interactions have been discussed in this thesis. The main theoretical aspects and experimental results have been reviewed. The reconstruction of the multiplicity and pseudorapidity has been studied and analysis procedures to obtain the distributions from the reconstructed ones have been developed.

The reconstruction can be performed with data from either the pixel detector or the Time Projection Chamber standalone, besides the final measurement with the fully reconstructed tracks in the whole ALICE tracking system. This thesis deals with the reconstruction based on data from the pixels only which has allowed results to be extracted from the very first data.

The method adopted to reconstruct signals in the two Silicon Pixel Detector layers compatible with tracks coming from the main interaction vertex is called tracklet algorithm: the basic algorithm strategy has been illustrated and its performance has been evaluated. The features emerged from this study led to develop a different iterative strategy from the one adopted by the Collaboration so far, to improve the performance of the algorithm, in particular in the most challenging case of central Pb-Pb events. The performance of this modified algorithm, in terms of efficiency in finding tracklets associated to primary particles and contamination from combinatorial background, has been studied as a function of the angular selection cuts used to define the tracklets themselves. In addition, selection criteria to be
adopted on reconstructed points in the pixel layers to limit the double reconstruction of tracks in the SPD overlap regions have been investigated and chosen. All these studies on the reconstruction algorithm have been carried out both on p-p and Pb-Pb (minimum-bias and 5% most central events) Monte Carlo samples.

A procedure to obtain the pseudorapidity density distribution of charged particles based on the tracklets reconstructed with the SPD has been developed and results on proton–proton and Pb-Pb Monte Carlo samples have been presented. Several correction factors, related to effects of detector and reconstruction efficiencies, background contamination and efficiency of trigger selection and vertex algorithms, have been evaluated and computed at two levels: at the tracklet level to obtain the number of generated primary tracks and at the event level to obtain the total number of events for a given event class, correcting for the efficiency in the event selection (vertex finding and triggering efficiencies). These correction matrices have been calculated and applied using the official simulation and reconstruction framework (AliRoot) and official Monte Carlo productions from the PDC09. The software developed has been integrated in the PWG2 directory of the AliRoot package.

A method for a first estimate of the multiplicity on event-by-event basis and of the multiplicity distribution has been developed and described: here results on a p-p Monte Carlo sample have been shown.

The $dN_{ch}/d\eta$ correction procedure has been applied to analyse the first sample of proton–proton data collected the 23rd of November 2009 at $\sqrt{s} = 900$ GeV, calculating corrections from dedicated Monte Carlo samples available on the CERN Analysis Facility. The $dN_{ch}/d\eta$ measurement, consistent with the UA5 results at the same energy in p-$\bar{p}$ collisions, has been the subject of the first physics paper of the LHC, submitted for publication by the ALICE Collaboration on the 28th of November 2009.
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Lastly, being at a conclusion, recently I have been often afraid of what will be next. I would like to thank the person who said I do not have to let it get me down and that I can make it, who said to be enthusiastic in whatever I build and who said that we “dream of stars” and we should keep dreaming of them...