Chapter 3

The Experimental Setup and the Analysis Framework

3.1 Introduction

This chapter contains a description of the particle accelerator, the ALICE experimental setup and the analysis framework. The detectors used in the analysis for this thesis work are treated in more details, while the rest of the detectors are only briefly mentioned.

3.2 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world. It is located as deep as 175 meters beneath the French-Swiss border near Geneva, Switzerland. It accelerates protons as well as Pb ions to unprecedented energies. The LHC is a circular collider with a circumference of 27 km, in which high energy particle beams travel in opposite directions inside two parallel beam pipes kept at ultrahigh vacuum (the pressure inside the beam pipe is about 10^{-7} Pa). Particles are injected into the LHC at 450 GeV from the SPS, and then boosted to energies at the TeV scale by accelerating radio-frequency cavities, tuned to oscillate at 400 MHz, which sort the particle beams into discrete packets called "bunches". Particles travel inside the LHC main ring curved by a strong magnetic field created by powerful superconducting magnets. In order to maintain the superconducting state, necessary to conduct electricity without resistance or energy loss, the electromagnets are operated at a temperature of 1.9 Kelvin. The cooling system uses 120 tons of liquid helium, circulating into 40,000 leak-tight pipes, making it the largest and most complex cryogenic system in the world.

Thousands of magnets of different types and sizes are used to guide the beams around the accelerator. These include 1232 dipole magnets, each 15 meters long which are used to bend the beams, and 392 quadrupole magnets, each 5–7 meters long, which focus the beams. Close to the 4 interactions points, on both sides, another type of magnet is used to "squeeze" the beams closer together in order to increase the luminosity and hence the chances of collisions. One point of the LHC (Point 6) hosts the Beam Dumping System, where horizontally deflecting extraction kickers (MKD) switch on to divert the beam towards a proper absorber. This operation is performed when the intensity of the circulating beams has dropped below a minimum threshold which does not guarantee a high frequency of collisions, and a new filling is required. All operations and different working phases of the LHC are steered by the CERN Control Center. The beams collide in 4 intersection points, where the LHC experiments are located: ALICE, ATLAS, CMS and LHCb.

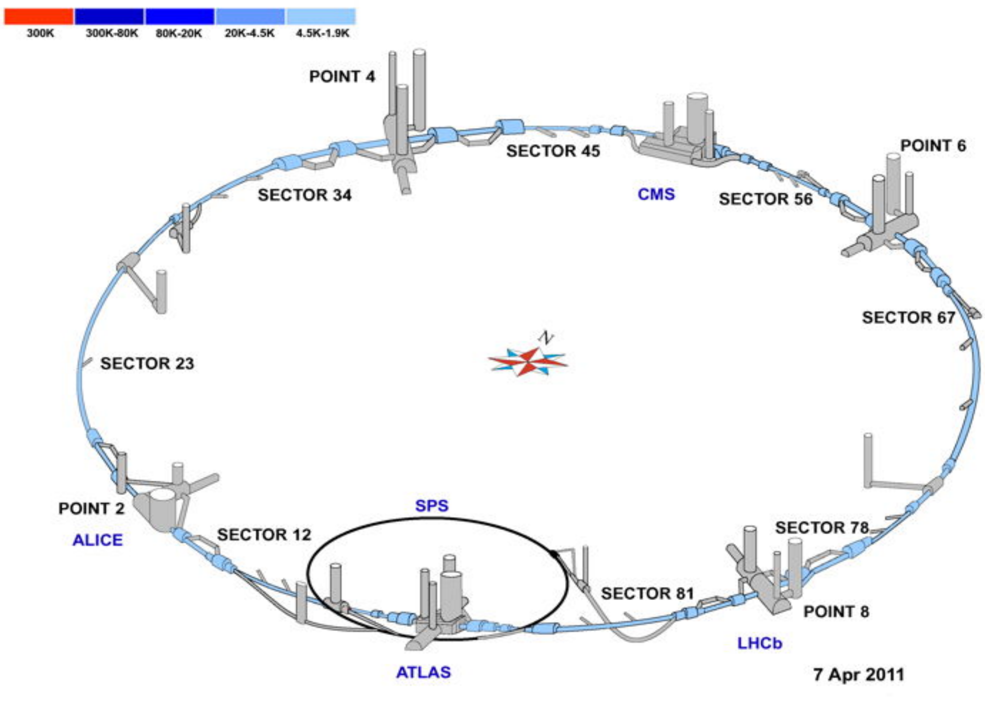

Fig. 3.1 : LHC diagram, showing the four main experiments: ALICE, ATLAS, CMS and LHCb.

3.3 The ALICE Detector

ALICE (A Large Ion Collider Experiment) is dedicated to the study of ultrarelativistic heavy-ion collisions at the CERN Large Hadron Collider (LHC) [105]. The primary goal of its scientific research program is to investigate the properties of the strong interaction under extreme conditions of energy density and temperature. This is achieved by creating microscopic and ephemeral drops of quark-gluon plasma in collisions between heavy nuclei and by measuring the properties of the particles produced in the collisions. Several experimental probes are used to investigate and characterize the properties of this novel state of matter. Although the main interest of this experiment is the study of collisions between ions, the experimental program of ALICE also includes the studies of proton-proton and proton-nucleus collisions, used as fundamental references for vacuum and cold nuclear matter effects in Pb–Pb measurements, respectively. The study of pp and p–Pb collisions is also interesting to investigate some QCD-related topics, such as multi-partonic interactions or collectivity effects in high-multiplicity pp and p–Pb collision events (for which ALICE is in competition with other LHC experiments). The detector has been specifically designed to cope with enormous particle multiplicities that were expected in Pb–Pb collisions at the LHC energies. The ALICE excellent tracking and particle identification capabilities, over a broad range in momentum, allow for a comprehensive study of charged hadrons, electrons, muons and photons produced in heavy-ion collisions. The ALICE detector has been built by a collaboration including over 1000 physicists and engineers from 105 universities and research institutes in 30 countries. Its overall dimensions are $16 \times 16 \times 26$ m^3 with a total weight of approximately 10 000 t. The ALICE experimental setup is divided into three main parts (Fig. 3.2):

- **Central barrel**: it contains several sub-detectors, covering the pseudorapidity range $|\eta| \lesssim 0.9$. These are used for tracking, determination of the collision vertex and particle identification. The detectors in the ALICE central barrel are embedded in a large solenoid magnet, previously used in the L3 experiment at LEP, which creates the magnetic field used for tracking. The detectors in the ALICE central barrel are used in measurements of charged hadrons, electrons, and photons.

- **Forward muon spectrometer**: this is a detector specifically dedicated for tracking and identification of muons. It is located on one side of the ALICE experimental hall, in the forward pseudorapidity region ($2.5 < \eta < 4$). It is used for measurements of heavy quarkonia and dimuons.

- **Forward detectors**: These include hadronic calorimeters and scintillators, used for timing, determination of the collision centrality and event plane.

An array of scintillators (ACORDE) on top of the L3 magnet is used for cosmic ray measurements [106]. It is operated when the beams are not circulating in the collider, e.g. during maintenance operations or regular shut-down periods.

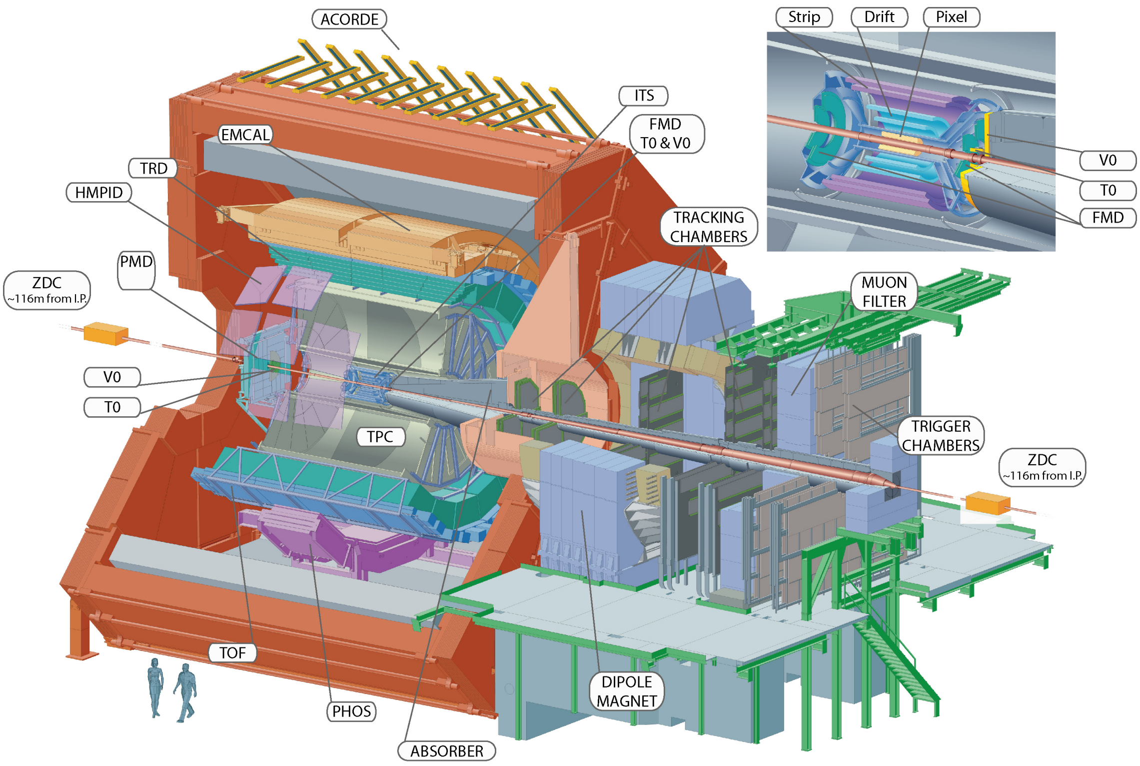

Fig. 3.2 : ALICE schematic layout.

3.3.1 Inner Tracking System (ITS)

The Inner Tracking System (ITS) [107] is the first detector encountered by particles produced in the collision events, that travel through the experimental apparatus. It consists of 6 cylindric layers of silicon detectors, concentric and coaxial to the beam pipe, with a total pseudorapidity coverage $|\eta| \leq 0.9$. Three different technologies have been used for this detector: the two innermost layers are made of Silicon Pixel Detectors (SPD), the two central layers of Silicon Drift Detectors (SDD) and the two outermost layers of double sided Silicon Strip Detectors (SSD) (Fig. 3.3). The detector radius ranges from 3.9 cm for the innermost layer up to 43 cm for the outermost layer. The main parameters of the various layers of the ITS are summarized in Table 3.1. The

Layer	Type	r (cm)	$\pm z$ (cm)	Area (m^2)	Ladders	Ladders/stave	Det./ladder	Total channels
1	pixel	3.9	16.5	0.09	80	4	1	5 242 880
2	pixel	7	16.5	0.18	160	4	1	10 485 760
3	drift	14.9	22.2	0.42	14	–	6	43 008
4	drift	23.8	29.7	0.89	22	–	8	90 112
5	strip	39.1	45.1	2.28	34	–	23	1 201 152
6	strip	43.6	50.8	2.88	38	–	26	1 517 568

Table 3.1 : Main parameters of the ITS detectors [107].

ITS is used in the determination of the primary and secondary vertices, and in the track reconstruction in the vicinity of the collision point. It is also used as a standalone tracker to reconstruct low momentum tracks which do not reach the Time Projection Chamber, the main tracking detector of the ALICE experiment (see next section). The ITS has particle identification capabilities via the measurement of particle energy loss in the silicon detectors, which are complementary to the PID signals from other detectors. A more detailed description of the ITS can be found in [107].

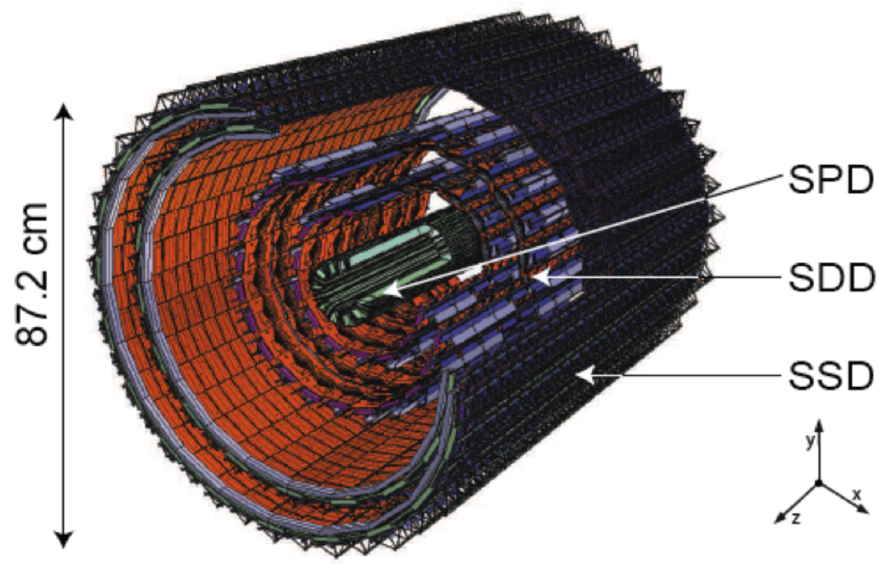

Fig. 3.3 : Schematic view of the inner tracking system (ITS) and its supporting structures.

3.3.2 Time Projection Chamber (TPC)

The Time Projection Chamber (TPC) is the largest detector and the main tracking device in the ALICE central barrel [108]. It is used for track finding and reconstruction, charged particle momentum measurement, via their curvature radius in the magnetic field, and for particle identification, via the measurement of the particle's specific energy loss in the TPC gas. The TPC is cylindrical in shape, coaxial with the beam pipe, with an active gas volume ranging from about 85 cm to 250 cm, in the radial direction, and a length of 510 cm, in the beam direction. The TPC volume is divided into two symmetric parts by a disc-shaped high voltage membrane, parallel to and equidistant from the two endcaps, which is used to create a highly uniform electrostatic field in the two drift regions of $\sim$ 250 cm length. The TPC end-plates are each segmented into 18 trapezoidal sectors and equipped with multi-wire proportional chambers, containing 560,000 electronics channels, with cathode pad readout covering an overall active area of 32.5 m^2. The sectors are segmented radially in two chambers with varying pad sizes, optimized for the radial dependence of the track density. The TPC active volume is filled with a gas mixture that is ionized by the passage of charged particles. The gas mixture, containing 90% Ne and 10% CO_2, is characterized by low diffusion, low-Z and large ion mobility. These requirements are needed for a good momentum and PID resolution, and to guarantee the highest possible acquisition rate. More recently it has been proposed to add 5% N_2 to the mixture, which turned out to provide higher gas gain stability and a better control of the drift velocity. Both gas mixtures require a high drift field (400 V/cm) to secure an acceptable drift time (88ms and 92ms respectively). The field cage of the TPC is surrounded by double-shelled containment vessels with CO_2 as an insulator. Composite materials based on carbon fiber were chosen for high mechanical stability and low material budget (only 3.5% of a radiation length for tracks with normal incidence). Charged particles traversing the TPC create ionization traces in the gas mixture. Depending on the electrical charge and momentum of the particle the track curvature will be larger or smaller in either direction. Electrons produced in the ionization drift at a constant velocity towards the TPC endcaps, pushed by the uniform electrostatic field existing between the endplates and the HV membrane. As the electrons approach the reading pads, they feel a stronger electric field created by the multiwire proportional chambers, and further ionization is created (charge amplification). Ions produced in this multiplication process drift back towards the TPC volume and are collected by a metallic Gating Grid (GG), located close to the, used to avoid the ion back-flow into the drift region. Since ions move much slower than electrons, they would accumulate into the TPC, thus creating space-charge effects which would distort the electric field. The operation of the Gating Grid requires some time to collect all ions ($\sim 200\mu$s), which results in a dead-time which intrinsically limits the TPC readout rate. The space coordinates of the reading pad and the time information of the collected signal allow for a 3-dimensional reconstruction of the particle's trajectory, based on the knowledge of the electric field and hence of the drift time of ionization electrons. The collected charge depends on the amount of ionization created, which is a measure of the energy loss of the particle. This depends on the momentum and identity of the particle and the energy loss measurement is used for particle identification (see Section 5.2).

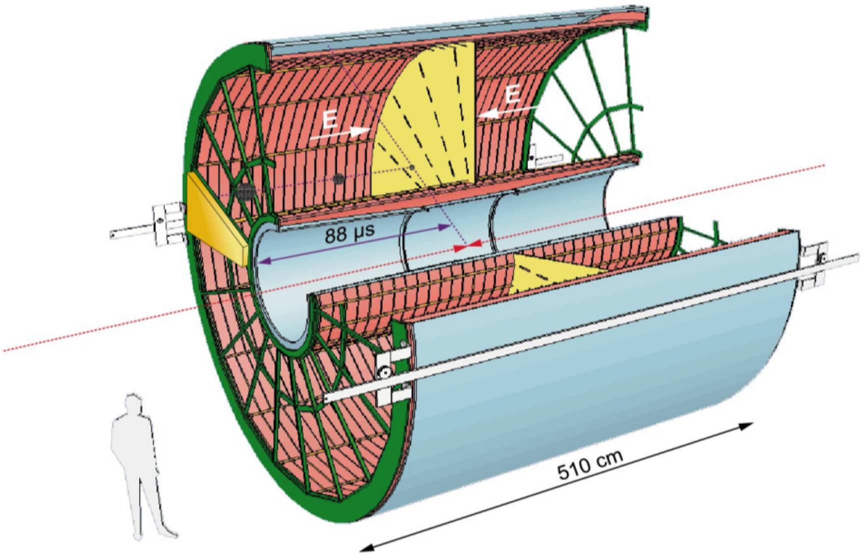

Fig. 3.4 : Schematic view of the Time Projection Chamber (TPC).

3.3.3 Time-Of-Flight (TOF)

The Time-Of-Flight detector (TOF) measures the time spent by particles to travel from the collision point to the TOF radius [109]. The starting time is provided by the T0 detector, a fast scintillator placed at forward rapidity (see next section). The TOF detector has a cylindrical shape, covering polar angles between 45 degrees and 135 degrees over the full azimuth. It has a modular structure with 18 sectors in ϕ, matching the TPC sectors in order to avoid dead zones. Each of these sectors is divided into 5 modules along the beam direction. The modules contain a total of 1638 detector elements (MRPC strips), covering an area of 160 m^2 with 157248 readout channels (pads). The detector chosen for the ALICE TOF is the Multigap Resistive Plate Chamber (MRPC). This is a stack of resistive glass plates. A high voltage is applied to the external surfaces of the stack. Further out there are pickup electrodes. A charged particle ionizes the gas and the high electric field amplifies this ionization by an electron avalanche. The resistive plates stop the avalanche development in each gap. They are however transparent to the fast signal induced on the pickup electrodes by the movement of the electrons. The total

signal is the sum of the signals from all gaps (the reason for many gaps is to achieve high efficiency), whereas the time jitter of the signal depends on the individual gap width (the reason for narrow gaps is to achieve good time resolution). The detector element is a long strip with an active area of 7.4×120 cm^2. It has 96 readout pads of 2.5×3.5 cm^2 arranged in two rows. It consists of 2 stacks of glass, each with 5 gas gaps of 250 μm. Spacers made of nylon fishing line keep the distance between the glass plates fixed.
The time resolution of the TOF MRPC is in the 50 ps range and the efficiency reaches 99.9 %.

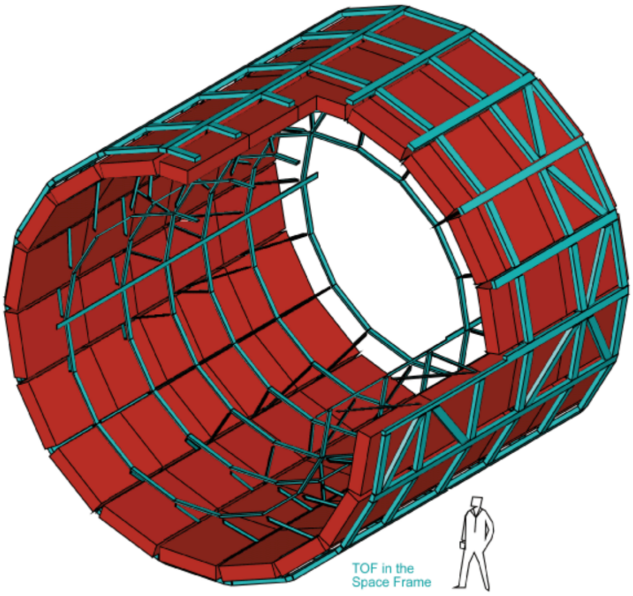

Fig. 3.5 : Schematic view of the Time-Of-Flight detector (TOF).

3.3.4 Forward Detectors (FWD)

A set of small forward detectors, installed at small angles to the beam, are used for timing information, trigger and centrality estimation. These include fast scintillators, calorimeters, Cherenkov and silicon detectors.

- **T0 Detector:** It consists of 2 arrays of PMTs equipped with Cherenkov radiators [110]. The arrays are installed on the opposite sides of the Interaction Point (IP), covering the pseudorapidity ranges: $-3.3 < \eta < -2.9$ and $4.5 < \eta < 5$. The main task of T0 is to supply fast timing signals which will be used in the L0 trigger for ALICE, to send a signal to activate the TRD and to deliver collision time reference for the Time-of-Flight (TOF) detector. The time resolution of T0 is better than

50 ps (σ). The triggering efficiency varies from about 50% for pp collisions up to 100% for A–A collisions. T0 is also used to give a fast evaluation of the multiplicity using a pre-programmed 3-grade scale (minimum bias, central and semi-central).

- **FMD:** It consists of 51,200 silicon strip channels distributed over 5 ring counters of two types which have 20 and 40 sectors each in azimuthal angle, respectively [110]. The main function of the FMD system is to provide (offline) precise charged particle multiplicity information in the pseudorapidity range $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.0$. The FMD will also allow the study of multiplicity fluctuations on an event by event basis.

- **V0 Detector:** The V0 detector consists of two arrays of scintillator counters (named V0A and V0C), installed on both sides of the ALICE collision vertex at small angles [110]. The V0A device is installed on the positive z-direction at a distance of about 340 cm from the interaction point (IP), while the V0C is installed on the negative z-direction along the absorber nose at a distance of 900 mm from the IP. The counters cover the pseudorapidity ranges $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C). Each array consists of 32 counters distributed in 4 rings. Each of these rings covers 0.5 - 0.6 unit of pseudorapidity and is divided into 8 sectors (45 degrees) in azimuth. This detector system has several functions. It provides minimum-bias (MB) triggers for the central barrel detectors in pp and Pb–Pb collisions, it serves as centrality estimator via the measurement of charged particle multiplicity and is used to reduce the background of beam-gas interactions.

- **ZDC:** The Zero Degree Calorimeters (ZDCs) are hadronic calorimeters, made by a stack of heavy metal plates grooved to allocate a matrix of quartz fibers (called "spaghetti calorimeters"), which detect the energy of the spectator nucleons [111]. This is used to determine the overlap region of the two colliding nuclei, i.e. the centrality. It is composed of four calorimeters, two to detect protons (ZP) and two to detect neutrons (ZN). These are located 115 meters away from the interaction point on both sides, exactly along the beam line.

3.3.5 Other Detectors

The ALICE experiment, besides the main tracking and PID detectors already described in the previous sections, is composed of many other detectors which give complementary information or have been specifically dedicated to some particular analyses. The Transition Radiation Detector (TRD) [112] contributes to the tracking, particle identification, and triggering capabilities of the experiment. It has been specifically designed to identify electrons and to trigger on high-momentum electrons. The detector is segmented into 18 sectors (corresponding to the TPC and TOF segmentation), of which only 13 were installed in Run 1, creating small charge asymmetries (see Section 6.2.1). Every super-module contains 6 layers of multi-wire proportional chambers, each of which is preceded by a radiator and a Xe/CO_2-filled drift volume. The particle identification is based on the specific energy loss of charged particles and additional transition radiation photons, the latter being a signature for electrons. During the Long Shutdown 1, the detector was completed and now covers the full azimuthal acceptance. The readout and trigger components have been upgraded.

The High Momentum Particle IDentification (HMPID) [113] system enhances the particle identification capabilities of ALICE beyond the momentum range allowed by the energy loss measurements (ITS and TPC) and by the TOF. The HMPID detector has been designed to extend the useful range for the identification of p and K up to 3 GeV/c and of p up to 5 GeV/c, on a track-by-track basis. It provides inclusive particle ratios and transverse momentum spectra in the region relevant in the study of phenomena connected with the pre-equilibrium stage of the nucleus-nucleus collisions.

Two electromagnetic calorimeters, EMCal and PHOS, are used to measure π^0, η and to improve jet reconstruction by measuring their neutral components. The calorimeter produces also a fast, high-p_{T} trigger and improves existing ALICE capabilities to measure high-momentum electrons [114, 115].

A Forward Muon Spectrometer (FMT), made of a carbon and concrete absorber, tracking and trigger chambers, is dedicated to muon measurements [116]. The spectrometer acceptance allows the measurement of resonances down to zero transverse momentum. The invariant mass resolution is of the order of 70 MeV in the J/Ψ region and about 100 MeV close to the Υ.

3.4 Particle Identification (PID)

Particle identification (PID) consists of the methods and techniques used to select the particle species of interest (electrons in this analysis). These are based on the different signals produced by different types of particles in the detectors dedicated for this purpose. The electron identification in the ALICE central barrel used for this thesis work is based on the average energy loss measured by the ITS and TPC, and the time-of-flight measured by the TOF system.

3.4.1 PID Based on Energy Loss Measurements

The average energy loss per unit of path length of a particle traversing a medium depends on the properties of the medium and on the mass and momentum of the particle. For moderately relativistic charged particles ($0.1 < \beta\gamma < 1000$) heavier than electrons, which lose energy primarily by ionization and atomic excitation, the mean rate of energy loss can be parametrized by the Bethe-Bloch equation:

$$\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right] \tag{3.1}$$

The variables used in this equation are defined in Table 3.2. The dependence on the particle species is contained in the term T_{max}, which is given by:

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2m_e \gamma / M + (m_e/M)^2} \tag{3.2}$$

For electrons a different version of the Bethe-Bloch equation is used, which is valid in the highly relativistic regime:

$$\begin{aligned} \left\langle \frac{dE}{dx} \right\rangle = \frac{2Z\pi e^4}{m_e v^2} \Bigg[& \ln \left(\frac{m_e v^2 E}{2I^2 (1 - \beta^2)} \right) - (\ln 2) \left(2\sqrt{1-\beta^2} - 1 + \beta^2 \right) \\ & + 1 - \beta^2 + \frac{1}{8} \left(1 - \sqrt{1-\beta^2} \right)^2 \Bigg] \end{aligned} \tag{3.3}$$

Fig. 3.6 shows the average energy loss per unit path length measured in the ITS (left) and in the TPC (right) for particles produced in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of the particle momentum. Different bands can be clearly seen, corresponding to the patterns defined by the Bethe-Bloch equation for different particle species, which are shown by the black lines.

The detector PID response is expressed in terms of deviations between the measured signal and the expectation for a given mass hypothesis, in units of the detector PID resolution (σ). For example, the PID response of the TPC, for the electron's mass hypothesis, is given by:

$$n\sigma_{TPC} = \frac{\langle dE/dx \rangle_{meas} - \langle dE/dx \rangle_{exp}(\mathrm{elec})}{\sigma^{TPC}_{elec}} \tag{3.4}$$

Variable	Definition
m_e	electron's mass
c	speed of light
β	v/c
γ	Lorentz factor: $\frac{1}{\sqrt{1-\beta^2}}$
I	Mean excitation energy
N_A	Avogadro's number
r_e	Classical electron radius
K	$4\pi N_A r_e^2 m_e c^2$
z	Atomic number of the particle
Z	Atomic number of the absorber
A	Mass number of the absorber
δ	Density effect correction to ionization energy loss
T_{max}	Maximum kinetic energy which can be imparted to a free electron in a single collision

Table 3.2 : Definitions of the variables used in the Bethe-Bloch equation (3.1).

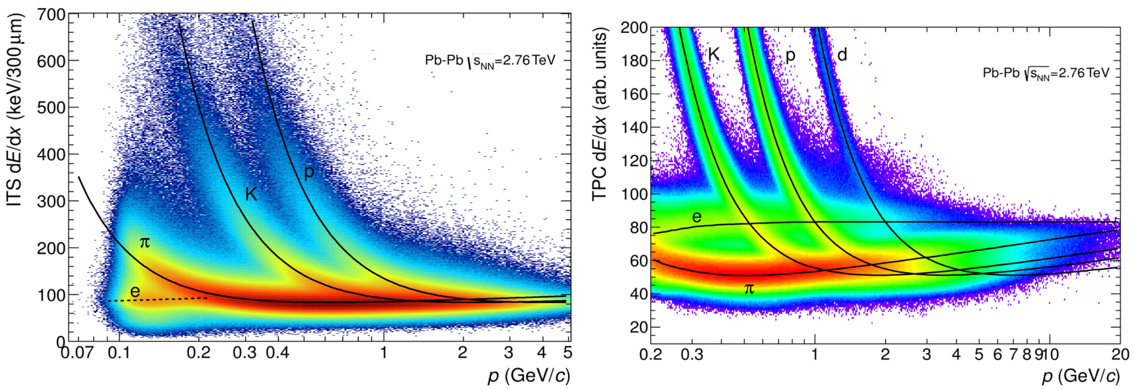

Fig. 3.6 : Mean rate of energy loss measured in the ITS (left) and in the TPC (right) for particles produced in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of the particle momentum. The parametrizations given by the Bethe-Bloch equation for different particle species are represented by the black lines.

3.4.2 PID Based on Time-Of-Flight Measurements

The time-of-flight (t_{TOF}) measured by the TOF system, complemented with the measurement of the track length L and momentum p, provided by the tracking detectors, is used to calculate the particle mass:

$$m = p \cdot \frac{t_{TOF}}{L}\sqrt{1 - \frac{L^2}{c^2 t_{TOF}^2}} \tag{3.5}$$

The procedure which is actually used in ALICE is to compare the time-of-flight measured by the TOF for a given track with the expected values obtained using different mass hypotheses for the particle. The difference between the measured and the expected time-of-flight for a given mass hypothesis is expressed, as usual, in units of σ. For example, assuming the electron mass:

$$n\sigma_{\mathrm{TOF}} = \frac{t_{\mathrm{meas}} - t_{\mathrm{exp}}(\mathrm{elec})}{\sigma^{\mathrm{TOF}}_{\mathrm{elec}}} \tag{3.6}$$

Fig. 3.7 shows the velocity of particles, normalized to the speed of light (β), as a function of the particle momentum measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. Different bands correspond to different particle species, as indicated in the figure.

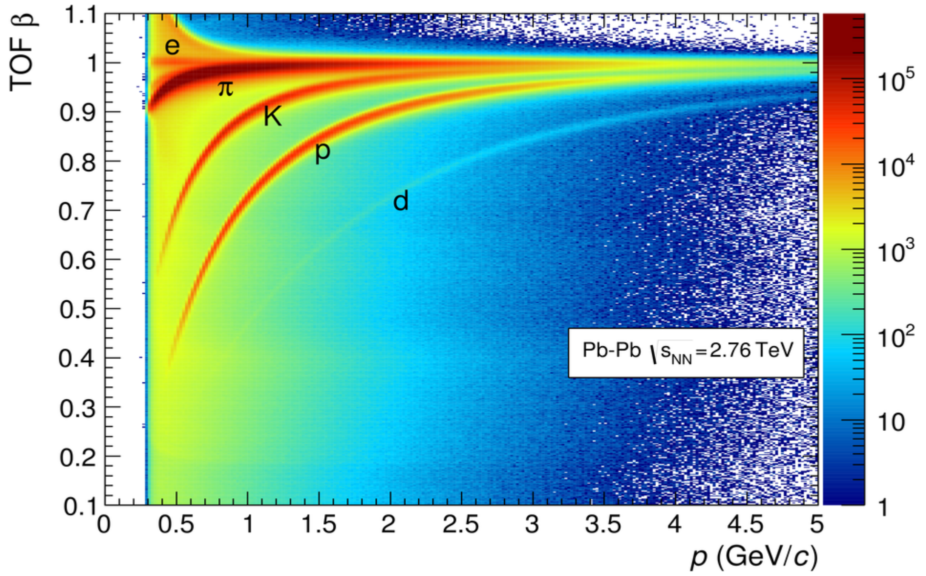

Fig. 3.7 : Particle velocity (β) as a function of momentum measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV.

3.5 Analysis Framework

The software used for data reconstruction, simulation and off-line analysis is an Object-Oriented ROOT-based framework, written in the C++ programming language. The software is divided into two main substructures:

- **AliROOT:** This is the core of the software which contains the ROOT fundamental libraries and the ALICE specific libraries and tools used for data reconstruction, simulation and analysis.

- **AliPhysics:** This is the analysis-oriented part of the framework, which contains specific user analysis tasks and more complex and structured packages used by the analysis groups.

ALICE data and the output of simulation are published and made available for the analyzers by ALIEN (ALICE ENvironment) via the GRID infrastructure. This is a network of thousands of computers and computer clusters, connected via the internet, holding a limited amount of data and used to run the analysis tasks producing small output files, which are eventually merged together by the virtual analysis manager. This infrastructure has been created in order to efficiently handle huge amounts of data which would be impossible to store and analyze using one single computer. The data analysis proceeds in parallel on the computers connected to the GRID. These are placed at different locations in research institutes and universities, making the process much faster and less demanding in terms of computer resources and memory consumption since each computer handles only a fraction of the total amount of data.

3.6 Monte Carlo Simulations

Simulations are done using particle generators, which produce particles by simulating elementary processes or based of phenomenological hadronization models according to parametrized input distributions and particle ratios. Particle generators simulate also particle decays based on real measurements of their branching ratios. The particle generator widely used to simulate nucleus-nucleus collisions is HIJING (Heavy Ion Jet INteraction Generator) [117]. This combines a QCD-based model of jet production with the Lund string fragmentation model. A nucleus-nucleus collision is regarded as a superposition of multiple nucleon-nucleon collisions, with no collective effects, in which parton shadowing effects are also taken into account. Stable particles or long-lived decay products of the generated particles are "transported" through the detector, simulating all processes which characterize the interaction between particles and the detector material, including ionization, excitation, bremsstrahlung or other physical processes such as photon conversion in the material or absorption. The propagation of particles through the detector, in the ALICE magnetic field, is simulated by GEANT 3. The energy deposited by the simulated particles in the active elements of the detector is converted into digits, which are ADC counts, produced considering the real energy thresholds measured in the calibration and testing phase of the detectors during their construction and assembling. The signals produced by simulated particles traversing the experimental apparatus are treated on the same footing as real raw data, which are then reconstructed by the offline framework. Dead or noisy channels and blind areas of the detectors are also taken into account during the reconstruction phase, in order to reproduce the detector status in the simulation on a run-by-run basis. The output of the simulation contains reconstructed tracks and their measured properties, such as momentum and PID signals, together with the information on the real kinematics of the particles that have produced them.