



Università degli Studi di Torino

DIPARTIMENTO DI FISICA
Scuola di Scienze della Natura

DOTTORATO DI RICERCA IN FISICA
CICLO XXXV

An upgraded muon identification system for ALICE at the LHC: from detector construction to testing and re-commissioning

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CERN-THESIS-2023-049
26/04/2023



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Abstract

ALICE (A Large Ion Collider Experiment) at the CERN Large Hadron Collider (LHC) is designed to study proton-proton (p-p) and Heavy-ion collisions at ultra-relativistic energies. The main goal of the experiment is to assess the properties of Quark Gluon Plasma (QGP), a state of matter where quarks and gluons are de-confined, reached in extreme conditions of temperature and energy density such as those obtained in Heavy-ion collisions at the LHC. The Universe is thought to have been in this state during the first few μs after the Big Bang.

One of the main observables used to study the QGP is the production of Heavy quarkonia in Pb-Pb collisions. Quarkonia are bound states of a Heavy quark (c or b) and the corresponding anti-quark. The presence of QGP modifies the quarkonium production rates in Heavy-ion collisions via the competing processes of suppression by colour screening and regeneration by quark recombination. The study of p-p collisions is also crucial to the ALICE physics program since, while the production of the Heavy quark pairs in p-p collisions is relatively well understood, the description of the (non-perturbative) hadronisation process into quarkonium remains unsatisfactory. No model is able to simultaneously describe different aspects of quarkonium production, such as polarization, transverse momentum and energy dependence of the cross sections.

For all the above reasons, ALICE is equipped with a forward muon spectrometer, detecting quarkonia via their di-muon decays. The muon spectrometer covers the pseudorapidity range $2.5 < \eta < 4$; it is composed of a silicon forward tracker, a hadron absorber, a dipole magnet, a five-station tracking system and a muon identification system.

The Muon IDentifier (MID) is the topic of my PhD project. The system is composed of 4 planes of 18 Resistive Plate Chamber (RPC) detectors each, located downstream of an iron wall. RPCs are gaseous detectors with resistive (bakelite) electrodes. During the Long Shutdown 2 (LS2) of LHC, ALICE underwent a major upgrade of its apparatus, in view of the LHC Run 3 started

in 2022, in which the experiment is operated at a larger-than-ever luminosity. For the MID system, in order to cope with the increased collision rate (from the current ~ 8 kHz to ~ 50 -100 kHz for Pb–Pb collisions), it is necessary to reduce the charge released per hit in the detector. For this reason, the detectors will be operated at a lower gain and the new front-end electronics will include an amplification stage.

Moreover a new production of RPC detectors was launched. This was needed because, at the end of the LHC Run 2, some of the RPCs have integrated a non-negligible charge with respect to their expected life-time, and ageing effects might appear at some point. Therefore, about 25% of the detectors currently installed in ALICE will be replaced during Run 3.

The first step of my PhD project was the testing of the new RPCs. These are made with a different type of bakelite, because the one used for the first generation of RPCs is no longer commercially available. The new bakelite has different surface and bulk properties, therefore it was necessary to verify if and how these new features affect the detector performance. The tests were performed in Torino, using cosmic rays and a dedicated set-up. Before the starting of my PhD, the RPCs production with the new bakelite was completely unsatisfactory in terms of performances. After several interactions with the RPC firm during the beginning of my PhD, a pre-production batch of 3 RPCs was launched. After the validation of this batch, the mass production of new modules was launched, completed and tested over my PhD.

Starting from summer 2021, I took an active role in the commissioning of the detectors with the new front-end electronics. This included the integration of the upgraded on-line systems (read-out, Detector Control System, Data Quality Control) in the ALICE environment, and in parallel a cosmic-ray data-taking campaign aimed to a first tuning of the new working parameters. Finally, the commissioning of the system was completed with the very first p–p LHC beams, and finally validated with Pb–Pb collisions. The first collected data were used to parameterise in detail the detector response (efficiency, cluster size and charge released in the gas gap per hit) in the new operation mode, and feeded it into the ALICE software.

This thesis is organized as follow:

- In Chapter 1 the main ALICE physics topic, the Quark Gluon Plasma (QGP), is covered. The field theory describing the strong interactions of quarks q and gluons g , the Quantum Chromodynamics (QCD), is briefly introduced. Then the phase transition to QGP and in particular

the QGP in Heavy Ion Collisions, together with the signatures of QGP formation (both soft and hard probes), are treated.

- In Chapter 2 the ALICE experiment is introduced, together with a quick overview on its physics program. All the ALICE detectors and their functions and upgrades for Run 3 are presented.
- In Chapter 3 the Muon IDentifier (MID) is presented in depth. The RPCs detectors are described, as well as the specific characteristics adopted for the ALICE MID RPCs. Then the upgrade of the MID for Run 3 is presented, involving the brand new front-end electronics, the read-out chain and the software tools for the detector performance studies.
- In Chapter 4 the characterization of the new RPC detectors in the INFN Torino laboratories is presented. The experimental set-up is described, together with the measurements performed. The test results of the pre-batch and the mass production of the new RPCs are also presented. The test on the RPCs provided a complete characterization of every detector in terms of efficiency, dark current, noise, working point and cluster size.
- In Chapter 5 the commissioning phase of the MID at CERN is presented. This involved some interventions in the ALICE cavern on the MID RPCs and the very first Run 3 data-taking campaign at the LHC record energy of 13.6 TeV in p-p collisions. This data-taking campaign allowed me to fine tuning the new RPCs working parameters, and to study and validate the MID performance in the new working mode with the new electronics. The performance of the MID during the only one day of Pb-Pb collisions are also shown.

Chapter 1

The Quark Gluon Plasma

The main goal of ultrarelativistic heavy-ion collisions is the investigation of the Quark Gluon Plasma (QGP), which is a complex and evolving system in extreme conditions of energy density and temperature. In this chapter the QGP in heavy-ion collisions and the most important signatures of its formation will be described. Before moving to the QGP, a brief introduction of the quantum chromodynamics (QCD) will be given.

1.1 The Quantum Chromodynamics (QCD)

The particle physics Standard Model (SM) was formulated in its present form in the 1970s after theoretical predictions and a variety of experimental discoveries. According to the SM, all matter is constituted by 12 elementary fermions, 6 quarks and 6 leptons. The interactions between these particles are mediated by 5 bosons. In figure 1.1 the SM with its particles is shown.

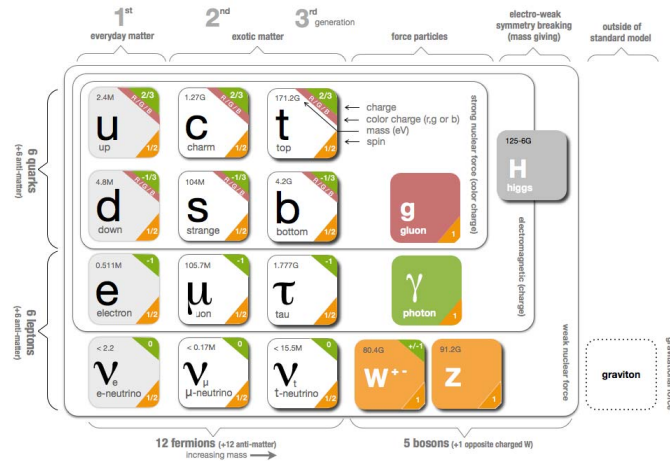


Figure 1.1: The Standard Model of particle physics with its fundamental particles.

After the success of the Quantum Electrodynamics (QED), i.e. the quantum theory of the electromagnetic field which describes all phenomena involving charged particles interacting by means of the electromagnetic force, the Quantum Chromodynamics (QCD) was developed. The QCD is the gauge field theory that explains the strong interactions of quarks q and gluons g through the color charge. It is a Yang-Mills non-Abelian theory and the symmetry group that describes the strong interaction is the non-Abelian group SU(3) of the SU(3)×SU(2)×U(1) unitary groups of the Standard Model. In the SU(3) group the quarks are organized in triplets and they have three color charges (blue, red, green) and six possible flavours (up, down, strange, charm, top, bottom). They are glued together inside the nucleus by eight massless coloured gluons, which can interact with each other and provide a vehicle for the strong nuclear force [1].

One of the fundamental properties of the QCD is the running coupling constant, i.e. the dependence of the coupling constant α_s on the scale of the momentum transfer q^2 . The mathematical expression of the strong constant α_s as a function of the transferred momentum q^2 for 1-loop corrections is the following:

$$\alpha_s(q^2) = \frac{\alpha_0}{1 + \alpha_0 \frac{11N_c - 2N_f}{12\pi} \ln(-\frac{q^2}{\mu^2})} \quad (1.1)$$

where μ is the energy scale, α_0 is the coupling constant calculated at μ energy, N_c is the colours number and N_f is the flavours number. In figure 1.2 the coupling constant α_s as a function of q^2 is shown.

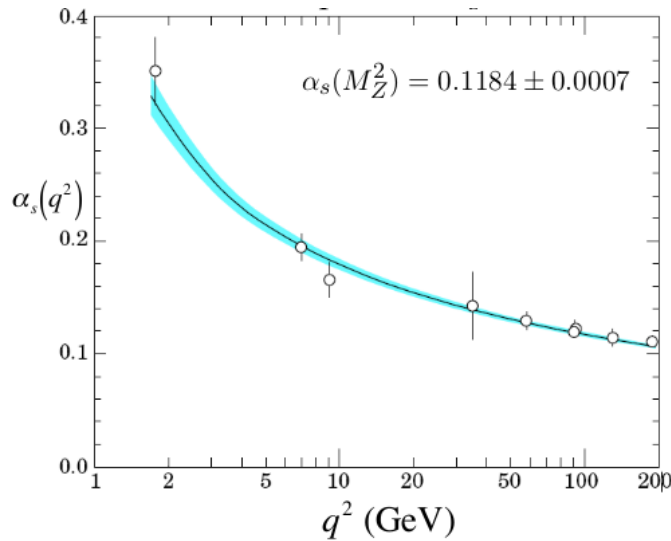


Figure 1.2: Coupling constant α_s , as a function of transferred momentum q^2 .

There are two different regimes, the *asymptotic freedom* and the *confinement*, delimited by the QCD scale $\Lambda_{QCD} \sim 200$ MeV [2].

When q^2 is higher than the force between quarks and gluons inside hadrons, i.e. q^2 higher than 200 MeV, and the scale of the interaction is very small, α_s is small. This is the so-called *asymptotic freedom* regime in which the colour field becomes too low to confine quarks and gluons in hadrons, and they behave as free particles. This means that in very high-energy reactions quarks and gluons interact weakly. In the framework of $\alpha_s \ll 1$, perturbative QCD approach can be used to make predictions for observables expressed in terms of powers of coupling constant α_s . As it will be explained in detail in section 1.3, the Quark Gluon Plasma (QGP) is a state of matter where quarks and gluons are no longer confined inside hadrons and can freely scatter.

On the other hand, at low energy, i.e. when q^2 is lower than 200 MeV, or large distances ($\simeq 1fm$), QCD is a non perturbative theory, quarks are subject to confining forces and the colour degree of freedom is confined into hadrons (bound states of quarks, antiquarks and gluons), i.e. in this case quarks are not observed as free particles. This phenomenon is called *confinement* since, due to the high value of α_s ($\simeq 0.3$), quarks and gluons cannot escape outside hadrons. In this regime α_s is not small enough to use perturbative QCD.

The quark-antiquark binding potential can be expressed as follows:

$$V(r) = -\frac{a}{r} + kr \quad (1.2)$$

where the first term is the Coulombian-like interaction induced by the exchange of a gluon between quark q and antiquark $\bar{q}$, and the second term is the confinement one, which parameterizes the non-perturbative effects. If one quark is departed from another, the confinement potential increases and, at a certain distance, the creation of a $q\bar{q}$ pair from the vacuum is energetically favorable.

1.2 The Big Bang model

The ordinary hadronic matter is confined, but the question is what happen in extreme conditions such as in the primordial Universe, or in the core of neutron stars, or in collisions between high-energy nuclei. In the following subsections the Big Bang model and the phase transition to QGP (both the cold QGP of neutron stars and the hot QGP of high-energy nuclei interactions) will be presented. The Universe we see nowadays was concentrated, 12-16 billion years ago, in a very small spatial region, and therefore had high energy

density and temperature. The Universe then expanded and cooled, from this initial state warm and dense, up to the vast and "cold" Universe in which we live. In figure 1.3 a schematic representation of the Universe evolution from the big bang up to nowadays is shown.

Different phases can be distinguished:

1. *Quark Gluon Plasma*: during the first microseconds of Universe's life, energy density was so high that hadrons could not form. Quarks and gluons were then deconfined and can freely scatter. In fact, according to the Big Bang theory, the QGP was one of the first stages of the Universe and occurred a few μs after the Big Bang;
2. *hadronization*: it is the phase transition from QGP to hadron matters. In fact when the temperature dropped to the *critical temperature* $T_{cr} \simeq 170 MeV \simeq 2 \times 10^{12}$ K (i.e. $\sim 10^5$ times the temperature in the center of the Sun), and the energy density decreased under the *critical energy density* $\epsilon_{cr} = 1 GeV/fm^3$, quarks and gluons gathered together into hadrons (colour-singlet objects having 1 fm dimension);
3. *primordial nucleosynthesis*: three minutes after the Big Bang the temperature dropped below the critical value of ≈ 100 keV ($10^9 K$) and therefore the first atomic nuclei were able to form and survive. In this phase matter was still ionized and opaque to the electromagnetic radiation;
4. *chemical freeze-out*: after these three minutes the chemical composition of the primordial Universe is fixed. The unstable hadrons are decayed and the antiparticles are annihilated leaving a small excess of protons, neutrons and electrons. The chemical composition of the Universe will change again only after hundreds of millions of years, with the formation of stars and the beginning of nuclear fusion processes inside stellar nuclei;
5. *thermal freeze-out*: when the temperature dropped to 3000 K (about 10^5 years after the Big Bang), electrons and nuclei combined and formed neutral atoms. The Universe became transparent and the Cosmic Microwave Background decoupled from matter with a black body spectrum having $T \approx 3000$ K. Due to the expansion of the universe, this black body radiation has undergone a redshift up to a temperature $T = 2.7$ K (the cosmic microwave background) [3].

The opacity of the Universe before the electromagnetic radiation decoupling, prevents us from "seeing" what happened in the first 10^5 years after the Big Bang, because we do not have direct probes. The only way to study the QGP

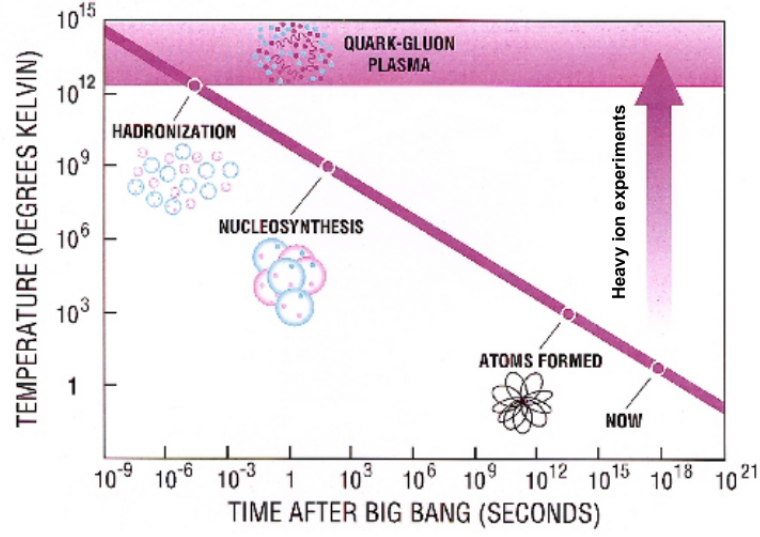


Figure 1.3: Schematic representation of the evolution of the Universe as a function of time elapsed after the Big-Bang.

is to reproduce it in laboratory with heavy-ion collisions at ultra-relativistic energy, which allow us to reach conditions of high temperature and energy density. The QGP produced in heavy-ion collisions is called *hot QGP*, but there is also the so-called *cold QGP* which is the state of matter in the core of neutron stars.

The study of the QGP and its properties is of great interest in order to confirm QCD theory, the Big Bang model, to lead to a deeper understanding of astrophysical bodies and to investigate unsolved problems of modern Physics, such as matter-antimatter asymmetry.

1.3 The phase transition to the QGP

Several models, using the QCD theory as input, predict that hadronic matter, in conditions of extreme energy density and temperature, could undergo a phase transition to the QGP state of matter in which quarks and gluons are deconfined [4].

At low energy in condition of standard nuclear matter, where quarks and gluons are confined inside hadrons, the nuclear energy density is $\epsilon_{nuclear} = 0.15 \text{ GeV}/fm^3$. If the energy density is high enough, i.e. $\epsilon_{QGP} = 1 \text{ GeV}/fm^3$, the coupling constant decreases and the interaction between quarks and gluons becomes weaker: there is a deconfinement and we have the QGP [5].

The (T, μ_B) phase diagram of nuclear matter is shown in figure 1.4, where T is the temperature, while μ_B is the baryon chemical potential, i.e. an index of the net baryon density. In thermodynamics the baryonic chemical potential

is defined as the partial derivative of the internal energy with respect to the number of baryons at volume and entropy fixed $\mu_B = (\frac{\partial E}{\partial N_B})_{S,V}$.

The low density and temperature region of the phase diagram corresponds to the ordinary hadrons. In the high temperature region the dominant degrees of freedom are quarks and gluons. The solid line between the hadronic phase and the QGP represent a first order phase transition, i.e. a transition with a discontinuity in the derivative of a state function with respect to a given thermodynamic variable. The dashed line represent a rapid crossover, i.e. a sudden but continuous transition. A critical endpoint separates the transition from the crossover region.

The precise determination of the transition line requires elaborate techniques. In particular there are three different approaches based on QCD in order to study the QGP:

- *perturbative QCD*: it can be used only to describe those processes which guarantee the $\alpha_s \ll 1$ condition, such as heavy-flavour production in hadron collisions;
- *Lattice QCD gauge theory*: it is a non-perturbative theory derived from QCD first principles, formulated on a discrete grid, or lattice, of points in space and time, and provides a quantitative understanding of the new phase of matter through a numerical solution of the QCD equations [6]. Moreover the Lattice QCD predicts the critical endpoint of the phase diagram [7]. Nevertheless these calculations show uncertainties related to limitations on the lattice spacing and size mainly due to the big amount of computing power needed;
- *phenomenological models*: they provide a phenomenological and qualitative description of the physical processes. For example the *Bag model* [8] is widely used for practical calculations. In this model particles (hadrons or partons) are treated as a non-interacting ideal gas confined in a bag of fixed dimensions. The confinement is a consequence of the balance between the pressure deriving from the kinetic energy of the quarks and an external pressure B , called bag pressure, introduced *ad hoc*. The *Bag model* is able to get rough predictions for the phase transition and can predict some of the fundamental properties of the hadronic matter, such as the transition temperature and density to QGP.

From the phase diagram it can be seen that there are two possibilities to create the QGP: either the energy must be increased or the distances decreased. The former can be achieved by increasing the temperature T , the

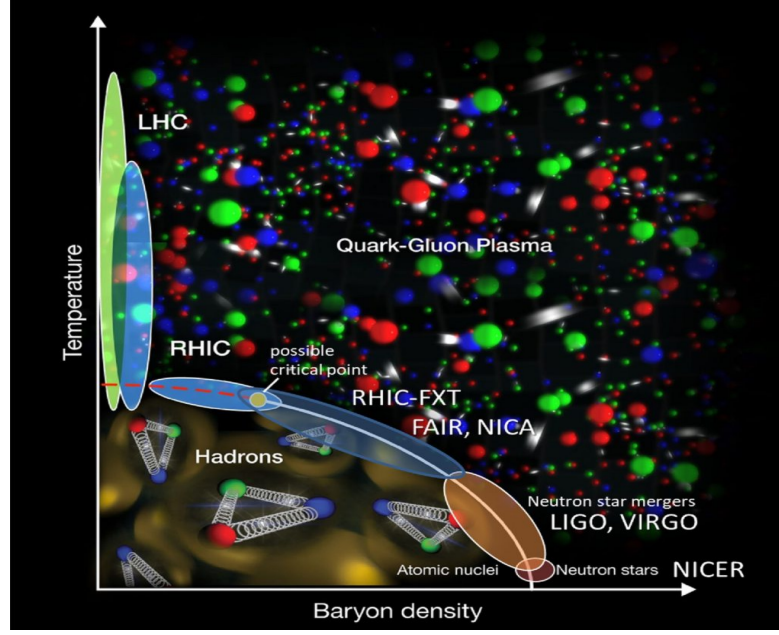


Figure 1.4: Phase diagram of nuclear matter and the facilities that can measure the phase transition [9].

latter by increasing the baryonic chemical potential μ_B for a certain volume. In other terms, in the context of the *Bag model*, the inner pressure can increase with the temperature of the matter (i.e. kinetic energy of the quarks) or the baryon density (i.e. the compression). If this happens, the constituents of the hadrons can be deconfined and we have the transition phase to QGP. So we can distinguish two cases: *Cold QGP*, also called QGP by compression, and *Hot QGP*, which is the one studied in heavy ion collisions.

In figure 1.4 also the facilities that can measure the transition are shown. Regarding the Large Hadron Collider (LHC), in order to investigate the QGP at the A Large Ion Collider Experiment (ALICE) at CERN, extreme conditions of density and temperature can be reached with relativistic heavy ion collisions. In this way, it is possible to study the macroscopic properties and the collective phenomena that emerge from the microscopic laws of particle physics, in a system involving many degrees of freedom.

1.3.1 Cold QGP (brief note)

At low temperatures and high densities, the system is similar to a degenerated gas of neutrons. In the core of neutron stars the gravitational pressure and the baryonic chemical potential exceed the critical value of μ_B , pushing the nucleons so tightly into each other that the constituting quarks cannot be assigned to one or another nucleon.

QGP at $T = 0$ K can be obtained by compressing nuclear matter to a density of 3-10 ρ_0 , where $\rho_0 = 0.15 \text{ fm}^{-3}$ is the nuclear density of ordinary matter. Depending on the details of the calculations, the critical chemical potential $\mu_{B,c}$ at $T = 0$ is around 1.1 - 1.2 GeV, according to the estimation provided by the *Bag model*. This is indeed the situation in cold neutron star cores [10]. The phase transition along the baryon chemical potential axis is believed to be a first order phase transition. For low temperatures and $\mu_B \rightarrow \infty$, quark matter should enter a phase other than QGP and is expected to form a superconductive color state, analogous to the superconductive phase of solid-state physics. For $\mu_B \neq 0$ the expectations rely on models interpolating between low-density hadronic matter (described by effective theories) and high-density QGP (described by QCD). In this regime, the uncertainties are larger than those at $\mu_B = 0$.

1.3.2 Hot QGP

As mentioned before, the universe is assumed to be created after a big bang expanding from a singularity and measurements of the cosmic microwave background provide the current temperature of the universe at $2.725 \text{ K} \simeq 2.3 \times 10^{-13} \text{ GeV}$ [3]. The QCD critical temperature was passed in the early universe few μs after the big bang. In the phase diagram this evolution is the one close to the y axis at low μ_B values, from high to low temperatures. In the context of the MIT *Bag model* [11], let us consider then the case where $\mu_B = 0$. When the temperature is high and $\mu_B = 0$, α_s is weak and the hadronic system can be treated, with some approximation, as an ideal gas, i.e. a gas of massless and non-interacting pions in thermal equilibrium at temperature T . It has to be pointed out that only at low temperature the baryon free matter is mostly composed of light mesons, such as pions, but at high temperature one should also take into account heavier mesons. However in the present discussion this is an inessential complication.

The energy density ϵ_{pions} is:

$$\epsilon_{pions} = n_{dof} \frac{\pi^2}{30} T^4 \quad (1.3)$$

where n_{dof} is the number of particle degrees of freedom. In case of pions are the three isospin states. By considering that the pressure P_{pions} is related to the energy density by $P = \epsilon_{pions}/3$, one obtains:

$$P_{pions} = n_{dof} \frac{\pi^2}{90} T^4 \quad (1.4)$$

The energy density and the pressure for a gas of quarks and gluons, instead of a gas of pions, are given by similar formulae:

$$\epsilon_{qp} = n_{dof} \frac{\pi^2}{30} T^4 + B \quad (1.5)$$

$$P_{qg} = n_{dof} \frac{\pi^2}{90} T^4 - B \quad (1.6)$$

where there is an additional term related to the bag pressure B . The value of n_{dof} is determined by the following relationship:

$$n_{dof} = n_g + \frac{7}{8}(n_q + n_{\bar{q}}) \quad (1.7)$$

where n_g , n_q and $n_{\bar{q}}$ take into account, respectively, the gluons, quarks and antiquarks degrees of freedom. The gluon contribution can be evaluated by accounting for the existence of 8 gluons with two possible polarization each. The degrees of freedom of the quarks depend on the number of colors $N_C = 3$, the spin states $N_S = 2$ and the number of flavors taken into account N_f , which is three if the temperature is below the charm quark mass. Hence:

$$n_g = 8 * 2 \quad (1.8)$$

$$n_q = n_{\bar{q}} = N_C * N_S * N_f = 3 * 2 * 3 \quad (1.9)$$

The factor $7/8$ arises from the Fermi-Dirac statistics. For a gas of quarks and gluons n_{dof} is 47.5, more than one order of magnitude larger than the pion gas one. This results in a steep rise of the energy density in the narrow region of temperature corresponding to the phase transition from hadron gas to QGP.

In figure 1.5 a schematic view of the variation of P as a function of T^4 for the massless pions gas and the QGP one is shown. It can be seen the existence of a transition temperature T_c , beyond which the QGP is thermodynamically favored, compared to the pion gas. From the *Bag Model*, the relation between the critical temperature and the bag pressure is:

$$T_c \approx 0.72 B^{1/4} \quad (1.10)$$

From hadron spectroscopy, depending on the details of the calculations, the bag pressure is about $B^{1/4} \approx 200 \text{ MeV}$, so in this model the critical temperature is $\approx 150 \text{ MeV}$. The *Bag Model* foresees also a first order phase

transition, characterized by a step-rise of the energy density.

However the main tool for *Hot* QGP calculations remains the *Lattice QCD*. From the latest calculations the critical temperature at which the phase transition to a deconfined matter occurs is around $T_c \approx 190 \text{ MeV}$ [12]. Moreover, the phase transition along the temperature axis is believed to be a rapid crossover, implying a smooth variation of the system properties.

The hot QGP can be produced in high-energy collisions of heavy cosmic rays with other heavy particles or in controlled heavy-ion collisions in accelerator experiments.

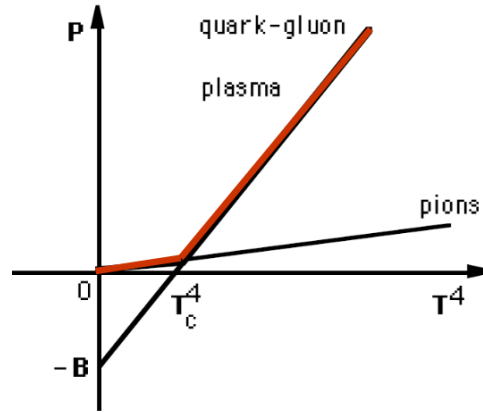


Figure 1.5: Schematic view of the pressure of the massless pion gas compared to the pressure of the QGP.

1.4 QGP in heavy-ion collisions

The region at high T and low μ_B of the QCD phase diagram is experimentally investigated with ultrarelativistic heavy-ion collisions in various experiments, such as at the RHIC at Brookhaven National Laboratory in the USA and at the LHC accelerator at CERN in Switzerland.

The process of multiple collisions occurring between the constituent nucleons of the colliding heavy ions allows in fact to deposit a large amount of energy in a small region, which is the fundamental requirement for the deconfinement. In order to be studied, the QGP realised in laboratory in heavy-ion collisions must have some features:

- the number of constituents of the system must be large, and the size of the system must be larger than the range of the strong nuclear interaction, i.e. $\sim 1 \text{ fm}$. In this way the system of strongly interacting particles can be described by means of macroscopic variables;

- the system temperature must be higher than the critical temperature T_C and it must be long-lived compared to the typical time-scales of the strong nuclear interactions, i.e. ~ 1 fm/c, so that it can reach equilibrium. In this case it is possible to use thermodynamical variables.

Heavy ion collisions at ultra-relativistic energy can lead to the creation of a system with the previous required characteristics.

1.4.1 Dynamic and energy density of the heavy-ion collisions

In figure 1.6 a schematic view of the dynamics of an heavy-ion collisions is shown.

Before the collision the two colliding nuclei are Lorentz-contracted along the beam direction. The physics of these collisions is related to the center of mass energy $\sqrt{s}$ measured per nucleon and, qualitatively speaking, the collision of high-energy heavy-ions can be divided into two different energy regions:

- if the energy per nucleon pair in the center of mass is $\sqrt{s} \simeq 10$ GeV there is a *baryon rich* medium region, i.e. baryons are stopped in the collisions region. This is the so-called *stopping regime*;
- if the energy per nucleon pair is $\sqrt{s} > 100$ GeV there is a *baryon free* medium region, i.e. the net baryon number in the center of mass, where there is high energy density, is almost zero because nuclei are transparent to each other and participants move over the collision region. This is the so-called *transparency regime* and in this case the system can be explained with the *Bjorken regime* [13].

During the multiple collisions the nucleons lose a fraction of their energy and are consequently slowed-down. At very high energy the slowed-down nucleons can have enough momentum to proceed forward along the beam direction, moving away from the interaction region. Their lost energy is deposited in the collision region, and consequently the created matter will have high energy density but a small net baryon content. Otherwise, at lower energies the baryons are stopped in the collision region, giving rise to a state of matter with an higher chemical potential.

Since the colliding nuclei are extended objects the total energy available in the center of mass depends on the geometry of the collisions. A new parameter called *impact parameter* b is introduced to describe the centrality of the collision and it is defined as the minimum distance between the two nuclei

centers. The number of nucleons that participate to the collisions depends on b . The nucleons in the overlapping region are called *participants*, while those not involved in the collisions and, therefore, proceed along the original trajectory, are called *spectators*. In a *central* collision, i.e. $b \simeq 0$ the number of spectators is small, while in a *peripheral* collision the number of spectators is large. In the experiments it is possible to distinguish between central and peripheral collisions by measuring the numbers of spectators with calorimeters placed along the beam direction.

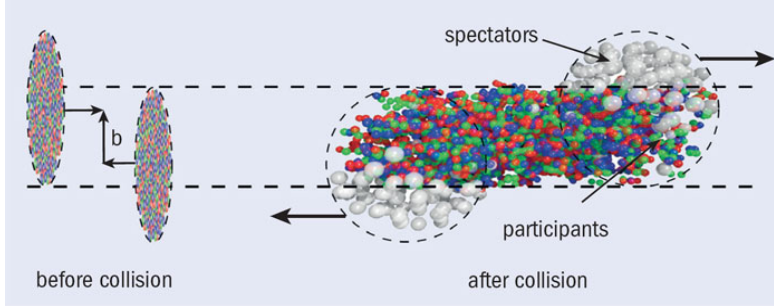


Figure 1.6: Schematic view of the configuration of two colliding nuclei before (left) and after (right) the collision, where the spectators proceed unperturbed while the participants generate a colour region filled of free partons.

As mentioned before, during the multiple collisions, a fraction of energy is lost and the nucleons are slowed-down. The energy density generated can be estimated by means of the Bjorken formula measuring the average charged particle multiplicity produced per rapidity unit:

$$\epsilon_{Bj} = \frac{1}{c\tau_f A} \frac{dE_T}{dy} \quad (1.11)$$

where A is the transverse area of the nuclei interaction region, dE_T/dy is the transverse energy per rapidity unit at mid-rapidity, which is experimentally measurable, and τ_f is the formation time of the particles, obtained from the indetermination principle.

This formula refers to the energy density available when secondary particles are formed but matter is not thermalised. For this reason, τ_f is usually substituted with the thermalisation time $t_{th} \geq 1\text{fm}/c$.

According to the MIT Bag Model, in order to create the QGP an energy density around $1\text{ GeV}/\text{fm}^3$ is needed. For example at the Relativistic Heavy Ion Collider (RHIC) the energy density in a central Au-Au collision, at $\sqrt{s} = 200\text{ GeV}$ per nucleon pair, is $\sim 5\text{ GeV}/\text{fm}^3$, larger than the critical point of $1\text{ GeV}/\text{fm}^3$; at the LHC at CERN, the center of mass energy per nucleon

pair and the energy density are larger, i.e. $\epsilon_{LHC} \sim 15 \text{ GeV/fm}^3$), allowing to create a longer living QGP [14].

1.4.2 Space time evolution of the system

The time evolution of the collision is shown in figure 1.7. Indicating with τ the proper time, i.e. $\tau = \sqrt{c^2 t^2 - z^2}$, on the left side of the figure, starting from bottom to top, the colliding nuclei are shown before the collision, when the collision takes place at $\tau = 0$, when the QGP is created at $\tau = \tau_0$, and after the phase transition back to the hadronic matter. On the right side of the figure each stage is delimited by an hyperbola and the entire process can be summarized as follows [15]:

1. $\tau < 1 \text{ fm}/c$, *pre-equilibrium*: the two Lorentz-contracted nuclei collide, partons scatter among each other depositing a large amount of energy in the overlap region. Hard ($\tau \sim 0 \text{ fm}/c$) and soft ($\tau \sim 0.2 \text{ fm}/c$) processes occur during the scattering and give rise to an abundant production of deconfined quarks and gluons. The system is not yet in thermal equilibrium;
2. $\tau \sim 1\text{-}2 \text{ fm}/c$, *thermalisation*: the multiple scattering among the quarks and gluons leads to a rapid increase of entropy and as a result matter reaches eventually the thermal equilibrium;
3. $\tau \sim 10\text{-}15 \text{ fm}/c$, *QGP formation*: at high energy densities the system reaches the deconfinement phase, the QGP is formed and the system expands, decreasing its temperature and energy density;
4. $\tau \sim 20 \text{ fm}/c$, *hadronization*: when the temperature of the expanding medium drops down below the critical value the hadronization starts, and quarks and gluons are confined into hadrons;
5. $\tau \rightarrow \infty$, *chemical freeze-out*: the expansion and the temperature fall lead to a reduction of inelastic interactions among hadrons and then the abundances of hadrons species are fixed;
6. *kinetic freeze-out*: this is the final evolution step. At this point, the elastic interactions stop, the kinematical spectra are fixed and hadrons freely stream out and can be detected.

The very short lifetime of the QGP created in laboratory (only a few 10^{-23}s) does not allow the direct observation of the phase transition, and only

indirect signals are able to probe the properties of the medium. In the next section the most important QGP signatures, i.e. the experimental observables affected by the formation of the deconfined medium, will be described.

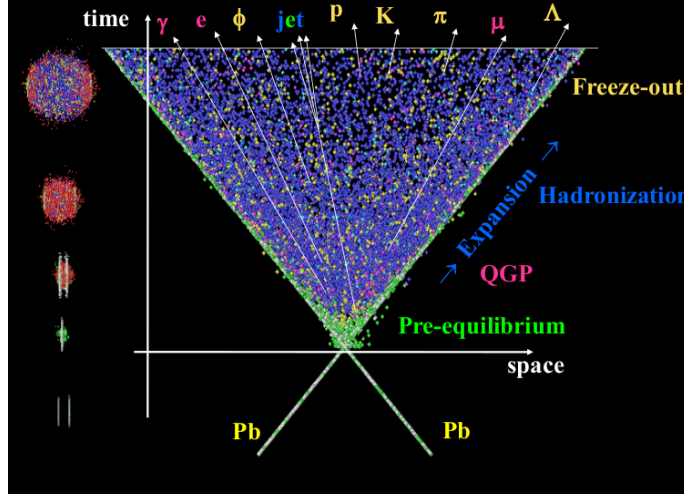


Figure 1.7: Schematic representation of the QGP space time evolution in a nucleus-nucleus collision.

1.5 Experimental signatures of the QGP

The strong interactions among the particles before the freeze-out stage carried out much information about their original production processes. For this reason, in order to extract information about the early collisions stage it is necessary to exploit features which are either established early and survive through the entire evolution of the system up to the freeze-out or can be reliably back-extrapolated. Following this, the QGP signatures produced in a nuclear collision can be divided into two classes: *soft* and *hard* probes.

Soft probes are produced during the evolution of the system formed in the collision and they reflect the collective behaviour of the medium. Hard probes instead are the one produced during the primary collisions, in high transferred momentum processes, and they are sensitive to the nature of the medium they have to cross, before reaching the detector. Unfortunately they are characterized by much lower production cross section.

The abundances and spectra of hadrons made of light quarks, i.e. u and d , belong to the first category and can provide useful information on the hadronization and freeze-out stages of the collision. Thermal photons irradiated by the strongly interacting plasma and heavy flavors instead constitute early probes of the medium, so they belong to the second category. Regarding photons they are also created during the evolution of the system, and conse-

quently it is difficult to distinguish QGP photons from the background ones which instead belong to soft probes.

As explained before, the phase transition to QGP implies a sudden change for quantities such as energy density and pressure as a function of the baryon chemical potential μ_B or the temperature T . These quantities must be deduced from measured ones. For example it has been shown that the energy density can be calculated from the total transverse energy per unit of rapidity of the particles produced in the collisions. From the kinematical spectra of particles instead, information about the evolution of the system can be obtained: the spectra can be fitted according to hydrodynamic models, or integrated in order to obtain the total abundancies and relative ratios of particle species. By comparing these quantities to thermal models of particle production, parameters such as T and μ_B can be obtained.

Another important quantity used to extract information on the created medium is the transverse impulse p_T distributions of the particles produced in the collision. In figure 1.8 the p_T spectrum of detected particles is shown for the ALICE experiment [16]. Each curve in the figure represents particles detected in a particular centrality class. The class 0 - 5% includes particles measured at low pseudorapidity values, perpendicularly to the beam axis of the collisions; the class 60 - 80% contains data at forward pseudorapidity. It can be seen that more than the 99.5% of the particles are soft probes, i.e. low energy particles having $p_T < 1$ GeV/ c , while hard probes have, as mentioned before, lower statistics.

In the following sections soft and hard probes with their related measurable observables will be described.

1.5.1 Soft probes

Processes involving soft probes production are characterized by a low transferred momentum. The following observables are related to soft probes:

- *particle multiplicity*: the multiplicity of particles produced is important for the determination of the energy density of the collision. The study of their transverse momentum spectra allows to obtain informations on the freeze-out;
- *collective flow*: the spatial anisotropy of the colliding nuclei leads to pressure gradients which cause anisotropic particle distributions. This effect can be explained as a collective motion of the particles produced in the collisions and its study is closely related to the determination of

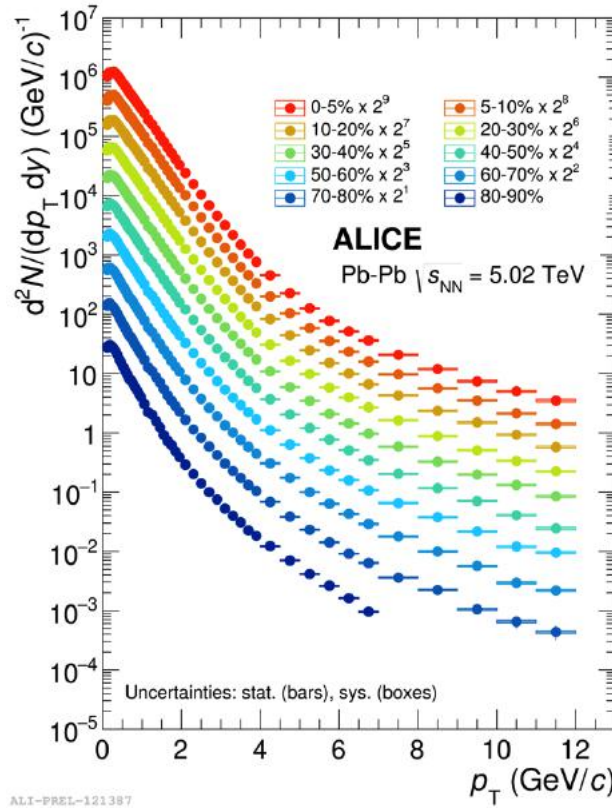


Figure 1.8: Transverse momentum p_T spectrum of the detected particles [16].

the equation of state for a deconfined medium;

- *electromagnetic probes*: the study of real and virtual photons is important for the determination of the medium temperature.

Collective flow and equation of state

The collective flow, which is as mentioned before the collective motion of particles superimposed to their thermal agitation motion, is due to the high pressures generated when the nuclear matter is compressed and heated.

In figure 1.9 the asymmetric shape of the expanding fireball in semi-central and peripheral collisions is shown. The expansion is not isotropic but it presents an elliptic flow due to the pressure gradients in the fireball. These pressure gradients that are at the origin of the elliptic flow are stronger in the first moments after the collision, therefore the elliptic flow is particularly sensitive to the equation of state of the system in the very first stages of the collision. This allows to distinguish between hadronic and partonic expansion models and to estimate the timescale of thermalisation.

In order to have informations about the collective flow, the particle kinematic spectra are then analysed [17].

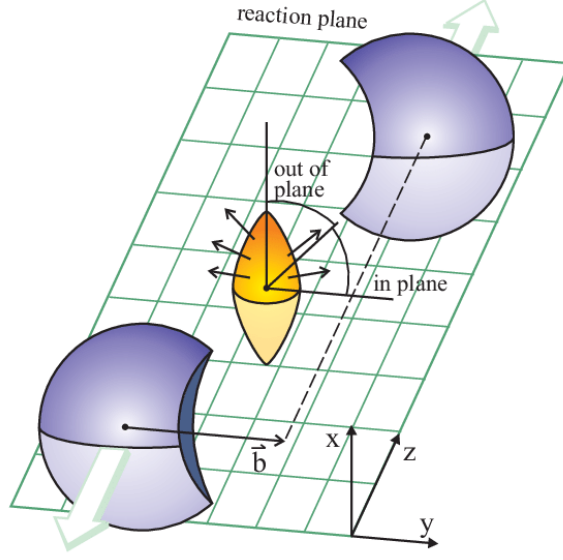


Figure 1.9: Schematic view of the asymmetric initial geometry of the fireball created in a heavy-ion collision with an impact parameter b different from 0.

Strangeness enhancement

One of the evidence of the QGP formation is the higher production of strange hadrons in heavy-ion collisions with respect to p-p collisions [18]. Due to the higher mass of the s quark with respect to the u and d quarks, their production is strongly suppressed in a hadronic environment. However in a deconfined medium an enhancement of the strange quarks production occurs, because they are abundantly produced via the gluon fusion process $gg \rightarrow s\bar{s}$, and they survive until the hadronisation phase. When the QGP cools down, these strange quarks eventually recombine into hadrons, and this results in a strong enhancement of the number of multi strange hadrons, such as Ω (sss) and Ξ (qss).

1.5.2 Electromagnetic probes: photons and dileptons

Before moving to hard probes, in this section electromagnetic probes will be briefly described.

As mentioned before, electromagnetic probes, such as photons and di-leptons (i.e. pairs of the same type of lepton with opposite charge), are of great interest because they interact weakly with the medium and consequently they carry information of the temperature of the medium at the stage in which they are

produced [19, 20].

Photons can be produced in any evolution phase of the fireball:

- *prompt photons* produced in the early stage of the evolution system, coming from the hard scattering between quarks;
- *thermal radiation photons* from the QGP at the equilibrium stage;
- *multiple scattering photons* produced between the hadronisation and the chemical freeze-out phases, coming from multiple scatterings in the hadron gas;
- *late photons* produced by the decays of heavy resonances after the freeze-out phase.

Regarding di-leptons production from the expanding fireball, it proceeds through similar stages as those mentioned for photons, and their invariant mass spectrum can be divided into:

- *low invariant mass di-leptons* created by the decays of light mesons produced in the hadronic phase;
- *intermediate invariant mass di-leptons* derived from thermal emission in the hadronic and deconfined phase;
- *high invariant mass di-leptons* from decays of heavy quarkonia (see section 1.6).

1.5.3 Hard probes

Processes involving hard probes production are characterized by an high transferred momentum. As mentioned before, hard probes are produced early during the collision and so these experimental signatures experience the full evolution of the system, in particular the early stage of the deconfined medium. The observables related to hard probes are:

- *open heavy flavours*: particles with valence heavy quarks c or b are very important for the study of the QGP. Heavy quarks lose energy in the interaction with the medium and this results in a modification of their differential spectra. The study of heavy flavours at low p_T provides information on the thermalisation process of the medium;
- *jets*: they are produced by the fragmentation of high momentum partons. They can lose energy in the scattering with other free partons in the

deconfined medium or through radiative gluon emission. The result is a quenched particle spectrum;

- *Quarkonia*: they are bound state of two heavy quarks, c or b and the corresponding antiquark, and they are named, respectively, charmonium ($c\bar{c}$) or bottomonium ($b\bar{b}$). For example J/ψ and Υ are the ground state of *charmonium* and *bottomonium*. Quarkonia are strongly affected by the formation of a partonic medium and this effect can result in a suppression due to a mechanism of color screening.

Open heavy flavours and jets will be briefly described in the following subsections, while Quarkonia will be treated more extensively in section 1.6, due to the fact that the ALICE Muon Spectrometer at the LHC at CERN, which is the subject of this thesis, was designed to study Quarkonia states.

Open heavy flavours

High p_T open heavy flavours crossing the QGP lose energy by means of two mechanisms: *collisional energy loss*, due to elastic scattering with other partons in the medium and *gluonstrahlung*, i.e. gluon radiation, that is a radiative energy loss.

The second one is the dominant mechanism at high energies. According to the BDMPs model (acronym of the model authors Baier, Dokshitzer, Mueller, Peigné, Schiff), the radiative energy loss is ruled by the following formula [21]:

$$\langle \Delta E \rangle \propto \alpha_S C_R \hat{q} L^2 \quad (1.12)$$

where $\langle \Delta E \rangle$ is the energy loss, α_S is the strong interaction constant, C_R is the Casimir coupling factor (4/3 for qg coupling and 3 for the gg one), and $\hat{q}$ is the transport coefficient.

A parton created in the hard collision, on a short time scale with respect to the evolution of the system, loses energy as it exits from the interaction region, i.e. its p_T decreases while crossing the medium. As a result the high p_T spectrum of the parton is quenched.

It is possible to use the formula 1.12 to estimate the minimum energy needed to a parton in order to cross and come out of the medium. Let suppose that the parton has to cross, for example, 5 fm in the medium: with $\hat{q} = 5 \text{ GeV/fm}^2$, $\alpha_S = 0.2$ and $C_R = 4/3$, $\Delta E \simeq 40 \text{ GeV}$ which is a very high value. This means that most of the crossing partons are quenched in the medium. For this reason, only high p_T hadrons emitted in the peripheral regions of the medium, which do not have to cross the entire fireball, can survive.

The study of azimuthal correlations between two high p_T particles can provide further experimental evidence in favor of this hypothesis.

Jets

A $q\bar{q}$ pair produced in the initial stage of the fireball has to respect the momentum conservation, so their resulting two jets should have back-to-back directions.

The $q\bar{q}$ produced inside the medium are slowed down while they cross the fireball and they hadronize in hadrons having low p_T . The situation is different for $q\bar{q}$ produced in the peripheral region of the fireball: the high p_T parton directed outside of the fireball gives rise to a jet that does not have to cross the medium and can be detected, while the high p_T parton directed inside the fireball have to cross the entire medium before coming out, so it loses energy and hadronizes in low p_T particles. Assuming that the higher p_T hadron is the triggering particle and it is at 0° azimuth, then the azimuthal distribution of the other particles with respect to the triggered one will exhibit two peaks, one at 0° and one at π radians, called respectively *near side* and *away side* jet.

At the LHC, in p-p collisions the angular distribution of the high p_T particles shows two peaks, one at 0° and one at 180° , i.e. the expected back-to-back emissions of the two jets. On the other hand in central Pb-Pb collisions the away-side-peak is not observed: the suppression of the away-side peak in heavy-ion collision is another confirmation of the QGP formation.

1.6 Quarkonia

As mentioned before, quarkonia are bound states of $c\bar{c}$ (*charmonium*) and $b\bar{b}$ (*bottomonium*). They represent a very important testing ground for the QCD theory and are a fundamental probe for the QGP, since their suppression, as it will be shown in the following sections, is a signature of the QGP formation.

The first quarkonium particle to be discovered was the J/ψ in 1974 by two different laboratories at the same time. The J/ψ is a $c\bar{c}$ meson with a mass of $3.1 \text{ GeV}/c^2$. The two laboratories that discovered it were the AGS at Brookhaven National Laboratory (BNL) and the electron-positron storage ring SPEAR at the Stanford Linear Accelerator Center (SLAC). Samuel Ting observed a sharp peak in the electron-positron invariant mass spectrum studying 30 GeV protons accelerated by the AGS [22], while B. Richter found the same

structure in $e^+ - e^-$ annihilation at SPEAR [23]. The first excited state of J/ψ , i.e. the $\psi(2S)$, was discovered by the same group at SLAC. Then another $b\bar{b}$ resonance, the Υ , together with its excited states, was discovered at the Fermi National Accelerator Laboratory (FNAL).

Then many efforts were done to discover particles with total charm or total beauty flavours different from 0 and, thanks to more and more recent generations of experiments, a large amount of heavier $c\bar{c}$ and $b\bar{b}$ mesons was found. The most important properties of quarkonia and the effects of the medium on this particles will be described in the following.

1.6.1 Spectroscopy of charmonium and bottomonium

In figures 1.10 the spectroscopy of charmonium (left) and bottomonium (right) are shown. Quarkonium states are divided into two groups, depending on whether they are above or below the 3.8 GeV decay threshold of the open heavy flavoured meson pair $D\bar{D}$ channel for charmonium or the 10.5 GeV decay threshold of the $B\bar{B}$ channel for bottomonium.

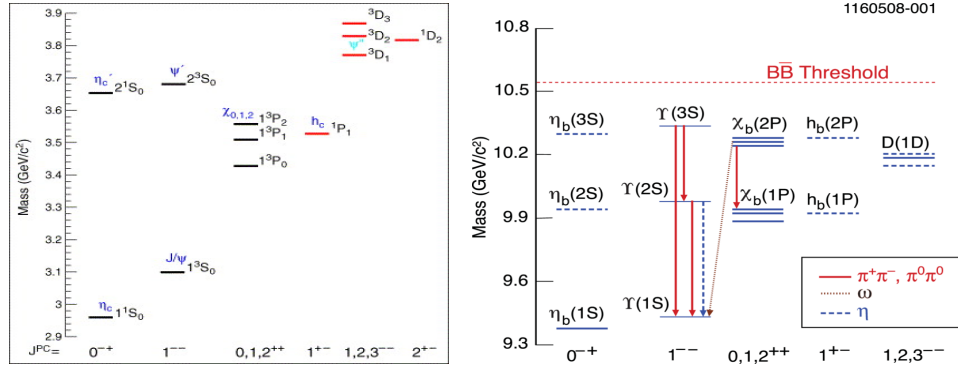


Figure 1.10: Left panel: charmonium spectroscopy [24]. Right panel: bottomonium spectroscopy [25].

The charmonium ground state is the J/ψ , which has a mass equal to 3.097 GeV and a decay width of $\Gamma = 91$ keV, while the ground state for bottomonium is the Υ with a mass of 9.46 GeV and a width of $\Gamma = 53$ keV. Their excited states below the open charm ($D\bar{D}$) and beauty ($B\bar{B}$) thresholds have widths ranging from a few tens of keV to a few hundreds of MeV. The ground states of the heavy quarkonium resonances are rather stable particles, due to their mass below the threshold for $D\bar{D}$ and $B\bar{B}$ productions. The states that can not decay into open charms or open beauty have very small decay width Γ , because their decay modes are either electromagnetic, about 30%, or OZI-suppressed, about 70%, [26]. Luckily for the experimentalists some of the electromagnetic

decays are easy to identify, even in heavy ion reactions in which a lot of particles are produced, for example $J/\psi \rightarrow \mu^+ + \mu^-$, which has a branching ratio of 5.97 ± 0.03 [27].

The spectroscopy of quarkonia can be understood in terms of a potential-model approach. The quark-antiquark binding potential was already expressed in the equation 1.2, here reported again:

$$V(r) = -\frac{\alpha}{r} + kr$$

The potential between quark and antiquark is of the so-called Cornell-type [28], consisting of a color Coulomb term, dominant at small $q\bar{q}$ separation r , and a linearly rising confining term at large separation. The Coulomb-like term accounts for gluon exchange between the two quarks, while the confining term parametrizes the non-perturbative effects.

1.6.2 Quarkonium production mechanism

The issue of quarkonium production mechanism is still an open research field. The efforts for establishing the theory are still ongoing and its completion will help to understand the phenomena expected in the medium created in heavy-ion collisions.

The motion of c and b quarks within the bound state is a non-perturbative problem since their motion is non-relativistic with a $\beta \sim 0.4$. The most plausible option is that the quarkonia production is mainly via gluon fusion process $gg \rightarrow q\bar{q}$. There are various theoretical models for the non-perturbative evolution of the $q\bar{q}$ pair into a quarkonium: Color Singlet Model (CSM) [29], Color Evaporation Model (CEM) [30] and Non-Relativistic QCD (NRQCD) [31] are the most complete. These three models will be briefly described in the following subsections.

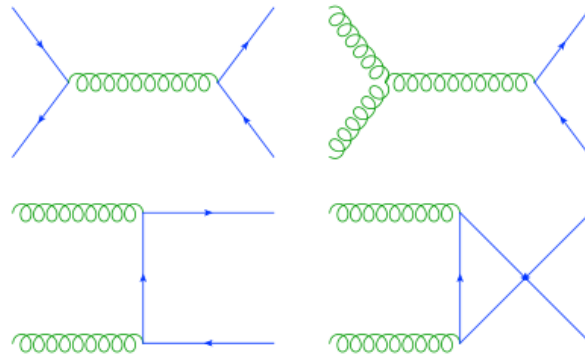


Figure 1.11: The Leading Order (LO) QCD processes for quarkonium production.

Color Singlet Model

The CSM was the first one to be proposed after the discovery of the J/ψ . Perturbative QCD is used to model the $q\bar{q}$ pair evolving in a quarkonium state. The heavy quarks pairs have the same quantum numbers as the quarkonium states into which they hadronize, so only $q\bar{q}$ pairs in a colour singlet state can be considered. The quantum numbers such as spin and angular momentum are conserved after the formation of the meson. The only inputs required in the model are the absolute value of the colour singlet $q\bar{q}$ wave function and its derivatives that can be determined from data of decay processes. Provided these quantities, the CSM has no free parameters.

Historically, CSM calculations at leading order (LO) in α_s predicted well the quarkonium production rates at relatively low energy, but they have been unable to reproduce the p_T dependence of the measured J/ψ production cross section measured by CDF experiment (see figure 1.12), probably because they ignore the fragmentation processes from higher states or B mesons, dominant at Tevatron energies [32]. Several improvements to the model have been worked out since then, such as the addition of all next-to-leading order (NLO) diagrams and the inclusion of other processes to the production of high p_T quarkonia (gluon fragmentation or the production of a quarkonium in association with a heavy quark pair). All these improvements contribute to a better agreement between theory and data, but lead to considerably larger theoretical uncertainties and to the introduction of extra parameters that have to be fitted to the data.

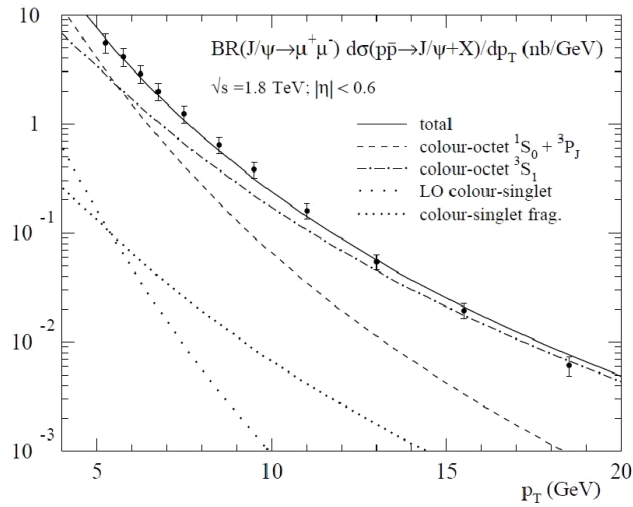


Figure 1.12: Comparison between CDF J/ψ measurements (full circles) and CSM (dotted lines), CEM (dashed and dashed dotted lines) and NRQCD (solid line) predictions [33].

Color Evaporation Model

The CEM is a purely phenomenological model, initially introduced in 1977 and later revived in 1996 [34] due to the unsatisfactory performance of the CSM model.

In this model the production cross section of a given quarkonium state is a certain fraction of the cross section of its constituting $q\bar{q}$ pair, with invariant mass below the corresponding lowest mass meson (D or B). This cross section has an upper limit on the $q\bar{q}$ pair mass, but the proportionality factor of the cross-section, for a given quarkonium state, is assumed to be universal and independent of its transverse momentum p_T and rapidity y , with no constraints on the colour or spin of the final state. This assumption leads to the prediction that the ratio between the yields of two quarkonium states, formed out of the same heavy quarks, is independent of the quarkonium spin, states, and of the collision energy as well as of p_T and y .

Since the fractions are assumed to be universal, once they are determined by data, they can be used to predict the cross sections of other processes and in other kinematic regions. In figure 1.12 the CDF measurements fitted with CEM predictions for charmonium states production are also shown.

Non-Relativistic QCD

In the framework of NRQCD contributions to the quarkonium cross section from the heavy-quark pairs produced in a color-octet state are also taken into account, in addition to the color-singlet contributions, described above for the CSM. The production cross-section can be written as a sum of all possible colours and angular momenta of the $q\bar{q}$ pair. The neutralization of the color-octet state into a color-singlet is treated as a non-perturbative process. The NRQCD model has recently been extended to NLO and it is the only model able to reproduce the cross section of charmonium production in $p\bar{p}$ collisions at Tevatron energies, as shown in figure 1.12, and it is also able to describe consistently the production cross section of quarkonia in p-p collisions at the LHC. However, it fails to describe the polarization of quarkonium (the polarization measures the degree of spin alignment of a particle with respect to a chosen axis). In fact NRQCD predicts a sizable transverse component for the polarization of the J/ψ , which is in contradiction with the data measured at the LHC.

1.6.3 Quarkonia suppression as a signature of QGP

As said before, heavy quarks are produced in the first moments of the collision, and their average lifetime is greater than the lifetime of the fireball. Secondary decay vertices of open heavy flavour hadrons have a $c\tau$ of the order of 100-500 μm , i.e. they are hundreds of micrometres away from the primary vertex where the collision occurred. So, since the formation of quarkonia happens on timescales compatible with the formation of QGP, they cross all the phases of the fireball and it makes sense to study the QGP effects on the quarkonium resonances.

As explained in section 1.6.1, the $q\bar{q}$ bond can be expressed through the Cornell potential. The presence of QGP in Pb-Pb collisions modifies the quarkonium rate of production and has two principal effects on the Cornell potential. Firstly, the QGP matter that surrounds the quarkonium alters the confinement term potential kr which vanishes. The second effect is the so-called *Debye screening*: the high density of colored partons around the heavy quark pair modifies as well the remaining Coulomb-like term by screening it and leads to a suppression of the $q\bar{q}$ state. The resulting potential is a short-range Yukawa-like one:

$$V(r) = -\frac{\alpha}{r}e^{-r/\lambda_D} \quad (1.13)$$

where λ_D is the Debye screening length, i.e. a quantity which roughly corresponds to the distance at which the two quarks can not "see" each other, because of the colour screening; if two quarks are closer than this parameter they can be considered as interacting and tied, otherwise resonance can not be formed. The effect is similar to the electromagnetic screening due to the atomic plasma made of positive and negative charges. The Debye screening length λ_D was calculated at the lowest order within the perturbative QCD, obtaining:

$$\lambda_D(pQCD) = \frac{1}{\sqrt{\frac{N_C}{3} + \frac{N_f}{6}g^2T}} \quad (1.14)$$

where N_C and N_f are the degrees of freedom and g is the coupling constant. As shown in this equation, the screening radius decreases with increasing temperature T of the medium. As shown in figure 1.13, there is a value of the Debye screening length below which the resonance can not form since the range of the attractive interaction is too small, and this implies a temperature above which the resonance is suppressed. In this case the two heavy quarks travel in the medium without binding until hadronization, when they eventually

combine with light quarks to form open charm and beauty mesons [35].

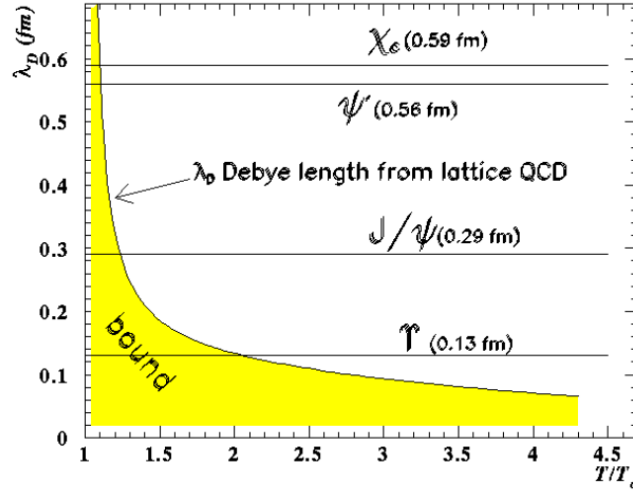


Figure 1.13: Debye screening radius in a deconfined medium, as a function of T/T_c , compared with estimates for the radius of a few quarkonium resonances

The heavy quarkonia suppression in a deconfined medium was discussed for the first time in 1986 [36].

The various states $c\bar{c}$ and $b\bar{b}$ can be characterized in terms of binding energy and dimensions. Since different quarkonium resonances have different dimensions and binding energies it is expected that the less tightly bound states have larger dimensions and melt at lower temperatures: this effect is known as *sequential suppression*. The sequential suppression of resonances may be interpreted as a "thermometer" for the QGP. By identifying the resonances that disappear, one can find the temperature obtained in the collisions. In table 1.1 the quarkonia binding energies, dimensions and dissociation temperatures are shown.

Table 1.1: Binding energy, dimension and dissociation temperature in units of $T_c = 173$ MeV of $c\bar{c}$ and $b\bar{b}$ states [37].

State	J/ψ	χ_C	ψ'	Υ	χ_b	Υ'
Mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56
T_d/T_c	2.10	1.16	1.12	> 4	1.76	1.60

Cold Nuclear Matter and quarkonium regeneration effects

It has to be pointed out that there are concurrent or alternative phenomena that may affect the quarkonia production yield, such as the Cold Nuclear

Matter (CNM) effect and the quarkonium regeneration.

The first effect is studied in p–Pb collisions in which the formation of QGP does not take place. The CNM effect can affect both the initial state (e.g. shadowing of the Parton Distribution Functions in the nucleus) and the final state (nuclear absorption). All these effects can cause a quarkonium suppression even if there is no QGP, but since they are known they can be experimentally measured in proton-A collision.

On the other hand, at high energies such as those at LHC, the high abundance of produced heavy quarks favors their recombination during the QGP phase, therefore a quarkonium regeneration may also be possible. As a result, an increase, rather than a suppression, of quarkonium production rate is expected to be observed at the LHC energy, so it is also important to take into consideration how the statistical regeneration phenomenon can affect the J/ψ production probability.

1.6.4 Experimental results

The quarkonium suppression can be quantified experimentally analysing the production yields in heavy ion nucleus-nucleus collisions normalized to a reference obtained in absence of QGP, usually in p–p or p–A collisions. The value quantifying this is the *Nuclear Modification Factor* R_{AA} , which is defined for a given quarkonium particle, for example the J/ψ , as:

$$R_{AA}(J/\psi) = \frac{1}{N_{coll}} \frac{\sigma_{AA}(J/\psi)}{\sigma_{pp}(J/\psi)} \quad (1.15)$$

where N_{coll} is the number of nucleon-nucleon collisions, $\sigma_{AA}(J/\psi)$ is the cross section in a heavy-ion collisions, and $\sigma_{pp}(J/\psi)$ is the one in a p–p collision where there is no suppression of the signal. The R_{AA} measures the deviation from the scaling with N_{coll} : one expects $R_{AA} = 1$ in absence of initial and final state effects in nuclear collisions.

Before the LHC era, the fixed target experiment NA50 at the SPS studied the J/ψ suppression in Pb–Pb collisions at 158 GeV/nucleon: an anomalous suppression, stronger than the expected one in case of only CNM effects, was observed in central Pb–Pb collisions [38]. A first evidence of the J/ψ suppression is shown in figure 1.14: NA50 experiment at SPS and PHENIX experiment at RHIC, measured a signal that can not be explained with a nuclear absorption. However the data of SPS were collected at lower energies than the RHIC ones, so a more important suppression was expected. Indeed, the suppression of the quarkonium by the deconfined medium increases with

increasing energy, but also the recombination increases and screens the absorption. For this reason the data from SPS and the data from RHIC seem very similar.

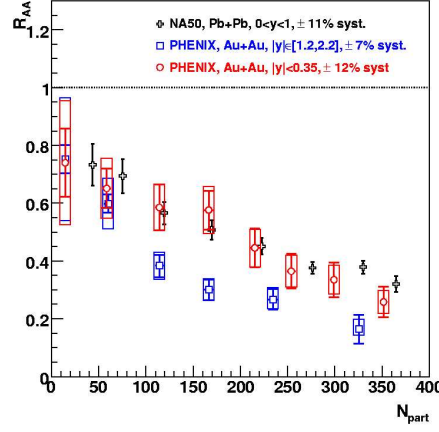


Figure 1.14: Comparison between the R_{AA} , as a function of the number of participants N_{part} , measured by NA50 and PHENIX experiments at, respectively, SPS (Pb–Pb) and RHIC (Au–Au).

ALICE at the LHC showed the first results obtained during 2010 and 2011 data taking in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [39]. In figure 1.15 the comparison between the R_{AA} measured by PHENIX and the one measured by ALICE are shown. The data at ALICE are affected by the recombination effect because they are taken at higher energies, and the recombination increases the J/ψ yield measured.

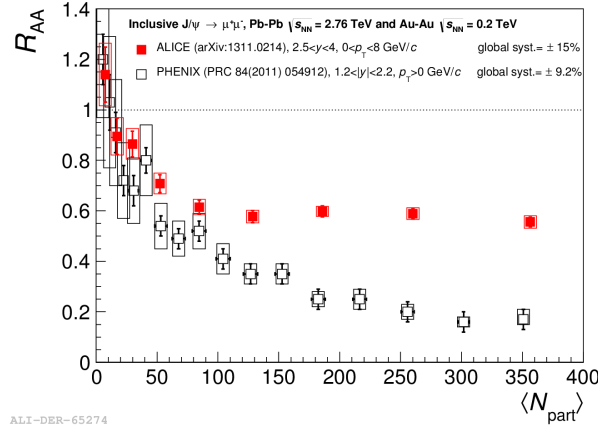


Figure 1.15: Comparison between the R_{AA} measured by PHENIX at RHIC, and ALICE at LHC [39].

The study of the quarkonia suppression is one of the main goals of the ALICE Muon Spectrometer, which measures these resonances through its di-muon decay channel.

Chapter 2

ALICE: A Large Ion Collider Experiment

A Large Ion Collider Experiment (ALICE) at the Large Hadron Collider (LHC) at CERN is one of the four main LHC experiments, and it is devoted to the study of the Quark Gluon Plasma. In this chapter the ALICE experiment will be introduced with all its detectors and their upgrades for Run 3. A brief introduction about LHC will also be given before moving to ALICE.

2.1 The Large Hadron Collider at CERN

The Large Hadron Collider (LHC) ([40]) is the latest addition to the CERN accelerator complex ([41]), placed in an underground tunnel between Switzerland and France, at a depth between 50m and 175m. Its 27 km circumference makes LHC the world largest and most powerful particle accelerator.

LHC first started up on 10 September 2008 and consists of a ring of superconducting magnets with a series of accelerating devices in order to boost the energy of the particles along the circumference. Each machine or accelerator of the CERN accelerator complex boosts the energy of two beams of particles (can be protons or ions depending on the experiments requirements) travelling in opposite directions in separate beam pipes - two tubes kept at ultrahigh vacuum - before injecting the two beams into the following machine in the sequence. Particles are first boosted by the Linear Accelerator (LINAC4), then they are injected first in the Proton Synchrotron (PS) and after in the Super Proton Synchrotron (SPS) rings. The SPS is used as injector for LHC: to be more specific it injects protons with an energy of 450 GeV. In the LHC particle beams are accelerated up to the record energy of 6.5 TeV per beam, leading to the highest colliding energies ever reached: 13 TeV per nucleon for

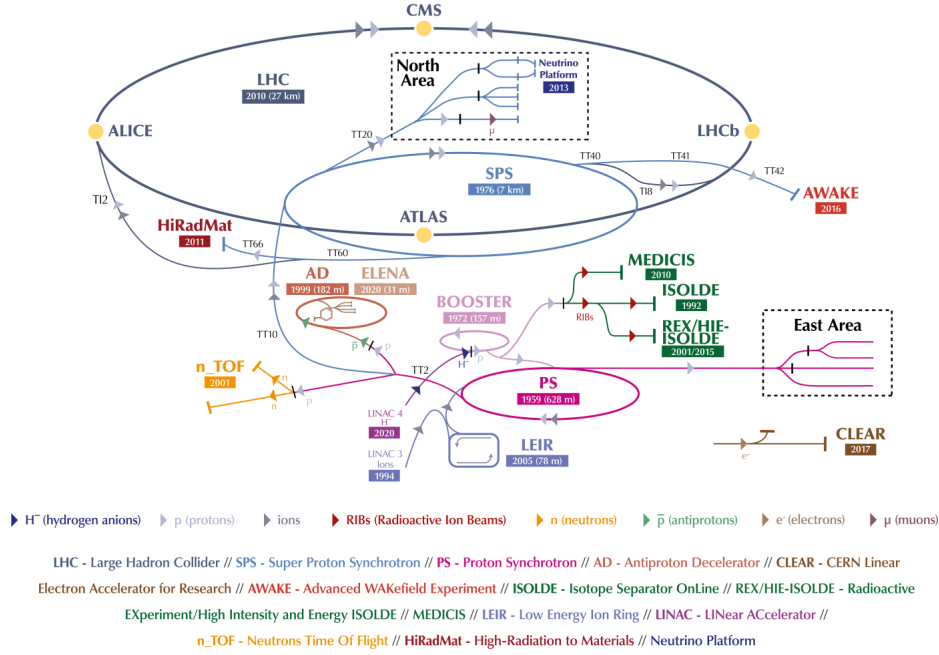


Figure 2.1: The CERN accelerator complex in 2022

protons and 5.5 TeV per nucleon for ions. These two beams collide in four points where the two rings of the machine intersect and where the four main CERN experiments (i.e. ATLAS, ALICE, CMS and LHCb) are collocated (as shown in figure 2.1). Some of the other smaller accelerators in the chain, such as the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) have their own experimental facilities where beams are used for experiments at lower energies.

As a general purpose ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) study the Higgs Boson, but they also look for extra dimensions and supersymmetry. The main topics of LHCb (Large Hadron Collider beauty) are the study of b-physics and the measurements of the CP violation parameters in order to investigate the matter-antimatter asymmetry. Regarding ALICE (A Large Ion Collider Experiment), it is the only LHC experiment specifically designed to study heavy ions collisions and to assess the properties of the QGP. ALICE will be described in details in this chapter, as my PhD thesis lays in the context of this experiment.

2.1.1 LHC upgrade for Run 3

After the end of Run 2 in November 2018, the LHC operations have been stopped for the Long Shutdown 2 (LS2), i.e. a three years period dedicated

to improvements, maintenance and upgrade of the apparatus both for the accelerator machines and the experiments [42].

The new period of data taking for the experiments, the Run 3, begun in July 2022, while beams have already been circulating in the CERN's accelerators since April 2022 for test and commissioning purposes. The Run 3 will last for four years and LHC is now running at the record energy of 6.8 TeV per beam - 13.6 TeV collision energy.

As said before, also the four big LHC experiments, in preparation for Run 3 data taking, have conducted major upgrades to their detector systems and computing infrastructures, in order to collect larger and higher quality data samples with respect to Run 2.

Concerning ALICE, during the past years of operation, the collaboration has explored temperature and energy density regions never reached before, and extended the knowledge about the QGP. However, there are still several topics [43] for which the previous experimental setup used for Run 2 is not fully optimized. For this reason, also ALICE underwent a major upgrade of its apparatus during the LS2. From the LHC point of view, the collision optics parameters for ALICE has not changed with respect to Run 2 (namely $\beta^* = 10$ m with an external vertical half-crossing angle of $200 \mu\text{rad}$ at the interaction point IP). However, in order to study the properties of the QGP far beyond the capabilities of the previous detector, the ALICE experiment is running at a larger-than-ever luminosity: the luminosity has been increased by a factor of $\sim 5 - 10$, i.e. Run 3 Pb-Pb instantaneous luminosity will be $L = 7 * 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, meaning that it will be reached an interaction rate of 50 kHz (to be compared to the previous 8 kHz of Run 2).

The ALICE experiment, the physics motivation, the design and performance of the detectors, together with their upgrades for Run 3, will be presented in the following section of this chapter.

2.2 Overview of the ALICE experiment

ALICE is a general-purpose heavy-ion experiment [44], sensitive to the majority of known observables (including hadrons, electrons, muons and photons), and it was operational since the start of the LHC in 2010.

The heavy-ion detector ALICE has been built as a common design from the nuclear and high-energy physics community working at CERN. The collaboration involves almost 2000 physicists from 174 institutes in 40 countries.

The overall dimensions of the ALICE detector are 26 m long, 16 m high, and 16 m wide, with a weight of approximately 10 000 t. It is housed at interaction point 2 (in the French territory of the LHC), in a vast cavern 56 m underground.

In the Letter of Intent (LoI) [45] in 1993 ALICE was first proposed as a central barrel detector ($\eta < 0.9$), and it was later complemented by a forward muon spectrometer [46] designed in 1995 ($2.5 < \eta < 4$). Figure 2.2 shows an overview of the ALICE experimental apparatus.

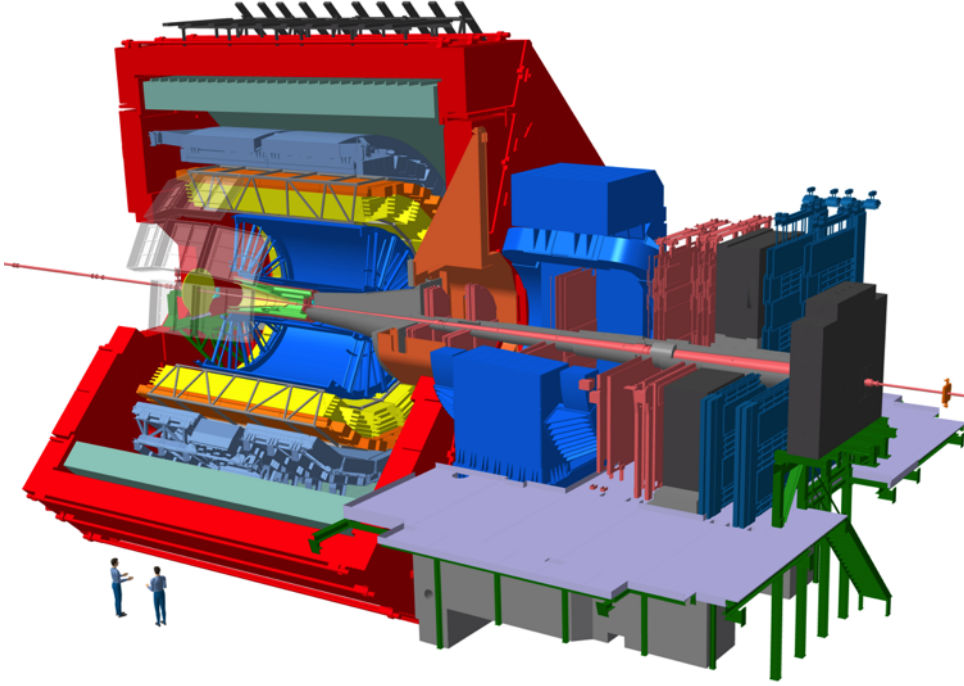


Figure 2.2: Overview of the ALICE detector at Point 2 at the LHC at CERN.

ALICE was designed to measure the flavour content and phase-space distribution event-by-event, for a large number of particles whose momenta and masses are of the order of Λ_{QCD} (~ 200 MeV), i.e. the typical energy scale involved. It was designed to cope with the high particle multiplicities per unit of rapidity anticipated for Pb–Pb collisions $dN_{ch}/dy = 8000$. During Run 1 and Run 2 the interaction rate at nominal luminosity, i.e. $L = 10^{27} s^{-1} cm^{-2}$, was $R = L \times \sigma s^{-1} \sim 10 kHz$ with $\sigma = 8b$. The experiment was able to detect particles (and reconstruct tracks) in a wide momentum range, from 100 MeV/c to around 100 GeV/c. Hardware triggers based on event multiplicity, calorimeter energy and track p_T provided event selectivity that allowed sampling of the full luminosity. The maximum readout rate of the ALICE detector until Run 2 was limited to 500 Hz of Pb–Pb events.

2.2.1 Upgrade strategy

For Run 3, ALICE aimed at precision measurements of the QGP, which will be accessible through measurement of heavy-flavor transport parameters, quarkonia down to zero p_T and low mass di-leptons. These processes do not exhibit signatures that can be selected by hardware triggers and they can only be collected by a zero bias (minimum bias) trigger [47].

On the basis of the above considerations and the main physics topics that ALICE wants to explore (see Section 2.3), the experimental approach taken by ALICE is to read all the Pb–Pb events and collecting more than 10 nb^{-1} of Pb–Pb collisions at a luminosity up to $L = 6 \times 10^{27} \text{ s}^{-1} \text{ cm}^{-2}$, which means at an interaction rate of 50 kHz, where each collision is shipped to the online systems in a continuous trigger readout mode. In addition, ALICE wants to collect 6 pb^{-1} of p–p collisions at the equivalent Pb–Pb nucleon energy, and 50 nb^{-1} of p–Pb collisions, both at a collisions rate of 500 kHz.

The upgrade strategy includes also an improvement of the vertexing and tracking capabilities at low transverse momentum [48]. More precisely the upgrade consists of:

- a brand-new high-resolution Inner Tracking System (ITS);
- a major upgrade of the Time Projection Chamber (TPC). Since the TPC drift time of $100 \mu\text{s}$ is 5 times longer than the average time between interactions, the wire chambers have been replaced with GEM detectors;
- a new beam pipe with smaller diameter. The new beampipe inner radius is 19.2 mm, to be compared with the previous value of 29 mm;
- upgrade of the ALICE detectors readout electronics to handle high rate operations;
- upgrade of the forward trigger detectors;
- implementation of a new online system capable of receiving and processing the full detector information;
- offline reconstruction and analysis framework.

2.3 ALICE Physics motivation

As mentioned before, ALICE is designed to address the physics of the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions.

LHC provides the optimal experimental conditions for QGP creation and analysis due to the fact that the net baryon density in the central region is very small (corresponding to the conditions of the early Universe), the initial temperature and energy density are the highest achievable in the laboratory, and the large collision energy ensures an abundance of perturbatively calculable hard QCD processes.

To establish and analyse the existence of QCD bulk matter and the QGP, ALICE studies a wide number of observables in a systematic and comprehensive way, in order to characterize the global features of the state created during the collision and to constrain theoretical models.

The main ALICE physics topics to investigate the QGP are the measurement of heavy-flavour hadrons, quarkonia, strangeness production, and low-mass dileptons at low p_T , together with measurements of jets and their constituents [49].

Moreover, even if the main goal is to study Pb–Pb collisions, the ALICE physics programme also includes collisions with lighter ions, such as Xenon and Oxygen, at lower energy, in order to cover a wider energy density range, as well as dedicated proton-nucleus runs in order to disentangle cold nuclear matter effects from QGP effects. ALICE takes data also during proton-proton runs to provide both a reference to ion-ion collisions that are expected to create QGP, but also to address a number of specific strong-interaction topics for which ALICE is complementary to the other LHC detectors.

Many of these measurements in Pb–Pb collisions are characterized by a very small signal-over-background ratio, which calls for large statistics with minimum-bias data. Thanks to all the upgrades carried on during the LS2 there will be an increase of statistics of about two orders of magnitude, allowing ALICE to improve the previous measurements and, with the new vertexing and tracking capabilities, also to open up to new physics measurements concerning especially charmonium, open heavy flavor production and low-mass dileptons, both in the central and forward rapidity region.

2.4 The ALICE Central Barrel

The central barrel is the central group of detectors, which covers $\pm 45^\circ$, i.e. a pseudo-rapidity range $|\eta| < 0.9$ over the full azimuth. It has a cylindrical arrangement around the Interaction Point (IP) and it is embedded in a large magnet which provides a solenoidal field up to 0.5 T, in order to bend charged particles paths to measure their momenta.

The central barrel is mainly devoted to particle identification (PID) and momentum measurements and it consists (from the inside out) of an Inner Tracking System (subsection 2.4.1), a cylindrical Time Projection Chamber (subsection 2.4.2), a Transition Radiation Detector (subsection 2.4.3) a large area PID array of Time Of Flight counters (subsection 2.4.4), small area single-arm detectors (an Electromagnetic Calorimeter (subsection 2.4.6) and a Photon Spectrometer (subsection 2.4.7)) and an array of counters optimized for high-momentum inclusive particle identification (subsection 2.4.5).

2.4.1 The Inner Tracking System (ITS)

The Inner Tracking System is the most central detector [50], surrounding the 800 μm thick berillium beampipe.

The basic functions of the ITS are:

- localize the primary vertex with a resolution better than 100 μm ;
- reconstruct secondary vertices, necessary for the reconstruction of charm and hyperon decays;
- track and identify particles with low-momentum, below 200 MeV/c;
- improve the momentum and angle resolutions for particles reconstructed by the TPC.

During Run 1 and Run 2 the beam pipe outer radius was 29 mm and the ITS consisted of six cylindrical layers of silicon detectors, located at a radii between 39 and 430 mm, coaxial with the beam pipe, covering the pseudo-rapidity range $|\eta| < 0.9$ for vertices located within ± 60 mm with respect to the nominal IP. Run 1 and 2 ITS was designed for up to 100 particles per cm^2 in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and consisted of three different detectors, each one composed of two layers. The innermost layers, for which a higher granularity is required, were made of Silicon Pixel Detectors (SPD). The two following layers were made of Silicon Drift Detectors (SDD), and the two outer layers were equipped with Silicon micro-Strip Detectors (SSD). The four outer layers had analogue readout and therefore could be used for particle identification via dE/dx measurement.

A crucial limitation of the ITS was given by its poor readout rate capabilities. The ITS could run up to a maximum of about 1 kHz, with 100% dead time. For the physics observables aimed at by the upgrade physics programme for Run 3, for which selective triggers cannot be applied, this rate limitation would have restricted ALICE to use only a small fraction of the full Pb–Pb

collision rate. Moreover it would have also prevented to collect the required reference data in p-p collisions [48].

ITS upgrade

Run 1 and Run 2 ITS was totally inadequate to fulfill ALICE requirements for Run 3. For this reason, during the Long Shutdown 2 of the LHC in 2021, the previous ITS of the ALICE experiment based on silicon pixel, silicon drift and silicon strip detectors, was entirely replaced by a brand-new high-resolution ITS using novel monolithic active pixel sensors (MAPS) [51].

Run 3 ITS consists of 7 concentric cylindrical layers (see figure 2.3) of MAPS sensors, with a granularity of $30 \times 30 \mu\text{m}$, implemented in a CMOS imaging technology provided by Towerjazz (similar to digital camera sensors), in which both the sensor collecting the charge signal and the readout circuit are hosted in the same substrate of silicon. The chip was developed by ALICE and it is called ALPIDE [52].

The new ITS active area is of about 10 m^2 segmented in 12.5 billion pixels (each ALPIDE chip covers an area of $15 \times 30 \text{ mm}^2$ and contains more than half a million pixels). The ALPIDE chips are tiled up in staves and the staves are assembled on cylindrical supports. The first detection layer is located at a radius of 22.4 mm with respect to the beam line, closer to the IP with respect to Run 2 thanks to the new smaller outer radius of the beam pipe, while the last layer is located at a radius of 430 mm.

The spatial resolution is $5 \mu\text{m}$ and satisfies, and even exceeds, the requirements for the ALICE ITS. The new detector is able to reconstruct tracks based on ITS information alone, can be read out at rates of 100 kHz for Pb-Pb and 1 MHz for p-p collisions and it improves the impact parameter resolution by a factor of three in the transverse plane and by a factor of five along the beam axis, allowing ALICE to perform measurements of heavy-flavour hadrons with unprecedented precision and down to zero p_T .

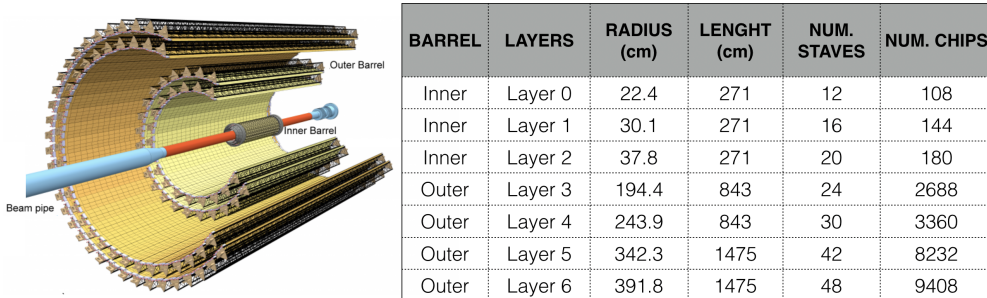


Figure 2.3: The Inner Tracking detector in Run 3 and its specifications

2.4.2 The Time Projection Chamber (TPC)

The Time-Projection Chamber (TPC) is the main tracking and particle identification detector of the central barrel [53].

The TPC is a cylindrical detector (see figure 2.4 for the detector layout) covering an acceptance of 2π in azimuthal angle and the pseudo-rapidity interval $|\eta| < 0.9$. It is a gaseous detector with an internal active volume of 88 m^3 , an inner radius of about 85 cm, an outer radius of about 250 cm, and an overall length along the beam direction of 500 cm. The gas mixture consists of 90% Ne and 10% CO_2 ; the neon based gas mixture was chosen to keep multiple scattering and space charge effects at a minimum. The active volume is divided in two drift regions by a central high voltage electrode. The field cage secures the uniform electric field along the z -axis. Each of the two end plates is divided into 18 sectors, each holding one Inner ReadOut Chamber (IROC) and one Outer ReadOut Chamber (OROC), for a total of 36 IROC and 36 OROC, covering an overall active area of 32.5 m^2 . The charged particle traversing the TPC frees electrons from the gas; electrons drift towards the end plates, over a distance of up to 2.5 m on either side of the central electrode, thanks to a 400 V/cm drift electrical field.

During Run 1 and Run 2, the design of IROC and OROC was based on Multi-Wire Proportional Chambers (MWPC) with cathode pad read-out. The maximum electron drift time for a Ne- CO_2 (90-10) gas mixture over the whole path is about $100 \mu\text{s}$. The spatial and temporal signals can be converted in tracks and provide momentum information through the dE/dx measurement. Even if it was a slow detector, during Run 1 and Run 2 TPC could provide charged-particle momentum measurements with a resolution up to about 2%, a good two-track separation (more than 90% efficiency in track finding), particle identification, and vertex determination, and it could cope with the minimum bias collision rate in Pb-Pb, that was around 8 kHz at nominal luminosity.

The electron drift time of $100 \mu\text{s}$ from the central electrode to the readout chambers, and the ion drift time of $180 \mu\text{s}$ from the sense wires to the gating grid, set the maximum readout rate of the TPC during Run 1 and Run 2 to 3.5 kHz. At a minimum bias event rate of 50 kHz foreseen for Pb-Pb in Run 3, the detector would have a sustained ion accumulation from several thousand collision events piling up in the drift volume. The space charge would distort the electron drift paths and the reconstruction of the particle trajectories would no longer be possible. Moreover, the foreseen particle rates at the wire chambers would reach 100 kHz/cm^2 and the space charge effects in the amplification region will result in a few percent gain drop, thus deteriorating

the dE/dx performance of the TPC [48].

TPC upgrade

For these reasons, during the LS2, the read-out Multi-Wire Proportional Chambers of the TPC were replaced with Gas Electron Multiplier (GEM) detectors that allow continuous operation to read out 50 kHz Pb–Pb collisions, with a brand new read-out electronics to cope with the continuous read-out working mode of Run 3 [54, 55].

In order to keep the ion-induced space-charge distortions at a tolerable level, a modification of the gas mixture was also necessary. The ALICE TPC Run 3 requirements leads to an upper limit of 2% for the ion escape probability per effective electron-ion pair produced in the gas amplification stage (ion backflow). After R&D studies [56] a gas mixture of Ne(85.7%)-CO₂(9.5%)-N₂(4.8%) has been chosen; with this gas mixture, at the operational gas gain of 2000, the ion back flow probability is less than 0.5%. Moreover the readout system provides a dE/dx resolution better than 5% in events with low particle multiplicity.

The replacement of multi-wire proportional chambers with GEM and the continuous readout working mode, required the development of a new front-end and readout electronics. The readout of the signal is done by the 524160 pads that form the anode plane of the GEM chambers and each pad is connected to a front-end electronics channel. Moreover, a dedicated ASIC (SAMPA) has been developed. The SAMPA chip is based on the ALTRO and S-ALTRO developments [57]. The signals from the Front-End Cards (FEC) are transformed into differential, semi-Gaussian voltage signals, and continuously digitized and processed by the SAMPA. In addition the FEC incorporates two optical readout links for the digitized data. In total, 6552 optical links are needed to send the digitized data off-detector, leading to an unprecedented data throughput of 3.28 TB/s. FPGA-based readout cards (Common Readout Unit, CRU) receive the data and perform online processing.

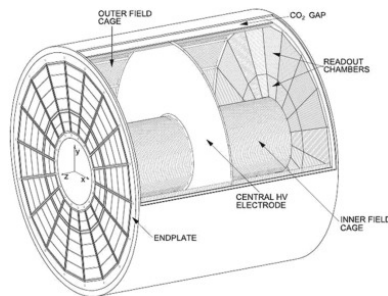


Figure 2.4: The Time Projection Chamber detector in Run 3

2.4.3 The Transition Radiation Detector (TRD)

The Transition Radiation Detector (TRD) performs electron identification for momenta above 1 GeV/c (below this momentum electrons can be identified via specific energy loss measurement in the TPC) and triggering on high momentum electrons and jets, providing a trigger decision in about 7 μ s [58]. It is a cylindrical gaseous detector 7m long, with 7m diameter and 750 m³ of active volume filled with a xenon-CO₂ mixture. It is composed of 522 modules, divided in 18 sectors in azimuth, each of 5 stacks in longitudinal direction, with 6 layers per stack (see figure 2.5 for the detector layout). It has over 500 drift chambers, each one made of a Multi-Wire Proportional Chamber (MWPC). It has around 1.15 million readout channels, each sampling the signal in 20 time bins.

The TRD good spatial resolution (500 μ m) improves the momentum resolution of the track and, together with ITS information, allows a correct detection of open charm, open beauty and vector mesons. It is also complementary to the Muon Spectrometer (which will be described in Section 2.6), since it allows the study of quarkonia and open heavy-flavored mesons in the electronic channel. The TRD was designed to cope with a Pb–Pb interaction rate of 10 kHz and a maximum track multiplicity of 8000 charged particles per rapidity unit, while the readout rate was limited to few hundred Hz [59]. The performance of the TRD readout chain depends on two major functional units, the Front-End Electronics (FEE) and the Global Tracking Unit (GTU). The FEE is mounted on each TRD chamber inside the 18 supermodules and provides digitization as well as data processing and readout. The FEE provides no multi-event buffering and remains busy until the full processing and readout sequence is completed, while the major limitation of the previous GTU, which prevents from running at higher rates, is the readout bandwidth to the DAQ system.

TRD upgrade

In view of the higher rate data taking, the FEE and readout system must accept the largest possible fraction of interactions without the need to provide a trigger. An upgrade of the FEE hardware during the LS2 was not realistically feasible since this would have required a complete removal, disassembly and rebuild of all 18 TRD supermodules and the FEE mounted on the 522 individual detector chambers. The chosen strategy was a reduction of data readout time with the existing FEE by changing its mode of operation and limiting the amount of event data read from the FEE. The impact on performance for tracking and electron identification has been extensively

studied to validate this strategy [47]. The readout of the optimized FEE data format at the full minimum bias event rate required new hardware with increased bandwidth to the DAQ system. For this purpose it was chosen to use the ALICE Common Read-Out Unit (CRU) [60].

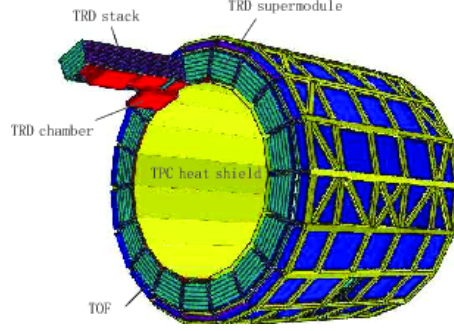


Figure 2.5: The Transition Radiation Detector detector

2.4.4 The Time Of Flight (TOF)

The Time-Of-Flight (TOF) [61] detector was designed to enhance PID in transverse momentum intervals not well covered by the other ALICE detectors. It measures, with a precision better than 100 ps, the time that particles take to travel from the IP to the detector itself, so that one can measure their speed. It is important in the identification of pions, kaons and protons in an intermediate p_T region ($0.2 \text{ GeV}/c \div 2.5 \text{ GeV}/c$), and it also perform π/K (π/p) separation for momenta above $0.5 \text{ GeV}/c$ and up to $2 (2.5) \text{ GeV}/c$, and e/π separation in the momentum range between 140 and 200 MeV [62]. Other than charged-particle PID, TOF provides also trigger for comics ray and ultraperipheral collisions.

The time of flight is measured by means of Multigap Resistive Plate Chamber (MRPC) strip detector, which are gaseous detectors with soda-lime glass resistive electrodes and multiple gas gaps. The TOF MRPC is based on a double-stack design: it is made of two stacks, each of five gas gaps, $250 \mu\text{m}$ thick. The signal obtained through gas ionization is amplified and the total signal is given by the sum of signals in every gap. The average time resolution is less then 50 ps.

Located at 3.7 m from the IP, TOF is constituted of a cylindrical array in the pseudorapidity region $-0.9 < \eta < 0.9$ (fig. 2.6). The array consists of 1593 MRPC strips divided in 18 azimuthal sectors. Each MRPC strip is segmented into two rows of 48 pickup pads of $3.5 \times 2.5 \text{ cm}^2$, for a total of 96 pads for each strip and 152928 total readout channels; in this way it is possible to guarantee a low detector occupancy even in the highest charged-particle-density scenario.

The TOF front-end cards host the fast amplifier and discriminator NINO. Output signals are transmitted to four VME electronics crates per each one of the 18 sectors. Each VME crate contains nine TDC Readout Module (TRM) cards, together with other cards for data readout and trigger elaboration. Finally, TRM card houses the high-performance time-to-digital converter eight-channel chips (HPTDC). The readout rate of the Time Of Flight detector (TOF) during Run 1 and 2 was limited to 40 kHz by the throughput of the VME system located in the crates at the end of the detector modules. In view of Run 3, an upgrade of this element was necessary.

TOF upgrade

The first limit on the TOF readout rate is the time needed to transfer the data from the HPTDCs. Since the TRMs, including the HPTDCs, are located inside the TOF supermodules, so in a region not easily accessible, any modification would have required the removal of TOF from the ALICE cavern and a disassembly of the supermodules, and this was not feasible within the installation time available during the Long Shutdown 2. The readout limit for HPTDC, according to their specifications, is 400 kHz for pp collisions [63], and the upgrade of the rest of the electronics chain is intended to eliminate all further restrictions on this rate.

Regarding the rest of the DAQ readout, data are transferred from DRM modules inside the TOF crates to the DAQ via the DDL link. These modules have been reengineered using a more performant FPGA chip and a new version of the DDL link. The upgrade of this element allow TOF to readout > 200 kHz Pb–Pb events, which easily satisfies the requirements.

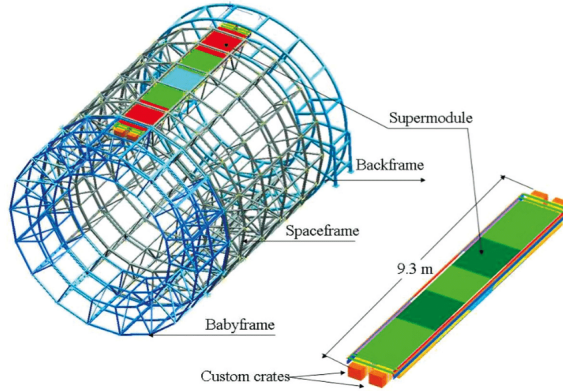


Figure 2.6: A schematic layout of one of the 18 TOF supermodules inside the ALICE spaceframe

2.4.5 The High-momentum Particle IDentification (HMPID)

The High Momentum Particle Identification Detector (HMPID) [64] identifies charged particles such as pions, kaons and protons, having large momentum. Its aim is to enhance the PID capability of ALICE by enabling identification of charged hadrons beyond the momentum interval attainable through energy-loss (in ITS and TPC) and time-of-flight measurements (in TOF). Thanks to the HMPID it is possible to identify and discriminate particles up to higher momenta: π/K and K/p discrimination is possible up to 3 GeV/c and 5 GeV/c respectively. The low yield of high-momentum particles in Pb–Pb collisions at the LHC energy regime justifies the single-arm geometry of the HMPID covering about 5% of the central barrel phase space.

It is made up of Ring-Imaging Cherenkov counters consisting of a radiator medium, where the Cherenkov light is produced and a photon detector providing patterns for the particle identification. The HMPID has an active area of 11 m² and it covers one unit in pseudorapidity $|\eta| < 0.5$ and 5% of TPC acceptance. It consists of 7 RICH counters of 1.4×1.3 m² each, installed on a support cradle inside the ALICE solenoid (see figure 2.7), based on Multi Wire Proportional Chambers (MWPCs) equipped with pad segmented photocathodes, activated with CsI. A fast particle crossing the 15 mm thick layer of liquid C₆F₁₄, which is used as Cherenkov radiator, produces Cherenkov photons, which are detected by the photon counter.

HMPID upgrade

Since 2021 the HMPID has been equipped with two aluminum targets to allow for the measurement of the (anti)-deuteron inelastic cross section. During Run 1 and Run 2 the maximum readout rate was 2.5 kHz for central Pb–Pb collisions. No upgrade of the electronics was planned during the LS2 since the detector could be easily integrated in the new ALICE read-out architecture as the upgraded ALICE system provides backward compatibility. Moreover it is possible to increase the 2,5 kHz rate significantly by parallelizing the readout cycles and replacing the DDL and RORC cards with those of the new generation (DDL3 and RORC3). Depending on the maximum achievable rate, the HMPID readout will be downscaled accordingly and the information will be combined to the one of other central detectors at the event building stage.



Figure 2.7: Photo of the ALICE HMPID.

2.4.6 The ElectroMagnetic CALorimeter (EMCal)

The ElectroMagnetic Calorimeter (EMCal) [65] enhances the capabilities of ALICE to measure highly energetic photons, neutral pions, jets of particles and electrons from heavy flavour decay.

It is a large Pb-scintillator sampling calorimeter with cylindrical geometry comprising 4416 individual modules that are grouped into twenty Super Modules (SM). Each of the modules is composed by 4 optically isolated towers, resulting in a total of 17664 individual towers. The optical readout of the towers is provided using wavelength shifting fibers coupled to an Avalanche Photo Diode (APD).

The EMCAL is located at a radius of 4.5 m from the beam line, inserted into support frames situated between the TOF and the solenoid. It covers the pseudorapidity interval $|\eta| < 0.7$ with an azimuthal acceptance of 110° , and is positioned approximately opposite in azimuth to the Photon Spectrometer (PHOS) calorimeter (see subsection 2.4.7).

An addition to the EMCal, called DCal [66] has been installed during LS1, in order to increase the azimuthal coverage by 70° (see figure 2.8) and consequently improve di-jet and hadron-jet correlation measurements in ALICE. In fact EMCal and DCal are placed in two independent regions in azimuth and since Run 2 the DCal extended significantly the jet quenching measurements enabled by the EMCal, by providing large acceptance for back-to-back correlation measurements of jets and hadrons.

EMCal and DCal are also equipped with triggering systems. The signals of groups of adjacent towers are summed up and a peak finding algorithm is used to find a signal peak, providing L0 and L1-level triggers to the ALICE

Central Trigger Processor, allowing to select online high energy objects such as photons and electrons. The signals from bigger groups of adjacent towers are also processed in order to detect wide objects as jets.

An individual tower is read out with an avalanche photodiode and a preamplifier mounted on the tower itself. The preamplifier signal is split into energy and trigger shaper channels on the Front End Electronics (FEE) boards [67]. Each FEE board provides readout of 32 towers and the energy shaper signals are sampled using the ALTRO chips designed for the TPC.

EMCal upgrade

The EMCal readout has been already upgraded during LS1, in order to provide more than an order of magnitude decrease in the readout time per event. Moreover this upgrade brought the EMCal close to the ALICE Run 3 goal of 50 kHz readout for minimum bias in Pb–Pb collisions. This was achieved with a modification of the EMCal readout architecture, minor modification of the existing FEE boards, and no modification on the trigger system.

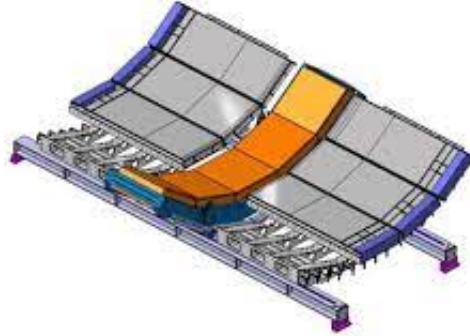


Figure 2.8: Schematic view of 6 DCAL super-modules (in gray) with the PHOS super-modules (in orange) in between.

2.4.7 The Photon Spectrometer (PHOS) and the Charged Particle Veto (CPV)

The PHOton Spectrometer (PHOS) [68] is a high-resolution electromagnetic spectrometer of high granularity, made out of 12544 detection channels based on lead-tungstate $PbWO_4$ crystals of $2.2 \times 2.2 \times 18 \text{ cm}^3$ (see figure 2.9). The scintillation light, in the visible near UV-wavelength range, is read out by a $5 \times 5 \text{ mm}^2$ avalanche photo-diode (APD) integrated with a low-noise pre-amplifier. It covers a limited acceptance domain at central pseudorapidity $|\eta| < 0.12$ and 70° in azimuthal angle and a total area of about 8 m^2 . It is

positioned on the bottom of ALICE set-up at a distance 460 cm from the IP. The main physics objectives are the direct photon measurements, for the test of thermal and dynamical properties of the initial phase of the collision, and the measurement of decay photons from high- p_T π_0 and η , that allows jet quenching analysis. The PHOS calorimeter is optimized for measuring photons of about 0.5-10 GeV/c, π_0 of about 1-10 GeV/c, and η mesons of about 2-10 GeV/c.

PHOS is equipped with a Charged Particle Veto detector (CPV) for photon identification via suppression of charged-particle contamination. The CPV is a set of proportional chambers with cathode pad readout installed in front of PHOS modules.

The PHOS readout electronics resembles very closely those from the ALICE EMCAL. In fact the EMCAL FE boards [67] were originally derived from PHOS. The basic unit in the readout chain is a FEE card (FEC) that processes and digitizes data from 32 crystals. The electronics chain for a crystal comprises the avalanche photo diode (APD), a charged sensitive preamplifier (CSP), and an analog shaper with a band-pass filter and amplifier.

PHOS upgrade

The PHOS calorimeters readout electronics, like the EMCAL one, was upgraded up to 50 kHz operation already during the LS1. This readout will be kept also beyond LS2 and the fact that not all of the 200 kHz minimum bias pp events can be read-out by the presente read-out chain is not considered an issue for the ALICE requirements.



Figure 2.9: Photo of the ALICE PHOS.

2.5 ALICE forward detectors

The forwards detectors are several smaller detectors for global event characterization and triggering, located at small angles with respect to the beam pipe axis.

During Run 1 and Run 2 ALICE forward detectors were the Zero Degree Calorimeter (ZDC) that will be used also for Run 3 and Run 4 and will be described in subsection 2.5.1, and three forward multiplicity detectors [69]: the Photon Multiplicity Detector (PMD), for the measurement of the multiplicity and spatial distribution of photons in the forward rapidity region $2.3 < \eta < 3.7$, the Forward Multiplicity Detector (FMD) that provided charged-particle multiplicity information in the pseudo-rapidity range $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.0$, and the V0 Detector that provided minimum-bias triggers for the central barrel detectors in pp and Pb–Pb collisions.

The PMD, FMD and V0 detectors have all been replaced during the LS2, and for this reason they will not be described in detail in this thesis.

In view of Run 3, the forward trigger detectors and the trigger system were upgraded since, to measure hard processes, the signal background had to be as low as possible, and new triggering techniques had to be developed. For this purpose, during the LS2 a brand new Fast Interaction Trigger (FIT) detector, which will be described in subsection 2.5.2, has been installed.

2.5.1 The Zero Degree Calorimeter (ZDC)

The Zero Degree Calorimeter (ZDC) [70] measures the energy deposited by the spectator nucleons in order to determine the overlap region in nucleus-nucleus collisions, and it provides important information in different collisions system: nucleus-nucleus, proton-nucleus and proton-proton runs. In heavy-ion collisions the ZDC is used for minimum bias event selection, event characterization by measuring the interaction centrality of the collision from the energy of the spectator nucleus, reaction plane orientation for flow analysis from the centroid of the spectrator neutron spot, and absolute luminosity from the rate of the electromagnetic dissociation in the neutron channel. In nucleus-proton runs it measures the centrality of the collision from the detection of slow nucleons, and it is also used in p-p runs for diffractive event selection.

The ZDC consists of two sets of hadronic calorimeters (see figure 2.10), located at 116 m on either side of the IP, where the two LHC beams circulate in two different pipes and spectator protons are spatially separated from neutrons by the LHC magnetic elements. Therefore, each of the two identical ZDC set

is made by two distinct detectors: one for spectator neutrons (ZN), placed between the beam pipes at 0° relative to the LHC axis, and one for spectator protons (ZP), placed externally to the outgoing beam pipe, on the side where the spectator protons are deflected from the ion beams by means of dipole magnet, while spectator neutrons fly at 0° without further changing direction. The ZDC detector has also two forward EM calorimeters (ZEM) placed at 7.35 m from the IP on the A side, covering the pseudorapidity range $4.8 < \eta < 5.7$, to discriminate between very peripheral and very central collisions.

The ZDCs are spaghetti calorimeters, composed of a dense absorber in which quartz optical fiber are interspersed (selected instead of scintillating ones because of the radiation-hardness requirements). It has to be noticed that the ZN and ZP dimensions are different since the two calorimeters have to satisfy different physical and technical requirements: the ZN transverse dimensions could not exceed the space between the two beam pipes, so a dense absorber has been chosen, i.e. W-alloy, while for the ZP the main requirement was to optimize the detection of the spectator protons spread over the horizontal coordinate and this has lead to the design of a larger device with respect to the ZN, and therefore to the choice of a less expensive absorber, i.e. brass.

The operation principle of the ZDC is based on the detection of Cherenkov light produced by the charged particles of the shower in the fibers. The quartz fibers are placed at 0° with respect to the beam line direction and come out from the rear face of the calorimeter, directly bringing the light to the photomultipliers. The response is very fast thanks to the intrinsic speed of the emission process, making the ZDC suitable for triggering purposes.

ZDC upgrade

The ZDC electronics has also been upgraded in order to provide all data for the 50 kHz Pb–Pb interaction rate upon an interaction trigger, without dead time. During Run 1 and Run 2 the readout rate was limited to 8 kHz and NIM and VME electronics modules (QDC and TDC) were used. Two custom modules were dedicated to the interface of the ZDC front-end with the ALICE trigger and readout systems: the ZDC Trigger Card (ZTC) aligned the ZDC trigger signals with the LHC clock and delayed them in order to satisfy the timing requirements for L1-level triggers, and the ZDC Readout Card (ZRC) was dedicated to data acquisition.

For Run 3 the ZRC had to be redesigned and the new one is readout by the ALICE CRU. The interface with the CRU is handled by one GBT link. The QDC modules have been replaced with digitizers which have on-board

FPGAs that allow a fast pre-processing of the data. In particular they allow integration of the signal and provide a time-stamp of arrival times. Moreover data are made available without the dead time due to charge integration and conversion typical of conventional QDCs.

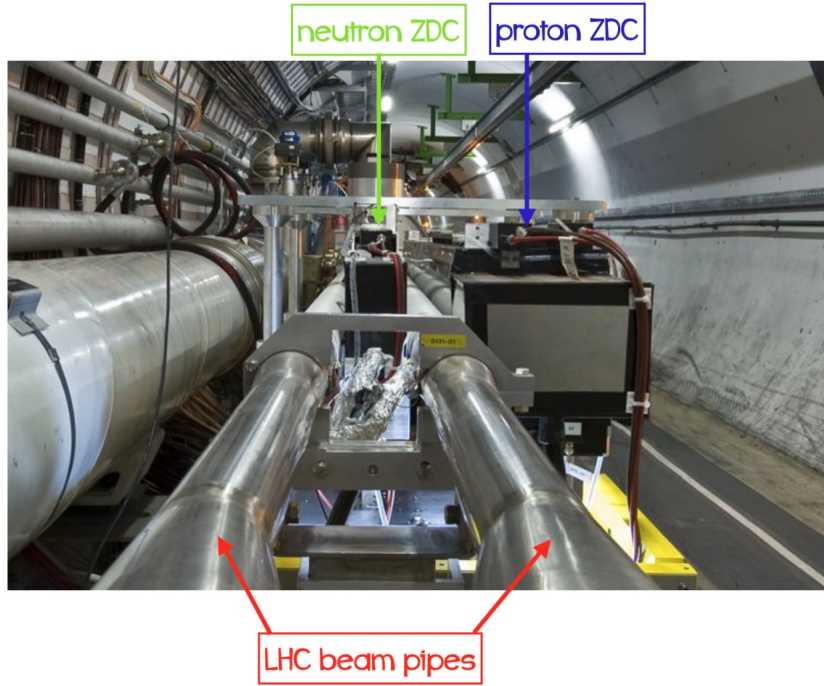


Figure 2.10: Photo of the ALICE ZDC in the LHC tunnel.

2.5.2 The Fast Interaction Trigger (FIT)

During the LHC Run 3 and Run 4 ALICE will operate at a significantly higher luminosity with respect to Run 1 and Run 2, and will collect two orders of magnitude more events. A part of the upgrade is the new Fast Interaction Trigger (FIT) [71] that combines, in one system, the functionality of the three forward detectors used by ALICE during the LHC Run 2: V0, FMD and PMD. The FIT detector has been successfully installed in the ALICE cavern in June 2021.

FIT will serve as an interaction trigger, online luminometer and background measurement (providing feedback to the LHC), initial indicator of the vertex position and forward multiplicity counter. The FIT electronics is designed to function both in the continuous and the triggered readout mode, and during the offline analysis FIT data will be used to extract the precise collision time needed for TOF particle ID. For the heavy-ion collisions, it will also determine multiplicity, centrality, and event plane.

The FIT detector is constituted by three subdetectors, FV0, FT0 and FDD (grouped into five arrays surrounding the LHC beamline), each utilizing a different technology. These detectors are placed next to the central tracking detectors inside the L3 magnet, at both sides of the IP, in the forward and backward rapidity regions (see figure 2.11).

FT0

The FT0 is a Cherenkov detectors consisting of two subdetectors, FT0A and FT0C, placed at opposite sides of the IP. The FT0A array consists of 24 modules, while the FT0C array has 28 modules. Each module has four, optically separated, 2 cm-thick quartz Cherenkov radiators, coupled to a customized PMT, for a total of 208 quartz radiators. FT0 time resolution for high-multiplicity heavy-ion collisions is about 7 ps, making FT0 one of the most precise timing detectors in high-energy physics experiments. This precise timing is crucial for online vertex determination and for identifying charged lepton and hadron species using TOF.

FV0

The FV0 is the largest of the three subdetectors and consists of a segmented scintillator disk assembled from 40 optically insulated elements, arranged in 8 sectors and 5 rings with progressing radii. Optical fibers deliver light from each element to a PMT. The FV0 time resolution is about 200 ps and it provides inputs for minimum bias and multiplicity triggers at L1-level and, thanks to its large acceptance, it delivers data for centrality and event plane determination.

FDD

The Forward Diffractive Detector (FDD) consists of two identical plastic scintillator arrays divided into four quadrants, FDDA and FDDC, covering very forward rapidity region at the opposite sides of IP. Each quadrant has two wavelengths shifting (WLS) bars connected to individual PMTs via optical fibers. The FDD contributes to cross section measurements of diffractive processes by recognising the absence of activity in the forward direction, studies the ultra-peripheral collisions, and it participates in beam monitoring and beam-gas rejection.

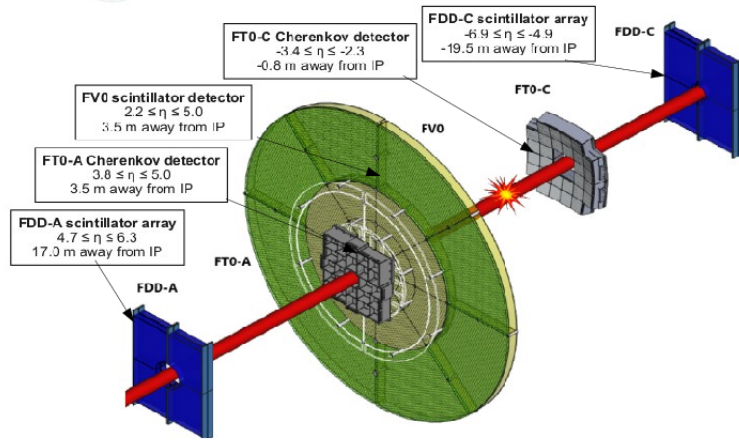


Figure 2.11: Schematic layout of the new FIT ALICE detector.

2.6 The ALICE Muon Spectrometer (MS)

The forward Muon Spectrometer (MS) [46], shown in figure 2.12, was designed to measure the complete spectrum of heavy quarkonia states, i.e. charmonium (J/ψ , ψ') and bottomonium (Υ , Υ' and Υ''), which are hard, penetrating probes sensitive to the QGP formation. Among the topics covered by the MS there are also open heavy flavours and vector-mesons production, both in heavy ion and p-p collisions.

The MS detects quarkonia via their decay in the $\mu^+ \mu^-$ channel, down to zero p_T . It covers the pseudorapidity region $2.5 < \eta < 4$ (corresponding to $2^\circ < \theta < 9^\circ$), the invariant mass resolution is of the order of $70 \text{ MeV}/c^2$ in the J/ψ region and $100 \text{ MeV}/c^2$ in the Υ region, allowing to resolve and measure individually all five resonance states.

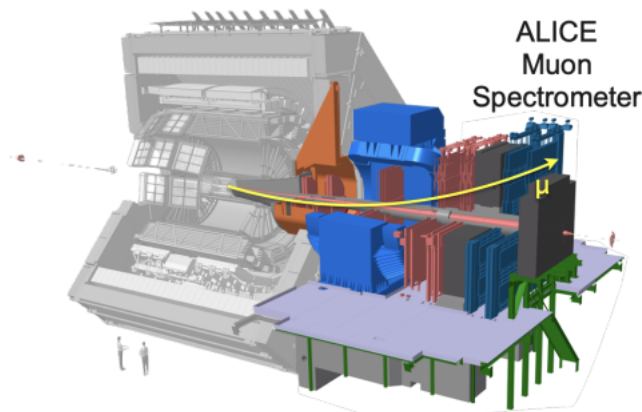


Figure 2.12: Schematic view of ALICE with highlighted the Muon Spectrometer.

Before the upgrade for Run 3, the MS consisted of a dipole magnet, a front hadron absorber, a beam shield, the Muon Tracking Chambers (MCH), an iron filter and the Muon TRigger (MTR), as shown in figure 2.13.

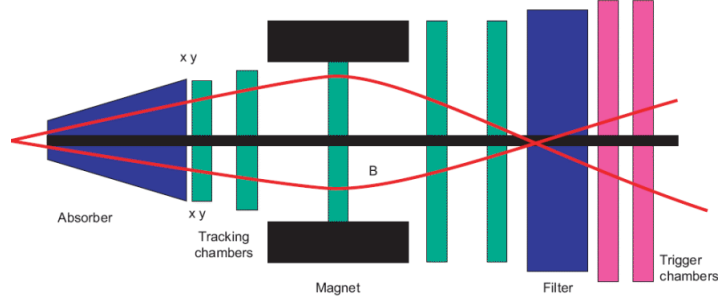


Figure 2.13: Schematic side view of the Muon Spectrometer during Run 1 and Run 2

From Run 3 onwards, a new Muon Forward Tracker (MFT) was added before the first absorber, and the MTR became a Muon IDentifier (MID), in order to cope with the new ALICE triggerless working mode (see figure 2.14). The MFT and the MCH will be described in section 2.6.1 and 2.6.4 respectively. The dipole magnet and the absorbers will also be briefly described in section 2.16, 2.6.2 and 2.6.5 respectively. Concerning the MID, since it is the subject of this thesis, it will be described in detail in the next chapter.

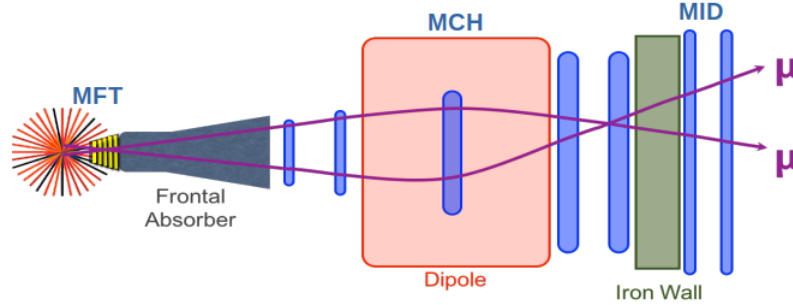


Figure 2.14: Schematic side view of the ALICE Muon Spectrometer during Run 3

2.6.1 The Muon Forward Tracker (MFT)

In order to improve the resolution of the secondary vertex and to allow new physics measurements, a brand new high resolution silicon-based detector, the Muon Forward Tracker [72] has been installed during the LS2. It is placed in front of the MS, upstream with respect to the front hadron absorber. Due to the multiple scattering induced on the muon tracks by the first hadron absorber, the details of the vertex region are completely smeared out and

this prevented ALICE during Run 1 and Run 2 to disentangle prompt J/ψ production (i.e. charmonium states directly produced in the hard scattering) from non-prompt J/ψ production (i.e. charmonium states coming from the decay of hadrons composed of a quark b). Thanks to the addition of the MFT, we are now able to reconstruct the secondary vertex of non-prompt J/ψ production, coming from the b -decays, by matching the extrapolated muon tracks, coming from the tracking chambers after the absorber, with the ones measured in the MFT planes before the absorber.

The MFT consists of two half-cones containing five detection half-disks each, placed along the beam axis between -460 mm and -768 mm away from the IP, and it covers the pseudorapidity range between $-3.6 < \eta < -2.5$ (see figure 2.15). The planes are constituted by ALPIDE Silicon pixel sensors [52], based on Monolithic Active Pixel Sensors (MAPS), developed together with the new ALICE Inner Tracking System. Each chip houses half a million pixels in an active area of 4.5 cm^2 and there are in total 936 silicon pixel sensors on 280 ladders of 2, 3, 4 or 5 sensors each. The sensor size is $15 \times 30 \text{ mm}^2$, while the pixel one is $27 \mu\text{m} \times 29 \mu\text{m}$. This very high pixel density translates into an enhanced resolution for high-precision measurements of particle tracks and an overall spatial resolution of the MFT of better than $5 \mu\text{m}$.

The read-out electronics, common to both ITS and MFT, has been jointly developed by the two projects, and the MFT was successfully installed in the ALICE cavern in January 2021.

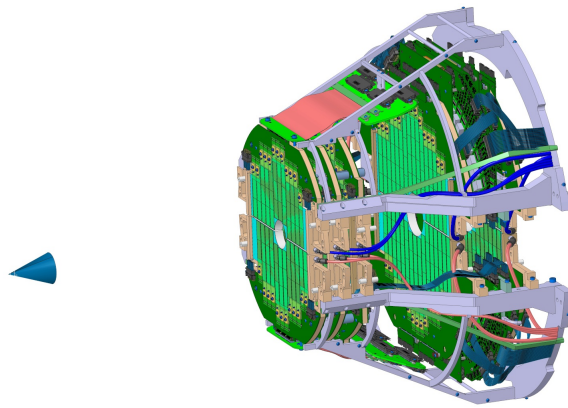


Figure 2.15: Schematic view of the ALICE MFT detector.

2.6.2 The front hadron absorber

The front absorber was a critical component of the MS since it has been designed to reduce the initial flux of primary hadrons from nucleus-nucleus collisions, and simultaneously it has to minimize the invariant mass resolution

deterioration of the spectrometer due to multi-scattering. In order to do so, the front absorber was made with low Z materials, such as carbon and concrete. Moreover this requirement imposes also an upper limit of the amount of material ($\sim 10\lambda_I$). The front absorber is 4.13 m long and it is located inside the solenoid magnet, starting 90 cm away from the IP. The front absorber stops most hadrons emitted in the MS acceptance; together with the beam shield around the beam pipe which reduce the low energy background due to secondary interactions along the pipe, it reduces the particle flux on the muon tracking chambers by two orders of magnitude.

2.6.3 The dipole magnet

The ALICE dipole magnet [73] with resistive coils provides the bending power to measure the momenta of muons in the MS. It is placed 7m from the IP and with its 5m length and 890 tons total weight it is one of the biggest warm dipoles in the world. The size was defined by the requirements on the angular acceptance of the MS while the field was defined by the requirements on the mass resolution. The magnet has an horizontal field in the forward direction of 3 Tm, i.e. perpendicular to the beam axis and parallel to the LHC radius (the bending plane is the xy plane and the non-bending plane is the xz plane, where z indicates the coordination along the beam line).

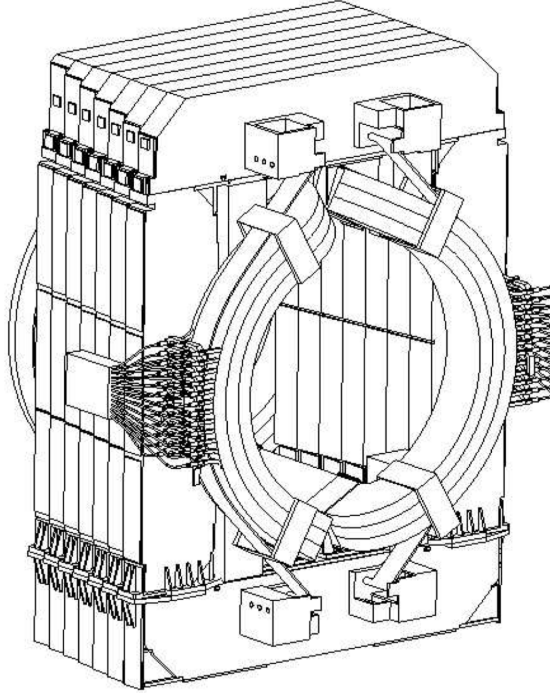


Figure 2.16: Schematic view of the ALICE Muon Spectrometer dipole magnet.

2.6.4 The Muon Chambers (MCH)

The MCH [46] is a tracking system made of 5 stations of 2 planes each, for a total of 156 multi-wire proportional chambers with more than one million electronics channels. The tracking system covers a total area of about 100 m^2 and, because of the different sizes of the stations (ranging from few square metres for station 1 to more than 30 m^2 for station 5) two different designs were adopted, i.e. Cathode Pad Chambers (CPC) and Cathode Strip Chambers (CSC). The gas mixture used for all the chambers is composed of 80% Argon and 20% CO_2 . The first two stations are placed before the dipole magnet, at a distance of 5.4 m and 6.8 m respectively from the IP and right behind the absorber in order to measure the exit points of the muons as precisely as possible; the third station is placed inside the dipole magnet, at a distance of 9.7 m from the IP, and the last two stations are placed after the dipole magnet, at 12.6 m and 14.2 m from the IP. Both cathode planes are read out in order to provide two-dimensional hit information.

To keep the occupancy at about 5%, a fine-granularity segmentation of the readout pads is needed. For instance, for the region of the first station close to the beam pipe, where the highest multiplicity is expected, were used pads with a size of $4.2 \times 6.3 \text{ mm}^2$. Since the hit density decreases with the distance from the beam, larger pads were used at larger radii. The chambers in station 1 and 2 have read-out electronic on the surface (as shown in figure 2.17), while those in station 3, 4 and 5 have read-out electronics on the side (as shown in figure 2.18).

During Run 1 and Run 2, the front-end card used, called MANU board (64 channels), consisted of 4 MANAS chips (pre-amplifier and shaper chip), several ADCs, and a controller chip (Muon Arm Read-out).

The tracking chambers were designed to achieve a spatial resolution of about $100 \mu\text{m}$ for the bending plane (y direction), and of 1 mm for the non-bending plane (x direction), necessary for an invariant-mass resolution of the order of $100 \text{ MeV}/c^2$ at the Υ mass. Muon transverse momenta in the bending plane (p_{xy}) are determined by tracking muons along the magnetic field. In order to obtain the required spatial resolution, all the chambers were made of composite material (about 3% of X_0 per chamber), to minimize the scattering of the muons.

MCH upgrade

To cope with the higher collision rate that was foreseen for Run 3, the CPC and CSC detectors have a new front-end electronics (FEE) and a new

readout chain [74]. The new FEE chip, called SAMPa, which supports both triggered and continuous readout mode, was developed jointly with the ALICE Time Projection Chamber upgrade project [47]. These new boards amplify, digitize, filter, and compress the signal. The data from Dual Sampa (DS) boards (each hosting two SAMPa) are sent through FE links implemented on printed circuit boards to a new concentrator board called SOLAR, via GBT links protocol [75]. The SOLAR board collects data from several DS through FE links and sends them to the new ALICE Common Readout Unit (CRU). The full chain was successfully validated in a beam test in 2017 at the CERN SPS and all the components were installed during the LS2 of LHC.

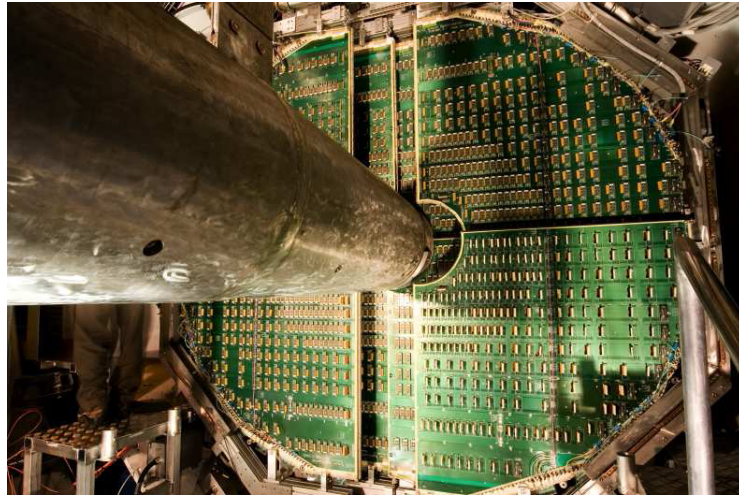


Figure 2.17: Layout of station 2 of the tracking system. Readout electronics is distributed on the surface of a quadrant structure



Figure 2.18: Layout of stations 4 and 5 of tracking system

2.6.5 The Muon Iron filter

While the front absorber and the beam shield are sufficient to protect the muon tracking chambers, additional protection is needed for the Muon Identification System, in order to remove the residual background of hadrons and to be sure that the particles crossing it are muons. For this reason a muon filter, i.e. an iron wall 1.2 m thick ($\sim 7.2\lambda_I$), was placed after the last muon tracking chamber, in front of the first MID chamber (14.5 m far from the IP). The front absorber and the muon filter combined together stop muons with momentum less than 4 GeV/c.

Chapter 3

The Muon IDentifier

The ALICE Muon IDentifier (MID) is the main topic of this thesis. For this reason it will be presented in detail in this chapter together with its upgrade for Run 3 and Run 4, starting from the Resistive Plate Chambers (RPCs) detectors, moving then to the Front-End electronics, the read-out chain and the software tools for the MID performances studies during the data-taking.

3.1 Introduction: from the Muon Trigger to the Muon IDentifier

The identification and selection of interesting events for muons physics during Run 1 and Run 2 was performed by the Muon Trigger System (MTR) [76], based on Resistive Plate Chambers (RPCs) detectors, placed at the end of the Muon Spectrometer, after the muon filter, as shown in figure 3.1.

The MTR was designed to select unlike-sign muon pairs from the decay of resonances, like-sign muon pairs for combinatorial background studies, and single muons from open heavy flavors. The selection of heavy quark resonances, J/ψ and Υ , required a selective trigger because of the small production cross-section and the small branching ratio in this channel. Depending on the mass range of interests, selecting these resonances in Pb–Pb collisions can be complicated by the presence of muons coming from the decay of π and K mesons, which generate a combinatorial background in the invariant mass spectrum. To reduce the probability of triggering on events where these low- p_T muons (i. e. background muons) are not accompanied by the high- p_T ones, emitted in the decay of heavy quarkonia (or in the semi-leptonic decay of open heavy flavours), a p_T cut had to be applied at the first level trigger by the MTR system.

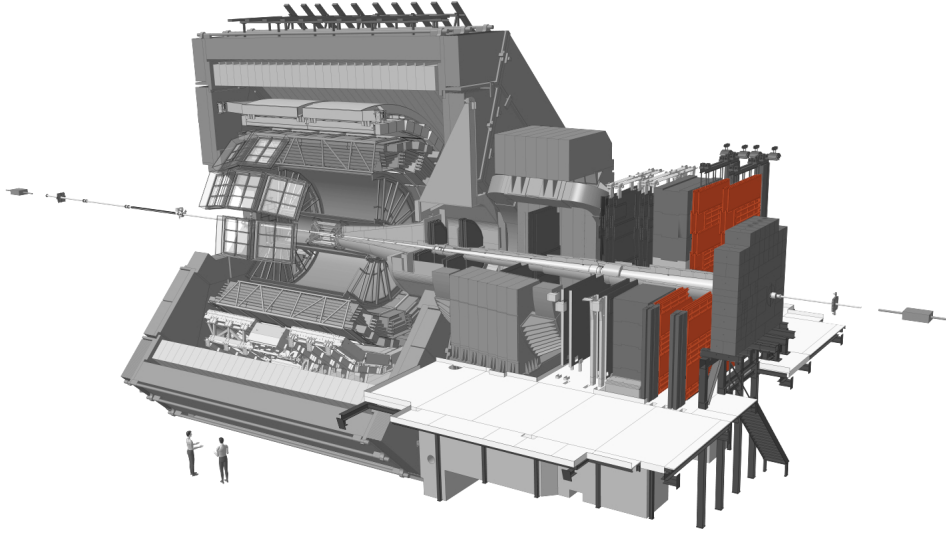


Figure 3.1: ALICE experiment with highlighted in red the RPCs.

In order to do so a fast signal and a large covered area were needed: to fulfill these requirements Resistive Plate Chambers detectors were chosen. RPCs are position-sensitive gaseous detectors with a spatial resolution of the order of mm, which can indeed cover large areas and provide fast signals of the order of ns. RPCs detectors will be described in detail in section 3.3.

As mentioned before, from Run 3 on, in order to meet the requirements posed by the forthcoming LHC high luminosity runs, the ALICE experiment is running in continuous readout mode (i.e. without trigger) and the Muon Trigger became the Muon Identifier (MID). The detailed description of the MID layout is presented in section 3.2.

Moreover the Pb–Pb collision rate is increased by a factor 5-10, i.e. the maximum counting rate is increased from about 10 Hz/cm² of Run 1 and 2 up to 90 Hz/cm² for Run 3, leading to some limitations for the RPCs detectors of the MTR.

The RPCs limitations for Run 3 and Run 4 were mainly related to the read-out speed and to the ageing effects. In fact during Run 1 and Run 2, the RPCs of the MTR were working in the so-called maxi-avalanche mode (see subsection 3.3.2), i.e. about 150-200 pC released per single hit in the gas gap, with a maximum rate capability of about 100 Hz/cm². This means that, after the LHC upgrade, the maximum counting rate in Pb–Pb collisions is very close to the maximum rate capability of the RPCs working in maxi-avalanche mode (see section 3.3.2). Moreover this increase in the collision rate will also induce an accelerated aging of the detectors (see subsection 3.3.3), and some of the RPCs installed in ALICE since 2007, i.e. before the start of LHC Run 1,

would reach the expected end of lifetime before the conclusion of Run 4.

In order to overcome these limitations and reduce the aging, some upgrades were necessary. More precisely, to increase RPCs rate capability and reduce the charge released per hit inside the gas gap, it was decided to use the same gas mixture used for Run 1 and Run 2, but at lower gain, i.e. to operate the RPCs in avalanche mode instead of the maxi-avalanche. This goal was reached by using a brand new front-end electronics with the addition of a signal pre-amplification stage upstream of the front-end discriminators. Both the old and the new front-end electronics are presented in section 3.4.

Furthermore, some of the most aged RPCs in the ALICE cavern have been replaced during the LHC winter shutdown in 2022-2023, in order to guarantee to operate the system at its best performance. The experimental set-up, the tests and characterization of the new production of gas gaps installed in the ALICE cavern (and the spares ones to replace the RPCs that will show aging effects during Run 3) are all described in chapter 4.

Finally, in order to switch to the new ALICE continuous readout mode, the readout architecture used during Run 1 and Run 2 was not suitable anymore and it had to be replaced with a brand new one. The MID new readout architecture is presented in section 3.5.



Figure 3.2: Photo of the MID system in the ALICE cavern.

3.2 Description of the MID system layout

The ALICE MID is composed of 72 single-gap bakelite RPCs arranged in two stations separated by one meter, called MT1 and MT2, located respectively 16.1 m and 17.1 m away from the IP, as shown in the left panel of figure 3.3. Both the MT1 and MT2 stations consist of two detection planes, covering an area of $5.5 \times 6.5 \text{ m}^2$ and each one of them consists of 18 RPC modules. Furthermore each plane is divided in two half-planes, one inside the LHC ring and one outside the LHC ring, named INSIDE and OUTSIDE in the rest of this thesis. The typical size of a single RPC module is $70 \times 270 \text{ cm}^2$, corresponding to a total active area of about 140 m^2 .

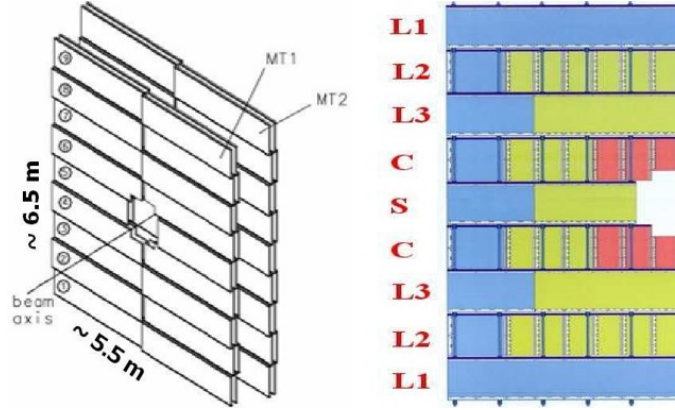


Figure 3.3: Schematic view of the MID, and the detector composition of an half plane.

In the center of the MID system there is a $1.2 \times 1.2 \text{ m}^2$ hole to allow the passage of the beam shield. For this reason the detectors have different shape and segmentation, i.e. Long, Cut and Short (L, C, S), as shown in the right panel of figure 3.3. Each half plane is composed by six L-type chambers, two C-type chambers with cut-corner and one S-type. Furthermore the detector size is larger in MT2 than in MT1, because they are arranged in projective geometry with respect to the IP.

Each RPC is equipped with two orthogonal read-out strips planes (see section 3.3 for the detailed description of the RPC detectors), one on each side of the gas gap, in order to provide the spatial information along the x and y direction, i.e. on the plane perpendicular to the beam pipe z-axis, and to allow a three dimensional hits reconstruction of the muon tracks. The vertical Y-strips measure the coordinate along the X direction, which defines the non-bending plane, while the horizontal X-strips measure the Y coordinate, i.e. along the bending plane and consequently they measure the bending

deviation due to the dipole magnetic field. The total number of read-out strips is $\sim 21\text{k}$ and there are six different strip pitches (see table 3.1). Vertical strips only have widths of 2 and 4 cm, since the resolution requirements in the non-bending plane are less stringent, while a better spatial resolution is needed for horizontal strips, since they determine the particle deviation in the bending plane. The particle density is maximum near the beam pipe and become lower with increasing distance. For this reason, in order to provide an almost flat occupancy throughout the entire plane surface and to keep the momentum resolution roughly constant over the detection planes, the strip pitch and length increase with increasing distance from the beam pipe axis. The detector planes are mounted on mechanical frames that can be moved in order to allow the maintenance and the replacement of the installed RPCs.

Table 3.1: Strip pitches of the Muon Identifier

MID Station	Strip pitches (mm) bending plane (horizontal strips)			Strip pitches (mm) non-bending plane (vertical strips)	
MT1	10.6	21.2	42.4	21.2	42.5
MT2	11.3	22.6	45.2	22.6	45.2

3.3 Resistive Plate Chambers (RPCs) detectors

A Resistive Plate Chamber (RPC) is a particle gaseous detector based on a constant and uniform electric field produced by two parallel electrode plates, made of a material with high bulk resistivity. This detector was developed by R. Santonico and R. Cardarelli in the early 1980's. [77]

The RPC detectors are widely used in the large LHC experiments (i.e. ALICE, ATLAS and CMS) for muon triggering purposes for several reasons:

- unlike detectors with cylindrical shape, the constant and uniform electrical field ensures a fast discharge with small temporal fluctuations;
- the spatial resolution is of few mm and the time resolution is of the order of ns, so this kind of detector is very suitable for trigger purposes;
- RPCs detectors are not very expensive, so they can be used for large area applications;
- they have a rate capability up to few hundreds of Hz/cm^2 .

3.3.1 Design of a RPC

The design of an RPC used for the MID is shown in figure 3.4 [78]. It is constituted by a 2 mm gas gap, which is the active part of the detector, enclosed by two resistive electrodes made of paper treated with a phenolic resin, named bakelite, having a resistivity of the order of $\rho = 3.5 \times 10^9 \text{ cm}$ and 2 mm thick. The two parallel plate electrodes are connected to the High Voltage (HV) and to the ground by a layer of conductive material (graphite layer) applied on their outer surface, and they are kept at a constant distance by means of insulating spacers distributed on a $10 \times 10 \text{ cm}^2$ grid inside the gas gap. A polycarbonate frame borders the gap ensuring the gas tightness. The inner surfaces of the gap are treated with a double deposition of linseed oil in order to ensure the smoothness of the bakelite surfaces and the homogeneity of the electric field. The uniform electric field in the gas gap is of the order of 4-5 kV/mm.

The signal is picked up inductively by means of copper read-out strips which are electrically insulated from the electrodes by PET foils 100 μm thick. These strips are separated by about 2 mm one from the other. Together with the ground plate, the strips constitute transmission lines of 50 Ω characteristic impedance. One end of the line is terminated with a 50 Ω resistor, to avoid reflection of the signal, while the other is connected to the Front-End Electronics (FEE).

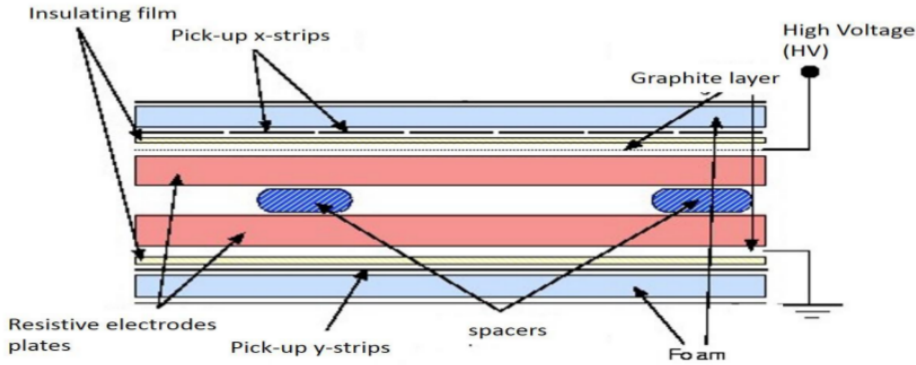


Figure 3.4: Schematic side view of a Resistive Plate Chamber.

3.3.2 Working principle of RPC

Avalanche and Streamer signals

An ionising particle which travels through the RPC gas gap (i.e. the sensitive region) causes the ionization of the gas and ion-electron pairs are produced. [79]

The free electrons, so-called primary electrons, under the influence of the external applied electric field drift towards the anode, while the ions move to the cathode in the opposite direction. These electrons are involved in a multiplication process since they accelerate under the influence of the electric field and they gain energy between consecutive electron-molecule collisions within the gas. If the gained energy is sufficient, secondary electron are liberated in subsequent collisions. In this way an *avalanche* electronic cloud (formed by primary and secondary electrons) is originated. Due to the greater mobility of electrons, compared to the much lower ions mobility, this *avalanche* cloud has the form of a drop. The *avalanche* grows until the internal field created by the charges in the drop compensated the external applied field. At this point the multiplication process stops and ion-electron recombination photons can further ionise the gas causing then the production of additional electron-ion pairs which generate secondary avalanches. In addition, electrons can be extracted from the cathode and generate other avalanches. This process can lead to formation of a conductive plasma: then, a spark is generated, which give rise to a *streamer*, i.e. a discharge.

In figure 3.5 the evolution from avalanche to streamer in a gaseous detector is shown.

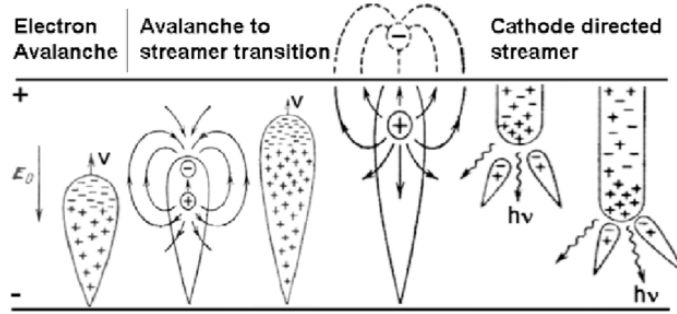


Figure 3.5: Evolution from an electron-avalanche to a streamer in a gaseous detector.

In the RPC detector the discharge is properly quenched, preventing it from permanently short-circuiting the electrodes [80]: due to the large electrodes resistivity, the discharge switches off the local electric field around the discharge region: since the discharge duration is of the order of 10 ns while the relaxation time of the bakelite electrodes is larger than 10 ms, the electrodes behave as insulators throughout the whole discharge duration, preventing the plasma from propagating beyond a small region of about 0.1 cm^2 . In this region the diminution of the local electric field makes the RPC temporarily inefficient, but out of the discharge region the sensitivity of the detector is unaffected. In addition secondary discharges from photon ionisation are prevented thanks to

UV photon absorption by organic gas in the gas mixture. Due to the RPC planar geometry, it is possible to use a gas mixture with strong quenching properties without loss in efficiency, since the electric field does not decrease with the distance from the anode like in cylindrical gaseous detectors, and the multiplication process occurs in the whole gas volume. Moreover, in the RPC, the localisation of the discharge provides bi-dimensional spatial information and the detector can be read on both sides with orthogonal strips.

The amplitude of the streamer signal induced on the strips is of the order of 100 mV and it is always preceded by the avalanche signal, which has an amplitude smaller than few mV. In figure 3.6 the typical avalanche and streamer pulses are shown [81]. It was observed by increasing the voltage that the first signal pulses are small and, as the voltage is increased, much larger pulses appear, i.e. the streamer ones. So the avalanche signal is indeed always present, while the streamer signal begin to appear above a critical voltage value. Regarding the timing, the one of the avalanche signal is more precise than the streamer one, because the avalanche is a direct consequence of the primary ionisation. The formation of the streamer signal is instead a stochastic event, with a larger time jitter with respect to the avalanche one.

Finally RPCs have low sensitivity to neutrons and photons at 1 MeV, of the order of about 10^{-3} and about 10^{-2} respectively [82], and they are weakly sensitive to magnetic fields. This is another positive feature of the detector since they have to cope with a high-particle density environment in the large LHC experiments.

Thanks to all these features, even if the first RPC purpose was to provide a large scintillators counter, it was soon recognized that this detector can be used also as a timing tracker due to its space-time localization of the discharge.

Gas mixture

The drift velocity and diffusion of electrons depend very strongly on the properties of the gases inside the gap, specifically on the inelastic cross-section of electrons on gas molecules. For this reason, while the structure of RPCs has remained essentially unaltered over the years up to nowadays, there is a lot of R&D effort on the optimisation of the gas mixture.

Depending on whether the RPC is chosen to operate in avalanche or streamer mode the gas mixture should be modified. In fact the gaseous mixture of a RPC is not standard and each implementation can differ from any other one, depending on the requirements.

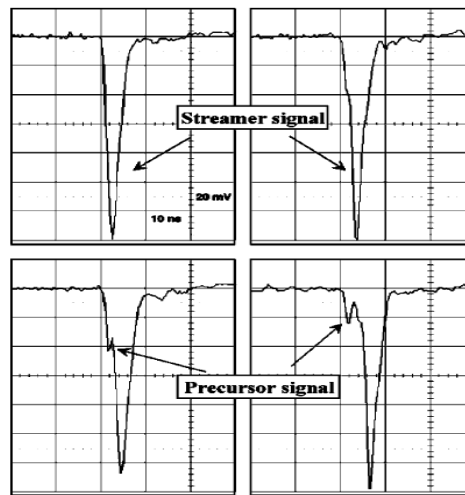


Figure 3.6: Typical pulses from an RPC operating in streamer mode. They are observed with an oscilloscope directly connected to the anode of a RPC with a $50\ \Omega$ termination. The four graphs (displayed with the same scales) were obtained in the same detector running conditions and corresponds to different possible signal shapes. It shows that the streamer signal can be delayed with respect to the precursor one by several nanoseconds. The precursor (i.e. avalanche) signal, with a typical amplitude of 20 mV, has the particularity to be synchronous with the particle crossing the RPC. The second peak is characterized by a time jitter with respect to the precursor, but with a large amplitude (typically ~ 100 mV) as expected for a streamer pulse.

A RPC operating in the streamer mode has typically a gas mixture which include a donor gas, like Argon, as a multiplier ($2/3$ in volume) and an X-ray quencher like isobutane ($1/3$ in volume) which is a gas with a high cross section for X-rays and high energy photons. The donor gas is the one that should be ionized by the crossing particle and which provides amplification of the deposited charge via secondary ionisation, while the quenching gas absorbs a large amount of UV photons, and disperses their energy in mechanical vibrational and rotational processes. Moreover electronegative components, like freon gases, have the effect of absorbing free electrons, thus reducing the transversal size of the electric signal induced on the strips. So an amount of freon, limited to a few percent in order to avoid excessive capture of primary ionization electrons, is also added to the gas mixture with the aim of reducing the charge deposited on the electrodes at each hit and increase the rate capability [83].

While the streamer mixture is mainly composed of Argon, in avalanche mixtures this gas is replaced by another one which, along with acting as a donor, has also quenching properties (for example the tetrafluoroethane). Together with tetrafluoroethane, also an organic gas like isobutane and a fraction of strongly

electronegative gases such as SF_6 are used for the avalanche gas mixture. A larger amount of quencher, with respect to the streamer gas mixture, are needed for the avalanche one in order to prevent that the signal degenerates into a streamer [84].

It is possible to work in avalanche mode obtaining a better time resolution and a smaller charge deposited on the electrodes, about 10 pC, with a corresponding better rate capability (see Sec. 3.3.4). In order to work in avalanche mode a lower threshold is required because of the lower amplitude signals. The price to pay is a more relevant noise background with respect to the streamer working mode, and an electronics for the pre-amplification of the signal is needed.

In the streamer mode it is possible to choose a higher threshold, since the signal amplitude is quite wide and this reduces the noise rate. The better discrimination between signal and noise with respect to the avalanche mode leads to a lower cluster size, thus to a better spatial resolution than in the avalanche working mode. The price to pay is a worse time resolution because, as mentioned before, the spark formation is a stochastic phenomenon. Moreover, there are more important aging effects of the detector (see Section 3.3.3) than in the avalanche mode, because of a larger charge crossing the gas gap and producing chemically active gas molecules fragments.

From all these considerations it is evident that the operating mode must be chosen according to the specific requirements that must be fulfilled. For example, as the first goal of ALICE is the study of heavy-ion collisions, the R&D of the ALICE RPC was focused on the requirements imposed by Pb–Pb data taking, characterised by a high particles hit multiplicity. This led to the choice of operating in streamer mode, in order to reduce the cluster size and increase trigger selectivity and two-track resolution. The chosen gas mixture is shown in table 3.2.

Table 3.2: ALICE RPC gas mixture for streamer working mode (Pb–Pb collisions).

Gas	Percentage %
Ar	50.5%
$\text{C}_2\text{H}_2\text{F}_4$	41.3%
<i>i</i> - C_4H_{10}	7.2%
SF_6	1%

This mixture with these percentages of gases facilitates the formation of the streamer signal and prevents its degeneration in a large discharge since, as mentioned before, the goal of the first studies was to improve the rate

capability of RPCs and minimize the charge released in the streamer mode. The presence of strong electronegative gases SF_6 , helps to avoid a too large streamer signal capturing free electrons, but on the other hand it increases the operating voltage, thus increasing the electrons energy and consequently the amount of fluorine freed in electron-molecule collisions [85] that could attack the linseed oil on the inner surfaces of gas gap and degrade them.

The constraints for the p-p data taking are different with respect to Pb-Pb. The multiplicity is smaller and the requirement on the spatial resolution is less stringent, but the rates are much higher due to the higher luminosity and beam-gas background. These conditions, together with the long data taking time period, make the detector lifetime issue quite important. An intense R&D was carried out on the possibility of having the RPC operating in highly-saturated avalanche mode [86], so-called maxi-avalanche, with the same FEE used for the streamer. This operation maxi-avalanche mode is characterized by higher gain with respect to the avalanche one, with a signal of the order of 10 mV. The HV applied is about 10400-10500 V at 940 mbar pressure and 20°C, with a detection threshold of 7mV. The resulting gas mixture which provides a better lifetime of the detector is shown in table 3.3.

Table 3.3: ALICE RPC gas mixture for maxi-avalanche working mode (p-p collisions).

Gas	Percentage %
$\text{C}_2\text{H}_2\text{F}_4$	89.7%
<i>i</i> - C_4H_{10}	10%
SF_6	0.3%

In both operating modes a percentage of water vapour is added to the gas mixture. Flushing wet gas in the gap keeps constant the humidity of the bakelite plates, preventing modifications in the resistivity and deformations of the surfaces. The relative humidity is about 37%.

So before the start of LHC Run 1, the original gas mixture used was different for Pb-Pb and p-p collisions. But during the first Pb-Pb collisions it was realized that the particle multiplicity was smaller than expected and this mean that the requirements for ALICE RPCs, in terms of cluster size, were too restrictive and the maxi-avalanche mixture was also suitable for Pb-Pb collisions, so the streamer mixture was abandoned for the ALICE RPCs, due to its more pronounced aging effects. The maxi-avalanche gas mixture, called *standard gas mixture* was the only one used in ALICE RPCs since then, either in p-p, p-Pb and Pb-Pb.

3.3.3 Aging in RPC detectors

The ALICE's RPCs were installed in the ALICE cavern in 2007, before the start of LHC Run 1 and they have shown stable performances during the first two runs of LHC. However, like other gaseous detectors also the gas gap of the RPCs can undergo performance degradation during long-term operation, especially when exposed to high particle fluxes.

Due to the exposure of the RPC to high hit rates, the amount of charge generated in the gas gap during irradiation at nominal voltage (both in the avalanche or streamer mode) can induce the generation of chemically active gas molecules fragments. In fact, fluorine is very reactive and it can modify the component of the original gas mixture and alter the bakelite electrodes surface. The already mentioned humidification of the gaseous mixture allows one to constantly hydrate the inner surface of the bakelite electrodes, keeping constant the original gas gaps shape and the bakelite resistivity value (see figure 3.7) [87].

ALICE RPCs were aging tested (before the installation in the ALICE cavern) at high-intensity gamma sources to simulate the effect of long-term operation [88] and more tests are still ongoing at the Gamma Irradiation Facility GIF++ facility at CERN, looking for new environment-friendly gas mixtures, since unfortunately the standard gas mixture has an high Global Warming Potential (GWP) [89].

The compounds released in the gas might deposit and corrode the inner surface of the electrodes, creating irregularities which can increase the RPC noise and then affect its efficiency. For this reason, the dark current (see section 3.3.4) absorbed by the detector is an important parameter which has to be constantly monitored during the detector operation, since aging effects are roughly proportional to the current drawn by the detector. Aging effects can be quantified with the integrated charge per unit surface (mC/cm^2), which can be estimated from the average charge deposited on the electrodes at every hit.

From Run 3 onwards, the increase in the collision rate will induce an accelerated aging of the ALICE RPCs if the reduced charge released per hit in the detector thanks to the new FEE will not compensate the higher Run 3 luminosity. The RPCs then might reach the end of the expected lifetime well before the conclusion of Run 4. In fact, the integrated charge limit, which guarantees safe operation for the chamber, is around $50 \text{ mC}/\text{cm}^2$ [86], which corresponds to ten years of safe operation mode in the LHC environment. As mentioned before, the RPCs were installed in ALICE in 2007, and most of them, especially

the ones closest to the beam pipe, have integrated a non-negligible charge with respect to their expected life-time. Therefore, about 25% of the detectors currently installed in ALICE will probably need to be replaced during Run 3, in order to operate the system at full efficiency. In Chapter 4 the tests performed in the Torino INFN laboratory, on the new gas gap for Run 3 and Run 4 that will replace the aged chambers currently installed in ALICE, will be described in details.

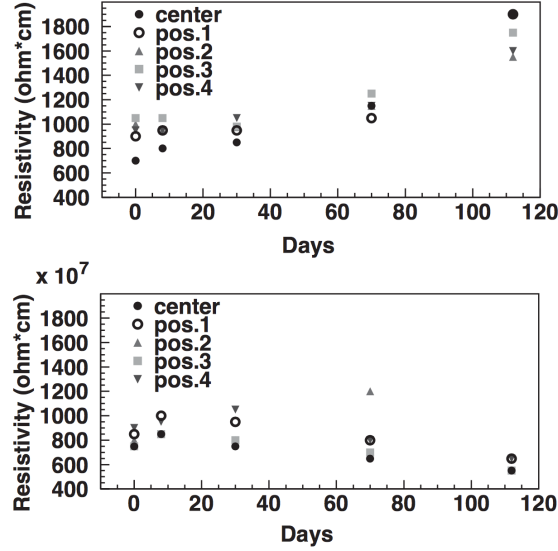


Figure 3.7: Resistivity trend over time for a prototype ALICE RPCs. Different marker styles correspond to different testing positions in the GIF facility at CERN. Top panel: a chamber provided with dry gas mixture. Bottom panel: a chamber provided with the same gas mixture, but humidified [90].

3.3.4 Working parameters

High Voltage (HV)

The HV applied to the electrodes of an RPC has to be high enough to allow the start and development of the charge multiplication process, and to give signals higher than the pre-set threshold to the FEE.

It has to be pointed out that the applied voltage is not the only parameter affecting the detector efficiency: temperature (T) and pressure (p) can also affect the multiplication process and the working point of the RPC. In fact, the electrons liberated by an ionising particle crossing the gas gap, and accelerated by the electric field, gain an energy U between two consecutive collisions in the gas mixture:

$$U = eE\lambda \quad (3.1)$$

where λ is the mean free path in the gas. If U exceeds the ionisation potential I of the gas molecule, a secondary electron can be liberated. So the multiplication process starts when:

$$eE\lambda = e\frac{V}{d}\lambda > I \quad (3.2)$$

where HV is the applied high voltage and d is the thickness of the gas gap. The mean free path λ can be written in function of T and p as:

$$\lambda = \frac{1}{\sigma N} = \frac{k}{\sigma \bar{V}} \frac{T}{p} \quad (3.3)$$

where σ is the electron-molecule cross section, N is the molecule density of the gas, k is the Boltzmann constant and $\bar{V}$ is the gas volume. Since T and p can vary during the operation period and consequently affect the detector efficiency during the data-taking, an effective voltage HV_{eff} is defined to take into account the dependancy of the efficiency on T and p :

$$HV_{eff} = HV_{app} \frac{T}{T_0} \frac{p_0}{p} \quad (3.4)$$

where $p_0 = 970$ mbar and $T_0 = 293.15$ K are reference values at which the applied voltage and the effective voltage are equal. In this way, HV_{eff} is the voltage really applied to the RPC and HV_{app} is the voltage set from the detector control system. For example, at room conditions and with an applied voltage around 8 kV, a 5° temperature variation results in an effective voltage variation of 150V. The same result corresponds to about 20 mbar in pressure variation. By dynamically adjusting the HV according to the previous formula, it is possible to operate the detector in stable efficiency conditions. To consider this, HV power supply system for RPC operates with a temperature and pressure monitor and the applied voltage is varied, so that the effective voltage remains constant.

The ALICE RPC during Run 1 and Run 2 were operated in highly-saturated avalanche mode with HV working point (WP) which slightly varies between the 72 RPCs and ranging from 10000 to 10500 HV. From Run 3 on, with the avalanche working mode and the new FEE, new HV WP had to be defined for all the RPCs. This study will be presented in detail in chapter 5.

Efficiency

One of the most important parameter used to characterize a RPC is the efficiency, which is defined as:

$$\epsilon = \frac{N_{measured}}{N_{total}} \quad (3.5)$$

where $N_{measured}$ is the number of particles detected by the RPC, while N_{total} is the actual number of particles that have crossed the detector.

The efficiency is measured as a function of the HV applied to the chamber. The resulting efficiency-HV curve, shown in figure 3.8, is used to identify the RPC working voltage. It can be seen from the plot that a typical efficiency-HV curve rises up to a so-called *knee*, where the slope drastically changes, and from which the efficiency reaches the plateau where its value is almost 1, and remains constant. The RPC WP is chosen typically only slightly higher than the one where the plateau begins, because if the gain in the gap is too high there is the risk of amplifying also the background signals, which they may exceed the discrimination threshold.

It has to be noticed that also the spacers inside the gas gap affect the efficiency of the RPC. They limit the sensitive region in the gas gap, so the maximum efficiency is usually slightly lower than 100%. Local inefficiencies may be caused also by non-perfect parallelism between electrodes or non-perfect smoothness of the surface. More details about efficiency measurements and RPC inefficiencies will be discussed in chapter 4 and 5. The plot in figure 3.8 shows is shown also the streamer probability, which is obtained by measuring the charge of the avalanche and the streamer as the integral of the voltage signals. The resulting values are plotted in a histogram and two peaks will appear, one related to the avalanche and one to the streamer. The total area is computed and the ratio between the streamer area and the avalanche one is the streamer probability.

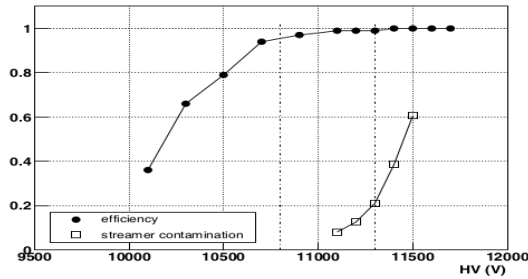


Figure 3.8: Efficiency plateau and streamer probability as a function of the applied HV. The two vertical lines refer to efficiency higher than 90% and streamer probability lower than 20% respectively. [86]

Spatial Resolution and Cluster Size

Assuming a uniform distribution of the particle hits on the detectors surface, the RPC spatial resolution σ is given by:

$$\sigma = \frac{w}{\sqrt{12}} \quad (3.6)$$

where w is the strip pitch (see table 3.1 for the MID RPC strip pitch values).

RPC cluster size effect, i.e. the number of adjacent strips on which a signal above the FEE discrimination threshold is induced in one same event, can modify the RPC spatial resolution. The cluster size depends on:

- the intensity of the avalanche or streamer signal, due to the gas mixture and its quenching properties. A poor quenching component might be the responsible of an excessive cluster size;
- the HV since it affects the signal size.

Moreover, the probability to have a high cluster size decreases at increasing values of the FEE discrimination threshold, and of course the strip pitch plays a role, since narrower strips lead to a larger cluster size.

When the crossing particle impacts between two adjacent strips, the typical cluster size is equal to 2. In this case, the actual spatial resolution will be better than the one given by previous equation because the coordinate can be better estimated. Cluster size larger than 2 might worsen both the spatial resolution and the occupancy of the detector. For this reason it is important to find a compromise between the efficiency and the cluster size which leads to an optimisation of all these variables.

For an RPC in streamer mode the typical cluster size is around 1.5 with strips 1 cm wide [91]. The streamer mode is best suited for experiments in which a smaller cluster size is required. This is due to the fact that the pulse amplitude spectrum of the streamer mode has a peak around a mean value, while in the avalanche mode the signal spectrum is similar to a negative exponential function and a lower discrimination threshold is needed in order not to lose the lower amplitude signals. In the avalanche mode, in case of large avalanches hitting one strip, it is very likely that even the neighbouring strips will be above the threshold, resulting in a large cluster sizes. A cluster size as close to 1 as possible is required for the ALICE RPC, for all the read-out strip pitches in order to preserve selectivity and two tracks resolution. Cluster size studies in the avalanche mode for the MID RPC will be presented in chapter 5.

Time Resolution

As mentioned before, in a RPC detector the electric field is constant and uniform throughout all the gas gap. For this reason, unlike what happens in a cylindrical counter where the electric field scales with the inverse of the distance from the anode wire, the RPC is able to produce the multiplication process everywhere in the gas gap, so there is no drift region and the spread of the signal arrival time is small.

A time resolution lower than the interval between different bunch crossing, i.e. 25 ns, is required for the ALICE RPC. This requirement is satisfied since the RPC time resolution depends on the applied HV and is of the order of 1 ns. It is better in the avalanche mode than in the streamer one, because, as mentioned before, in the avalanche it is due to the primary ionisation so it is a deterministic process, while the streamer signal is a stochastic event (see figure 3.9).

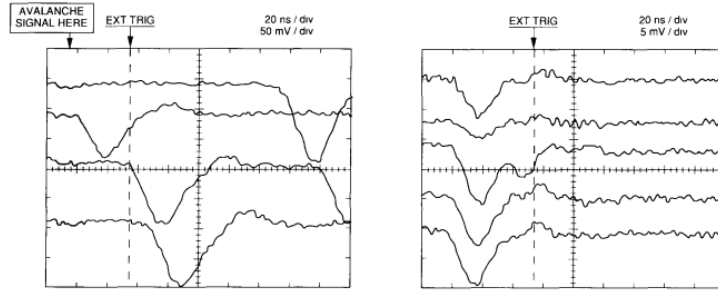


Figure 3.9: Left panel: jitter of a streamer signal in a RPC. Right panel: avalanche signals in a RPC [84].

Noise

As mentioned in section 3.3.3, the main background source of RPCs is the noise due to intrinsic detector imperfections in the electrodes surface: if the surface is not smooth enough there will be spike effects and the electric field will be locally higher. As a consequence, electrons may be extracted from the cathode, cross the whole gas gap and create a discharge, i.e. an unwanted fake signal.

A high noise rate causes a local inefficiency of the detector due to the recovery time after a discharge, so such effects must be prevented, not only in order to reduce the noise rate and consequently the inefficiency, but also to reduce

aging effects and to improve rate capability (which will be discuss in section 3.3.4).

For this reason, to ensure a smooth surface, the inner electrode surfaces is coated with a double layer of linseed oil diluted with 70% pentane.

Due to the lower threshold required in avalanche mode with respect to the streamer mode, the noise rate is higher in the avalanche working mode.

Rate capability

The rate capability is the maximum irradiation rate that can be reached without efficiency degradation due to the local voltage drop. In fact a signal, both avalanche or streamer, deposits on the electrodes a certain amount of charge, so induces a diminution of the local electric field in the region where the signal was generated. This makes the detector temporarily inefficient in that region until the electric field reaches again its nominal value and, if a particle crosses the RPC in that region during the dead time, the detector can not detect it. This will of course affect the detector efficiency.

As shown in figure 3.10, the RPC can be assumed to behave like an RC circuit, with some approximations. The circuit parameters are:

$$R_p = \frac{\rho d}{S}; \quad C_p = \epsilon_r \epsilon_0 \frac{S}{d}; \quad C_g = \epsilon_0 \frac{S}{g} \quad (3.7)$$

where ρ , d , S , and ϵ_r are respectively the electrodes resistivity, the thickness, the surface and the relative dielectric constant; g is the gas gap thickness and ϵ_0 is the absolute dielectric constant of vacuum.

A capacitor can be associated with the detector and, after the discharge, the capacitor restores the original voltage HV_0 , according to the following exponential law:

$$HV = HV_0(1 - e^{-t/\tau}) \quad (3.8)$$

The relaxation time of the electrodes $\tau = RC$ can be estimated by putting $d = g$:

$$\tau = RC = 2R_p\left(\frac{C_p}{2} + C_g\right) = \epsilon_r \epsilon_0 \rho \left(1 + \frac{2}{\epsilon_r}\right) \quad (3.9)$$

The relaxation time is of the order of 10 ms, with resistivity values of the order of $\rho \sim 10^{11} \Omega cm$, and $\epsilon_r \simeq 5$.

In this simple model, the RPC rate capability depends only on the dielectric constant and the resistivity of the electrodes, but it is not possible to reduce the rate capability by using electrodes with lower and lower resistivity since

for resistivities below $10^9 \Omega cm$ there will be a too high noise rate and the chamber will draw too much current. One can improve the rate capability by finding a compromise between a suitable choice of the gas mixture and the resistivity of the electrodes.

As said before, the RPC detectors for the ALICE experiment had to satisfy some requirements. One of these was a rate capability of a few hundred of Hz/cm^2 . In their early versions ALICE RPCs were supposed to be operated in streamer mode, but this working mode imposed severe constraints on the rate capability of the detector: the best performance reported in the literature is about 300 Hz/cm^2 [78]. Later on it was decided to operate the RPCs in maxi-avalanche mode, which has a better rate capability. In the avalanche mode, the detector is still efficient for particle fluxes of about 1 kHz/cm^2 [92]. The beam test performed at the GIF facility in maxi-avalanche mode showed that the detector was fully efficient at about 80 Hz/cm^2 [86], fulfilling the requirement on the rate capability, suitable for both p-p and Pb-Pb collisions.

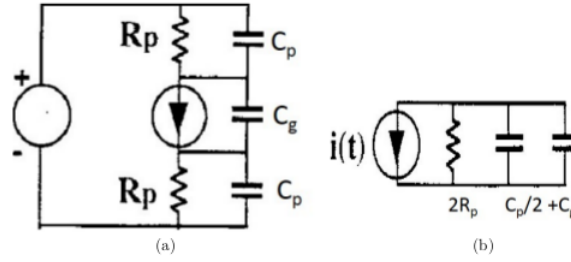


Figure 3.10: (a) Circuit modeling a RPC during the recharge of the electrodes and (b) its equivalent.

Current

The current flowing through a RPC has several components summarized by the following equation:

$$I_{RPC} = I_{Ohmic} + I_{cosmic} + I_{noise} + I_{beams} \quad (3.10)$$

where:

- I_{Ohmic} is the Ohmic (or leakage) component due to the non-perfect insulation of the HV electrodes from the rest of the system, so it depends linearly on the applied HV;
- I_{cosmic} is the current due to Cosmic irradiation and, more in general, the environmental irradiation, i.e. natural or activated radiation sources of ionising particles;

- I_{noise} is the noise current, i.e. the component due to discharges in the gap caused by electrons extraction from the cathodes that can cause the development of avalanche or streamer;
- I_{beams} is the current caused by the ionizing particles coming from beams collisions.

The first three components are always present when the RPC is at the WP, while of course the fourth component is present only when beams collisions are ongoing. So if the detector is switched on at nominal HV and fully operational when no beams are present from LHC (for example when ALICE is taking cosmic data), the amount of current flowing through the RPC is the so-called *dark current*:

$$I_{dark} = I_{Ohmic} + I_{cosmic} + I_{noise} \quad (3.11)$$

Along with the efficiency of the detector the dark current and the dark rate, i.e. the counting rate of the detector at nominal HV in absence of beams, are two important parameters to be monitored to assess the aging of the RPC. To be more precise, among the components of the dark current, the cosmic and the noise currents are relevant for aging effects, while the Ohmic current is not expected to have an effect on the detector aging since it is not associated to the liberation of charges in the gas gap.

The current circulating through the electrodes is monitored during all the RPC operations. The leakage component can be measured only at low voltages, when the gas ionization contribution is negligible. On the contrary, if the electrodes are perfectly insulated, the current is only due to the multiplication processes within the gas gap of the detector. Currents studies for the MID will be shown in chapter 5.

3.4 Front-end electronics

As already mentioned, in order to cope with the requirements posed by the LHC high luminosity runs, in which ALICE decided to switch to continuous data-taking mode (i.e. without trigger), the Muon Trigger had to be upgraded and became a Muon Identifier. One of the upgrade for the new MID involved the front-end electronics (FEE). In fact the old one used for Run 1 and Run 2, called ADULT (A DUal Threshold), had to be completely replaced by the new FEERIC (Front-End Electronics Rapid Integrated Circuit). Both the old and the new electronics will be described in the following sections, since the

old one is still used in the test station in the INFN Torino laboratories for the test of the new gas gaps (see chapter 4).

3.4.1 The old front-end electronics: ADULT

The detectors installed in ALICE during Run 1 and Run 2 worked in maxi-avalanche mode and the electrical signal induced by an ionizing particle in the chamber has an amplitude which can be processed by the FEE without any amplification step needed. The RPCs were then equipped with a dual-threshold front-end discriminators called ADULT [93].

The ADULT design for the almost 21000 MTR channels was driven by the requirements imposed by the initially planned streamer working mode, with the goal of a time resolution as accurate as possible. The MTR FEE processed the RPC pulses and sent logical signals to the local trigger electronics. The role of the old trigger was to store all input signals in a pipeline memory and to select single tracks with a transverse momentum above pre-defined cuts.

As seen before (figure 3.6), the RPC pulses in streamer mode exhibit two peaks, called precursor and streamer: the first peak is an avalanche signal with an amplitude of ~ 20 mV, synchronous with the ionising particle crossing the gap, while the second peak is the signal generated by the streamer charge and characterized by an amplitude around 120 mV, with a time jitter up to 15 ns with respect to the precursor. This time jitter deteriorates the time resolution if a single threshold discriminator technique is used, so a dual thresholds discrimination technique was developed. A first low threshold of 10 mV (corresponding on a mean charge per hit produced in the gas gap between 150 and 200 pC) detects the precursor signal, while a second higher one around 80 mV detects the streamer signal. To detect a particle, the coincidence of the two discriminators outputs is then required (the precursor signal is delayed to allow the coincidence of the two). The coincidence of these two discriminator output signals defines an hit on a strip. If the streamer-precursor delay is larger than 15 ns, the precursor signal is considered noise and the first low threshold discrimination is not taken into account. In figure 3.11 the schematic view of the ADULT technique is shown.

This technology is very well suited to improve the time resolution in streamer mode. In fact the time resolutions of the RPC equipped with ADULT ASIC, is around 1 ns. This value has to be compared with the 3 ns time resolution of a technique based on a single threshold discriminator, in the same running conditions.

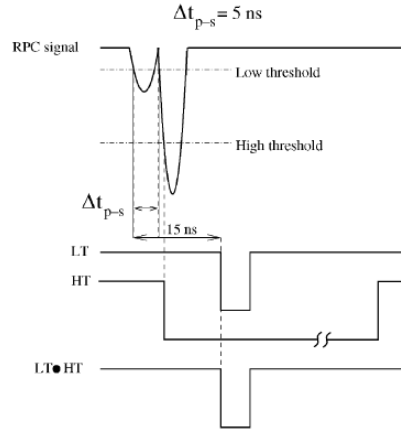


Figure 3.11: Schematic view of the timing with the ADULT technique: is shown a typical RPC pulse in streamer mode, where Δt_{p-s} stands for precursor-streamer delay, and LT-HT is the coincidence output between the low threshold output, delayed by 15 ns, and the high threshold output.

It is possible to run the RPC both in streamer and maxi-avalanche mode. For the streamer mode operation the two thresholds are set to 80 mV and 10 mV, while for the maxi-avalanche working mode operation the high threshold value is set equal to the low threshold one, i.e. 10 mV, since in this case there is only a small signal with similar characteristics of the precursor. After the discrimination by the FEE, the strips signals were converted into logical LVDS (Low Voltage Differential Signaling) 22 ns wide and directly sent to the trigger electronics to be processed.

The ADULT technology is implemented on dedicated boards, shown in figure 3.12, where an ASIC chip is used to discriminate the strip signals. A termination board with 50 Ω resistors is associated to each FEE board at the other end of the strips, to avoid signal reflection. The boards are plugged to the RPC mechanical structure and connected to the copper strips with metal connector, also shown in figure 3.12. The connector pitch corresponds to the one between the centers of two adjacent strips.

There were in total 2400 FEE boards, discriminating signals from 21000 strips.

ADULT limitations for Run 3

As said in the previous section, the mean charge per hit release in the RPCs of the Muon Trigger operated in maxi-avalanche mode with the ADULT ASIC was around 150-200 pC. This results in a counting rate limit of 50 hits/s/cm² [94], including some safety margins. Another limit comes from RPC aging because the efficiency of the detectors cannot be guaranteed for a cumulative

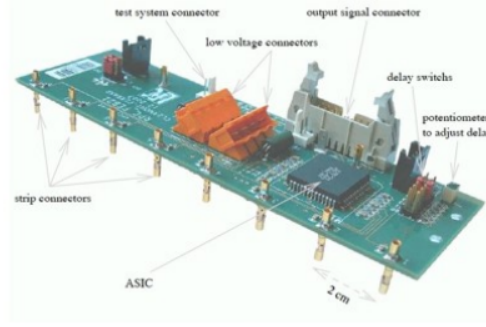


Figure 3.12: Photo of one ADULT front-end card of the old MTR system.

dose larger than 50 mC/cm^2 , i.e. 500 Mhits/cm^2 . These two limitations are not compatible with an efficient operation of the RPCs after the LS2. Indeed, peaks of counting rates up to 125 Hz/cm^2 (see table 3.4) and a cumulative dose of 100 mC/cm^2 in maxi-avalanche with the ADULT 150 pC charge per hit would be reached for the most exposed RPCs in Pb–Pb collisions.

Table 3.4: Expected RPC counting rate for Run 3 in Pb–Pb collisions at $\sqrt{s} = 5.5 \text{ TeV}$, 100 kHz

RPC counting rate (mean)	RPC counting rate (peak)
75 hits/s/cm^2	125 hits/s/cm^2

3.4.2 The new front-end electronics: FEERIC

To reduce the aging and make the detector lifetime comparable to the experiment data taking period, and to increase the RPCs rate capability, the FEERIC (Front-End Electronics Rapid Integrated Circuit) electronics was developed at Clermont-Ferrand (France) [95].

It was chosen to use the same gas mixture used in Run 1 and Run 2, but at lower gain, i.e. in avalanche mode instead of the maxi-avalanche, in order to reduce the charge released per hit inside the gas gap. For this reason a brand new front-end electronics was developed that, unlike the ADULT one, performs a pre-amplification of the analog input signal upstream of the front-end discriminators. In this way it is possible to transfer the gain from the gas gap to the electronics, decreasing the charge released per hit by about a factor 4 and hence improving the rate capability.

Furthermore, FEERIC reference thresholds will be passed via wireless system, allowing the tuning of the values of the single card level in order to set the threshold according to the local RPC efficiency and to minimize the noise. This is a large improvement with respect to the ADULT one, in which the

thresholds were set by means of an analog voltage distribution, allowing for one single threshold value per RPC side. The ZIGBEE technology has been chosen, which uses the 2.4 GHz radio communication band and is based on Microcontroller Atmel SAMD21; the software is based on Arduino libraries (I2C, SD cards and Xbee). The threshold system is implemented on Xbee cards (for a total of 26 Xbee cards), designed by the LPC Clermont-Ferrand group. The master cards are connected to the Detector Control System PC of the MID via ethernet and the ZIGBEE (wireless) protocol from master to nodes is used. Moreover it is planned to replace the wireless Xbee communication by Wi-Fi, which is more stable & and powerful in term of bandwidth. Unfortunately the Wi-Fi system for the FEERIC threshold distribution will be installed in the ALICE cavern only in February-March 2023, so after the end of this thesis work.

The time resolution of the electronic is less than 500 ps rms for an input charge of $\simeq 100$ fC, which is the typical charge expected for RPCs operated in avalanche mode. The absolute response time is 21.3 ns for a typical charge of 100-200 fC.

In February 2015, so since the beginning of the LHC Run 2, one ALICE RPC was already equipped with FEERIC boards prototypes, in order to test in real life the expected performance improvement. It has to be pointed out that the FEE boards of this pre-series were not exactly identical to the final production ones, however the installation of this pre-series boards on one RPC in cavern had the goal to help to understand the main open question about the mean charge per hit expected on the RPC in the new working conditions.

Regarding the final production, there are 6 types of FEE boards, one for each strip pitch of each MID station. Each FEE card handles 8 strips of width 2 cm and 4 cm while each FEE card for the strip width of 1 cm supports 2 FEERIC ASIC and hence handles 16 strips. FEERIC is able to treat both positive and negative signals with as little differences (gain, response time, etc) as possible. The signal polarity is positive for the horizontal strips (bending-plane) and negative for the vertical strips (non-bending plane). The 2384 FEERIC cards (2720 when including the spare cards) of the final production have been produced and installed in the ALICE cavern since July 2019.

The performance during the first year of Run 3 of the MID equipped with the final FEERIC boards production in terms of efficiency, cluster size, currents, cluster rate and charge released per hit will be shown and discussed in details in chapter 5.

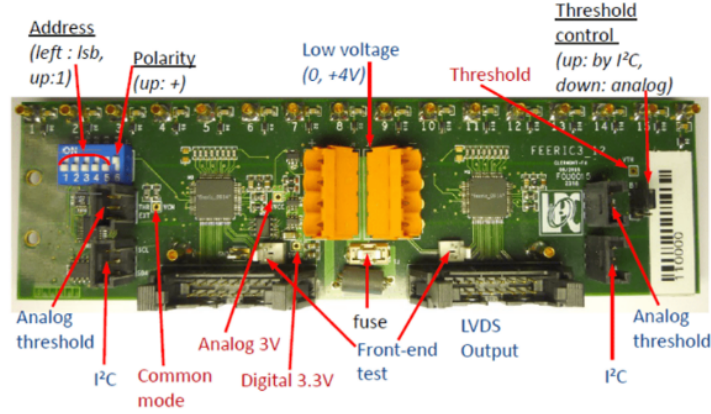


Figure 3.13: Photo of one new FEERIC front-end card for the MID system.

3.5 Read-out architecture chain

In order to cope with the new triggerless working mode, the upgrade from the MTR to the MID involved also a brand-new read-out architecture chain, which will be described in this section.

For the MTR in Run 1 and Run 2, the main aims of the read-out electronics were to perform the local trigger algorithm, i.e. it had to produce the level 0 muon trigger for heavy quark and quarkonia measurements in the forward region, implementing a p_T cut on the single tracks. Then it had to deliver the trigger decision on single tracks and store strip bit patterns and trigger decision in a pipeline memory which was read-out on occurrence of an ALICE trigger sequence.

In order to switch to the new ALICE continuous read-out mode, all the read-out electronics cards used for Run 1 and Run 2 had to be replaced.

The MID new read-out chain [47] consists of 16 similar *regional crates* for the full project: one full crate has 16 Local cards, 1 Regional card and 1 J2 bus. In total there are 234 Local cards (16 maximum per VME crates), 16 Regional FPGA-based cards, interfaced with the ALICE Common Readout Unit via 2 GBTs links, and 16 J2 buses between the Local and the Regional cards. The scheme of the electronics is shown in figure 3.14. All of the cards were designed in SUBATECH, Nantes (France).

The local cards receive the LVDS chamber signals from FEERIC, consisting in the x and y fired strip patterns of the four detection planes for each bunch crossing. Each local board receives the signal from the same xy area coming from all the 4 different MID planes. In figure 3.15 a schematic view of one of the four MID plane showing the 18 RPCs and the 234 local boards is shown. The local board density reflects the strip segmentation which is finer

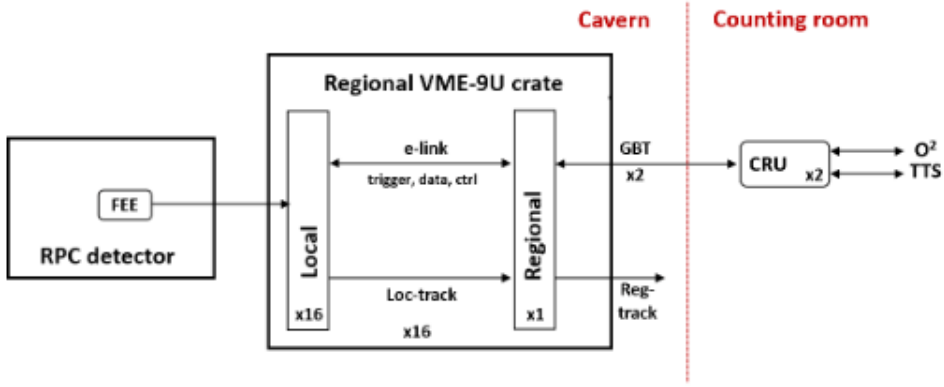


Figure 3.14: Schema of the read-out chain for the MID system.

in the region closest to the beam pipe, where the particle density is higher. In both the bending and the non-bending plane each local board collects the information of either 8 or 16 strips according to a scheme that depends indeed on the strip pitch and the board width: in general the local boards group 16 strips with a 1 cm pitch or 8 strips with a 2 cm and 4 cm pitch, with few exceptions. The FPGA in the local board:

- applies a remotely configurable noisy channel mask;
- compensates the different transimission delays from cables of different lengths;
- calculates a Loc-trk signal for each bunch crossing corresponding to a track crossing the detector;
- provides a 16-bit counters for monitoring the detector counting rate;
- zero-suppresses the input data and provides a multi-event buffer.

Each of the 16 regional crates is controlled by one regional card that collects the informations from the local boards via 16 serial links (J2 buses) and assembles the raw events in their final format. The regional card has two bi-directional optical 3.2 Gbit/s GBT links in order to send the data to two CRUs, each one processing one half of the MID, i.e. inside and outside. The CRUs then forward all the MID data to one DAQ First Level Processor (FLP), placed in the counting rooms over the ALICE cavern. For the MID there is one GBT link per each regional card.

Regarding the data acquisition system, if at least three out of four detection planes have been fired, the track is accepted and processed from the read-out architecture. The 3/4 condition was chosen to face possible detector inefficiencies or dead channels.

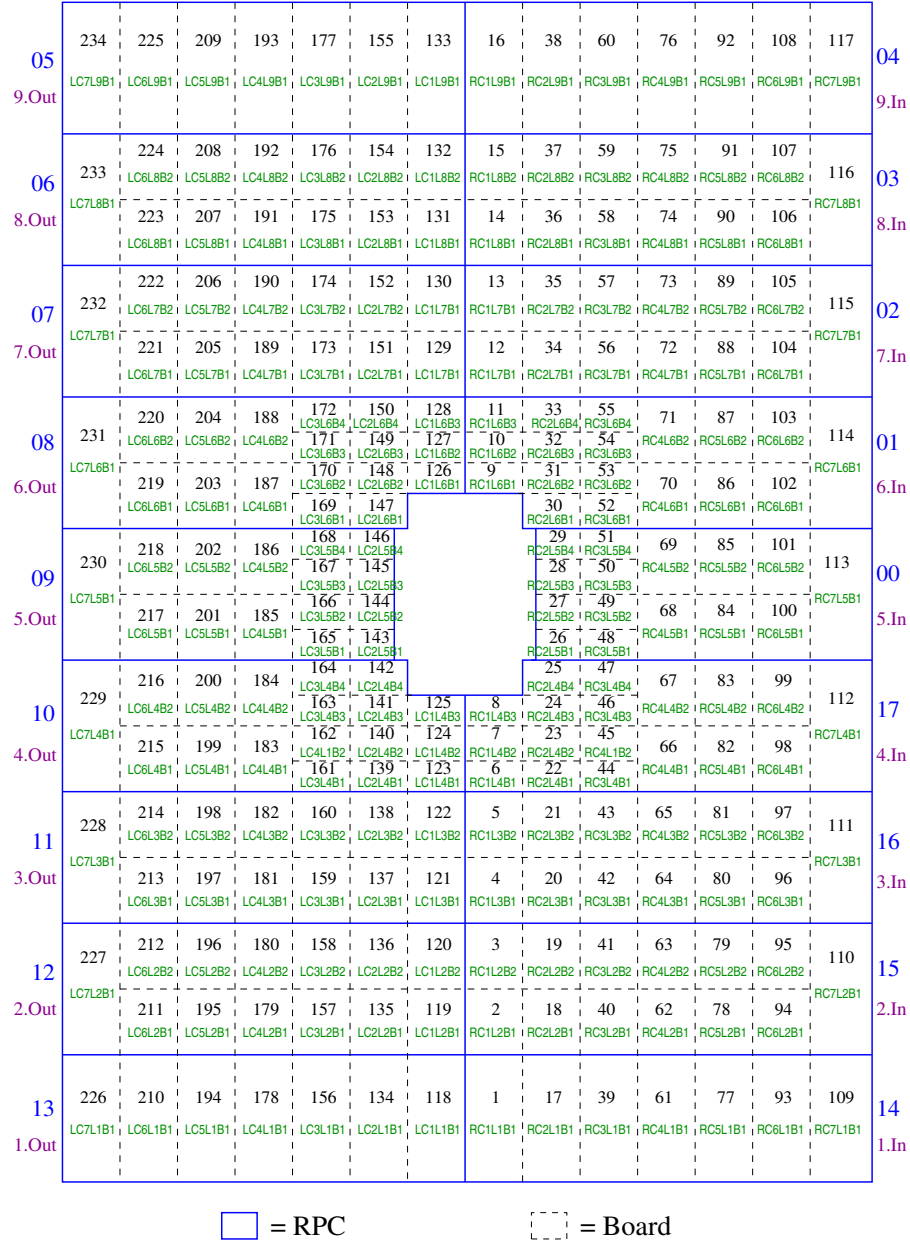


Figure 3.15: Schematic view of one of the MID planes (looking from the IP) showing the 18 RPCs and the 234 local boards. The board enumeration, both in labels and numbers, is also shown.

3.6 MID data sources

3.6.1 The Detector Control System and DARMA

The ALICE experiment is equipped with a complex hardware monitoring system for all its detectors, called Detector Control System (DCS).

This system provides an interface for each detector that allows to remotely control and monitor all its working parameters. It allows modifying the values of the high and low voltages, it shows power supply and electronics statuses of the detectors, it monitors the temperature and pressure and so on. The readings of all the sensors related to devices handled by the DCS are sent to a database which records them.

Concerning specifically the MID, the DCS is able to record, monitor and store the values of the currents, of the High and Low voltage supply, the FEE thresholds for each RPC, as well as the gas flow, composition, humidity, temperature and pressure.

These read-out values are accessible online by using custom Siemens WinCC applications which allow also to produce plots and trends for some detector variables over time in order to monitor them during the data-taking period.

The DCS values are also accessible offline in order to perform offline reconstructions and studies of the detector performances. The data points are saved in the DCS database following two guidelines: first the values are stored in the database whenever a given threshold on percent variation, with respect to previously stored value, is passed; secondly a slow clock of 5 minutes triggers the storage of the current read value all the time (independently of the fact that a data-taking run is ongoing or not), in order to keep track of smaller variations as well as of the stability of the system. The values can then be accessed through an ALICE web interface called DARMA by executing database-like queries and downloading structured data text files that can be analysed.

3.6.2 The Online-Offline (O²) project

Most of the physics topics addressed by ALICE concern low p_T physics probes characterized by very small signal-to-background ratios, which, as mentioned before, require the read-out of all Pb–Pb collisions in order to collect very large statistics. The upgrade of the ALICE detectors electronics allows to increase the collected data to a value of ~ 2 orders of magnitude larger with respect to Run 1 and Run 2. To cope with the data rate increase it was necessary to upgrade the ALICE computing capabilities by developing a new acquisition and processing tool, which required an enormous technical

and economical effort. The basic idea was to reduce the data size on the fly in parallel with the data collection, as early as possible in the data stream from the detector itself to the storage and reconstruction, by adding a pre-processing and reconstruction layers close to the detectors acquisition logic.

For this purpose, the ALICE Online-Offline (O^2) [96] system was developed to perform a partial calibration and reconstruction online and to replace the original raw data with compressed data, keeping the total data throughput within an envelope compatible with the available data storage space.

O^2 is a common computing system shared by all the ALICE systems which includes a definition of a common computing model and the development of a software framework. The computing nodes integrate several hardware technologies, from FPGAs to GPUs: O^2 operates on several softwares, tools and sets of libraries, for example ZeroMQ as message passing protocol, CMake as project build and test manager, Geant4 as particles propagation engine and FairROOT, an evolution of ROOT focused on improved usability, that allows for easy data visualization, storage and offline analysis.

In figure 3.16 the functional flow of the O^2 computing system is shown. The detectors electronics provide a continuous stream of compressed raw data, pre-processed and packed by the read-out logic. Partial informations coming from different detectors and systems are aggregated and the full set of data is processed and reconstructed. Up to this step all the computation is performed synchronously. The processed data are then stored and retrieved later for a finer asynchronous reconstruction. The solution introduced by O^2 in order to reach the highest rate capability is the so called Time Frame (TF), which is a data container defined by two temporal boundaries that define its validity interval. A TF packs the data collected by the detectors in its validity interval. Since the raw data format is too large for persistent storage, they are converted in a much more compressed one (Compressed Time Frame).

In figure 3.17 a sketch of the acquisition flow is shown. The data stream from the FEE of each detector are sent to the First Level Processor (FLP). At this level, only the information of one single detector is available and the data format is called Sub-Time Frame (STF). The processed data from the FLPs of all the detectors involved in the data-taking are then sent to the Event Processing Nodes farm (EPNs) and here aggregated into global TFs. The data samples are retrieved with the addition of an heartbeat clock for time stamping purposes, in order to be able to correctly aggregate data within the TF they belong to.

For the first year of Run 3 data-taking, following some requirements, ALICE

decided that 1 TF validity interval, i.e. its duration, will be limited to $\sim 11\text{ms}$ which corresponds to 128 LHC beam orbits.

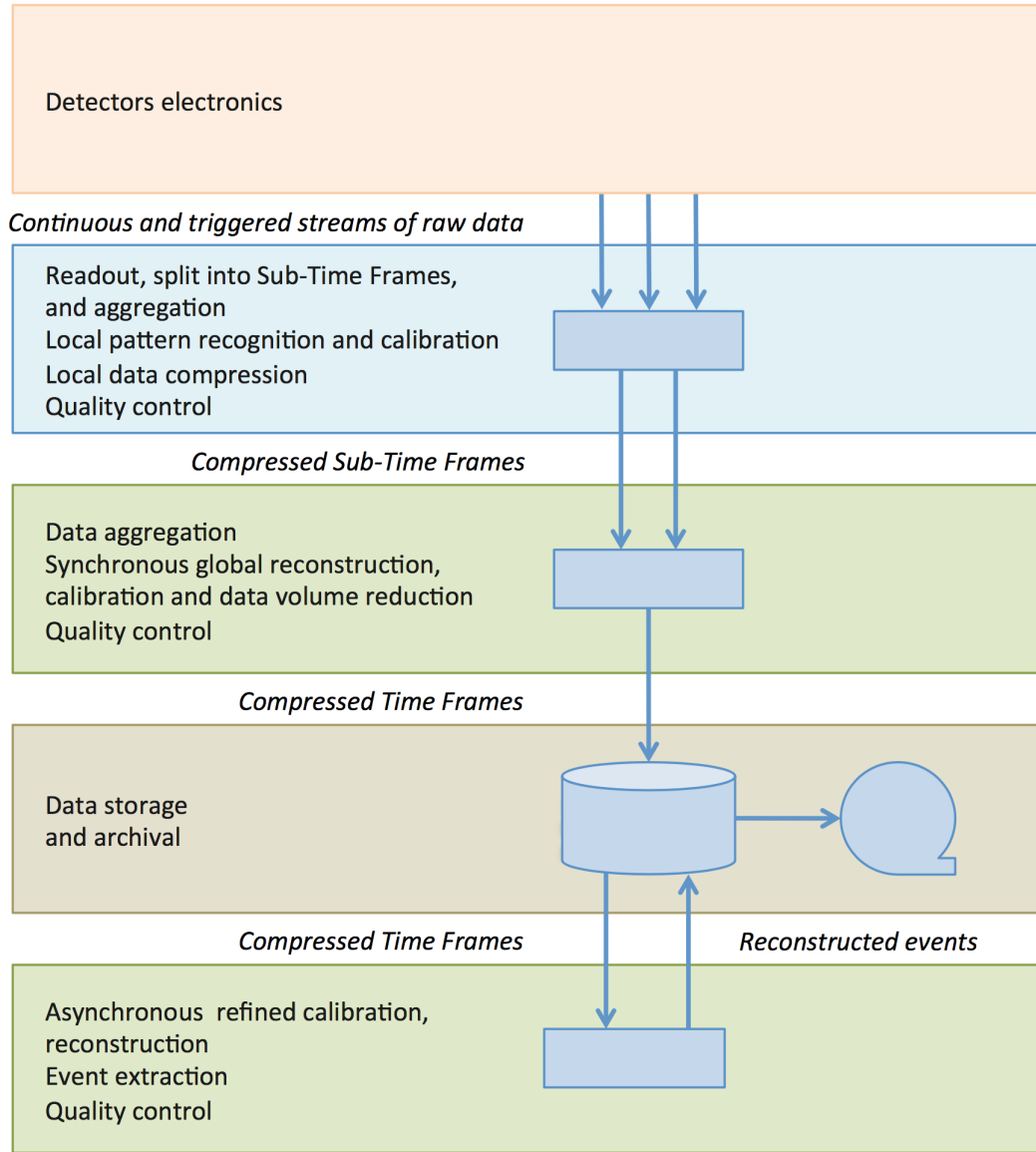


Figure 3.16: Functional flow of the ALICE O² computing system.

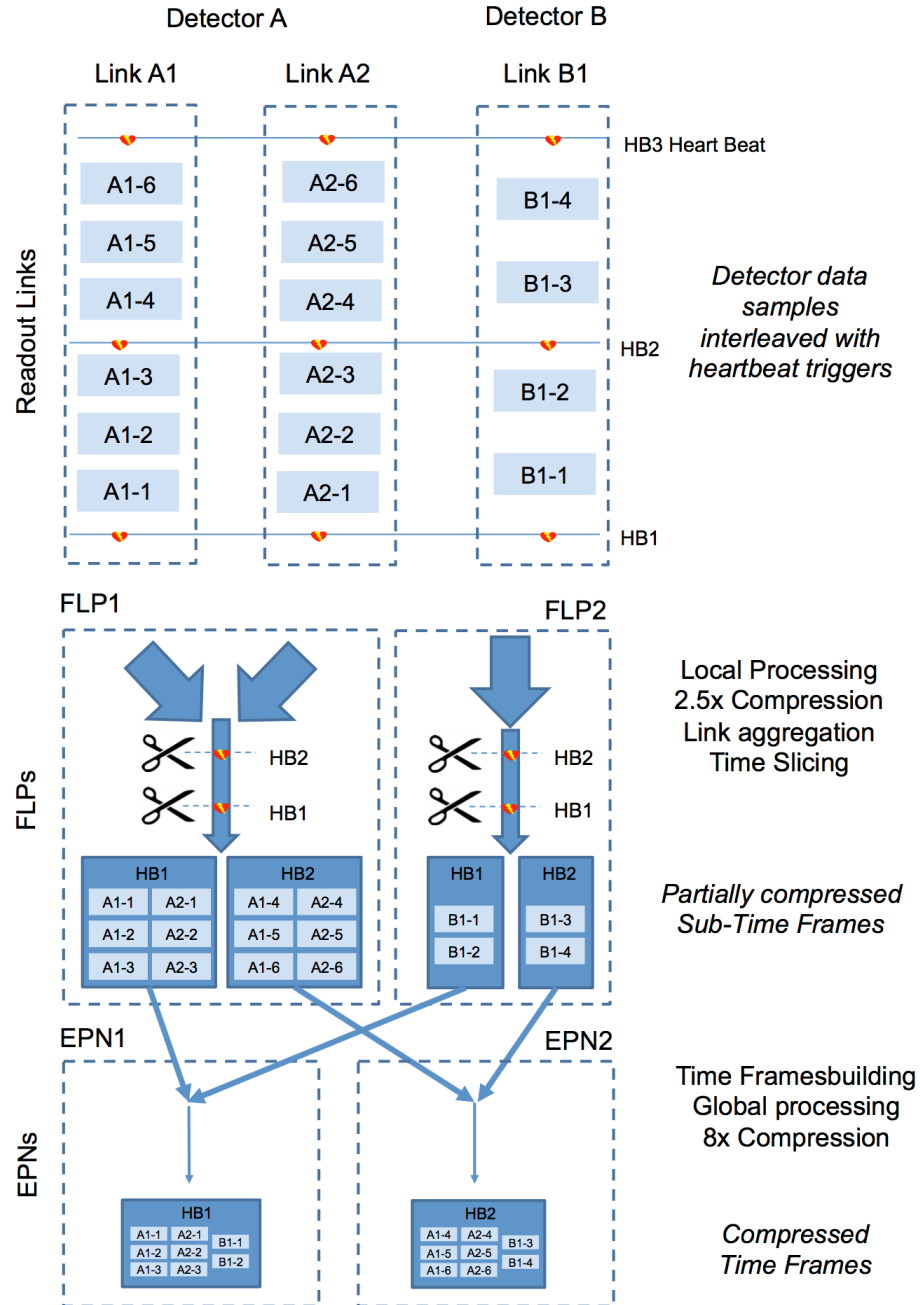


Figure 3.17: Sketch representing the acquisition flow with two detectors, A and B. The aggregation of data, from the detectors read-out to the full Time Frames built on the EPNs is shown.

3.6.3 ALIce ENvironment (AliEn)

Since its start in 2008, the ALICE experiment at LHC collected data at a rate of few PBite per year and the data storage and processing represented a huge challenge for the experiment.

The issue was solved by the High Energy Physics (HEP) CERN community with the so-called Monarc model [97] in which computing resources are concentrated in a hierarchy of centers called Tiers. Tier-0 is CERN, Tier-1 are the major computing centers in which the raw-data are stored, Tier-2 the small regional centers and Tier-3 the university local clusters or also the users workstations. Tier-1 share also the reconstruction tasks, while subsequent data reduction, data analysis and Monte Carlo productions are a collective operation of Tiers-1 and Tiers-2. The basic principle of the model is that every physicist of the experiment should have access to the data and resources. The resulting system is of extreme complexity and it was developed in the so-called Grid project [98].

In order to provide a transparent access to the Grid resources distributed worldwide, the AliEn (ALICE ENvironment) framework was also developed [99], i.e. a set of middleware tools and services that implement the Grid infrastructure. The basic AliEn components are the file catalogue, the data management tools for data transfer and storage, the interfaces to others Grid implementations, a ROOT interface and monitoring. The file catalogue is one of the key component of AliEn: it is a virtual file system that does not own the files but provides the mapping between the Logical File Name with the Physical File Names on real storage systems, providing the full path to the storage element in which the local file is placed. Input and output associated with any job can be registered in the AliEn file catalogue.

During the last years the whole system had more and more users getting involved in the analysis of both Monte Carlo grid production and real data. In a typical analysis process, a subset of the datasets can be extracted from the virtual file catalogue using conditions provided by the user. Then the tasks are automatically split according to the location of datasets, following a compromise between best use of available resources and minimal data movements. At the end of the task execution, the output files are moved to the storage and registered to the file catalogue, thus made available to the user.

In this way AliEn provides a functional computing environment that fulfills the needs of ALICE allowing to cope with the LHC data challenge and defines stable interface to the users.

Chapter 4

Characterization of the RPCs in Torino

As explained before, the RPCs of the ALICE Muon Identification System (MID) are operating since 2007. In order to guarantee the system to operate at the best of its performance during Run 3 and Run 4, about 25% of the detectors installed in ALICE may need to be replaced by the end of Run 3. In this chapter the detector production will be briefly described. Next, the experimental cosmic ray set-up in the INFN Torino laboratory and the test performed on the gas gaps will be presented, together with the complete characterization and validation of the new production of RPCs that have been installed in the ALICE cavern during the winter shutdown 2022-2023.

4.1 RPC production

4.1.1 Gas Gap production

The 2 mm thick bakelite sheets utilized in 2003 to produce the RPCs presently installed in the ALICE cavern, were produced by Frati Laminati (Gambolò, Italy). Before the installation in cavern their resistivity was measured in the INFN Torino laboratory in controlled climatic conditions of $\sim 20^\circ\text{C}$ and $\sim 40\%$ relative humidity, with the Hewlett-Packard high resistivity meter HP4339B: 50 V were applied through brass electrodes kept in contact with the bakelite sheets by means of conductive rubber, with 10 kg of lead cylinders applied on top of the electrodes to ensure good electrical contact between electrodes and bakelite [100]. The sheets that had the required resistivity, i.e. $\rho = 3 - 6 \times 10^9 \Omega \text{ cm}$, were then visually inspected to detect possible deep scratches or bumps on the surfaces. After this, the bakelite

sheets were first sent to Riva Laminati Plastici (Cinisello Balsamo, Italy) to be cut to the required L, C and S shapes, and finally were sent to General Tecnica (Monte San Giovanni Campano (FR), Italy) where gas gaps were manufactured.

Regarding the new production of gas gaps for Run 3 and Run 4, the old bakelite can no longer be used as it is not commercially available anymore. Bakelite sheets are now produced by Puricelli s.r.l. (Costa Masnaga (LC), Italy) and since the new bakelite could have different surface and bulk properties with respect to the old one, it is important to extensively test the RPCs equipped with these electrodes in the INFN Torino laboratory before the installation in the ALICE cavern.

In the General Tecnica firm the sheets are cleaned and visually inspected again: then, a layer of graphite painting with surface resistivity of $\sim 100 \text{ k}\Omega/\square$ is applied on the external surfaces, being careful to leave an 11 mm wide graphite-free contour along the borders to avoid discharges. On the side of the bakelite layer without the graphite painting, i.e. the internal surfaces, polycarbonate spacers which keep the electrodes at a constant distance of 2 mm are placed and glued in a $10 \times 10 \text{ cm}^2$ square matrix. Then the second bakelite sheet is superimposed and glued on the grid of spacers. It has to be pointed out that in the old gas gap production the gluing procedure of the spacers was performed by dedicated machines. For the new production, the gluing procedure was done manually, leading to several issues, as it will be shown later in this chapter, section 4.2.1.

Finally, insulating PET sheets $190 \mu\text{m}$ thick are glued on the external graphite-painted surfaces, together with U-shaped PET ribbon along the gap edges. After the production, the gaps are filled with linseed-oil/n-pentane 40/60 mixture and slowly drained out. Air circulation at 28°C is forced inside the volume, to ensure linseed oil polymerization. This procedure is performed twice in order to get a double layer of linseed oil which provides better aging performances with respect to a single layer [101].

4.1.2 External mechanics

The gas gap external mechanics have been entirely manufactured in the Torino INFN Laboratory, starting from the readout strip planes shown in figure 4.1.

The strips and the ground foils are both etched on 0.19 mm thick mylar foils, coated with a copper layer $20 \mu\text{m}$ thick. A milling machine rotating at 6000

rpm makes 0.1 mm deep grooves on the mylar foil, with a longitudinal speed of 4000 mm/min. Then the engraved strip and ground planes are glued on the opposite sides of a 3 mm thick insulating foam sheet.

The external stiffener planes are made of two aluminium sheets with 10 mm thick Nomex panels in between. In order to connect the readout strips to the Front-End Electronics (FEE), stiffener and strip planes are coupled and drilled to insert the cylindrical FEE connectors. Finally, L-shaped aluminium profiles are fixed along the long edge, to support the screws for the final assembly and to allow space for the gas pipes.



Figure 4.1: One strip layer, for a Long-shaped RPC, horizontal strips (bending plane).

4.1.3 Final assembly

For the 2003 production of RPCs there was a further step before the tests and characterization in the Torino laboratories. After the manufacturing at General Tecnica, the gas volumes were transported to the OPERA [102] RPC test stand at the INFN-LNGS, to check the gas tightness and spacer gluing. For the first test, the chamber was filled with Argon with an overpressure of 6 mbar and the overpressure was monitored for at least 300 s. A gas gap was accepted if the difference between the initial and the final measure was less than 0.1 mbar. A total of 2% of the gas gaps of the old production were rejected for this reason.

To check the correct gluing of the spacers, a system of weights was then placed sequentially on the gas gaps in correspondance of the spacers grid. If originally one spacer was not properly glued, the 6 mbar overpressure inflating the volume would separate the spacer from the bakelite, leading to a gap thickness greater than the expected 2 mm; the weight placed on the spacer brought it back to the original 2 mm value, thus increasing the pressure inside the gas volume. By monitoring the pressure, it was possible to detect the unglued spacers. A gas gap was accepted if it had up to two non-adjacent unglued

spacers. For the old gas gap production, when the gluing procedure was done with dedicated machines, 6% of the gas gaps presented one unglued spacer, and only 1% two non-adjacent unglued spacers.

Regarding the spare production of gas gaps from 2011-on, the gas tightness was checked in the Torino laboratory and the gas leakage test will be presented in section 4.4.1. For the spacer gluing, after several issues with the gas gaps production in 2018, it was decided to perform a new pressure test in the Torino laboratory. This test will be shown in section 4.2.1.

Finally the gas gaps are inserted in the external mechanics in Torino, and tested in climatic controlled conditions of $\sim 20^\circ\text{C}$.

4.2 Overview on detector production

As said before, new productions batches of RPCs were started in 2015 and 2018 in order to provide spares for the detectors installed in ALICE. Due to issues with these productions, several interactions with the General Tecnica firm were needed. After these interactions two other productions were launched during my PhD in 2019 and 2020.

All these productions with their differences will be presented in the following sections.

4.2.1 2015-2018 RPCs production

It has to be pointed out that the 2015 gaps were largely unsatisfactory. Many of these RPCs had shown efficiency disuniformity all over the detector surface; moreover, with respect to the 2003 production, RPCs belonging to production bunches 2015-onwards have their HV working point at higher voltages, shifted of about 300-400 V.

For these reasons, it was decided to open some of these chambers and it was observed that the grid of plastic spacers that keep the two planes separated at a constant distance of 2 mm was not regular, with some spacers displaced by 2-3 mm, as shown in the right panel of figure 4.2. There were also gluing problems with the spacers, as shown in the left panel of figure 4.2, in particular for some of them there was too much glue, and for others there was none at all. This implies a general carelessness in the production process, especially in the gluing procedure, which was done manually and without the dedicated machinery utilized in 2003.

In 2018, it was asked to the General Tecnica an improvement of the glueing procedure, and as a consequence of this, the factory managed to introduce

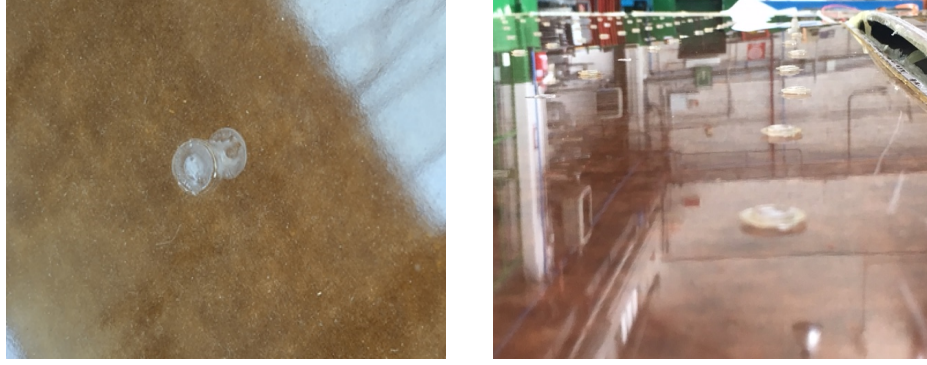


Figure 4.2: Photo of bakelite sheets of one opened gas gap from 2015 production. Left panel: excessive glue on one spacer. Right panel: displaced spacers.

a new glue delivering system, able to control and standardize the amount of glue put on each spacer. Two new chambers were ordered from the production company: one of these RPCs was damaged in the factory, and it was impossible to test it; the other one is the RPC number 590-18 (where the last two digits refer to the production year), which is then the only prototype of the 2018 production.

Tests on this RPC shown that unfortunately also this new prototype did not had an uniform efficiency throughout all its surface, showing instead several inefficiency zones (efficiency measurements procedure, studies and results will be shown in detail in section 4.4.3).

By studying the efficiency at different voltage values around the working point it was clear that, as the voltage decreases, the inefficient areas widened. This behaviour could be a consequence of a locally wider gas gap that caused a locally lower electric field between the electrodes. A possible cause for the wider gas gap might be a detachment of some spacers.

Pressure test

In order to investigate this issue, it was decided to perform a pressure test on the spacers in the Torino laboratory, to check the position and gluing of the spacers.

Air was pumped in the gas gap inlet and a "Smart Probes Testo 510i" pressure meter was connected to the gas gap outlet in order to measure the pressure variation. By applying a constant pressure directly on the spacers positions, as explained before, it is expected that the outlet pressure remains the same if the spacer is correctly glued; otherwise, if the spacer is not well glued, it is expected that by applying a pressure on it, the gap volume will be reduce and,

consequently, the pressure will increase. The pressure difference was measured at each point of the grid corresponding to a spacer.

In figure 4.3 the pressure difference measured in correspondence of each spacer is shown. Each X and Y indicate row and column of a spacer on the grid. In the lower right half of the map the ΔP for some spacers is higher with respect to the others, indicating that some of them could be detached from the bakelite surface. Also in the upper half of the map it is possible to notice that some spacers could be detached from the bakelite surface. These areas corresponds to the RPCs inefficiency "holes" found during the tests on the chamber, as it will be shown in section 4.5.2.

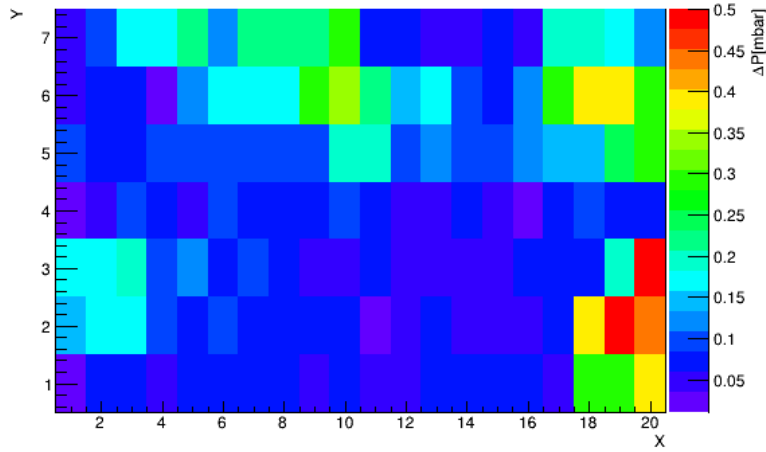


Figure 4.3: Distribution of ΔP (mbar) for chamber 590-18. Each units indicate a spacer.

Because of these serious efficiency problems, this RPC could not be used for the MID. Therefore, the chamber was sent back to General Tecnica and opened, in order to check the spacers position and gluing. It was possible to verify that the spacers were well aligned and correctly positioned; moreover the amount of glue used was not excessive as in the case of the 2015 RPCs, therefore indicating that the chamber had been carefully produced. However, most of the spacers remained attached on only one side of the electrodes; this would seem to indicate gluing problems due to the new type of bakelite surface. Consequently, the production company was required to perform preliminary gluing tests on bakelite samples, in order to understand the causes of the gluing failure.

To summarize, for the 2015 RPCs there was a gluing problem (too much glue on the spacers) and a general carelessness in the production process (displaced and misaligned spacers), while for the 2018 RPC that I have tested, there was

a gluing problem between the spacers and the new type of bakelite surface. In general, it was clear that the inefficiency problem shown by these chambers can be traced back to a bad gluing.

4.2.2 Pre-production batch (2019) and gas gaps mass production (2020)

After understanding the gluing problem, a pre-batch constituted of three new RPC prototypes was requested to the production company in 2019. As soon as they were ready, before bringing them to Torino, it was decided to perform the pressure test directly at General Tecnica. In figure 4.4 the three gas gaps, all Short type, together with two small $50 \times 50 \text{ cm}^2$ prototypes for test beams at the GIF++ facility at CERN, are shown.

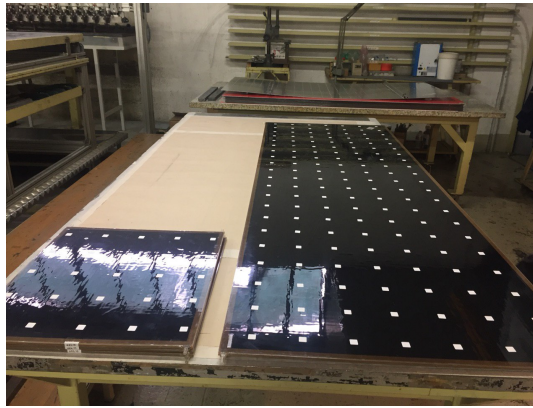


Figure 4.4: Photo of the pre-production batch of RPCs, taken in the General Tecnica firm in 2019.

The pressure test was performed on all the pre-batch RPCs as it was described in the previous section. In figure 4.5 the pressure test result for chamber 682-19 is shown. As it can be seen in the map, there are only two not perfectly glued spacers, and they are non-adjacent, so the gas gap was not rejected. Moreover the 0.12 mbar value for these two spacers was smaller than the 0.5 mbar of the chamber 590-18. The other two gas gaps of the pre-batch were accepted too, since for one there was only one problematic spacer, while for the third one the pressure test did not shown any gluing issue.

The validation test of such new RPC modules and their complete characterization in terms of efficiency, noise and more, have been performed during 2020. The tests results will be shown through this chapter. Since the results were finally quite promising, the pre-batch was validated and the full production

for the chambers to be installed in the ALICE cavern was finally launched in 2020 and delivered to the Torino laboratory in 2021.

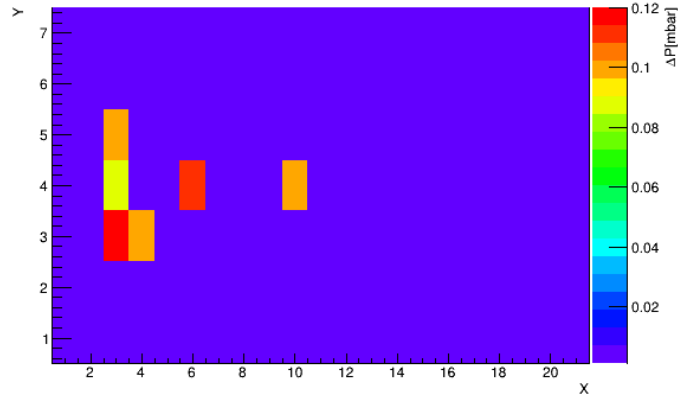


Figure 4.5: Distribution of ΔP (mbar) for chamber 682-19. Each units indicate a spacer.

4.3 Experimental cosmic ray set-up

The tests on the detectors are performed in Torino, at the INFN laboratory, with a dedicated set-up, using cosmic rays.

During 2020 it was necessary to completely rearrange the entire experimental set-up due to the moving in a brand-new INFN laboratory building. In particular, during the commissioning of the new laboratory, a new improved gas distribution system was designed, in order to perform tests with new eco-friendly gas mixtures.

In figure 4.6 the new commissioned INFN RPC laboratory is shown, with the test station on the right and the spare gas gaps ready to be tested on the left.



Figure 4.6: Photo of the new INFN laboratory in Torino.

4.3.1 Test station layout

The dedicated test station is shown in figure 4.7 and is composed of:

- 3 arrays, one above and two below the RPCs under test, of 9 scintillators $150 \times 10 \times 1 \text{ cm}^3$, arranged side by side to cover an area of $90 \times 150 \text{ cm}^2$, and placed on a moving supports;
- 2 tracking RPCs, one above and one below the tested RPCs, in the same scintillators moving support, covering an area of $172 \times 87 \text{ cm}^2$ each;
- between the 2 tracking RPCs, there are 4 test slots where the RPCs to be tested are placed.

The tracking RPCs and the scintillators form the cosmic trigger system, described in the following paragraph. Two half-RPCs at a time are tested, because the active area covered by the tracking RPCs is not sufficient to test the entire detector. For example in the schematic view in figure 4.7 two right-half chambers are tested. This is why tracking RPCs and scintillator planes are placed on a moving support structure with wheels: it is possible to select the two half-RPCs to be tested by moving the scintillators and tracking RPCs along the longitudinal direction. While these RPCs are tested, the RPCs in the two remaining slots (not showed in the schematic side view of the set-up) are fluxed with gas and undergo the HV ramp-up procedure (described in section 4.4) in order to be ready for the efficiency tests.

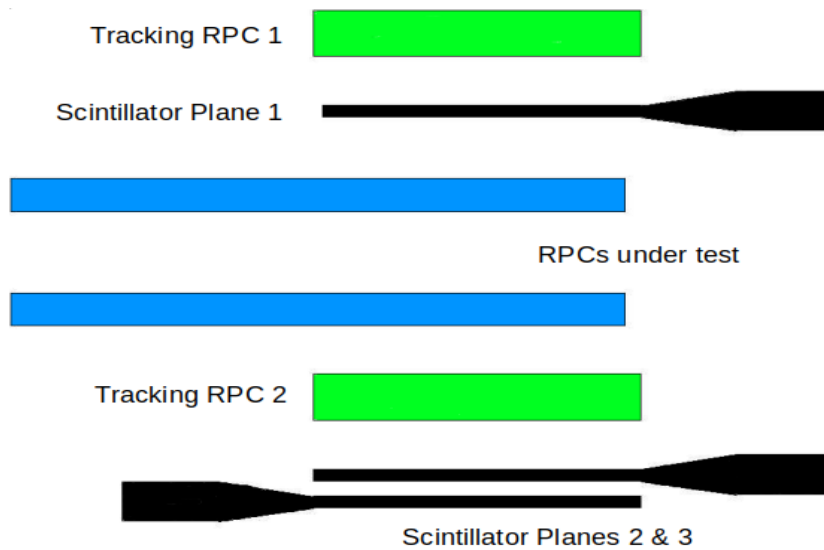


Figure 4.7: Schematic side view of the RPCs test station. Only the two test slots of the RPCs under test are shown, instead of the four available ones.

4.3.2 Electronics chain

The logical scheme of the electronics chain for the efficiency measurement is shown in figure 4.8.

The two RPCs under test and the tracking RPCs are read out by means of a FPGA based-DAQ CAEN V1495 module, while the scintillator planes are read out by means of CAMAC LeCroy discriminators. The trigger is issued if at least one strip per each strip plane (x and y) of the two tracking RPCs and at least one scintillator in each plane have been fired. In this way the trigger is given by the coincidence of all the three scintillator planes and all the four strip planes of tracking RPCs.

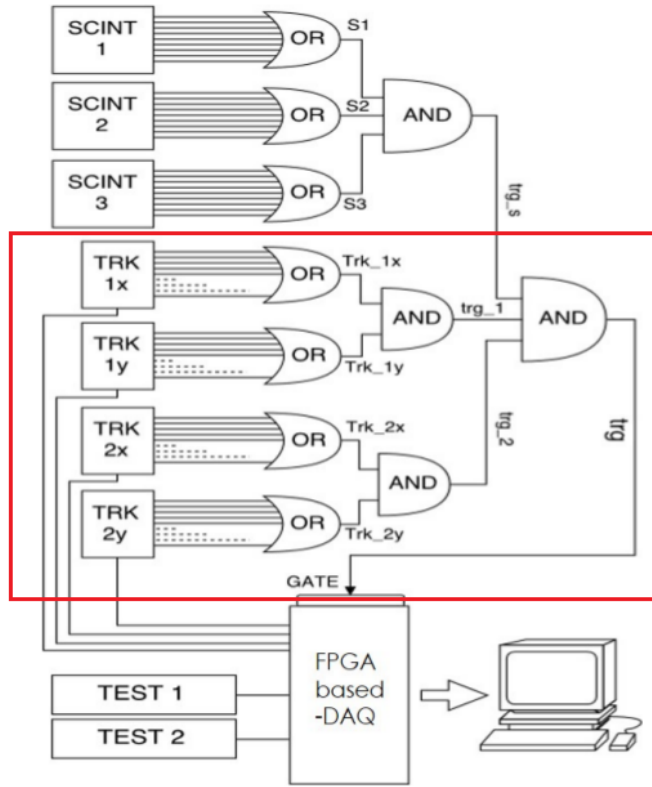


Figure 4.8: Trigger scheme for the measurement of efficiency. The red box indicates what is performed by the FPGA.

4.4 Tests performed on the detectors

The tests are made with the ALICE streamer gas mixture (50.5% Ar, 41.3% $C_2H_2F_4$, 7.2% $i-C_4H_{10}$, 1% SF_6), even if the RPCs will operate with an avalanche mixture in ALICE. This is done because it is necessary to compare the tests results of the new detectors with the ones related to the first detector bunch (the one currently installed in ALICE), that were tested

with the streamer mixture, since originally ALICE RPCs were supposed to run in the streamer working mode. Furthermore, with the avalanche mixture, a much lower detection threshold with respect to the streamer one is set, because of the lower amplitude signals; consequently, the electromagnetic noise background is much more relevant than in streamer mode, and the Torino testing environment is much noisier than the ALICE cavern one. Regarding the front-end electronics, for these tests ADULT ASIC, i.e. the one used for Run 1 and Run 2, with a detection threshold of 80 mV, is still used.

Five different tests are carried out for each RPC:

- *gas leakage*: the detection of eventual gas leaks in the gas gaps;
- *ramp-up*: a progressive increase of the HV from zero up to the working point, with continuous current monitoring;
- *efficiency-HV curves*: measurement of the efficiency as a function of HV and of the impact position of cosmic rays on the detectors (20×20 cm² cells);
- *high-statistics efficiency maps*: the efficiency map as a function of cosmic impact position at working HV, with a granularity of 2×2 cm²;
- *noise map*: intensity and localization of the single rate of the detectors, measured with the so-called autotrigger method.

These tests allow to completely characterize the RPCs by measuring the efficiency, the cluster size, the absorbed current and the noise. Moreover these tests are also important to verify that the problems encountered for the 2015-2018 productions (i.e. higher HV working point and disuniformity in the efficiency) were solved.

The gas gaps showing the best performances were chosen to be installed in the ALICE cavern for the MID, to replace the most aged detectors.

4.4.1 Gas leakage

The first preliminary test is the detection of eventual gas leaks. This is particularly important since the ALICE mixture is flammable because of the isobutane component.

For this test a U-shaped pipe is utilized, partially filled with water. This pipe is connected on one end with the gas gap outlet, while the gas gap inlet is connected to a hand pump with a no-return valve, used to pump air in the gap. Air is pumped until the water in the pipe is displaced up to 5 mm. When the

valve is closed the water level should not change: if the water level decreases, it means that there is a gas leak.

At this point it is important to find the gas leak and, if possible, repair it, otherwise the gas gap is rejected.

4.4.2 Ramp-up

After the gas leakage test the gas gap, is inserted inside the mechanical structure, and is placed on the test station, and it is flushed for the first time with the ALICE streamer gas mixture for at least 10 volume changes, corresponding to ~ 1 day of flushing.

Then the detector is connected to the high voltage. The HV is slowly ramped up to ~ 7000 V, by step of 500 V, then by step of 100 V until ~ 8500 -8700 V. For each voltage value the corresponding current value is measured.

The current-HV curve is needed to detect possible leakage ohmic current which is, as explained in chapter 3, current that does not pass through the gas inside the gap and is not due to the multiplication process. In an ideal case, the current should be zero until $HV = 7000$ V, because this HV value is below the multiplication threshold in the gas. Otherwise, if below 7000 V the detector draws a sizeable amount of current (more than $1 \mu A$), it is left at that voltage hoping for a current decrease with time. In fact a possible cause of the temporarily higher current value is that in the gas gap could be some impurities, such as dust on the bakelite sheets or uncured linseed oil, which can be attenuated with time during the RPC ramp-up. If the current does not decrease over time, the detector may present then an ohmic current. As previously said, possible reasons for the ohmic current could be the not perfect insulation of the electrodes with respect to the mechanical structure, or a partial short-circuit between the two electrodes.

4.4.3 Efficiency measurement

As explained in chapter 3, temperature and pressure affect the working voltage of the RPCs. In order to consider the pressure and temperature dependence, and to have a HV working point independent of any variations in p or T , an effective voltage HV_{eff} is defined. For each variation of p or T , the voltage value to be applied is calculated, so that the effective voltage at the detector remains constant over time. The effective voltage is defined

according to the formula 3.4, here reported again:

$$HV_{eff} = HV_{app} \frac{T}{T_0} \frac{p_0}{p}$$

where $T_0 = 293.15$ K, and $p_0 = 970$ mbar are reference values at which the applied and effective voltage coincide. As for the MID, also in the Torino laboratory, to take into account this, HV power supply system operates with a temperature and pressure monitor which updates the applied voltage online, so that the effective voltage remains constant. The HV_{app} is updated every 10-20 minutes.

The implementation of a dedicated cosmic-ray tracking system constituted by the 2 tracking RPCs and the 3 planes of scintillators allows one to reconstruct the presumed impact point of cosmic rays on the two-half RPCs under tests in order to obtain a local measurement of the efficiency, used to check the detector uniformity (see figure 4.9).

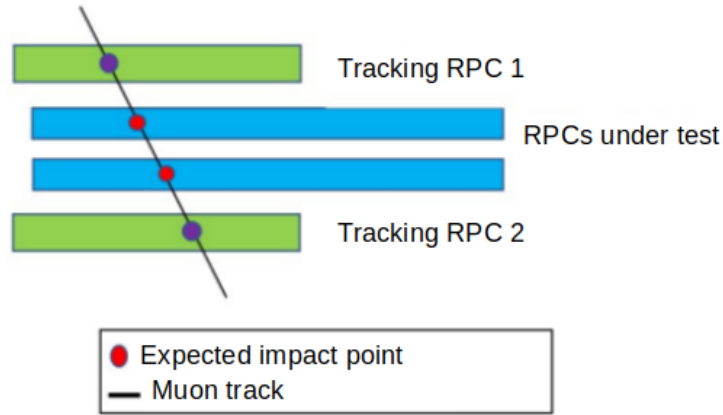


Figure 4.9: Reconstruction of the impact point for the local measurement of the RPC efficiency by means of two tracking chambers

The tracking RPCs are equipped on both sides with orthogonal 2 cm wide read-out strips. For cosmic ray tracking, only events with one cluster per plane on both tracking RPCs is required, in order to avoid ambiguities. Moreover a cluster size smaller than 3 is also required to improve the resolution and to reject cosmic showers.

The impact coordinates on the two tracking RPCs are indicated with (x_1, y_1) and (x_2, y_2) , located respectively at heights z_1 and z_2 . The expected impact coordinates on the two RPCs under test $(x_{test,1}, y_{test,1})$ and $(x_{test,2}, y_{test,2})$, located respectively at heights $z_{test,1}$ and $z_{test,2}$, are calculated as follows::

$$x_{test,i} = x_1 + \frac{z_{test,i} - z_1}{z_2 - z_1}(x_2 - x_1) \quad i = 1, 2 \quad (4.1)$$

$$y_{test,i} = y_1 + \frac{z_{test,i} - z_1}{z_2 - z_1}(y_2 - y_1) \quad i = 1, 2 \quad (4.2)$$

The detector surface of the tested chamber is virtually divided in cells and, once the impact point on the testing RPCs has been reconstructed, the event is assigned to a cell on the grid. Given the above mentioned resolution of the two tracking RPCs, the size of the cell has been chosen as $2 \times 2 \text{ cm}^2$ for the high-statistics efficiency map measured around the working point, since it guarantees a good resolution and statistical errors lower than 5%, in a reasonable data collecting time, i.e. around 24 hours.

Before moving to the high statistics efficiency measurements for the efficiency maps, low-statistics runs over a wide range of HV values are performed, in order to obtain the efficiency-HV curves and having a first idea of the HV working point to choose for the high statistics efficiency maps. In this case, the size of the cell has been chosen as $20 \times 20 \text{ cm}^2$.

The efficiency ϵ of each cell is:

$$\epsilon = \frac{N_D}{N_E} \quad (4.3)$$

where N_D is the number of cosmic rays detected by the tested RPC, and N_E is the number of cosmic rays that actually crossed the same cell.

The statistical error σ_ϵ can be calculated through the binomial distribution:

$$\sigma_\epsilon = \frac{\sigma_{N_D}}{N_E} = \sqrt{\frac{\epsilon(1 - \epsilon)}{N_E}} \quad (4.4)$$

taking into account that the second momentum of the distribution is $\sqrt{np(1 - p)}$, where p is represented by ϵ and n is represented by N_E .

One of the aims of the efficiency tests is to ascertain the uniformity of the detectors efficiency. It is important to avoid RPCs with non-uniform efficiency throughout their surface. Non-uniformity of the efficiency may be due to a different electric field in that region which in turn, with the same applied potential difference between the electrodes throughout all the detector surface, is due to a different gap between the electrodes. As said before, one of the most common causes of non-uniform efficiency is the lack of gluing of the spacer which can end up in a gas gap locally wider than 2 mm, lowering the local electric field.

For this reason, the measurement of efficiency are performed by virtually

dividing the detector surface in cells and measuring the efficiency separately for each cell.

4.4.4 Residual distribution

Before moving to efficiency and noise measurements it is necessary to correct for the residual distribution of the impact point.

The impact point of cosmic rays on the tested RPCs is calculated in the reference system of the tracking RPCs. To understand where the tested RPCs are with respect to the trajectory of the cosmic rays, two paths can be followed: either the tested RPCs are always positioned in the same position, or the alignment is performed offline. The second one has been chosen to avoid the need for precise positioning.

The tracking chambers define the reference frame, and the testing planes must be aligned with it. In order to do so, the difference between the expected impact coordinates $(x_{test,i}, y_{test,i})$ and the coordinate measured by the testing chambers is calculated offline. The peak value of the distribution obtained (see figure 4.10) both in x and y, is the *offset* between the zero of the reference frame and the edge of the testing planes. Then, this value is subtracted from the reconstruction of the position, so that the peak of the distribution is centered around zero, as shown in figure 4.11, which represent the distribution of the difference between expected and measured coordinates for a RPC under test, after including the offset value.

This residual distribution can be also used to evaluate the error on the position reconstruction, which depends on the strips width but also on the trajectory changes of the cosmic rays. The uncertainty is of the order of the FWHM, which is less than 2 cm with 2 cm wide strip. A new parameter t is introduced, named tolerance value. It is (arbitrarily) defined as:

$$t = \sqrt{(1.5w)^2 + (1.5 * 2cm)^2} \quad (4.5)$$

where w is the strip pitch of the RPC under test, while 2 cm is the strip pitch of the tracking RPCs. The event is considered detected by the RPC under test if, on both planes, the residual distribution is smaller than t . Depending on w , t takes different values: for 1 cm strips pitch $t = 3.4\text{ cm}$, for 2 cm strips pitch $t = 4.2\text{ cm}$, and for 4 cm strips pitch $t = 6.7\text{ cm}$.

The efficiency does not depend strongly on t , because the *tolerance value* is larger than the detector resolution. So the main effect of this cut is to

reduce false coincidences between noise counts of the RPCs under test and the triggered cosmic rays.

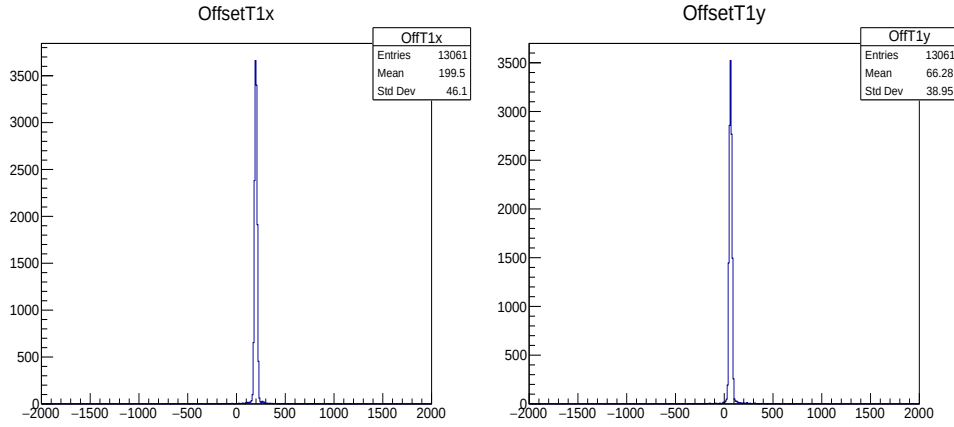


Figure 4.10: Distribution of the difference between expected and measured coordinates for RPC 716-21 along x (left) and y (right) direction, before the correction and then shifted with respect to 0.

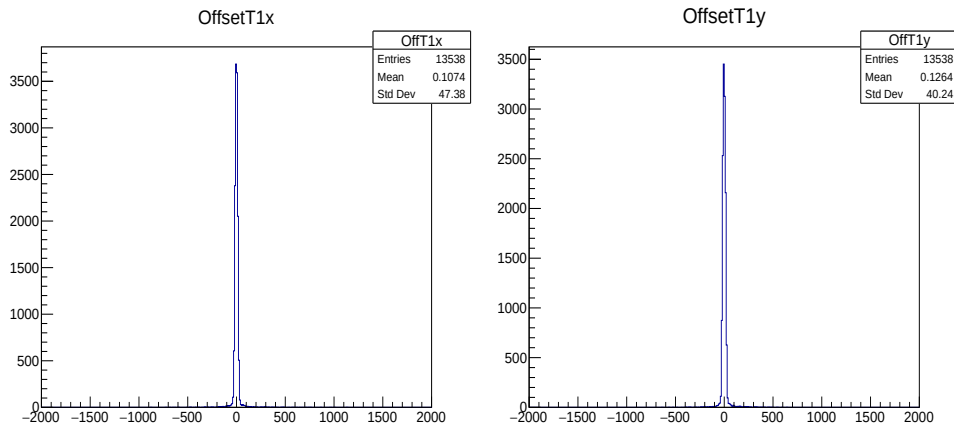


Figure 4.11: Distribution of the difference between expected and measured coordinates for RPC 716-21 along x (left) and y (right) direction, peaked on 0 after the correction.

4.4.5 Noise and dark current measurements

As previously stated, the noise of the detectors is defined by the dark counting rate, i.e. the counting rate with no beam or irradiation, when the hits are only due to intrinsic noise.

To measure locally the counting rate the *autotrigger method* is used: the trigger is given by the detector itself and coincidence events with at least one hit on both strip planes are selected, in a temporal window of 25 ns.

In figure 4.12 the logical scheme of the electronic chain for the autotrigger

measurements, which is different from the efficiency one, is shown.

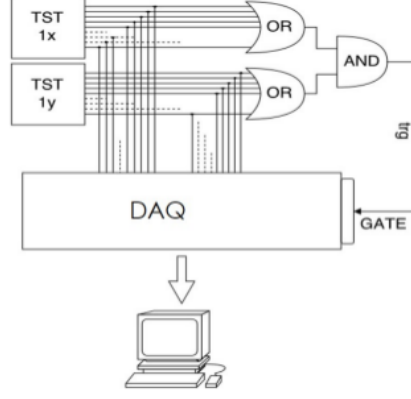


Figure 4.12: Trigger scheme for the autotrigger measurement

As done in the case of the efficiency measurement, the RPC surface is virtually divided in cells. In this case the cells are defined by the crossing of strips in the two directions. The number of hits on strip i , i.e. x direction, and j , i.e. y direction, define the number of hits $N_{i,j}$ in every cell. The number of hits $N_{i,j}$ at every strip crossing is counted and divided by the elapsed time (corrected for the dead acquisition time) and strip crossing area to obtain the single counting rate. The rate R_{ij} [Hz/cm^2] of cell (i,j) is evaluated with the following equation:

$$R_{i,j} = \frac{N_{i,j} N_{non-vetoed}}{\Delta t N_{vetoed} A_{i,j}} \quad (4.6)$$

where $A_{i,j}$ is the area of the strip crossing, Δt is the acquisition time, and the ratio of non-vetoed to vetoed counts over the whole detector accounts for the dead time of the data acquisition system. Since the hits per second are divided by the crossing area of the strips, the noise rate depends on the strips pitch.

With the autotrigger method it is possible to obtain the noise map of the detector, in order to detect any noisy spots.

The mean noise rate of every RPC is defined as:

$$R = \frac{N_{non-vetoed}}{A \Delta t} \quad (4.7)$$

where A is the area of the entire half-RPC under test. The mean rate of the whole detector is evaluated as the average of the mean noise rates of the left and the right halves of the RPC.

The measurement of the noise map is performed over a wide range of HV values to disentangle genuine detector noise effects from noisy channels in the readout electronics.

Dark Current

The main source of the dark current is the dark counting rate, but it is not the only cause. Other effects, such as ohmic parasitic currents or local reduction of electrodes resistivity due to persistent localized noise, may increase the dark current, so it is important to monitor and measure it.

For this reason the evolution with time of the current has been monitored, for each RPC, during all the testing procedure, especially during the high statistics efficiency run, in order to make sure that the current value is always stable.

4.5 Performances of the tested RPCs

The three RPCs of the 2019 pre-production were all tested and characterized and, since the results were promising, a new mass production of ~ 30 gas gaps was launched in the 2020 and delivered in 2021. In the following sections the tests results will be shown. These results are compared with those obtained from the old gas gaps currently installed in ALICE produced before the start of Run 1, since the new bakelite has different surface and bulk properties, and our goal is to replace some of the detector currently installed in ALICE with new gas gaps having the same (or even better) performances. The new gas gaps results are also compared with the 2015 and 2018 gaps which, as it will be shown, were largely unsatisfactory.

4.5.1 Efficiency-HV curves

The efficiency-HV curve test should give a first information of the best operating working voltage choice for each RPC, even if the actual working voltage will be determined during the MID commissioning in the ALICE cavern, in the avalanche working mode and with the FEERIC front-end electronics. The efficiency is measured for 13 HV values by step of 100 V, starting from the point in which the efficiency is different from 0, with 20000 events run per each voltage value. The efficiency maps for low-statistics runs are divided in 21 virtual cells with a surface of $20 \times 20 \text{ cm}^2$. Moreover the efficiency can be

measured separately for the two orthogonal strip planes, X and Y because, in this way, it is possible to disentangle problems due to the FEE, from problems arising from the gas gap. In fact, if inefficiencies appear on both readout planes X and Y, then they are due to the gas gap, otherwise, if it is limited to one of the two planes, then it can be due to faulty FEE channels.

In figures from 4.13 to 4.18 the efficiency maps for two different HV values, 8100 V and 7500 V respectively, left-half of RPC 716-21 (i.e. the new production), are shown. In both cases, on the left panels, the efficiency maps are shown for X-strips only, Y-strips only, and X and Y strips both. On the right panels the statistical errors on the efficiency measurements are shown.

The efficiency is evaluated with the procedure explained in section 4.4.3. It can be seen how at 8100 V the chamber shows an efficiency higher than 95% for all the cells and, as expected, efficiency decreases with decreasing voltage.

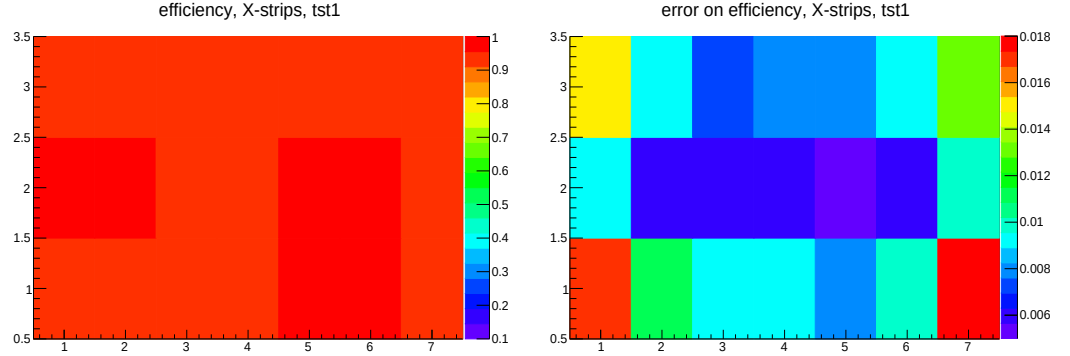


Figure 4.13: Left panel: efficiency map of RPC 716-21 at 8100 V, X-strips only, left-half, low statistics. Right panel: statistical error on efficiency map.

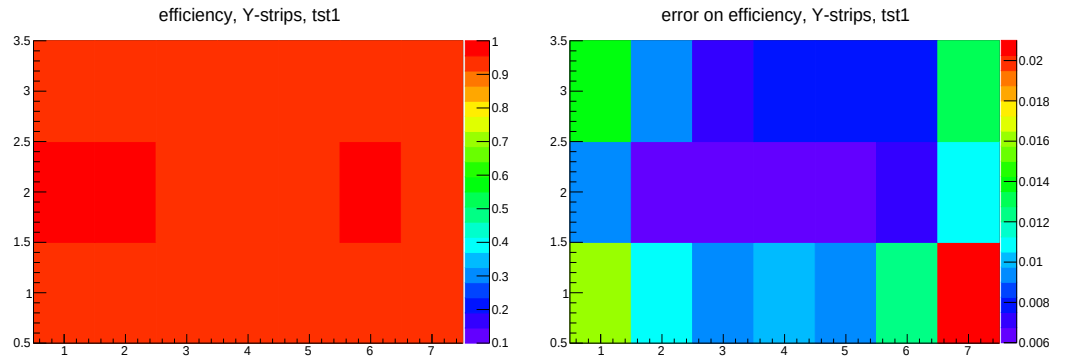


Figure 4.14: Left panel: efficiency map of RPC 716-21 at 8100 V, Y-strips only, left-half, low statistics. Right panel: statistical error on efficiency map.

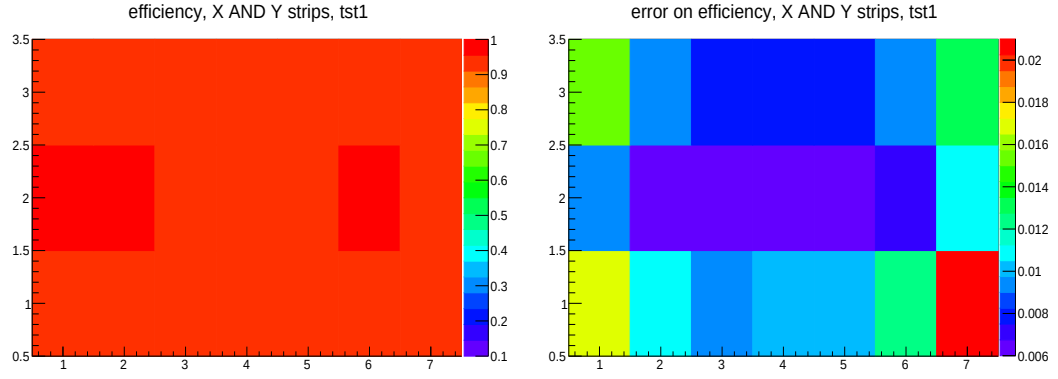


Figure 4.15: Left panel: efficiency map of RPC 716-21 at 8100 V, X and Y strips, left-half, low statistics. Right panel: statistical error on efficiency map.

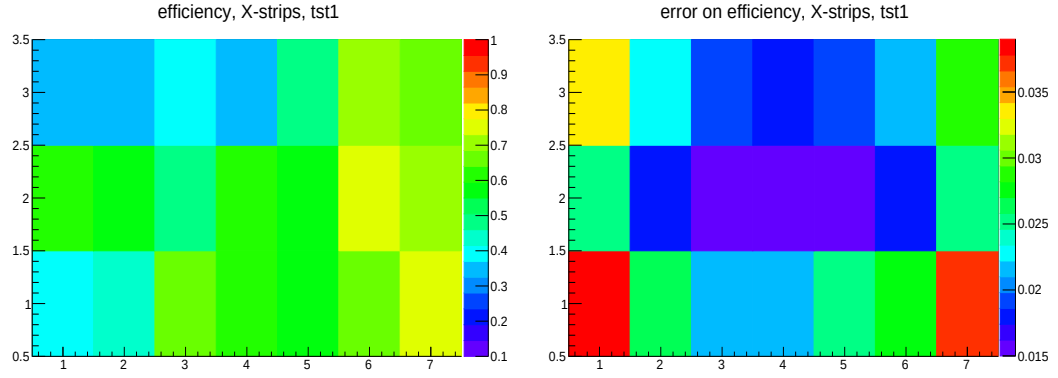


Figure 4.16: Left panel: efficiency map of RPC 716-21 at 7500 V, X strips only, left-half, low statistics. Right panel: statistical error on efficiency map.

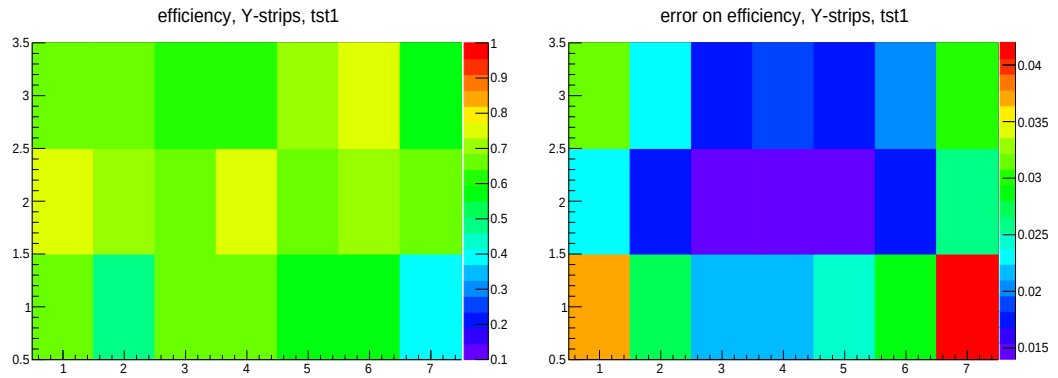


Figure 4.17: Left panel: efficiency map of RPC 716-21 at 7500 V, Y strips only, left-half, low statistics. Right panel: statistical error on efficiency map.

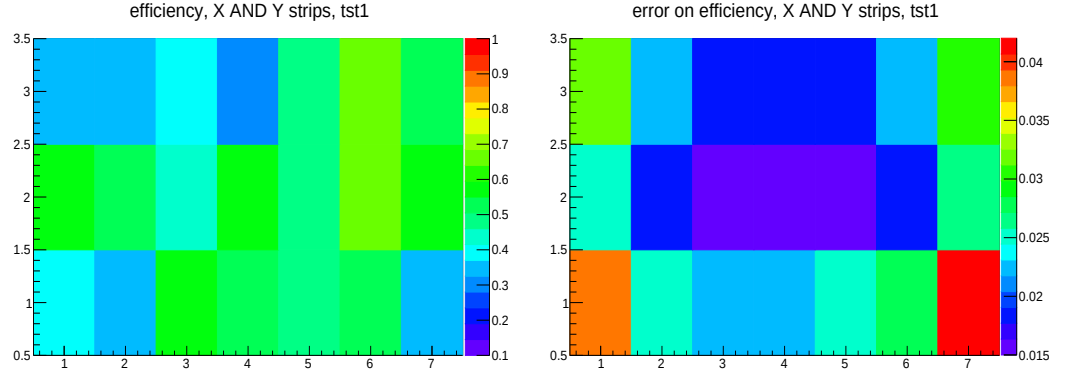


Figure 4.18: Left panel: efficiency map of RPC 716-21 at 7500 V, X and Y strips, left-half, low statistics. Right panel: statistical error on efficiency map.

It is important to point out that such a high efficiency at these voltage values was not seen for the old RPCs. The RPCs currently installed in ALICE, i.e. produced with the old bakelite type, showed an efficiency higher than 90% at 8400 V for most of the cells, as it can be seen in the left panel of figure 4.19. The RPCs produced between 2015 and 2018, which were also made with the new bakelite type as the 2020 production, showed an efficiency lower than 90% at 8400 V for most of the cells, as can be seen in the right panel of figure 4.19.

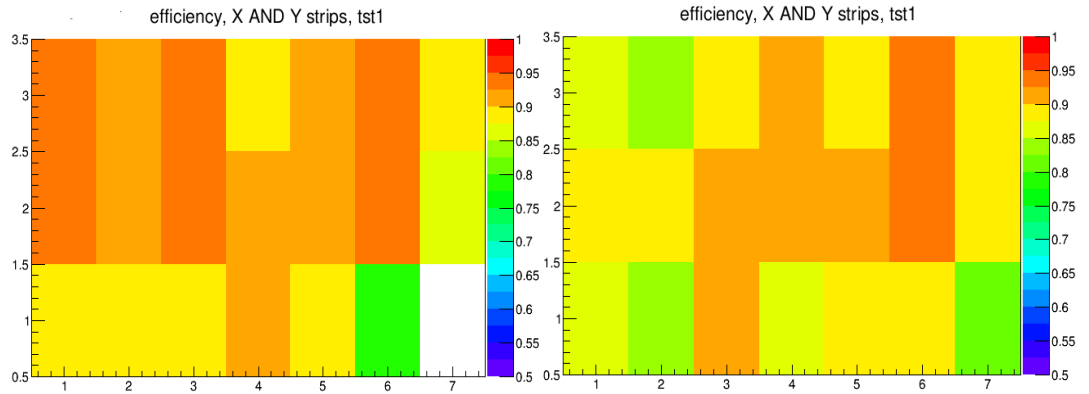


Figure 4.19: Left panel: efficiency map of RPC 15 at 8400 V, right-half, X and Y strips. It can be noticed that this RPC is a Cut type, and this explain why the bottom right corner of the map is missing. Right panel: efficiency map of RPC 491-15 at 8400 V, left-half, X and Y strips.

From the efficiency maps at the 13 HV values, the efficiency-HV curves are calculated for each one of the 21 virtual cells. The curves could slightly different from cell to cell, and each curve is fitted with a suitable function, i.e.

the integral of an asymmetric gaussian distribution:

$$\epsilon(HV) = \epsilon_{max} \frac{\int_{HV_{min}}^{HV} e^{-(t-\mu)^2/2\sigma^2(t)} dt}{\int_{HV_{min}}^{HV_{max}} e^{-(t-\mu)^2/2\sigma^2(t)} dt} \quad (4.8)$$

where:

$$\sigma(t) = \sigma_1 + \sigma_2 \frac{t - \mu}{\sigma_1} \quad (4.9)$$

As an example, in figure 4.20 are shown four efficiency-HV curves for 4 out of 21 virtual cells of the RPC 716-21, obtained from the efficiency maps shown before.

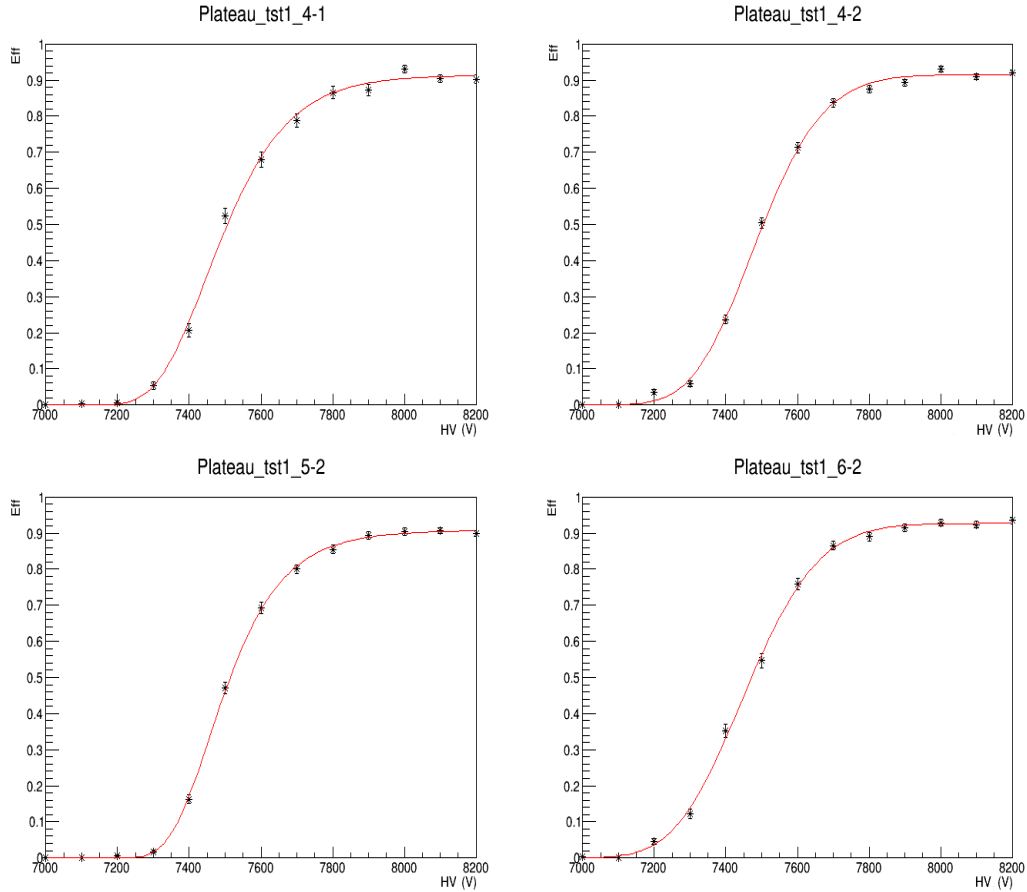


Figure 4.20: Efficiency curves for the cell 4-1, 4-2, 5-2, 6-2 (all $20 \times 20 \text{ cm}^2$) of the RPC 716-21, left-half.

Once the fit parameters are extracted, other parameters are evaluated from these, such as HV_{50} and HV_{90} which are, respectively, the voltage value at which the detector reaches 50% of the efficiency and the voltage value at which the detector reaches 90% of the efficiency. In particular, the spread of the HV_{50} parameter can be used to roughly evaluate the uniformity of the

detectors. In figure 4.21 the *HV 50* and the *HV 90* for RPC 716-21, left-half, are shown. As it can be seen in the *HV 50* plot, the mean value at which the RPC reaches 50% of the efficiency is ~ 7500 V, with an RMS of ~ 38 V.

The 2015-2018 RPCs had a much worse behaviour. In fact they had a higher voltage value for the *HV 50*, around 8000 V with an RMS of about 100 V, and there was a disuniformity in the efficiency of different cells of the same chamber, as it can be seen in the right panel of figure 4.22. Regarding 2003 production instead, as shown in the left panel of figure 4.22, the *HV 50* mean value is ~ 7700 V, with an RMS of ~ 30 V and the distribution shows a narrow peak around a central voltage value, meaning that the chamber shows an uniform behaviour with all the cells reaching the same efficiency value at about the same voltage value.

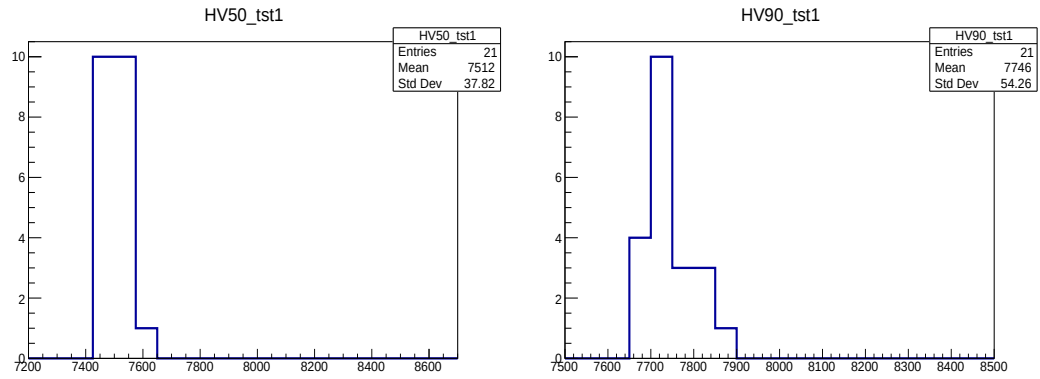


Figure 4.21: Distribution of the voltage at which the RPC 716-21 (left-half chamber) reaches 50% (left) and 90% (right) efficiency for cosmic ray.

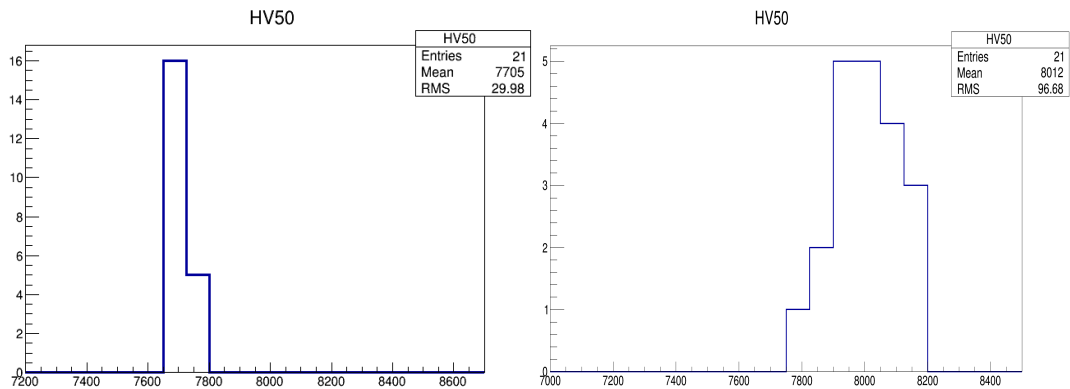


Figure 4.22: Left panel: distribution of the voltage at which the RPC 15 from 2003 production reaches 50% of the efficiency for cosmic ray, left-half chamber. Right panel: distribution of the voltage at which the RPC 450-15 reaches 50% efficiency for cosmic ray, left-half chamber.

To summarize, the 2015 RPCs had their working point at higher voltages with respect to the 2003 generation, shifted about 300-400V. Moreover in order to have the same efficiency throughout the entire detector surface, it was necessary to apply a voltage value higher than 8700 V, but some areas were already efficient at lower voltage values, around 8400 V. For this reason, in order to recover the efficiency over the entire detector surface, some areas were in overvoltage, leading to larger signals and, therefore, to a larger cluster size. Given that, it was not advisable to install them in the MID.

Regarding the new production instead, the *HV 50* distribution have a narrow peak around 7500 V, i.e. at lower voltage with respect to the 2003 RPCs. The 2020 production seems to have in fact an even lower working voltage value with respect to the old production, i.e. ~ 8100 V instead of 8400 V.

4.5.2 Efficiency map

The previous test gives an idea of the HV working point for the given gas gap. In order to evaluate with high precision the efficiency uniformity of the detector, and eventually detect any imperfections, high resolution efficiency maps are measured, with a granularity for the virtual cells of $2 \times 2 \text{ cm}^2$. In order to do so, high statistics runs are needed, i.e. around 1 million events for each voltage value (these maps are measured at two different HV values), which corresponds roughly to $\simeq 10\text{h}$ acquisition time and a statistics of about 500 events in central cells, and 50-100 events in the corners.

In the left panels of figures 4.23, 4.24 and 4.25 the efficiency map for RPC 716-21 (left-half chamber) at 8100 V is shown for, respectively, X-strips only, Y-strips only, and X and Y strips both. In the right panels the statistical error map at 8100 V for the same RPC are shown. Units are given in cells.

It can be seen that the detector shows uniform efficiency throughout all its surface. The low efficiency cells that appear every 10 cm corresponds to the spacers, whose diameter is 1 cm.

It has to be pointed out that the number of tracked cosmic rays is maximum in the center of the detector surface and decreases in the peripheral regions, due to the geometry of the tracking system of the experimental set-up. This can be seen in figure 4.26 in which the distribution of triggered events over the surface of the half tested chamber is shown. For this reason the statistical error on the efficiency, calculated with the formula 4.9, ranges from 1% in the center to 10% in the corners regions, and takes into account the statistical fluctuations on the number of particles revealed.

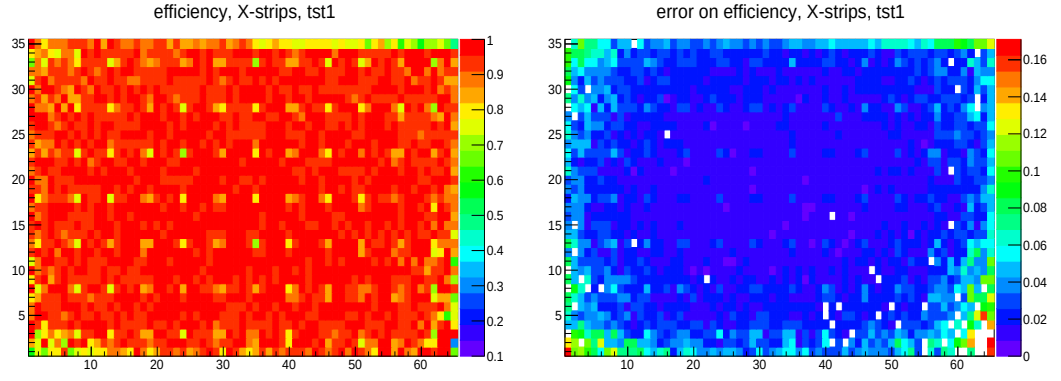


Figure 4.23: Left panel: efficiency map of RPC 716-21 at 8100 V, X strips only, left-half, high statistics. Right panel: statistical error on efficiency map.

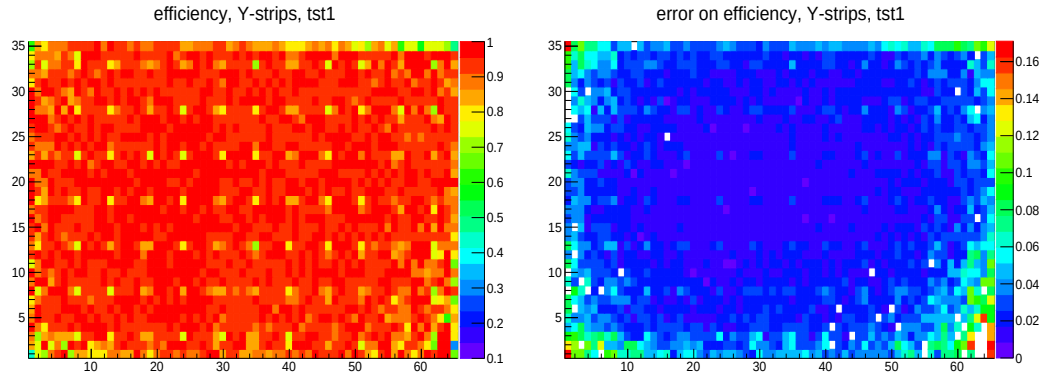


Figure 4.24: Left panel: efficiency map of RPC 716-21 at 8100 V, Y strips only, left-half, high statistics. Right panel: statistical error on efficiency map.

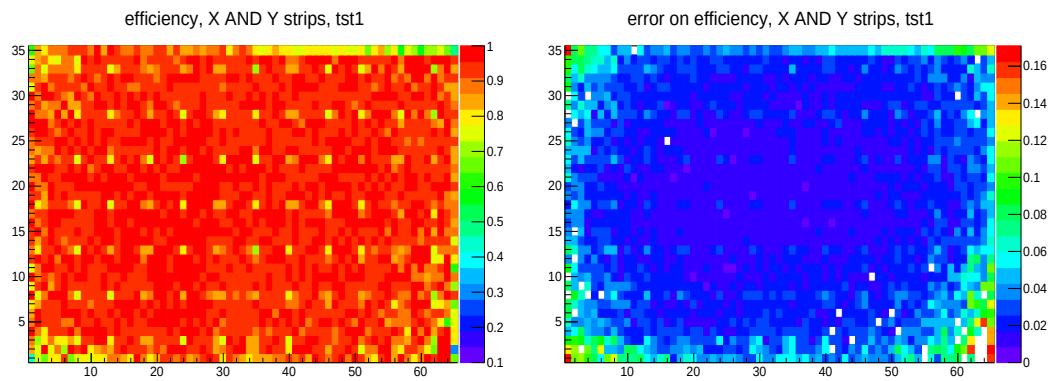


Figure 4.25: Left panel: efficiency map of RPC 716-21 at 8100 V, X and Y strips, left-half, high statistics. Right panel: statistical error on efficiency map.

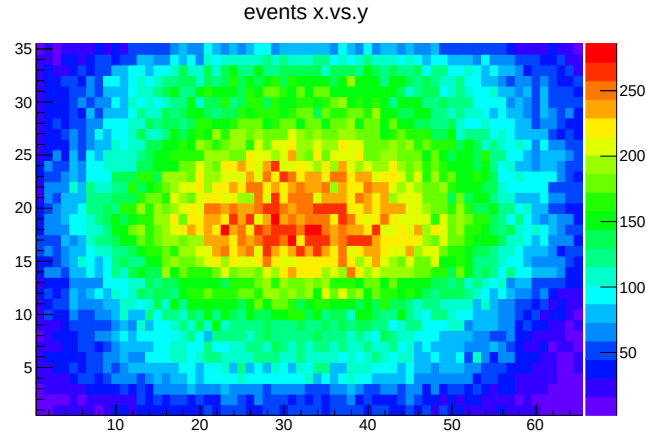


Figure 4.26: Distribution of triggered events for efficiency measurement over the surface of an half tested chamber. Units are given in cell and the area of the cells is $2 \times 2 \text{ cm}^2$.

In figure 4.27 two others efficiency maps for another gas gap from 2021 production, RPC 717-21, are shown. In the left panel the efficiency map at 8100 V, right-half chamber, X-strips only is shown, while in the right panel the efficiency map for Y-strips only is shown. First it is possible to notice that RPC 717-21 is a Cut-shape one, in fact the bottom right corner is empty. Secondly, the inefficiency zones along several strips Y are due to a problem related to the readout planes (e.g. short-circuited strips, or unstable electric contact, or bad insulation) or most probably to the FEE board itself. In fact, the inefficiency zone disappear in the efficiency map made from the X strips plane only, so it is not due to the gas gap.

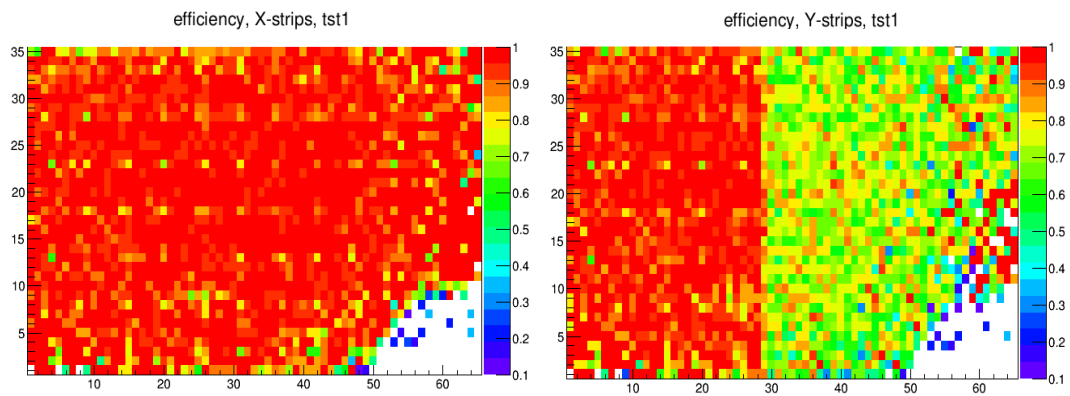


Figure 4.27: Left panel: RPC 717-21 efficiency map at 8100 V, right-half, X-strips only. Right panel: RPC 717-21 efficiency map at 8100 V, right-half, Y-strips only.

RPCs produced in 2003 production showed uniform efficiency throughout all the detector surface, without inefficiency zones, with a working point around

8400 V.

Unlike what happened for 2003 RPCs, for 2015 productions there were some regions of local inefficiency. An example is shown in figure 4.28. The gas gap shows inefficiency holes even at 8700 V, i.e. higher voltage with respect to the 8400 V working point for 2003 RPCs. Possible causes may be locally wider gas gap (so a lower electric field) caused, as mentioned before, by a detachment of the spacers. As explained in section 4.2, there was a general carelessness in the production process for 2015 chambers. After several interactions with the firm, a new gas gap was ordered in 2018.

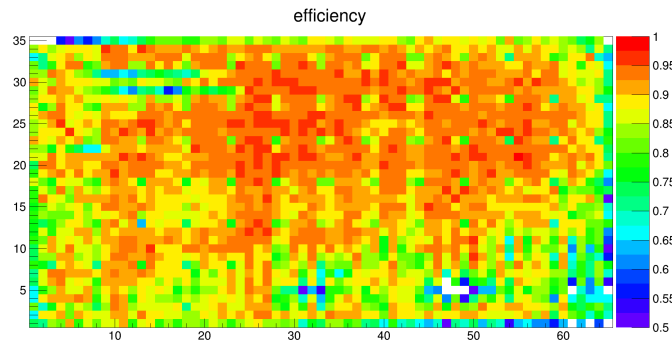


Figure 4.28: Efficiency map at 8700 V, for RPC 450-15, left-half, X and Y strips.

Unfortunately the results for the 2018 gas gap prototype was even worse. This detector had inefficiency holes in several parts of its surface. In order to study the problem, more high statistics runs were launched, over a wide range of voltages, from 9200 V to 7700 V, by steps of 100 V. In figure 4.29 only the cases at 8700 V and 8500 V, X-strips only, are shown as an example. The maps for this RPC were measured with only the X strips because there were inefficient FEE channels on some Y strips. From the efficiency maps it was seen that as the voltage decreased, the inefficient areas widened, and it was necessary to reach 9200 V to have an uniform efficiency throughout all the chamber surface. This behaviour could be a consequence of a locally wider gas gap that causes a locally lower electric field between the electrodes, due to a detachment of the spacers. In order to understand the problem, as explained in section 4.2.1, a pressure test was performed to check the position and the gluing of the spacers. As it can be seen in figure 4.3, the area with the highest pressure difference ΔP , i.e. the lower right half of the map, corresponds exactly to the inefficiency hole position in the left panel of figure 4.29. Also in the upper half of the pressure map it is possible to notice that some spacers, placed in correspondence of the inefficiency areas that begin to appear at 8500

V could be detached from the bakelite surface.

Because of these serious inefficiency problems, the RPCs from 2015 to 2018 productions cannot be used for the MID.

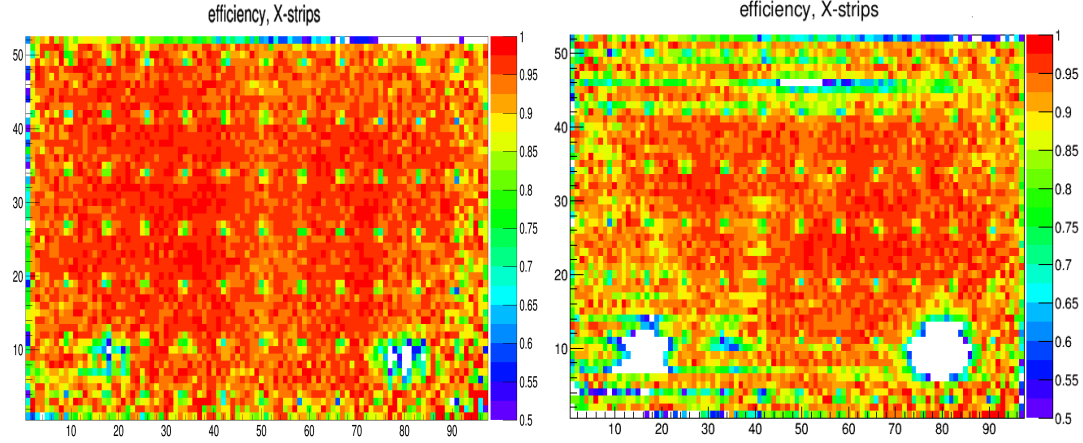


Figure 4.29: Left panel: RPC 590-18 efficiency map at 8700 V, left-half, strips X only. Right panel: RPC 590-18 efficiency map at 8500 V, left-half, strips X only.

4.5.3 Noise and dark current

The complete characterisation of the performances of the RPCs requires a parallel evaluation of the efficiency on one hand and of the noise on the other. This is needed because these parameters increase with increasing voltages: a detector is fully efficient when it is possible to choose an operating voltage at which the efficiency is uniform throughout all the chamber surface and at the same time the noise and current do not exceed reasonable limits.

For this reason, even if a detector shows a good and uniform efficiency, it can be discarded if the noise rate or the current are too high.

Concerning the dark current, most of the detector of 2021 production show values of dark current of few μA , which is a perfectly reasonable and acceptable value. However for some chambers, when they were ramped up for the first time, the dark current was quite high, of the order of several tens of μA . In this case, the detector was left with the HV on at $\sim 7800 \text{ V} - 8000 \text{ V}$ for few days, in order to see if the current decreased over time. As explained before in fact, sometimes some impurities, such as dust, could remain inside the gas gap, on the inner surfaces of the bakelite sheets, leading to temporarily high dark currents. These impurities could be burned by high voltages with time, so if the current decreases over time then it was only due to these impurities and the gas gap can be recovered. Otherwise, if the dark current does not decrease over time, the problem could be related to some other damage of

the gas gap and it is not advisable to install it in the MID.

Regarding the noise map, as explained before, the noise of the detector is defined by the counting rate of the chamber with no beam or irradiation. The noise map of the detector is evaluated with the autotrigger method explained in section 4.4.5, and its measurement allows to identify the noisy spots. It is important to monitor the noisy spots since they may cause local inefficiencies due to continuous discharges, and they can also speed up the aging of the detector.

The noise rate has been measured over a wide range of HV values, from around 7100 V up to around 8300 V, for a total of 13 runs, by step of 100 V for each chamber, with 20000 events run per voltage.

In figure 4.30 the 2D noise maps of RPC 716-21, left-half chamber, at two different HV values, i.e. 8100 V and 7800 V respectively, are shown. It is possible to note that, lowering the voltage the noise rate decreases. For example, on the top right there is a noisy spot which has ~ 0.7 Hz/cm² noise rate at 8100 V and the noise rate decreases to ~ 0.45 Hz/cm² at 7800 V.

Unfortunately in few cases it was seen that lowering the voltage the noise rate does not decrease uniformly: some spots disappear while others appear. Discovering the causes of this behavior could help to understand the nature of noisy spots and the detector noise in general, therefore this kind of problems requires further investigation.

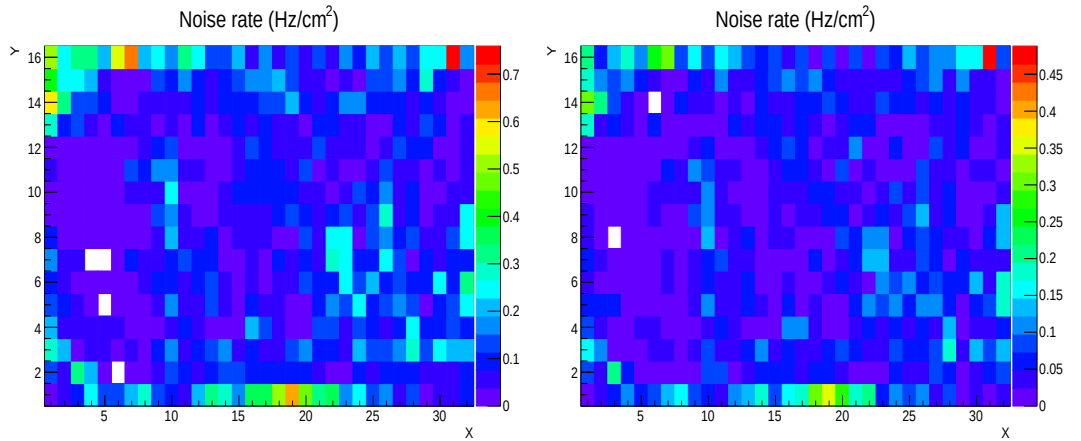


Figure 4.30: 2D noise map of RPC 716-21, left-half chamber, operated at 8100V and 7800V.

However, for all the 2020 tested detectors the noise rate at the working voltage is never higher than 1-2 Hz/cm² for the most noisy spots, while the mean value of the noise rate at the working voltage is ~ 0.1 Hz/cm², as it can be seen for example in figure 4.31, in which the noise rate for RPC 706-21 at

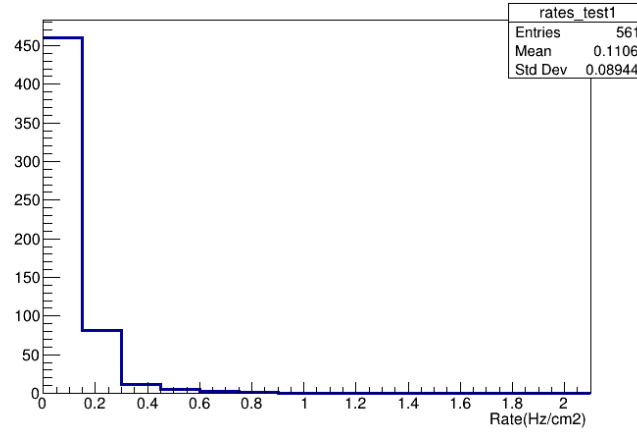


Figure 4.31: Noise rate for RPC 706-21 at 8100 V.

8100 V is shown.

These values of noise rate are the same seen for the 2003 RPCs currently installed in ALICE. Regarding 2015 production, for most of those chambers it was also seen that lowering the voltage values the noise rate was not decreasing uniformly. Moreover the number of noisy spots was higher than that of the 2003 and 2020 productions, and the mean value of noise rate was $\sim 0.2 \text{ Hz/cm}^2$.

4.6 Tests results

Regarding the detectors noise, the 2003 and 2021 RPCs behave better than the 2015-2018 RPCs. The dark current instead, even if it is low for most of the 2021 detectors, it is quite high for a small sample of them and it should be accurately monitored in order to understand the problem.

Regarding the efficiency, the 2003 RPCs are better than those of 2015, which in turn are better than the 2018 RPC prototype. For the 2015 RPCs there was a gluing problem, more precisely there was too much glue on the spacers, and also a general carelessness in the production process, while for the 2018 RPC, there was a gluing problem between the spacers and the new type of bakelite surface.

The 2019 pre-batch and the 2021 productions have a good and uniform efficiency so far, and even a lower HV working point with respect of the 2003 production, i.e. 8100 V instead of 8400 V.

For this reasons two of the new RPCs production were already installed in the ALICE cavern in December 2022, and two other gas gaps will be installed in March 2023.

In the meanwhile the remaining RPCs of the 2021 production will be tested in Torino, in order to finally assess the fitness of the whole production.

Chapter 5

Performance of the MID during Run 3

As emphasized before in this thesis, the main goal of the new FEERIC upgrade is to reduce the total charge produced in the gas gap in order to minimize RPCs aging effects. In this chapter the MID performance in terms of currents drawn, charge per hit, cluster size and efficiency in the first year of Run 3 data-taking are shown. The RPCs equipped with FEERIC are also compared to the RPCs equipped with ADULT during Run 1 and Run 2, in order to verify if the performance needed for Run 3 and Run 4 are met.

5.1 Currents

Currents measurements were performed using DARMA DCS database tool as data source (see section 3.6.1). It has to be pointed out that the DCS currents readings have no run number, beam condition or LHC status information, but only the timestamp of the current reading values. Both the dark current and the physics current measurements procedure will be described in the following section, together with current trends and integrated charge studies.

5.1.1 Dark current

The definition of dark current was already given before in the formula 3.11, and is reported here again:

$$I_{dark} = I_{Ohmic} + I_{cosmic} + I_{noise}$$

As said before, the dark current is the current drawn by the RPCs when they are at working HV and no collisions are taking place at the LHC. The

only way then to measure it is during the so-called "cosmic runs", i.e. runs taken by ALICE when detectors HV are on and no beam is present, mainly for experiment commissioning purposes.

Unfortunately this kind of runs are not frequent, so they do not provide a good coverage of the operation period. Moreover, it is not always true that if no beam is present, then a cosmic run is ongoing, since during the operation period it can often happen that without beams other commissioning operations are ongoing on the detector, like hardware interventions or tests and improvements of the data acquisition chain.

Another possibility for measuring the dark current with a better coverage of the data-taking period, could be selecting calibration runs. In fact one calibration run, lasting 2 minutes, is always performed at the end of every physics fill of the LHC, after the beams dump, when the MID is still at nominal working HV, with the aim of spotting FEE noisy or dead channels. However it was observed that the dark current measured immediately after the dump, i.e. after a physics fill, is systematically higher than the current measured in "quiet" periods. This could be due to the fact that after an operation period with beams some impurities remain in the gas gap for a while before being fluxed away by the gas system.

For these reasons retrieving the dark current information during cosmic runs remain the only available option.

The dark current trend was then estimated by checking the timestamp of the MID cosmic runs and then reading the currents values from DARMA in the same timestamps range. For each cosmic runs, an average I_{dark} value was obtained for each one of the 72 RPCs.

Performance analysis

The dark current trend during time, using cosmic runs only, is displayed in figure 5.1. In each plot one MID half-plane (i.e. 9 RPCs) is shown, for a total of 8 dark current trends plots. It was chosen to plot separately in groups the RPCs in order to spot eventual problematic detectors or aging hints. In fact, as said before, the evaluation of the dark current trend is fundamental to understand the health of the inner surfaces of the detectors since it strongly depends on the presence of irregularities on the surfaces of the RPCs, hence can be used as a diagnostic tool. On the y axis is displayed the I_{dark} in $\mu\text{A}/\text{cm}^2$, i.e. the currents have been divided by the corresponding RPC area, to account for RPCs different shapes (Long, Cut and Short) and different areas.

The first cosmic runs were taken during the commissioning period before the start of the LHC Run 3 the 5th of July 2022. These runs were taken only when possible, i.e. when LHC was not doing its own commissioning, since in this case the detector must be switched off for safety reasons. Then, when collisions started, it was possible to take other cosmic runs from time to time during no-beam days (usually once a week or less). At the end of August 2022, there was a problem on an RF cavity at the LHC and the Run 3 data-taking had to be stopped for more than a month. During these weeks it was then possible to take several cosmic runs. Last runs were taken at the end of November 2022, when the first year of LHC Run 3 ended, before switching off the detector for the winter shutdown. In fact every year the LHC beams are stopped for the winter, typically from the end of November to the first 3 months of the following year. During this period the irradiation caused by the beam operations is absent.

From the plots it can be observed that the dark current drawn by most of the RPCs remains more or less constant and with negligible values during the operation period, with few exceptions. For example:

- regarding the behaviour of the RPC MT21 OUT 6, this is due to some issues with the HV cable and the HV connector on chamber side. In fact, during the commissioning period with cosmics, just before the first p–p collisions started, it was necessary to intervene on the HV connector that was not working anymore. Unfortunately in that moment it was not possible to properly replace it, and a makeshift repair had to be made. This led to very unstable current for this RPC during the operation period. The RPC MT21 OUT 6 will be replaced in March 2023 during the LHC winter shutdown;
- for RPC MT22 OUT 6 instead, the higher dark current drawn with respect to the other RPCs is probably due to a gas leakage. In fact, also this RPC underwent an intervention on the gas inlet on chamber side just before the start of the first p–p collisions in 2022. Before the reparation, the gas leakage on this RPC was total, i.e. the 100% of the gas was lost, since the inlet was completely broken. A fast repair reduced the problem to a small gas leakage, but the current remained higher than average. Also this gas gap will be replaced in March 2023 during the winter shutdown;
- the RPC MT22 IN 2 was the RPC drawing the higher dark current among all the RPCs of the MID. This could be due to the fact that this

gas gap was used to do some tests with pure argon gas during the LS2 between Run 2 and Run 3, and probably the gap was slightly damaged in the process. This RPC has already been replaced during the winter shutdown, in December 2022.

Even if these three RPCs can be considered the worst case scenario and most of the RPCs show a stable behaviour, there are still few outliers that should be constantly monitored in order to promptly notice eventual worsening of performance.

Finally, the current peak that can be observed in all the RPCs at the end of August is due to the fact that just before that cosmic run ALICE was performing high collisions rate runs with p-p beams. In fact, from time to time, ALICE performs this high collisions rate scans with p-p for commissioning and tests purposes in view of the Pb-Pb runs. The behaviour is in principle the same mentioned before for explaining the higher dark currents drawn after the beams dump, i.e. after an operation period with beams some impurities remain in the gas gap for a while before being washed away by the gas system, leading to temporarily higher dark currents.

It is important to compare these currents with those drawn by the RPCs equipped with ADULT during Run 1 and Run 2 (from 2010 to 2018), shown in figure 5.2. In this case in each figure is plotted one full MTR plane (18 RPCs), for a total of 4 plots. The min (in green) and max (in red) show the RPCs whose dark current over the entire period is the lowest or highest, respectively, while in black is plotted the average dark current of one entire MTR plane. In the specific case, for MT11 plane they correspond to the RPC IN 2 (minimum) and OUT 3 (maximum), for MT12 to the RPC IN 8 (minimum) and OUT 2 (maximum), for MT21 to the RPC IN 7 (minimum) and OUT 1 (maximum), and for MT22 to the RPC OUT 8 (minimum) and OUT 6 (maximum).

For all the MID planes, the dark currents drawn by the RPCs during Run 3 are negligible and also lower than the ones drawn at the end of Run 2 in 2018, even if the luminosity in Run 3 is higher (hence the irradiation of the chambers is stronger) with respect to the previous runs. This was expected, because the working voltage was lowered thanks to the pre-amplification stage implemented in FEERIC. It is also important to observe that while all the RPCs equipped with ADULT showed an increase of the dark current over Run 1 and Run 2 years of operations, the values of dark currents for the RPCs equipped with FEERIC electronics are compatible with a constant behaviour.

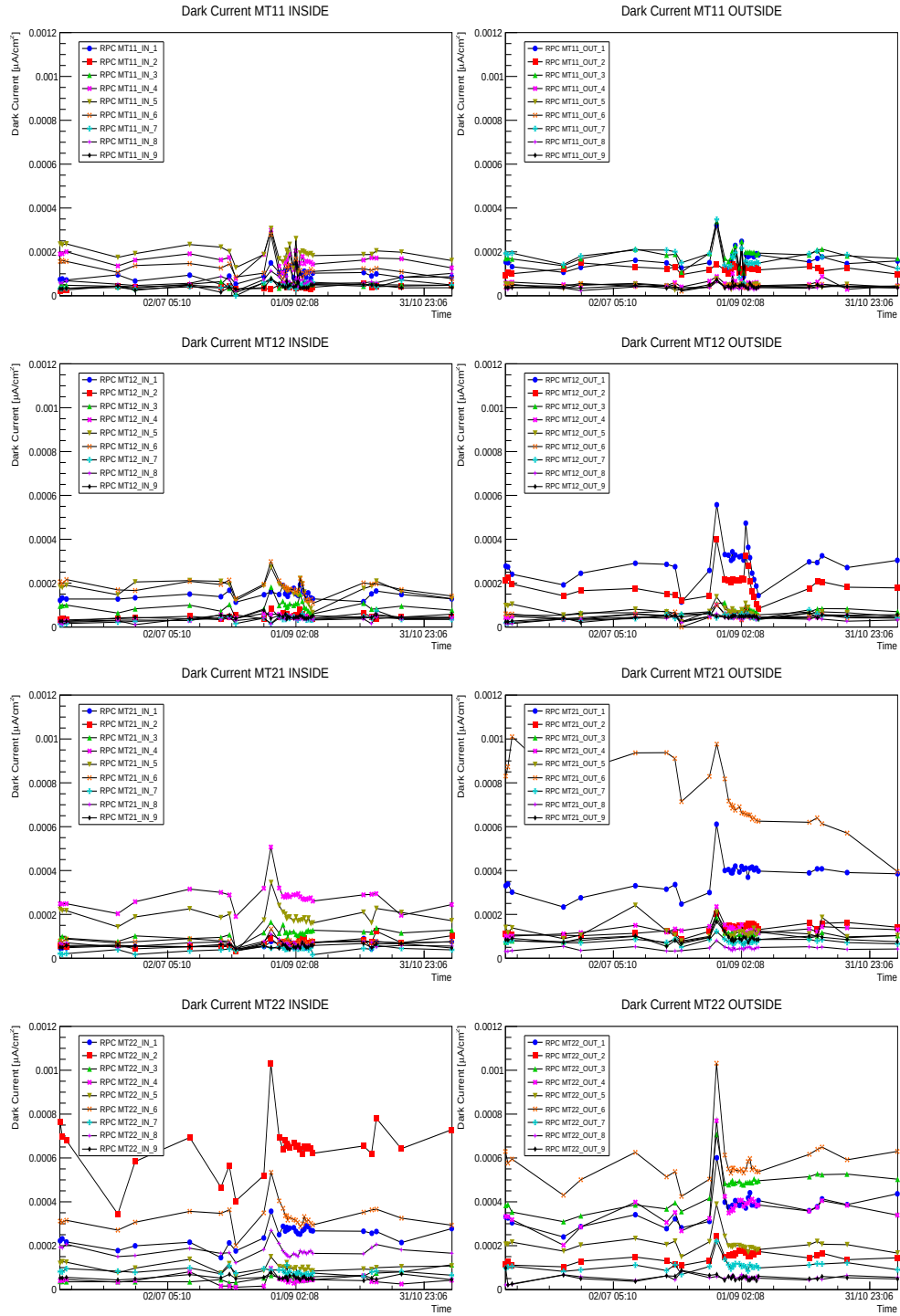


Figure 5.1: Dark currents measured during several cosmic runs over 2022 operation period. In each plot one half-plane with 9 RPCs is shown.

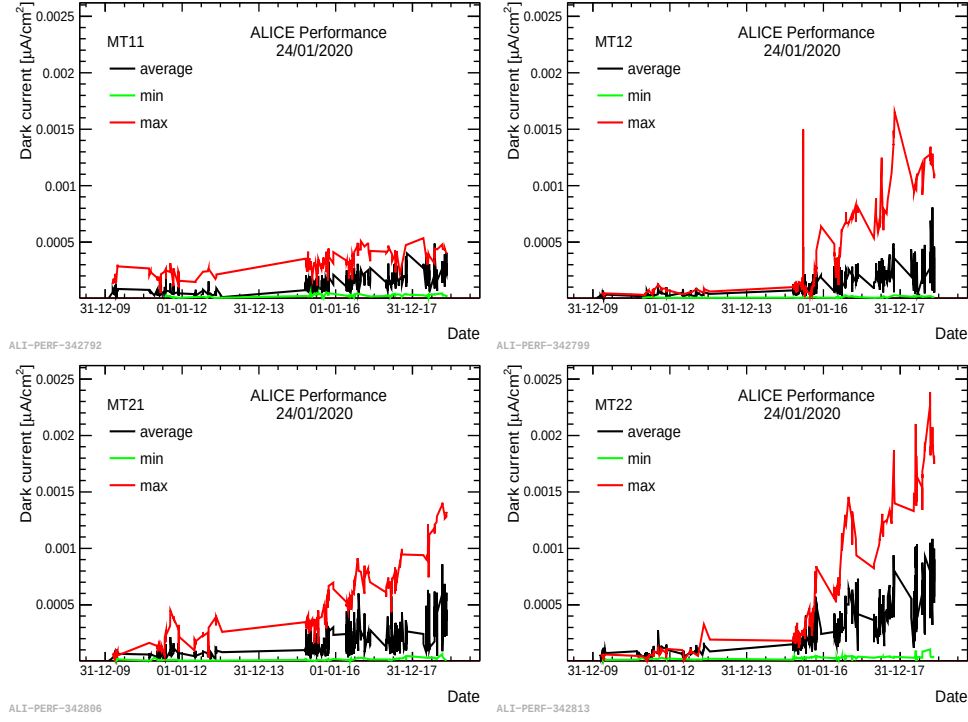


Figure 5.2: Average, minimum and maximum dark current for the 4 planes (i.e. MT11, MT12, MT21 and MT22) of the Muon Trigger (MTR) equipped with the old ADULT FEE in the years 2010-2018.

Average MID dark current before and after hardware interventions

As mentioned before, several hardware interventions were performed on the MID during the commissioning period. Every time an intervention was completed, an HV ramp-up was performed on the MID in order to obtain the I_{dark} -HV curves for each RPCs, and consequently check the dark current drawn in order to spot any possible issue.

In figure 5.3 the average dark current drawn by the entire MID during some of these ramp-up, between 2018 and 2023, is shown. All the ramp-up were performed at step of 500V, starting from 0 V up to the HV working point, around 9500 V depending on the RPCs (as it will be shown in section 5.4), and for each value of HV the average value of the dark current I_{dark} was taken. In blue the I_{dark} -HV curve of the RPCs at the end of Run 2, in November 2018, is shown. After that the detector was turned off for more than two years, during the LS2, in which all the previous mentioned upgrades in view of Run 3 and Run 4 were performed. The MID was turned on again, for the first time with the new electronics, in July 2021. The I_{dark} -HV curve is shown in red. As it can be seen in the plot the average dark current drawn was higher than that drawn at the end of 2018. This was due to several problems on different RPCs (regarding for example broken HV cables, gas leakages, malfunctioning

HV boards etc.), leading to an higher dark current for these specific chambers and, consequently, an higher average dark current for the MID, even if the detector was off for more than two years and, in principle, no growth should have been observed in the dark current.

After all the interventions and reparations the MID was turned on again, in May 2022, and the reference I_{dark} -HV curve is shown in green. As it can be seen, the average dark current drawn, especially around the working point at 9500 V, was again the same drawn at the end of 2018, as expected.

Then in December 2022, after the end of the first year of Run 3, the two most aged gas gap, i.e. MT22 IN 1 and MT22 IN 2, were replaced with two gas gap from the new 2020 production, i.e. 706-21 and 707-21, which had passed all the tests shown in chapter 4. It can be seen that, as expected, the average MID dark current was of course lower than that drawn before the replacement, since the old gas gaps were drawing an high dark current, $\sim 6 \mu A$ and $\sim 18 \mu A$ respectively for MT22 IN 1 and MT22 IN 2, while the new ones are drawing only $0.2 \mu A$ at the working point. Two other gas gaps drawing an high dark current, i.e. MT21 OUT 6 and MT22 OUT 6 will be replaced in March 2023, further decreasing the average MID dark current.

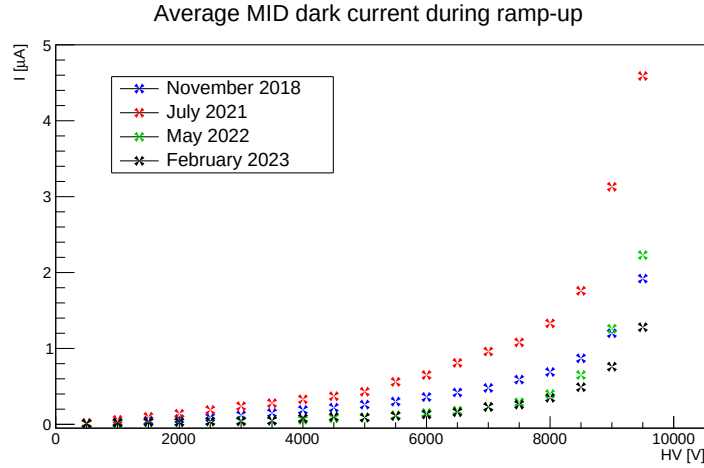


Figure 5.3: MID average dark current during several ramp-ups. In blue the I_{dark} -HV curve in November 2018, at the end of LHC Run 2, is shown. In red the current drawn at the very first MID ramp-up during LS2 in July 2021, after more than two years in which the detector HV was off, is shown. In green the ramp-up drawn in May 2022 after all the hardware interventions on the RPCs is shown. Finally in black the dark current drawn in February 2023, after the replacement of two gas gaps showing aging effects, is shown.

5.1.2 Physics current and integrated charge

The definition of the total current I_{RPC} was already given before in the formula 3.10, and is reported here again:

$$I_{RPC} = I_{Ohmic} + I_{cosmic} + I_{noise} + I_{beams}$$

Ideally, to obtain a precise evaluation of the current causing aging of an RPC, one should consider all the previous contributions except the I_{Ohmic} one which, as said before, it is not due to current passing through the gas gap. Since it is not unfortunately possible to extract I_{Ohmic} from I_{dark} two approaches are possible, assuming that I_{dark} can be dominated by either of its terms:

1. if $I_{dark} \approx I_{Ohmic}$ then the dark current contribution must be subtracted from I_{RPC} to obtain the current value which causes aging effects;
2. if $I_{dark} \approx I_{cosmic} + I_{noise}$ then the dark current contribution to the total current takes part in the aging effects.

The charge integrated by the RPC is obtained by time-integration of the current flowing through the detector gas gap. In either of the two previous cases, the integration of I_{RPC} over time provides a value that can be compared to the limit value obtained in the tests [86]. In order to be conservative, it was decided to follow the second approach, so all the integrated charge shown in this thesis have been obtained assuming $I_{dark} \approx I_{cosmic} + I_{noise}$, i.e. assuming that the contribution from the noise and the cosmic rays is more important than the Ohmic one.

In order to estimate the physics currents trend, the timestamps of LHC stable beams were considered instead of the ones of ALICE physics runs. In fact it was not always true that when p-p collisions were ongoing, also a physics run was: due, for example, to issues with the data read-out or other ALICE experiment related problems, it could happen that sometimes ALICE was not taking data with beams collisions ongoing, even if detector HV was on. However, even if a physics run was not ongoing with stable beams, MID could still be at nominal HV: hence, the currents drawn in these cases must be considered in the evaluation of the integrated charge. For this reasons the total physics currents trend was estimated by crossing the timestamps information of the LHC stable beams and the timestamps information, also present on DARMA, of MID in "READY" state, i.e. MID at nominal HV. Then the physics current information was retrieved in this timestamps ranges.

During the 2022 there were in total 145 LHC fills that reached STABLE BEAMS mode. For each LHC fill an I_{RPC} average value was taken, for each one of the 72 RPCs.

Performance analysis

The total current measurements are reported in figure 5.4 as a function of time, starting from the beginning of July until the end of November 2022, i.e. the first Run 3 year of data-taking with p-p. Each point corresponds to an LHC fill.

In one plot the trends of one MID half-plane with 9 RPCs is shown, as done for the dark current trends. Also for the physics currents on the y axis the average current value for each fill is displayed in $\mu\text{A}/\text{cm}^2$, in order to take into account the different RPCs surfaces.

Since I_{RPC} is mainly related to the irradiation of the detectors, it is expected to increase with the intensity of the beam. The peaks of current visible for all the RPCs correspond to fills in which ALICE performed the higher collisions rate runs.

At the end of September, after one month of no beam due to the RF issue at the LHC, a reduction of the current value can be observed for all the RPCs. It is commonly accepted that such a reduction of the current is caused by the fact that, since during these weeks the irradiation caused by the beam operations was absent, the gas flow through the chambers extracts impurities. This recovery effect causes a reduction of the current and can systematically be observed for all the RPCs.

Also for the physics run current, the RPC drawing the highest currents are the ones that underwent some interventions, i.e. MT21 OUT 6, MT22 OUT 6 and MT22 IN 2, already discussed in section 5.1.1.

For each LHC fill the total current drawn by the RPCs has been integrated over the time of the fill (stable beam mode only) in order to obtain the integrated charge. In figure 5.5, the integrated charge per fill is shown. In each plot one half MID plane with 9 RPCs is displayed again and on the y axis the integrated charge is shown in $\mu\text{C}/\text{cm}^2$ in order to compare the results between different RPC sizes.

Then in figure 5.6 the integrated charge growth over time is shown. The time intervals with a constant charge correspond to periods with no collisions at the LHC.

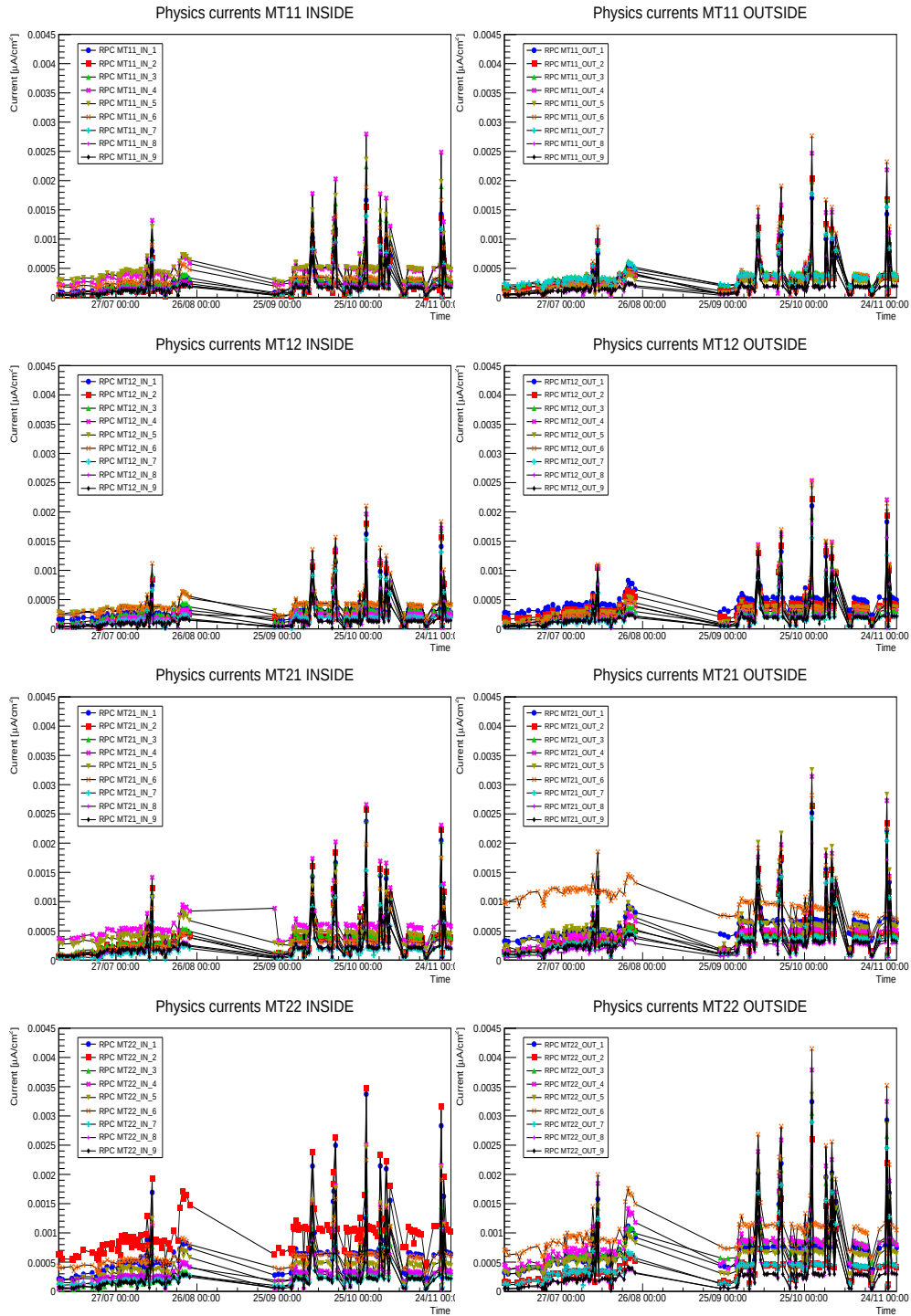


Figure 5.4: Physics currents during 2022 Run 3 data-taking period. In each plot one half-plane with 9 RPCs is shown.

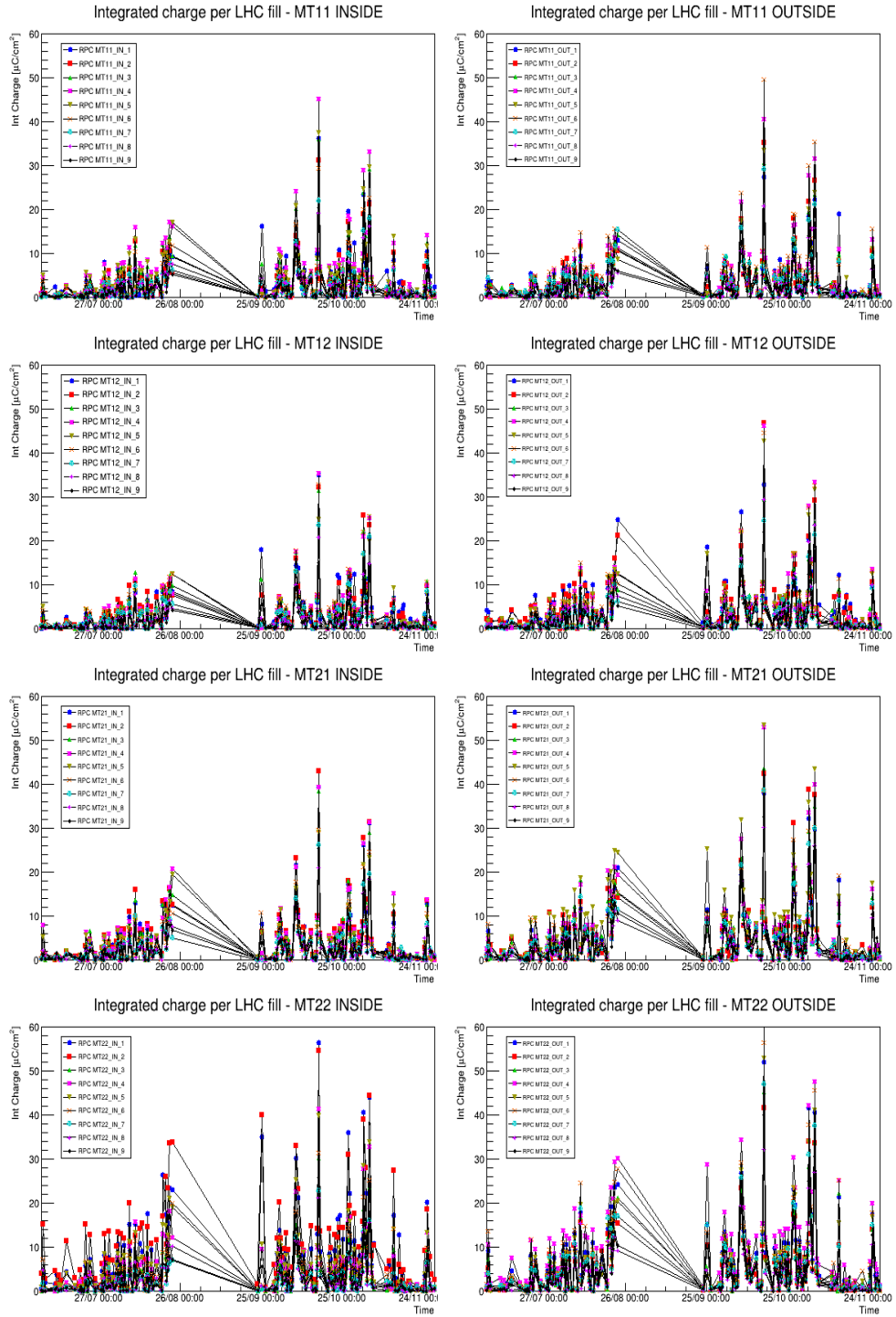


Figure 5.5: Integrated charge per each 2022 Run 3 LHC fill. In each plot one half-plane with 9 RPCs is shown.

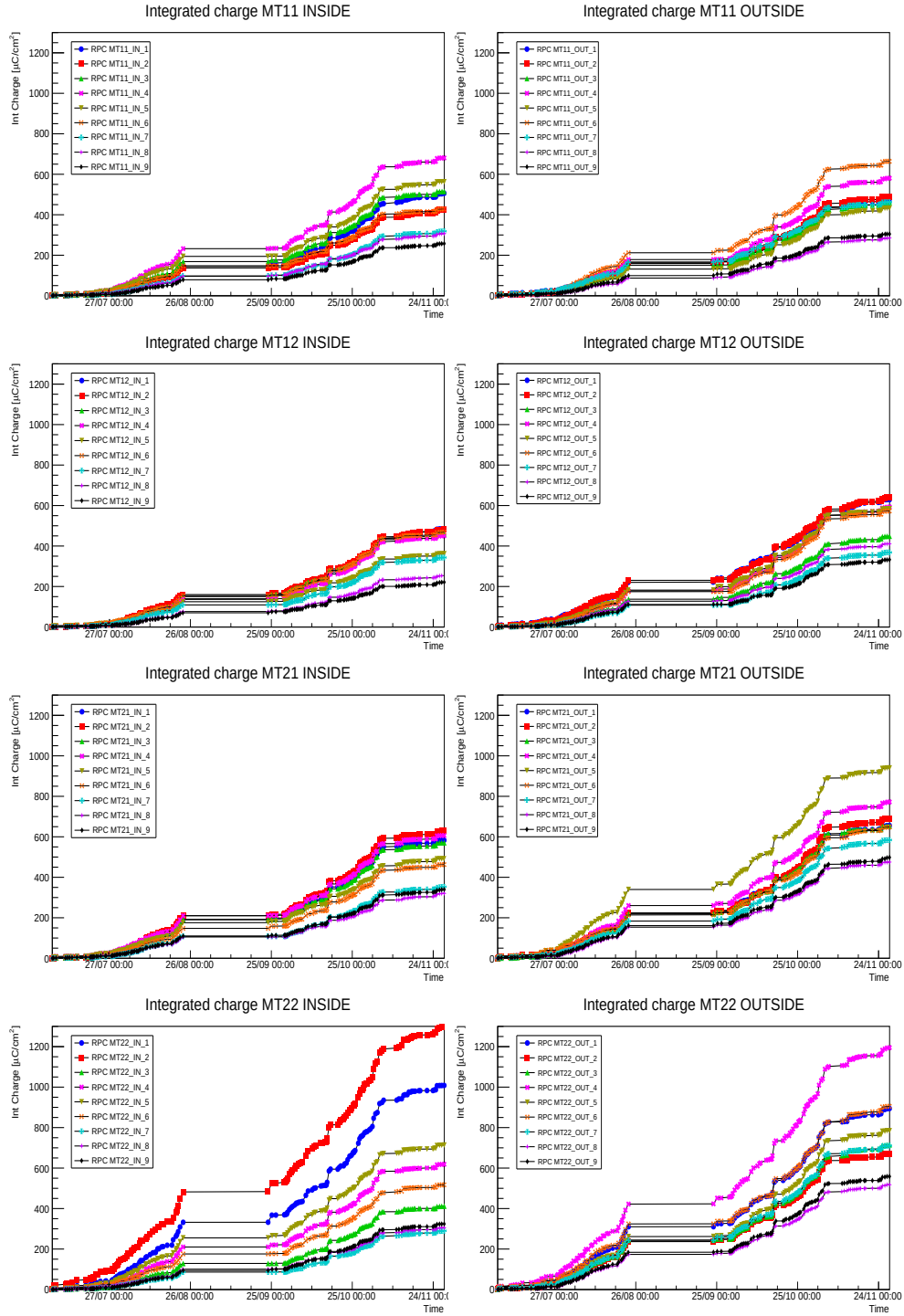


Figure 5.6: Physics cumulative integrated charge growth over time, during 2022 Run 3 data-taking period. In each plot one half-plane with 9 RPCs is shown.

Finally in figure 5.7 a plot summarizing the integrated charge for each one of the 72 RPCs at the end of 2022 is shown. The chamber that integrated the highest charge value is MT22 IN 2, with a value of $\sim 1.2 \text{ mC/cm}^2$.

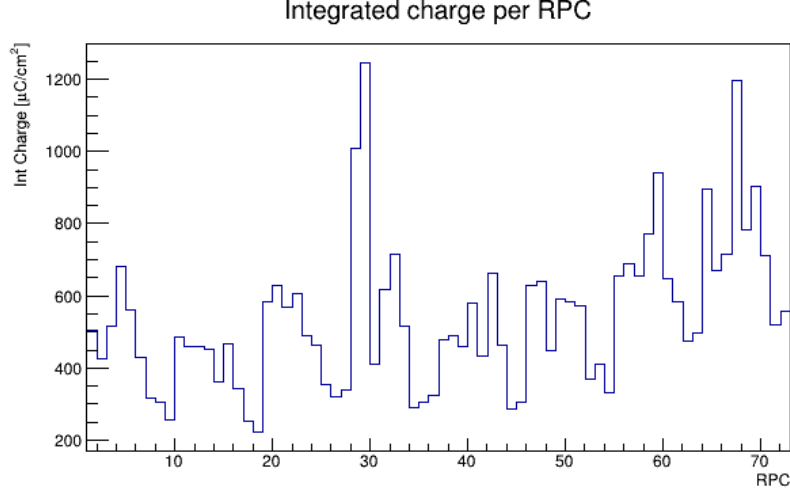


Figure 5.7: Total Integrated charge per each RPCs at the end of 2022.

It is again important to compare these results with those obtained during Run 1 and Run 2. In figure 5.8 the average, minimum and maximum cumulative integrated charge for the four MTR planes in the years 2010-2018 is shown. The min and max are the RPCs that have collected at the end of the entire period the minimum and maximum charge, respectively. They correspond for MT11 to RPC OUT 9 (minimum) and IN 4 (maximum), for MT12 to RPC IN 9 (minimum) and OUT 5 (maximum), for MT21 to RPC IN 9 (minimum) and OUT 5 (maximum), for MT22 to RPC IN 9 (minimum) and IN 2 (maximum). It can be seen that in one year of Run 3 data-taking the RPCs have integrated an average charge much lower than the one integrated during one year of Run 2, despite the higher interaction rate in Run 3. At the end of Run 2 the RPC that integrated the highest charge was the MT22 IN 2, i.e. $\sim 18 \mu\text{C/cm}^2$, the same that integrated the highest charge in the first year of Run 3, leading to a total integrated charge for this RPCs of $\sim 20 \mu\text{C/cm}^2$. Even if this value is still comfortably far from the limit of $50 \mu\text{C/cm}^2$ reached in the aging test, this gas gap was replaced during the winter shutdown due to the high dark current drawn.

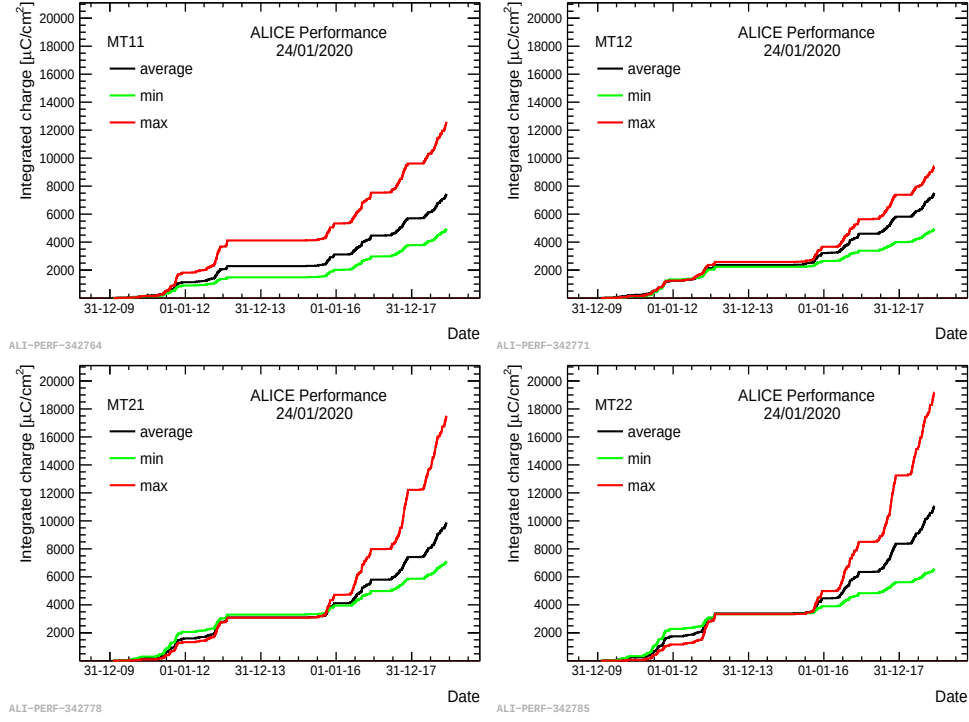


Figure 5.8: Average, minimum and maximum integrated charge for the 4 planes (i.e. MT11, MT12, MT21 and MT22) of the Muon Trigger (MTR) equipped with the old ADULT FEE in the years 2010-2018.

5.2 Cluster Size

The RPCs spatial resolution was already given in equation 3.6, here reported again:

$$\sigma = \frac{w}{\sqrt{12}}$$

where w is the strip width. The cluster size is, as already explained in section 3.3.4, the number of adjacent strips on which a signal above the discrimination threshold is induced. As showed in tabel 3.1, the MID has RPCs with different strip pitches, depending on the proximity to the beam axis.

Cluster size analysis has been performed in the O^2 framework. For each physics run, a ROOT file is produced with several informations (not only for cluster size measurements purposes, as it will be shown in the following sections). It is possible to choose how many timeframes, for each physics run, one wants to analyse, knowing that one TF corresponds to 128 LHC orbit, i.e. ~ 11 ms. For the cluster size analysis, a 3D scatter plot, shown in figure 5.9, is saved. In this plot the dimension of the clusters (in cm) for each detection element *DetID* (i.e. an RPC) is shown, as a function of the 7 different columns in which each MID half-plane is divided. In fact, as already explained in section 3.5 and as showed in the mapping in figure 3.15, different local boards read

different columns, i.e. areas, of the MID planes. From the 3D scatter plot, 72 different 2D maps are extracted, one for each RPC, showing the dimension of the cluster, still in cm, as a function of the column ID. As an example, in figure 5.10, the RPC MT21 OUT 5 (a Short type), bending plane only, is shown. The fact that, for each RPC, a different strip pitch corresponds to a different column is used to extract the cluster size information for the different strip pitches, starting from the hits maps in cm and by using the mapping in figure 3.15. So, when the hit patterns are known, the dimensions of the clusters are used to obtain the cluster size distribution per RPC and strip pitches. For each physics run and for each strip pitch, histograms with the cluster size distribution are filled. The average cluster size is then defined as the mean value of these histograms, and the associated uncertainty is calculated assuming a Poissonian distribution of the clusters.

In this way it has been possible to measure the cluster size for all the different strip pitches distinguishing also between the slightly different pitches of the two MID stations. Moreover different scans have been performed, measuring the variation of the cluster size as a function of different collisions rates and as a function of the RPCs HVs values. Both the results will be shown in the following subsections 5.2.1 and 5.2.2, respectively for the high rate scan and the HV scan.

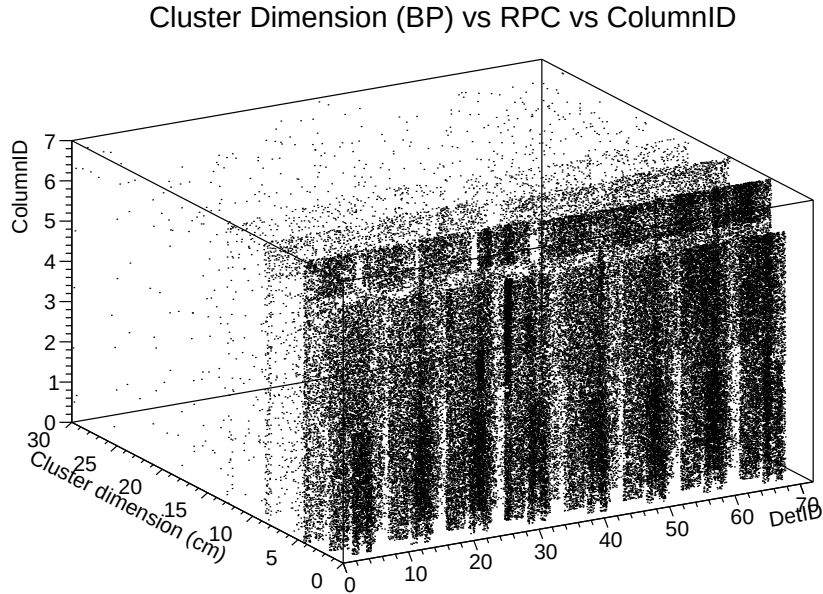


Figure 5.9: 3D scatter plot for a physics run at 500 kHz collision rate, showing the cluster dimension (in cm) of the hits as a function of the detection element ID *DetID*, i.e. the RPC, and the columnID. Each column correspond to a different area of the MID planes, as shown in the mapping 3.15.

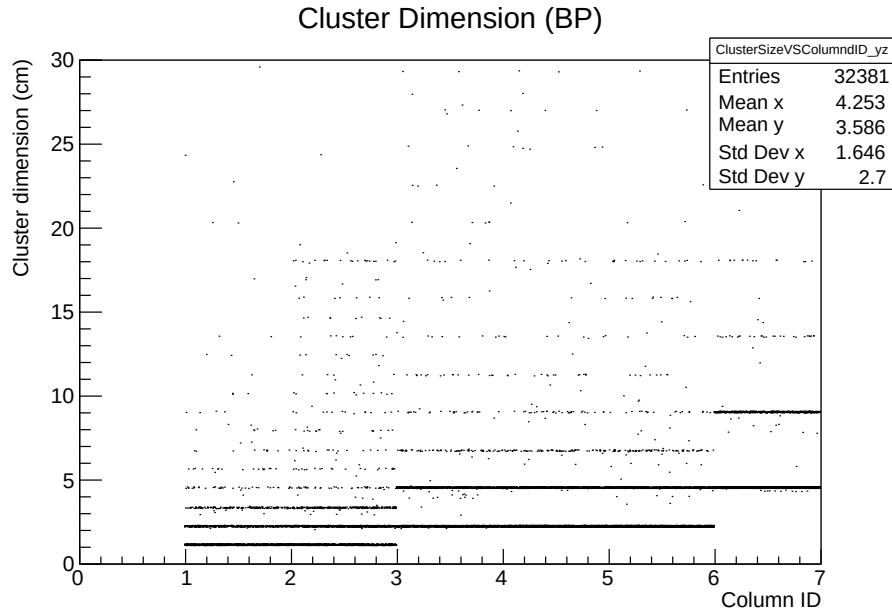


Figure 5.10: 2D map for the RPC MT21 OUT 5, bending plane, extracted from the plot in figure 5.9, showing the cluster dimension of the hits in cm, for the 7 different columns. Each column in the Bending Plane corresponds to a different strip pitch (see figure 3.15). Since this RPC is a short type, the first column (starting from 0) is of course empty.

5.2.1 Performance during the high interaction rate scan

As mentioned before, from time to time the ALICE experiment has performed high interaction collision rate scans for commissioning purposes. These scans have been used, among other things, to study some of the performances of the MID. In particular, for the cluster size measurement, four different collision rate values have been considered: 50 kHz, 100 kHz, 500 kHz and 1 MHz.

In figures 5.11, 5.12 and 5.13 the curves of the cluster size as a function of the collision rate, for the three different strip pitches (i.e. 4 cm, 2 cm and 1 cm respectively) are considered, and for each figure four different curves for the different MID planes are plotted (bending plane only). For each one of the four collision rates values an average cluster size value per MID plane has been evaluated.

It can be noticed that the average cluster size increases with increasing collision rates. Furthermore the dependence on the strip width discussed in section 3.3.4 is clearly visible. The cluster size is obviously much lower for strips 4 cm wide as compared to 2 cm and 1 cm wide, and for 4 cm and 2 cm wide as compared to 1 cm wide: it is equal to ~ 1.4 for 4 cm pitch, to ~ 1.6 for 2 cm pitch, and to ~ 1.8 for 1 cm pitch. Moreover the cluster size, as expected,

is independent from the plane and, therefore, from the distance from the interaction point.

Before the installation of the FEERIC boards in the ALICE experiment, several measurements have been done in laboratory in order to have an estimation of the foreseen performances of the FEE in cavern. In particular the cluster size was measured for different discrimination thresholds values.

At this point a premise is necessary: during the first year of Run 3 it was not possible to performe a thresholds scan, since the temporary system that was supposed to deliver the thresholds (before the installation of the definitive wireless system) to each single FEERIC board was unstable. So it was decided to run with a not finely tuned fixed threshold of 100 mV for all the cards. During the winter shutdown, in February 2023, the new wireless system (see section 3.4.2) to tune the threshold on each FEERIC board will be installed, and when p-p collisions will be back, thresholds scans will be performed in order to tune also this important parameter.

However, from FEERIC PRR [94], with a thresholds of 105 mV (i.e. close to the 100 mV one in the ALICE cavern), and at 9500 V (which is also the mean working point value of the RPCs installed in cavern, ranging from 9250 V to 9750 V depending on the RPC) a cluster size of 1.6 for 2 cm strip pitch was measured, which is exactly the value obtained in p-p collisions.

On the other hand, during Run 1 and Run 2, in maxi-avalanche mode with ADULT cards with a threshold of 7 mV, at the working point (which was ranging between ~ 10 kV and ~ 10.5 kV depending on the RPC) the cluster size was lower, except for 1 cm pitch: ~ 1.1 for strips of 4 cm width, ~ 1.4 for strips of 2 cm width, and ~ 1.9 for strips of 1 cm width [103]. This is a well known advantage of the maxi-avalanche as compared to the avalanche mode with amplification. Regarding 1 cm strip pitch, as it will be shown in the HV scan in section 5.2.2, the uncertainty is higher with respect to the other strip pitches, and its value with FEERIC is varying a lot with the HV, ranging from 1.8 and 2: probably in the high rate scan the cluster size value for 1 cm strip pitch was low since at that time the correct RPC working point was not well tuned yet.

5.2.2 Performance during the HV scan

The cluster size was studied also by varying the HV of the RPCs. In September, when p-p collisions were back after the one month LHC shutdown because of the RF issue, an HV scan was perfomed with the MID running alone without the other detectors, with the aim of studying the HV-efficiency

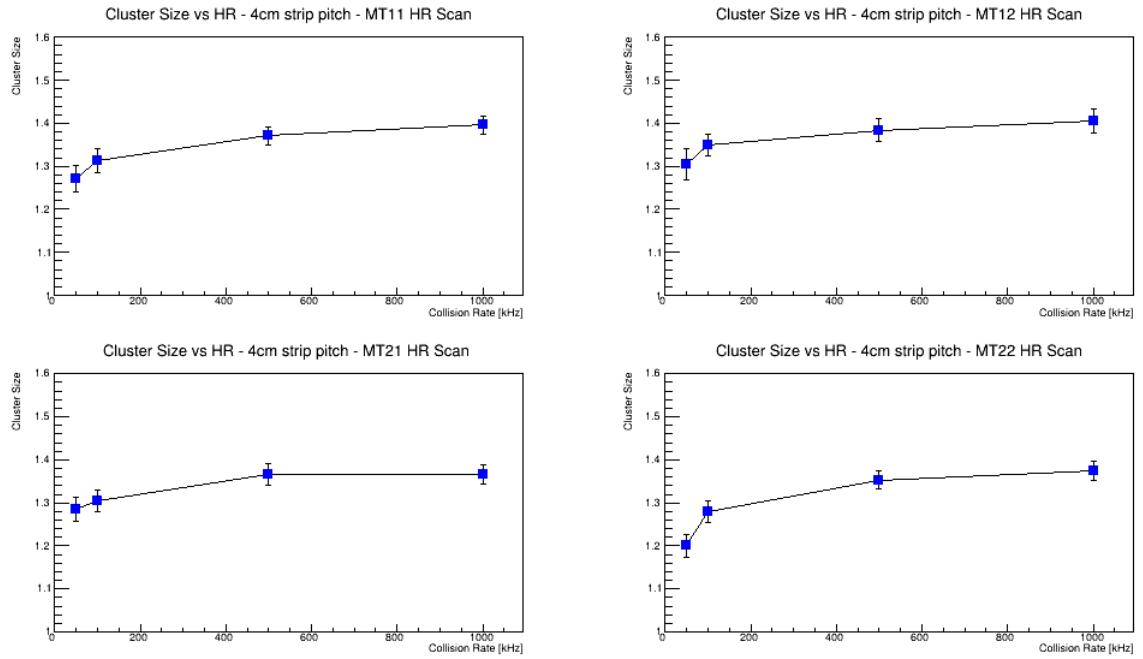


Figure 5.11: Cluster size during high rate scan. Each plot represents the mean cluster size for one MID plane, for 4 cm strip pitch.

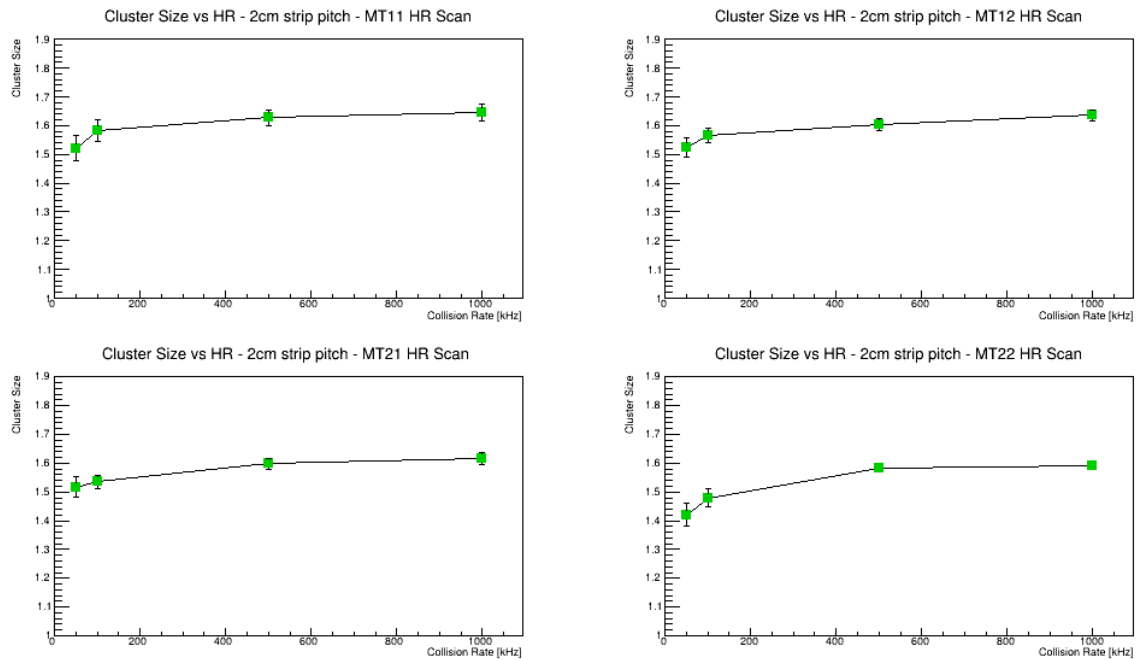


Figure 5.12: Cluster size during high rate scan. Each plot represents the mean cluster size for one MID plane, for 2 cm strip pitch.

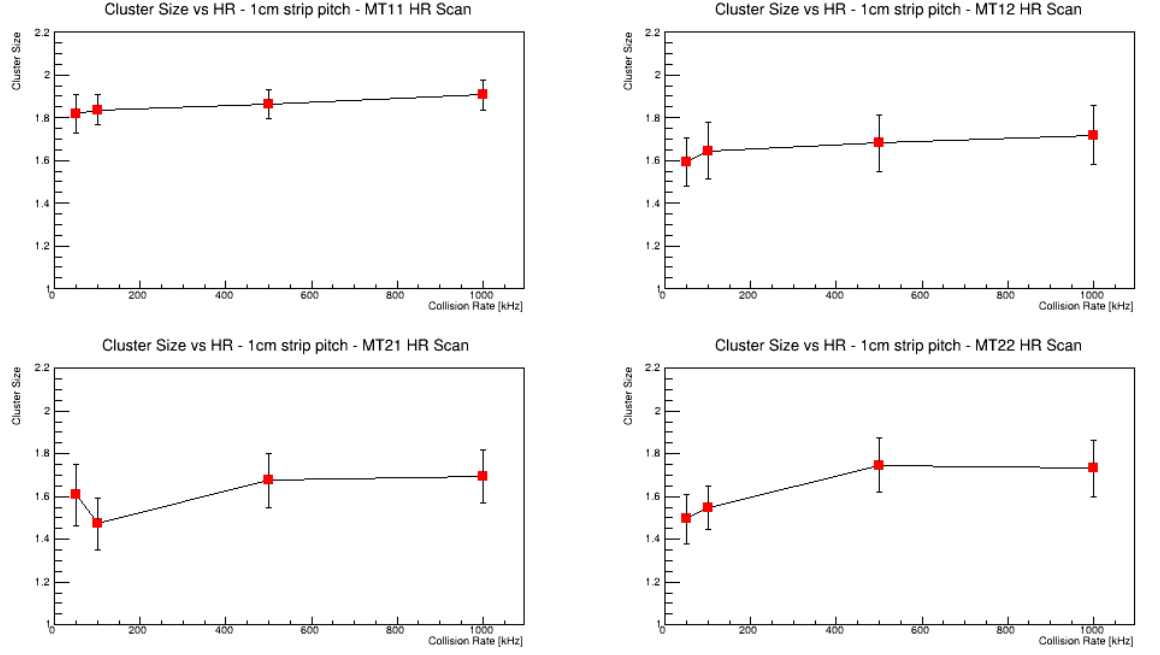


Figure 5.13: Cluster size during high rate scan. Each plot represents the mean cluster size for one MID plane, for 1 cm strip pitch.

curves for each RPC to find the new HV working point in the new operation mode. During the scan, together with the efficiency (whose results will be shown in section 5.4) other parameters such as the cluster size were studied. The scan has been performed by varying the HV in one plane at the time and by keeping the other three at a fixed HV value. If the same local board saw an event coming from the RPCs of the three planes at fixed HV, then the event was considered for the measurement. The measurements were done at step of 100 V per HV point, starting from -1400 V up to -500 V with respect to the Run 2 working point, recalling that the RPC working point in Run 2 were ranging between 10 kV and 10.5 kV depending on the RPC.

In figures 5.14, 5.15 and 5.16 the cluster size-HV curves are shown, respectively, for 4 cm, 2 cm and 1 cm pitches, and in each figure 4 curves are shown, one per MID plane (bending plane only). It can be seen how the cluster size increases at increasing HV values, as expected. Around the presumed working point, the average cluster size is again ~ 1.4 for 4 cm strip pitch and ~ 1.6 for 2 cm strip pitch, as in the high collision rate scan. Moreover the cluster size value is again the same, at fixed strip pitch, for all the MID planes, confirming the not dependance of the cluster size from the distance to the interaction point. Regarding 1 cm strip pitch the average cluster size value is again subjected to greater variation with respect to 4 cm and 2 cm, ranging from 1.8 to 2. Further measurements and studies are then necessary. As it will be explained

better in section 5.4, one important improvement needed on this measurement is to repeat the HV scan not only with the MID, but with the MCH and MID detectors together in order to match the MCH tracks with MID tracklets, to be sure to select only muons coming from p–p collisions while excluding other sources, such as for example beam interactions gas, or electronic noise.

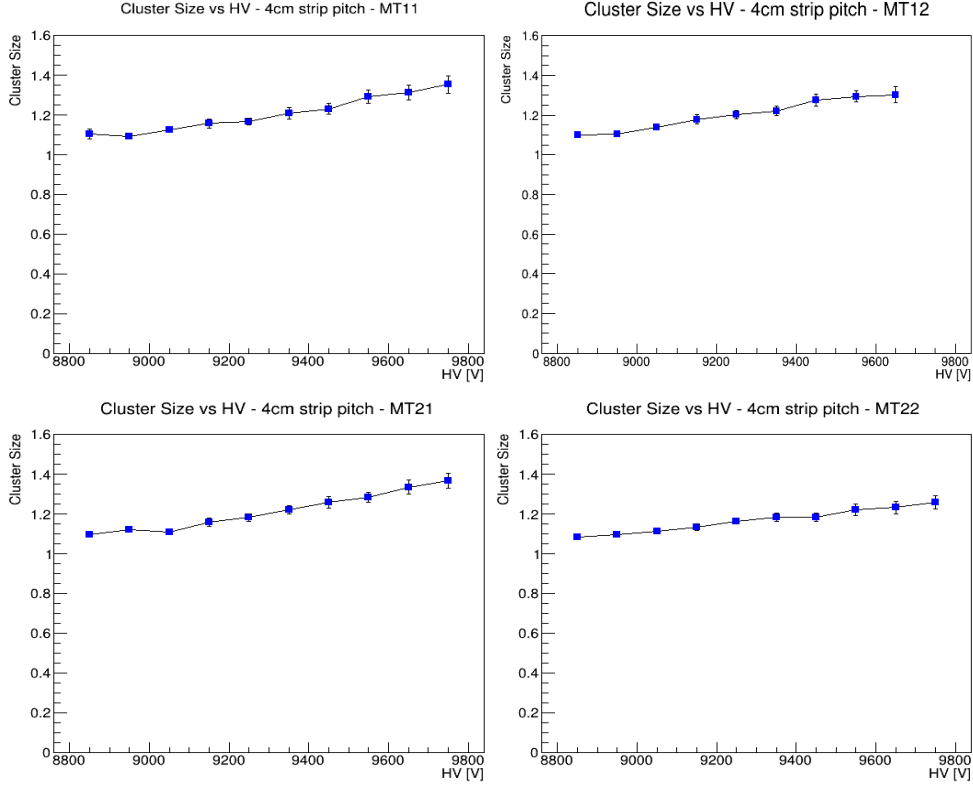


Figure 5.14: Cluster size during HV scan. Each plot represents the mean cluster size for one MID plane, for 4 cm strip pitch.

5.2.3 Performance during data taking

Finally, the average cluster size has been plotted as a function of the time, when physics runs with stable beams were ongoing, in order to have an idea of the temporal stability of the MID.

In figures 5.17, 5.18 and 5.19 the cluster size as a function of time is shown, respectively, for 4 cm, 2 cm and 1 cm strips pitches, and in each figure 4 curves are shown, one per MID plane (bending plane only). The plotted cluster size values refer to p–p collision at 500 kHz collisions rate, with fixed HV values equal to -700 V for all the RPCs with respect to Run 2 working point. It is important to note that no substantial changes on the settings of the detector were made during the data taking phase shown in these plots, i.e. from the end of September 2022 (after the LHC RF issue recovery) up to the end of

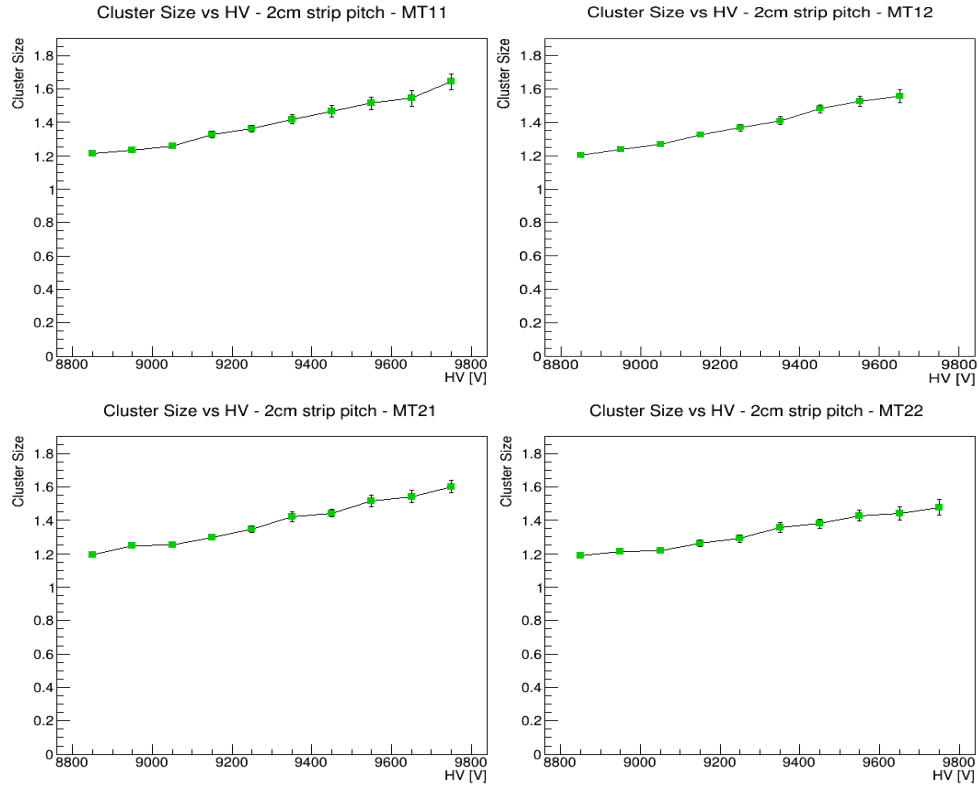


Figure 5.15: Cluster size during HV scan. Each plot represents the mean cluster size for one MID plane, for 2 cm strip pitch.

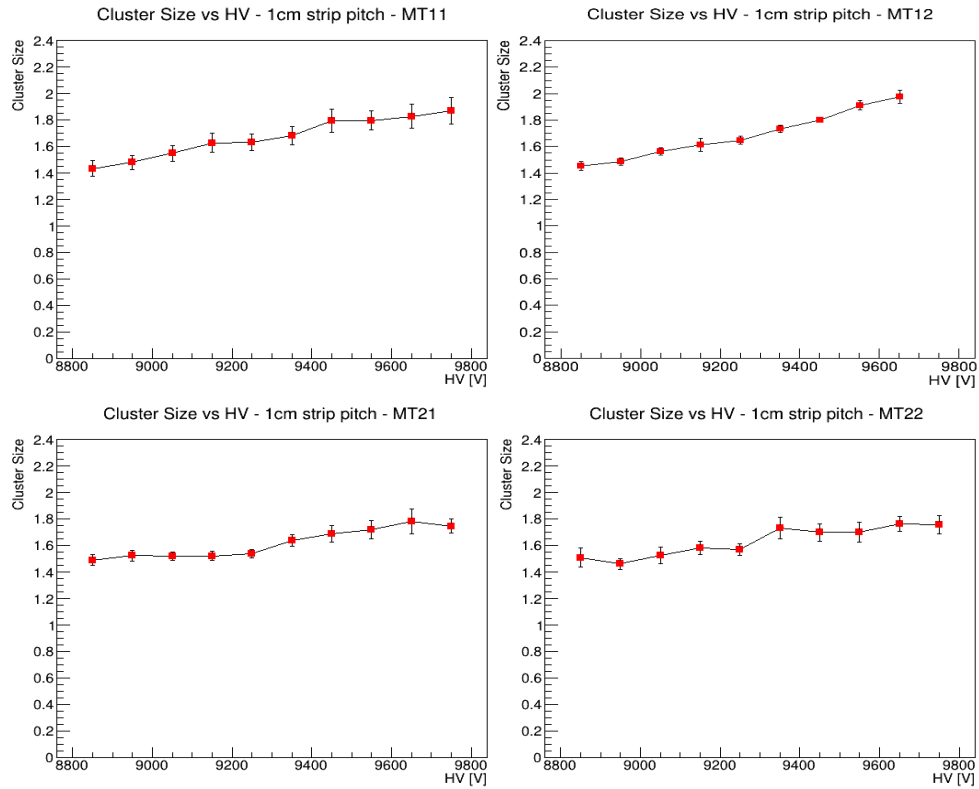


Figure 5.16: Cluster size during HV scan. Each plot represents the mean cluster size for one MID plane, for 1 cm strip pitch.

November 2022 (when LHC winter shutdown started). The short periods with no points were due to different reasons: LHC machine development periods or other LHC related issues (leading to no physics runs ongoing), the Pb–Pb week in November, or ALICE running with different collision rates values. It can be noticed that the average cluster size values are quite stable over time, especially for 4 cm and 2 cm strip pitches. The 1 cm value is as usual affected by a slightly higher instability, however no upward trend is present.

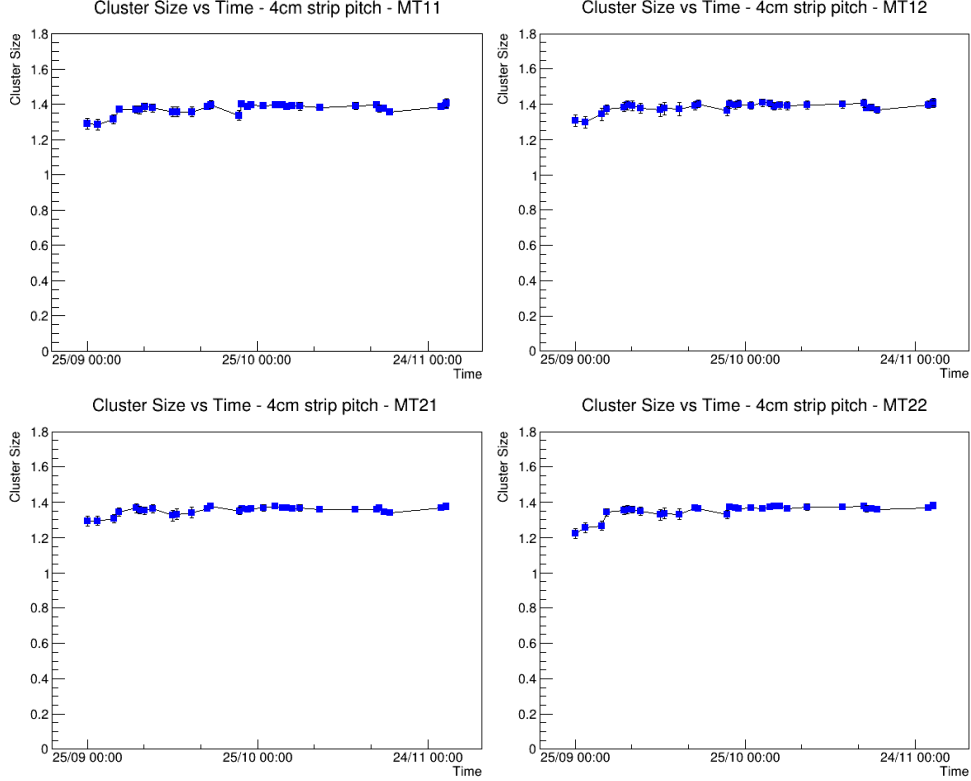


Figure 5.17: Cluster Size monitored over time during Run 3 data-taking, for 4 cm strip pitch.

5.3 Cluster rate and charge per hit

The measurements of the cluster rate and the charge released per single hit in the gas gap, like the cluster size one, have been performed in the O^2 framework, producing an output ROOT file with several informations, for each physics run. Also in this case, in each run it is possible to choose how many TFs are included in the analysis.

In order to retrieve the cluster rate information, for each physics run a histogram is produced with the number of all hits in each RPCs, in both bending and non bending plane. Then, knowing the number of TFs analysed

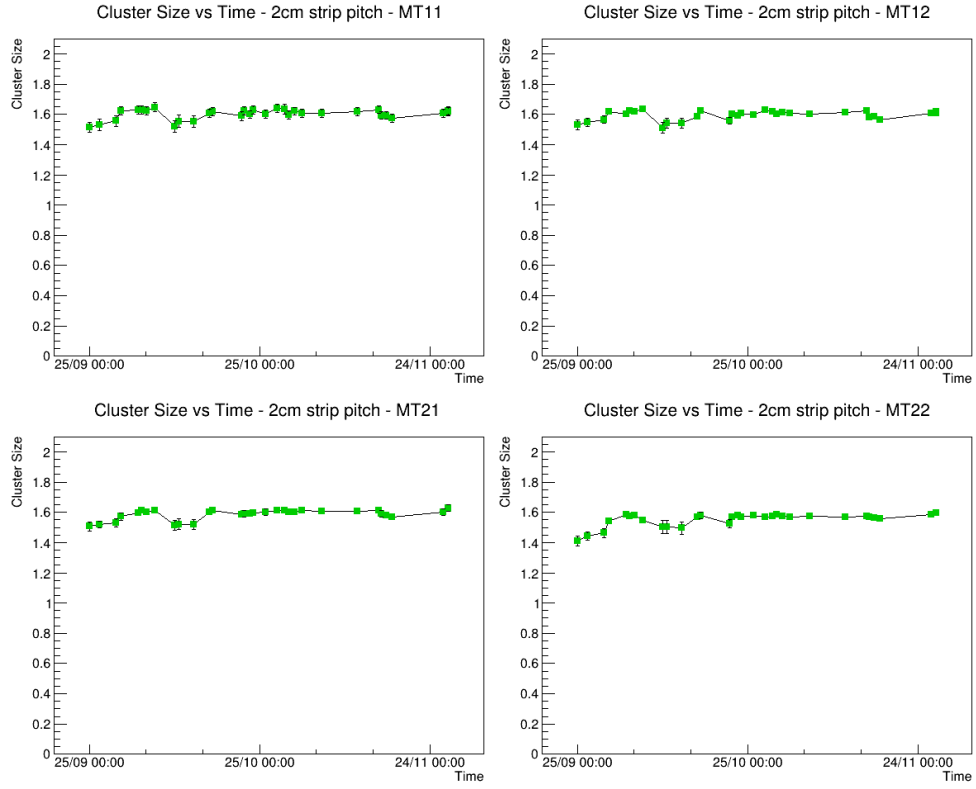


Figure 5.18: Cluster Size monitored over time during Run 3 data-taking, for 2 cm strip pitch.

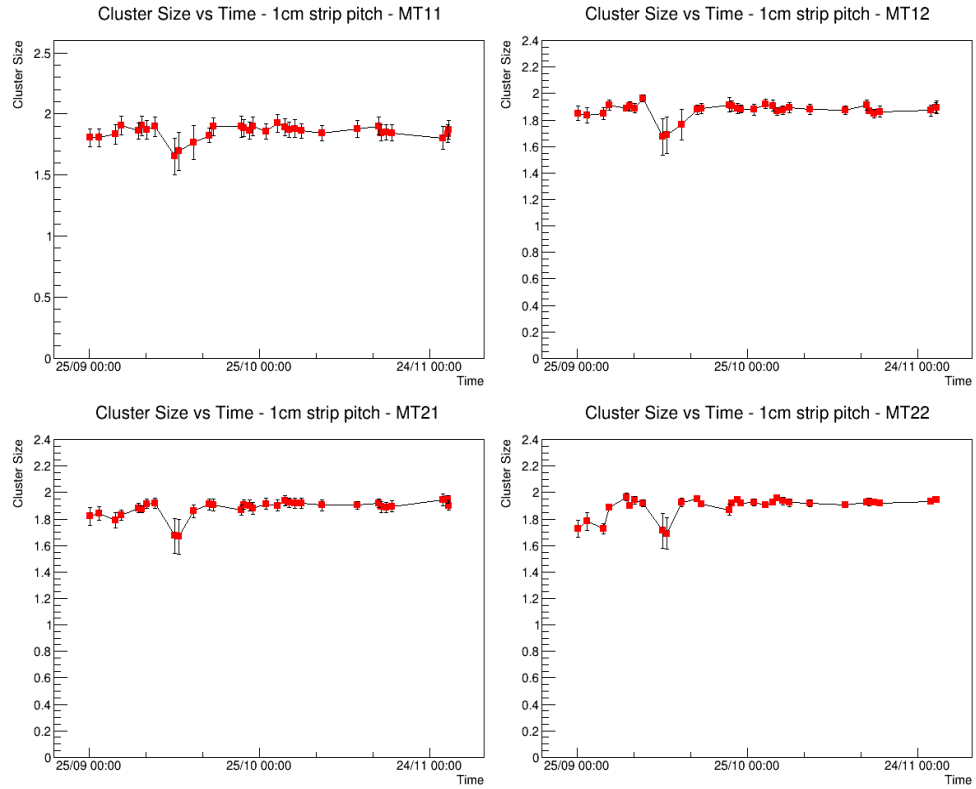


Figure 5.19: Cluster Size monitored over time during Run 3 data-taking, for 1 cm strip pitch.

(and that one TF is ~ 11 ms) and considering the different areas of the RPCs depending if they are Long, Cut or Short type, it is possible to evaluate the cluster rate in Hz/cm^2 as:

$$C.R. = \frac{\#hits}{t_{run}A_{RPC}} \quad (5.1)$$

where t_{run} is the duration of the analysed physics run and A_{RPC} is the RPC area.

In figure 5.20 the cluster rate for the 72 RPCs, for a p-p physics run at 500 kHz collisions rate, is shown. RPC are enumerated from 1 to 72, considering that the first 36 are the INSIDE RPCs, and from 37 to 72 there are the OUTSIDE RPCs. The first 9 are the INSIDE RPC of plane MT11, where the numbers 4,5 and 6 are the ones closest to the beam pipe, then there are the 9 RPCs of the plane INSIDE MT12 and so on. From the plot it is possible to notice the higher cluster rate for the RPCs nearest to the beam pipe, with respect to the ones furthest from it.

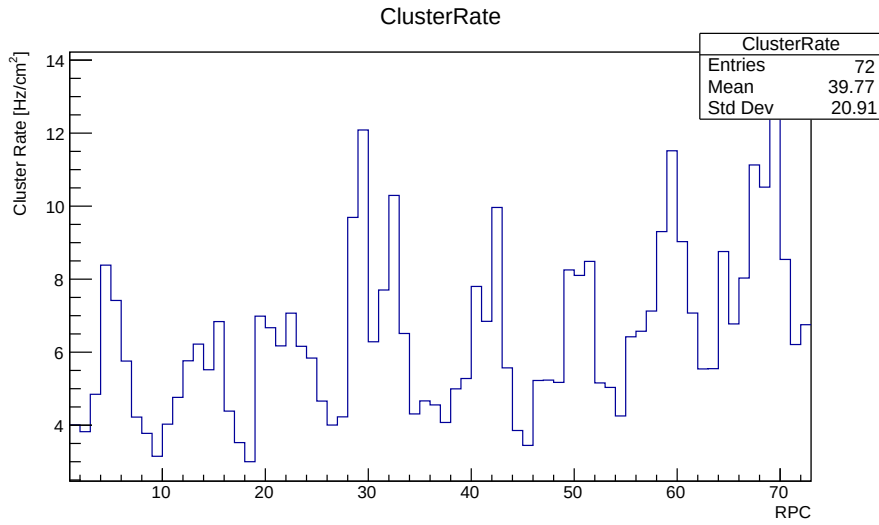


Figure 5.20: Cluster rate in Hz/cm^2 for each one of the MID 72 RPCs, for a p-p physics run, at 500 kHz collision rate, both bending and non bending planes. It can be noticed the higher cluster rate on the RPC nearest to the beam pipe.

5.3.1 Correlation between cluster rate and physics current

It is important to study correlations of different parameters, since they are valuable tools to provide a deeper understanding of the RPC. In particular the correlation plot which allows to better understand the "health" of a chamber is the one representing the physics current values correlated with the cluster

rates. The estimated physics current of an RPC is expected to be proportional to the cluster rate of the RPC itself. This proportionality is related to the charge released per each hit in the chamber. The corresponding correlation can then easily highlight the presence of RPCs with abnormal discharge per hit.

This correlation has been studied in two different cases: during the high collisions rate scan, and during Run 3 data-taking with different LHC filling schemes (and consequently different rates on the chambers). Both these cases are reported in the two following subsections.

High rate scan

The correlation of the physics current as a function of the cluster rate during the same high collisions rate scan used for the cluster size measurement, i.e. at 50 kHz, 100 kHz, 500 kHz and 1 MHz, is shown in figure 5.21. The average physics current per cm^2 is plotted as a function of the average cluster rate per cm^2 , during the 4 runs at different collisions rate per each one of the 72 RPCs. In each plot, one half-plane with 9 RPCs is shown.

One can observe that there is a strong correlation between the physics current and the estimated rate. The correlation however is not perfect for all the RPCs and, for a given rate, a dispersion of the physics currents can be sometimes observed. Such a deviation can be due to different factors, such as different muon crossing angles, resulting in different path length in the gas gap, or also to an intrinsically different response between different chambers.

The charge released per single hit in the gas gap has been evaluated by performing a linear fit of these plots for each RPC. The results from the fit, with their correlated errors, are plotted in figure 5.22 in which the charge per hit for each RPC is shown. The average charge per hit is between $\sim 45 \mu\text{C}/\text{cm}^2$ and $\sim 60 \mu\text{C}/\text{cm}^2$ depending on the RPCs, with much larger uncertainty for those RPCs in which the current was more unstable.

The study of the correlation between the physics current and the cluster rate has been repeated using several runs at different rates, by considering different LHC filling schemes, as shown in the next subsection, with the aim of measuring the charge released per hit in the gas gap with less uncertainty.

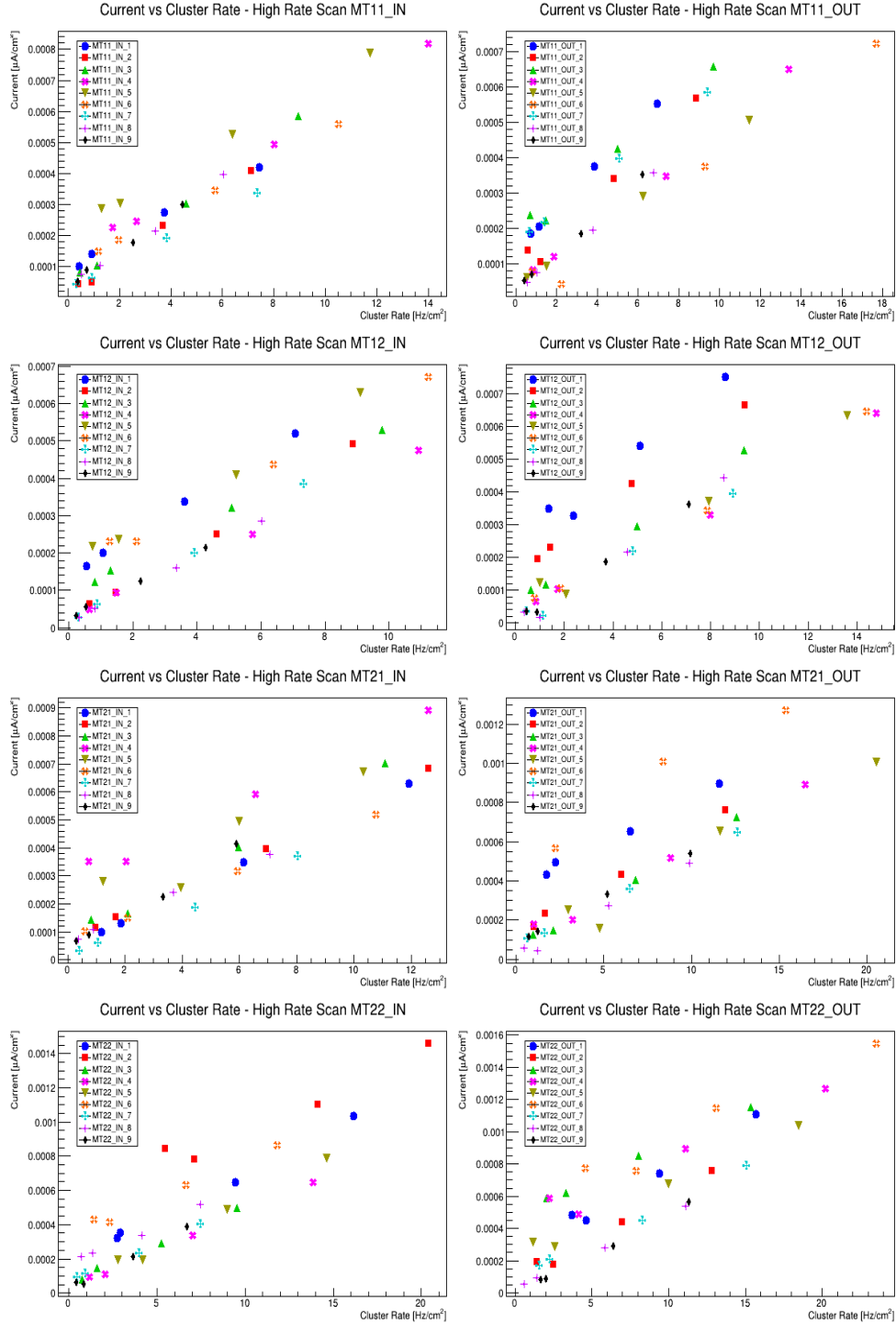


Figure 5.21: Correlation plot between average physics currents and average cluster rate during high rate scan runs. Each plot represents one half-plane with 9 RPCs, and each point corresponds to a run at different collisions rate scan: 50 kHz, 100 kHz, 500 kHz and 1 MHz.

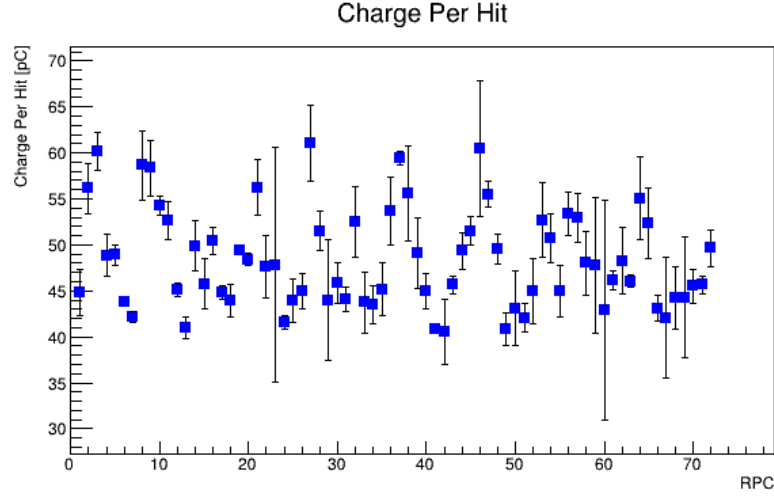


Figure 5.22: Average charge per hit determined during the high rate scan.

Run 3 data-taking

In figures 5.23 the correlation plots between average physics currents and average cluster rate during several run 3 physics runs, taken between September and November 2022, with different LHC filling schemes, are shown. Each plot represents one half-plane with 9 RPCs, and each point corresponds to a run. By doing the linear fit for each RPC, the charge released per hit has been measured, and the result is shown in the right panel of figure 5.24. The average charge per hit is in this case between $\sim 35 \mu\text{C}/\text{cm}^2$ and $\sim 50 \mu\text{C}/\text{cm}^2$ depending on the RPCs, with smaller error bars with respect to the high collision rate scan measurement case. The RPC MT21 OUT 6 shows instead a much lower average charge per hit of $\sim 25\text{-}30 \mu\text{C}/\text{cm}^2$. This is due to the fact that the current of this chamber was particularly unstable during the operation period. The RPC will be replaced during the winter shutdown, in March 2023.

The charge per hit values obtained must be compared to those expected from FEERIC performances studies. It is expected, from FEERIC PRR [94], that the charge released per hit should be 4 times lower for FEERIC equipped RPCs with respect to ADULT equipped ones. During Run 1 and Run 2, the charge released in the gas gap with ADULT FEE was about 150 - 200 pC, then with FEERIC we should expect a charge between $\sim 35 - 50 \mu\text{C}/\text{cm}^2$, which are exactly the values obtained in figure 5.24, with few exceptions for some RPCs. These cases are due to unstable currents, and these chambers are kept under constant monitoring in order to detect any aging effect.

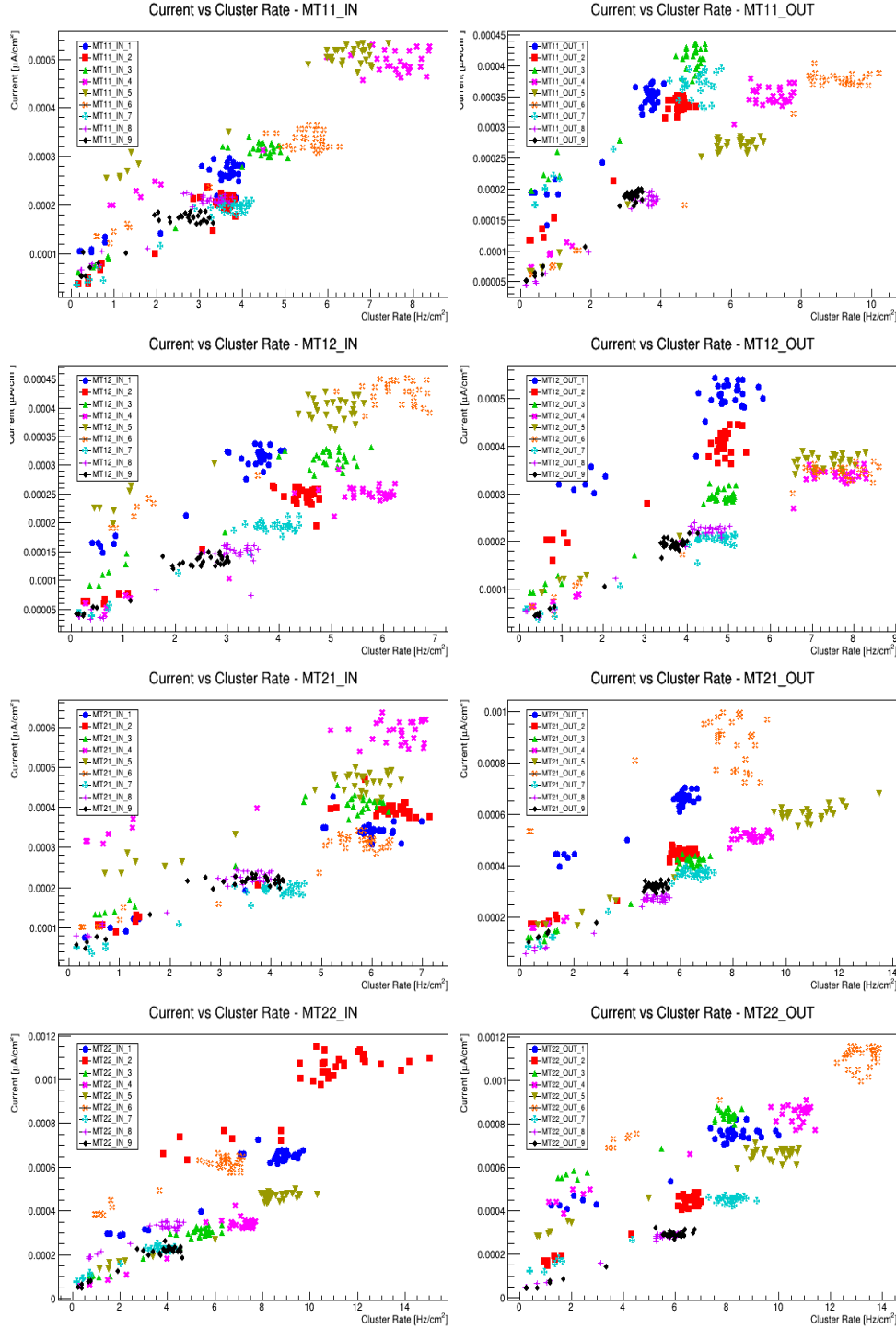


Figure 5.23: Correlation plot between average physics currents and average cluster rate during Run 3 data-taking runs with different LHC filling schemes. Each plot represents one half-plane with 9 RPCs, and each point corresponds to a run at different filling scheme.

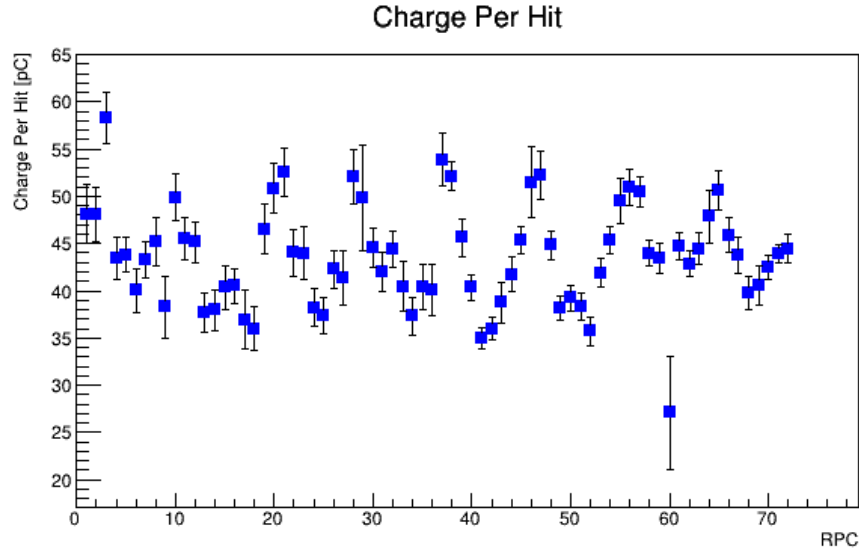


Figure 5.24: Average charge per hit for both Bending Plane and non bending plane, for each RPCs, determined using several Run 3 runs.

5.4 Efficiency

Measuring and monitoring over time the detector efficiency is fundamental for two main reasons. First the determination of physical quantities (such as the inclusive or differential cross sections), requires acceptance and efficiency corrections to the measured data, which have to be properly determined. Even if the efficiency of each RPC is already measured during the commissioning phase in the Torino laboratory, before the final installation *in situ*, and proven to be higher than 95%, for detectors designed to work for some years, the possibility that the initial efficiency can undergo some variations or degradation with time has to be taken into account. Second, another interesting correlation beyond those already presented is between aging effects and efficiency drop of the detectors. It is important to monitor the RPCs efficiency during the experiment lifetime to look for any efficiency modification which could be qualitatively correlated with some of the aging indicators already presented. Moreover, due to the large area covered by the MID, the possible variation in efficiency might be not homogeneous, so the efficiency maps should be measured with the highest granularity achievable.

As mentioned before, the signal of the RPCs is collected by orthogonal strips positioned on both sides, read out by the FEERIC FEE. The MID reconstruction algorithm searches, separately in the bending and the non bending plane, for fired strips which lie within a defined, and adjustable, width (or area): a track is flagged "good" for efficiency studies if it fires the strips in at least three out of four MID planes, in both the bending and non bending plane. The

algorithm for the efficiency measurement analyzes the reconstructed tracks searching for the presence of the associated fired strips in all planes. To be more precise, the search for a fired strip is done in the region of ± 1 strip around the intersected one of the reconstructed track. If the strip pitch is smaller than 2 cm, as it is the case for the strips in the bending plane closest to the beam pipe, the region is set to ± 2 cm.

For each analysed physics run, in the O^2 framework, from the reconstructed and the efficiency workflows an output ROOT file is produced with several histograms containing:

- N_{tot} , i.e. the number of reconstructed tracks that actually crossed the MID;
- N_{BP} , i.e. the number of tracks detected by the bending plane, for each one of the four planes;
- N_{NBP} , i.e. the number of tracks detected by the non bending plane, for each one of the four planes;
- N_{both} , i.e. the number of tracks detected by both the bending and the non bending plane, for each one of the four planes.

Recalling the equation 4.3 for the efficiency measurement using cosmic rays, here reported again:

$$\epsilon = \frac{N_D}{N_E}$$

where N_D is the number of cosmic rays detected by the detector and N_E is the number of cosmic rays that actually crossed the detector, then N_{tot} is N_E , while N_{BP} , N_{NBP} and N_{both} are N_D when one wants to measure, respectively, the efficiency of a given bending plane, non bending plane, or both bending and non bending.

Without any further constraint, it is possible to evaluate the average efficiency of each MID plane for a given physics run, separately for the bending and non bending plane, or even for the AND of the two planes. The projective geometry of the MID allows also to determine the efficiency for each RPC. It is sufficient to apply the above explained method to a sub-sample of tracks that cross the RPCs placed at the same position in each plane (e.g. a track crossing the RPCs MT11 IN 1, MT12 IN 1, MT21 IN 1 and MT22 IN 1 is flagged "good" for single RPC efficiency measurement). Even for the single RPC it is possible to evaluate separately the efficiency for the bending and non bending plane, or for the AND of the two planes. Then the efficiency determination can be

repeated for the smallest part of the detector entering the reconstruction and efficiency algorithms, i.e. the Local Boards. The method adopted is the same used to determine the efficiency for each plane or RPC: since local boards are disposed in a projective geometry it is possible to calculate the efficiency for the sub-sample of tracks crossing the boards placed at the same position in all planes, following the usual mapping in figure 3.15, remembering that the same LB gives the information of the same corresponding area on the four planes. In this way it is possible to measure the efficiency up to 936 (234 per plane) zones for both bending, non bending planes and the AND of the planes.

The output ROOT file mentioned before will then contain not only the 4 histograms with N_{tot} , N_{BP} , N_{NBP} and N_{both} , i.e. the histograms with the informations to evaluate the efficiency of the 4 planes, but also the corresponding histograms with the number of reconstructed tracks per each RPCs and per each LBs.

The error on the reconstructed efficiency is statistical and is derived from the number of successes, which follows a binomial distribution. For example for the bending plane is:

$$\sigma_\epsilon = \frac{\sigma_{N_{BP}}}{N_{tot}} = \sqrt{\frac{\epsilon(1-\epsilon)}{N_{tot}}} \quad (5.2)$$

In order to get a 1% statistical error σ_ϵ on each local board, assuming a nominal efficiency ϵ of 95% and assuming also a uniform hit distribution on the 4 planes, from the previous formula around 500 tracks are needed per each local board. This means a total number of MID tracks (N_{tot}) of about $500 \times 234 = 1.17 \times 10^5$. Such statistics can be collected in few minutes of p-p data taking, depending on the collision rate and the LHC filling scheme. It is worth noting that this value is a mere guideline, since the local boards occupancy changes with the distance from the beam pipe and the hit distribution is not uniform. So even if the given numbers are reasonable for almost all RPCs, a slightly higher number of tracks is needed to determine the efficiency with a 1% statistical error for the local boards furthest from the beam pipe.

This simple method can be applied to all available data, with no need of dedicated runs. In this way the MID efficiency can be constantly monitored during time, with high statistics. To summarize, for each physics run, the efficiency has been measured for each one of the 4 planes, for each one of the 72 RPCs and for each one of the 234 Local Boards. In all cases the efficiency has been evaluated in the BP, the NBP and the AND of the two planes. As an example, in figures 5.25, 5.26 and 5.27 the results of the efficiency measured

during a p-p run at 500 kHz are shown. Because of the large statistics, the efficiency error bars for most of the points in the plots are too small to be visible. It has to be pointed out that these values can be affected by an high number of countings due to different noise sources, which are under studying. During the first year of Run 3 the efficiency was measured not only during time in order to monitor its stability, but also during a dedicated HV scan in order to find the HV working point of each RPC in the new working mode. The results of the HV scan and the efficiency trend over time are presented in subsection 5.4.1 and 5.4.2 respectively.

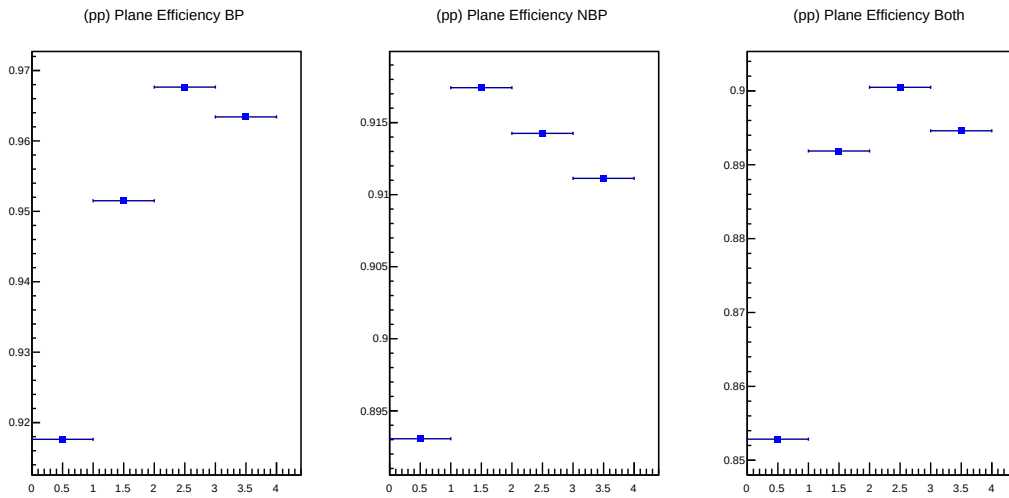


Figure 5.25: Average efficiency for the 4 planes for, respectively, bending, non bending and the AND of the two planes, for one p-p physics run at 500 kHz. The points in each plot correspond, in order, to the plane MT11, MT12, MT21 and MT22.

5.4.1 Efficiency-HV curves

Even if the HV scan was used also for cluster size measurement, as shown in section 5.2.2, its main purpose was to measure efficiency-HV curves in order to find the new HV working points for each RPCs in the new avalanche working mode, with the new electronics.

The HV scan was performed by 100 V steps, starting from a voltage value corresponding to -500 V with respect to the RPC HV working point of Run 1 and Run 2, down to -1400 V. As previously mentioned, all the runs were performed with the MID alone, without the others detectors. The RPCs HV values were changed in only one plane at the time, while the others (which provide the trigger) were kept at a constant HV values of -700 V, and the scan

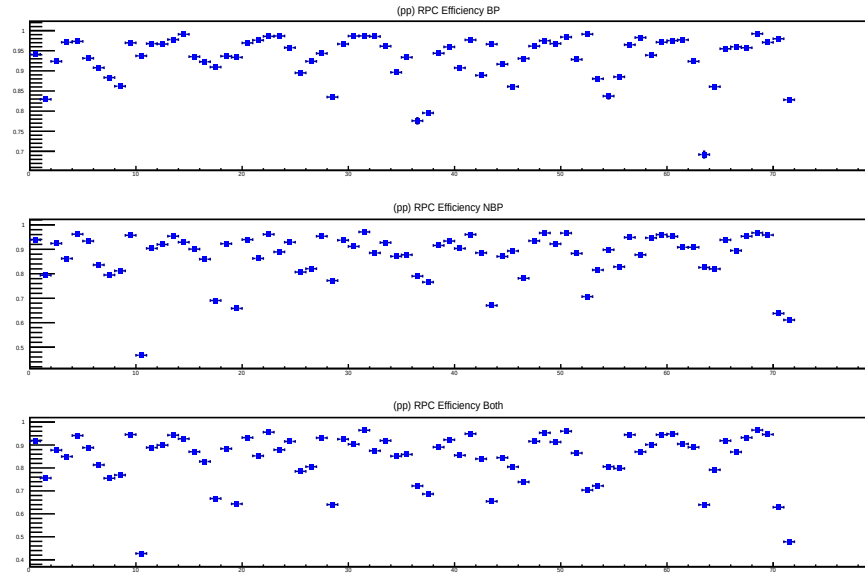


Figure 5.26: Average efficiency for the 72 RPCs for, respectively, bending, non bending and the AND of the two planes, for one p–p physics run at 500 kHz. The points from 1 to 36 in each plot correspond to the INSIDE RPCs, while from 37 to 72 to the OUTSIDE RPCs. For both INSIDE and OUTSIDE the first 9 RPCs are from plane MT11, followed in order by the other planes.

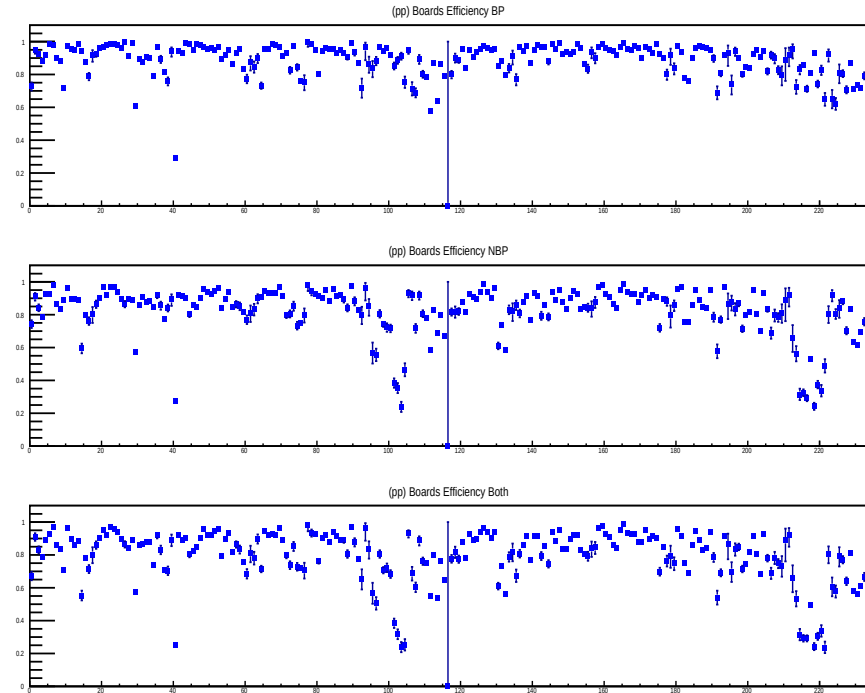


Figure 5.27: Average efficiency for the 234 Local Boards for, respectively, bending, non bending and the AND of the two planes, for one p–p physics run at 500 kHz. The Local Board mapping, in order to retrieve the area of the MID they correspond to, is shown in figure 3.15. In these plot one Local Board was unfortunately broken and it was replaced after several months due to a temporary lack of available spares.

was repeated in the same exact way for each plane at a time.

In figures 5.28, 5.29 and 5.30 the efficiency-HV curves for, respectively, bending, non-bending and both bending and non-bending, for the four MID planes are shown. The HV values on the x axis are mean HV values considering that, for each plane, the 18 corresponding RPCs have slightly different HV values. For example at -700 V, RPCs HVs are ranging from 9250 V to 9750 V.

The efficiency-HV curves for each RPCs, again for bending, non bending, and both planes, are shown in figures from 5.31 to 5.36. The curves were measured also for each one of the 234 local boards: remembering that one LB gives the information about the same area on the four planes, 936 efficiency-HV curves were obtained, which are not reported in this thesis for practical reasons.

During the HV scan the currents of all the RPCs were kept under monitoring, in order to spot any non-standard behaviour. In figure 5.37 the current-HV curves for each RPCs are shown. Each point correspond to the average current value during the entire run at the same HV value. It can be seen how the current increases for each RPC at increasing HV values, as expected.

As expected, also the efficiency increases at increasing voltages and the rise to the efficiency plateau is found to be quite sharp for the majority of the RPCs, with few exceptions, in particular for the RPCs belonging to external planes, i.e. MT11 and MT22, and the furthest from the beam pipe, for example MT11 IN 1 and MT11 IN 2. The strange behaviour of these RPCs will be treated in more detail in the next subsection.

It is important to compare the results obtained with FEERIC with those with ADULT. The working point of the RPCs equipped with ADULT cards for a threshold of 7 mV in maxi-avalanche mode without FEE pre-amplification stage, was between 10000 V and 10500 V. A clear shift towards lower HV working points can be observed with FEERIC in the efficiency-HV curves of figures 5.31 - 5.36. However, before setting the new HV working points for each RPC it is important to notice that the HV shift depends strongly on the FEERIC discrimination thresholds but, as mentioned before, it was not possible to perform the efficiency scan at different threshold values, due to the instability of the threshold setting system, so the discrimination threshold values are not finely tuned yet.

However, from FEERIC PRR [94], we know that full efficiency can be reached at lower RPC HV values for lower threshold values. In fact, the HV working points, from preliminary studies, should be expected to be around:

- 9375 V for 70 mV thresholds;
- 9500 V for 105 mV thresholds;

- 9625 V for 140 mV thresholds.

The thresholds values are applied to RPC signals after the amplification stage. In the MID case, the FEERIC threshold was 100 mV during the HV scan, then a value of about ~ 9500 V should be expected as new working point. As it can be seen in the efficiency-HV curves, this is the value obtained for the majority of the RPCs.

However, it is evident that some improvements can be done. Moreover, as it will be shown in the next section, it is important to re-study the MID performances by matching the tracks in the muon identifier with those in the MCH. In this way it will be possible to exclude several noise sources which could generate fake triggers or deadtime, thus allowing an improvement of the measurement.

It was decided then to run, for 2022, with a temporary value of -700 V for the working point for all the RPCs, and to repeat the HV scan as soon as possible with p-p collisions, by varying the thresholds values when the wifi setting system will be installed, and adding the matching of the MCH-MID tracks in the efficiency algorithm.

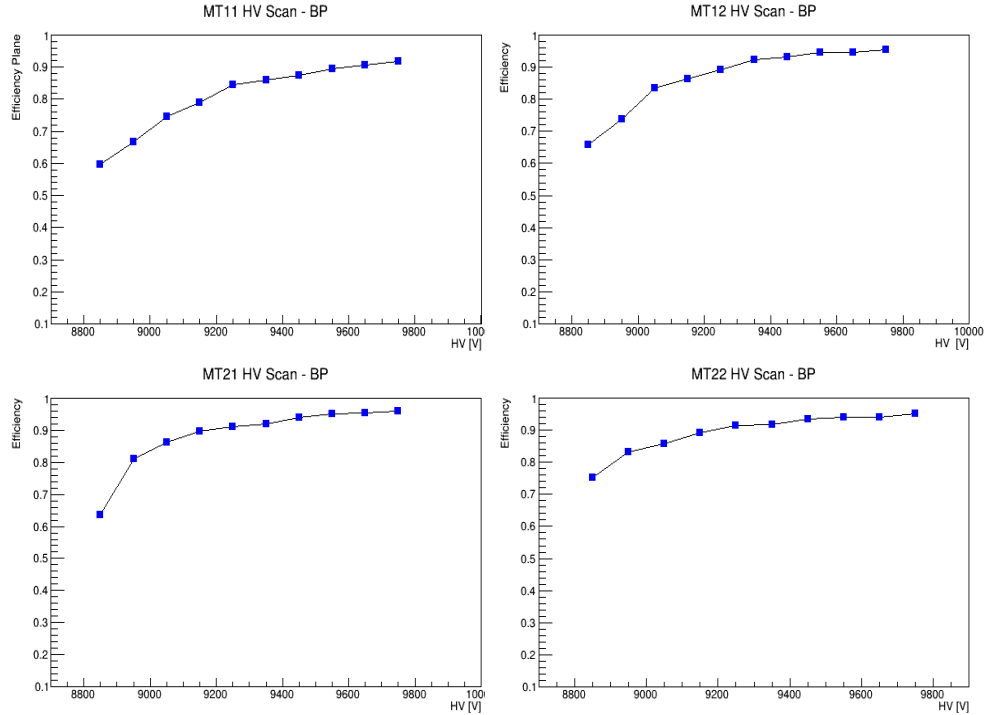


Figure 5.28: Efficiency of the 4 MID planes during the HV scan, Bending Plane only.

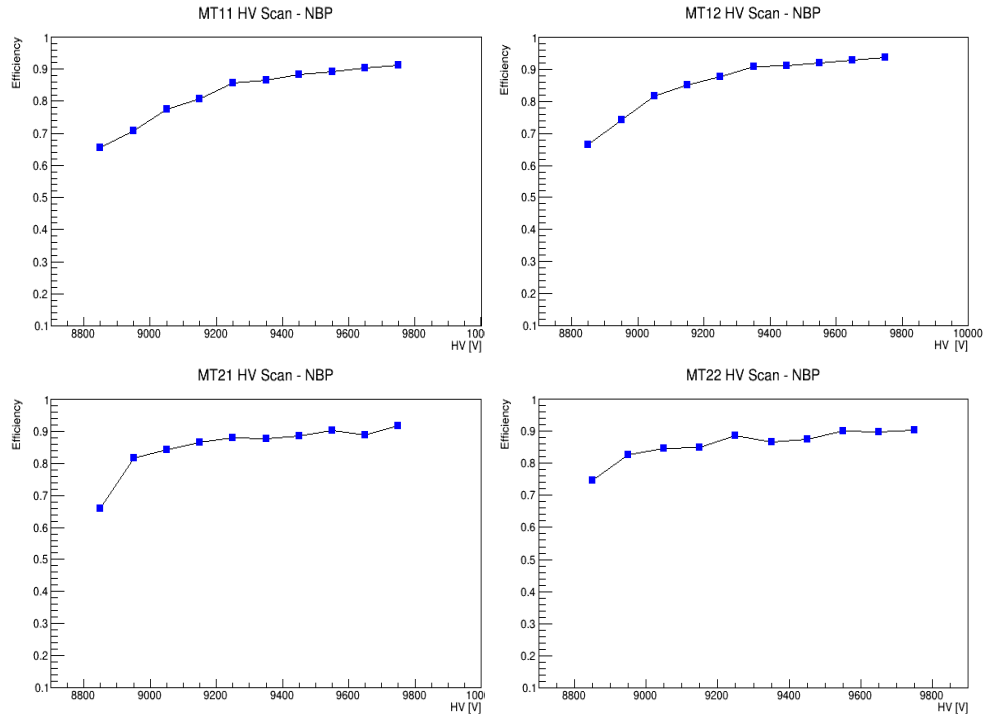


Figure 5.29: Efficiency of the 4 MID planes during the HV scan, Non-Bending Plane only.

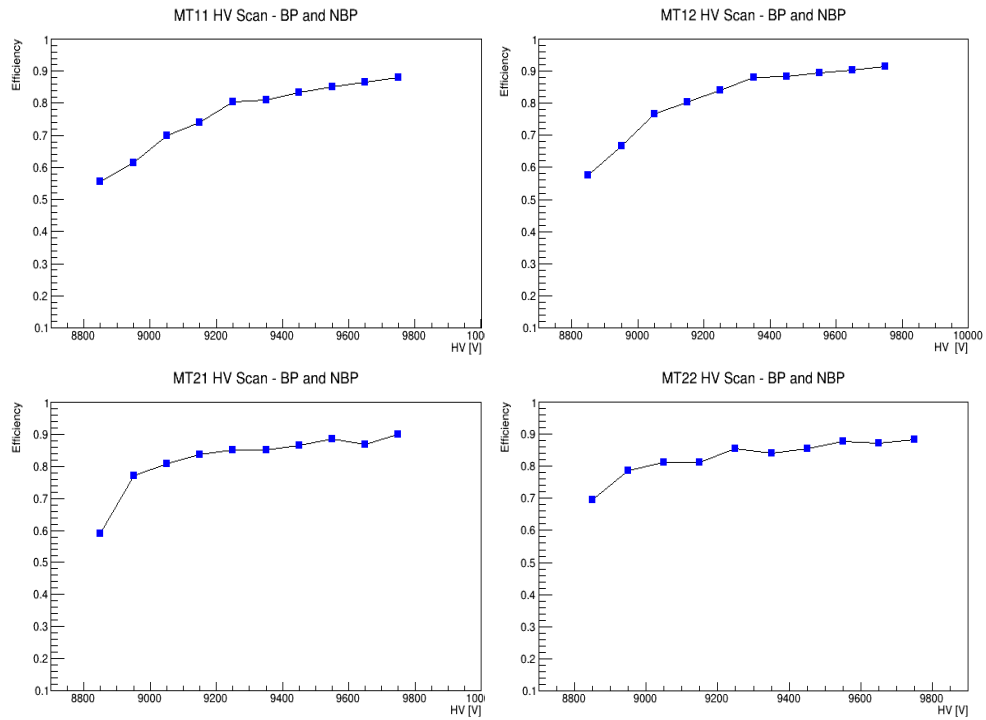


Figure 5.30: Efficiency of the 4 MID planes during the HV scan, Bending and Non-Bending Plane.

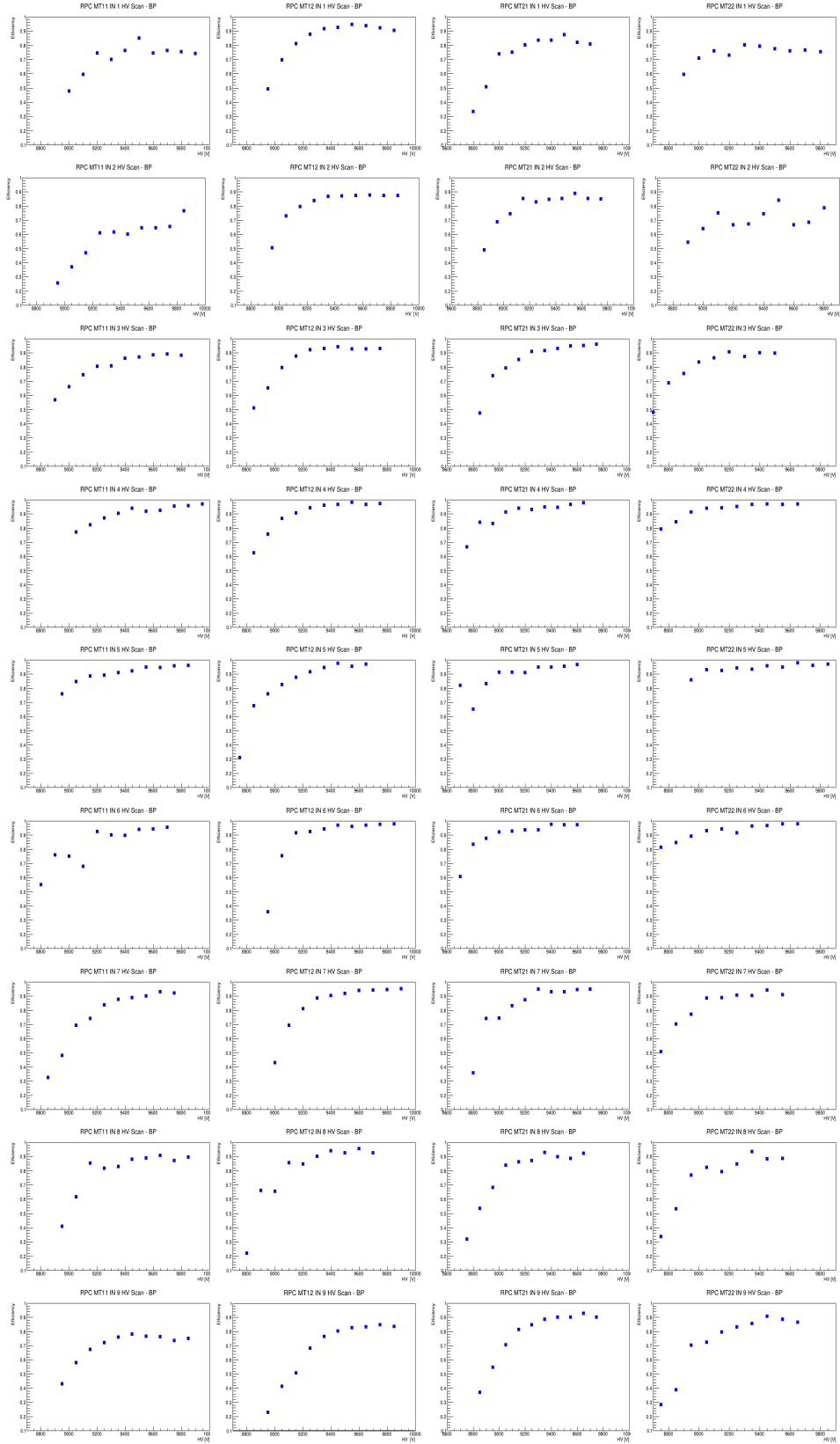


Figure 5.31: Efficiency of 36 INSIDE RPCs during the HV scan, Bending Plane only.

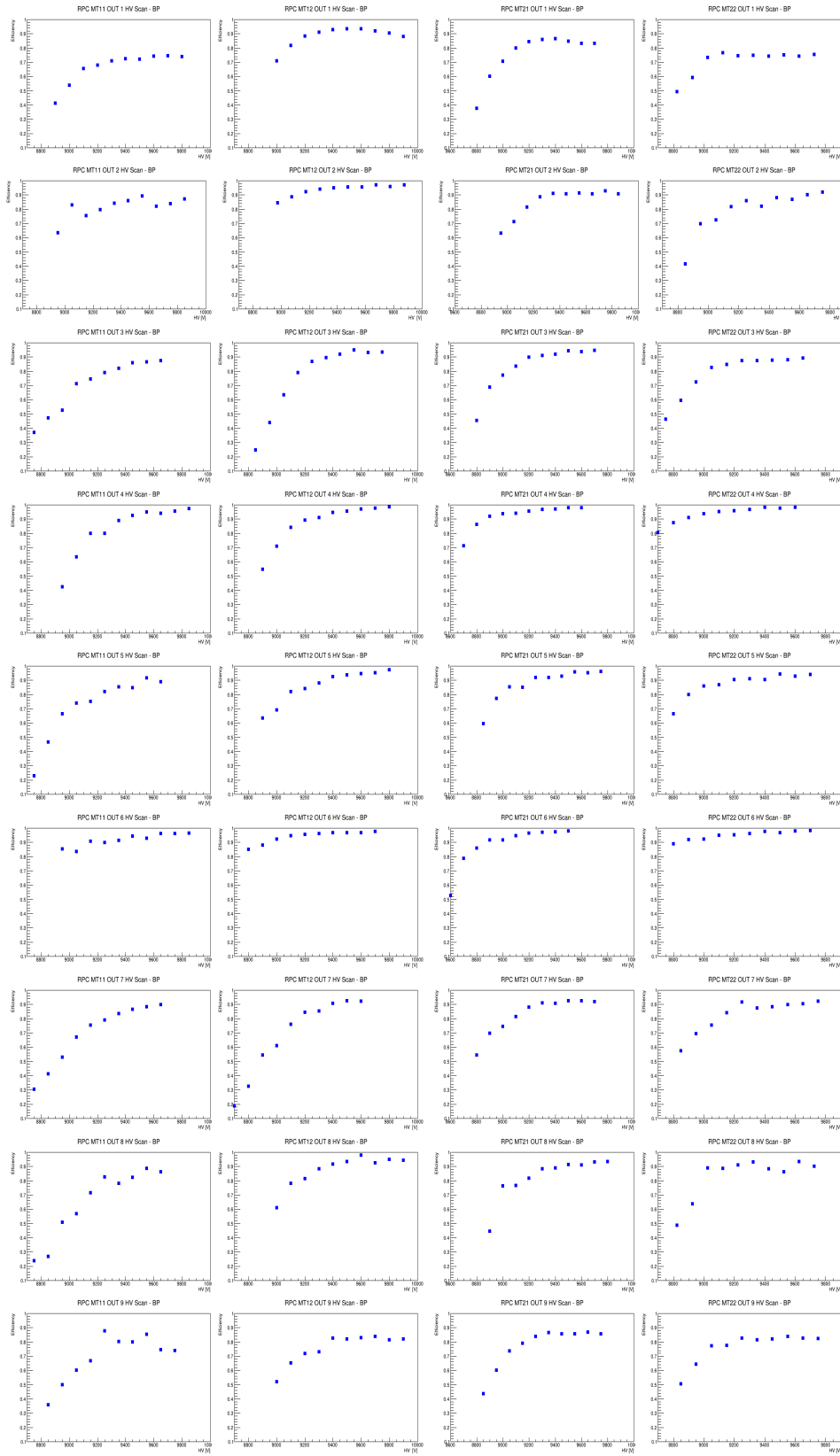


Figure 5.32: Efficiency of 36 OUTSIDE RPCs during the HV scan, Bending Plane only.

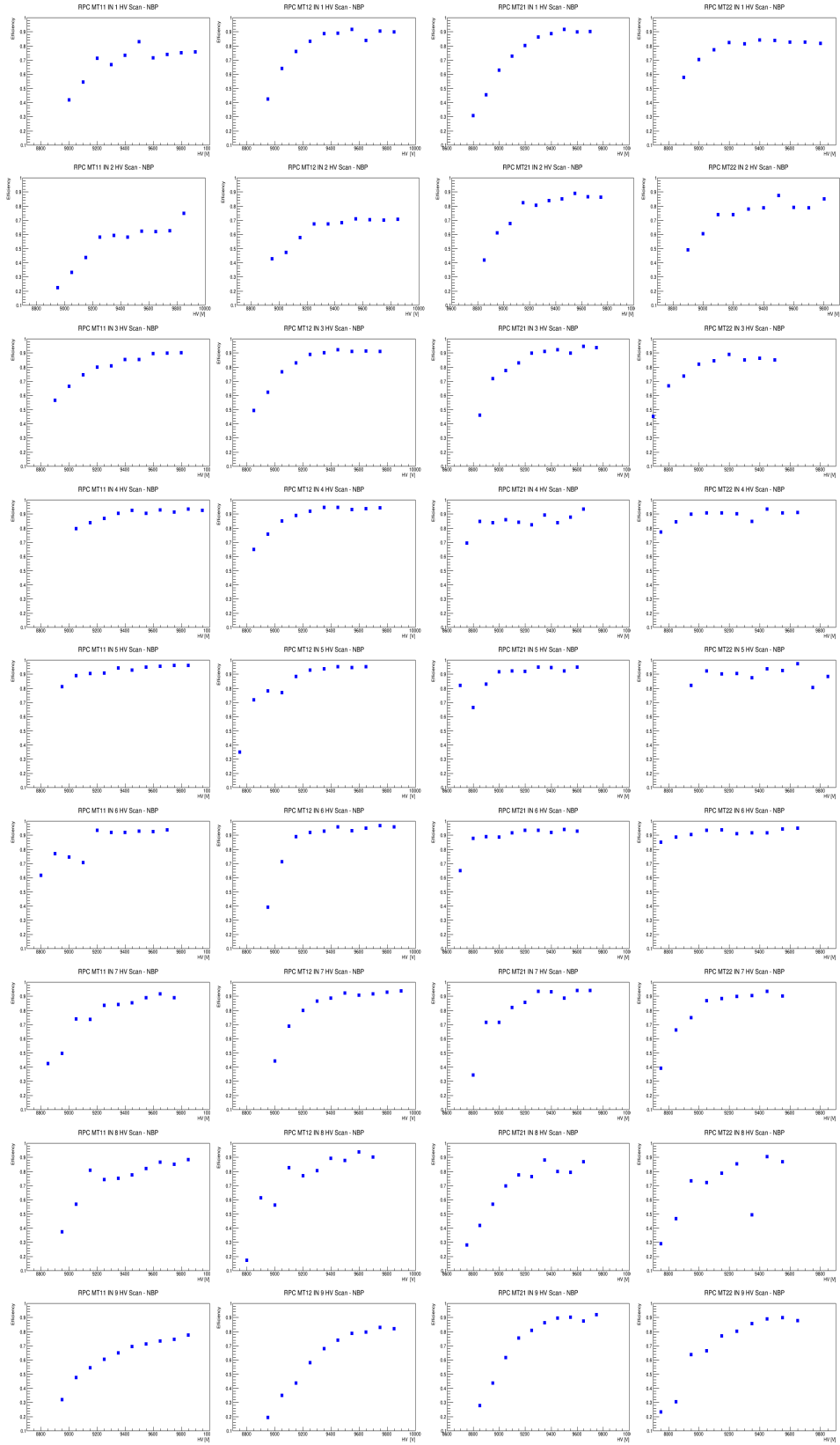


Figure 5.33: Efficiency of 36 INSIDE RPCs during the HV scan, Non-Bending Plane only.

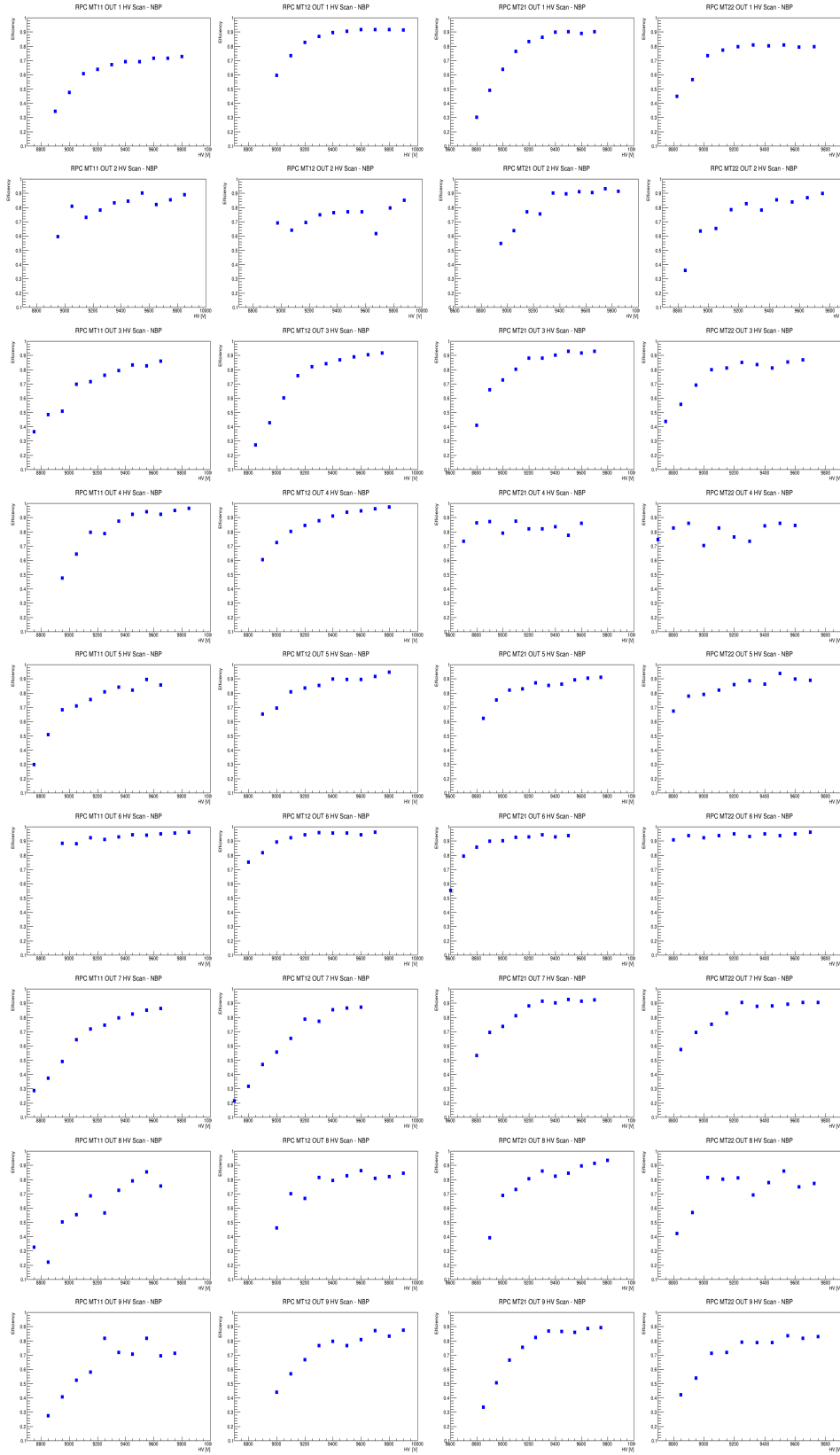


Figure 5.34: Efficiency of 36 OUTSIDE RPCs during the HV scan, Non-Bending Plane only.

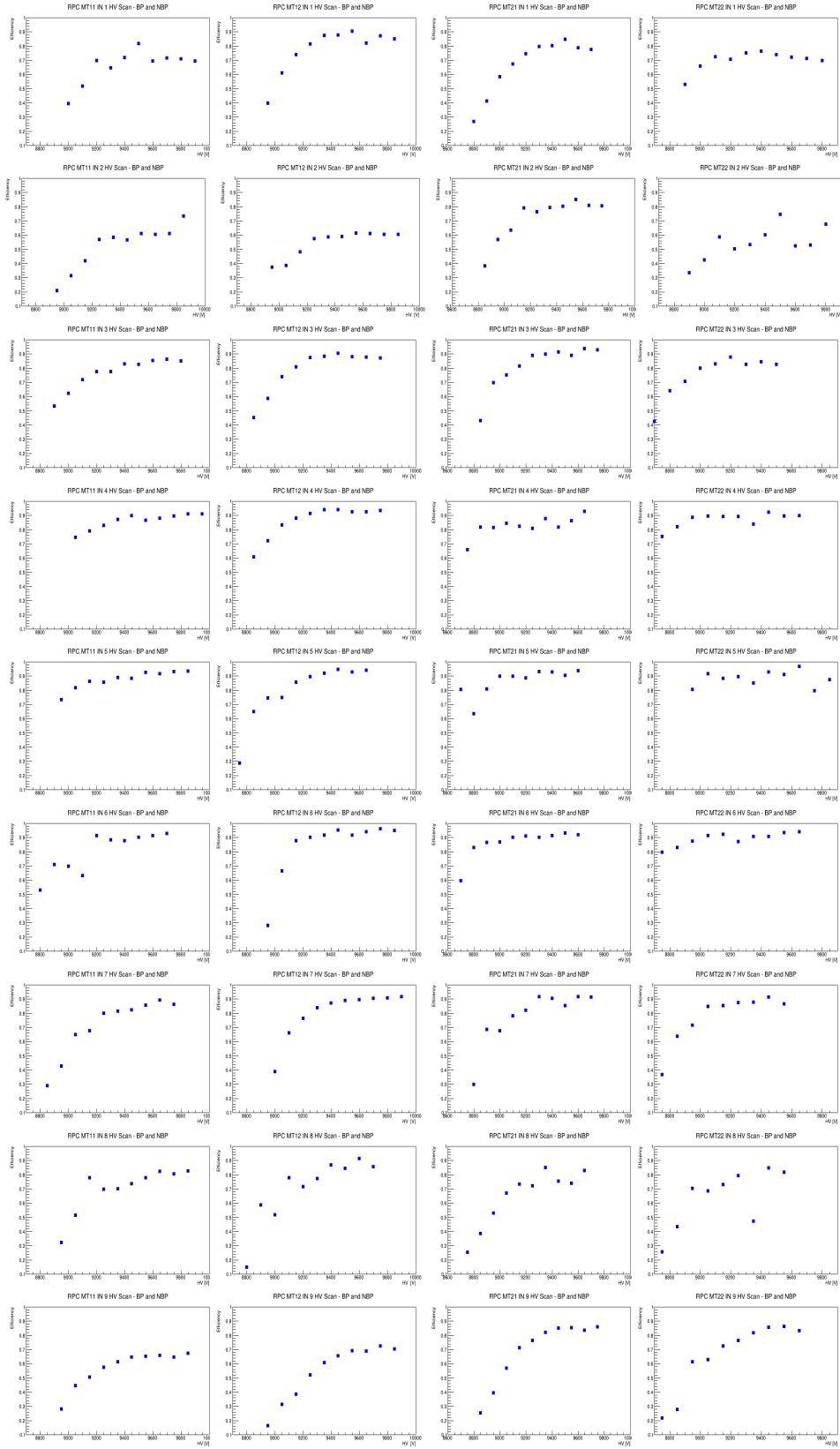


Figure 5.35: Efficiency of 36 INSIDE RPCs during the HV scan, Bending and Non-Bending Plane.

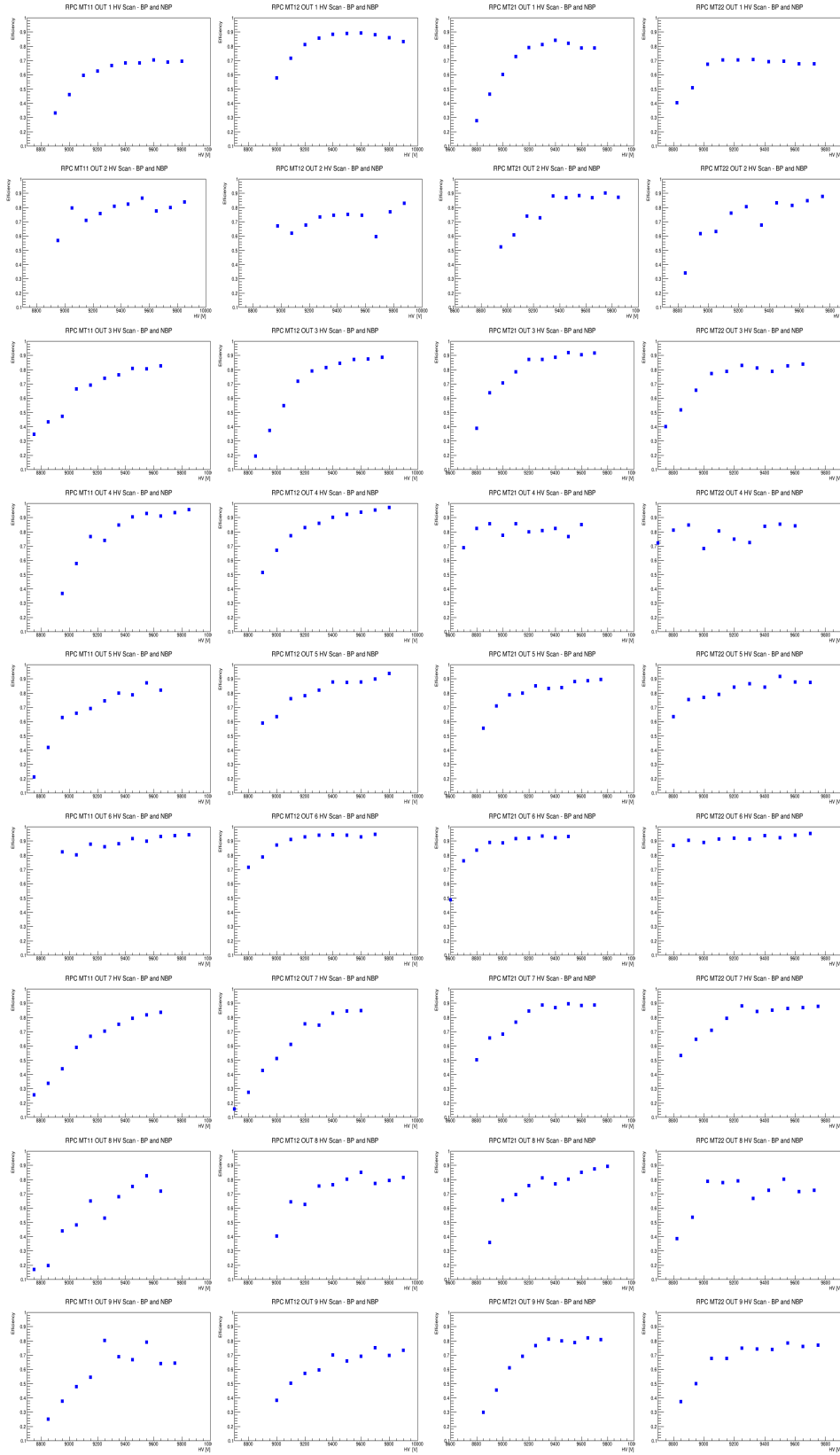


Figure 5.36: Efficiency of 36 OUTSIDE RPCs during the HV scan, Bending and Non-Bending Plane.

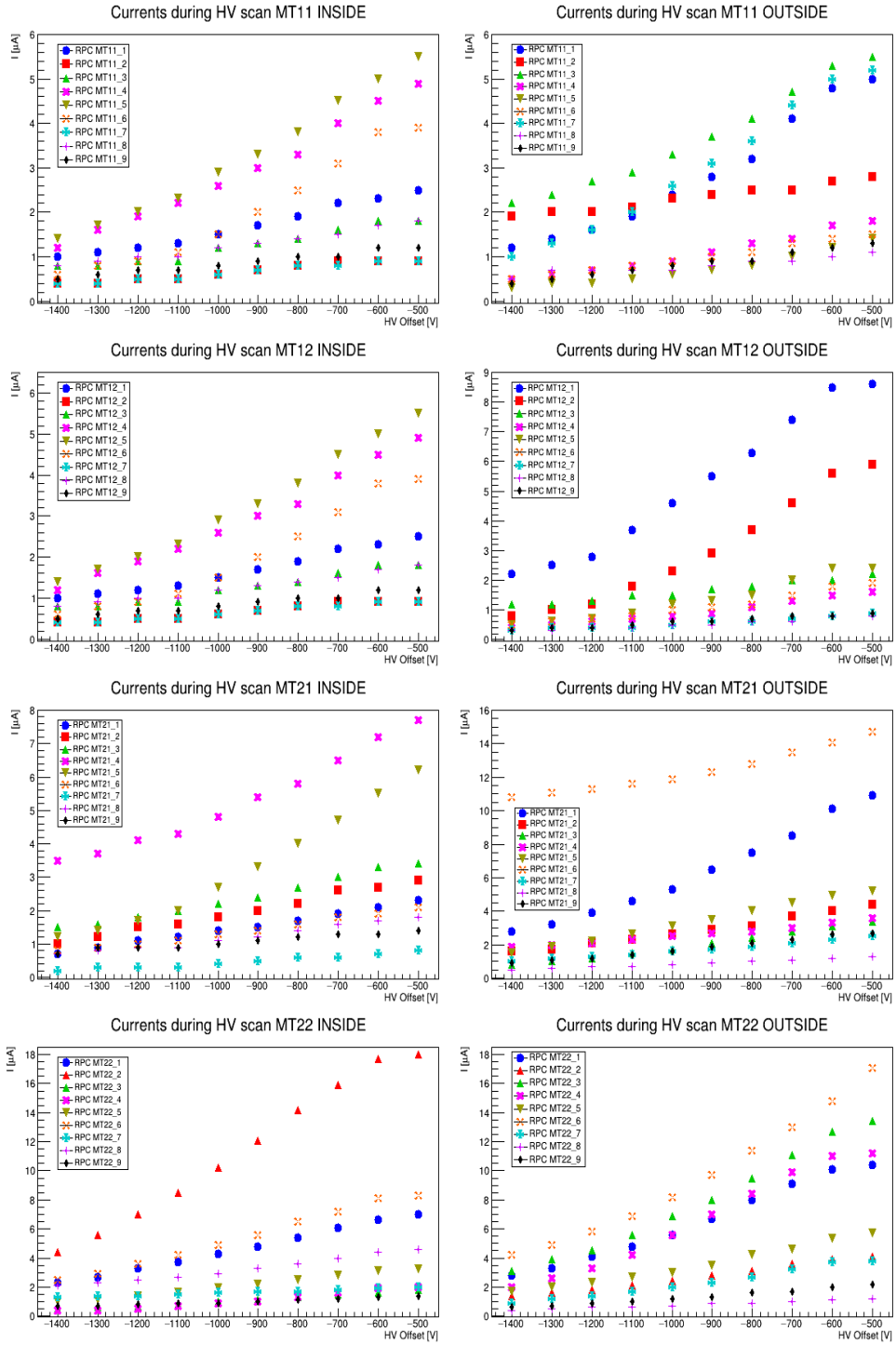


Figure 5.37: Currents during the HV scan. Each plot shows one MID half-plane with 9 RPCs

5.4.2 Performance during data taking

As mentioned before, it is fundamental to monitor the efficiency over the data-taking period, in order to detect any worsening of the detector performance. The efficiency trends from September 2023, after the LHC RF issue recovery, up to the end of November 2023, i.e. the end of the first Run 3 data-taking year, are shown in figures 5.38, 5.39 and 5.40 for, respectively, the bending, non-bending and both planes. In each figure there are 4 plots, one for each plane, and each point corresponds to a different run. The efficiency trend for the 72 RPCs are shown in figures from 5.42 to 5.45. Each plot corresponds to one RPC and also in this case, bending, non bending and the AND of the two planes are shown. The efficiency trends have been studied also for the LBs, obtaining 936 different plots (234 per each plane) for bending, non bending and both planes (again not reported in this thesis for practical reasons). The efficiency trend is generally stable over the whole period, however several issues can be spotted.

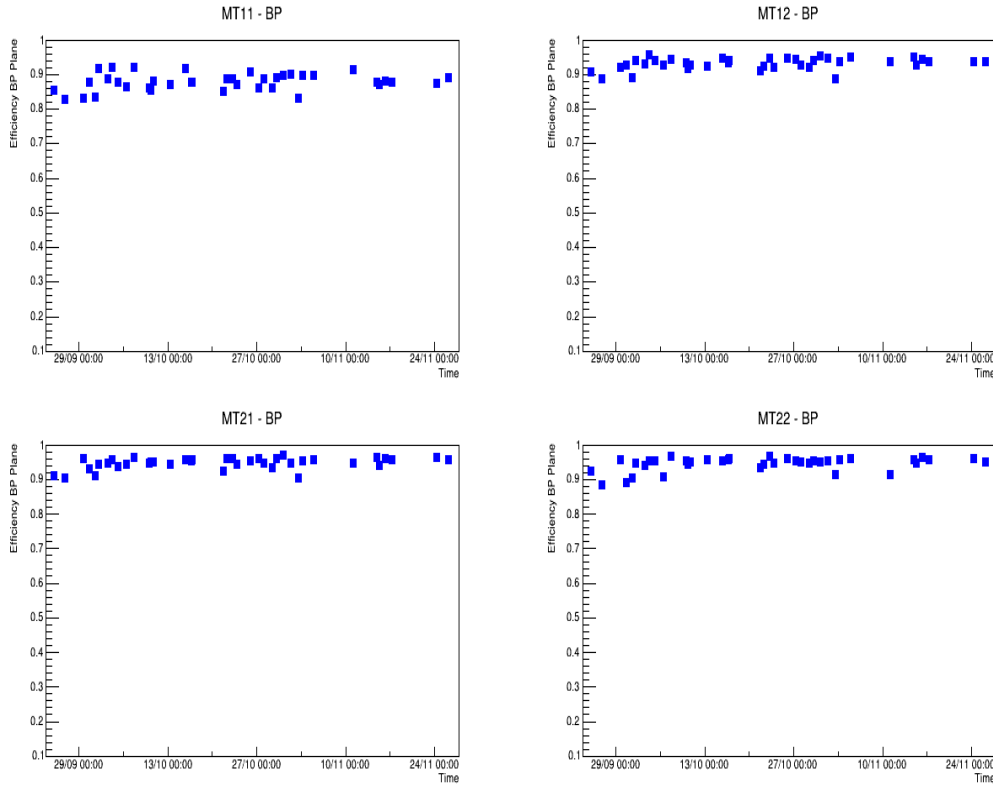


Figure 5.38: Efficiency of the 4 MID planes, bending plane only, monitored over data-taking period.

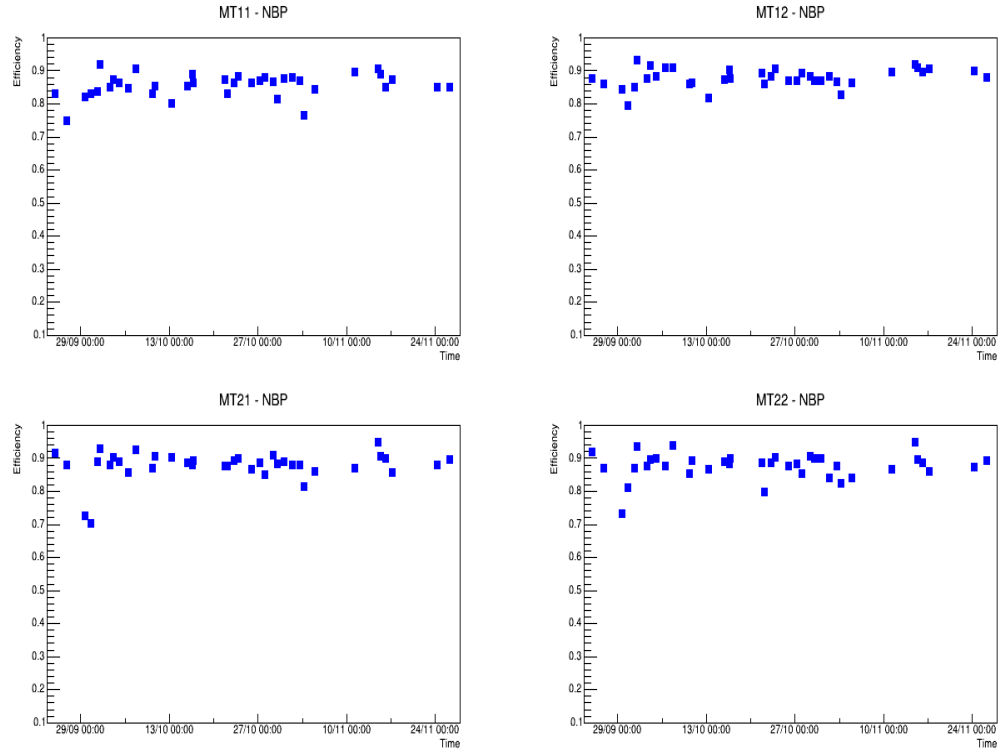


Figure 5.39: Efficiency of the 4 MID planes, non bending plane only, monitored over data-taking period.

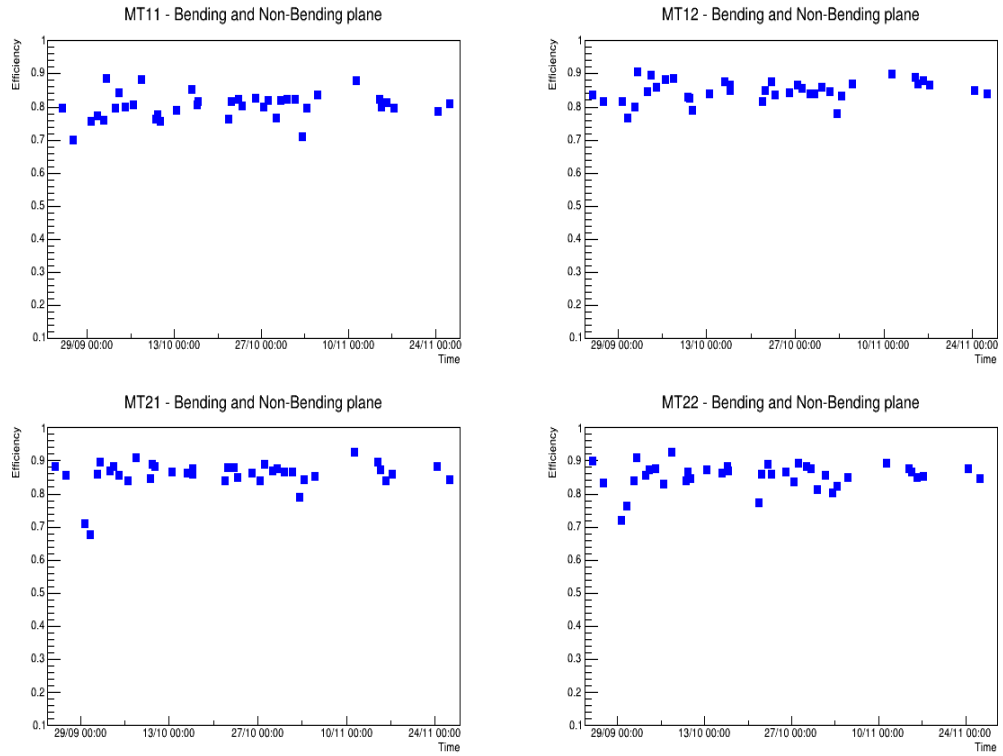


Figure 5.40: Efficiency of the 4 MID planes, bending and non bending plane, monitored over data-taking period.

First it can be noted a general lower efficiency of the non-bending plane with respect to bending one. This is mostly due to electronic noise in several local boards (the electronics used for the non-bending plane is less precisely set with respect to the one used for the bending plane).

It can also be noted that the average efficiency of the plane MT11 is lower with respect to the other planes. The lower average efficiency of this plane is due to few RPCs, in particular MT11 IN 1 and MT11 IN 2, which have a considerably lower efficiency with respect to the others, thus lowering the average efficiency of the whole MT11 plane. At this point one has to study the behaviour of the local boards reading the information of these RPCs, in order to understand if the problem could be related to the electronics. It was seen indeed that the efficiency of a couple of LBs of these RPCs was almost 0, so most probably it is necessary to replace the FEE boards related to that specific RPCs area. In figure 5.41 an example of a local board with a good efficiency (left) and a local board with almost 0 efficiency (right) for RPM MT11 IN 2, is shown. In any case the behaviour of these specific RPCs is closely monitored in order to understand if it is necessary to replace also the gas gaps at the first opportunity.

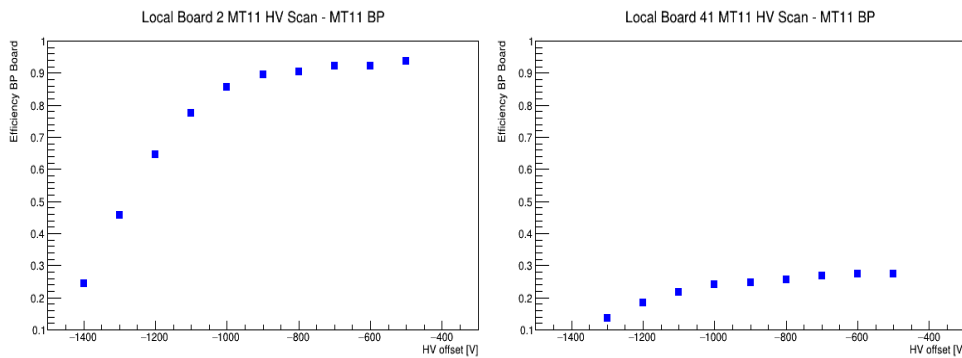


Figure 5.41: Example of two different local boards reading the information of RPC MT11 IN 2. Left: local board with an high efficiency around the (alleged) working point. Right: local board with almost 0 efficiency.

Concerning the small variations observed between some runs, they are usually due either to the presence of electronic noise in the local boards of some of the RPCs, or to the changes in the running conditions, or even to a mis-configuration of the detector. In fact after all the upgrades, the MID, during this first year of data-taking, was undergoing an important commissioning phase in which all its working parameter had to be redefined and it was not running at its best conditions yet. For example the electronic noise can change with time, being often fixed with dedicated interventions on the local boards along the year.

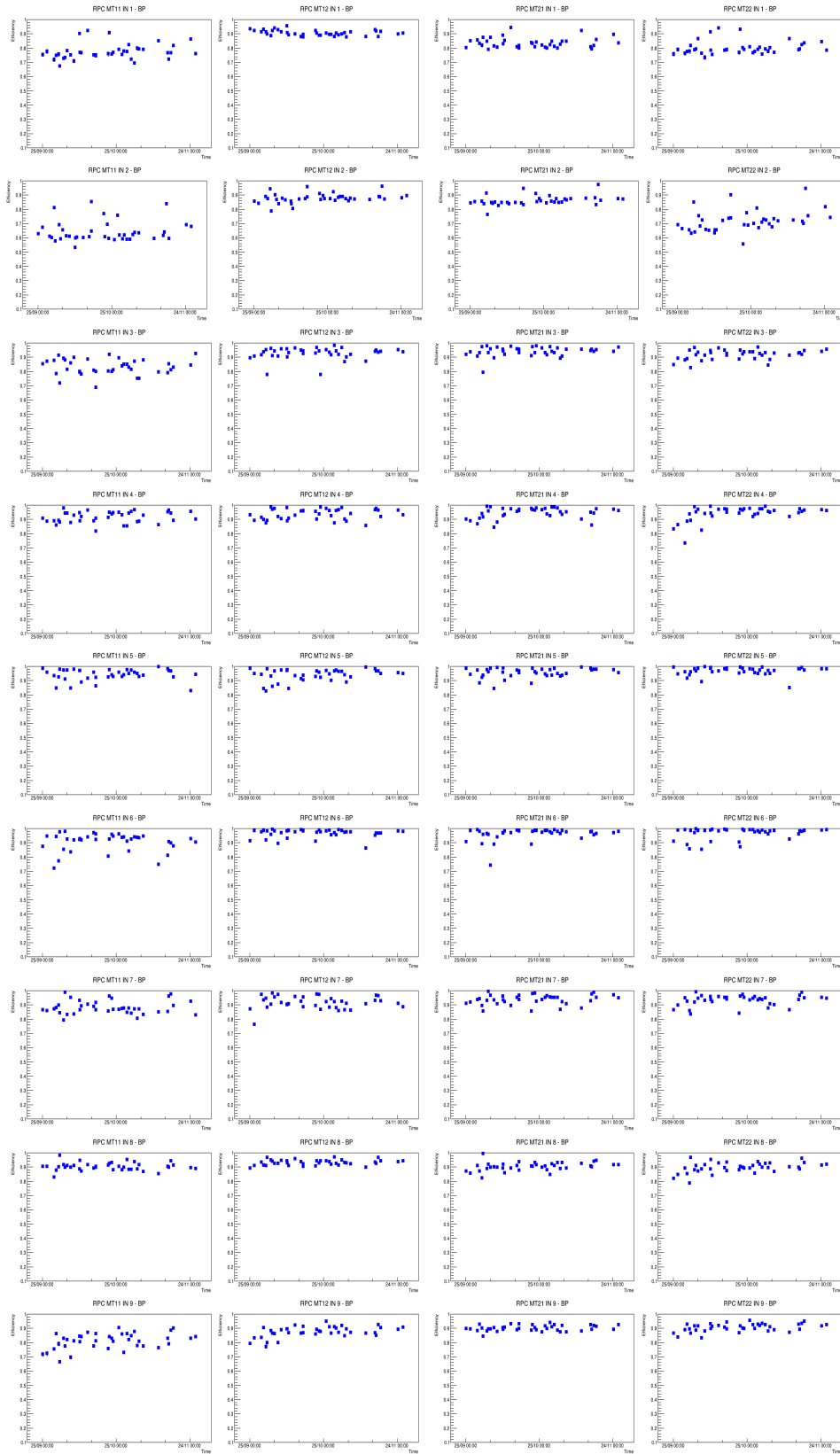


Figure 5.42: Efficiency of 36 INSIDE RPCs bending Plane only, monitored over data-taking period.

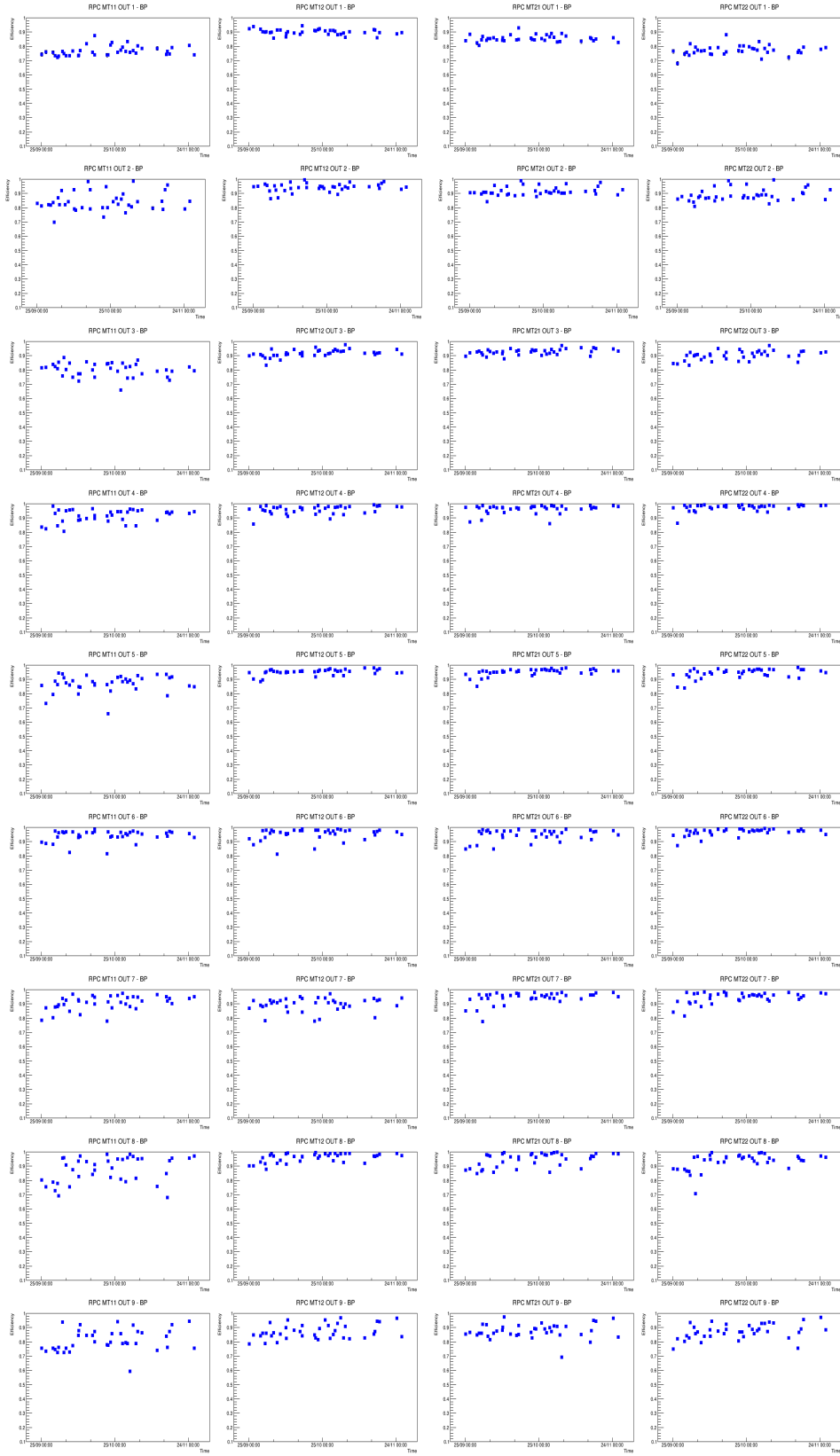


Figure 5.43: Efficiency of 36 OUTSIDE RPCs bending Plane only, monitored over data-taking period.

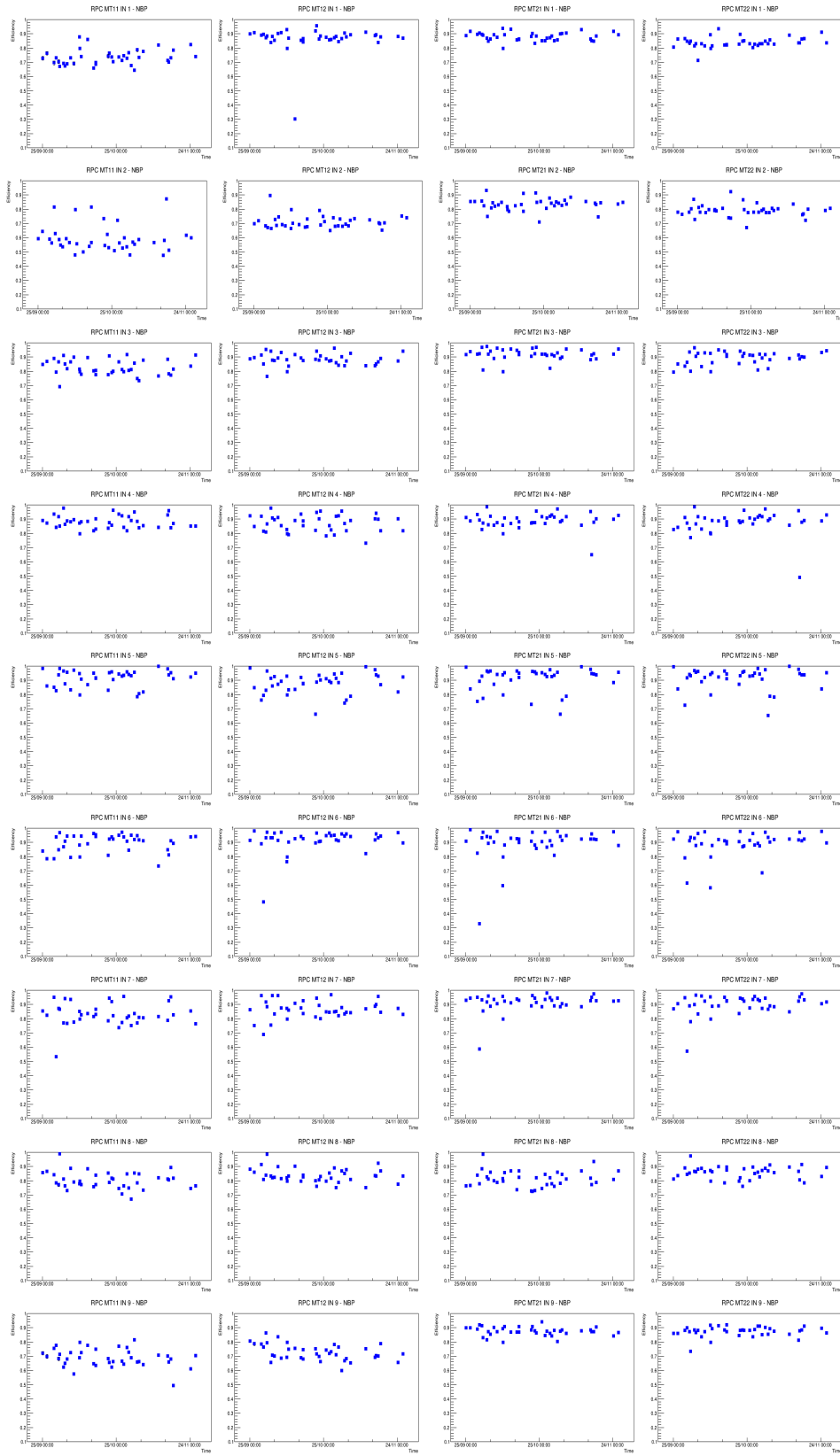


Figure 5.44: Efficiency of 36 IN RPCs non bending Plane only, monitored over data-taking period.

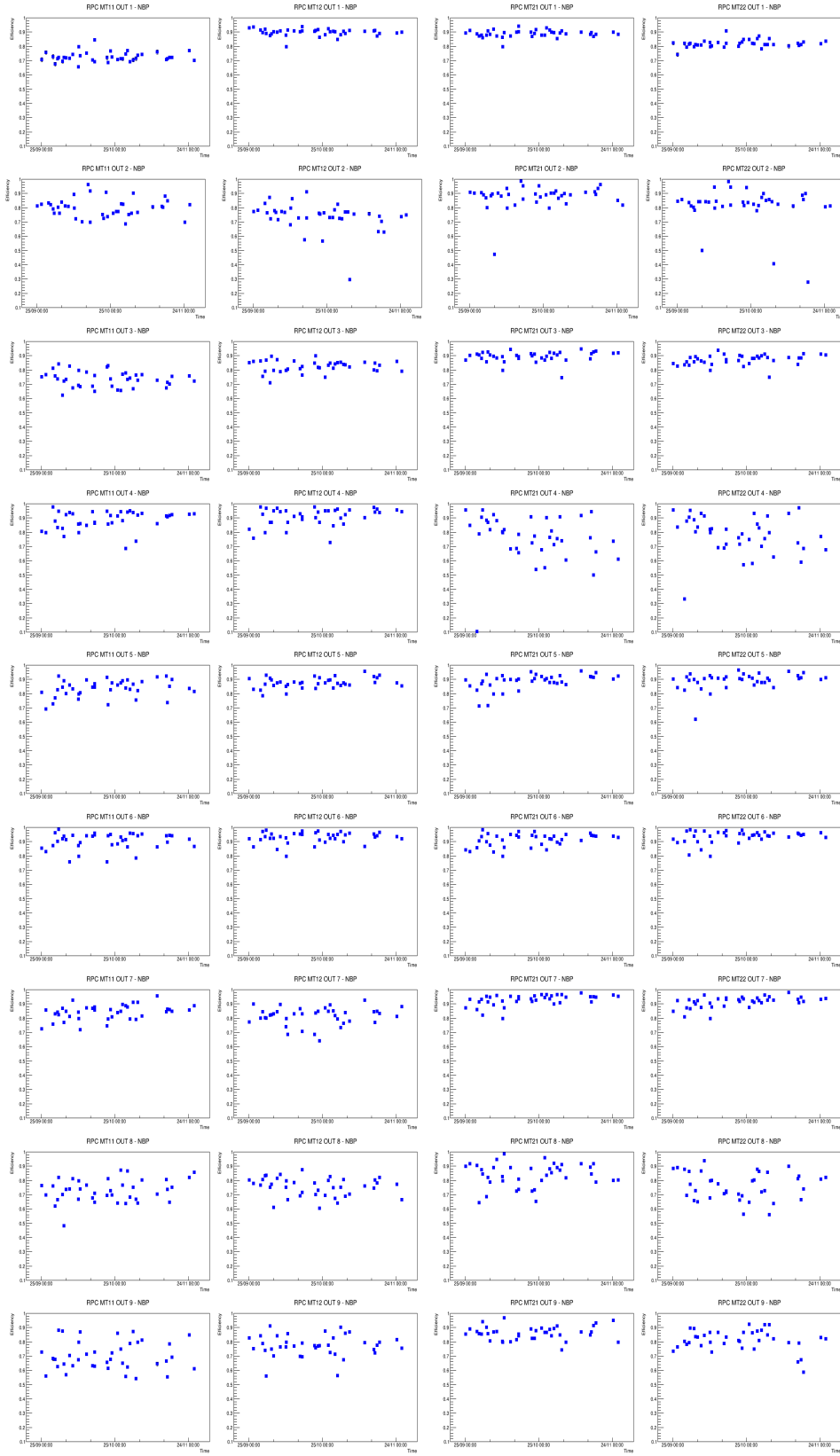


Figure 5.45: Efficiency of 36 OUTSIDE RPCs non bending Plane only, monitored over data-taking period.

From these trending plot however it is clear that the efficiency results are not completely satisfactory and lot of work, both on hardware and software sides, can be done. It is possible in fact to compare the average efficiency of the MID planes obtained in Run 3 with the average MTR efficiency during Run 1 and Run 2. In figure 5.46 the average efficiency of the four planes of the MTR, for both bending and non bending planes, between 2015 and 2018 is shown. It can be seen that during Run 1 and Run 2 the average efficiency was higher than 95% for all the planes, both bending and non bending.

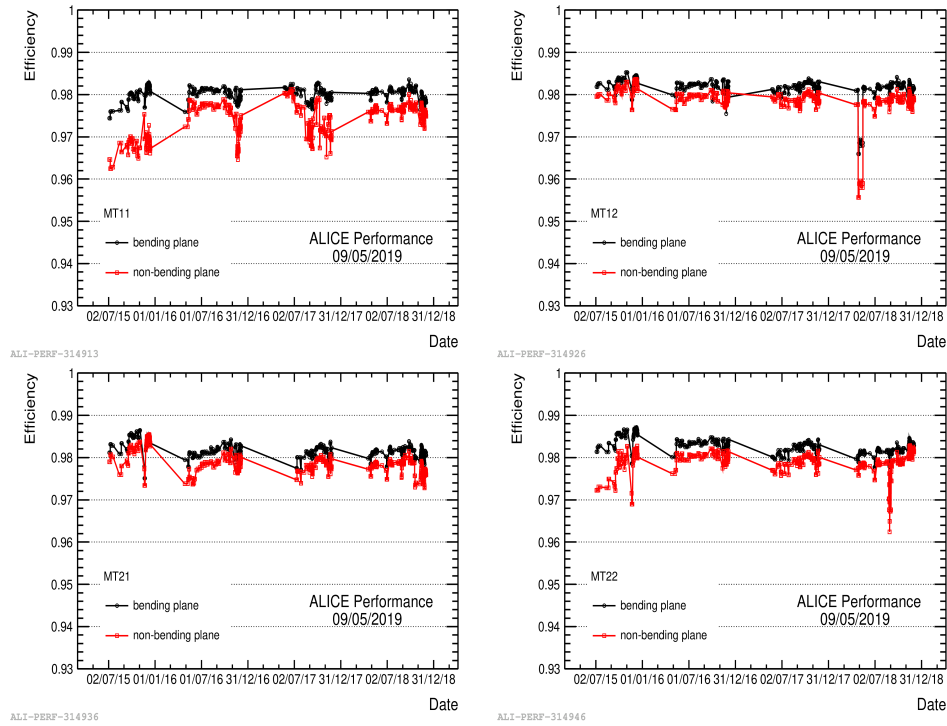


Figure 5.46: Average efficiency of, respectively, the planes MT11, MT12, MT21 and MT22 as a function of time in the years 2015-2018. bending plane and non bending plane are shown separately.

Some of the improvements to pursue are:

- setting the correct HV working points for each RPCs, retrieved from the HV efficiency scan;
- performing a fine tuning of the threshold values for each FEE boards by performing dedicated threshold scan runs once the Wifi thresholds delivering system will be installed;
- adding the matching of the tracks of the MID with those in the MCH in the efficiency algorithm, in order to remove fake triggers from the efficiency evaluation;
- replace the most aged gas gaps, and also faulty FEERIC or local boards.

It has also to be noted that in some cases we see many strips fired in a restricted region. Under these circumstances the reconstructed track may be biased and the probability of mismatch between the track and the corresponding fired strips increases. These difficulties can be also resolved by requiring the matching between MCH and MID tracks in the efficiency algorithm.

5.4.3 MID efficiency during Pb–Pb pilot run

In November 2022, a short pilot run (only one day) with Pb–Pb beams was performed. The collisions rate was really low, as it can be seen in the cluster rate plot for each RPCs showed in figure 5.47, since this run was done mainly for commissioning purposes, both on the LHC and ALICE side.

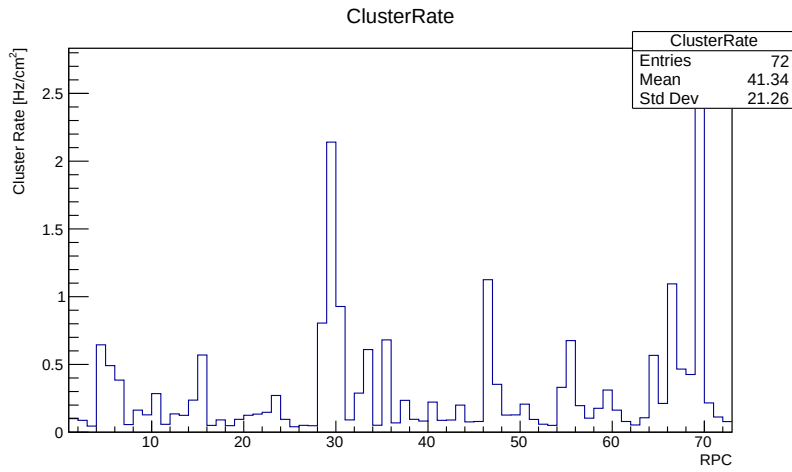


Figure 5.47: Cluster rate for the 72 RPCs during Pb–Pb run.

The efficiency has been studied for the Pb–Pb run with the same method described in section 5.4. The results for the efficiency of, respectively, the four planes, the 72 RPCs and the 234 local boards are shown in figure 5.48, 5.49 and 5.50. In all cases bending, non-bending and the AND of the two planes are shown. It can be noted that the average efficiency is lower for the Pb–Pb run with respect to the p–p ones. Similar consideration as for the p–p runs can be done for the Pb–Pb regarding the improvements to be done: the correct HV working points and thresholds values must still be set, the matching MCH-MID has to be added to the efficiency algorithm, and few hardware interventions (gas gaps to be replaced, local boards to be checked) will be done during the winter shutdown.

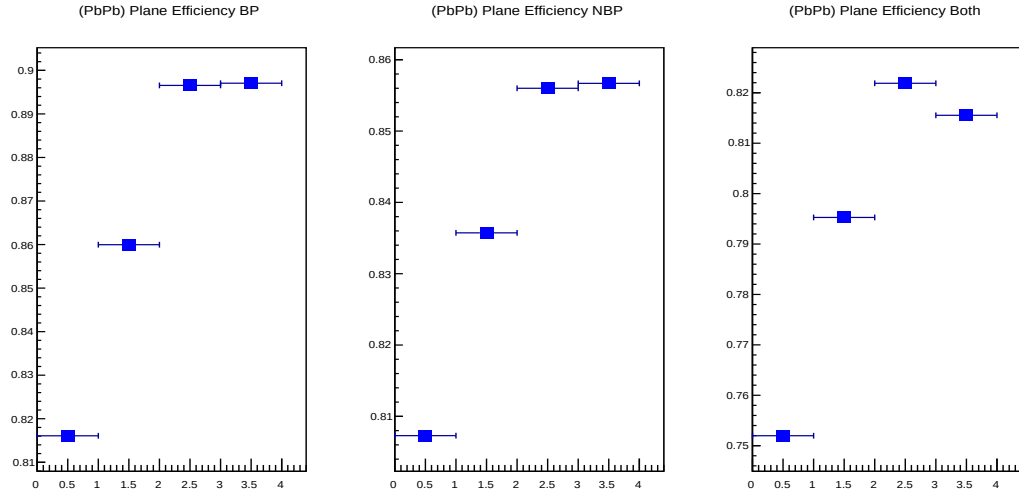


Figure 5.48: Average efficiency of the 4 planes for, respectively, bending, non bending and the AND of the two planes, for the Pb-Pb run. The points in each plot correspond, in order, to MT11, MT12, MT21 and MT22.

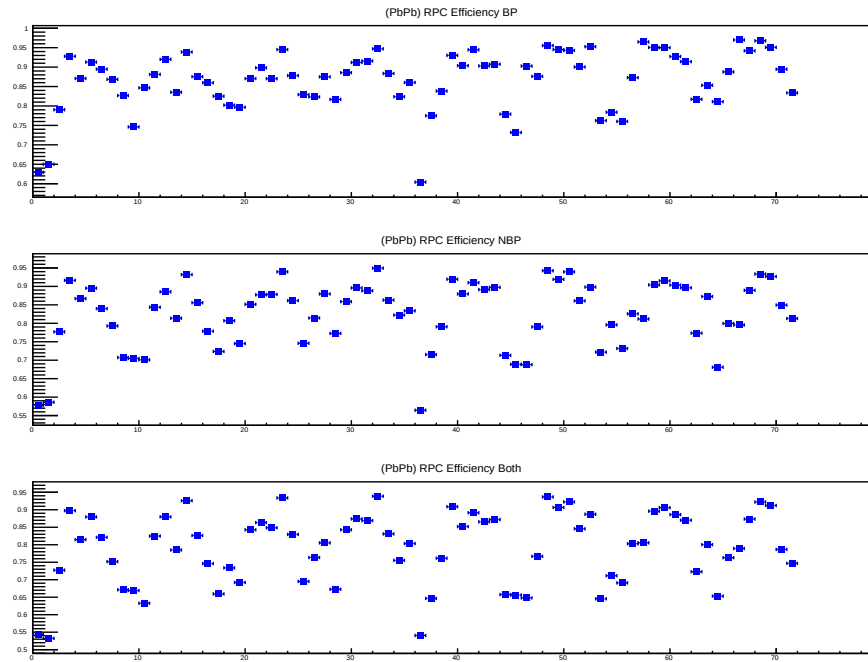


Figure 5.49: Average efficiency for the 72 RPCs for, respectively, bending, non bending and the AND of the two planes, for the Pb-Pb physics run. The points from 1 to 36 in each plot correspond to the INSIDE RPCs, while from 37 to 72 to the OUTSIDE RPCs. For both INSIDE and OUTSIDE the first 9 RPCs are from plane MT11, followed in order by the other planes.

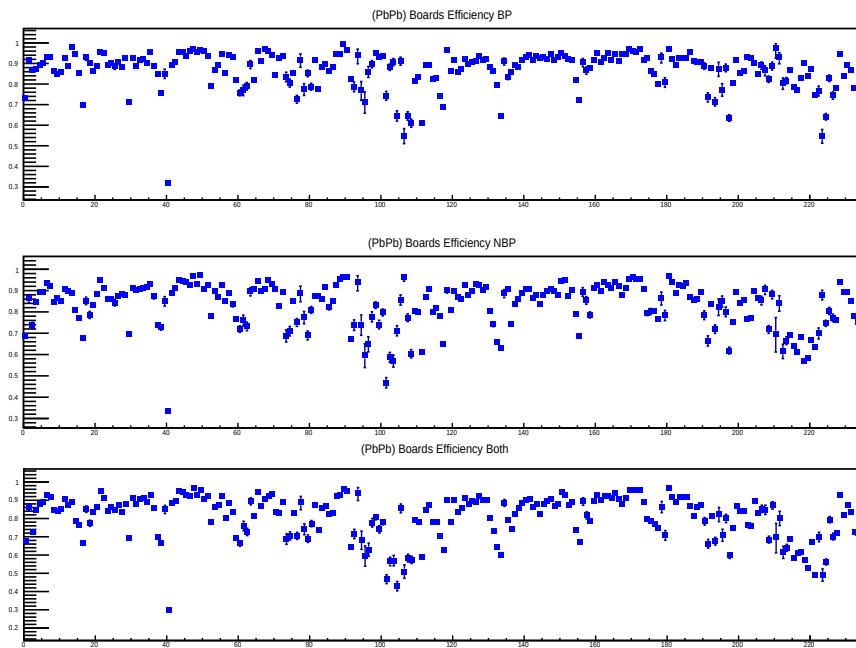


Figure 5.50: Average efficiency for the 234 Local Boards for, respectively, bending, non bending and the AND of the two planes, for the Pb–Pb physics run. The Local Board mapping, in order to retrieve the area of the MID they correspond to, is shown in figure 3.15.

Conclusions

The ALICE Muon Spectrometer (MS) has been designed to probe the QGP through the detection of heavy quarkonia in Pb–Pb collisions, by studying their di-muon decays in the pseudorapidity range $2.5 < \eta < 4$.

In view of Run 3 data taking in which the ALICE experiment is operated at a larger-than-ever luminosity, the whole ALICE collaboration spent lots of effort in order to improve the detector performances. The aim of this thesis was the test and characterization of the new RPC detectors for the Muon IDentification (MID) system for the MS, and the re-commissioning of the MID for Run 3 and Run 4 after all the upgrades done during the Long Shutdown 2 (LS2).

My thesis can be then divided into two part.

In the first part of this thesis the new production of RPC detectors has been described in detail. In fact at the end of the LHC Run 2, some of the RPCs have integrated a non-negligible charge with respect to their expected life-time, and aging effects started to appear. Therefore, about 25% of the detectors installed in ALICE may need to be replaced during Run 3. The new gas gaps are made with a different type of bakelite, because the one used for Run 1 and Run 2 RPCs is no longer commercially available. The new bakelite has different surface and bulk features, therefore it was important to test the new gas gaps in order to understand if and how these new properties affect the RPC performances. The tests and characterization of the new gaps were performed in Torino, in a brand new INFN laboratory, using a dedicated cosmic rays set-up. In this thesis it was also shown how, before the starting of my PhD, the RPCs production with the new bakelite was completely unsatisfactory in terms of performances. During the first year of my PhD several interactions with the firm were necessary, also in person at the company headquarters near Frosinone (Italy). A new pre-production batch of 3 RPCs was requested in order to validate the new gaps before launching the mass production. After the validation of this batch, the mass production of new modules was launched, completed and tested over my PhD. As extensively shown, current, efficiency,

cluster size and noise were measured and the mass production was validated, leading to the installation of four new gaps during the winter shutdown 2022-2023 in the ALICE experimental cavern (the very first ones with the new bakelite installed in the MID system).

In the second part of my thesis the period spent at CERN with the aim of the re-commissioning of the MID for the forthcoming Run 3 data-taking has been described. Several upgrades were indeed performed during the LS2 since, in order to cope with the increased collision rate (from the previous ~ 8 kHz during Run 2, up to ~ 50 -100 kHz for Pb-Pb collisions in Run 3), it was necessary to reduce the charge released per hit in the gas gap. For this reason, the detector is now operated at a lower gain (i.e. with a lower applied HV) with respect to Run 2, and a brand new front-end electronics, FEERIC, which include a pre-amplification stage has been installed.

In the last chapter the commissioning phase of the MID at CERN was presented. This involved also some hardware interventions in the ALICE cavern on the MID RPCs and the very first Run 3 data-taking campaign at the LHC record energy of 13.6 TeV in p-p collisions. The performances of the MID during the only one day of Pb-Pb collisions were also shown.

The re-commissioning of the MID with the new electronics included the integration of the upgraded on-line systems (read-out, Detector Control System, Data Quality Control) in the ALICE environment and a data-taking campaign aimed to a first tuning of the new working parameters. In fact the commissioning of the system started with the very first p-p LHC beams, continued with the first Pb-Pb pilot run, but it is not completed yet and some improvements have still to be done. The first collected data were used to have a first idea of the detector response in terms of efficiency, cluster size, cluster rate, charge released in the gas gap per hit, physics and dark currents in the new avalanche operation mode.

Moreover in this thesis it was pointed out how important is to monitor the long term evolution of the detector performances and it has been shown which are the relevant parameters for the aging effects for the RPC detectors: the integrated charge and the dark current. Several sources of data were combined in order to study these parameters. The main result of the study is that an increasing trend of dark current is observed for few detectors. Even if this effect is not accompanied by a decrease of the efficiency, the status of these chambers shall be carefully monitored to avoid a future worsening of the performances and, for few RPCs, it was however decided to replace them. Moreover, further studies to understand the origin of the dark current are

recommended. By comparing the performances of the gas gaps equipped with FEERIC with those equipped with ADULT, a more stable dark current was observed for the FEERIC equipped RPCs, and a much smaller charge per hit, which is a very promising result.

The cluster size of the MID with the new electronics has been also measured, for all the RPCs strip pitches. In fact the average cluster size value strongly depends on the strip widths: it ranges from 1.4 for the strips of 4 cm to 1.6 for those of 2 cm, up to 1.8 for those of 1 cm. The cluster size is found to be on average independent to the detection plane, as expected, and to increase with increasing HV values or increasing collision rates. The stability of the cluster size value with time has also been monitored during the data-taking period, indicate a satisfying performance of the MID apparatus throughout the first years of data taking.

Another very important variable is the efficiency of the Resistive Plate Chambers. Many efforts have been put in the development of the reconstruction and the efficiency algorithms for the study of RPCs performances in avalanche mode. In fact, although the efficiency of each chamber was measured during the validation tests in Torino, after the production and then before the installation in the ALICE cavern, it is still fundamental to monitor any global or local variation of the efficiency for each RPC, since they cover a very large area and they are designed to collect data over a long time period in an high radiation environment. In this thesis, a method for measuring the efficiency of each plane, each RPC and each local boards from physics data was presented. Few minutes of p-p or Pb-Pb data taking allow to collect enough statistics for the determination of the efficiency with a statistical accuracy better than 1% allowing us to monitor the efficiency without requesting dedicated runs. Even if many steps have been done, there is still margin of improvements and a fine tuning of the new working parameters is currently ongoing.

Ringraziamenti

Arrivata alla fine del mio dottorato, è per me importante esprimere i miei ringraziamenti per tutti coloro che hanno giocato un ruolo in questo percorso, sia dal punto di vista scientifico, umano e di supporto, o entrambi.

Per ringraziare Alessandro, il mio supervisor, non so davvero da dove iniziare e quali parole usare, ma ci proverò. Dicono che il dottorato sia per lo più fonte di stress e pieno di difficoltà, ma guardandomi indietro tutto quello che ricordo e che mi resta impresso è il divertimento e la passione per la fisica che abbiamo condiviso in questi anni di ricerca e lavoro in laboratorio. Avere la fortuna di essere guidata, supportata, consigliata e aiutata da qualcuno che non solo ama il suo lavoro, ma sa trasmettere questa passione, è una fortuna incredibile. Per non parlare del fatto che sono stata incoraggiata durante tutto il percorso da una persona che, in ogni momento, era evidente tenesse sinceramente a me e al mio futuro. Inoltre è importantissimo per me ringraziarlo anche per la possibilità che mi è stata data di svolgere gran parte di questo percorso al CERN, come fortemente desideravo. Quindi, grazie carissimo Ale per l'impatto positivo che hai avuto sulla mia carriera e più in generale sulla mia vita!

A Martino, che nonostante non sia stato ufficialmente il mio supervisor sulla carta, ha avuto un ruolo fondamentale nel conseguimento del mio PhD. Dire che sia stato incredibilmente e costantemente presente è dire poco. Mentre guardo indietro a questo percorso, mi rendo conto che non avrei potuto farcela senza il suo aiuto. Sembrerò ripetitiva, ma ho davvero avuto la fortuna di lavorare con persone appassionate per il loro lavoro, nel trasmettere la loro conoscenza, ma che soprattutto ci hanno tenuto veramente e sinceramente a me, al di là del rapporto supervisor-studente, ma come amici! Anche a Martino devo una quantità immensa di grazie per il ruolo che ha avuto nel permettermi di lavorare per gran parte del mio dottorato (e soprattutto dopo) al CERN: grazie per la fiducia nel darmi il ruolo che desideravo, e per esserti

impegnato tanto per aiutarmi ad ottenerlo. So che non è stato facile, grazie Capo! Anzi, visto che siamo a Torino, grazie Maestro!

P.s. un ultimo grazie per la lista di ristoranti che mi hai fatto scoprire a Ginevra e dintorni: è di fondamentale importanza per la mia sopravvivenza al CERN!

A Diego, per l'aiuto ricevuto con il MID al CERN. Da lui ho imparato (e sto continuando a imparare) tantissimo. Grazie per la pazienza infinita nel rispondere alle mie mille e più domande ogni santo giorno, perfino durante il weekend e festivi, nonostante mi ripetessi continuamente di fare una pausa e smettere di lavorare almeno per un giorno, e poi invece eri sempre il primo a rispondermi ad ogni ora punto e momento, anche durante le vacanze!! Questa tesi non sarebbe stata possibile senza di te. E speriamo che quest'anno il MID ci dia meno problemi dello scorso anno!

A tutto il meraviglioso gruppo di ALICE Torino: Ermanno, Chiara, Roberta, Livio, Nora, Enrico, Giorgio e tutti gli altri. Siete un team straordinario con cui lavorare, imparare e migliorarsi. Grazie infinite per l'accoglienza che mi avete riservato, e per avermi fatto sentire parte integrante del gruppo, come se fossimo in famiglia. Spero che questa collaborazione, ma soprattutto questa amicizia possano continuare anche dopo la fine del mio dottorato.

A Luca, collega certamente, ma prima di tutto amico e, permettimi di dirlo, ormai praticamente un fratello. Ti avevo definito compagno di avventura e disavventura nei ringraziamenti di tesi magistrale, e questa definizione è diventata mille volte più vera durante questo dottorato. Ne abbiamo passate un po' e non potrei aver potuto desiderare un amico migliore per questo lungo percorso che è iniziato in magistrale, è continuato nei tre anni di dottorato e, per fortuna, non è ancora finito. Ti voglio bene! E speriamo di venire prima o poi a capo di tutti i misteri delle RPC senza impazzire.

Ai miei genitori, mia sorella e mio fratello. In questi anni avete creduto in me molto di più di quanto non abbia mai fatto io. Vedo quanto siete fieri di me ogni giorno, nei vostri sguardi e nelle vostre parole, e spero davvero di potermelo meritare e di esserne all'altezza. Mi avete dato tanto, e di più, e sono fiera di potermi vantare della mia straordinaria e meravigliosa famiglia. So anche che la distanza fisica (che purtroppo è andata solo ad aumentare nel tempo) non è stata facile nè per voi, e non lo è soprattutto per me, ma spero in fu-

turo di potervi venire a trovare di più. Vi voglio bene e mi mancate ogni giorno.

A Maria Roberta, la mia migliore amica. Come ben sai non credo nell'esistenza delle anime gemelle (come non ci credi tu) ma se dovessero esistere, io e te di sicuro lo saremmo! In questi 10 anni e passa non hai idea del ruolo che hai avuto nell'aiutarmi a credere in me stessa, a migliorarmi e ad uscire dal mio guscio, osando e rischiando sempre di più. Devo gran parte della mia attuale felicità a te. Come ci diciamo ogni giorno: ti amo!

Alle mie meravigliose e più care amiche: Sara P., Elena L., Giorgia G., Giuliana G., Giulia S. e Laura B. Non avete idea di quanto queste ragazze abbiano sopportato i miei scleri (quasi) quotidiani e miei lunghissimi e improponibili audio, con una pazienza, un amore e un affetto rari. I vostri preziosi consigli sono sempre di aiuto, soprattutto quando come mio solito sono troppo su di giri per inquadrare le situazioni!

Alla mia seconda famiglia, quella che ci scegliamo: Antonello P., Antonio P., Caterina A., Davide F., Edoardo P., Flavio R., Francesco C., Francesco I., Marco G., Mattia C., Mattia V., Nicolò V., Roberto S., Simone C. e Vincenzo M.! Vi voglio troppo troppo bene matti!

L'ho già detto quanto sono dannatamente fortunata e irrimediabilmente felice e grata per tutto quello che ho?

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