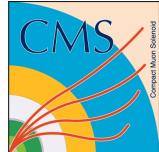
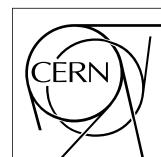

2 **Consolidation and longevity studies on CMS**
3 **Resistive Plate Chamber system in the context**
4 **of upgrade of CMS Muon System towards High**
5 **Luminosity LHC**

6 Alexis Fagot

7



Thesis to obtain the degree of
Doctor of Philosophy in Physics
Academic years 2012-2018





Universiteit Gent
Faculteit Wetenschappen
Vakgroep Fysica en Sterrenkunde

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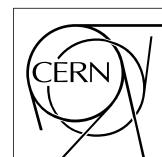
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²⁰ Ici on remerciera tous les gens que j'ai pu croiser durant cette aventure et qui m'ont permis de passer
²¹ un bon moment

Gent, ici la super date de la mort qui tue de la fin d'écriture
²³ Alexis Fagot

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Nederlandse samenvatting –Summary in Dutch–

¹³⁰

¹³¹ Le resume en Neerlandais (j'aurais peut-être pu apprendre la langue juste pour ça...).

English summary

¹³³ Le meme résume mais en Anglais (on commencera par la hein!).

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666

List of Acronyms

667

List of Acronyms

668

669

A

670

672 AFL

Almost Full Level

673 ALCTs

anode local charged track boards

674

675

B

676

678 BARC

Bhabha Atomic Research Centre

679 BLT

Block Transfer

680 BMTF

Barrel Muon Track Finder

681 BNL

Brookhaven National Laboratory

682 BR

Branching Ratio

683

684

C

685

687 CAEN

Costruzioni Apparecchiature Elettroniche Nucleari S.p.A.

688 CERN

European Organization for Nuclear Research

689 CFD

Constant Fraction Discriminator

690 CFEBS

cathode front-end boards

691 CMB

Cosmic Microwave Background

692 CMS

Compact Muon Solenoid

693 CSC

Cathode Strip Chamber

694 CuOF

copper-to-optical-fiber translators

695

696

D

697

699 DAQ

Data Acquisition

700 DCS

Detector Control Software

701 DQM

Data Quality Monitoring

702	DT	Drift Tube
703		
704		
705	E	
706		
707	ECAL	electromagnetic calorimeter
708	EMTF	Endcap Muon Track Finder
709		
710		
711	F	
712		
713	FCC	Future Circular Collider
714	FEE	Front-End Electronics
715	FEB	Front-End Board
716	FWHM	full-width-at-half-maximum
717		
718		
719	G	
720		
721	GE-/-	Find a good description
722	GE1/1	Find a good description
723	GE2/1	Find a good description
724	GEANT	GEometry ANd Tracking - a series of software toolkit platforms developed by CERN
725		
726	GEB	GEM Electronics board
727	GEM	Gas Electron Multiplier
728	GIF	Gamma Irradiation Facility
729	GIF++	new Gamma Irradiation Facility
730	GWP	Global Warming Potential
731		
732		
733	H	
734		
735	HCAL	hadron calorimeter
736	HL-LHC	High Luminosity LHC
737	HPL	High-pressure laminate
738	HV	High Voltage
739		
740		
741	I	
742		
743	ICRU	International Commission on Radiation Units & Measurements
744	iRPC	improved RPC

745	IRQ	Interrupt Request
746	ISR	Intersecting Storage Rings
747		
748	L	
749		
750		
751	LEIR	Low Energy Ion Ring
752	LEP	Large Electron-Positron
753	LHC	Large Hadron Collider
754	LS1	First Long Shutdown
755	LS2	Second Long Shutdown
756	LS3	Third Long Shutdown
757	LV	Low Voltage
758	LVDS	Low-Voltage Differential Signaling
759		
760		
761	M	
762		
763	MiC1	first version of Minicrate electronics
764	mip's	minimum ionizing particles
765	MC	Monte Carlo
766	MCNP	Monte Carlo N-Particle
767	ME-/	Find good description
768	ME0	Find good description
769	MRPC	Multigap RPC
770		
771		
772	N	
773		
774	NIM	Nuclear Instrumentation Module logic signals
775		
776		
777	O	
778		
779	OH	Optohybrid Board
780	OMTF	Overlap Muon Track Finder
781		
782		
783	P	
784		
785	PAI	Photo-Absorption Ionisation
786	PAIR	Photo-Absorption Ionisation with Relaxation
787	PMT	PhotoMultiplier Tube

788	PS	Proton Synchrotron
789	PU	pile-up
790		
791		
792	Q	
793		
794	QCD	Quantum Chromodynamics
795	QED	Quantum Electrodynamics
796		
797		
798	R	
799		
800	RE/-	Find a good description
801	RE2/2	Find a good description
802	RE3/1	Find a good description
803	RE3/2	Find a good description
804	RE4/1	Find a good description
805	RE4/2	Find a good description
806	RE4/3	Find a good description
807	RMS	Root Mean Square
808	ROOT	a framework for data processing born at CERN
809	RPC	Resistive Plate Chamber
810		
811		
812	S	
813		
814	SC	Synchrocyclotron
815	SLAC	Stanford Linear Accelerator Center
816	SM	Standard Model
817	SPS	Super Proton Synchrotron
818	SUSY	supersymmetry
819		
820		
821	T	
822		
823	TDC	Time-to-Digital Converter
824	TDR	Technical Design Report
825	ToF	Time-of-flight
826	TPG	trigger primitives
827		
828		
829	W	
830		
831	webDCS	Web Detector Control System

832

833

834

835

836 YETS Year End Technical Stop

Y

1

Introduction

837

838

2

839

840

Investigating the TeV scale

841 „We may regard the present state of the universe as the effect of the
842 past and the cause of the future. An intellect which at any given mo-
843 ment knew all of the forces that animate nature and the mutual posi-
844 tions of the beings that compose it, if this intellect were vast enough
845 to submit the data to analysis, could condense into a single formula
846 the movement of the greatest bodies of the universe and that of the
847 lightest atom; for such an intellect nothing could be uncertain and
848 the future just like the past would be present before its eyes.”

849

850 - Pierre Simon de Laplace, *A Philosophical Essay on Probabilities*, 1814

Throughout history, physics experiment became more and more powerful in order to investigate finer details of nature and helped understanding the elementary blocks of matter and the fundamental interactions that bond them in the microscopic world. Nowadays, the Standard Model (SM) of particle physics is the most accurate theory designed to explain the behaviour of particles and was able to make very precise predictions that are constantly verified, although some hints of new physics are visible as bricks are still missing to have a global comprehension of the Universe.

To highlight the limits of the SM and test the different alternative theories, ever more powerful machines are needed. This is in this context that the Large Hadron Collider (LHC) has been thought and built to accelerate and collide particles at energies exceeding anything that had been done before. Higher collision energies and high pile-up imply the use of enormous detectors to measure the properties of the interaction products. The Compact Muon Solenoid (CMS) is a multipurpose experiment that have been designed to study the proton-proton collisions of the LHC and give answers on various high energy physics scenari. Nevertheless, the luminosity delivered by the collider will in the future be increased to levels beyond the original plans to improve its discovery potential giving no choice to experiments such as CMS to upgrade their technologies to cope with the increased radiation levels and detection rates.

2.1 The Standard Model of Particle Physics

In this early 21st century it is now widely accepted that matter is made of elementary blocks referred to as *elementary particles*. The physics theory that classifies and describes the best the behaviour and interaction of such elementary particles is the so called Standard Model that formalizes 3 of the 4 fundamental interactions (electromagnetic, weak and strong interactions). It's development took place during the 20th century thanks to a strong collaboration in between the theoretical and experimental physicists.

2.1.1 A history of particle physics

The idea that nature is composed of elementary bricks, called *atomism*, is not contemporary as it was already discussed by Indian or Greek philosophers during antiquity. In Greece, atomism has been rejected by Aristotelianism as the existance of *atoms* would imply the existance of a void that would violate the physical principles of Aristotle philosophy. Aristotelianism has been considered as a reference in the european area until the 15th century and the italian *Rinascimento* where antic text and history started to be more deeply studied. The re-discovery of Platon's philosophy would allow to open the door to alternative theories and give a new approach to natural sciences where experimentation would become central. A new era of knowledge was starting. By the begining of the 17th century, atomism was re-discovered by philosophers and the very first attempt to estimate an *atom* size would be provided by Magnetus in 1646. Although his *atoms* correspond to what would nowadays be called *molecules*, Magnetus achieved feats by calculating that the number of molecules in a grain of incense would be of the order of 10^{18} simply by considering the time necessary to smell it everywhere in a large church after the stick was lit on. It is now known that this number only falls short by 1 order of magnitude.

An alternative philosophy to atomism popularized by Descartes was corpuscularianism. Built on ever divisible corpuscles, contrary to atoms, it's principles would be mainly used by alchemists like Newton who would later develop a corpuscular theory of light. Boyle would combine together ideas of both atomism or corpuscularianism leading to mechanical philosophy. The 18th century have

seen the development of engineering providing philosophical thought experiments with repeatable demonstration and a new point of view to explain the composition of matter and Lavoisier would greatly contribute to chemistry and atomism by publishing in 1789 a list of 33 chemical elements corresponding to what is now called *atoms*. In the early 19th century Dalton would summarize the knowledge on composition of matter and Fraunhofer would invent the spectrometer and discover the spectral lines. The rise of atomic physics, chemistry and mathematical formalism would unravel the different atomic elements and ultimately, the 20th century would see the very first sub-atomic particles.

Discovery of the inner structure of the atom

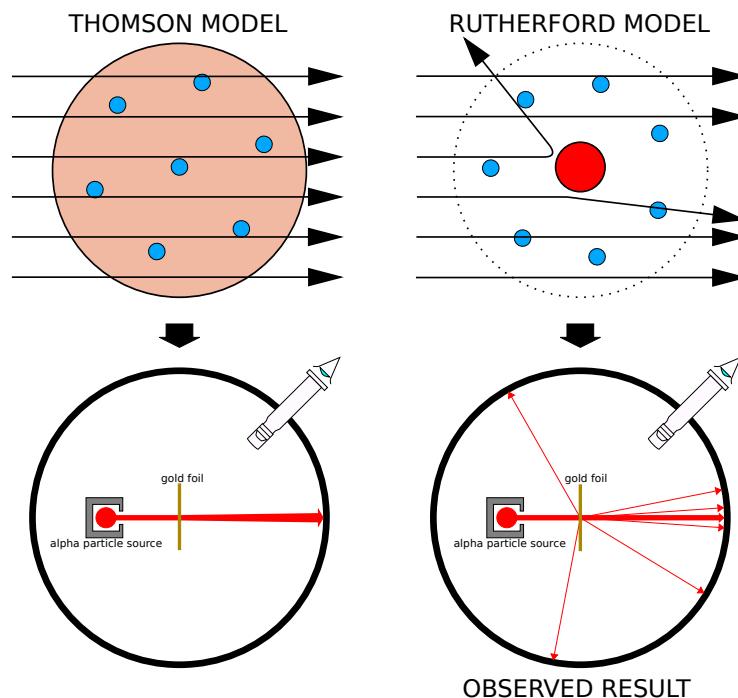


Figure 2.1: Through the gold foil experiment Rutherford could show that most of the mass of atoms was contained in a positively charged nucleus and could then propose a more accurate atomic model than that of Thomson.

The negative *electron* would be the first to be discovered in 1897 by Thomson after 3 decades of research on cathode rays by proving that the electrification observed in an electroscope, as reported by Perrin, was due to the rays themselves and that they had to be composed of electrically charged particles. In 1900, Becquerel would show the *beta rays* emitted by radium had the same charge over mass ratio than what measured by Thomson for cathode rays, pointing to electrons as a constituent of atoms. In 1907, Rutherford and Royds showed that *alpha* particles, once captured in a tube and subjected to an electric spark causing an electron avalanche, where helium ions as they could combine with 2 electrons to form a ${}^4\text{He}$. This discovery was directly followed by the constraint of the atom structure in 1909 through the gold foil experiment in which the deflection angle of alpha particles fired at a very thin gold foil was measured and highlighted atoms where mainly empty with

nearly all its mass contained into a tiny positively charged *nucleus*. With these two observations, he could formulate the Rutherford model of the atom in 1911, shown together with the Thomson plum pudding model in Figure 2.1. The link in between atomic number and number of positive and negative charges contained into the atoms would fast be understood and the different kind of element transmutation appeared to be purely nuclear processes making clear that the electromagnetic nature of chemical transformation could not possibly change nuclei. Thus a new branch in physics appeared to study nuclei exclusively: the nuclear physics.

Moreover, in 1913 quantum physics would be introduced into the atomic model by Bohr based on the assumptions of Plank to explain spectral lines, and other observed quantum effects. The same year, Moseley would confirm Bohr's model and Debye would extend it by introducing elliptical orbits.

By studying alpha emission and the product of their interaction with nitrogen gas, Rutherford reported in 1919 the very first nuclear reaction leading to the discovery that the hydrogen nucleus was composed of a single positively charged particle that was later baptised *proton*. This idea came from 1815 Prout's hypothesis proposing that all atoms are composed of "*protyles*" (i.e. hydrogen atoms). By using scintillation detectors, Rutherford could highlight typical hydrogen nuclei signature and understand that the impact of alpha particles with nitrogen would knock out an hydrogen nucleus and produce an oxygen 17, as explicated in Formula 2.1 and would then postulate that protons are building bricks of all elements.



With this assumption and the discovery of isotopes together with Aston, elements with identical atomic number but different masses, Rutherford would propose that all elements' nuclei but hydrogen's are composed of both charged particles, protons, and of chargeless particles, which he called *neutrons*, and that these neutral particles would help maintaining nuclei as one, as charged protons were likely to electrostatically repulse each other, and introduced the idea of a new force, a *nuclear* force. Though the first idea concerning neutrons was a bond state of protons and electrons as it was known that the beta decay, emitting electrons, was taking place in the nucleus, it was then showed that such a model would hardly be possible due to Heisenberg's uncertainty principle and by the recently measured *spin* of both protons and electrons. The spin, discovered through the study of the emission spectrum of alkali metals, would be understood as a "two-valued quantum degree of freedom" and formalized by Pauli and extended by Dirac, to take the relativist case into account. Measured to be $\frac{1}{2}\hbar$ for both, it was impossible to arrange an odd number of half integer spins and obtain a global nucleus spin that would be integer. Finally, in 1932, following the discovery of a new neutral radiation, Chadwick could discover the neutron as an uncharged particle with a mass similar to that of the proton whose half integer spin would reveal to be the solution to explain the nuclear spin.

947 Development of the Quantum Electrodynamics

Historically, the development of the quantum theory revolved around the question of emission and absorption of discrete amount of energy through light. Einstein used the initial intuition of Plank about the black-body radiation to develop in 1905 a model to explain the photoelectric effect in which light was described by discrete quanta now called *photons*. For this model, Einstein introduced the concept of wave-particle duality as classical theory was not able to describe the phenomenon.

With the new understanding of atoms and of their structure, classical theories also proved unable to explain atoms stability. Indeed, using classical mechanics, electrons orbiting around a nucleus should radiate an energy proportionnal to their angular momentum and thus loose energy through time and the spectrum of energy emission should then be continuous, but it was known since the 19th century and the discovery of spectral lines that the emission spectrum of material was discrete.

This was Bohr who first suggested that a quantum description of the atom was necessary in 1913. Using the correspondence principle stating that at large enough numbers the quantum calculations should give the same results than the classical theory, he proposed the very first quantum model of the hydrogen atom explaining the line spectrum by introducing the principal quantum number n describing the electron shell. This model would then be improved by Sommerfeld that would quantize the z-component of the angular momentum, leading to the second and third quantum numbers, or azimuthal and magnetic quantum number, l and m defining for the second the orbital angular momentum of the electrons on their shells and thus, the shape of the orbital, and for the third the available orbital on the subshell for each electron. Nevertheless, although the model was not only limited to spherical orbitals anymore, making the atom more realistic, the Zeeman effect couldn't be completely explained by just using n , l and m . A solution would be brought after the discovery of Pauli in 1924, as Uhlenbeck, Goudsmit, and Krong proposed in 1925 the idea of intrinsic rotation of the electron, introducing a new angular momentum vector associated to the particle itself, and not to the orbital, and associated to a new quantic number s , the *spin* projection quantum number explaining the lift of degeneracy to an even number of energy levels.

The introduction of the *spin* happened 1 year after another attempt of improvement of the theory was made by De Broglie in his PhD thesis. The original formulation of the quantum theory only considered photons as energy quanta behaving as both waves and particles. De Broglie proposed that all matter are described by waves and that there momentum is proportional to the oscillation of quantized electromagnetic field oscillators. This interpretation was able to reproduce the previous version of the quantum energy levels by showing that the quantum condition involves an integer multiple of 2π , as shown by Formula 2.2.

$$(2.2) \quad p = \hbar k \Leftrightarrow \int pdx = \hbar \int kdx = 2\pi\hbar n$$

Although the intuition of De Broglie about the wave-particle duality of all matter, his interpretation was semiclassical and it's in 1926 that the first fully quantum mechanical wave-equation would be introduced by Schrödinger to describe electron-like particles, reproducing the previous semiclassical formulation without inconsistencies. This complexe equation describes the evolution of the wave function Ψ of the quantum system, defined by its position vector \mathbf{r} and time t as an energy conservation law, in which the hamiltonian of the system \hat{H} is explicit, by solving the Equation 2.3.

$$(2.3) \quad i\hbar \frac{\partial}{\partial t} |\Psi(\mathbf{r}, t)\rangle = \hat{H} |\Psi(\mathbf{r}, t)\rangle$$

In 1927, Dirac would go further in his paper about emission and absorption of radiation by proposing a second quantization not only of the physical process at play but also of the electromagnetic field, providing the ingredients to the first formulation of *Quantum Electrodynamics (QED)* and the description of photon emission by electrons dropping into a lower energy state in which the final number of particles is different than the initial one. To complete this model to the many-body wave functions of identical particles, Jordan included creation and annihilation operators for fields

obeying Fermi-Dirac statistics leading to a model describing particles that would be referred to as *fermions*. Nevertheless, in order to properly treat electromagnetism, the incorporation of the relativity theory developed by Einstein. Including gravity into quantum physics still is a challenge nowadays, but in 1928 Pauli and Jordan would show that special relativity's coordinate transformations could be applied to quantum fields as the field commutators were Lorentz invariant. Finally derived the same year, the Dirac equation, shown as Equation 2.4, similarly to Schrödinger's equation, is a single-particle equation but it incorporates special relativity in addition to quantum mechanics rules. It features the 4×4 gamma matrices γ^μ built using 2×2 Pauli matrices and unitary matrix, the 4-gradient ∂_μ , the rest mass m of any half integer spin massive particle described by the wave function $\psi(x, t)$, also called a Dirac spinor, and the speed of light c . In addition to perfectly reproduce the results obtained with quantum mechanics so far, it also provided with *negative-energy solutions* that would later be interpreted as a new form of matter, *antimatter* and give a theoretical justification to the Pauli equation that was phenomenologically constructed to account for the spin as in the non-relativistic limit, the Dirac equation is similar.

$$(2.4) \quad i\hbar\gamma^\mu\partial_\mu\psi - mc\psi = 0$$

The successes of the QED was soon followed with theoretical problems as computations of any physical process involving photons and charged particles were showed to be only reliable at the first order of perturbation theory. At higher order of the theory, divergent contributions were appearing giving nonsensical results. Only two effects were contributing to these infinities.

- The self-energy of the electron (or positron), the energy that the particle has due its own interaction with its environment.
- The vacuum polarization, virtual electron–positron pairs produced by a background electromagnetic field in the vacuum which is not an "empty" space. These virtual pairs affect the charge and current distributions generated by the original electromagnetic field.

Solving this apparent problem was done by carefully defining the concepts of each observables, for example mass or charge, as these quantities are understood within the context of a non-interacting field equation, and that from the experiment point of view, they are abstractions as what is measured are "renormalized observables" shifted from there "bare" value by the interaction taking place in the measuring process. The infinities needed to be connected to corrections of mass and charge as those are fixed to finite values by experiment. This was the intuition of Bethe in 1947 who successfully computed the effect of such *renormalization* in the non-relativist case. Fully covariant formulations of QED including renormalization was achieved by 1949 by Tomonaga, Schwinger, Feynman and Dyson and Feynman is now famous for his association of diagrams to the term of the scattering matrix, greatly simplifying the representation and computation of interactions as the diagrams directly corresponded the measurable physical processes and would then be used in every quantum field theories. With the resolution of infinities, QED had mostly reached its final form, being still today the most accurate physical theory and would serve as a model to build all other quantum field theories.

Development of the quark model and Quantum Chromodynamics

To explain the nuclear force that holds *nucleons* (protons and neutrons) together, Yukawa theoretically proposed in 1934 the existence of a force carrier called *meson* due to it's predicted mass in

the range in between the electron and nucleon masses. Discovered in 1936 by Anderson and Neddermeyer, and confirmed using bubble chambers in 1937 by Street and Stevenson, a first meson candidate was observed in the decay products of cosmic rays. Assuming it had the same electric charge than electrons and protons, this particle was observed to have a curvature due to magnetic field that was sharper than protons but smoother than electrons resulting in a mass in between that of electrons and protons. But its properties were not compatible with Yukawa's theory, which was emphasized by the discovery of a new candidate in 1947, again in cosmic ray products using photographic emulsions.

This new candidate, although it had a similar mass than the already believed *meson*, would rather decay into it. For distinction, the first candidate would then be renamed "*mu meson*" when the second would be the "*pi meson*". The *mu meson* was behaving like a heavy electron and didn't participate in the strong interaction whereas the pion was believed to be the carrier of the nuclear interaction. This lead to classify the *mu* in a new category of particles called *leptons* together with the electron that shared similar properties and *the neutrino*, and be renamed *muon*. The *pi meson* was finally found to be a triplet of particles: a positively charged, a negatively charged, and a neutral particle. The neutral *pi meson* has been more difficult to identify as it wouldn't leave tracks on emulsions nor on bubble chambers and needed to be studied via it's decay products. It was ultimately identified in University of California's cyclotron in 1950 through the observation of its decay into 2 photons.

Also discovered in 1947 but in cloud chamber photographs, the *K meson* as also been an important step towards the establishment of the Standard Model. A triplet of particle, 2 charged and a neutral, with a mass roughly half that of a proton, were reported. These particles were baptised *K meson* in contrast to the "light" *pi* and *mu* "L-mesons". The particularity of the *K* were there very slow decays with a typical lifetime of the order of 10^{-10} s much greater than the 10^{-23} s of *pi*-proton reactions. The concept of *strangeness*, a new quantum number was then introduced by Pais as an attempt to explain this phenomenon as *strange* particles appeared as a pair production of a strange and anti-strange particle.

With the development of synchrotrons, the particle *zoo* would grow to several dozens during the 1950s as higher energies were reachable through acceleration. In 1961, a first classification system, called Eightfold Way, was proposed by Gell-Mann and finding its roots in the Gell-Mann–Nishijima formula, which relates the electric charge Q , the third component of the isospin I_3 , the *baryon* number B and the strangeness S , as explicitated in Formula 2.5. The isospin was a quantum number introduced in 1932 to explain symmetries of the newly discovered neutron using representation theory of SU(2). The baryon number, was introduced by Nishijima as a quantum number for baryons, i.e. particles of the same family as nucleons. The mesons were classified in an octet and baryons of spin $\pm \frac{1}{2}$ and $\pm \frac{3}{2}$ were respectively classified into an octet and a decuplet, as shown in Figure 2.2. To complete the baryon decuplet, Gell-Mann predicted the existance of baryon Ω^- which would later be discovered in 1964.

$$(2.5) \quad Q = I_3 + \frac{1}{2}(B + S)$$

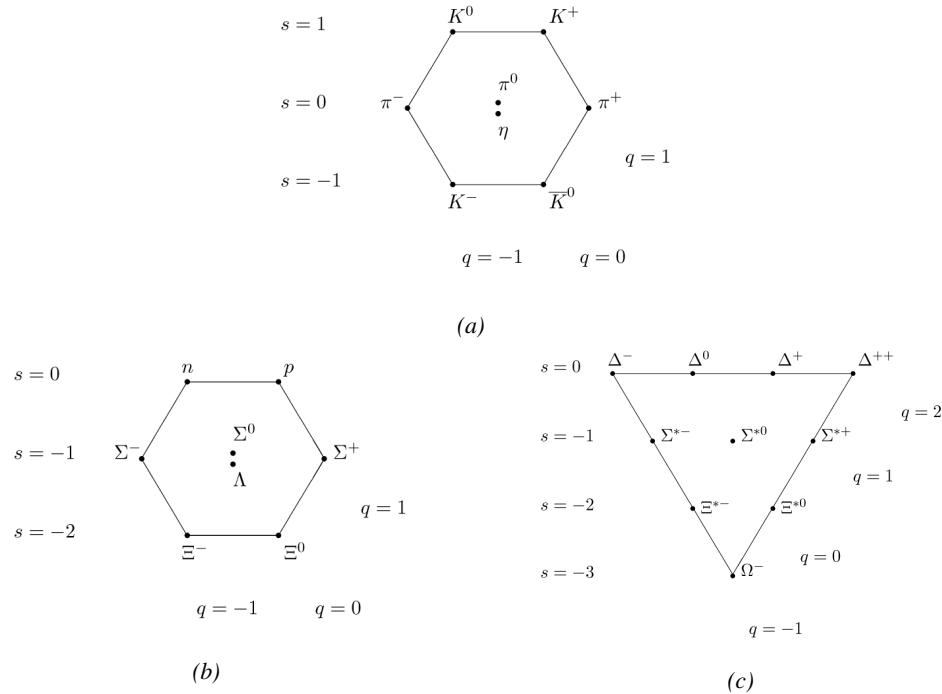


Figure 2.2: Figure 2.2a: Meson octet. Figure 2.2b: Baryon octet. Figure 2.2c: Baryon decuplet.

Strong of this classification using an SU(3) flavor symmetry, Gell-Mann, and independently Zweig, would propose a full theoretical model in which *hadrons* (strongly interacting particles, i.e. mesons and baryons) were not elementary particles anymore. They would rather be composed with 3 flavors of particles called *quarks* and there anti-particles. The 3 flavors were called *up*, *down* and *strange*. *Up* and *down* would be used to explain the nucleons and non-strange mesons, while *strange* would come into the composition of hadrons showing strangeness. *Up* and *down* flavors would be discovered in 1968 thanks to the deep inelastic scattering experiments conducted at the Stanford Linear Accelerator Center (SLAC), and *strange* could only be indirectly validated even though it provided a robust explanation to *kaon* (K) and *pion* (π). However, in the decade following the Gell-Mann-Zweig quark model proposition, several improvement to the model were brought, first by Glashow and Bjorken the same year that predicted the existence of a fourth quark flavor, the *charm*, that would equalize the then known number of quarks and leptons and finally in 1973 by Kobayashi and Maskawa that would increase the number of quarks to 6 to explain the experimental observation of CP violation. These two quarks would be referred to as *top* and *bottom* for the first time in 1975. It's only after these additions to the quark model that finally the *charm* would be discovered in 1974 at both SLAC and Brookhaven National Laboratory (BNL). A meson where the *charm* was bound with an *anti-charm*, called J/ψ , would help convince the physics community of the validity of the model. The *top* would be discovered soon after in 1977 in Fermilab and indicate the existence of the *bottom* that would resist to discovery until Fermilab's experiments CDF and D \emptyset in 1995 due to its very large mass and the energy needed to produce it.

As remarked by Struminsky, the original quark model proposal composed of 3 quarks should possess an additional quantum number due to mesons such as Ω^- or Δ^{++} . Indeed, these mesons are composed of 3 identical quarks, respectively 3 *strange* and *up* quark, with parallel spins, which

should be forbidden by the exclusion principle. Independentle, Greenberg and Han-Nambu proposed an additional SU(3) degree of freedom possessed by the quarks, that would later be refered to as *color charge gauge*, that could interact through *gluons*, the gauge boson octet corresponding to this degree of freedom. Nevertheless, as observing free quarks proved to be impossible, two visions of the quarks were argued mainly due to the failures to observe these particles free to prove their existence. On one side, Gell-Mann proposed to see quarks as mathematical construct instead of real particles, as they are always confined, implying that quantum field theory would not describe entirely the strong interaction. Opposed to this vision, Feynman on the contrary argued that quarks were real particles, that he would call *partons*, that should be described as all other particles by a distribution of position and momentum. The implications of quarks as point-like particles would be verified at SLAC and the concept of *color* would be added to the quark model in 1973 by Fritzsch and Leutwyler together with Gell-Mann to propose a description of the strong interaction through the theory of Quantum Chromodynamics (QCD). The discovery the same year of asymptotic freedom within the QCD by Groos, Politzer and Wilczek, allowed for very precise predictions thanks to the perturbation theory. Nowadays, the confinement of quarks is studied in experiments such as ALICE, through exploration of the quark-gluon plasma.

1108 The Weak interaction, spontaneous symmetry breaking, the Higgs mechanism and the Elec- 1109 troweak unification

1110 The weak interaction is the process that causes radioactive decays. Thanks to the neutron discovery,
 1111 Fermi could explain in 1934 the beta radiations through the beta decay process in which the neutron
 1112 decays into a proton by emitting an electron. Though the missing energy observed during this
 1113 process triggered a huge debate about the apparent non conservation of energy, momentum and spin
 1114 of the process, Fermi, as Pauli before him, proposed that the missing energy was due to a neutral
 1115 not yet discovered particle that would then be baptised *neutrino*. The impossibility to detect such
 1116 a particle would leave some members of the scientific community sceptical, but hints of energy
 1117 conservation and of the existence of the neutrino were provided by measuring the energy spectrum
 1118 of electrons emitted through beta decay, as there was a strict limit on their energy. It's only 30 years
 1119 later in 1953 that it would be discovered by the team of Cowan and Reines using the principle of
 1120 inverse beta decay described through Formula 2.6. The experiment consisted in placing water tanks
 1121 sandwiched in between liquid scintillators near a nuclear reactor with an estimated neutrino flux of
 1122 $5 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$. However, in order to explain the absence of some reactions in the experiment
 1123 of Cowan and Reines, and constraint the beta decay theory of Fermi and extend it to the case of
 1124 the muon, Konopinski and Mahmoud proposed in 1953 that the muon decay would eject a particle
 1125 similar to the neutrino and thus predicted the existence of a muon neutrino that would be different
 1126 than the one involved in the beta decay, related to the electron. With this, the idea of lepton number
 1127 would arise. The muon neutrino would successfully be detected in 1962 by Lederman, Schwartz and
 1128 Steinberger.

$$(2.6) \quad \bar{\nu} + p \rightarrow n + e^+$$

1129 The theory could not be valid though as the probability of interaction, called cross-section, would
 1130 have been increasing without bond with the square of the energy. Fermi assumed in a two vector
 1131 current coupling but Lee and Yang noted that an axial current could appear and would violate parity.
 1132 The experiment of Wu in 1956 would confirm the parity violation and Gamov and Teller would try to

1133 account for it by describing Fermi's interaction through allowed (parity-violating) and superallowed
1134 (parity-conserving) decays. But the success of QED as a quantum field theory would spark the
1135 development of such a theory to describe the weak interaction.

1136 As previously discussed, the great success of QED was built on an underlying symmetry, inter-
1137 preted as a gauge invariance so that the effect of the force is the same in all space-time coordinates,
1138 and of the possibility to renormalize it in order to absorb the infinities. Independently in 1958,
1139 Glashow, and Salam and Ward used 1957 Schwinger ideas about vector intermediary for the decay
1140 processes, could find a way to unite both the electromagnetic and weak interaction into a gauge
1141 theory involving 4 gauge bosons, 3 of which were massive and carried out the weak interaction and
1142 a massless boson carrying the electromagnetic interaction. Among the 3 massive bosons, 2 were
1143 charged and 1 was neutral, similarly to the previously theorized *pi meson* vector of the Yukawa
1144 model and all have a mass much greater than nucleons and thus a very short life time implying a
1145 finite very short range contrary to the contact interaction originally proposed by Fermi.

1146 Breakthrough in other fields of physics contributed in giving theoretical support and interpreta-
1147 tion to the unified electroweak theory. The stepping stone would be the use of spontaneous symmetry
1148 breaking that was inspired to Nambu at the end of the 1950s following the development of the BCS
1149 superconductivity mechanism in 1957. Cooper had shown that BCS pairs, pairs of electrons bound
1150 together at low temperature, could have lower energy than the Fermi energy and where responsi-
1151 ble for superconductivity. This lead to the discovery of Goldstone-Nambu bosons as a result of the
1152 spontaneous breaking of the chiral symmetry in a theory describing nucleons and mesons devel-
1153 opped by Nambu and Jona-Lasinio in 1961, and now understood as a low-energy approximation of
1154 QCD. Similarly to mechanism of energy gap appearance in superconductivity, the nucleon mass
1155 is suggested to the result of a self-energy of a fermion field and is studied through a four-fermion
1156 interaction in which, as a consequence of the symmetry, bound states of nucleon-antinucleon pairs
1157 appear and can be regarded as virtual pions. Though the symmetry is maintained in the equations,
1158 the ground state is not preserved. Goldstone would later the same year show that the bound states
1159 corresponds to spinless bosons with zero mass.

1160 Although the model in itself didn't revolutionize particle physics, spontaneous symmetry break-
1161 ing would be generalized to quantum field theories. As all fundamental interactions are described
1162 using gauge theories based on underlying symmetries, processes such as the chiral symmetry break-
1163 ing would be introduced soon after the publication of Nambu and Jona-Lasinio. In 1962, Anderson,
1164 following an idea of Schwinger who suggested that zero-mass vector bosons were not necessarily
1165 required to describe the conservation of baryons contrary to the bosons emerging from chiral sym-
1166 metry breaking, discussed the implications of spontaneous symmetry breaking in particles physics.
1167 A model was finally independently built in 1964 by Brout and Englert, Higgs, and Guralnik, Hagen,
1168 and Kibble, who discovered that combining an additional field into a gauge theory in order to break
1169 the symmetry, the resulting gauge bosons acquire a nonzero mass. Moreover, Higgs stated that this
1170 implied the existence of at least one new massive, i.e. self-interacting, scalar boson, that are now
1171 known as *Higgs bosons* corresponding to this additional field. The Higgs mechanism today specific-
1172 ally refers to the process through which the gauge bosons of the weak interaction acquire mass. In
1173 1968, Weinberg could point to the Higgs mechanism to integrate a Higgs field into a new version
1174 of the electroweak theory in which the spontaneous symmetry breaking mechanism of the Higgs
1175 field would explicitly explain the masses of the weak interaction gauge bosons and the zero-mass
1176 of photons.

1177 2.1.2 Construction and test of the model

1178 The Standard Model of particle physics was built in the middle of the 1970s after the experimental
 1179 confirmation of the existence of quarks. It is based on the assembly of the models previously intro-
 1180 duced and describing the fundamental interactions, except for gravitation, and their gauge bosons
 1181 as well as the way elementary "matter" particles interact with the fields associated with these force
 1182 carriers. In this sense, the development of QED and the unification of the electroweak interaction,
 1183 of the Yukawa interaction and of QCD, and of the Higgs mechanism made it possible to explain most
 1184 of contemporary physics.

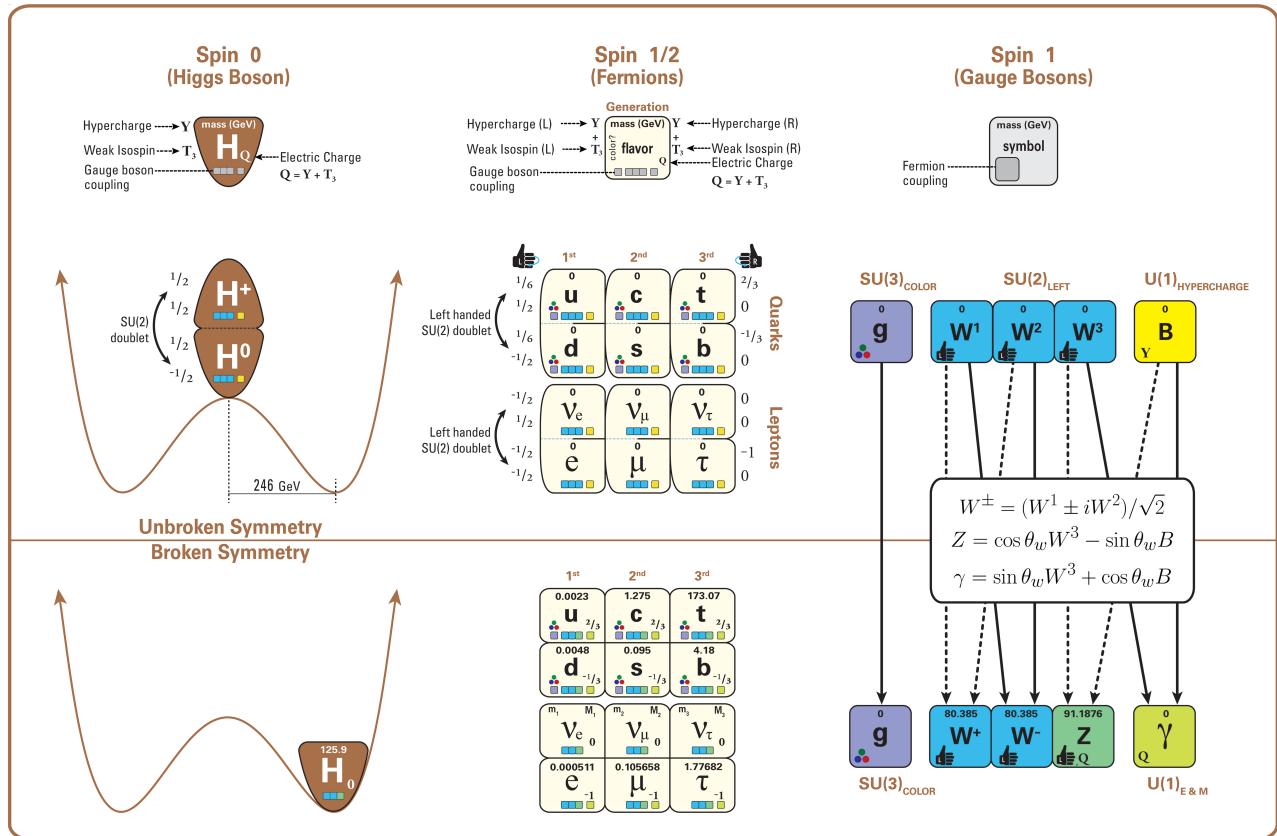


Figure 2.3: The elementary particles of the Standard Model are showed along with their names and properties. Their interactions with the strong, weak and electromagnetic forces have been explicited using color squares. In the left column, the scalar higgs boson is depicted, while the central is focused on the matter particles, the fermions, and the right on the force carriers, the gauge bosons. The role of the Higgs boson in electroweak symmetry breaking is highlighted, and the corresponding way properties of the various particles differ in the (high-energy) symmetric phase (top) and the (low-energy) broken-symmetry phase (bottom) are showed.

1185 In the SM, "matter" particles, are described by 12 fermion fields of spin $\frac{1}{2}$ obeying the Fermi-
 1186 Dirac statistics, i.e. subjected to the Pauli exclusion principle. To each fermion is associated its
 1187 corresponding antiparticle. The fermions are classified according to the way they interact and, thus,
 1188 according to the charges they carry. 6 of them are classified as quarks (u, d, c, s, t , and b) and
 1189 are subjected to all interactions and the 6 others as leptons ($e^-, \mu^-, \tau^-, \nu_e, \nu_\mu$, and ν_τ). Leptons

1190 are not subjected to the strong interaction and among them, the 3 neutrinos only interact weakly as
 1191 they are neutral particles, which explains why they are so difficult to detect. The gauge boson fields
 1192 are the gluons g for the strong interaction, the photon γ for the electromagnetic interaction and the
 1193 weak bosons W^+ , W^- , and Z^0 for the weak interaction. Finally, the Higgs field H^0 is responsible,
 1194 through the spontaneous symmetry breaking, of the mixing of the massless electroweak boson fields
 1195 W_1 , W_2 , W_3 , and B leading to the observable states γ , W^+ , W^- , and Z^0 that can gain mass while
 1196 interacting with the Higgs field. This picture of the SM is summarized through Figure 2.3 where the
 1197 antifermions are not showed.

1198 When the model was first finalized, the existence of the weak gauge bosons, of the charm, of the
 1199 third quark generation composed of top and bottom quarks to explain the observed CP violation was
 1200 not proven but the predictions were measured with good precision in the years following. First, the
 1201 charm quark would be discovered in 1974, followed by the bottom quark in 1977. The weak bosons
 1202 would be discovered during the next decade in 1983. The top quark would resist until 1995 due to
 1203 its very large mass but would offer the last piece of the elementary QCD particles. The very last
 1204 predicted elementary particle of the model that was not observed yet would prove to be very difficult
 1205 to observe. The Higgs boson needed the start of the LHC to finally be observed in 2012. A few years
 1206 more of tests were necessary to measure its properties to confirm the observation of a scalar boson
 1207 compatible with the predicted Higgs boson H^0 . Even though only quark-antiquark (mesons) and 3
 1208 quark states (baryons) were observed, exotic hadrons were not forbidden by QCD and no limit of
 1209 quark is imposed by the theory. Moreover, gluons could form bond states by themselves and with
 1210 quarks. These two types of states are called *glueballs* and *hybrid hadrons*. For decades, experi-
 1211 ments have been conducted without confirmation of such possible states existing. Nevertheless, in
 1212 2014, tetraquarks were observed by LHCb, one of LHC's main experiments, and in 2015, the same
 1213 experiment reported the discovery of pentaquarks making the SM one of the best tested theories of
 1214 physics.

1215 2.1.3 Investigating the TeV scale

1216 Even though the SM is a well tested theory, several hints of physics going beyond its scope have
 1217 been observed. First of all, gravity is not explained through this model and huge difficulties are en-
 1218 countered when trying to include gravitation. The strength of gravitational interaction is expected to
 1219 be negligible at the scale of elementary particles, nevertheless, adding gravitation in the perspective
 1220 of developing a "theory of everything" leads to divergent integrals that could not be fixed through
 1221 renormalization.

1222 Moreover, the SM considers neutrinos to be massless but it was shown in the late 1960s by the
 1223 Homestake experiment that the flux of solar neutrinos (i.e. ν_e) measured didn't match the predicted
 1224 values due to neutrino oscillations, confirmed in the early 2000s by the Sudbury Neutrino Obser-
 1225 vatory. This oscillation implies that neutrinos that can be observed are a superposition of massive
 1226 neutrino states. The research on neutrino oscillation is already quite advanced with experiments
 1227 looking at atmospheric, reactor or beam neutrinos in order to determine the elements of the mixing
 1228 matrix similar to the CKM matrix describing the mixing of quarks. Nevertheless, no answer to the
 1229 origin of neutrino mass is provided.

1230 Another intriguing fact is that the universe is dominated by matter. However, the SM predicted
 1231 that matter and antimatter should have been created in equal amounts and no mechanism is able to
 1232 explain this matter-antimatter asymmetry. Although this asymmetry is seen from the visible uni-
 1233 verse, it may be possible that other unknown regions of the Universe are dominated by antimatter.

1234 Another possibility to explain the apparent asymmetry would be the existence of a electric dipole
1235 in any fundamental particle that would permit matter and antimatter particles to decay at different
1236 rates.

1237 The discrepancy of velocity dispersion of stars in galaxies with respect to the visible mass they
1238 contain is known since the end of the 19th century where Kelvin proposed that this problem could
1239 be solved if a "*great majority of [the stars] would be dark bodies*". Throughout the 20th century,
1240 physicists like Kapteyn, Zwicky, showed the first hints of a "*dark matter*" by studying star veloc-
1241 ities and galactic clusters, followed by robust measurements of galaxy rotation curves by Babcock
1242 which suggested that the mass-to-luminosity ratio was different from what would be expected from
1243 watching the visible light. Later in the 1970s, Rubin and Ford from direct light observations and
1244 Rogstad and Shostak from radio measurements showed that the radial velocity of visible objects in
1245 galaxies was increasing with increasing distance to the center of the galaxy. Finally observation of
1246 lensing effect by galaxy clusters, temperature distribution of hot gas in galaxies and clusters, and
1247 the anisotropies in the Cosmic Microwave Background (CMB) kept on pointing to a "*dark matter*".
1248 From all the data accumulated, the visible matter would only account to no more than 5% of the total
1249 content on the visible universe. Alternative theories have tried to investigate modified versions of
1250 the General Relativity as this theory is only well tested at the scale of the solar system but is not suf-
1251 ficiently tested on wider ranges or even theories in which gravitation is not a fundamental force but
1252 rather an emergent one, but so far, such theories have difficulties to reproduce all the experimental
1253 observations as easily as through dark matter.

1254 A possible theory to offer dark matter candidates would be supersymmetry (SUSY) which pro-
1255 poses a relationship in between bosons and fermions. In this model, each elementary particle,
1256 through a spontaneous spacetime symmetry breaking mechanism would have a *super partner* from
1257 the other family of particles. On top of providing heavy dark matter candidates, supersymmetry
1258 could also help solving the *Hierarchy problem*, the very large scale difference in between the weak
1259 interaction and gravity, although, as mentioned before, in the case gravity is found not to be a funda-
1260 mental force, this problem would automatically fade.

1261
1262 All these different aspects of physics beyond the Standard Model of particle physics and the
1263 Standard model itself can be tested through the use of very energetic and intense hadron and ion col-
1264 liders. The LHC at CERN is a perfect tool to seek answers to these open questions except maybe for
1265 the gravity as gravity is extremely weak at particles level. For example, one of LHCb experiment's
1266 goal is to investigate CP-violation and thus baryonic asymmetry. In 2017, the collaboration has an-
1267 nounced to have so far a 3.3σ statistical significance over a CP-violation through the study of the
1268 decays of Λ_b^0 and $\overline{\Lambda}_b^0$ into a proton (or antiproton) and 3 pions. Many analysis teams are also working
1269 hard on supersymmetry both in ATLAS and CMS collaborations, the two multipurpose experiments
1270 of LHC, even though no evidence of a supersymmetrical theory was seen, the few hint having the
1271 tendency to confirm the standard model. These experiments also have the possibility to investigate
1272 ways to explain Majorana neutrino mass through Yukawa interactions of scalar particles.

1273 The higher the center-of-mass energy, the smaller details the experiments will be able to see, the
1274 heavier the potential particle creation barrier will be, the stronger the cross-section of certain rare
1275 decay channels will be. As a comparison, with collisions happening at 14 TeV, the LHC is approxi-
1276 mately 2 orders of magnitude more sensitive to the Higgs than the Tevatron was with its already very
1277 powerful 2 TeV. All these advantages eventually lead to new discoveries and deeper understanding
1278 of the models describing our Universe. But the LHC only is a step forward to gather more precise
1279 tests of the Standard Model and new knowledge about the physics beyond it. A successful physics

1280 campaign will probably serve to justify the building of new accelerators with even greater discovery
1281 potential like for example the Future Circular Collider (FCC) that would push even further the study
1282 of the unanswered questions of contemporary physics.

1283 2.2 The Large Hadron Collider & the Compact Muon Solenoid

1284 Throughout its history, CERN has played a leading role in high energy particle physics. Large re-
1285 gional facilities such as CERN were thought after the second world war in an attempt to increase
1286 international scientific collaboration and allows scientists to share the forever increasing costs of
1287 experiment facilities required due to the need for increasing the energy in the center of mass to
1288 deeper probe matter. The construction of the first accelerators at the end of the 50s, the Synchro-
1289 cyclotron (SC) and the Proton Synchrotron (PS), was directly followed by the first observation of
1290 antinuclei in 1965 [1]. Strong from the experience of the Intersecting Storage Rings (ISR), the very
1291 first proton-proton collider that showed hints that protons are not elementary particles, the Super
1292 Proton Synchrotron (SPS) was built in the 70s to investigate the structure of protons, the preference
1293 for matter over antimatter, the state of matter in the early universe or exotic particles, and lead to
1294 the discovery in 1983 of the W and Z bosons [2–5]. These newly discovered particles and the elec-
1295 troweak interaction would then be studied in details by the Large Electron-Positron (LEP) collider
1296 that will help to prove in 1989 that there only are three generations of elementary particles [6]. The
1297 LEP would then be dismantled in 2000 to allow for the LHC to be constructed in the existing tunnel.

1298 2.2.1 LHC, the most powerful particle accelerator

1299 The LHC has always been considered as an option to the future of CERN. At the moment of the
1300 construction of the LEP beneath the border between France and Switzerland, the tunnel was built in
1301 order to accomodate what would be a Large Hadron Collider with a dipole field of 10 T and a beam
1302 energy in between 8 and 9 TeV [7] directly followed in 1985 with the creation of a 'Working Group
1303 on the Scientific and Technological Future of CERN' to investigate such a collider [8]. The decision
1304 was finally taken almost 10 years later, in 1994, to construct the LHC in the LEP tunnel [9] and the
1305 approval of the 4 main experiments that would take place at the 4 interaction points would come in
1306 1997 [10] and 1998 [11]:

- 1307 • ALICE [12] has been designed in the purpose of studying quark-gluon plasma that is believed
1308 to have been a state of matter that existed in the very first moment of the universe.
- 1309 • ATLAS [13] and CMS [14] are general purpose experiments that have been designed with
1310 the goal of continuing the exploration of the Standard Model and investigate new physics.
- 1311 • LHCb [15] has been designed to investigate the preference of matter over antimatter in the
1312 universe through the CP violation.

1313 These large scale experiments, as well as the full CERN accelerator complex, are displayed on
1314 Figure 2.4. The LHC is a 27 km long hadron collider and the most powerful accelerator used for
1315 particle physics since 2008 [16]. The LHC was originally designed to collide protons at a center-
1316 of-mass energy of 14 TeV and luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, as well as Pb ions at a center-of-mass
1317 energy of 2.8 TeV/A with a peak luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$. Run 1 of LHC, when the center-of-
1318 mass energy only was half of the nominal LHC energy, was enough for both CMS and ATLAS to

discover the Higgs boson [17] and for LHCb to discover pentaquarks [18] and confirm the existance of tetraquarks [19]. Nevertheless, after the Third Long Shutdown (LS3) (2024-2026), the accelerator will be in the so called High Luminosity LHC (HL-LHC) configuration [20], increasing its instantaneous luminosity to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for pp collisions and to $4.5 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$, boosting the discovery potential of the LHC. The HL-LHC phase should last at least another 10 years depending on the breakthrough this machine would lead to. Already a new accelerating device, the FCC, as been proposed to prepare the future of high energy physics after the LHC.

CERN's Accelerator Complex

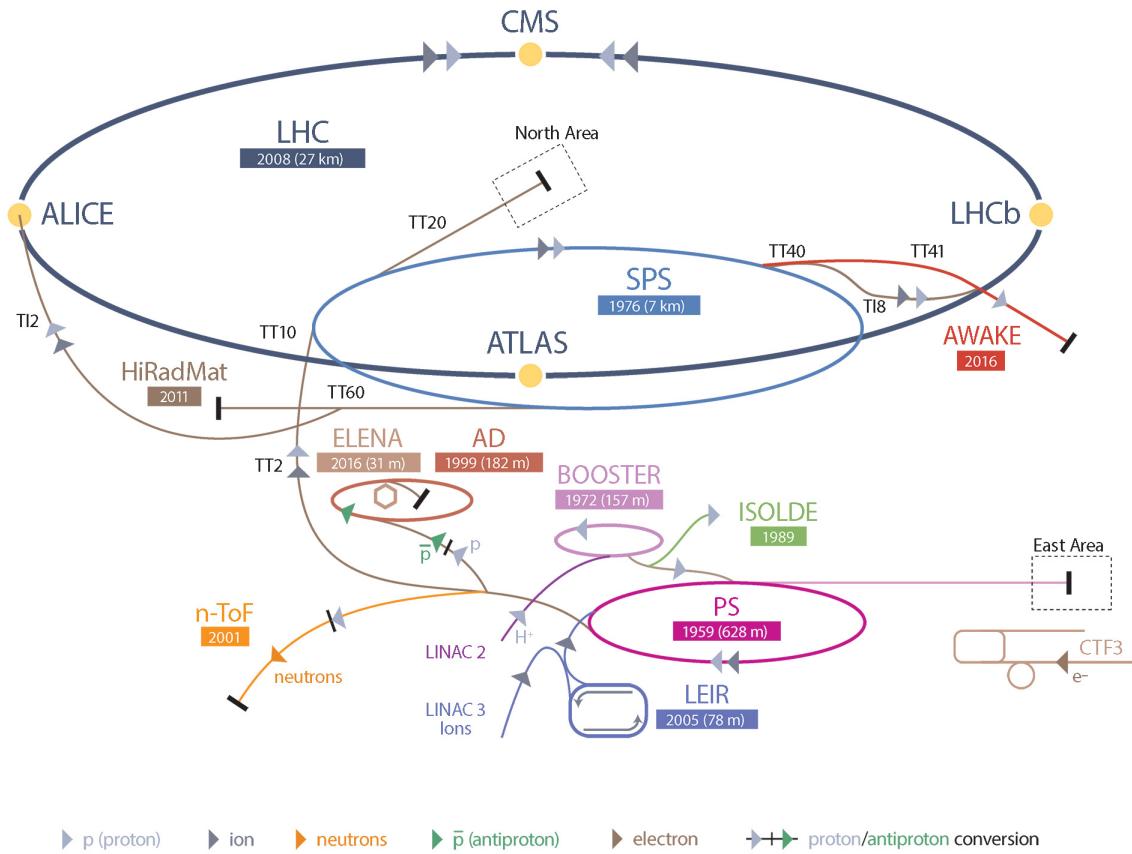


Figure 2.4: CERN accelerator complex.

2.2.1.1 Particle acceleration

The LHC is the last of a long series of accelerating devices. Before being accelerated by the LHC, the particles need to pass through different acceleration stages. All these acceleration stages are visible on Figure 2.4 and pictures of the accelerators are showed in Figure 2.5.

The story of accelerated protons at CERN starts with a bottle of hydrogen gas injected into the source chamber of the linear particle accelerator *LINAC 2* in which a strong electric field strips the

1333 electron off the hydrogen molecules only to keep their nuclei, the protons. The cylindrical conductors,
 1334 alternatively positively or negatively charged by radiofrequency cavities, accelerate protons by
 1335 pushing them from behind and pulling them from the front and ultimately give them an energy of
 1336 50 MeV, increasing their mass by 5% in the process.

1337

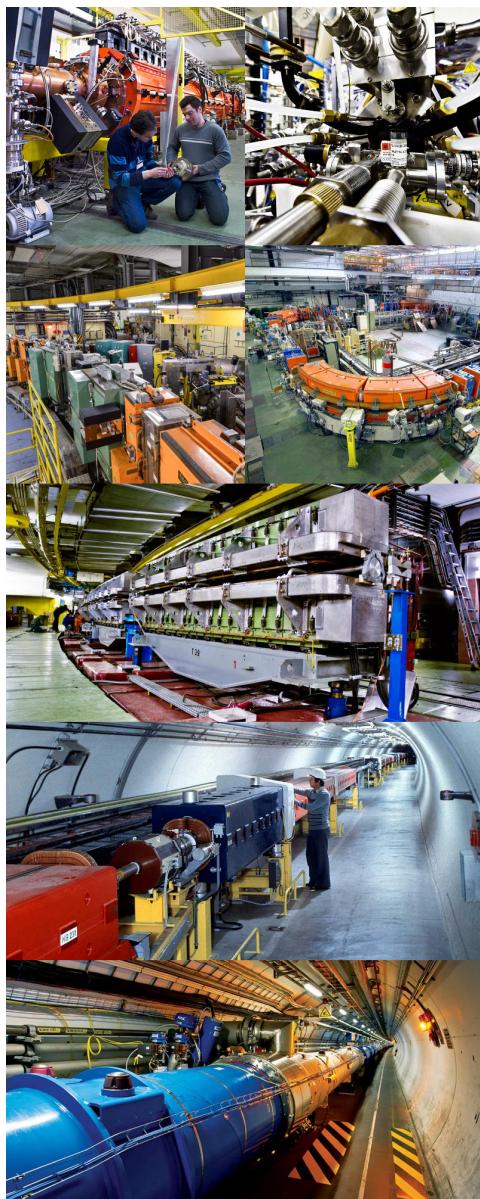


Figure 2.5: Pictures of the different accelerators. From top to bottom: first the LINAC 2 and the Pb source of LINAC 3. Then the Booster and the LEIR. Finally, the PS, the SPS and the LHC.

1338 When exiting the LINAC 2, the protons are divided into 4 bunches and injected into the 4 su-
 1339 perimposed synchrotron rings of the *Booster* where they are then accelerated to reach an energy of

1340 1.4 GeV before being injected into the PS. Before the Booster was operational in 1972, the protons
 1341 were directly injected into the PS from the LINAC 2 but the low injection energy limited the amount
 1342 of protons that could be accelerated at once by the PS. With the Booster, the PS accepts approxi-
 1343 mately 100 times more particles.

1344

1345 The 4 proton bunches are thus sent as one to the PS where their energy eventually reaches
 1346 26 GeV. Since the 70s, the main goal of this 628 m circumference synchrotron has been to sup-
 1347 ply other machines with accelerated particles. Nowadays, not only the PS accelerates protons, it also
 1348 accelerates heavy ions from the *Low Energy Ion Ring (LEIR)*. Indeed, the LHC experiments are not
 1349 only designed to study *pp*-collisions but also *Pb*-collisions. Lead is first injected into the dedicated
 1350 linear collider *LINAC 3*, that accelerate the ions using the same principle than LINAC 2. Electrons
 1351 are striped off the lead ions all along the acceleration process and eventually, only bare nuclei are
 1352 injected in the LEIR whose goal is to transform the long ion pulses received into short dense bunches
 1353 for LHC. Ions injected and stored in the PS were aceelerated by the LEIR from 4.2 MeV to 72 MeV.

1354

1355 Directly following the PS, is finally the last acceleration stage before the LHC, the 7 km long
 1356 *SPS*. The SPS accelerates the protons to 450 GeV and inject proton in both LHC accelerator rings
 1357 that will increase their energy up to 7 TeV. When the LHC runs with heavy lead ions for ALICE
 1358 and LHCb, ions are injected and accelerated to reach the energy of 2.8 TeV/A.

1359

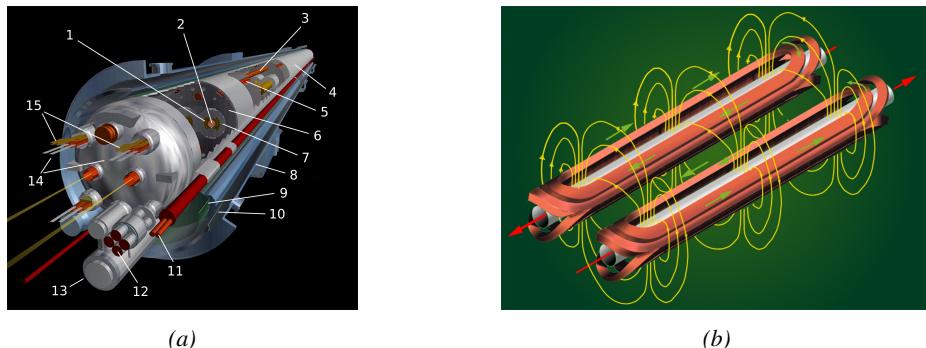


Figure 2.6: Figure 2.6a: schematics of the LHC cryodipoles. 1: Superconducting Coils, 2: Beam pipe, 3: Heat exchanger Pipe, 4: Helium-II Vessel, 5: Superconducting Bus-bar, 6: Iron Yoke, 7: Non-Magnetic Collars, 8: Vacuum Vessel, 9: Radiation Screen, 10: Thermal Shield, 11: Auxiliary Bus-bar Tube, 12: Instrumentation Feed Throughs, 13: Protection Diode, 14: Quadrupole Bus-bars, 15: Spool Piece Bus-bars. Figure 2.6b: magnetic field and resulting motion force applied on the beam particles.

1360

1361 The LHC beams are not continuous and are rather organised in bunch of paticles. When in *pp*-
 1362 collision mode, the beams are composed of 2808 bunches of 1.15×10^{11} protons separated by 25 ns.
 1363 When in *Pb* collision mode, the 592 *Pb* bunches are on the contrary composed of 2.2×10^8 ions
 1364 separated by 100 ns. The two parrallel proton beams of the LHC are contained in a single twin-
 1365 bore magnet due to the space restriction in the LEP tunnel. Indeed, building 2 completely separate
 1366 accelerator rings next to each other was impossible. The dipoles of the 1232 twin-bore magnets are
 1367 showed in Figure 2.6 alongside the magnetic field generated along the dipole section to accelerate the
 1368 particles. The dipoles generate a nominal field of 8.33 T, needed to give protons and lead nucleons
 their nominal energy. Some 392 quadrupoles, presented in Figure 2.7, are also used to focus to the

1369 beams, as well as other multipoles to correct smaller imperfections.

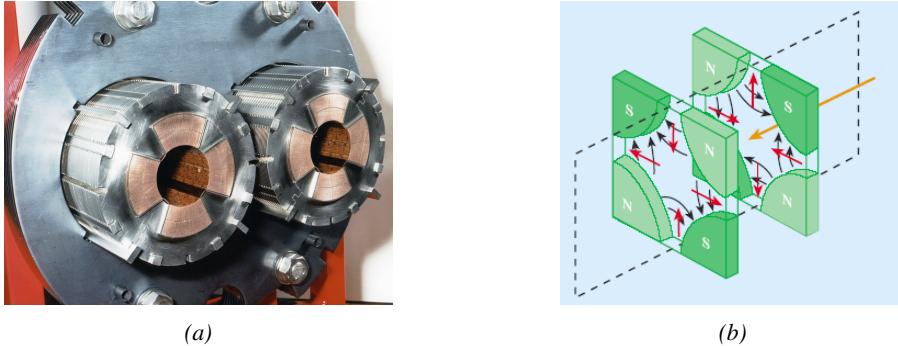


Figure 2.7: Figure 2.7a: picture of the LHC quadrupoles. Figure 2.7b: magnetic fields and resulting focussing force applied on the beam by 2 consecutive quadrupoles.

1370 2.2.2 CMS, a multipurpose experiment

1371 Among the four main LHC experiments is the Compact Muon Solenoid used as a multipurpose tool to
1372 investigate the SM and physics beyond its scope. Proposed through a letter of intention in 1992 [14],
1373 and as its name suggests, this very compact detector's uses the muons as a clear tag of most of SM
1374 and new physics interesting channels. In the original 1997 Technical Design Report (TDR) [21], the
1375 very first sentences were stating that "*Muons are an unmistakable signature of most of the physics*
1376 *LHC is designed to explore. The ability to trigger on and reconstruct muons at the highest lumi-*
1377 *nosities is central to the concept of CMS, the Compact Muon Solenoid.*" CMS participated in the
1378 discovery of the Higgs boson and the measurement of its properties and couplings together with
1379 ATLAS and is also actively involved in the search for SUSY and heavy ion collisions. Other exotic
1380 physics are also being investigated using the data collected by CMS.

1381 The CMS apparatus in itself is the heaviest detector ever built starring a SI15m diameter and a
1382 29 m length for a total weight of 14 kT. A thick 4 T solenoid magnet located at the beam interaction
1383 point hosts trackers and calorimeters. Extending in all directions around the magnet, heavy iron
1384 return yokes are installed to extend the magnetic field and support a muon system. The apparatus
1385 consists of a barrel, referring to the magnet and the detectors contained in it and the part of the muon
1386 system built directly in the cylinder around the magnet, and of 2 endcaps in the forward and back-
1387 ward region of the detector that closes the apparatus and complete the detection coverage along the
1388 beam line. A front view on the barrel is provided in Figure 2.8 while a detailed view of the apparatus
1389 is given in Figure 2.9.

1390

1391 In order to efficiently detect all long leaving particles and measure their properties with good
1392 precision, the CMS detector uses an onion like layout around of the interaction point in order to
1393 maximize the covered solid angle. As detailed in Figure 2.10, in the innermost region of the detector,
1394 closest to the interaction point, the silicon tracker records the trajectory of charged particles. Around
1395 it, the electromagnetic calorimeter (ECAL) stops and measure the energy deposition of electrons
1396 and photons. In the next layer, the hadron calorimeter (HCAL), hadrons are stopped and their energy
1397 measured. These layers are contained inside of the magnet of CMS, the superconducting solenoid.
1398 Outside of the magnet are the muon chambers embedded into iron return yokes used to control the

1399 magnetic field and gives muons, the only particles traveling completely through the whole detector, a
 1400 double bending helping in reconstructing their energy and trajectory. Note that photons and neutral
 1401 hadrons are differentiated from electrons and charged hadrons in the calorimeters by the fact that
 1402 don't interact with the silicon tracker and that they are not influenced by the magnetic field.

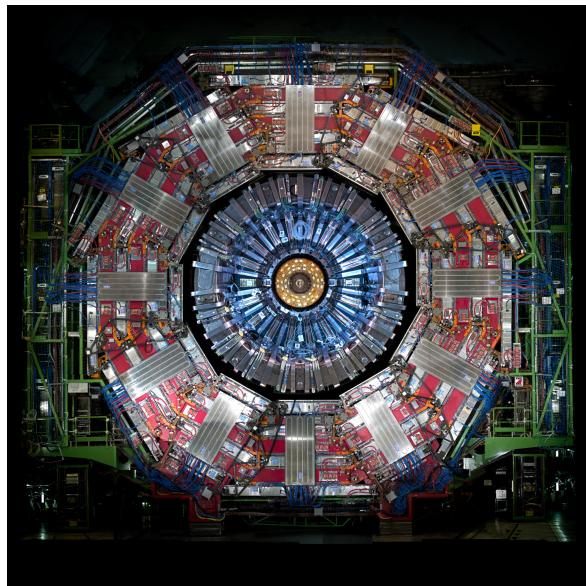


Figure 2.8: Picture of the CMS barrel. The red outer layer is the muon system hosted into the red iron return yokes. The calorimeters are the blue cylinder inside in magnet solenoid and the tracker is the inner yellow cylinder built around the beam pipe.

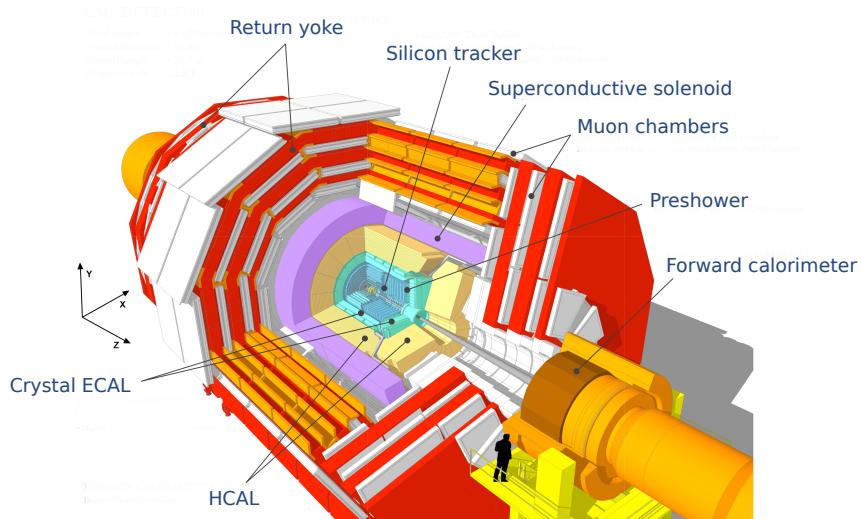


Figure 2.9: View of the CMS apparatus and of its different components.

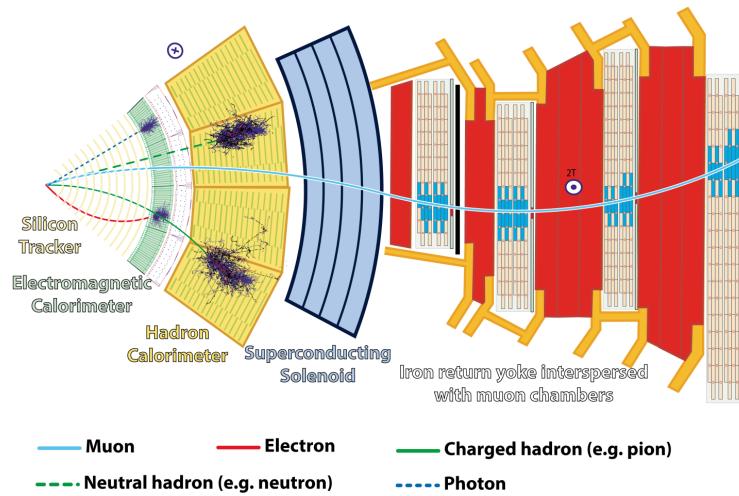


Figure 2.10: Slice showing CMS sub-detectors and how particles interact with them.

2.2.2.1 The silicon tracker, core of CMS

The silicon tracker visible on Figure 2.11 is divided into 2 different sub-systems: the *pixel detector* at the very core and the *microstrip detector* around it. This system is composed of 75 million individual readout channels with up to 6000 channels per squared centimeter for the pixels making it the world's biggest silicon detector. This density allows for measurements of the particle tracks with a precision of the order of $10\ \mu\text{m}$. This is necessary to reconstruct all the different interaction vertices with precision and have a precise measure of the curvature of the charged particles traveling through the magnetic field to estimate their charge and momentum.

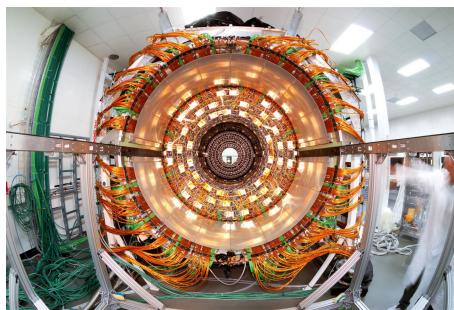


Figure 2.11: CMS tracker.

2.2.2.2 The calorimeters, measurement of particle's energy

The ECAL directly surrounding the tracker is composed of crystals of lead tungstate, PbWO_4 , a very dense but optically transparent material used to stop high energy electrons and photons. These crystal blocks basically are extremely dense scintillators which scintillate in fast, short light bursts proportionally to the energy deposition. The light is yielded rapidly and contained at 80% in the corresponding 25 ns lasting bunch crossing. Each crystal is isolated from the other by the carbon fiber matrix they are embedded in. It is composed of a barrel containing more than 60,000 crystals

1418 and of closing endcaps containing another 15,000 crystals. In front of the ECAL endcap is installed
 1419 a preshower detector made out of two layers of lead and silicon strip detectors to increase the spatial
 1420 resolution close to the beam line for pion-photon and single-double photon discrimination purposes.
 1421 Figure 2.12 shows the calorimeter inside of the magnet and the crystals.

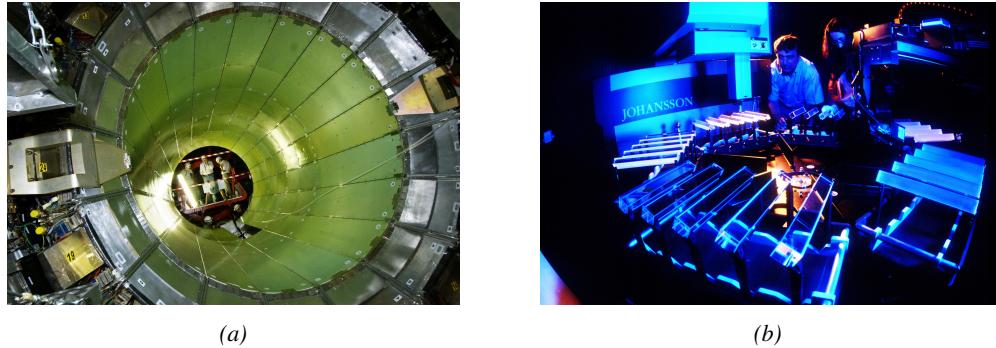


Figure 2.12: Figure 2.12a: picture of the ECAL. Figure 2.12b: picture of the lead tungstate crystals composing the ECAL.

1422 The next layer is the HCAL measuring the hadrons momentum and providing indirect hints of
 1423 non interacting neutral particles, such as neutrinos, as missing transverse momentum. Several layers
 1424 of brass or steel are interleaved with plastic scintillators readout by photodiodes using wavelength-
 1425 shifting fibers. The HCAL is also composed of a barrel, showed in Figure 2.13 and of endcaps. It
 1426 also features forward calorimeters on both sides of CMS in the region very close to the beam line at
 1427 high pseudorapidity ($3.0 < |\eta| < 5.0$). The role of these forward calorimeters, made using steel and
 1428 quartz fibers, is to measure very energetic hadrons.



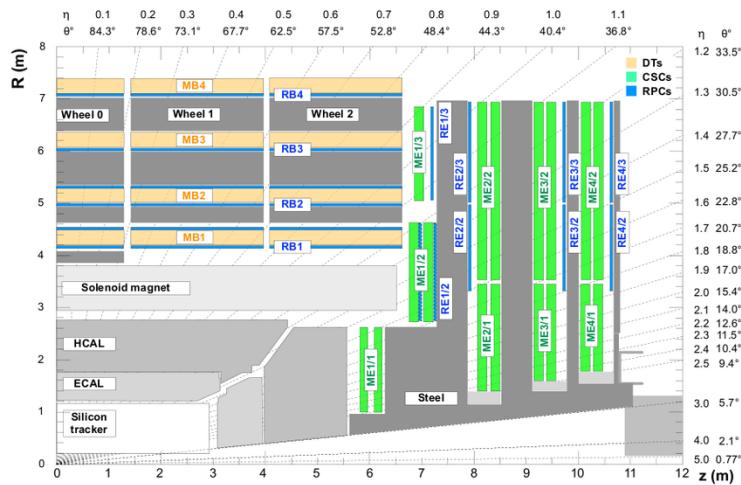
Figure 2.13: CMS hadron calorimeter barrel.

1429 Finally, in the outer region of the apparatus, a muon system is used to trigger on potentially
 1430 interesting event by identifying muons. Indeed, the muon system is a very important part of the
 1431 CMS trigger infrastructure designed to efficiently select data from the enormous data flow received
 1432 by the detectors as the LHC delivers collisions at a rate of 40 MHz with a pile-ip of 20 to 30 collisions
 1433 per bunch crossing during Phase-I and up to 200 during Phase-II, representing billions of interactions
 1434 per second among which a large quantity are low energy collisions that are not likely to produce new
 1435 reactions, and which is physically impossible for nowadays technologies to cope with. Working at
 1436 a maximum rate of 100 kHz, the trigger system is able to select the 100,000 more interesting events

1437 by looking at the energy distribution of the interaction products and clear signatures like muons
 1438 reconstructed by the muon system. the vast majority of these events will not finally be stored after
 1439 physics tests are applied.

1440 **2.2.2.3 The muon system, corner stone of CMS**

1441 The challenge for the muon system is to provide a robust and fast measurement of muons. Three
 1442 different subsystems, and soon 4 after LS2, compose the muon system as showed in Figure 2.14 in
 1443 which a quadrant of the CMS detector focused on muon system. Drift Tube (DT) are found in the
 1444 barrel region covering the low pseudorapidity region where particles transverse momentum is lower
 1445 and Cathode Strip Chamber (CSC) are found in the endcap region covering higher pseudorapidity
 1446 region closer to beam line where particles have a stronger momentum. The redundancy of the system
 1447 is insured by Resistive Plate Chamber (RPC) in both the barrel and endcap region. Nevertheless, the
 1448 region closest to the beam line ($|\eta| > 1.8$) was not equipped with RPCs. This lack of redundancy
 1449 in the high pseudo rapidity region will be solved during LS2, the following Year End Technical
 1450 Stop (YETS) in 2021 and 2022, and LS3 where the necessary services, detectors and Link System,
 1451 that collects the data and synchronizes them, will be installed.



1452 *Figure 2.14: A quadrant of the muon system, showing DTs (yellow), RPCs (blue), and CSCs (green).*

1453 The barrel region is divided into 5 *wheels* made out of 4 *rings* of detectors with iron return yokes
 1454 in between them whereas the endcaps are made out of 4 disks, each divided into pseudorapidity
 1455 stations, 2 for CSCs (except for the first disk where 3 stations are equipped) and 3 for RPCs, although
 1456 only 2 RPCs stations are equipped at present. The wheels and disks are showed in Figure 2.15. So
 1457 far, each subsystem was dedicated to a particular task. DTs, in the barrel, and CSCs, in the endcaps,
 1458 are used mainly for their spatial resolution. Indeed, DTs' resolution is of the order of 100 μm along
 1459 both the $(r - \phi)$ and $(r - z)$ components while the resolution of CSCs is similar but varies in a range
 1460 from 50 μm to 140 μm depending on the distance to the beamline. On the other hand, RPCs are used
 1461 for their time resolution as they can deliver an information on the muon tracks within 1.5 ns.

1462 The 250 CMS DTs, found in the barrel covering the pseudorapidity region $0 < |\eta| < 1.2$
 1463 and whose structure is shown in Figure 2.16, are composed of 3 *superlayers* of DT cells. Two of
 1464 these superlayers are dedicated to measuring the ϕ coordinate of the muons and while the last one

measures the η (or z) coordinate. Each superlayer consists on 4 layers of 60 to 70 DT cells arranged in quincunx to allow for a precise reconstruction of the muon path through the DT layers. Each DT cell is a rectangular aluminium gas volume with a central anode wire. Cathode strips are placed on the narrow surface of the cells and electrode strips are placed on the wide surface to help shaping the electric field to ensure a consistent drift velocity of electrons in the drift volume. These detectors are operated using a 85/15 mixture of Ar and CO_2 .

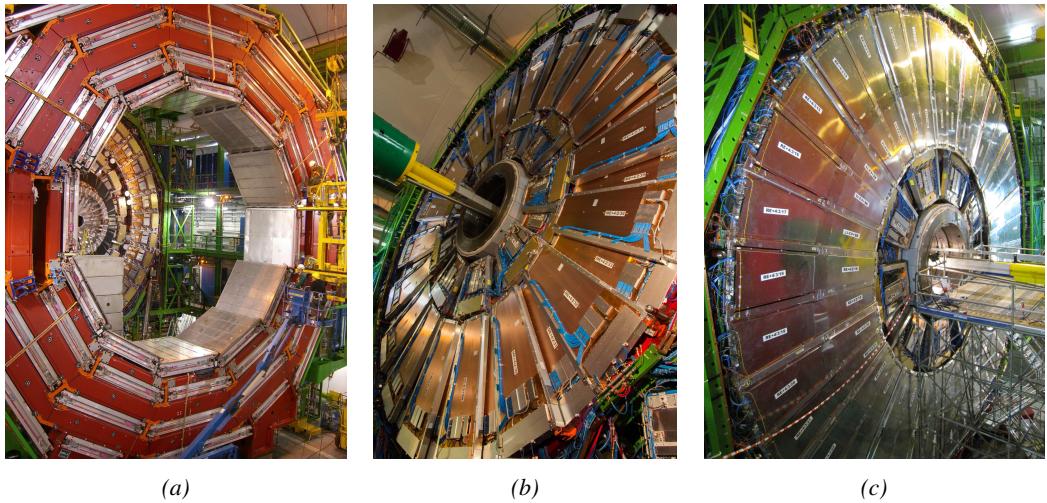


Figure 2.15: Figure 2.15a: Barrel wheel with its detector rings and return yokes. Figure 2.15b: CSC endcap disk with the 2 CSC stations. The outer station is made of 10 deg detectors while the inner station is made of 20 deg detectors. Figure 2.15c: RPC endcap disk. The inner station is not equipped and the inner CSC station can be seen.

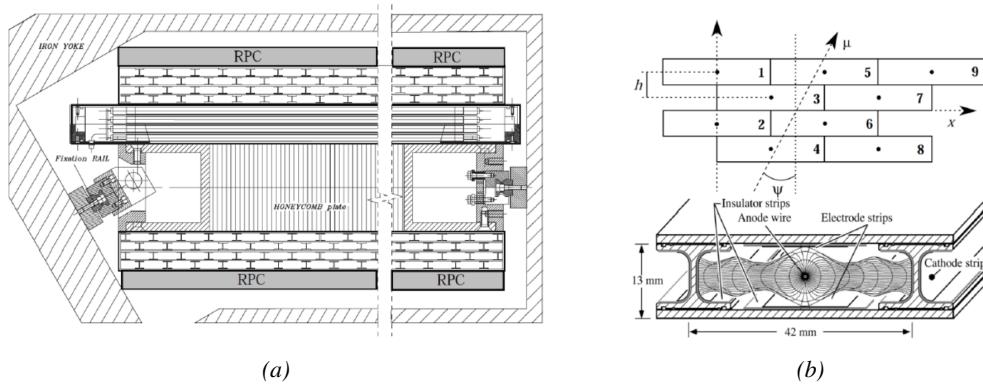


Figure 2.16: Figure 2.16a: Cross section of a DT module showing the two superlayers measuring the ϕ coordinate, perpendicular to the cross section plane, and the superlayer measuring the η coordinate, placed in between the two others with honeycomb and parallel to the cross section plane. The DT detector is sandwiched in between 2 RPCs whose readout strips are perpendicular to the cross section plane, measuring the ϕ coordinate. Figure 2.16b: A DT cell is shown together with its electric field. The path of a muon through a superlayer is shown.

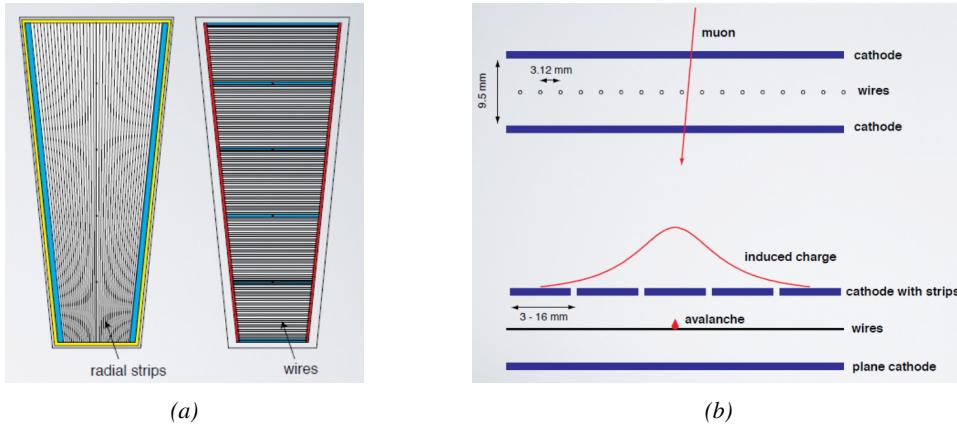


Figure 2.17: Figure 2.17a: cathode strips and anode wire layout of a CSC panel. Figure 2.17b avalanche development and charge collection by anode wires and induction on cathode strips inside of a CSC panel.

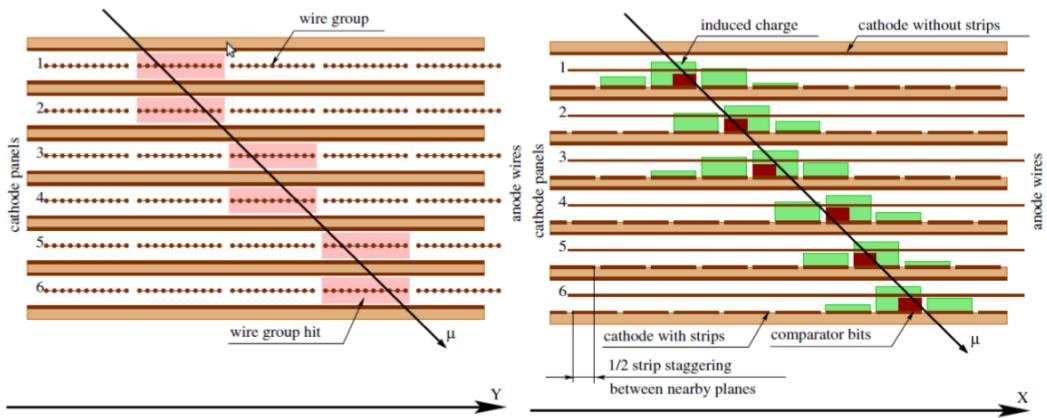


Figure 2.18: Muon track reconstruction through the 6 panels of a CMS CSC using the information of anode wire groups and cathode strip charge distribution combined with comparator bits to decide on which half strip the muon is more likely to have passed.

1470 The 540 CMS CSCs, found in the endcaps covering the pseudorapidity region $0.9 < |\eta| < 2.5$
 1471 and described through Figure 2.17, are composed of 6 panels of CSC, each panel consisting in
 1472 a wide gas volume of 9.5 mm (7 mm in the case of ME1/1 station) containing anode wires and
 1473 whose surfaces are cathodes. The top cathode is a wide copper plane of the size of the gas volume.
 1474 The bottom cathode is divided into thin trapezoidal copper strips radially arranged to measure the
 1475 azimuthal coordinate ϕ with a pitch ranging from 8 to 16 mm. The $0.50 \mu\text{m}$ anode wires are placed
 1476 perpendicularly to the strips to measure radial coordinate r and are grouped by 10 to 15 with a wire
 1477 to wire space of 3.2 mm. In the specific case of ME1/1 placed against the HCAL endcap, the $0.30 \mu\text{m}$
 1478 anode wires have a wire to wire distance of 2.5 mm and are not disposed perpendicularly to the strips
 1479 but slightly tilted by an angle of 29 deg to compensate for the lorentz force due to the very strong
 1480 local magnetic field of 4 T. These detectors are operated with a 40/50/10 mixture of Ar, CO₂ and
 1481 CF₄. Combining the information of the multiple CSC panels, the detectors achieve a very precise
 1482 measurement of the muon track.

Despite their excellent spatial resolution, the wire chambers (DTs and CSCs) are limited in terms of time resolution by the fact that the charge needs to drift towards the anode wire and be collected before having the confirmation that a particle was detected as the drift volume is not used to develop avalanches. Indeed, the stronger electric field close to the anode wire triggers the avalanche and the gain of the detector. Due to the drift, the time resolution is thus limited at best to approximately 2 to 3 ns. In addition, even though the intrinsic time resolution of the tracking chambers is rather good compared to the 25 ns in between successive collisions, the processing time of the trigger system doesn't allow for very fast triggering as it provides a time precision of only 12.5 ns. Thus, detectors fully dedicated to timing measurement have been installed as a redundant system. These detectors are RPCs, also gaseous detectors but that use current induction instead of charge collection allowing for a time resolution of the order of 1.5 ns only. Theoretically, depending on the design used, RPCs could reach a time resolution of the order of 10 ps but in the context of LHC where bunch crossing happen every 25 ns, a time resolution of 1.5 ns is sufficient to accurately assign the right bunch crossing to each detected muon.

The 1056 RPCs equipping the CMS muon system both in the barrel and endcap regions and covering the pseudorapidity region $0 < |\eta| < 1.6$ are composed of two layers of RPC *gaps* as described in Figure 2.19. Each gap consists in two resistive electrodes made out of 2 mm thick Bakelite enclosing a 2 mm thick gas volume containing a 95.2/4.5/0.3 mixture of $C_2H_2F_4$, $i - C_4H_{10}$ and SF_6 . Due to this geometry, the electric field inside of a gap is homogeneous and linear at every point in the gas translating into a uniform development of avalanches in the gas volume as soon as a passing muon ionises the gas. The two gaps sandwich a readout copper strip plane. A negative voltage is applied on the outer electrodes, used as cathodes, and the inner electrodes, the anodes, are simply connected to the ground as well as the readout panel that picks up the current induced by the accumulated charge of the growing avalanches in one or both of the gas gaps. This OR system allows for a lower gain (i.e. a lower electric field) on both gaps to reach the maximal efficiency of such a detector.

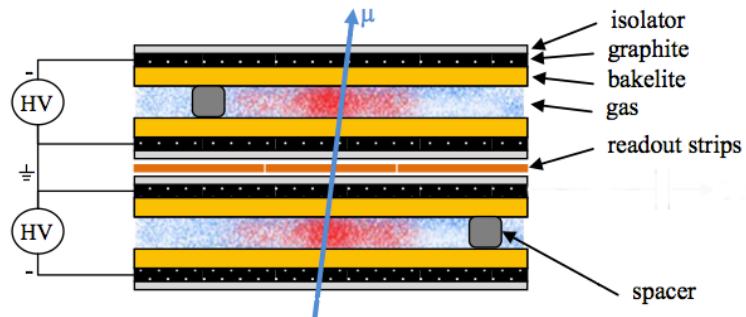


Figure 2.19: Double gap layout of CMS RPCs. Muons passing through the gas volumes will create electron-ion pairs by ionising the gas. this ionisation will immediately translate into a developing avalanche.

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Muon Phase-II Upgrade

1511 The very first proton beam successfully circulated in the LHC in September 2008 directly followed
1512 by an incident leading to mechanical damage that would delay the LHC program for a year until
1513 November 2009, the very first collisions at a center-of-mass energy of 7 TeV taking place in March
1514 2010. The energy of the beam would be increased after a First Long Shutdown (LS1) starting early
1515 2013 after less than 3 years of data taking. Nevertheless, this first data taking period at only 7 TeV
1516 was sufficient to claim the discovery of a new particle compatible with the Higgs boson in July 2012.
1517 During the 2 years of shutdown, the upgrade of the accelerator allowed for several maintainances
1518 along the beam pipes, repair and consolidation of magnet connection and high-current splices. But
1519 not only the LHC was upgraded. Indeed, the experiments at the 4 collision points also took the
1520 advantage of this time to upgrade their system in prevision of the next LHC run (Run-II) until
1521 2018 and the Second Long Shutdown (LS2) as the luminosity and energy of the beam would be
1522 continuously increasing. By the end of Run-II, the luminosity will have reached twice its nominal
1523 value when the center-of-mass energy has already got close to its nominal value by reaching an
1524 historical 13 TeV for the first time in 2017.

1525 The next long shutdown will occur at the end of this year and will again be the occasion for sim-
1526 ilar maintenance and consolidation in prevision of Run-III and the future upgrade of LS3. Still, the
1527 main occupation of LS2 on LHC side will be the upgrade of LHC injectors. On the experiments side,
1528 LHCb and ALICE will, in a very tight schedule, implement major upgrades while ATLAS and CMS
1529 will wait until LS3 to upgrade their detectors in prevision of high luminosity *LHC-Phase-II*. ALICE
1530 main challenge is an upgrade of their apparatus to cope with the 50 kHz $Pb - Pb$ collisions. Simi-
1531 larly, LHCb will upgrade their frontend readout electronics to cope with the full 40 MHz collisions
1532 delivered by LHC. ATLAS will perform standard maintenance and CMS will focus on the urgent up-
1533 grade of the pixel detector and on the installation of new muon detectors in order to take profit of LS2
1534 time to mitigate the upgrade of detectors foreseen during LS3. Run-III will start in 2021 with the LHC
1535 at its nominal center-of-mass energy and will bring LHC-Phase-I to an end at the end of 2023. By
1536 then the luminosity will only increase to reach 2.5 times the nominal luminosity but during these 3
1537 years of run, the LHC will deliver as much integrated luminosity as what what brought during the al-

most 7 years of both Run-I and II of data taking. Phase-I will end with an overall 300 fb^{-1} delivered.

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1540 3.1 High Luminosity LHC and muon system requirements

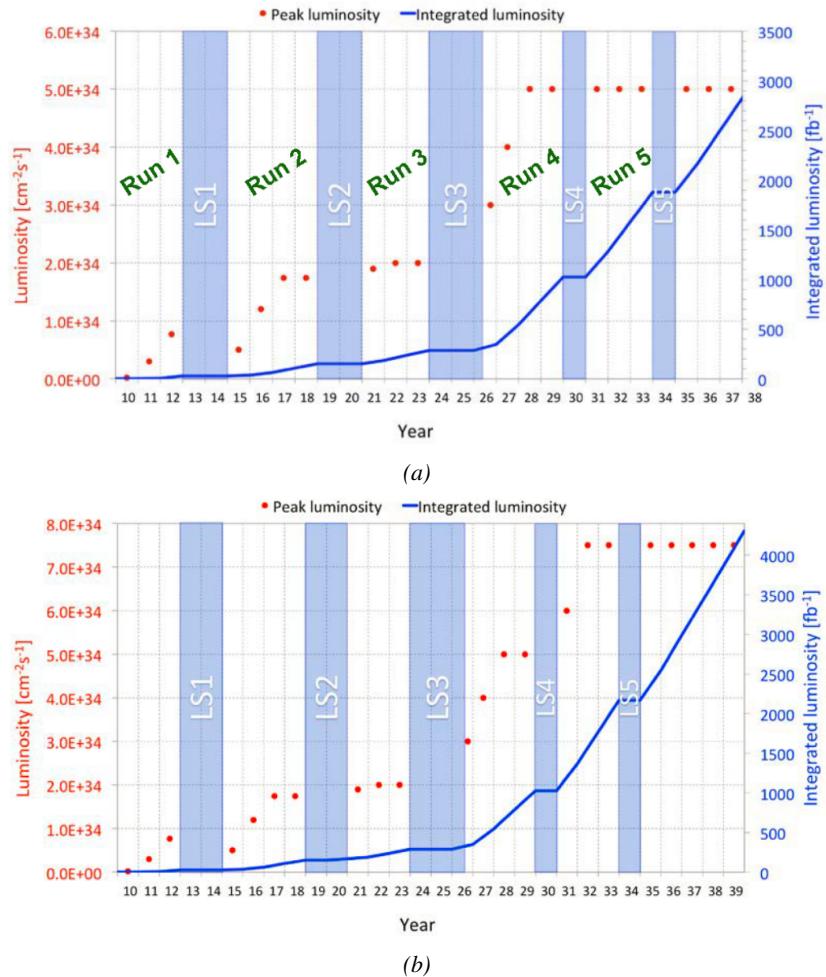


Figure 3.1: Detailed timeline projection of for LHC and HL-LHC operation until 2039 showing the evolution of the instantaneous and integrated luminosity as designed (Figure 3.1a) and in the ultimate case where the instantaneous luminosity is increased to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (Figure 3.1b) [20, 22].

After approximately 15 years of operation, the LHC will undergo a new series of upgrade during the LS3 in order to boost its discovery potential as showed in Figure 3.1. This moment onward is what is referred to HL-LHC or Phase-II. The goal is to aim for a luminosity 5 to 7 times stronger than the nominal one trying to reach even 10 times this value if possible. Increasing the luminosity means that the beam size at the collision points needs to be reduced to boost the number of collisions per bunch crossing. For this purpose, new focusing and bending magnets, and collimators will be installed at the collision points as well as newly developed "crab cavities" that will tilt the particle

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1548 bunched just prior to the collisions by giving them transverse momentum and thus increasing their
 1549 meeting area. In addition, the full proton injection line will be upgraded.

1550 Over its full lifetime, the HL-LHC is expected to deliver an outstanding integrated luminosity of
 1551 3000 fb^{-1} leading, in the case of Higgs studies to measuring the couplings of the boson to a precision
 1552 of 2 to 5% thanks to the estimated 15 millions of Higgs created every year providing a more precise
 1553 measurement of potential deviations from the theoretical predictions. SUSY and heavy gauge boson
 1554 studies would also see their mass range limits pushed away by at least 1 TeV and could lead to a new
 1555 breakthrough. SUSY is a particularly important topic as it could give an answer to why the Higgs
 1556 boson can stay so light while coupled to heavy particles by introducing the contributions of the super
 1557 partners on top of providing dark matter candidates. Finally, the increase of luminosity will give the
 1558 possibility to investigate "exotic" mode like for example the models introducing extra dimensions to
 1559 explain the hierarchy problem.

1560 On the experiments side, the pile-up (PU) will be increased up to 150 to 200 interactions per
 1561 bunch crossing in ATLAS and CMS, making necessary an strong upgrade of the trigger system and
 1562 of the inner trackers and of the calorimeters. Both ATLAS and CMS will also need to upgrade
 1563 the muon trigger at the level of the endcaps mainly focusing on the coverage near the beam line in
 1564 order to increase the detection acceptance and event selection. Moreover, the increased luminosity
 1565 will also lead to an increased background rate and a faster ageing of the detectors. This PhD work
 1566 takes place into this very specific context of muon detector consolidation and certification for the
 1567 HL-LHC period in order to provide the CMS experiment with robust new detectors and confirm that
 1568 the present system will survive through the next 20 years of HL-LHC.

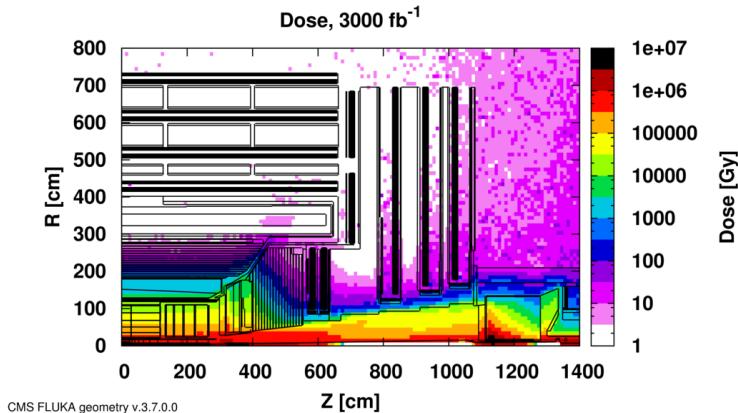


Figure 3.2: Absorbed dose in the CMS cavern after an integrated luminosity of 3000 fb^{-1} . Using the interaction point as reference, R is the transverse distance from the beamline and Z is the distance along the beamline.

1569 The end of 2018 will mark the beginning of LS2 and the start of Phase-II upgrade activities.
 1570 From the HL-LHC period onwards, i.e. past LS3, the performance degradation due to integrated
 1571 radiation as well as the average number of inelastic collisions per bunch crossing, seen as pile-up
 1572 into the detectors' readout that far exceeds this of the original LHC plans, will rise substantially and
 1573 become a major challenge for all of the LHC experiments, like CMS, that were forced to address
 1574 an upgrade program for Phase-II [23]. Dealing with the data from the muon detectors will force
 1575 to upgrade the detectors and electronics towards the most recent technologies. Simultaneously, this
 1576 will push new latency requirements onto the Level-1 trigger and the Data Acquisition (DAQ) that

will only be fulfilled by upgrading the system with electronics having deeper buffering and faster processing. Simulations of the expected distribution of absorbed dose in the CMS detector under HL-LHC conditions show, in Figure 3.2, that detectors placed close to the beam line will have to withstand high irradiation, the radiation dose being of the order of a few tens of Gy.

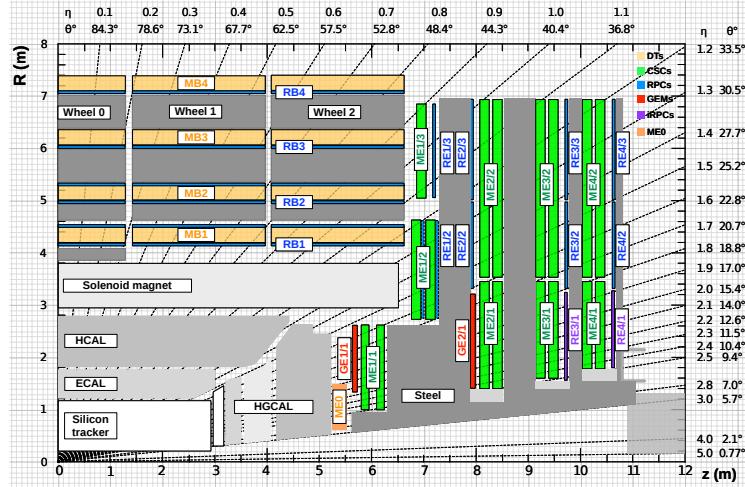


Figure 3.3: A quadrant of the muon system, showing DTs (yellow), RPCs (blue), and CSCs (green). The locations of new forward muon detectors for Phase-II are contained within the dashed box and indicated in red for GEM stations (ME0, GE1/1, and GE2/1) and dark blue for improved RPC (iRPC) stations (RE3/I and RE4/I).

The increase of irradiation close to the beam line will affect the background rate seen by the muon detectors in this area and tracking muons will prove to be difficult as this region is not yet equipped with all the detectors that were already foreseen for Phase-I. Improving this situation will come with the increase of hit numbers recorded along the particle track to reduce the ambiguity on muon versus background detection. Moreover, the measurement of small production cross-section and/or decay branching ratio processes, such as the Higgs boson coupling to charge leptons, and in particular to muons, or the $B_s \rightarrow \mu^+ \mu^-$ decay, is of major interest and specific upgrades in the forward regions of the detector will be required to maximize the physics acceptance to the largest possible solid angle.

To ensure proper trigger performance within the present coverage, the muon system will be completed with new chambers and the electronics of the present system will need to be upgraded to ensure an efficient triggering. Figure 3.3 shows the addition of Gas Electron Multiplier (GEM) and improved RPC (iRPC) in the pseudo-rapidity region $1.6 < |\eta| < 2.4$ to complete the redundancy of the already existing CSCs as originally scheduled in the CMS Technical Proposal [24]. A first step into this direction will be taken by installing GEMs on the first endcap disk in position GE1/1 during LS2, during which preparations for the future installation of more GEMs and RPCs will take place by installing the needed services. During the YETS following LS2, iRPCs will be installed on the third and fourth endcap disks in position RE3/I and RE4/I, and more GEMs will equip the second endcap in position GE2/1 and the inner layer, closest to the HCAL endcap called ME0 during LS3, finally completing the redundant coverage of the muon system and extending it a little by extending the reach to $|\eta| = 2.8$, the redundancy in the region $2.4 < |\eta| < 2.8$ being maintained by the 6 GEM layers contained in each ME0 detector that provide enough tracking points to efficiently reject

1603 neutron-induced background.

1604 Nevertheless, the region beyond $|\eta| > 2.8$ and extending to $|\eta| = 5.0$ only is covered by the
1605 forward HCAL detectors and lack redundant muon detector coverage. Extensions of the tracker in
1606 the context of HL-LHC will increase its coverage up to $|\eta| = 4.0$ but the identification of muons and
1607 measurement of their energy with reasonable precision only using the tracker is nearly impossible.
1608 Thus, this increased tracker coverage range needs to be put in parallel with a matching muon detector
1609 and will open doors to multi-lepton final states in which leptons are likely to have a low transverse
1610 momentum and to be found near the beam line.

1611

1612 Finally, as the muon system is composed only of gaseous detectors, strong environmental con-
1613 cerns have risen over the last years as the European directives will restrict the use of fluorine based
1614 gas mixtures. Both the CSC and RPC subsystems, using CF_4 , $C_2H_2F_4$, or SF_6 , will need to adapt
1615 their working gas in order to strongly reduce the greenhouse potential of the mixtures released into
1616 the atmosphere due to gas leaks.

1617 3.2 Necessity for improved electronics

1618 Drift Tubes and Cathode Strip Chambers are important components used to identify and measure
1619 muons, especially thanks to their spatial resolution of the order of $100\text{ }\mu\text{m}$. Nevertheless, the lumi-
1620 nosity and irradiation during HL-LHC will cause serious event loss and ageing on the electronics of
1621 these subsystems that will comprise the triggering and data transferring needs of CMS. Thus, elec-
1622 tronics upgrade are foreseen to address these expected problems. While only the RPCs' electronic
1623 system is able to operate under Phase-II requirements, DTs and CSCs will need to improve their
1624 trigger accept rate and latency to ensure that Level-1 trigger threshold stays at the same level [25],
1625 and DAQ data transfer rate, that respectively need to achieve a minimum of 500 kHz , get down to
1626 $12.5\text{ }\mu\text{s}$ [26], and increase to 1082 Gbit/s DTs and to 1026 Gbit/s for CSCs. As of today, the Level-
1627 1 trigger accept rate of DTs doesn't reach 300 kHz while this of CSCs is below 250 kHz but the
1628 foreseen upgrades are expected to increase the rate way beyond the requirement in the of DTs and
1629 up to 4 MHz for CSCs [23].

1630 The first version of Minicrate electronics (MiC1) used by DTs don't allow for high enough
1631 trigger rate. In addition to this problem, it was showed that these electronics contain components
1632 that are not radiation hard enough to sustain HL-LHC conditions and thus, a too large number of
1633 channels may fail due to radiations. Considering the most optimistic scenario, at least 19% of the
1634 channels could have failed by LS4, as explicitated in Figure 3.4, far before the end of the HL-LHC
1635 campain. The MiC1 will be replaced on each detector by an improved version referred to as MiC2
1636 while front-end electronics and high-voltage modules will not need any replacement. On the other
1637 hand, CSCs showed that there electronics would be able to live through the 10 years of Phase-II but
1638 the limited buffer depth might cause memory overflows and readout inefficiencies with a fraction
1639 of event loss ranging from 5 to more than 10% at an instantaneous luminosity similar to which of
1640 HL-LHC depending on the expected background, as showed on Figure 3.5 through the different
1641 detector positions. Thus the replacement of CSCs' cathode front-end boards (CFEBs) by digital
1642 ones, DCFEBS, with deeper buffer would permit to make event loss negligible and satisfy HL-LHC
1643 requirements [23].

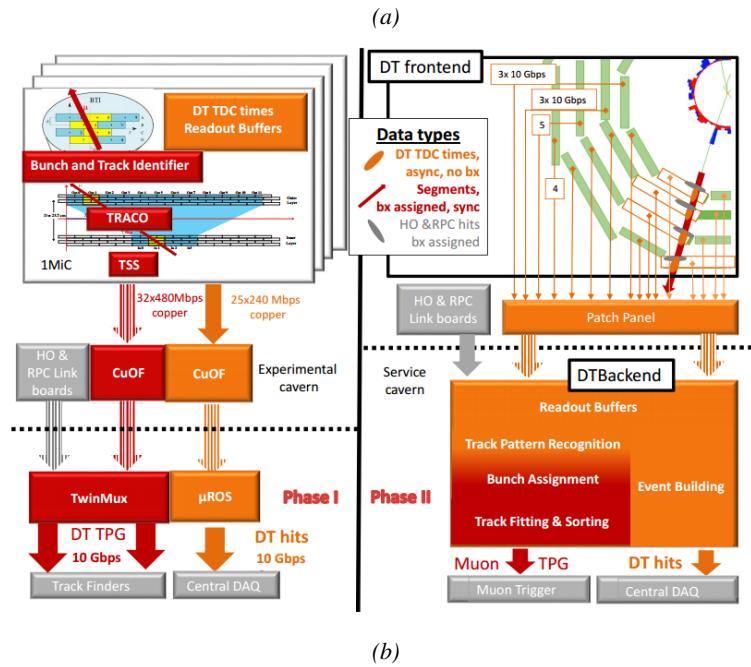
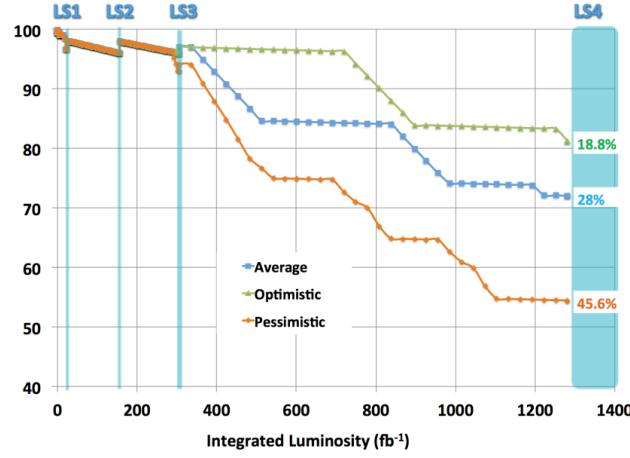


Figure 3.4: Figure 3.4a: Extrapolated fraction of failing channels of the present DT MiC1 electronics as a function of the integrated luminosity for different scenari until LS4. Figure 3.4b: Comparison of the current (left) and upgraded (right) DT data processing. So far, the data is sent to service cavern of CMS facility via copper-to-optical-fiber translators (CuOF) by each MiC1. There, data including RPCs and outer hadron calorimeter is combined into trigger primitives (TPG) and transmitted by the TwinMux system to CMS Track Finder. The time-to-digital converter (TDC) data is collected and sent to the CMS data acquisition system (DAQ) by the micro read-out server (μ ROS). After the upgrade, the TDC data will be sent via optical links to a patch panel inside the experimental cavern by each MiC2, and transferred to the back-end, where triggering and event building will be performed.

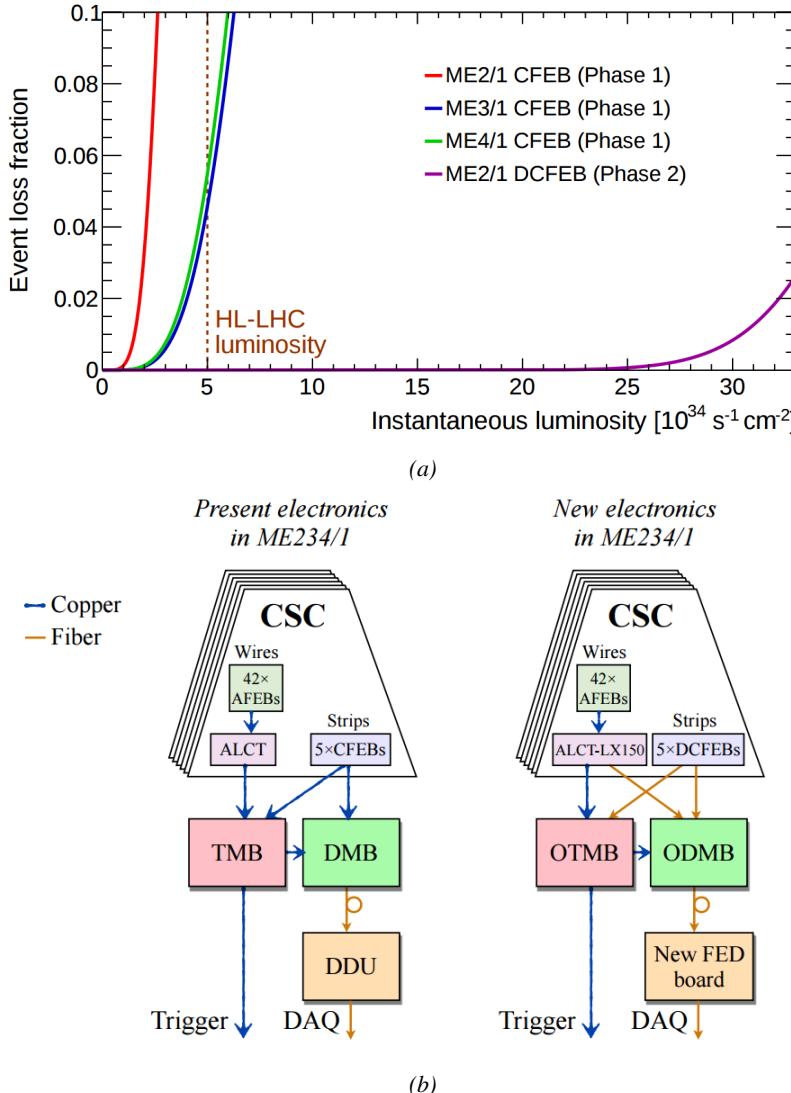


Figure 3.5: Figure 3.5a: The event loss fractions as a function of the instantaneous luminosity is compared for CFEBs (Phase-1) and DCFEBs (Phase-II) at different CSC locations. HL-LHC luminosity is marked with the dashed brown line. Figure 3.5b: Comparison of the current (left) and upgraded (right) CSC data processing. A part of the connections in between ALCTs and DCFEBs, and the trigger mother boards (TMBs) and data acquisition mother boards (DMBs) will be upgraded toward optical data transfer. The detector dependent units (DDUs) used as interface in between CSCs' front-end electronics and the CMS DAQ will be replaced by new FED boards.

1644 All these new DT and CSC electronics will be connected to the trigger electronics via optical
 1645 links to ensure a faster communication. The main change will come from the new DT minicrate
 1646 modules which will not anymore be responsible for trigger and event building logic which will be
 1647 transferred to the back-end electronics instead located in the service cavern via the patch pannels to
 1648 which the Time-to-Digital Converter (TDC) data will be sent. The trigger and data transfer logic will
 1649 barely change for CSCs. The existing copper cable connections of cathode and anode FEBs (CFEBs,

and AFEBs which data is transmitted through the ALCTs) toward the trigger and data mother boards (TMBs and DMBs) will simply be replaced by optical fibers and the TMBs and DMBs upgraded with optical versions (OTMBS and ODMBs). As a new feature, the full anode wire data from ALCTs will be sent to the ODMBs causing a lack of FPGA memory resources in these ALCT boards that will thus need replacement.

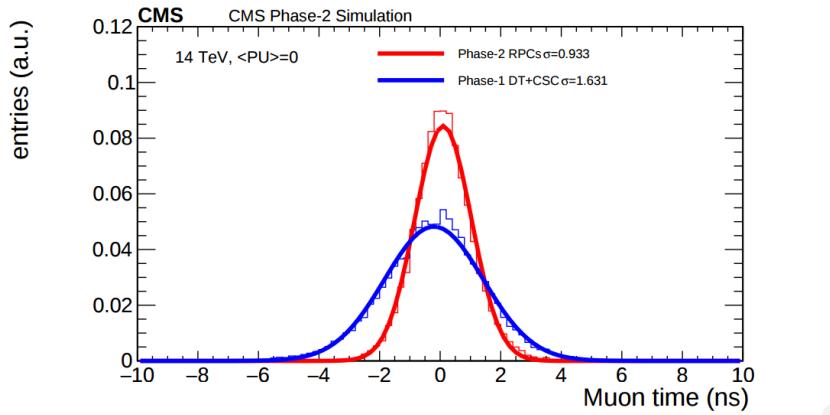


Figure 3.6: Comparison of the simulated time residuals in between reconstructed and true muon times without (blue) and with (red) the upgraded RPC link system.

The upgrade on the side of Resistive Plate Chambers will then not come from their on-board electronics but from the Link System located in the service cavern of CMS and that connects the front-end electronics data of RPCs into CMS trigger processors. The main motivation for such an upgrade is that the electronic board composing the link system are built using obsolete components and weak components that can easily suffer from the electromagnetic noise. These components may be the source of failing channels throughout Phase-II. Moreover, these link boards were originally designed only to match RPC digitized signals with the corresponding bunch crossing. Due to this feature, the time resolution of the full RPC chain is thus limited to 25 ns and does not exploit the full time resolution of the detectors. This would make the synchronization of the RPC system easier and allow to have a finer offline background removal within the 25 ns in between bunch crossings thanks to the order of magnitude gained in terms of time resolution.

Upgrading RPC link system will require the installation of 1376 new link boards and 216 control boards. The new boards will make use of the recent progress made with fast FPGAs and will be a great improvement to the ASICs formerly used as they will be able to process signals from several detectors in parallel. The benefit from using the full RPC time resolution thanks to the upgraded link system can be seen through Figure 3.6 where the resolution of the RPC system itself is better than that of DTs and CSCs that was used until now.

3.3 New detectors and increased acceptance

In the present muon system, the redundancy of was assured by RPCs used for their good timing performances. The extension of the muon system towards higher pseudo-rapidity in order to complete the redundancy in this very region and to contribute to the precision of muon momentum measurements will require muon chambers with a spatial resolution less or comparable to the contribution

¹⁶⁷⁷ muon of multiple scattering through the detector volume [21]. Most of the plausible physics is
¹⁶⁷⁸ covered only considering muons with $p_T < 100$ GeV thus, in order to match CMS requirements,
¹⁶⁷⁹ a spatial resolution of $\mathcal{O}(\text{few mm})$ will be necessary for the proposed new RPC stations while the
¹⁶⁸⁰ GEMs will need a resolution better than 1 mm, as showed by the simulation in Figure 3.7.

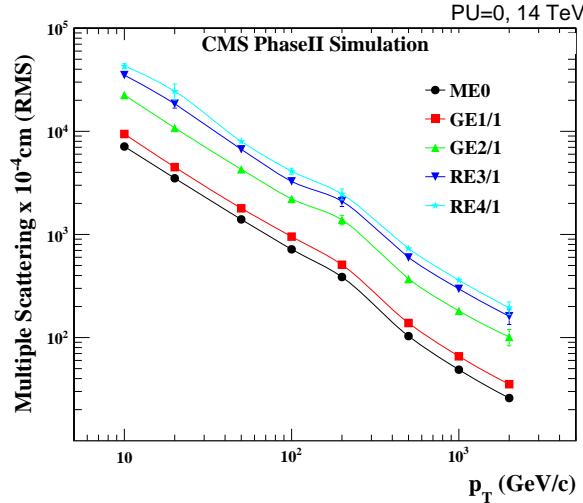


Figure 3.7: RMS of the multiple scattering displacement as a function of muon p_T for the proposed forward muon stations. All of the electromagnetic processes such as bremsstrahlung and magnetic field effect are included in the simulation.

¹⁶⁸¹ 3.3.1 Improved forward resistive plate chambers

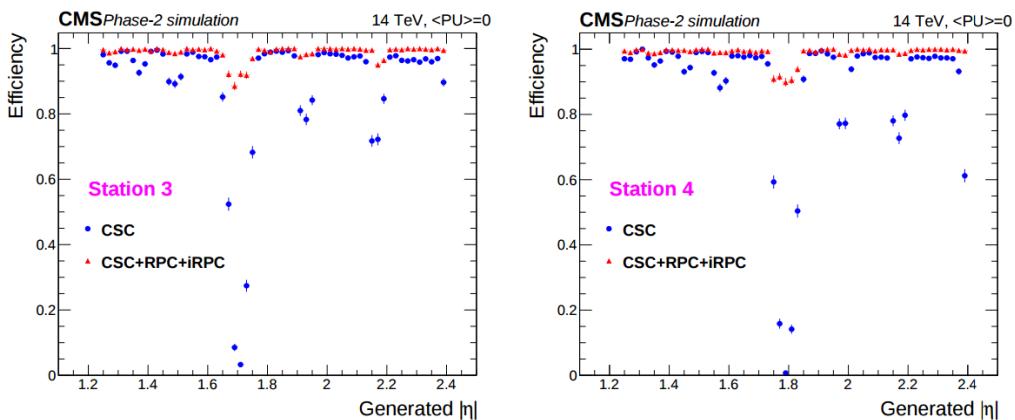


Figure 3.8: Simulation of the impact of RPC hit inclusion onto the local trigger primitive efficiency in station 3 (left) and station 4 (right). The contribution of iRPC starts above $|\eta| = 1.8$.

¹⁶⁸² Figure 3.3 shows that the iRPCs that will equip the third and fourth endcap disks in position RE3/1
¹⁶⁸³ and RE4/1 will finally be the partners of the CSCs in position ME3/1 and ME4/1 and complete
¹⁶⁸⁴ Phase-I plans but bringing the needed upgrades in the scope of Phase-II as the older chambers are

not suitable to equip the forward region of CMS due to HL-LHC rates and charge deposition. By completing the redundancy, more track along the muon trajectory will be available and the lever arm will be improved. The benefits from extending the redundancy of the muon system with iRPCs to the forward most region is showed in Figure 3.8 in which the trigger efficiency is showed with and without RPCs in which it is possible to see that the efficiency of CMS trigger with the complete redundancy is improved is above 95% in the region $|\eta| > 1.8$ as the iRPCs help filling the holes in the CSC system.

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The detectors that will be installed in the coming years will be similar to the already existing RPC system. 18 of the new chambers, each spanning 20° in φ around the beam axis with 96 radially oriented trapezoidal read-out strips, will cover each muon endcap disk leading to the production of 72 iRPCs. The main difference with the old RPC chambers is that these detectors will not have readout strips segmented in η as by using fast front-end electronics the strips will be read-out on both sides allowing for a radial spatial resolution of the order of 2 cm in order to contribute to the better reconstruction of muon in the forward region where the bending of muons by the magnetic field is low. This is motivated by the fact that, in the case a η segmentation was used, at least 5 pseudorapidity partitions would have been necessary to reach the minimal radial spatial resolution (≈ 20 cm). Having only one strip read-out from both along the chamber reduces by 60% the total number of channels and the necessary cabling and allows for a better spatial resolution. The strip pitch will range from 6.0 mm (5.9 mm) on the high pseudo-rapidity end to 12.3 mm (10.9 mm) on the low one on position RE3/1 (RE4/1). The spatial resolution in the direction perpendicular to the strips should reach approximately 3 mm, better than the minimal needed resolution (Figure 3.7), and the overall time resolution of the new installation will be equally 1.5 ns, as for the present due to the same link system being used.

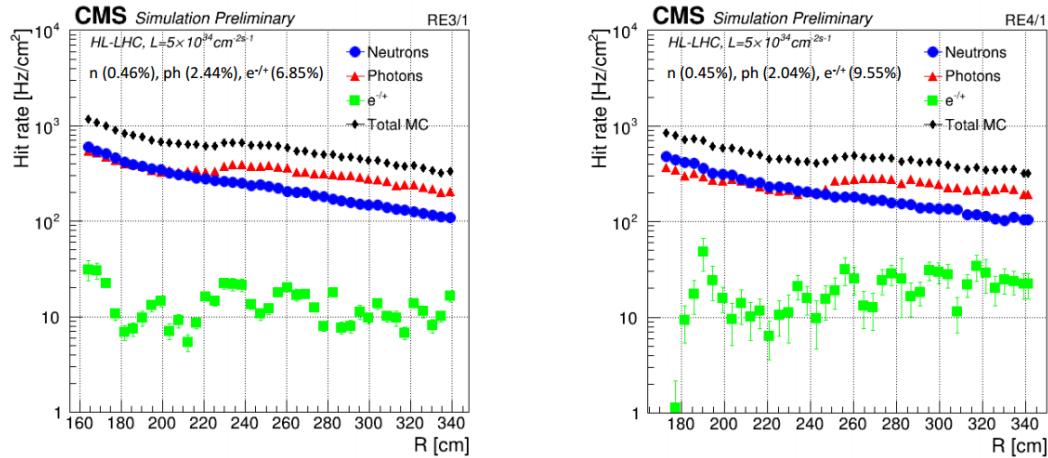


Figure 3.9: Expected hit rate due to neutrons, photons, electrons and positrons at HL-HLC instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in RE3/1 and RE4/1 chambers. The sensitivities of iRPCs used in the simulation for each particle are reported and differ from one endcap disk to another as the energies of the considered particles varies with the increasing distance from the interaction point.

Nevertheless, having only a single strip instead of pseudo-rapidity segmentation will increase the probability of double hits in the same channel. This probability was estimated to be low enough

as it shouldn't exceed 0.7%. This estimation was made assuming an average hit rate per unit area of 600 Hz/cm² in the iRPCs (see Figure 3.9), a cluster size (average number of strips fired per muon) of 2, a strip active area of 158.4 × 0.87 cm² and a safety factor 3 leading to an estimated rate per strip of 380 kHz corresponding to an average time interval of 2600 ns in between 2 consecutive hits. The time for a signal to go through the full strip length is about 10 ns to which can be added 1 ns of dead time and 2 TDC clock cycles of 2.5 ns for a minimal time interval of 16 ns necessary to avoid ambiguities. The probability of having ambiguous double hits in a strip is then the ratio in between this minimal time interval in between 2 consecutive hits and the average time interval estimated from the rate the detectors are subjected to.

The instantaneous luminosity at HL-LHC being very high, the rates at the level of the new chambers needed to be simulated in order to understand the necessary requirements for these detectors. The simulated results for different background components (neutrons, photons, electrons and positrons) are showed in Figure 3.9 assuming known sensitivities to these particles. It is showed that on average over the iRPC areas the rates would be of the order of 600 Hz/cm² (600 Hz/cm² seen in RE3/1 and 480 Hz/cm² in RE4/1) [27]. Thus, taking into account a safety factor of about 3, it was decided that improved RPCs should at least be certified for rates reaching 2 kHz/cm² which would be achieved thanks to several improvements on the design and on the electronics. The detectors design will be based on the existing RPC design as they will be double gaps. Similarly to the existing RPC system, the electrode material will be HPL although the thickness of the electrodes and of the gas gap will be reduced to 1.4 mm as a thinner gas gap leads to a decrease of deposited charge per avalanche as showed in Figure 3.10. The smaller the gas gap, the more the detector becomes sensitive to gap non-uniformities across the electrode planes making a gap of 1.4 mm a good compromise in between these two competing factors.

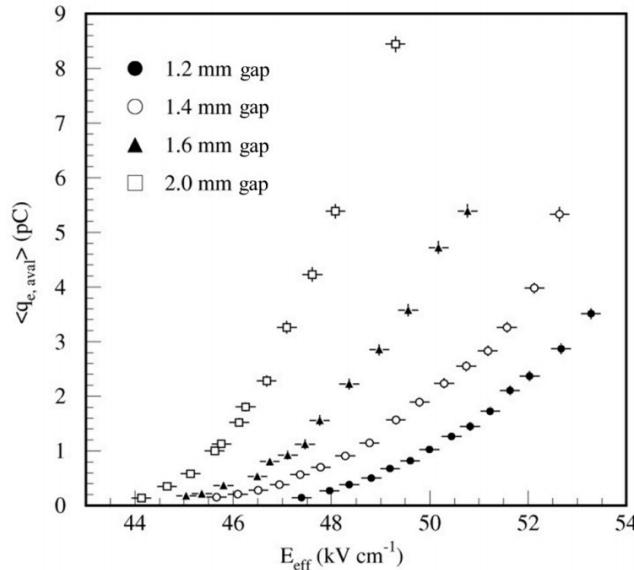


Figure 3.10: Measured average charge per avalanche as a function of the effective electric field for different gas gap thickness in double gap RPCs using HPL electrodes.

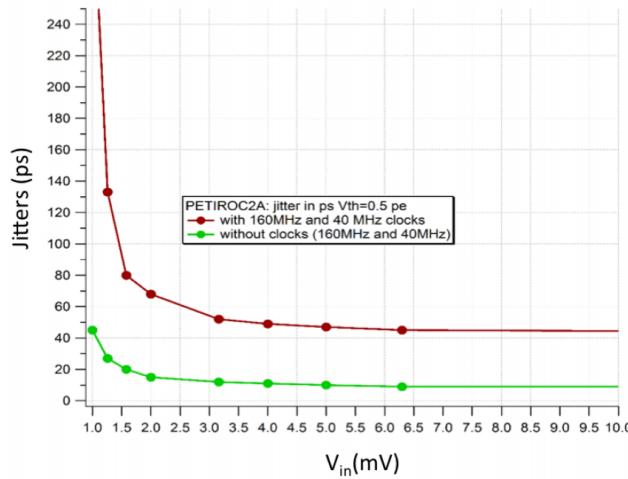


Figure 3.11: The PETIROC time jitter as a function of the input signal amplitude, measured with and without internal clocks.

1734 A lower charge deposition inside of the detector volume means a slower ageing and a longer life-
 1735 time for detectors subjected to high irradiation. But, in order to take advantage of the lower detector
 1736 gain, more sensitive electronics are required so that the part of gain that was formerly done in the gas
 1737 volume can be moved to the electronics. Achieving this with the technology developed more than
 1738 10 years ago for the present system is not possible as the signal over noise ratio of such electronics
 1739 doesn't allow to detect charges as low as 10 fC. Moreover, the new front-end electronics will need
 1740 to be radiation hard to survive to more than 10 years of HL-LHC conditions. The new technology
 1741 that has been chosen is based on the PETIROC ASIC manufactured by OMEGA and is a 64-channel
 1742 ASIC called CMS RPCROC on which the original SiGe technology will be replaced by CMOS to
 1743 increase its radiation hardness while keeping fast pre-amplification and discrimination with a very
 1744 low jitter that can reach less than 20 ps if no internal clock is used, as can be seen from Figure 3.11.
 1745 The ASIC is associated with an FPGA which purpose is to measure time thanks to a TDC with a
 1746 time resolution of 50-100 ps developed by Tsinghua University and that will provide a measurement
 1747 of the signal position along the strip with a precision of a few cm by measuring the signal timing
 1748 on both ends of the strips. In order to read-out all 96 strips, 3 ASICs and 3 TDCs, each having 64
 1749 channels, are hosted on a front-end board attached to the chamber.

1750

1751 [Wait for the analysis of 2018 GIF++ data to add interesting information about the time and
 1752 spatial resolution measured during test beam periods.]

1753

1754 3.3.2 Gas electron multipliers

1755 In the region closer to the interaction point where the spatial resolution is requested to be better
 1756 than 1 mm for the new detectors (at least for GE1/1 and ME0, GE2/1 being in the same order of
 1757 requested spatial resolution than the new iRPCs that will equip the third and fourth endcaps), the
 1758 choice has been made to use triple GEMs, micro pattern gaseous detectors, in the place of RPCs.
 1759 The GE1/1 project had been the first to be approved and demonstrators had been installed in CMS

¹⁷⁶⁰ already during LS1. The rest of the detectors will be installed during LS2 while the GE2/1 and ME0
¹⁷⁶¹ projects are still under development. ME0, GE1/1 and GE2/1 will be installed respectively next to
¹⁷⁶² the HCAL endcap, on the first and on the second muon endcap disks as can be seen from Figure 3.3.

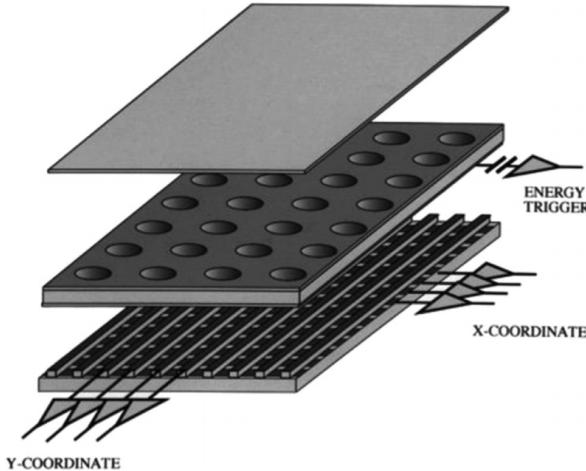


Figure 3.12: Schematics of a GEM showing the cathode on top, the GEM foil separating the gas volume into the drift region, in between the cathode and foil, and the induction region, in between the GEM foil and the anode, and the anode on which a 2D read-out is installed. A negative voltage is applied on the cathode while the anode is connected to the ground.

¹⁷⁶³ Gas Electron multipliers are gaseous detectors [28] which gas volume is confined in between
¹⁷⁶⁴ 2 planar electrodes, the anode serving as read-out panel. The gas volume is divided in 2 or more
¹⁷⁶⁵ regions by a single or multiple *GEM foils* as showed in Figure 3.12. These foils are very thin, of
¹⁷⁶⁶ the order of a few tens of μm , and are pierced with holes as can be seen in Figure 3.13. Both
¹⁷⁶⁷ surfaces of the GEM foils are clad with copper in order to apply a strong electric field in between
¹⁷⁶⁸ each side that will generate very strong potentials in the holes. The gas region contained in between
¹⁷⁶⁹ the cathode and the GEM foil is called the drift region as the electric field is not strong enough to
¹⁷⁷⁰ cause avalanches and thus start an amplification. The primary electrons drift toward the foil and are
¹⁷⁷¹ accelerated and amplify by the very high potential within the holes, as showed in Figure 3.13. Then
¹⁷⁷² the electrons reach the second drift region in which they will induce signal on the read-out located
¹⁷⁷³ on the anode. By restraining the amplification process at the level of the holes, the electrons can stay
¹⁷⁷⁴ in a very confined space and thus induce a very localized current, providing the GEMs with a very
¹⁷⁷⁵ good spatial resolution.

¹⁷⁷⁶ In order to achieve a stronger amplification, the amplification process can be repeated several
¹⁷⁷⁷ times in a row. The GEMs that will be used in CMS are triple GEM detectors operated with a 70/30
¹⁷⁷⁸ gas mixture of Ar/CO_2 . They contain 3 GEM foils and thus 3 electron amplifications, as can be
¹⁷⁷⁹ seen in Figure 3.14. The GEM foils used in CMS are 50 μm foils clad with 5 μm of copper on
¹⁷⁸⁰ each side. The foils are pierced with double-canonical holes which inner and outer diameters are
¹⁷⁸¹ respectively 50 and 70 μm which are placed 140 μm from each other in an hexagonal pattern, as
¹⁷⁸² showed in Figure 3.13. These detectors have a time resolution better than 10 ns and reach very good
¹⁷⁸³ spatial resolutions of less than 200 μrad as indeed the position of the hits is not measured along the
¹⁷⁸⁴ strips but following the azimuthal angle granularity of the radially organized trapezoidal strips.

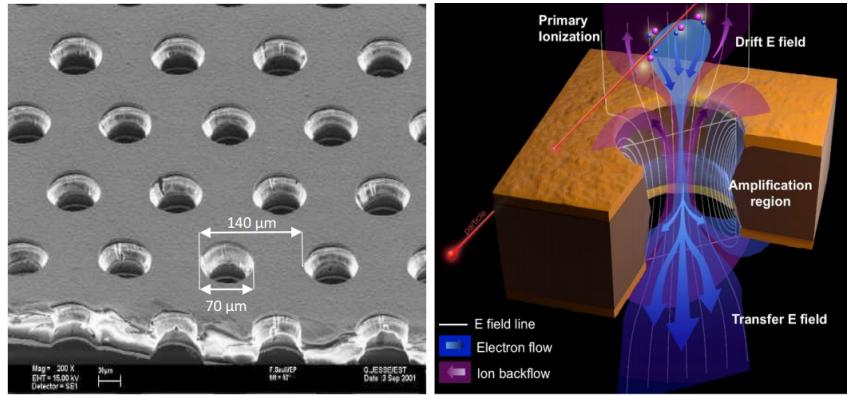


Figure 3.13: Left: Picture of a CMS GEM foil provided by a scanning electron microscope. Right: Representation of the electric field lines in a GEM hole and of the amplification that electrons and ions undergo in the hole's volume due to the very intense electric field.

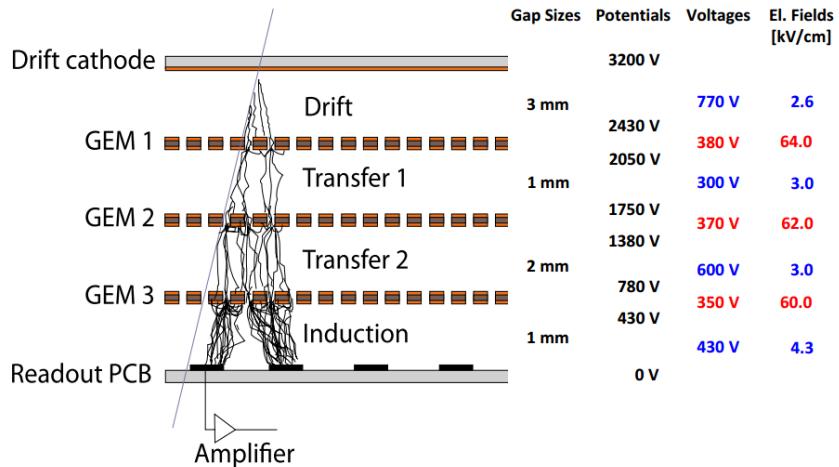


Figure 3.14: Schematic representation of CMS triple GEMs. The gas volume is divided into 4 areas. The drift area is the region where the primary electrons are created before being amplified a first time while passing through the first GEM foil. Then the process of drift and amplification is repeated twice in following two transfer areas and GEM foils. Finally, the charges have been amplified enough to induce current in the read-out strips while in the last drift area. The dimensions, potentials and electric fields are provided.

1785 The GEM Upgrade is divided into 3 subsystems as GE1/1 was the first approved project [29]
 1786 and that the detectors will already be installed during LS2. GE2/1 and ME0, on the other hand,
 1787 will profit of the R&D knowledge and skills developed for GE1/1 while the requirements for each
 1788 subsystem are different as they are not placed at the same distance from the interaction point. In this
 1789 very forward region, a different position with respect to the center of the detector can change dra-
 1790 matically the conditions in which the detectors will have to be operated. In terms of rate capability,
 1791 GE2/1, which is the furthest, is required to withstand 2.1 kHz/cm² while GE1/1 needs to be better
 1792 than 10 kHz/cm² and ME0, better than 150 kHz/cm². In terms of ageing with respect to charge
 1793 deposition, ME0 needs to be certified to 840 mC/cm², GE1/1 to 200 mC/cm² and GE2/1 only to

1794 9 mC/cm². All 3 detectors need to have a time resolution better than 10 ns and an angular resolution
 1795 better than 500 µrad.

1796 On each GE1/1 ring, 36 super chambers, consisting of 2 single GEM layers and spanning 10°,
 1797 will be installed covering the pseudo-rapidity region $1.6 < |\eta| < 2.2$ together with ME1/1 CSCs and
 1798 the reach of the muon system will be improved thanks to the GE2/1 that will overlap with the GE1/1
 1799 and cover a region from $|\eta| > 1.6$ to $|\eta| < 2.4$ and complete the redundancy of ME2/1. The super
 1800 chambers, built with 2 triple GEM layers each consisting of 4 single GEM modules due to the rather
 1801 large surface of the GE2/1 chambers, that will be installed on the first ring of the second endcap will
 1802 span 20° each, hence, a total of 72 chambers will be assembled to equip the muon system. Finally,
 1803 the ME0 installed near the HCAL endcap will cover the region $2.0 < |\eta| < 2.8$ and this subsystem
 1804 will consist in super modules of 6 layers of triple GEM detectors covering an azimuthal angle of 20°
 1805 leading to the construction of 216 single detectors.

1806 All these new GEM detectors will be using a similar internal layout which is described in Fig-
 1807 ure 3.14. The incoming muons will create detectable electron-ion pairs in the 3 mm thick drift
 1808 volume in which an electric field of 2.6 kV/cm is applied for the electrons to drift to the first GEM
 1809 foil on which a very intense field of 64 kV/cm is applied over a distance of only 60 µm which allows
 1810 for an average electronic gain of 20 to 25. After the first amplification stage, the electrons drift over
 1811 the 1 mm separating the 2 first GEM foils thanks to an electric field of 3.0 kV/cm and are again
 1812 amplified by a factor 20 to 25 while going through the second GEM foil to which is applied an elec-
 1813 tric field of 62 kV/cm. The electron drift another 2 mm towards the last GEM foil through a field of
 1814 3.0 kV/cm and are multiplied one last time from a similar factor passing through the 60 kV/cm
 1815 of the last GEM foil holes. Finally, they drift along the 1 mm of the induction volume in a field of
 1816 4.3 kV/cm to reach the trapezoidal strips on the read-out PCB used as anode. The total detector
 1817 gain is approximately of the order of 10^4 and the resulting output signal is both due to the induction
 1818 of moving charges in the induction volume and of charge pic-up once they read the read-out strips.

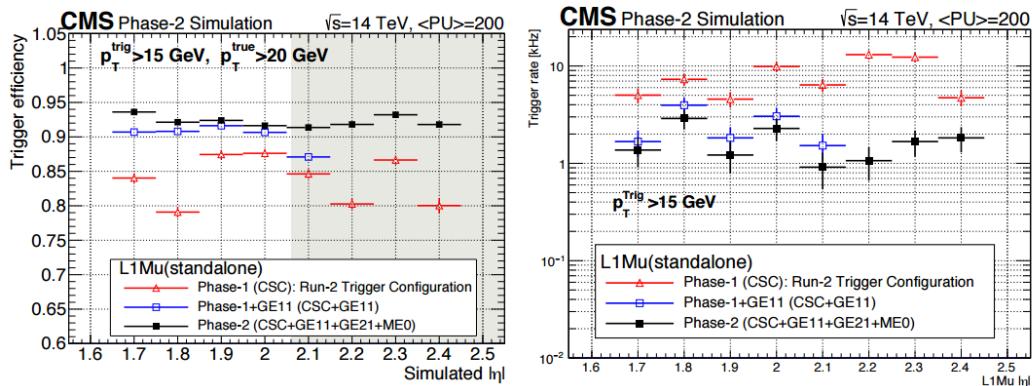


Figure 3.15: Simulated efficiency and rate of the standalone Level-1 muon trigger using tracks reconstructed in CSCs and all GEM stations compared with Phase-I values in the case where only CSCs are used or CSCs+GE1/1. The zones of inefficiency of the CSC subsystem are compensated by the addition of GEMs during Phase-II and the trigger rates is kept from increasing due to the high luminosity.

1819 Adding the GEMs into the forward region of the muon system will allow to strongly enhance
 1820 the Level-1 Trigger performance by reducing the inefficiency regions and the trigger rate as showed
 1821 in Figure 3.15. Moreover, benefiting from the good spatial and angular resolution of the GEMs, the

precision into the muon measurement will also be greatly improved by the addition of GEMs as can be seen from the simulation presented in Figure 3.16.

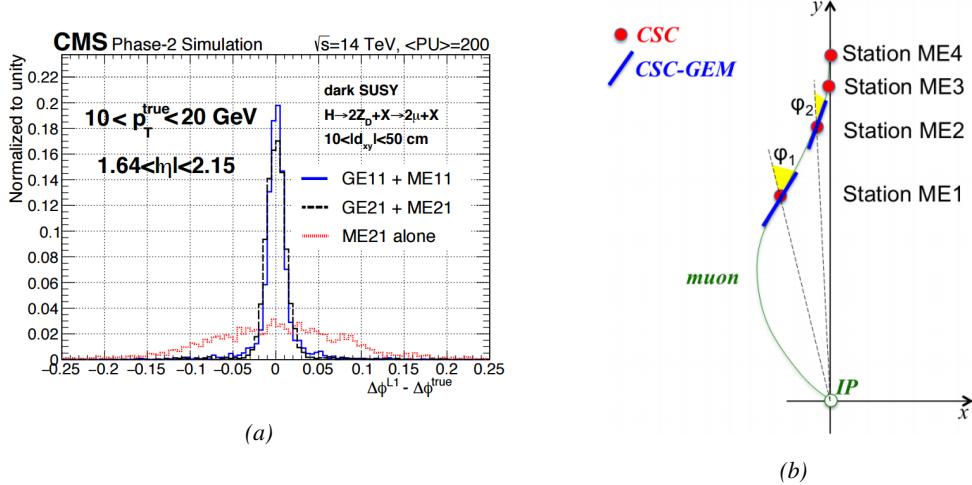


Figure 3.16: Figure 3.16a: Simulated resolution of the muon direction measurement $\Delta\phi$ with Phase-II conditions. In the second endcap station, the resolution is compared in the case of CSCs (ME2/I) alone and CSCs+GEMs (GE2/I+ME2/I) while a similar resolution measurement is given in the case of the first station (GE1/I+ME1/I). Figure 3.16b: The addition of GEM detectors on stations 1 and 2 (ME0 is considered to contribute to station station 1) as redundant system to CSCs allows to improve the muon momentum improvement through a more accurate measurement of the local bending angles ϕ_1 and ϕ_2 .

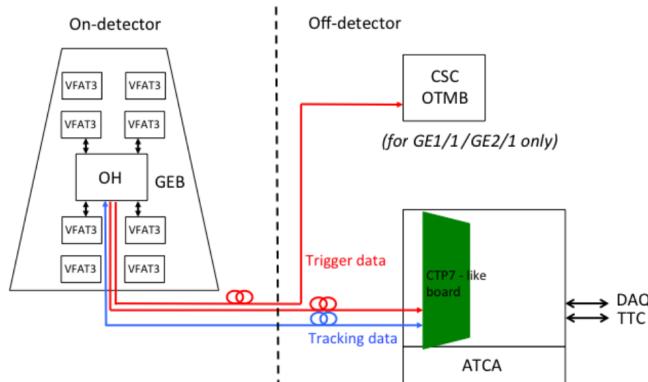


Figure 3.17: Schematics of the data communication chain for DAQ of the GEM subsystems. The sending of trigger data via optical links to the CSC OTMBs is only done for GE1/I and GE2/I to match the data with ME1/I and ME2/I.

The read-out of GEMs will use the same technology. The anode planes used as read-out PCBs and referred to as GEM Electronics board (GEB) host on their outer surface VFAT3 ASICs that connect to a total of 128 strips for a very fine angular granularity. Along the endcap radius, the strips are divided into 8 pseudo-rapidity partitions. In the case of GE1/1 and ME0, each η -partition consist in 384 read-out strips connected into 3 VFAT3 ASICs and offering a while the large GE2/1 partitions

1829 contain twice as many channels. Both GE1/1 and GE2/1 strips have an angular pitch of $474\text{ }\mu\text{m}$
 1830 while this of ME0 is twice larger due to its proximity with the interaction point. The VFAT3 ASICs
 1831 allow for a latency better than the $12.5\text{ }\mu\text{s}$ required by CMS Level-1 Trigger and there frequencies
 1832 goes up to 1 MHz. They are connected into the Optohybrid Board (OH) and this full ensemble
 1833 (GEB+VAT3+OH) constitute the on-chamber electronics. The OH is then sending the data to the
 1834 modules constituting the DAQ of the GEM system via optical fibers. These back-end electronics
 1835 modules are located in the service cavern of CMS and host CMS communication devices, used to
 1836 have a common clock, and control and links to the Endcap Muon Track Finder (EMTF) system.
 1837 Moreover, GE1/1 and GE2/1 also have links with the CSC OTMBs as the OH of these 2 subsystems
 1838 send data into these boards. This communication chain can be seen in Figure 3.17.

1839
 1840 The detectors that will placed in CMS will have to live through Phase-II without significant
 1841 performance degradation to ensure an efficient data taking and the possibility to investigate more
 1842 exotic physics. As the 3 GEM subsystems will be using the same detector technology, the choice
 1843 was made to certify the GEMs in the worst of the 3 environments, i.e. the ME0 station located right
 1844 behind the HCAL. According to FLUKA simulation, including all the latest foreseen upgrades into
 1845 the CMS detector geometry, it was shown that the maximal hit rate expected in ME0 would be of
 1846 the order of 50 kHz/cm^2 with contributions of neutrons (6 kHz/cm^2), photons (35 kHz/cm^2), and
 1847 electrons and positrons (8 kHz/cm^2) resulting in a charge deposition a little lower than 300 mC/cm^2
 1848 after 10 years of HL-LHC [23]. It is necessary to understand the classical ageing effects on the GEMs
 1849 but also premature ageing due to contaminants in the gas mixture leading to polymerization on the
 1850 surface of the GEM foils during operation and the effect of discharges on the detector operations if
 1851 they have to happen during their lifetime.

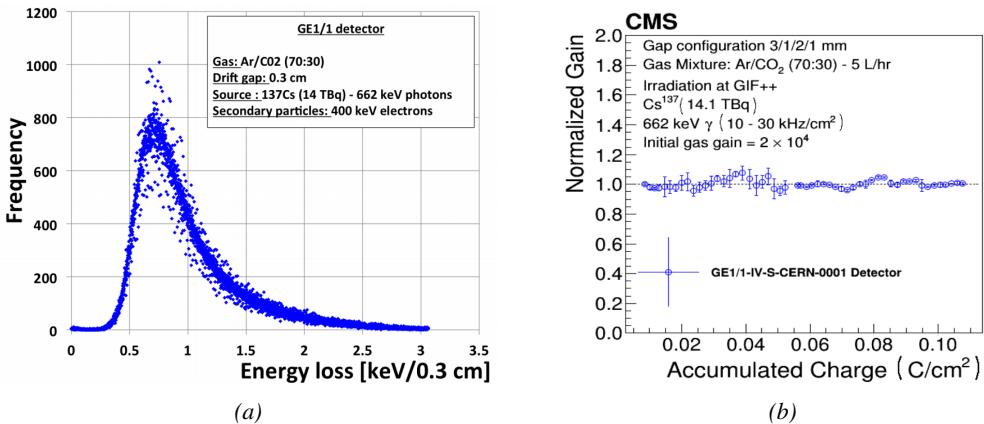


Figure 3.18: Figure 3.18a: Energy spectrum of GIF^{++} ^{137}Cs source as measured by the GE1/1 detector installed in GIF^{++} . Figure 3.18b: Evolution of the normalized gain of the GE1/1 detector installed at in GIF^{++} as a function of the integrated charge per unit area. The first part of the study, up to a charge of 55 mC/cm^2 had been done in the former Gamma Irradiation Facility (GIF) that has now been dismantled following the construction of GIF^{++} . No variation of the normalized gain can be observed after an accumulation of 110 mC/cm^2 .

1852 To characterize the classical ageing effects, a campaign is being conducted in the new Gamma
 1853 Irradiation Facility (GIF^{++}) of CERN where a GE1/1 detector operated at its nominal gain is placed
 1854 50 cm from the facility's 14 TBq ^{137}Cs source which emits gammas at an energy of 662 keV. In

order to spot any ageing of the detector, the effective gain is kept monitored, as can be seen in Figure 3.18b, as its variations gives clues about different aspects of the detector such as the geometry of the holes, the electric field configuration or the gas composition. The monitoring of the gamma energy distribution, showed on Figure 3.18a, can give an idea on the evolution of the performance of the chamber and finally, the evolution of the currents through time also is a good indicator of the appearance of dark current in the detector that would be due to the emission of electrons by thin insulating layers of the detector subjected to a long lasting irradiation known as Malter effect. At the time the Technical Design Report (TDR) for the Phase-II upgrade of the muon system was written [23], the GEM group had reported a total integrated charge of 110 mC/cm^2 which, if compared with 10 years of HL-LHC operation, represents a safety factor of 18 for the GE1/1 subsystem and a factor 37 for the GE2/1 subsystem but only 39% of the total expected ME0 integrated charge. It is estimated that reaching the total integrated charge necessary to certify the detectors for Phase-II operation will take another 2 to 3 years. Nevertheless, the present status of the longevity study shows no degradation of the performance of the detector installed in GIF++ as can be seen through Figure 3.18.

Aside of the classical ageing tests, outgassing of the different materials composing the GEMs have been conducted by placing the different materials to be tested into an outgassing box that consists in a stainless steel cylinder through which the CMS GEM 70/30 gas mixture of Ar/CO_2 with the possible contaminants is flowed while the detector is exposed to the continuous irradiation of a radioactive source and the heat is raised to enhance the outgassing. From the detector that was placed into this outgassing box, only one component was identified to cause loss of performance due to outgassing. This component was the polyurethane *Cell-Pack* used to coat the internal frame of the GEMs and the polymerization on its surface caused a 20% decrease of the gas gain. this polyurethane was replaced with a new one for which no outgassing effect causing a loss of performance was reported.

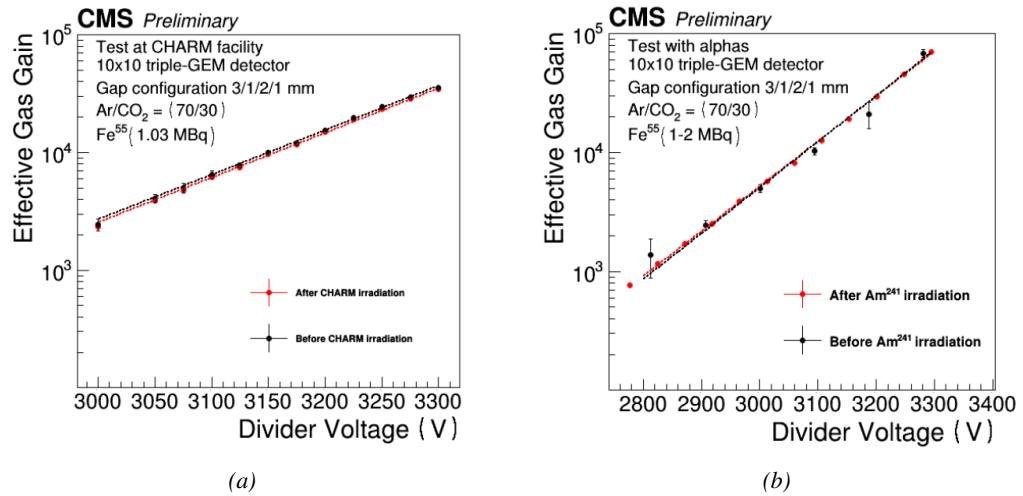


Figure 3.19: Figure 3.19a: Comparison of the gas gain as a function of the divider voltage before and after the irradiation of a triple-GEM by neutrons in CHARM. Figure 3.19b: Comparison of the gas gain as a function of the divider voltage before and after the irradiation of a triple-GEM by alpha particles.

Finally, even though the triple-GEM technology makes the detectors safe of discharges thanks to

its several amplification stages that allow to reach high gas gain using a relatively low electric field applied on the foils and to the distance separating the last foil from the read-out panel that is high enough to prevent discharging from developing all the way to the read-out, and hence, be stopped before it can cause any harm, it is important to have a good understanding of the discharge probability to ensure a safe operation over long periods. In order to further prevent discharges to develop in the detector volume, the GEM foils' power supply have been sectorized and protection resistors have been installed to limit the energy available for the discharge development. To reproduce the high-energy neutron background conditions of CMS, a GE1/1 detector have been placed in the CHARM facility of CERN. This facility allows to irradiate the detectors with a neutron fluence as high as $2.5 \times 10^8 / \text{cm}^2$. The detectors were operated with a slightly higher gain of 3.5×10^4 . It was measured that the discharge probability for a GEM operated under CMS conditions was of 2.85×10^{-9} per heavily ionizing particle with a 95% confidence level that would correspond to 225 discharges per cm^2 in ME0, 17 in GE1/1 and 12 in GE2/1 during the full HL-LHC period. According to Figure 3.19a, no degradation of the performance was observed after the irradiation at CHARM were 24 discharges per unit area were reported. Nevertheless, another test were the detector was exposed to a 5.5 MeV alpha source and were 450 discharges per unit area were reported didn't show any drop of performances either, as can be seen in Figure 3.19b.

3.3.3 Installation schedule

The previous discussion on the different upgrade projects makes it clear that a lot of work is scheduled for CMS to be ready at the end of LS3 for HL-LHC. Conducting all the upgrades of the muon system together with upgrades of the other subsystems like the replacement of the Tracker and of part of the ECAL, will prove to be very difficult as the opening of CMS to access the Barrel will be done by fully opening the endcaps leaving only the first disk to be accessible. Thus, most subsystems have planned early installation over LS2, and the following YETS until LS3 in order to give more space to LS3 schedule.

First of all, LS2 will see the installation of GE1/1 detectors, all the on-detector schedule of CSCs and the installation of the necessary services for the improved RPCs to be installed later, such as the HV and LV power supply lines, the gas and cooling lines or signal cables. CSCs will have a huge work to do during LS2 as they will need to extract all of their detectors to refurbish them with upgraded DCFEB and ALCT mezzanine boards. The GE1/1 services were installed during LS1 together with a few demonstrator and only the detectors needs to be integrated into the first endcap disk. The detectors are presently being built and tested at the different assembly site to prepare for a smooth LS2 work.

The work of GEMs will be continued during the following YETS during which is planned the installation of the GE2/1 stations to only leave the ME0 to be installed during LS3. The iRPC program will follow a similar path as the new detectors will be installed during the YETS preceding LS3 in preparation of the fact that the endcap disks will not be accessible during LS3. This way, all the subsystems, but DTs, made great effort on planning their installation and integration within CMS only to have to deal with off-detector issues during the LS3 period, such as the replacement of ODMBs and HV system in the case of CSCs or the upgrade of the RPC Link System. Finally, during LS3 are scheduled the replacement of DT minicrates electronics and the installation and integration of ME0 GEMs together with the HGCAL.

3.4 Implications of the different upgrades on the Level-1 Trigger. Improvement of physics performance.

The upgrades of the different subsystems will have a subsequent impact on the Level-1 Trigger. Indeed, although its main scheme will not be affected, the efficiency of the trigger in identifying muons and provide the DAQ with good and fast trigger that can cope with HL-LHC instantaneous luminosity is a major improvement. In addition to the upgrade of the muon system in terms of trigger accept rate and latency, the Level-1 Trigger will get extra information in including the Tracker Trigger into its Muon Track Finder logic and combine the L1 Muon Trigger with Tracker and Calorimeter Triggers to generate a Global L1 Trigger with a much better momentum resolution, as showed in Figure 3.20.

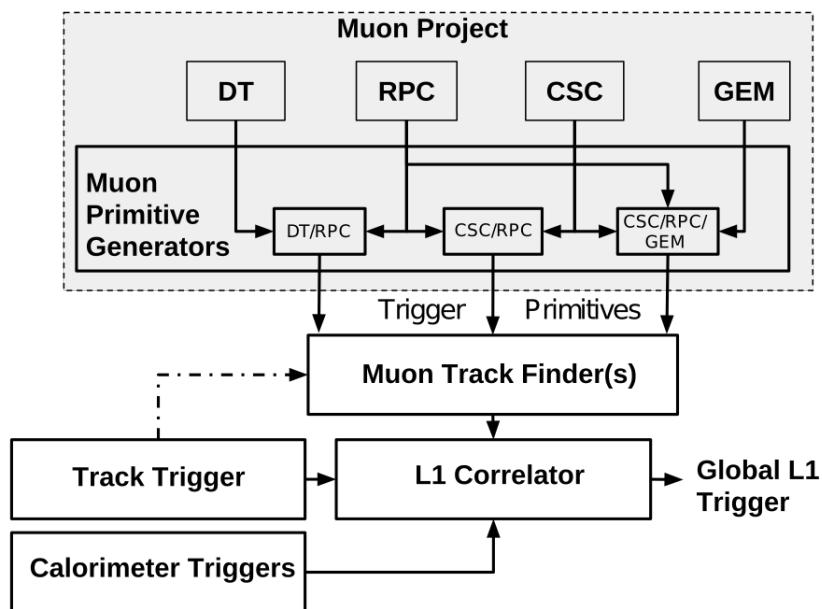


Figure 3.20: Data flow of the Level-1 Trigger during Phase-II operations.

In terms of muon trigger, 3 regions are considered due to their different track finding logic: the Barrel Muon Track Finder (BMTF), the Endcap Muon Track Finder (EMTF) for both the barrel and endcap regions, and finally the Overlap Muon Track Finder (OMTF) which concerns the pseudo-rapidity region in which there is a common coverage by both the barrel and endcap muon systems. This region can be seen in Figure 3.3 for $0.9 < |\eta| < 1.2$ and requires a specific more complex logic to provide with an efficient reconstruction of the muons due to the different orientation of the detectors and of the more complex magnetic field of this region that needs to be taken into account. The benefits of the upgrade for each of these track finders will be coming from different improvements and will be detailed sector by sector.

The main contribution to the improvement of the BMTF is the time resolution improvement of RPC link systems that will allow to take profit of the full 1.5 ns resolution of the detectors. From the perspective of RPCs only, this improvement will help reducing the neutron induced background and

slightly improve the bunch crossing assignment. The upgrade of DT electronics is also to take into account as the trigger primitive generator will be renewed through the use of TDCs that will send the digitized signals directly to the back-end electronics instead of having an on-detector trigger logic as it will be the case until the end of Phase-I. The front data of both DTs and RPCs will be sent to the same back-end electronics. These upgrades were detailed in section 3.2 and will lead to a more robust operation of the trigger in the barrel region. Indeed, the combination of RPC hits together with DT primitives will bring improvement in the bunch crossing assignment and improve the efficiency of the trigger in between the wheels where the quality of DT primitives is the poorest. Moreover, having a redundant information is important in the case of failure and loss of efficiency of one of either subsystems.

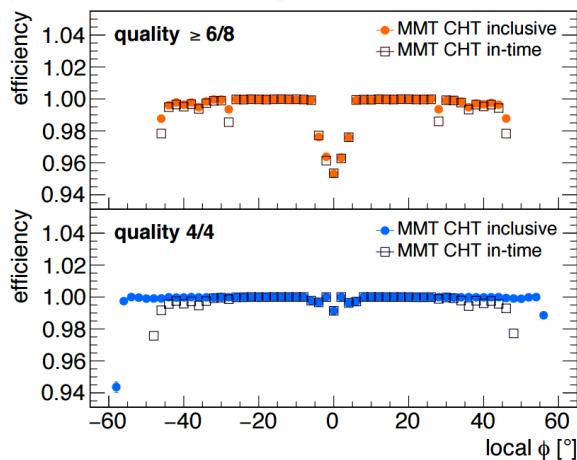


Figure 3.21: Comparison of Phase-II DT trigger primitives algorithmic efficiency for segments obtained with 2 super-layers ($\text{quality} \geq 6/8$) and 1 super-layer only ($\text{quality} = 4/4$). The simulation was done by generating 2×10^6 muons. The candidate tracks with correct time identification is showed with open symbols.

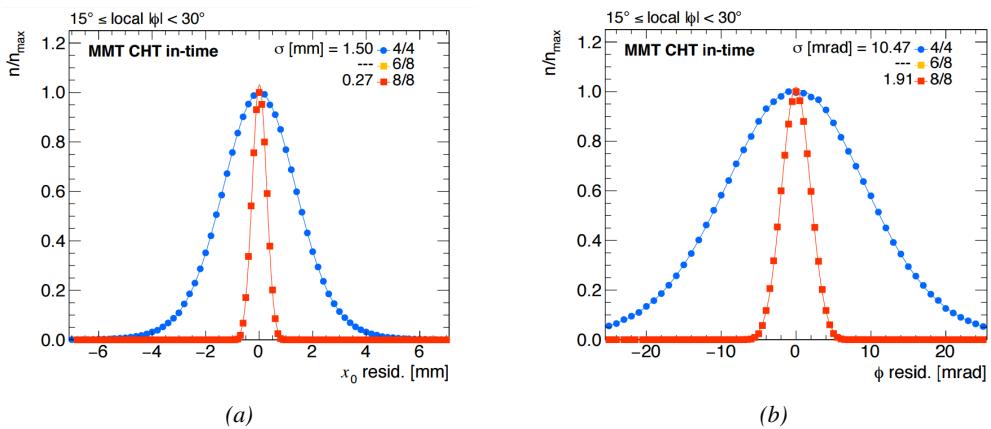


Figure 3.22: Simulated spatial (3.22a) and angular (3.22b) resolution of the algorithm using 8 aligned hits in both super-layers ($\text{quality} = 8/8$) and 4 aligned hits in only one super-layer ($\text{quality} = 4/4$). The contribution of intermediate quality tracks (6 aligned hits) is negligible in the angular range shown. [Be careful to update this caption as it uses a text to close to the published one.]

1957 The loss of single hit efficiency of DTs due to ageing will also force the DT to change the algorithm
 1958 use to identify tracks. So far, the identification was only performed at the level of a single DT
 1959 super-layer, which is composed of 4 single DT layers. In the perspective the single efficiency drops,
 1960 this will require to be upgraded to try to combine the data of more than a single super-layer to keep
 1961 a high muon track identification efficiency. In addition to this change in trigger primitive candidate
 1962 quality, new algorithms with higher efficiency are being developed. According to Figure 3.21, the
 1963 efficiency of the new algorithm, both in the cases using 1 or 2 super-layers, is higher than with the
 1964 current system [30]. Moreover, the overall efficiency of an algorithm requesting at least a muon
 1965 detected in 6 DT layers out of the 8 composing the 2 super-layers of a DT module would stay com-
 1966 parable to the 4 DT layers out of 4 algorithm within the local bending angle range. On the other
 1967 hand, despite the slight loss of efficiency in the low angle range, the algorithm using more DT layers
 1968 achieves both higher spatial and angular resolution according to Figure 3.22.

1969

1970 With new detectors to cover the very forward region and the upgrade of RPC Link System,
 1971 the EMTF will be greatly improved. The current EMTF already use more sophisticated algorithms
 1972 by combining together RPC hits and CSC primitives and will also benefit from the improved time
 1973 resolution of the RPC system. The GEMs, in stations 1 and 2, and the iRPCs, in stations 3 and 4,
 1974 will be added into the EMTF algorithm. Both these contributions will help increasing the efficiency
 1975 of the L1 trigger in the endcap region in one hand, and help lowering the L1 trigger rate in the other
 1976 hand, especially in the most forward region. The improvement of the efficiency will come both from
 1977 the better time resolution of RPC link boards and from the addition of more hits along the muon
 1978 tracks and also a contribution from the GEMs to the lever arm of each track thanks to their high
 1979 angular resolution.

1980

1981 The rate will be partly reduced in the forward region thanks to the better spatial resolution of
 1982 iRPCs, with respect to the current RPC system, that will reduce the ambiguity brought by multiple
 1983 local charged tracks in CSCs, as explained through Figure 3.24. Indeed, as the rates will increase,
 1984 the probability to record more than a single local charged track will greatly increase. This is due to
 1985 the fact that the trigger algorithm uses information from 3 consecutive bunch crossings to find muon
 1986 tracks. It is estimated that with iRPCs operated at 95% efficiency the resolution of ambiguous events
 would be of the order of 99.7%.

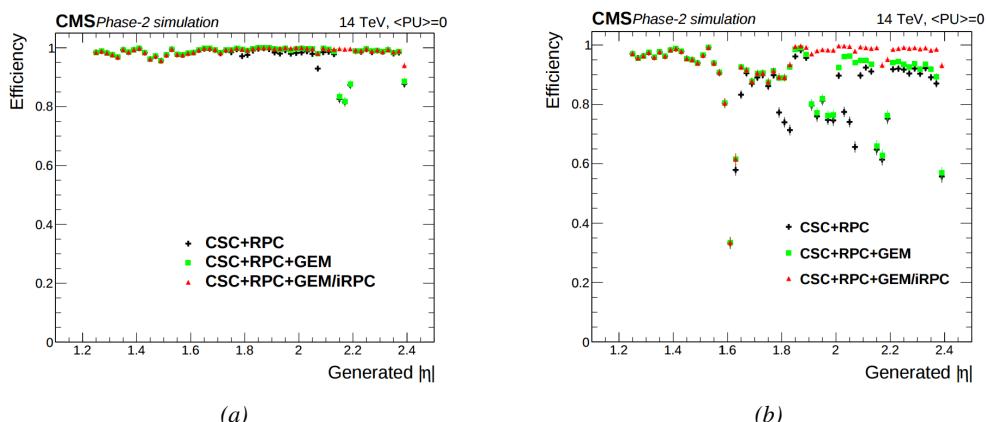


Figure 3.23: Efficiency of the L1 trigger in the endcap region after Phase-II upgrade in the case CSC/GEM/RPC hits are requested in at least 2 stations out of four (3.23a) and in all four stations (3.23b).

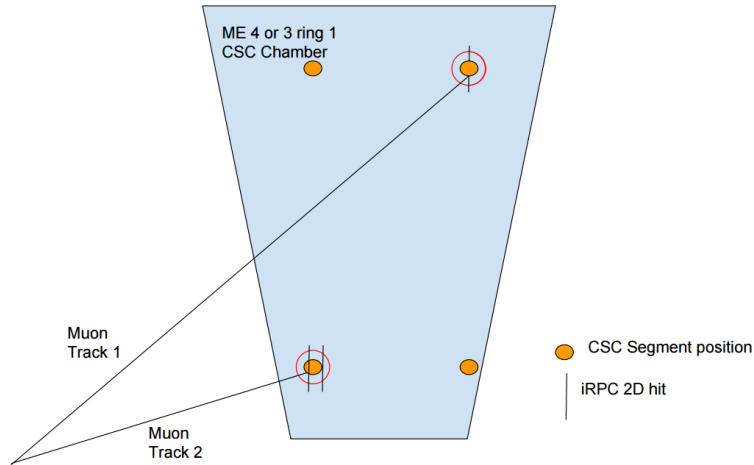


Figure 3.24: Resolution of the LCT ambiguous events thanks to the combination of CSC and iRPC readout data. Using CSCs only, 2 pairs of hits are possible.

The addition of GEMs will improve greatly the measured muon momentum resolution by improving the global resolution of the direction of muon tracks, as can be seen in Figure 3.25, which will contribute to lowering the trigger rate and increase the efficiency, as can be seen from Figure 3.26 that focuses especially in the most challenging pseudo-rapidity region. Data from both CSCs and GEMs are combined into the OTMB to build on each station, GEM/CSC primitives matching space and time information from both subsystems.

Finally, the development of a track finder specific to the overlap region was already achieved during the Phase-I upgrade of the L1-Trigger [31]. Nevertheless, the improvements of DT spatial resolution and RPC timing will be carried and implemented into the OMTF.

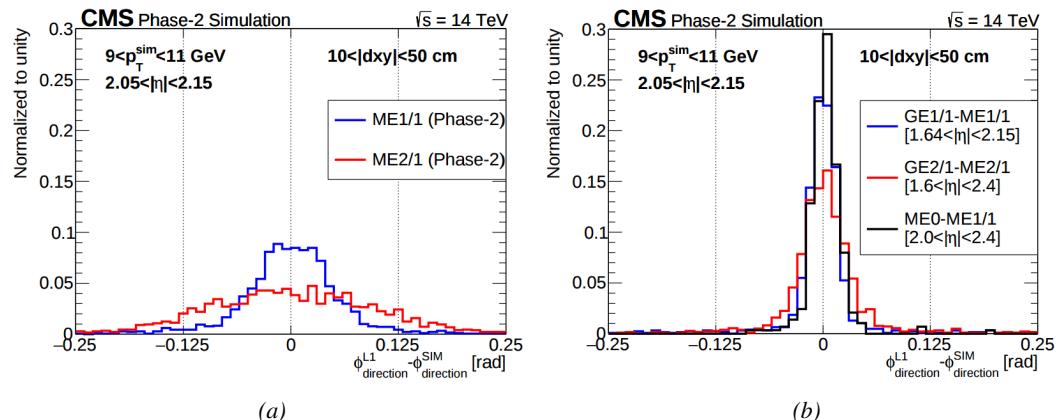


Figure 3.25: The angular resolution on reconstructed muon tracks in the GEM overlap region $2.0 < |\eta| < 2.15$ is compared for Phase-II conditions in the case CSC are alone (Figure 3.25a) and in the case the GEMs' data, including ME0, is combined to which of CSCs (Figure 3.25b).

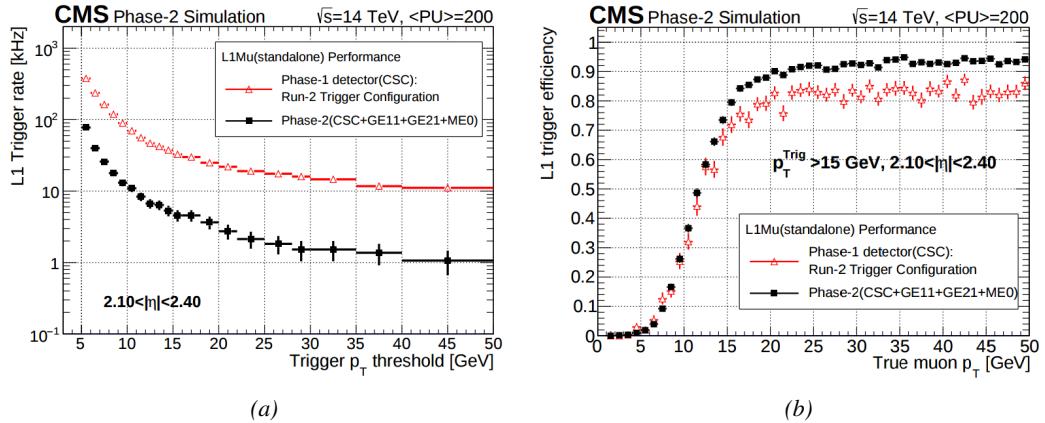


Figure 3.26: Comparison of L1 trigger performances for prompt muons with and without the addition of GEMs in the region $2.1 < |\eta| < 2.4$ at Phase-II conditions. GEMs would allow a reduction of the trigger accept rate by an order of magnitude (Figure 3.26a) while increasing the trigger efficiency (Figure 3.26b).

3.5 Ecofriendly gas studies

Future strict restrictions in the use of certain gases will affect the gaseous detectors of several experiment, including CMS. The European Commission adopted a new "F-gas regulation" in 2014 [32] with the goal to strongly control and reduce the use of fluorinated gases with high Global Warming Potential (GWP). Using CF_4 , $C_2H_2F_4$ and SF_6 , both CSC and RPC subsystems will need to address this problem by finding new gas mixture for the operation of their detectors. Finding a replacement for these gas component that were used for very specific reasons will be a great challenge. Indeed, CSCs use CF_4 in order to enhance the longevity of the detectors, increase the drift velocity of electrons and quench photons with a non-flammable gas mixture. RPCs use a mixture mainly composed of $C_2H_2F_4$, or $R134a$, that features a high effective Townsend coefficient and the great average fast charge allowing for operations with a high threshold, and contains a small fraction of SF_6 that is used for its electronegative properties that prevents the development of delta-rays in the gas volume that might trigger multiple ionization and avalanches.

	CSC	RPC
Greenhouse gases used	CF_4	$C_2H_2F_4$ and SF_6
Greenhouse gases fraction in the gas mixture	10%	95.2% and 0.3%
Global Warming Potential (relative to CO_2)	6500	1300 and 23900
Gas mixture re-circulation	Yes, 90%	Yes, 85%
Gas mixture replenishing rate (l/hr)	700	1100
F-gas recuperation	Yes, $\approx 40\%$	No
F-gas venting rate (l/hr)	42	1047 and 3.3
CO_2 -equivalent rate (m^3/h)	273	1440
Relative impact (entire muon system = 100%)	16%	84%

Table 3.1: Details of the greenhouse fluorinated gases used in CMS and of their GWP [23].

Nevertheless, all these gases have a very high GWP, as reported in Table 3.1, and only few options are left. The subsystems need to work on strongly decrease the loss of these gases due to leaks in the

gas system or completely change their gas mixture for more ecofriendly ones. Reducing the amount of F-gas released in the atmosphere due to leaks on the current gas system will require installation of a F-gas recuperation system on RPCs side and an upgrade of CSCs existing one in addition to the repair of existing leaks. With such measures, it is expected that the total rate of greenhouses gas vented in the atmosphere would represent only 1.6% of the current levels [23]. In the most critical case the F-gas were to be banned, it would be necessary to have replacement mixtures to operate CMS. CSC is presently investigating replacement for CF_4 such as CF_3I , C_4F_6 , IC_3F_6 , C_3F_8 or CHF_3 while RPCs, in collaboration with the ATLAS RPC group which uses the same gas mixture and, hence, faces similar restrictions, have identified CF_3I ($GWP \leq 1$) and $C_3H_2F_4$ ($GWP < 1$), referred to as HFO-1234ze, as potential candidates with mixtures containing CO_2 but more R&D needs to be conducted for both subsystems before concluding on the best alternative. No good alternative to the present mixtures will require very efficient abatement system in CMS to burn and convert the greenhouse gases into less harmful ones. This way, the air pollution would be strongly reduced.

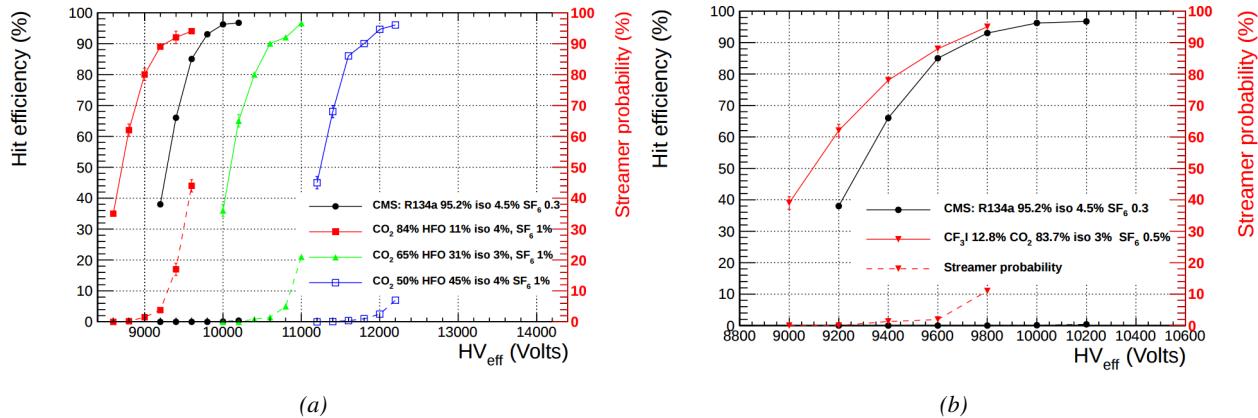


Figure 3.27: The efficiency (solid lines) and streamer probability (dashed lines) of HFO/CO₂ (Figure 3.27a) and CF₃I/CO₂ (Figure 3.27b) based gas mixtures as a function of the effective high-voltage are compared with the present CMS RPC gas mixture represented in black. The detector used for the study is a single gap RPC with similar properties than CMS RPCs. The streamer probability is defined as the proportion of events with a deposited charge greater than 20 pC.

The status of RPC studies are presented in Figure 3.27 in which the performance (efficiency and streamer probability) of an RPC operated with alternative gas mixtures is compared to the present CMS RPC mixture. Although the efficiency of detectors operated with mixtures containing CO₂/CF₃I or CO₂/HFO as a replacement for C₂H₂F₄ seem to reach similar levels than which of the detectors operated with the present mixture, the new gas mixtures feature a streamer probability (probability to have very large avalanches whose induced charge is greater than 20 pC) that far exceeds which of the present fluorinated mixture. The SF₆, being a component of the mixture added in order to reduce the probability of large avalanches thanks to its electronegativity, doesn't seem to prevent streamers as efficiently even when used at levels more than 3 times higher than with the standard CMS RPC mixture. Nevertheless, it is important to note that these results were obtained with a single gap RPC while the use of a double gap RPC would reduce the operation voltage by 200 to 300 V, lowering the induced charge. A compromise in between good efficiency and acceptable level of streamer probability and the fine tuned composition of potential replacement gas mixtures

₂₀₃₈ will be studied using a standard double-gap CMS RPC.

4

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Physics of Resistive plate chambers

2041 A Resistive Plate Chamber (RPC) is a gaseous detector used in high-energy physics experiments as
2042 described in Chapter 3. It has been developed in 1981 by Santonico and Cardarelli [33], under the
2043 name of *Resistive Plate Counter*, as an alternative to the local-discharge spark counters proposed in
2044 1978 by Pestov and Fedotovich [34, 35]. Working with spark chambers implied using high-pressure
2045 gas and high mechanical precision which the RPC simplified by formerly using a gas mixture of
2046 argon and butane flowed at atmospheric pressure and a constant and uniform electric field propagated
2047 in between two parallel electrode plates. Moreover, a significant increase in rate capability was
2048 introduced by the use of electrode plate material with high bulk resistivity, preventing the discharge
2049 from growing throughout the whole gas gap. Indeed, the effect of using resistive electrodes is that
2050 the constant electric field is locally canceled out by the development of the discharge, limiting its
2051 growth.

2052 Through its development history, different operating modes [36–38], gas mixtures [33, 38–43]
2053 and new detector designs [44–46] have been discovered, leading to further improvement of the rate
2054 capability of such a detector. The low developing costs and easily achievable large detection ar-
2055 eas offered by RPCs, as well as the wide range of possible designs, made them a natural choice to
2056 as muon chambers and/or trigger detectors in multipurpose experiments such as CMS [21] or AT-
2057 LAS [47], time-of-flight detectors in ALICE [48], calorimeter with CALICE [49] or even detectors
2058 for volcanic muography with ToMuVol [50].

2059 4.1 Principle

2060 RPCs are ionisation detectors composed of two parallel resistive plate electrodes in between which
2061 a constant electric field is set. The space in between the electrodes, referred to as *gap*, is filled with
2062 a dense gas that is used to generate primary ionization into the gas volume. The free charge carriers
2063 (electrons and cations) created by the ionization of the gas molecules are then accelerated towards the
2064 electrodes by the electric field, as shown in Figure 4.1 [51]. RPCs being passive detectors, a current
2065 on pick-up copper read-out placed outside of the gas volume is induced by the charge accumulation

2066 during the growth of the avalanche resulting from the acceleration of the charge carriers. As a
 2067 consequence, the time resolution of the detector is substantially increased as the output signal is
 2068 generated while the electrons are still in movement. The advantage of a constant electric field, over
 2069 multi-wire proportional chambers, is that the electrons are being fully accelerated from the moment
 2070 charge carriers are freed and feel the full strength of the electric field that doesn't depend on the
 2071 distance to the readout and that the output signal doesn't need for the electrons to be physically
 2072 collected.

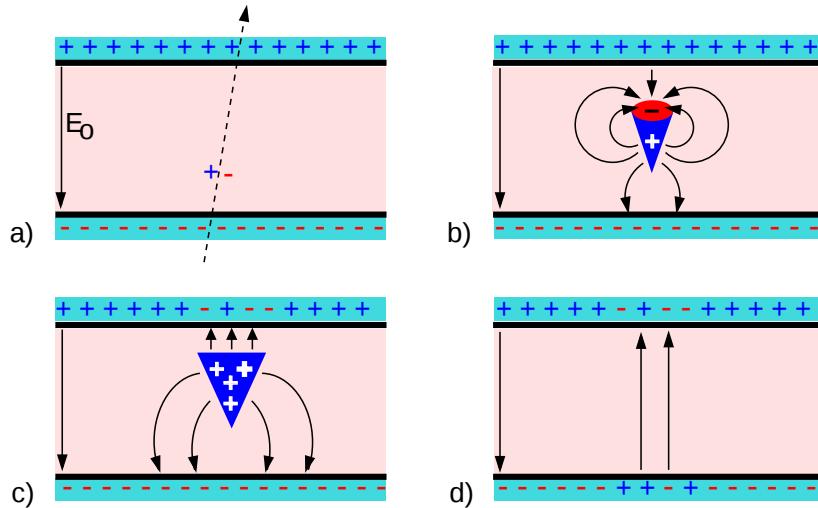


Figure 4.1: Different phases of the avalanche development in the RPC gas volume subjected to a constant electric field E_0 . a) An avalanche is initiated by the primary ionisation caused by the passage of a charged particle through the gas volume. b) Due to its growing size, the avalanche starts to locally influence the electric field. c) The electrons, lighter than the cations reach the anode first. d) The ions reach the cathode. While the charges have not recombined, the electric field in the small region around the avalanche stays affected and locally blinds the detector.

2073 After an avalanche developed in the gas, a time long compared to the development of a discharge
 2074 is needed to recombine the charge carriers in the electrode material due to their resistivity. This
 2075 property has the advantage of affecting the local electric field and avoiding sparks in the detector
 2076 but, on the other hand, the rate capability is intrinsically limited by the time constant τ_{RPC} of the
 2077 detector. Using a quasi-static approximation of Maxwell's equations for weakly conducting media,
 2078 it can be shown that the time constant τ_{RPC} necessary to the charge recombination at the interface
 2079 in between the electrode and the gas volume is given by the Formula 4.1 [52].

$$(4.1) \quad \tau_{RPC} = \frac{\epsilon_{electrode} + \epsilon_{gas}}{\sigma_{electrode} + \sigma_{gas}}$$

2080 A gas can be assimilated to vacuum, leading to $\epsilon_{gas} = \epsilon_0$ and $\sigma_{gas} = 0$, and the electrodes
 2081 permittivity and conductivity can be written as $\epsilon_{electrode} = \epsilon_r \epsilon_0$ and $\sigma_{electrode} = 1/\rho_{electrode}$,
 2082 showing the strong dependence of the time constant to the electrodes resistivity in Formula 4.2.

$$(4.2) \quad \tau_{RPC} = (\epsilon_r + 1)\epsilon_0 \times \rho_{electrode}$$

Very few materials with a low enough resistivity exist in nature. The resistivity targeted to build RPCs ranges from 10^9 to $10^{12} \Omega \cdot \text{cm}$. The most common RPC electrode materials are displayed in Table 4.1. When the doped glass and ceramics can offer short time constants of the order of 1 ms, the developing cost of such materials is quite high due to the very low demand. Thus, High-pressure laminate (HPL) is often the choice for high rate experiments using very large RPC detection areas. Other experiments working at cosmic muon fluxes can safely operate with ordinary float glass.

Material	$\rho_{\text{electrode}} (\Omega \cdot \text{cm})$	ϵ_r	$\tau_{\text{RPC}} (\text{ms})$
Float glass	10^{12}	~ 7	~ 700
High-pressure laminate	10^{10} to 10^{12}	~ 6	~ 6 to 600
Doped glass (LR S)	10^9 to 10^{11}	~ 10	~ 1 to 100
Doped ceramics (SiN/SiC)	10^9	~ 8.5	~ 1
Doped ceramics (Ferrite)	10^8 to 10^{12}	~ 20	~ 0.2 to 2000

Table 4.1: Properties of the most used electrode materials for RPCs.

4.2 Rate capability and time resolution of Resistive Plate Chambers

The electrode material plays a key role in the maximum intrinsic rate capability of RPCs. R&D is continuously being done to develop at always cheaper costs material with lower resistivity. Nevertheless, the amount of charge released, i.e. the size of the discharge, if reduced leads to a smaller blind area in the detector, increasing the rate capability of the detector. On the other hand, the drift velocity of electrons in the gas volume being quite stable with the applied electric field, the design of a detector and the associated read-out and pulse-processing electronics will be a major component of the time resolution of RPCs. Moreover, the sensitivity of the electronics will also help increasing the rate capability by lowering the gain the gas volume needs to be operated at, increasingly lowering the gas volume in which the signals will develop.

4.2.1 Operation modes

Being a gaseous detector using an accelerating electric field to amplify the signal of primary charge carriers, the RPC can be operated into different modes as the electric field intensity varies. Each mode offers different performances for such a detector, and it will be showed that the operating mode corresponding to the lowest electric field possible is best suited for high rate detectors working in collider experiments.

RPCs where developed early 1980s. At that time it was using an operating mode now referred to as *streamer mode*. Streamers are large discharges that develop in between the 2 electrodes enough to locally discharge the electrodes. If the electric field inside of the gas volume is strong enough, with electrons being fast compared to ions, a large and dense cloud of positive ions will develop nearby the anode and extend toward the cathode while the electrons are being collected, eventually leading to a streamer discharge due to the increase of field seen at the cathode. The field is then strong enough so that electrons are pulled out of the cathode. Electrodes, though they are a unique volume of resistive material, can be assimilated to capacitors. At the moment an electric field is applied in between their outer surfaces, the charge carriers inside of the volume will start moving leading to a situation where there is no voltage across the electrodes and a higher density of negative charges,

i.e. electrons, on the inner surface of the cathode. Finally, when a streamer discharge occurs, these electrons are partially released in the gas volume contributing to increase the discharge strength until the formation of a conductive plasma, the streamer. This can be understood through Figure 4.2 [36]. Streamer signals are very convenient in terms of read-out as no further amplification is required with output pulses amplitudes of the order of a few tens to few hundreds of mV as can be seen on Figure 4.3.

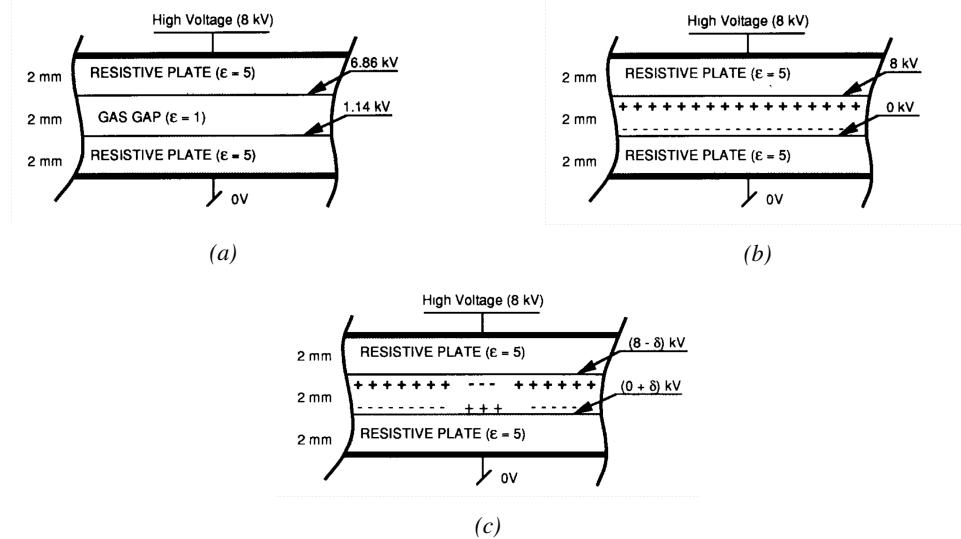


Figure 4.2: Movement of the charge carriers in an RPC. Figure 4.2a: Voltage across an RPC whose electrode have a relative permittivity of 5 at the moment the tension is applied. Figure 4.2b: After the charge carriers moved, the electrodes are charged and there is no voltage drop over the electrodes anymore. The full potential is applied on the gas gap only. Figure 4.2c: The streamer discharge initiated by a charged particle transports electrons and cations towards the anode and cathode respectively.

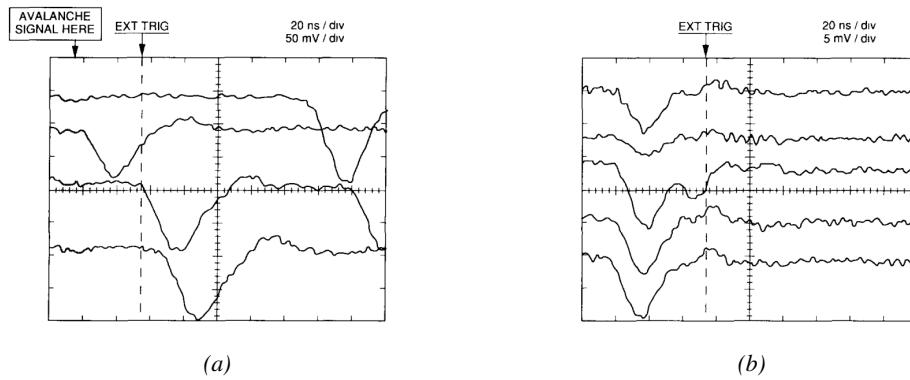


Figure 4.3: Typical oscilloscope pulses in streamer mode (Figure 4.3a) and avalanche mode (Figure 4.3b). In the case of streamer mode, the very small avalanche signal is visible.

When the electric field is reduced though, the electronic gain is small until the electrons get close enough to the anode and the positive ion cloud is much smaller. The electric field cannot rise to the

point a field emission of electrons on the cathode is possible. The resulting signal is weak, of the order of a few mv as shown on Figure 4.3, and requires amplification. This is the *avalanche mode* of RPC operation. This mode offers a higher rate capability by providing smaller discharges that don't affect the electrodes charge and are more locally contained in the gas volume as was demonstrated by Crotty with Figure 4.4 [36]. The detector only stays locally blind the time the charge carriers are recombined and there is no need for electrode recharge which is a long process affecting a large portion of the detector. Another advantage of avalanche signals over streamer is the great time consistency. Figure 4.3 shows very clearly that avalanche signals have a very small time jitter. Thus, using such a mode is a natural choice for experiments in which the detectors are required to have a high detection rate.

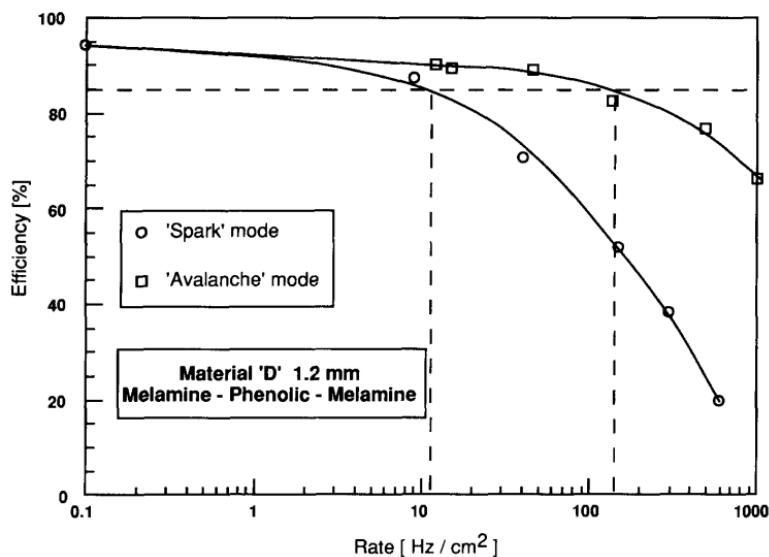


Figure 4.4: Rate capability comparison for the streamer and avalanche mode of operation. An order of magnitude in rate capability for a maximal efficiency drop of 10% is gained by using the avalanche mode over the streamer mode.

4.2.2 Standard gas mixture for RPCs operated in collider experiments

The first RPC working in streamer mode was operated with a 50/50 mixture of argon and butane [33], a standard mixture used at that time in multi-wire proportional chambers, taking profit of the good effective Townsend coefficient of argon to maximize the number of primary charge carriers freed in the gas by ionizing particles and of the quenching properties of butane. Before the discovery of the avalanche mode of RPC operation and concerned about the rate capability of RPCs operated in streamer mode, the performance improvement of the detectors through the increase of fast charge ratio in the signal development ,decreasing the charge induced per avalanche as can be seen through Figure 4.5, was studied by adding Freon based gases, such as CF_3Br , into the typical Ar/C_4H_{10} gas mixture was studied and showed that a lower induced charge could lead to an improvement the rate capability [39]. This consideration lead to the discovery of the avalanche mode which confirmed that the smaller the induced charge, the better the rate capability of the RPCs [36]. This discovery could happen thanks to the increased number of lower induced charge events allowed by adding a

²¹⁴⁷ fraction of strong quencher in the gas mixture.

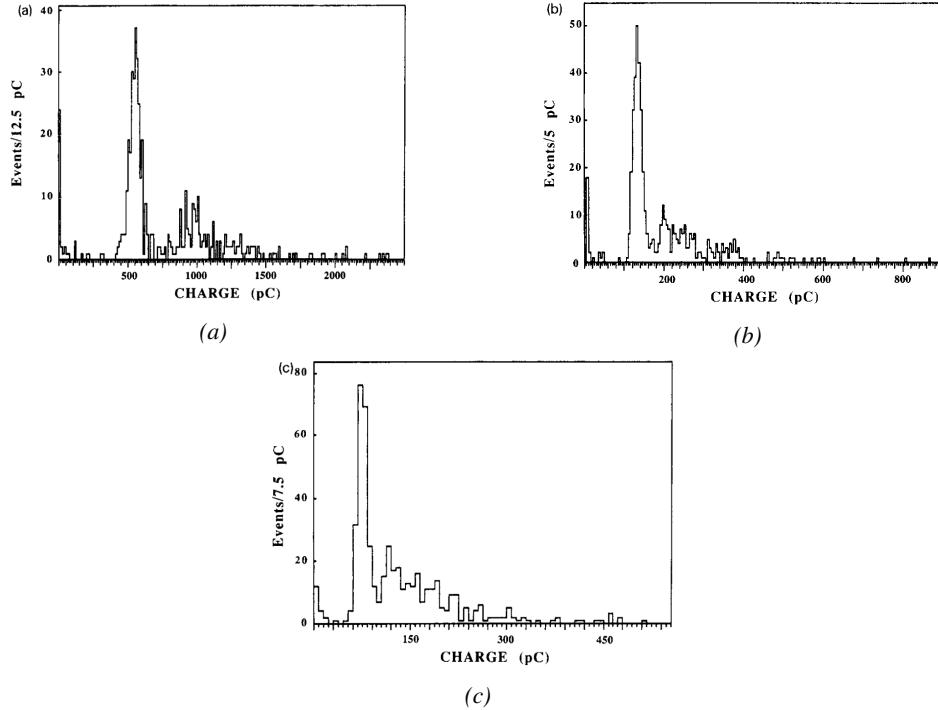


Figure 4.5: Comparison of the charge distribution of signals induced by cosmic muons in an RPC operated with a gas mixture of argon, butane and bromotrifluoromethane (CF_3Br). The Ar/C_4H_{10} is kept constant at 60/40 in volume while the total amount of CF_3Br in the mixture is varied: 0% (Figure 4.5a), 4% (Figure 4.5b) and 8% (Figure 4.5c) [39].

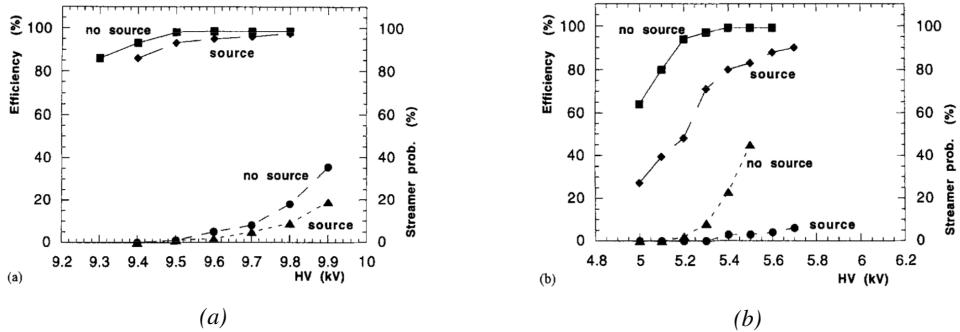


Figure 4.6: Comparison of the efficiency and streamer probability, defined as the fraction of events with an induced charge 10 times larger than that of the average avalanche, with and without irradiation by a 24 GBq ^{137}Cs source of an RPC successively operated with a 90/10 mixture $C_2H_2F_4/i-C_4H_{10}$ (Figure 4.6a) and a 70/5/10/15 mixture of $Ar/i-C_4H_{10}/CO_2/C_2H_2F_4$ (Figure 4.6b) [40].

²¹⁴⁸ From this moment onward, more and more studies were conducted in order to find a gas mixture
²¹⁴⁹ that would allow for the best suppression of streamers for the benefit of low charge avalanches. Most

R&D groups working with narrow gaps started using freon-based gas mixtures while users of wide gap RPCs kept using Ar/CO_2 based mixtures. The differences in between narrow and wide gaps will be later discussed in Section 4.2.3. The CF_3Br having a high GWP, tetrafluoroethane ($C_2H_2F_4$) was preferred to it as more suitable ecofriendly gas in the middle of the 90s. An advantage of this new freon component is that it featured a high primary ionization and a low operating voltage, as reported by Cardarelli [38]. Thus, the new gas mixtures used were mainly composed of tetrafluoroethane alone with lower content of isobutane in order to reduce the flammability of the mixtures in the case it were to be used in accelerator experiments for safety reasons. Performance and models about such mixtures were discussed in papers of Abbrescia [40, 41] and showed a better suitability of such a gas mixture, with respect to argon based ones, for operations with high radiation backgrounds leading to a need for high rate capability of the detectors, as can be seen from Figures 4.6 and 4.7. Indeed, although the operating voltage of a tetrafluoroethane based mixture is higher than which of an argon based mixture but the efficiency under irradiation is more stable, the voltage range with negligible streamer probability is much wider, and the fast charge ratio available is much greater, providing with more stable operation of the detector.

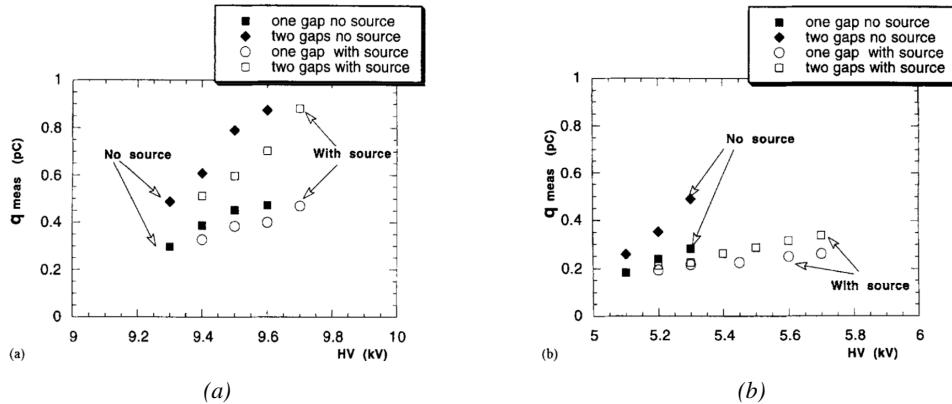


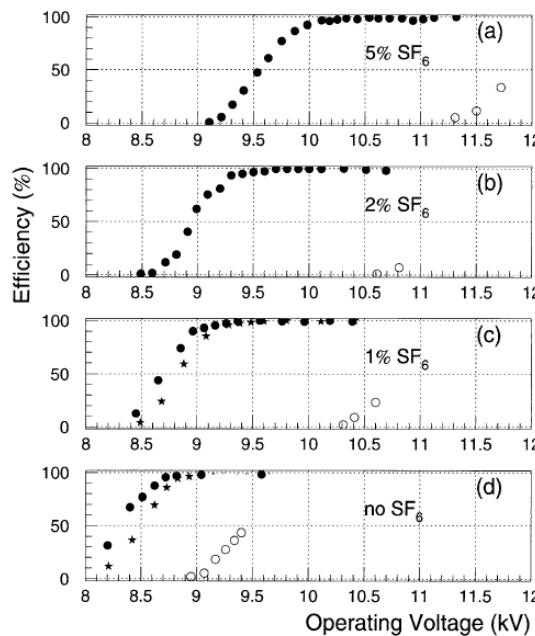
Figure 4.7: Comparison of the fast charge ratio with and without irradiation by a 24 GBq ^{137}Cs source of an RPC successively operated with a 90/10 mixture $C_2H_2F_4/i-C_4H_{10}$ (Figure 4.7a) and a 70/5/10/15 mixture of $Ar/i-C_4H_{10}/CO_2/C_2H_2F_4$ (Figure 4.7b). The results are provided for both single gap and double gap operation [40].

Aside of the improvement of the rate capability through linseed oil surface treatment of HPL electrodes, which allowed for a lower intrinsic noise rate and dark current of the detectors by improving the smoothness of the electrodes surface [53], it was later found that the streamers could be further suppressed by adding an electronegative compound into the gas mixture. The benefits of adding SF_6 in order to push the transitions from avalanche to streamers towards high voltages has been discussed in 1998 [42, 43] and eventually the high rate RPC destined to be used in accelerator physics would unanimously start using this compound into RPC gas mixtures. Being able to control the creation of streamers allows for slower ageing of the detector and lower power consumption as the currents driven by the electrodes consecutively to the induced charges would be smaller. In summary, the typical gas mixture RPCs are operated with is generally composed of the following 3 gas compounds, although, as mentioned in Chapter 3.5, research is being conducted into new more ecofriendly gas mixture using gases with a much lower Global Warming Potential:

- Tetrafluoroethane ($C_2F_4H_2$), also referred to as *Freon* or *R134a*, is the principal compound

2178 of the RPC gas mixtures, with a typical fraction above 90%. It is used for its high effective
 2179 Townsend coefficient and the great average fast charge that allows to operate the detector
 2180 with a high threshold with respect to argon, for example, that has similar effective Townsend
 2181 coefficient but suffers from a lower fast charge. To operate with similar conditions, argon
 2182 would require a higher electric field leading to a higher fraction of streamers, thus limiting the
 2183 rate capability of the detector [40, 41].

- 2184 • Isobutane ($i\text{-C}_4\text{H}_{10}$), only present in a few percent in the gas mixtures, is used for its UV
 2185 quenching properties [54] helping to prevent streamers due to UV photon emission during the
 2186 avalanche growth.
- 2187 • Sulfur hexafluoride, (SF_6), simply referred to as SF_6 , is used in very little quantities for its
 2188 high electronegativity. Excess of electrons are being absorbed by the compound and stream-
 2189 ers are suppressed [42, 43]. Nevertheless, a fraction of SF_6 higher than 1% will not bring
 2190 any extra benefice in terms of streamer cancelation power but will lead to higher operating
 2191 voltage [42], as can be understood through Figure 4.8.



2192 *Figure 4.8: Efficiency (circles and stars with 30 mV and 100 mV thresholds respectively) and streamer prob-
 2193 ability (open circles) as function of the operating voltage of a 2 mm single gap HPL RPC flushed with a gas
 2194 mixture containing (a) 5%, (b) 2%, (c) 1% and (d) no SF_6 [42].*

2195 In the last steps of R&D, the gas mixture of CMS RPCs was foreseen to be a 96.2/3.5/0.3 compo-
 2196 sition of $\text{C}_2\text{H}_2\text{F}_4/i\text{-C}_4\text{H}_{10}/\text{SF}_6$ [55] but finally it was slightly changed into a 95.2/4.5/0.3 mixture
 2197 of the same gases [56]. A summary of the operation performance of the RPCs since the start of LHC
 and of CMS data taking is given in Figure 4.9 [57]. The performance of the detectors is regularly
 monitored and the operating voltages updated in order to obtain a very stable performance through
 time. Nevertheless, the detectors will face new challenges during Phase-II during which they will

exposed to more extreme radiation conditions. Description of the longevity tests with extreme irradiation and the conclusions regarding the operation of the present RPC system will be given in Chapter 5.

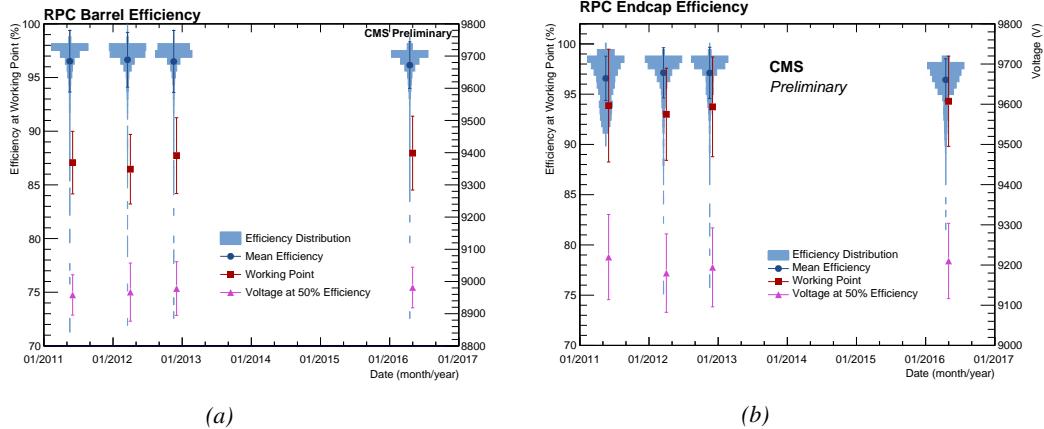


Figure 4.9: Evolution of the efficiency, working voltage, and voltage at 50% of maximum efficiency for CMS Barrel (Figure 4.9a) and Endcap (Figure 4.9b) RPCs obtained through yearly voltage scans since 2011. The working voltage of each RPC is updated after each voltage scan to ensure optimal operation [57].

It was already discussed that in the future, it is likely that the use of freon gases could be banned. As potential replacement for tetrafluoroethane was proposed the trifluoriodomethane (CF_3I), a molecule with similar properties than CF_3Br which was replaced by the tetrafluoroethane, and the 1,3,3,3-tetrafluoropropene ($C_3H_2F_4$ or HFO-1234re), a molecule with similar properties than the actual tetrafluoroethane and proposed as a replacement in refrigerating and air conditioning systems [58]. These 2 gases have stronger quenching properties than $C_2H_2F_4$ which means a much stronger electric field needs to be applied on the parallel electrodes of the RPCs in order to reach full efficiency. But the power supply system of CMS RPC is limited to 15 kV and so is ATLAS power supply system which is participating in a joined R&D. As can be seen from Figure 3.27, reducing the working voltage was achieved by mixing the potential replacements together with CO_2 . Introducing carbon dioxide into the mixture while keeping similar levels of isobutane and SF_6 increases the streamer probability and the best candidate identified for a compromise in between low enough working voltage and acceptable levels of streamers corresponds to a mixture containing 50% of CO_2 , 45% of HFO, 4% of isobutane and 1% of SF_6 but is not yet considered satisfactory. On the other hand, no good replacement for SF_6 has yet been identified. With its very high Global Warming Potential (23900), even small fraction of this gas in the mixture (it only represents 0.3% of CMS standard mixture but more than 5% of its overall GWP) substantially increase the danger for the environment. Although finding a replacement for this gas is less critical than for the tetrafluoroethane composing more than 90% of usual RPC standard mixtures, the problem will need to be addressed.

4.2.3 Detector designs and performance

Different RPC design have been used and each of them present its own advantages. Historically, the first type of RPC to have been developed is what is now referred to as *narrow gap* RPC [33, 59].

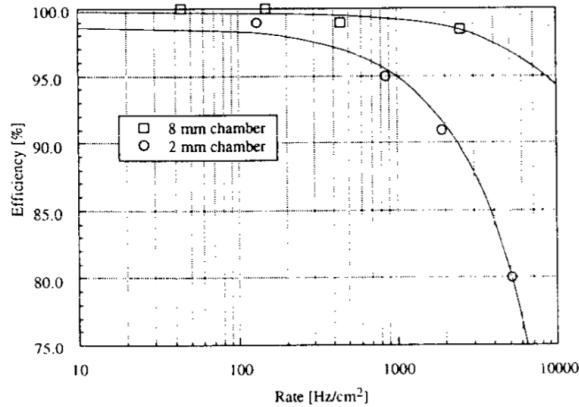


Figure 4.10: Comparison of the rate capability of 8 mm and 2 mm wide RPCs. The lines are linear fits on the data [59].

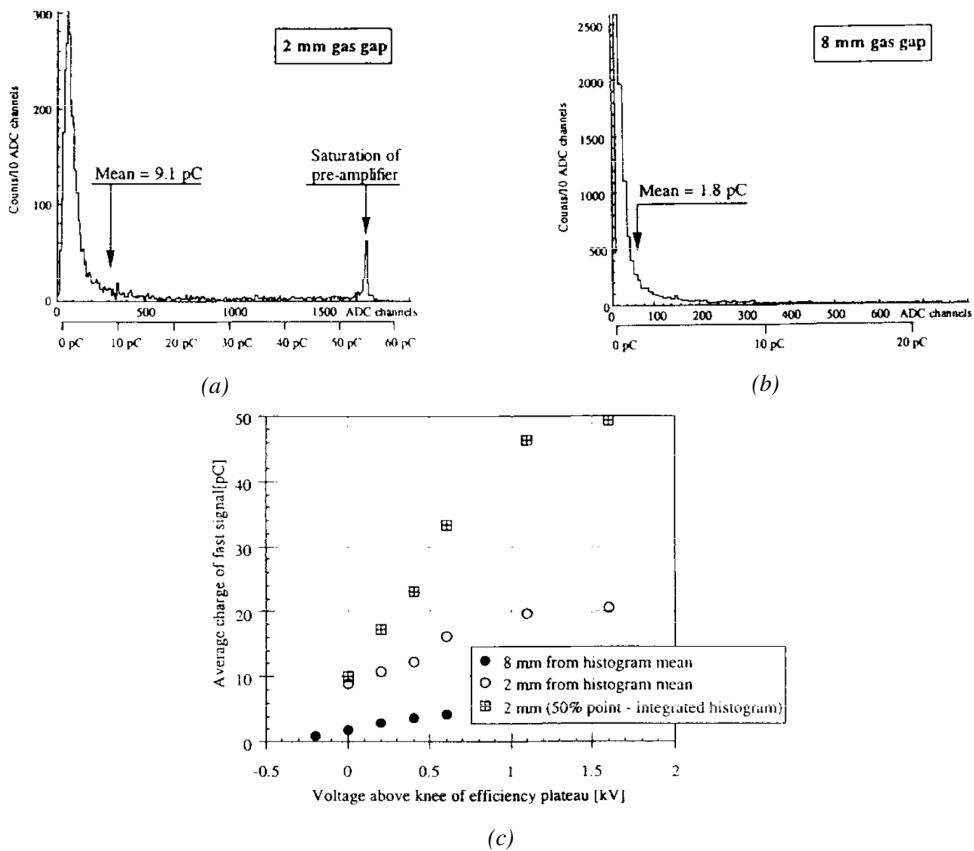


Figure 4.11: Distributions of the induced charge of fast signals on 2 mm (Figure 4.11a) and 8 mm (Figure 4.11b) RPCs exposed to a radiation rate of 100 Hz/cm^2 . Average induced charge of fast signals as a function of the high voltage applied on 2 mm and 8 mm RPCs (Figure 4.11c). In the case of the 2 mm RPC, a saturation of the pre-amplifier was observed. The average of the distribution is underestimated and the median is showed together with the average to account for this bias [59].

After the avalanche mode has been discovered [36], it has been showed that increasing the width of the gas gap lead to higher rate capability, due to lower charge deposition per avalanche, and lower power dissipation [59], as is showed in Figures 4.10 and 4.11. The distance in between the electrode being greater, a weaker electric field can be applied and a lower gain used as a longer gas volume will contribute to the signal induction on the read-out circuit. Nevertheless, by increasing the gas gap width, the time resolution of the detector decreases. This is a natural result if the increase of active gas volume in the detector is taken into account. Indeed, for a given detection threshold on the induced charge per signal, only the small fraction of gas closest to the cathode will provide enough gain to have a detectable signal. In the case of a wider gas volume, the active region is then larger and a larger time jitter is introduced with the variation of starting position of the avalanche, as discussed in [44] and showed in Figure 4.12.

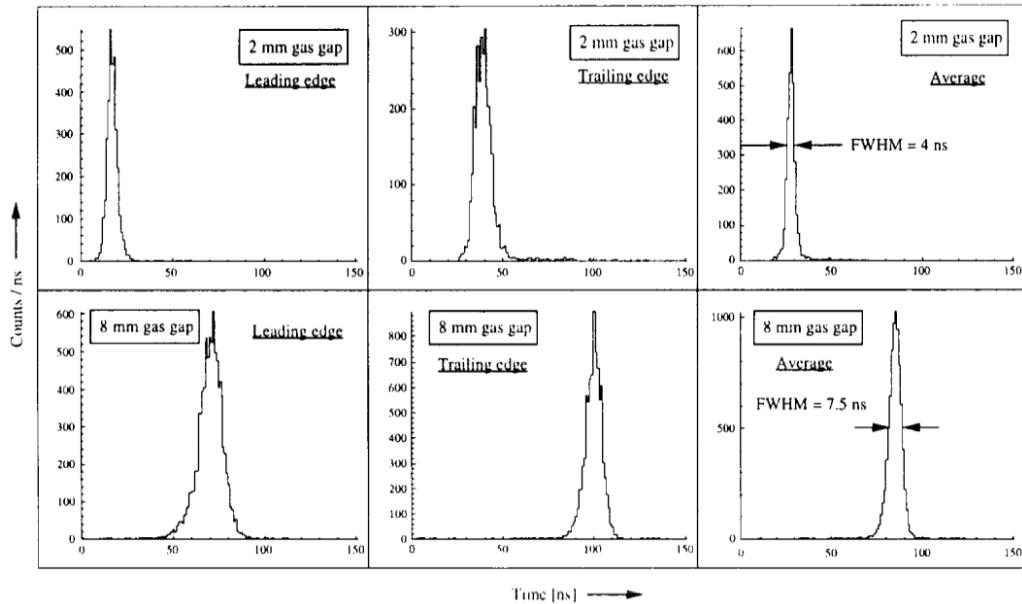


Figure 4.12: Time distributions of the leading, trailing, and average of both leading and trailing edges for 2 mm (top row) and 8 mm (bottom row) RPCs exposed to a 100 Hz/cm² radiation rate. The data was collected with RPCs operated at the voltage corresponding to the knee of the efficiency distribution, defined as the point where 95% of the maximum efficiency is obtained [59].

To improve both the time resolution and the rate capability, different methods were used trying to take advantage of both narrow and wide gap RPCs into a single design. Thus, double gap RPCs, combining two narrow gaps into a single detector to increase the effective sensitive volume, and multigap RPCs, which divided the large volume of a wide gap RPC into thinner sub-gaps by adding intermediate electrodes in between the cathode and anode to improve the time resolution by mimicking narrow gap RPCs, were developed starting from the middle of the 90s.

4.2.3.1 Double gap RPC

Made out of 2 narrow RPC detectors stacked on top of each other as shown in Figure 4.13, this detector layout, popularized by the two multipurpose experiments CMS [21] and ATLAS [47] at LHC, can be used as an OR system in which each individual chamber participates in the output signal

and increases the overall sensitive volume of the detector apparatus. Keeping the copper strip read-out system at the ground, CMS and ATLAS, due to different goals, have chosen different designs as CMS RPCs possess a 1D read-out while ATLAS RPCs offer a 2D read-out. The difference comes from placing the read-out in between the gaps, the anodes facing each other, or to have both RPC gaps in between 2 layers of read-out panels, one along the X-axis and one along the Y-axis, the cathodes facing each other.

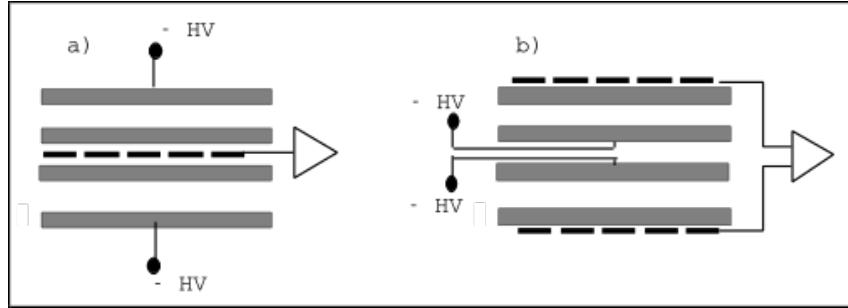


Figure 4.13: Possible double-gap RPC layouts: a) "standard" 1D double-gap RPC, as used in CMS experiment, where the anodes are facing each other and a 1D read-out plane is sandwiched in between them, b) double read-out double-gap RPC as used in ATLAS experiment, where the cathodes are facing each other and 2 read-out planes are used on the outer surfaces. This last layout can offer the possibility to use a 2D reconstruction by using orthogonal read-out planes.

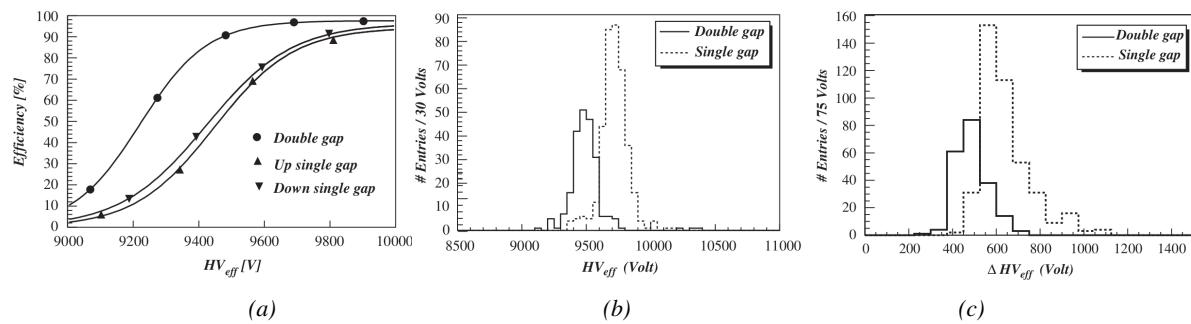


Figure 4.14: Comparison of performance of CMS double and single gap RPCs using cosmic muons [55]. Figure 4.14a: Comparison of efficiency sigmoids. Figure 4.14b: Voltage distribution at 95% of maximum efficiency. Figure 4.14c: $\Delta_{10\%}^{90\%}$ distribution.

The gain of such a detector is reduced by a factor 2 with respect to single-gap RPCs with an efficiency plateau reached at lower voltage, as visible on Figure 4.14, due to the two gas gaps contributing to the signal formation and offering a dynamic range closer to that of a wide gap RPC. A double gap is then fully efficient while the individual RPC gaps composing it are only 70 to 80% efficient. Naturally, by operating the double gap at a lower voltage, the rate capability is found to be increased as the induced charge per gap is then lower than in the case of a single gap detector also leading to a reduction of the streamer probability and a better extraction of the fast charge of the total signal as could be seen through previously presented Figure 4.7.

2259 **4.2.3.2 Multigap RPC (MRPC)**

2260 MRPCs are layouts in which floating sub electrode plates are placed into a wide gap RPC to divide
 2261 the gas volume and create a sum of narrow gaps [44, 45]. Similarly to the double gap RPC for which
 2262 the gain could be reduced by increasing the dynamic range, the multigap reduces the gain while
 2263 keeping a total dynamic range similar to which of a wide gap RPC by reducing the size of each
 2264 individual sub-gap composing the detector. The dynamic range, associated to the sensitive volume,
 2265 and the comparison of each detector layout to the wide gap RPC is showed in Figure 4.15.

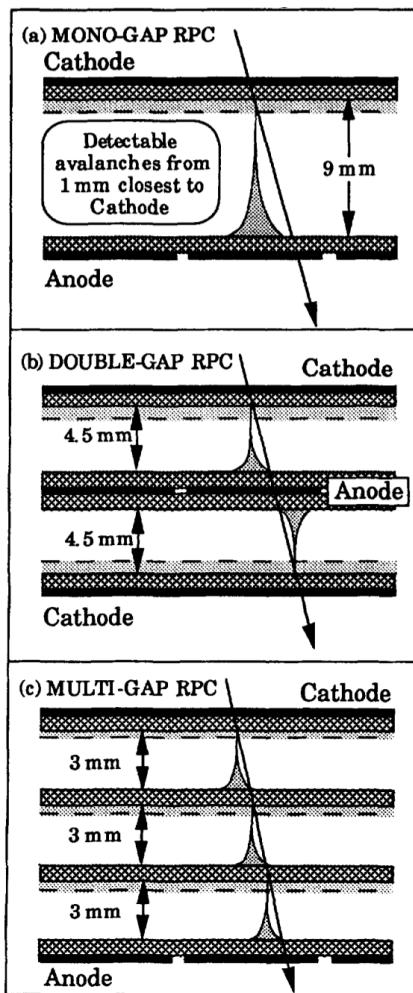


Figure 4.15: Representation of different RPC layouts (wide gap on Figure (a), double gap on Figure (b) and multigap on Figure (c)), of the corresponding sensitive volume in gray, and of the associated avalanche size [45].

2266 By operating the detector with thinner gaps, the time resolution is improved. Comparatively to
 2267 the time resolution presented in Figure 4.12 for the wide gap RPC of 8 mm, a complementary study
 2268 was conducted on multigaps using two 4 mm and four 2 mm subgaps and showed, via Figure 4.16,
 2269 an improvement of the time resolution with the reduction of the gap width and of the number of gaps

while the same sensitive volume was kept [45].

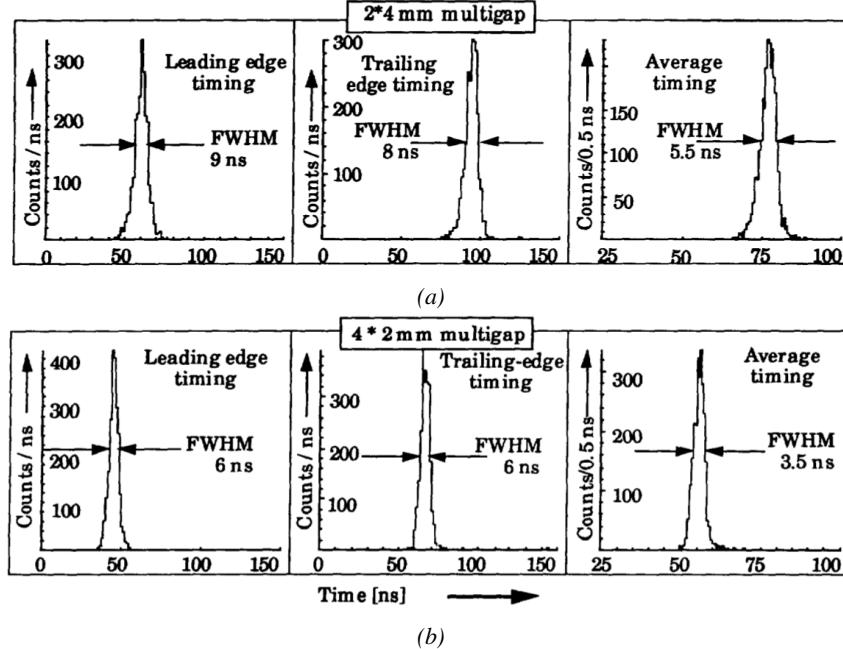


Figure 4.16: Time distributions of the leading, trailing, and average of both leading and trailing edges for multigap RPCs consisting in two 4 mm (Figure 4.16a) and four 2 mm (Figure 4.16b) exposed to a 100 Hz/cm² radiation rate. The data was collected with RPCs operated at the voltage corresponding to the knee of the efficiency distribution, defined as the point where 95% of the maximum efficiency is obtained [45].

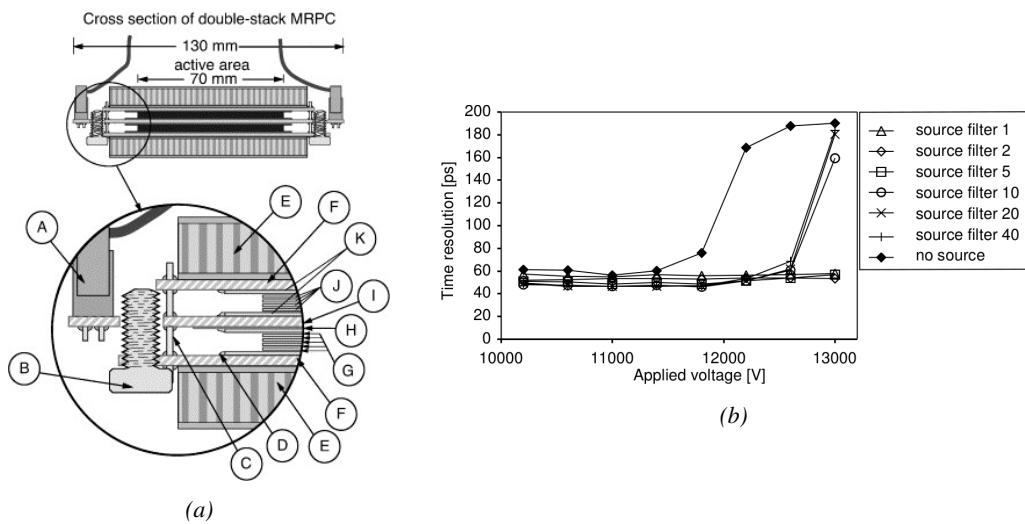


Figure 4.17: Presentation of a study of a possible ALICE MRPC cell using 250 µm gas gaps, 620 µm outer glass electrodes, and 550 µm inner floating electrodes (Figure 4.17a), and of its time resolution performance as a function of the applied high voltage for different radiation levels referred through different filter settings of the 740 GBq ¹³⁷Cs source the former CERN GIF facility [60].

After the problem of streamers was solved by adding SF_6 into the gas mixture, the size of the MRPCs decreased as the research groups started applying the concept of dividing the gas volume into subvolumes to the narrow gap RPCs leading to the now widely used micro gap MRPCs. The time resolution of such a detector can reach of few tens of ps, with gas gaps of the order of a few hundred μm as showed in Figure 4.17 representing a single cell of ALICE Time-of-flight (ToF) system consisting of double MRPCs, as it was studied in the early 2000s [60].

Sometimes used as a double multigap RPC, taking advantage of the OR of double gap RPCs to both be able to operate a higher number of gaps while keeping a reasonable high voltage applied in between the cathode and anode and to further reduce the gain, the MRPC is mainly used as ToF detector [60–64] due to its excellent timing properties that allow to perform particle identification as explained by Williams in [65]. The principle of particle identification using ToF is simply the measurement of the velocity of a particle. Indeed, particles are defined by their mass (for the parameter of interest here, their electric charge being measured using the bending angle of the particles traveling through a magnetic field) and this mass can be calculated by measuring the velocity β and momentum of the particle:

$$(4.3) \quad \beta = \frac{p}{\sqrt{p^2 + m^2}}$$

Intuitively, it is trivial to understand that 2 different particles having the same momentum will have a different velocity due to the mass difference and thus a different flight time T_1 and T_2 through the detector and this is used to separate and identify particles. The better the time resolution of the ToF system used, the stronger will the separation be:

$$(4.4) \quad T = \frac{L}{v} = \frac{L}{c \cdot \beta}, \quad \Delta T = T_1 - T_2 = \frac{L}{c} \left(\sqrt{1 + m_1^2/p^2} - \sqrt{1 + m_2^2/p^2} \right) \cong (m_1^2 - m_2^2) \frac{L}{2cp^2}$$

An example of particle identification is given for the case of STAR experiment in Figure 4.18.

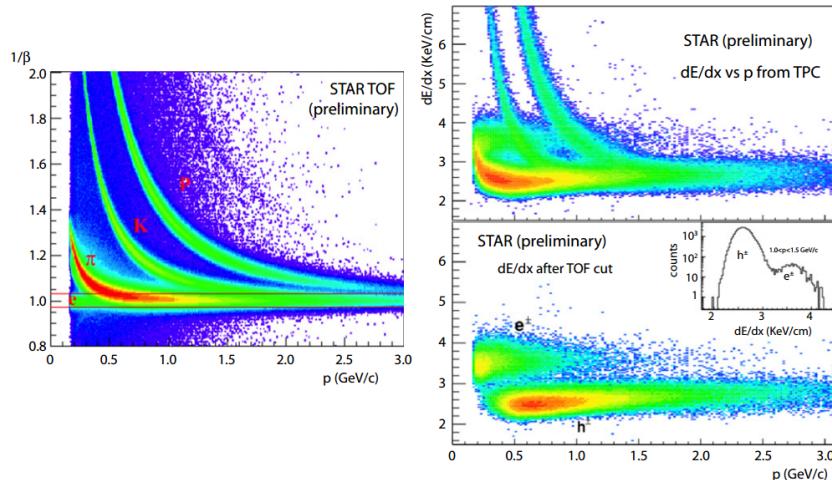


Figure 4.18: Particle identification applied to electrons in the STAR experiment. The identification is performed combining ToF and dE/dx measurements [65].

2291 Taking into account the distortion effect on the electric field inside of a MRPC built using micro
 2292 gaps due to the exposition to irradiation, distortion that can be understood by monitoring the current
 2293 drawn by the detector which should stay constant at constant electric field, another benefice of using
 2294 such small gas gaps is the strong reduction of the average avalanche volume and thus of the blind
 2295 spot on MRPCs leading to an improved rate capability. Multigaps can sustain backgrounds of several
 2296 kHz/cm² as demonstrated in Figure 4.19.

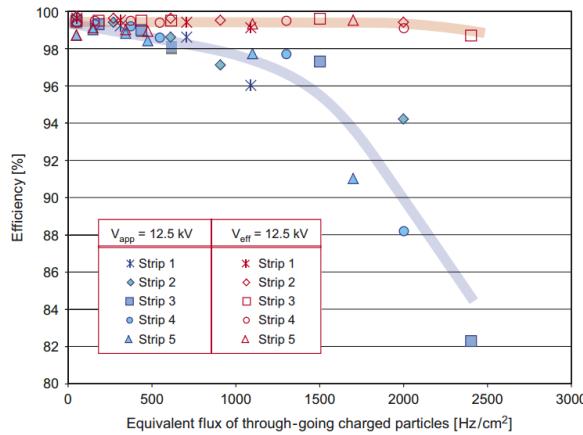


Figure 4.19: Comparison of the detector performance of ALICE ToF MRPC [66] at fixed applied voltage (in blue) and at fixed effective voltage (in red). The effective voltage is kept fixed by increasing the applied voltage accordingly to the current drawn by the detector.

2297 4.2.3.3 Charge distribution and performance limitations

2298 [This part could be moved in the next section of the chapter and deepened using the perspective
 2299 of the avalanche physics.]

2300 The direct consequence of the different RPC layouts is a variation of intrinsic time resolution of
 2301 the RPC as the gap size decreases and of the rate capability when the deposited charge per event is
 2302 spread over a larger number of amplification volumes, allowing for a reduction of the overall gain of
 2303 the detectors which is replaced by an on-electronics pre-amplification of the signals. in this sense,
 2304 an advantage is given to multigaps whose design use sub-millimeter gas volumes providing very
 2305 consistent signals.

2306 From the charge spectrum point of view, each layout has its own advantages. When the double-
 2307 gap has the highest induced over drifting charge ratio, as seen in Figure 4.20, the multigap has a
 2308 charge spectrum strongly detached from the origin, as visible in Figure 4.21. A high induced over
 2309 drifting charge ratio means that the double gap can be safely operated at high threshold or that at
 2310 similar threshold it can be operated with a twice smaller drifting charge, meaning a higher rate
 2311 capability if operated with sensitive enough electronics. On the other hand, the strong detachment
 2312 of the charge spectrum from the origin in the MRPC case allows to reach a higher efficiency with
 2313 increasing threshold as most of the induced charge is not low due to the convolution of several
 2314 single gap spectra. The range of stable efficiency increases with the number of gap, as presented in
 2315 Figure 4.22.

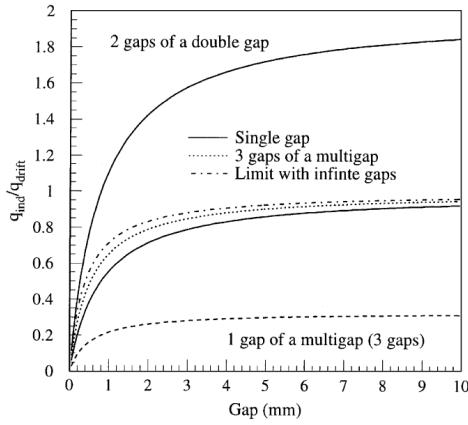


Figure 4.20: Ratio between total induced and drifting charge have been simulated for single gap, double-gap and multigap layouts [67]. The total induced charge for a double-gap RPC is a factor 2 higher than for a multigap.

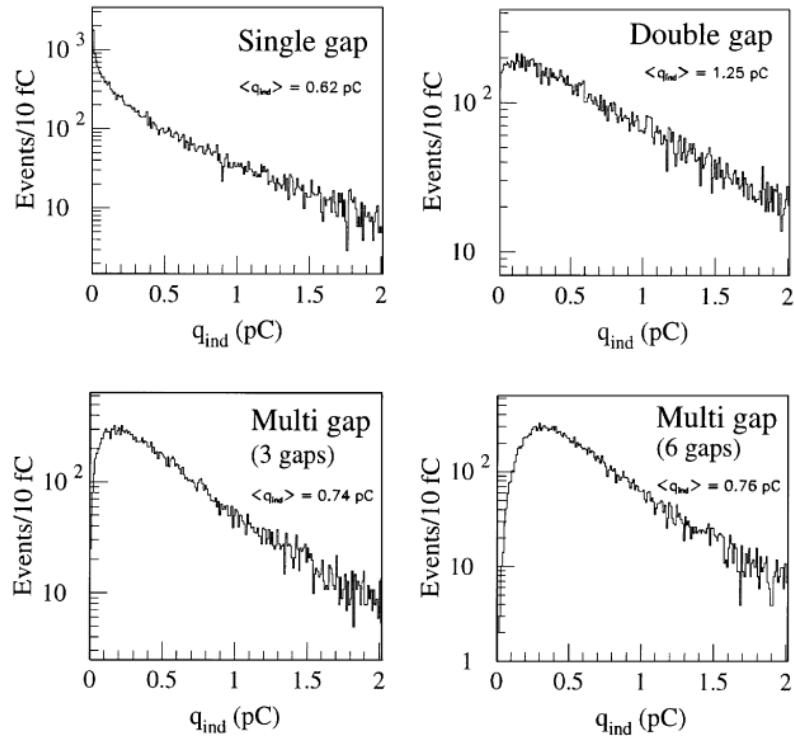


Figure 4.21: Charge spectra have been simulated for single gap, double-gap and multigap layouts [67]. It appears that when single gap shows a decreasing spectrum, double and multigap layouts exhibit a spectrum whose peak is detached from the origin. The detachment gets stronger as the number of gaps increases.

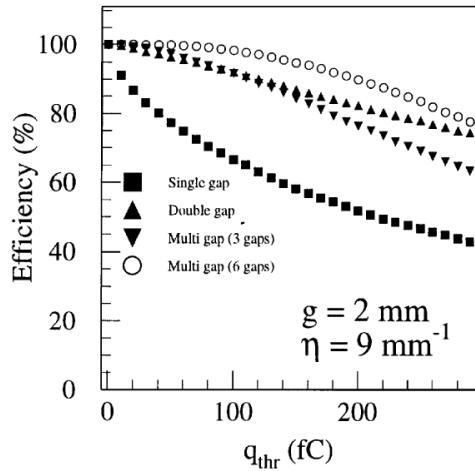


Figure 4.22: The maximal theoretical efficiency is simulated for single gap, double-gap and multigap layouts [67] at a constant gap thickness of 2 mm and using an effective Townsend coefficient of 9 mm^{-1} .

4.3 Signal formation

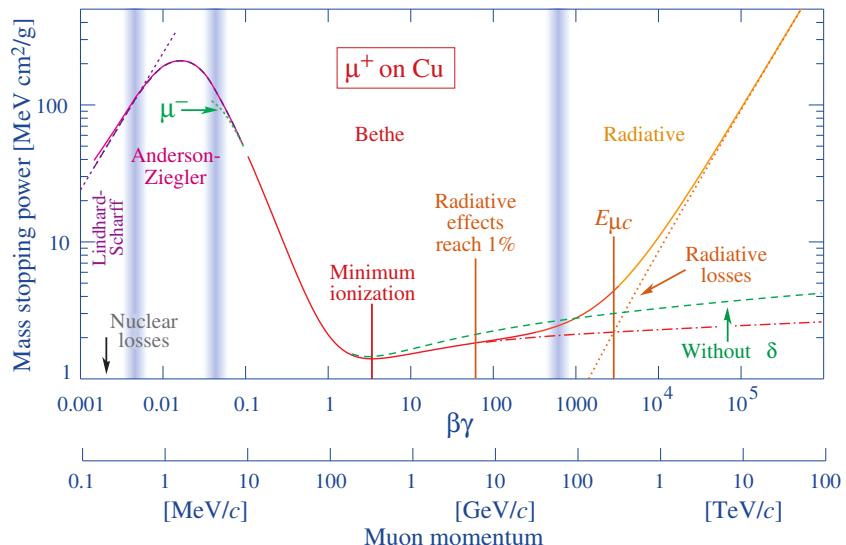


Figure 4.23: Mass stopping power as a function of $\beta\gamma = p/Mc$ for positive muons in copper [68]. The total stopping power is indicated with solid line and local components with dashed lines. The vertical bands are used to indicate boundaries between different approximations used at different energy range.

The physics of Resistive Plate Chambers still is far from being fully understood and work is regularly being accomplished in trying to model these detectors the best way possible by phenomenological models using well-defined physics [51, 69, 70]. These theoretical works have nevertheless lead to a better understanding of the key principles that account for RPCs signal formation. As previously

discussed, the typical mixture of such a detector is in great majority composed by a ionizing gas with some quenching properties and a low ionization potential to easily produce electrons, with the addition of UV quencher and electronegative compounds. The electronic avalanche formation will be triggered by a charged particle passing through the gas, typically a muon in the case of most uses of RPCs. The production of electrons in the gas of a detector is related to the energy lost by the incoming particle traveling through a material medium. The example of the mass stopping power of copper on muons is given in Figure 4.23 on which the different energy loss mechanisms at different energy ranges are visible. Once primary electrons have been freed in the gas volume, the electric field applied in between the electrodes of the RPC will make the charges move and there will be a competition in the gas in between the Townsend and attachment coefficient which describe the evolution of the number of electrons in an avalanche. While drifting through the gas, the electrons are also subjected to diffusion that will affect the evolution of the avalanches. Finally, when the avalanche is big enough, the accumulation of negative (electrons) and positive (ions) charges in the gas volume will start affecting the local electric field. This effect is known as space charge effect.

4.3.1 Energy loss at intermediate energies

Intuitively, a particle traveling through a medium will interact with its components, losing energy. When a muon travels through the gas of a gaseous detector, at the energy range usually observed, it interacts with the molecules of the gas leading to dissipation of the transferred energy in the form of inelastic diffusion or ionization. The photons and electron-ion pairs resulting from these interaction can trigger avalanches in the gas which will contribute to feed the avalanche growth thanks to the strong electric field applied in between the 2 electrodes of a RPC.

The mass stopping power of moderately relativistic ($0.1 \lesssim \beta\gamma \lesssim 1000$) heavy particles ($M \gg m_e$) traveling through a medium via excitation and ionization processes was studied by Bethe in 1930 [71] and is well described by the so called the Bethe Formula given in Equation 4.5.

$$(4.5) \quad \left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \delta(\beta\gamma) \right)$$

The different parameters used in this equation are

E	- incident particle energy γMc^2	MeV
x	- mass per unit area	g cm^{-2}
N_A	- Avogadro's number	$6.022\ 140\ 857(74) \times 10^{23} \text{ mol}^{-1}$
c	- speed of light in vacuum	$299\ 792\ 458 \text{ m s}^{-1}$
μ_0	- permeability of free space	$4\pi \times 10^{-7} \text{ N A}^{-2}$
ϵ_0	- permittivity of free space $\epsilon_0 = 1/\mu_0 c^2$	$8.854\ 187\ 817\dots \times 10^{-12} \text{ F m}^{-1}$
α	- fine structure constant $\alpha = e^2/4\pi\epsilon_0\hbar c$	$1/137.035\ 999\ 139(31)$
r_e	- classical electron radius $r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\ 940\ 3227(19) \text{ fm}$
e	- elementary charge of the electron	$-1.6021766208(98) \times 10^{-19} \text{ C}$
$m_e c^2$	- electron mass $\times c^2$	$0.510\ 998\ 9461(31) \text{ MeV}$
K	- constant defined as $K = 4\pi N_A r_e^2 m_e c^2$	$0.307\ 075 \text{ MeV mol}^{-1} \text{ cm}^2$
z	- charge number of incident particle	
Z	- atomic number of absorbing medium	
A	- atomic mass of absorbing medium	g mol^{-1}
β	- velocity of particle $\beta = v/c$	
γ	- Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$	

W_{max}	- maximum energy transfer through a single collision	MeV
I	- mean excitation energy of absorbing medium	eV
$\delta(\beta\gamma)$	- density effect correction to ionization energy loss	

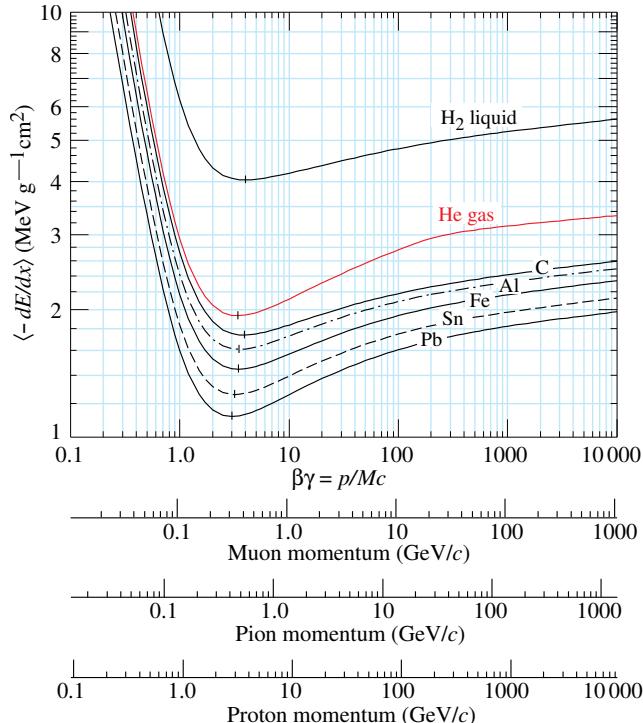


Figure 4.24: Mean mass stopping power for liquid hydrogen, as used in bubble chambers, gaseous helium, carbon, aluminum, iron, tin, and lead without the inclusion of radiative effect at higher $\beta\gamma$ necessary for pions and muons in denser materials [68].

In this equation, the maximum energy transfer W_{max} is defined as function of the incident particle mass M , expressed in MeV/c^2

$$(4.6) \quad W_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2}$$

and the mean excitation energy I depends on the absorber and its determination is non-trivial but recommendation are given by the International Commission on Radiation Units & Measurements (ICRU) based on experimental measurements and interpolations as showed in Figure 4.25.

For the case of copper, the mean stopping power is visible in Figure 4.23. The mean stopping power corresponding only to the Bethe range for other materials is given in Figure 4.24 and shows that $\langle -dE/dx \rangle$ is similar for each material with a slow decrease with Z . The factor affecting the equation the most is β as the dependence on M is introduced at higher energies in the logarithm via the max transfer energy per single collision but in most practice cases, only the dependence on β is considered as most of the relativistic particles are closed to the lowest mean energy loss rate and are

2357 referred to as minimum ionizing particles (mip's). The almost logarithmic relation in between the
 2358 mean energy loss rate for minimum ionizing particles and Z is showed in Figure 4.26.

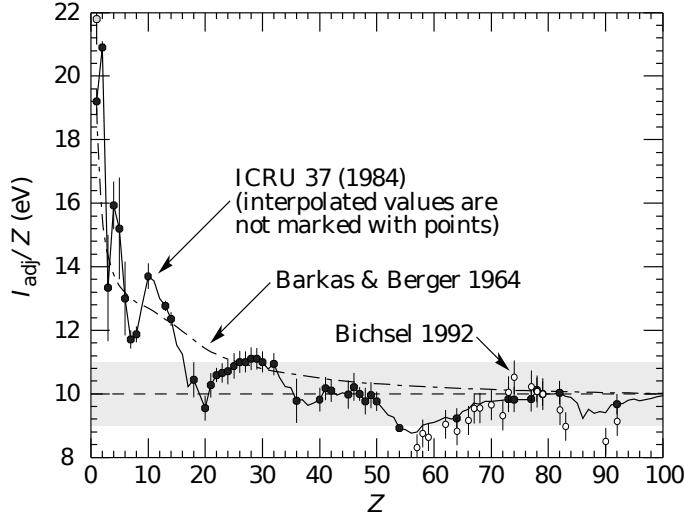


Figure 4.25: Mean excitation energies normalized to the atomic number as adopted by the ICRU [68, 72, 73].

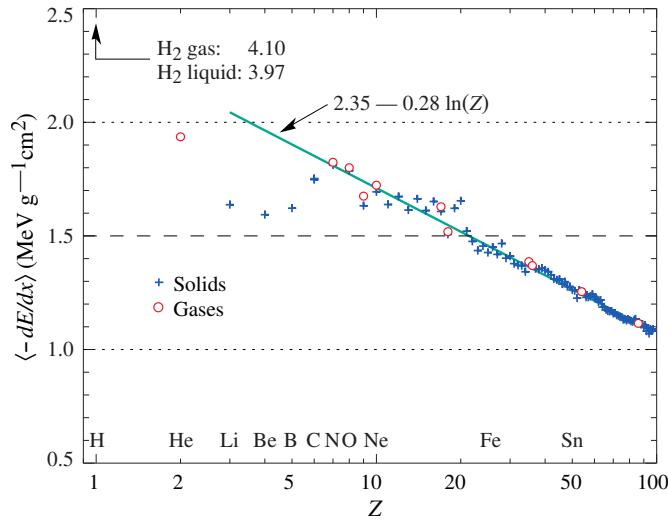


Figure 4.26: Mean mass stopping power at minimum ionization as a function of the atomic number [68].

2359 Finally, the term $\delta(\beta\gamma)/2$ corresponds to the density effect correction introduced to account for
 2360 the polarization of a real media that limits the spatial extension of the electric field of relativistic
 2361 particles. Indeed, as the energy of a particle increases, the associated electric field will flatten and
 2362 extend. Due to this effect, the distant collision contribution to Equation 4.5 will increase as $\ln(\beta\gamma)$
 2363 but the polarization of the media trunc this rise. At high energies, the correction is given by Equa-

2364 tion 4.7

$$(4.7) \quad \delta/2 \longrightarrow \ln(\hbar\omega_p/I) + \ln(\beta\gamma) - 1/2$$

2365 where $\hbar\omega_p$ represents the plasma energy that depends on the electron density of the media and
 2366 the electron mass and can be calculated as $\sqrt{\rho\langle Z/A\rangle} \times 28.816$ eV. The introduction of this cor-
 2367 rection term reduces the increase of the mean stopping power at higher energies as can be seen in
 2368 Figure 4.23. Moreover, due to poorer electron density, the effect is less visible on gases than on
 2369 liquids and solids has van be seen from Figure 4.24.

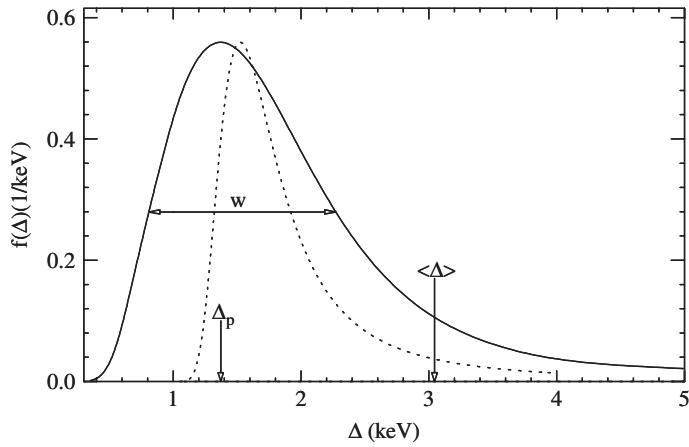


Figure 4.27: Example of straggling function $f(\Delta)$ of particles passing through 1.2 cm of Argon gas with a $\beta\gamma$ of 3.6 and represented with a solid line. The original Landau distribution is showed with a dashed line [74].

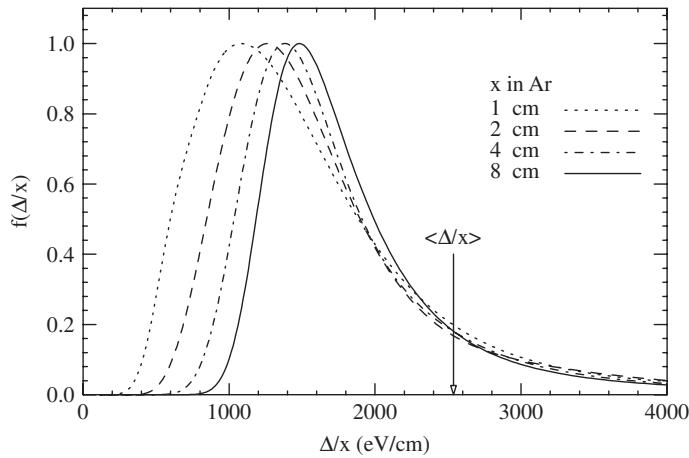


Figure 4.28: Evolution of straggling functions $f(\Delta)$ of particles passing through a volume of Argon gas with a $\beta\gamma$ of 3.6 with increasing thickness x [74].

2370 The mean energy loss per collision can be difficult to measure for low data samples and is not
 2371 always representative of the energy loss distribution for a given incident particle energy. Hence, it is

2372 easier to access the most probable energy loss which is a lower value than than the average loss due
 2373 to the distribution of the energy transfer. This value is well described by a highly skewed Landau
 2374 distribution for detectors with "moderate" thickness x , expressed in g mol $^{-1}$. But for gas volumes,
 2375 a Landau distribution greatly underestimates the width w of the distribution and only succeeds to
 2376 provide with a correct value for the most probable energy loss, as showed in Figure 4.27. Thus,
 2377 the energy loss distribution is better represented by its most probable energy loss Δ_p and its full-
 2378 width-at-half-maximum (FWHM) w . As showed by Figure 4.28, the distribution is affected by
 2379 the thickness of the gas volume and the most probable energy loss normalized to the thickness is
 2380 increased and the width decreased, converging towards the Landau distribution, whereas the mean
 2381 energy loss is unchanged. Correction are brought to the original Landau equation in order to account
 2382 better for the number of collisions leading to an increased width of the energy loss distribution [74].

2383 In the case of gas mixtures, composed of several elements, using Bragg additivity it can be
 2384 understood that the mean energy loss of the mixture is the sum of the mean energy losses in each
 2385 individual element j layer of weight w_j .

$$(4.8) \quad \left\langle \frac{dE}{dx} \right\rangle = \sum w_j \left\langle \frac{dE}{dx} \right\rangle_j$$

2386 4.3.2 Primary ionization

2387 Using Bethe formula to understand the mean energy transfer of charged particle when traveling
 2388 through a gas volume give an intuition of the physics that affect the particle but doesn't provide a
 2389 detailed enough information about the individual ionizations along its tracks at a microscopic level.
 2390 In order to simulate efficiently an RPC and hence understand the processes governing avalanches
 2391 creation and growth, knowledge on the ionization process is necessary.

2392 To convert the energy loss rate into a number of primary ionizations was developed in 1980 the
 2393 Photo-Absorption Ionisation (PAI) model [75] based on the cross section of ionization of gas atoms
 2394 to real photons and the dielectric constant of the medium through which the charged particles are
 2395 going. Indeed, the interaction of charged particles with the gas molecules being of electromagnetic
 2396 nature, it is mediated by quasi-real photons and, hence, the cross section to photon ionization is
 2397 important to understand. This approach is nevertheless semi-classical as it relies on classical elec-
 2398 trodynamics and it only gives access to the energy transfer to the gas atoms and no information on
 2399 the energy dissipation and secondary emissions is available on the output of the model. The energy
 2400 transferred to the medium is not all used for ionization. For an energy deposition Δ , the number of
 2401 electron-ion pairs produced is:

$$(4.9) \quad \Delta = n_i W$$

2402 W corresponds to the mean work per pair production that depends on the medium and is greater
 2403 than the ionization potential leading to the conclusion that part of the transferred energy is dissipated
 2404 through other processes [70, 76]. In order to understand the energy dissipation and the secondary
 2405 emissions, the fine structure of each atom is taken into account. Through the PAI model, the incident
 2406 charged particle interacts is assumed to interact with the full atom rather than with a single electron.

2407 Although, considering that the particle interacts with a single electron, leads to the possibility
 2408 to study the excited state of the atom once the photo-electron has been emitted with an energy

corresponding to the transferred energy minus the binding energy of the electronic shell. The resulting vacancies in the electronic shell will be filled through emission of photons or Auger electrons and can contribute to further ionization or excitation in the gas volume. Fluorescence photons are usually not considered as they only constitute a very small fraction of secondary emissions [77]. Assuming that the transferred energy is absorbed in its totality by a single electronic shell, the PAI model was modified to include relaxations and constitute the new Photo-Absorption Ionisation with Relaxation (PAIR) model [77]. In this model, the cross section corresponding to the whole atom is re-expressed using a sum of partial cross sections corresponding to the different electronic shells. When one or more electrons are knocked out of the atom, the vacancies are filled by electrons of the shell above with relaxation by Auger electron emission. These processes happen in cascade from the inner shell to the outer one until all the vacancies are filled and the energy has been released.

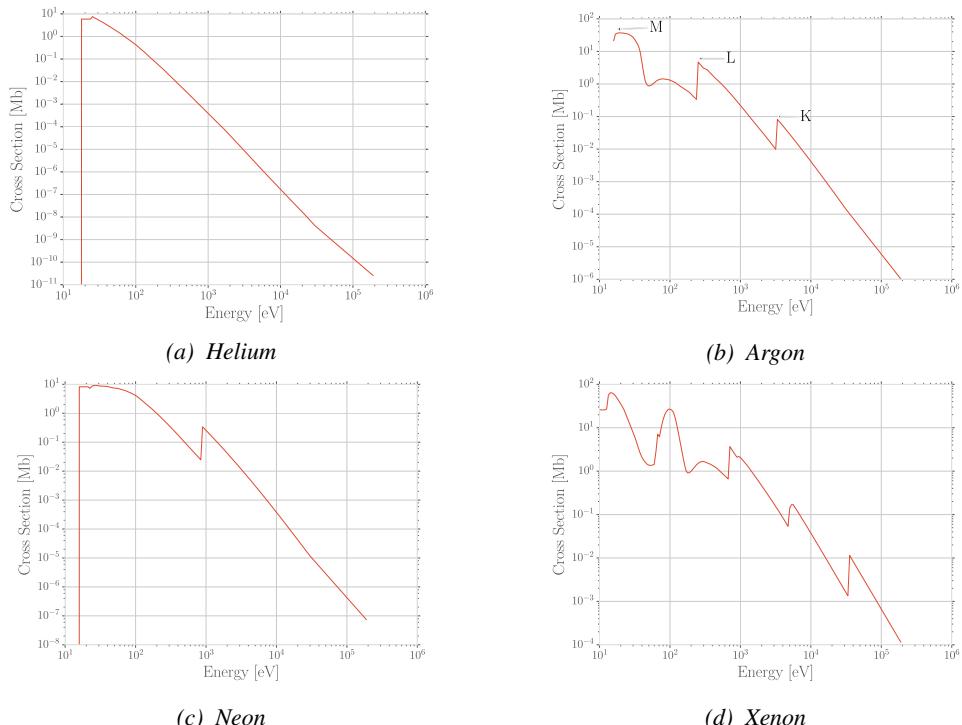


Figure 4.29: Photo-absorption cross section as computed by HEED for nobles gases with different electric shell numbers [70].

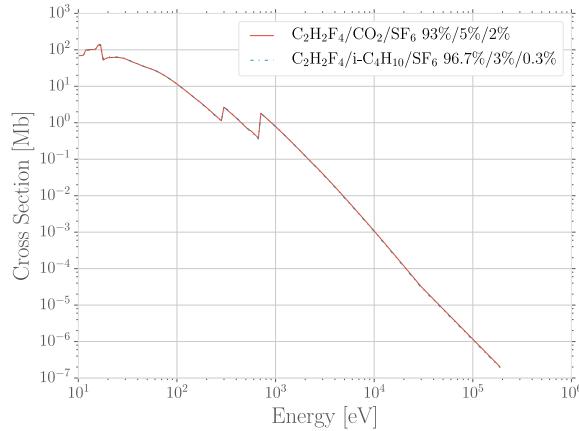


Figure 4.30: Photo-absorption cross section as computed by HEED for typical RPC gas mixtures [70]. The RPC mixture with CO₂ corresponds to the mixture used by CALICE SDHCAL [78] while the other one was foreseen for the experiment ATLAS [79] but has been changed since then.

This model is included in the program HEED developed at CERN [80] and called by Garfield, a program developed for the simulation of gaseous detectors. The results for the cross section for a few noble gases are given in Figure 4.29. It can be seen that for each shell, the cross section is increased. More complex patterns are seen with bigger atoms such as Xenon on Figure 4.29d. For gas mixtures, like the typical RPC mixtures, the cross section is showed in Figure 4.30. Both mixtures being mainly composed of C₂H₂F₄, the variations in between the 2 cross section profiles are very subtle and depends on the concentration of the other compounds.

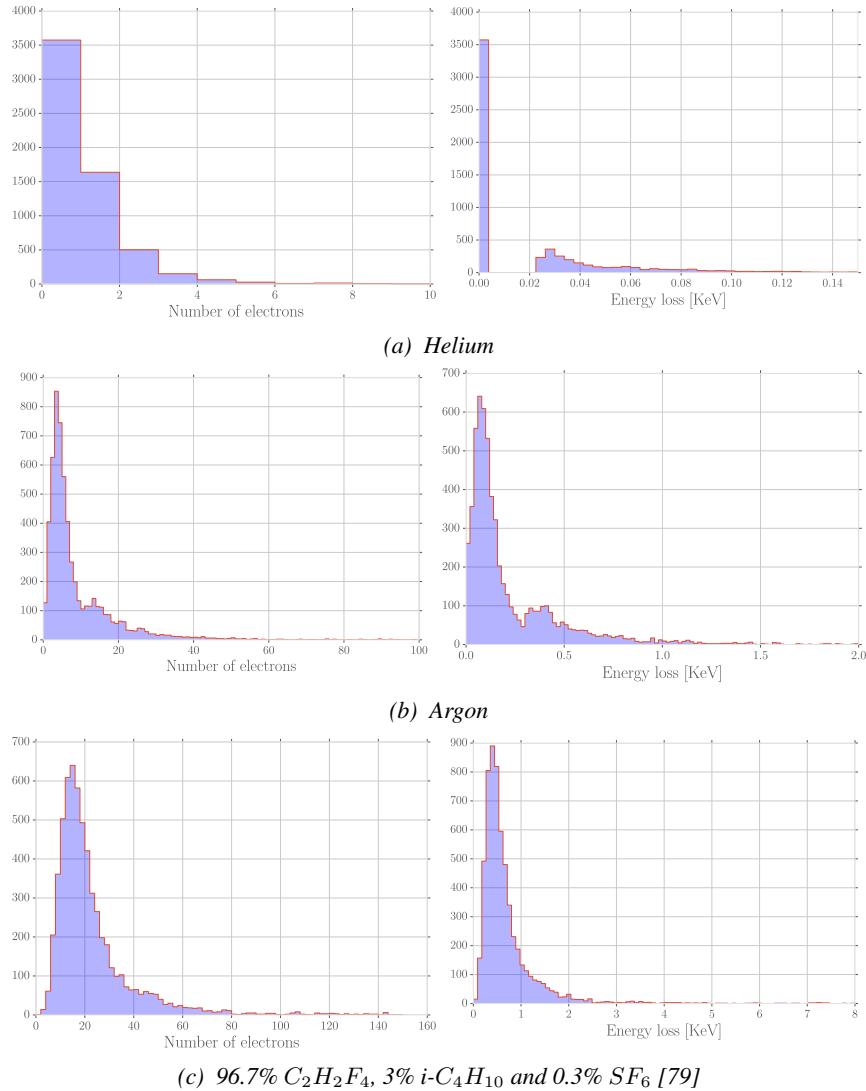


Figure 4.31: Distributions of number of electrons (left) and energy loss (right) for a 5 GeV/c muon passing through 1.2 mm of Helium (Figure 4.31a), Argon (Figure 4.31b) or a typical RPC gas mixture (Figure 4.31c) [70].

Once the cross section of interaction is known, it is possible to extract the distribution of energy loss and of the number of electron produced, as showed in Figure 4.31 for Helium, Argon, which is used in gaseous detectors, and for a typical RPC mixture [70]. The distributions are computed using HEED and show typical straggling function profiles with some complex structures that can be related to interaction of the incoming particle with the different electronic shells. Helium does not have a great photo-absorption cross-section according to Figure 4.29a and a muon will not be likely to lose a lot of energy and to create a lot of electrons whereas in a more complex atom like Argon, the cross-section is greater and will lead to a greater energy loss of muons and more electron produced. Finally, a complex gas mixture used in RPCs will offer an even greater cross-section, a wider energy loss distribution and will be able to produce more electrons. The same information is seen by looking

at the evolution of the mean number of cluster as a function of the lorentz factor associated to muons showed in Figure 4.32a. Indeed, the greater photo-absorption cross-section of RPC mixtures allow for a much greater amount of clusters to be created by charged particles. The size of these clusters is studied through Figure 4.32b which shows that, in most of the cases ($\approx 80\%$), the clusters only are composed of a single electron which is consistent with minimum ionizing particles.

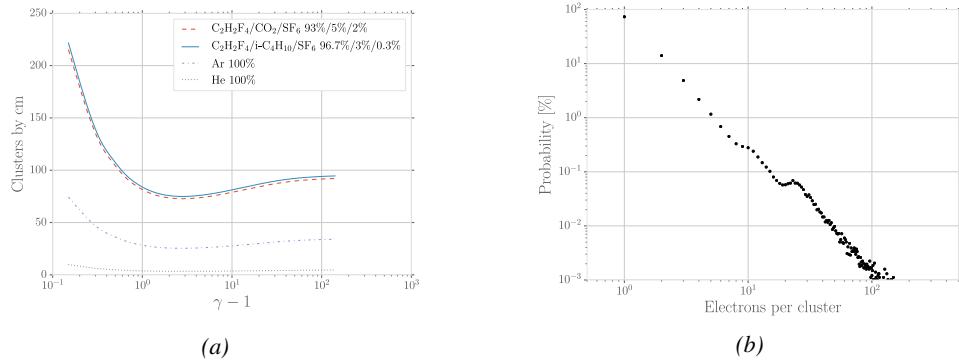


Figure 4.32: Figure 4.32a: Mean cluster density for muons through different gas volumes [70]. Figure 4.32b: Distribution of the number of electrons per cluster for a 5 GeV/c muon traveling through a mixture of 96.7% $C_2H_2F_4$, 3% $i-C_4H_{10}$ and 0.3% SF_6 [70, 79].

4.3.3 Development and propagation of avalanches

From the clusters released in the gas volume by the charged particles, free electrons will start drifting due to the electric applied in between the electrodes of the RPC. Gaining velocity and energy, these electrons in their turn will be able to ionize the gas. This process being repeated by all the produced electrons will trigger an avalanche to develop.

The growth of the avalanche can be intuitively understood as a competition between 2 effects. Due to their increasing energy, electrons have a probability to trigger new ionizations by interacting with gas molecules. On the other hand, before the minimal amount of energy is reached, the electrons can get attached to a gas molecule instead. These two effects can be described using a simple model in which the multiplication and attachment processes are given by the Townsend coefficient α and the attachment coefficient η , assuming that the history of previous interactions in the gas does not influence new interactions. This model simply takes into account probabilities to have at the gas depth z for a given number n of free electrons in the gas $n+1$ or $n-1$ electrons at the depth $z+dz$ (respectively $n\alpha dz$ and $n\eta dz$). Then, the mean number of electrons \bar{n} and cations \bar{p} can be written for single compound gases as

$$(4.10) \quad \frac{d\bar{n}}{dz} = (\alpha - \eta)\bar{n}, \quad \frac{d\bar{p}}{dz} = \alpha\bar{n}$$

which, assuming the initial conditions $\bar{n}(0) = 1$ and $\bar{p}(0) = 0$, lead to the mean number of electrons and cations at a depth z

$$(4.11) \quad \bar{n}(z) = e^{(\alpha-\eta)z}, \quad \bar{p}(z) = \frac{\alpha}{\alpha-\eta} \left(e^{(\alpha-\eta)z} - 1 \right)$$

2459 The Townsend and attachment coefficient as a function of the applied electric field are given in
 2460 Figure 4.33 for a standard RPC gas mixture using Magboltz [81].

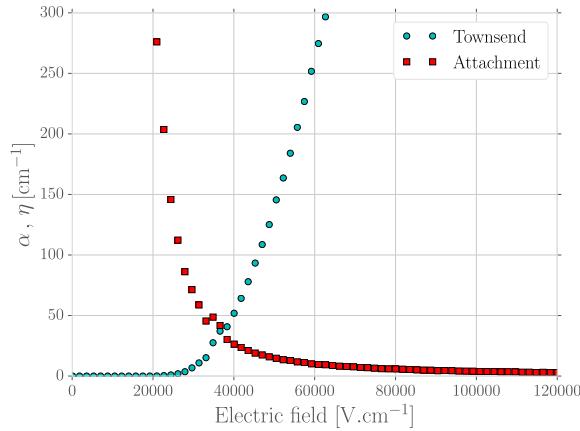


Figure 4.33: Townsend and attachment coefficient for a typical 96.7/3/0.3 mixture of $C_2H_2F_4/i-C_4H_{10}/SF_6$, at a temperature $T = 296.15\text{ K}$ and a pressure $P = 1013\text{ hPa}$ [70, 79].

2461 Nevertheless, there are more to the avalanche growth than simply these two factors. Throughout
 2462 the 20th century, models have been developed to better understand the physics of discharges in gas.
 2463 In 1937, Furry developed a model to describe electromagnetic cascades [82] that would be used for
 2464 electron avalanches in gas during the 1950s. Furry realized that the use of a Poisson law to describe
 2465 the distribution of shower sizes could not be accurate as he understood that the events occurring in
 2466 the development of a cascade are not independent from each other, as a Poisson law would suggest.
 2467 Indeed, part of the particles produce others and this process depends on both their original energy
 2468 and energy lost. Experimental results showed excess of small showers and an under estimate of very
 2469 large ones. To solve this problem, Furry proposed a distribution of sizes of following the likelihood
 2470 described in Equation 4.12, in which $\bar{n} = e^{\alpha z}$, compared with a Poisson law in Figure 4.34.

$$(4.12) \quad P(n, \bar{n}) = \bar{n}^{-1}(1 - \bar{n}^{-1})^{n-1}$$

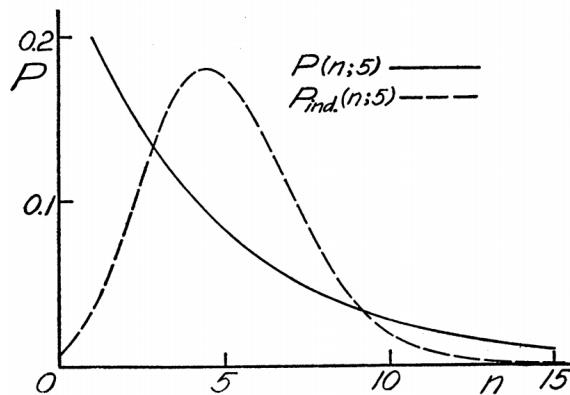


Figure 4.34: Comparison of the distribution law of Furry and the Poisson law for $\bar{n} = 5$ [82].

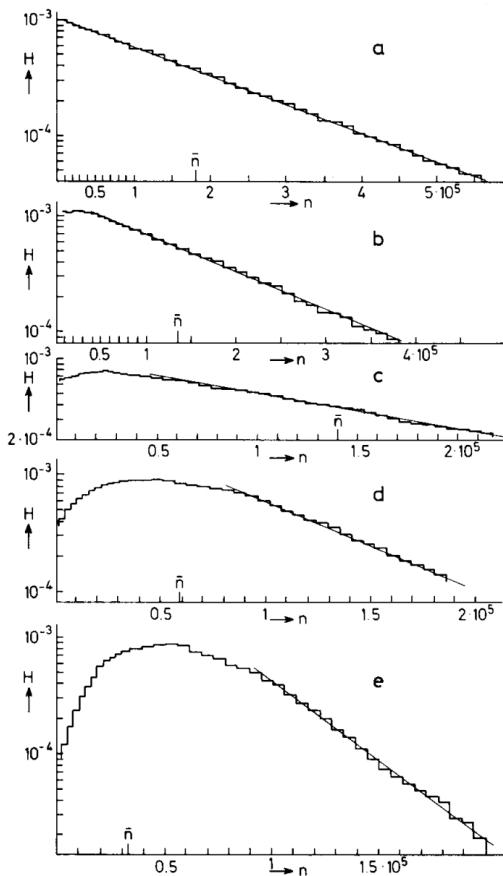


Figure 4.35: Single-electron avalanche size distribution in a proportionnal counter filled with methylal at different E/p values. (a) 70, (b) 76.5, (c) 105, (d) 186.5, (e) 426V/cm torr [83].

In this model, no extra energy is brought to the electrons in the showers, contrary to the case of a gaseous detector such as a RPC where an electric field accelerates them. Using the Furry model, Genz studied the fluctuations in electron avalanches in gaseous detectors [83]. Collisions leading to ionizations leave electrons with an energy much smaller than the ionization energy eU_i , where U_i is the ionization potential of a gas molecule. Hence, the electrons need to travel a distance $s = U_i/E$ along the electric field E to acquire a high enough energy to trigger a new ionization. For the probability of a new ionization to be independent from the path followed by the electrons since the previous ionization, the mean free path $1/\alpha$ of electrons in the gas has to be large compared to s and thus $E/\alpha \gg U_i$. The Townsend coefficient is related to the gas pressure leading to conditions on the value of E/p . Avalanches in gas are large compared to the showers Furry has studied in his original paper. For very large avalanche sizes, Equation 4.12 can be written as an exponential, as showed in Equation 4.13.

$$(4.13) \quad P(n, \bar{n}) = \bar{n}^{-1} e^{-n/\bar{n}}$$

This exponential behaviour is showed through Figure 4.35. In practice, to fully understand the avalanche growth, taking into account the path followed by electrons from one ionization to another

will become necessary. In the same paper, Genz then discusses models using Polya distributions to estimate the multiplication by looking at the size of the avalanche it self. Indeed, the number of charge carriers in the avalanche might become important enough to have an effect on the multiplication process. To account for this, it was proposed to use a varying Townsend coefficient such as described by Equation 4.14 depending on the position x in which θ is an empirical parameter leading to the probability distribution of Equation 4.15. In the limit case where θ goes to 0, the formula describes again the Furry model. But the data deviates from this model as well at large n values. Moreover, the introduction of an empirical parameters makes the model hard to interpret physically.

$$(4.14) \quad \alpha(n, x) = \alpha(x) \left(1 + \frac{\theta}{n}\right), \quad n > 0$$

$$(4.15) \quad P(n, x) = \frac{1 + \theta}{\bar{n}} \frac{1}{\theta!} \left(\frac{n(1 + \theta)}{\bar{n}}\right)^{\theta} e^{-\frac{n(1 + \theta)}{\bar{n}}}$$

In order to have a model that describes reality better, the introduction of the attachment into the model is an important step. Despite its limitations, the Furry model had the advantage to describe well avalanches occurring when the attachment could be ignored. This is only natural that this model was then extended to included attachment. This was done by Riegler, Lippmann and Veenhof [79] which showed that what was important was to consider both the Townsend coefficient describing the multiplication *and* the attachment coefficient, not only the effective multiplication coefficient $\bar{\alpha} = \alpha - \eta$. The probability to see an avalanche started by a single electron grow to a size n after having traveled a distance z through the gas is given by Equation 4.16.

$$(4.16) \quad \begin{aligned} P(n, z) = & P(n-1, z) (n-1)\alpha dz (1 - (n-1)\eta dz) \\ & + P(n, z) (1 - n\alpha dz) (1 - n\eta dz) \\ & + P(n, z) n\alpha dz n\eta dz \\ & + P(n+1, z) (1 - (n+1)\alpha dz) (n+1)\eta dz \end{aligned}$$

The first term of this probability that from a state with $n-1$ electrons, only 1 multiplies while the others don't get attached. Both the second and third terms describes the probability that from a state with already n electrons the total number of electrons stay the same. On the second term, no electron gets attached nor multiplies while on the third term, 1 electron gets multiplied and 1 gets attached to compensate. Finally, the fourth term describes the probability to fall from a state with $n+1$ to a state with n electrons due to the attachment of a single electron. At the first order, the evaluation of the previous expression leads to Equation 4.17 which general solution is given in Equation 4.18 in which are introduced the variables $\bar{n}(z)$, defined as in Equation 4.11, and $k = \eta/\alpha$ making explicit the fact that the distribution not only depends on the effective Townsend coefficient.

$$(4.17) \quad \frac{dP(n, z)}{dz} = -P(n, z)n(\alpha + \eta) + P(n-1, z)(n-1)\alpha + P(n+1, z)(n+1)\eta$$

$$(4.18) \quad P(n, z) = \begin{cases} k^{\frac{\bar{n}(z)-1}{\bar{n}(z)-k}}, & n = 0 \\ \bar{n}(z) \left(\frac{1-k}{\bar{n}(z)-k}\right)^2 \left(\frac{\bar{n}(z)-1}{\bar{n}(z)-k}\right)^{n-1}, & n > 0 \end{cases}$$

2510 The example given through Figure 4.36 shows the importance of each individual process in
 2511 the growth of avalanches and the fluctuation of their size. The values of α and η will influence
 2512 the probability distribution, as can be seen from Figure 4.36a. Then, Figure 4.36b shows that the
 2513 fluctuation really takes place within the very first interactions. Indeed, when the avalanche contains
 2514 a large enough amount of charge carriers (a few hundreds), its size then increases like $e^{z(\alpha-\eta)}$.

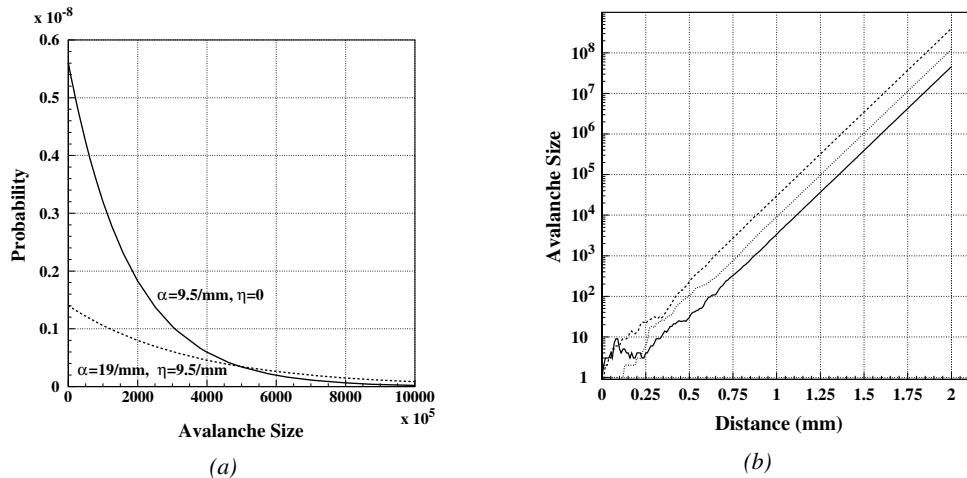


Figure 4.36: Figure 4.36a: Comparison of avalanche size distributions for different values of Townsend and attachment coefficients. The effective Townsend coefficient is the same for both distributions. Figure 4.36b: Fluctuation in avalanche size for avalanche started by a single electron with $\alpha = 13 \text{ mm}^{-1}$ and $\eta = 3.5 \text{ mm}^{-1}$ [79].

2515 4.3.4 Drift and diffusion of the electron cloud

2516 During the growth of avalanches, an electron cloud drifting along the electric field through the gas
 2517 will undergo thermal diffusion due to random collisions with the gas molecules. This phenomenon
 2518 can be studied using Maxwell-Boltzmann distribution whose mean is defined by the thermal energy
 2519 of the cloud $\langle E \rangle = 3/2kT$ with an extra component coming from the constant drift motion. The
 2520 drift of electrons along the field lines is usually observed on a macroscopic scale through which the
 2521 speed can be assimilated to a constant v_D which corresponds to the mean drift speed over a large
 2522 number of collisions in the gas.

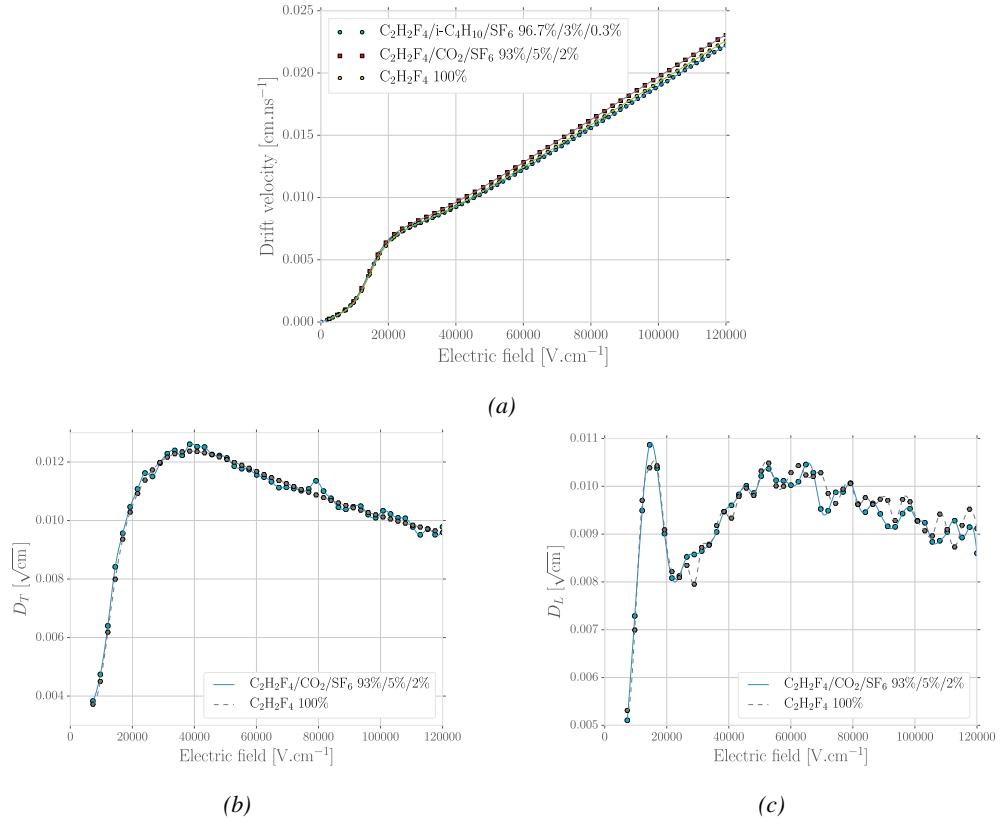


Figure 4.37: Figure 4.37a: Electron mean drift velocity v_D in pure C₂H₂F₄ and typical RPC gas mixtures. Figure 4.37b: Transverse diffusion coefficient in pure C₂H₂F₄ and a typical RPC gas mixture. Figure 4.37c: Longitudinal diffusion coefficient in pure C₂H₂F₄ and a typical RPC gas mixture. All results are given with a pressure $P = 760$ Torr and a temperature $T = 296.15$ K [70].

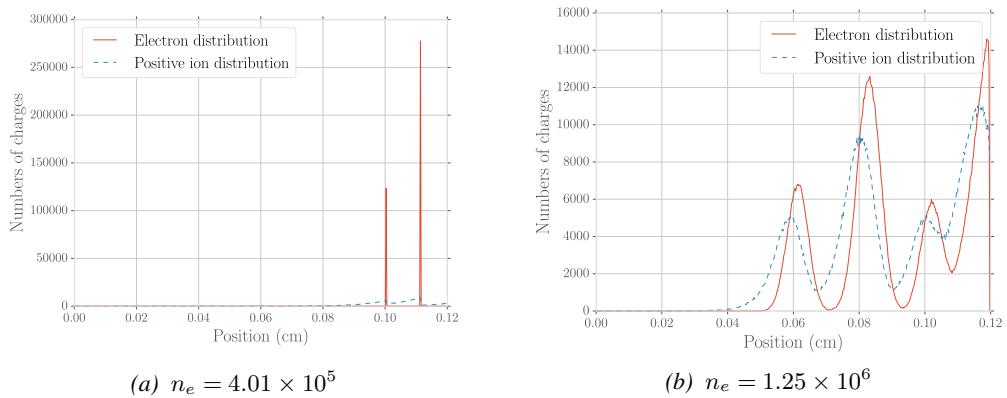


Figure 4.38: Comparison of the free charge carriers in the gas after a time $t = 7.90$ ns in the case where no diffusion is taken into account to simulate the avalanche (Figure 4.38a) and in the case where the diffusion is implemented (Figure 4.38b) [70].

Indeed, at the microscopic scale, the electrons are drifting over a distance δz while acquiring the corresponding kinetic energy $T = e_0 |\vec{E}| \delta z$ until they are slowed down by a collision in which they lose part of their energy. This process is repeated as long as electrons are free carriers. Starting from a point-like electron cloud, the Gaussian density distribution at \vec{r}_0 will be described by Formula 4.19 in which the width of the isotropic distribution is $\sigma = 2\bar{D}t$, with \bar{D} being a diffusion coefficient expressed in m^2/s [51].

$$(4.19) \quad \varphi(\vec{r}, t) = \frac{1}{(\sqrt{2\pi}\sigma(t))^3} \exp\left(-\frac{(\vec{r} - \vec{r}_0)^2}{2\sigma^2(t)}\right)$$

Now, if the constant drifting motion is added, the distribution is anisotropic and can be divided onto transversal (Formula 4.20) and longitudinal (Formula 4.21) terms, $\varphi(r, z, t) = \varphi_T(r, t)\varphi_L(z, t)$, with a cylindrical symmetry around the field axis [51]. The variables t and $\sigma_{T,L}(t)$ can be hidden to the profit of the diffusion coefficients by using the relations $v_D = l/t$ and $\sigma_{T,L}^2(t) = 2\bar{D}_{T,L}l/v_D$ and introducing new diffusion coefficients $D_{T,L} = \sqrt{2\bar{D}_{T,L}/v_D}$ in order to explicitly show the dependence of the Gaussian width in drifted distance l .

$$(4.20) \quad \varphi_T(r, t) = \frac{1}{D_T^2 l} \exp\left(-\frac{(r - r_0)^2}{2D_T^2 l}\right)$$

$$(4.21) \quad \varphi_L(z, t) = \frac{1}{\sqrt{2\pi l} D_L} \exp\left(-\frac{(z - z_0)^2}{2D_L^2 l}\right)$$

These coefficients, as well as the drift velocity of the electrons, can be calculated thanks to Magboltz as showed in Figure 4.37. The influence of the diffusion on the distribution of charge carriers throughout the gas volume is depicted in Figure 4.38. From very localised electron clusters in the gas in Figure 4.38a, a Gaussian diffusion is then visible in Figure 4.38b. Due to the interactions with gas molecules during the drift, diffusions can occur in the forward and backward direction. Electrons diffused backward will effectively drift over a longer distance and multiply more than electrons diffused forward that will see a shorter drift length. As an effect, the avalanche develops over a longer time and extends over a greater gas volume than in the case the electron cloud is considered as point like and without diffusion. Moreover, as a side effect to the longer growth of the avalanche due to backward longitudinal diffusion, the total production of electrons is increased.

4.3.5 Space charge effect & streamers

Now that have been considered the basic processes that influence the development of avalanches in a gaseous detector in the previous sections, it is now important to consider the influence of the charge carriers present in the avalanche on the electric field seen by the avalanche. Indeed, each charged particle induces an electric field and it is only natural that the increasing density of electrons and ions in the detector volume will affect the electric field. Thus, parameters such as the Townsend and attachment coefficients, drift velocity or diffusion coefficients will find themselves to be modified along the gas gap length due to this effect referred to as *space charge effect*. Figure 4.39 is a more detailed version of Figure 4.1 (b) in which three electric regions are distinguished [51]. When compared to the linear electric field of strength E_0 that is developed in between the detector's electrodes, the

2555 accumulation of negative charges (electrons) on the front of the avalanche will reinforce the effective
 2556 electric field in between the anode of the avalanche front. Deeper in the gas volume, the positive
 2557 charges (cations) slowly drift towards the cathode and can induce together with the avalanche front
 2558 opposite electric field loops. Finally, due to the density of positive charges, the electric field seen in
 2559 between the ions tails and the cathode charged with negative charges is on average stronger than E_0
 2560 and compensate for the locally reversed field E_2 . Lippmann roughly estimated by considering that
 2561 10^6 charges were contained in a sphere of radius $r_d = 0.1$ mm that the space charge effect could
 2562 change the electric field by 3% and the Townsend and attachment coefficient up to 14% [51, 70].

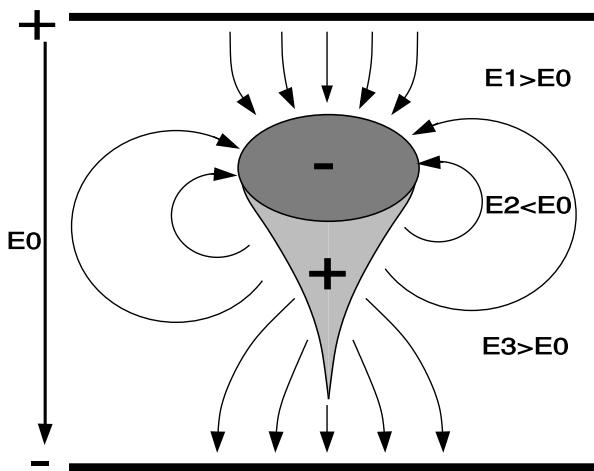


Figure 4.39: Schematic representation of an avalanche and of the electric field deformation it causes due to the local concentration of charge carriers [51].

2563 To account for the space charge effect, the electric potential and field of free charges are solved
 2564 and applied to each charges in the avalanche [51, 70]. As discussed by Français who has been work-
 2565 ing on simulating RPCs similar to that used by the SDHCAL project of ILC, the computation of
 2566 these equations for each individual charge carrier to dynamically know the space charge field at ev-
 2567 ery stage of an avalanche development is a difficult task and would require far too much computation
 2568 time and a solution is to pre-compute an interpolation table keeping an adequately large number of
 2569 values of the space charge field for each positions in space thanks to which the values stored in the
 2570 interpolation table become very close to the analytic solution and allow for a much faster simulation.
 2571

2572 The study of space charge effect through simulation shows that it can lead to a saturation of
 2573 the avalanche growth due to the deformation of the electric field, as showed through Figure 4.40.
 2574 Additionnally, a more precise understanding of the space charge effect is given through Figure 4.41
 2575 which looks at the distribution of charges and the distortion of the electric field at different steps of
 2576 the evolution of an avalanche in a RPC. At the moment a 5 GeV muon ionizes the gas, electron-ion
 2577 pairs are created in the gas in different clusters (Figure 4.41a). Later, the first clusters have reached
 2578 the anode while the clusters that where created the closest to the cathode are now big enough to start
 2579 influencing the electric field in the gap (Figure 4.41b). When a cluster is big enough, the electric field
 2580 in front of it locally increases a lot and contributes to a stronger but very localised multiplication. At
 2581 the same moment, the positive ions right behind the cluster avalanche front decrease the electric field,
 2582 saturating the electron multiplication on the tail of the electron cloud (Figure 4.41c). Finally, when

2583 all the electrons have reached the anode and are relaxing, the electric field still is very deformed
 2584 by the distribution of both positive and negative ions in the the gas volume closest to the anode
 2585 (Figure 4.41d).

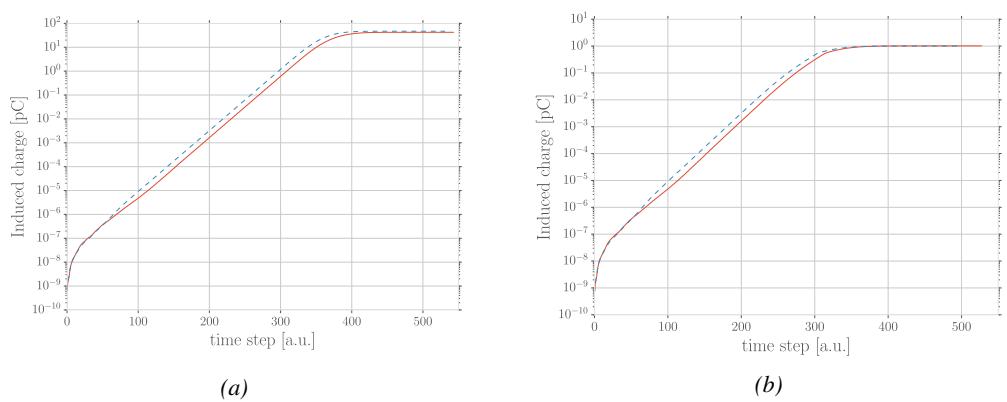


Figure 4.40: Evolution of the charge induced by an avalanche started by a single electron in a 1.2 mm thick RPC with an applied electric field of 54 kV/cm in the case space charge is not taken into account (Figure 4.40a) and in the case it is implemented into the simulation (Figure 4.40b). The total induced charge is correlated to the size of the avalanche [70].

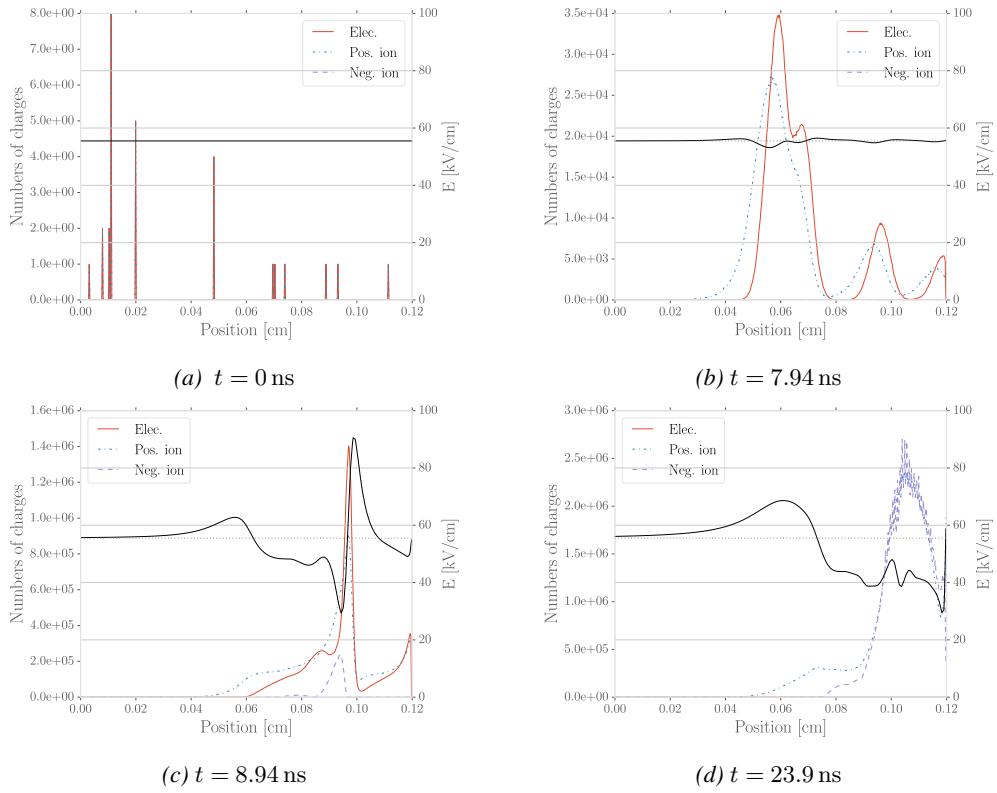


Figure 4.41: Distributions of charge carriers within the gas volume of a 1.2 mm thick RPC and the corresponding deformation of the electric field at different time steps with an applied electric field of 55.5 kV/cm [70].

2586 The electric field following the development of an avalanche can stay perturbed for a long time
 2587 with respect to the avalanche development due to the slow drift of the much heavier ions. This can
 2588 result in powerful secondary avalanches triggered by the fluctuation of the electric field together with
 2589 the emission of UV-photons leading to emission of electrons at the surface of the electrode. This is
 2590 a slow phenomenon compared to the development of avalanches. Experimentally, it is observed that
 2591 the stronger the electric field applied over the gap, the sooner after the avalanche, referred to as *pre-*
 2592 *cursor signal* in this context, and the stronger will the secondary avalanche be, possibly reaching the
 2593 streamer regime. This could be due to the amount of UV-photons emitted by the growing precursor.
 2594 These photons will be able to trigger new avalanches in a radius of a few mm around the precursor
 2595 by knocking electrons from the cathode by photoelectric effect. The strong distortions of the electric
 2596 field due to a large avalanche will be more likely to emit UV-photons as the electric field at the front
 2597 of the precursor avalanche will be large, providing the electrons with a larger energy. Eventually, the
 2598 new avalanches can grow to form streamers.

2599 **4.4 Effect of atmospherical conditions on the detector's performance**

2600

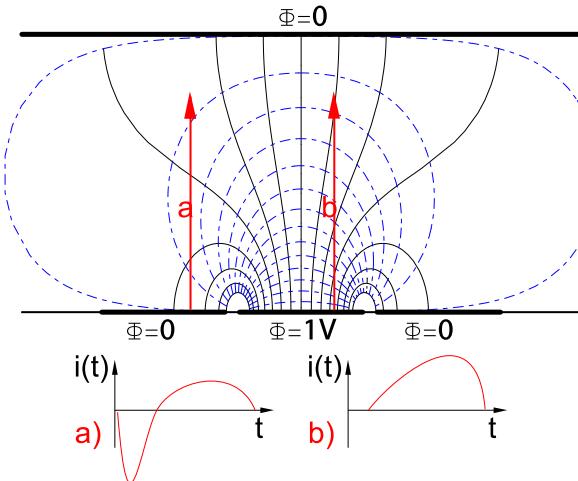


Figure 4.42: Representation of the weighting field in the volume of a RPC and the resulting induced current in the strip placed at 1 V and its neighbour connected to the ground. The induced current corresponds, as can be understood from Formula 4.22 [51].

2601 Accordingly to Ramo's theorem, the movement of charge carriers, and in particular, the movement
2602 of a dense electron cloud toward the anode induces a current signal on one or more of the readout
2603 electrodes (strips or pads). The ions on the other hand induce only a very small current as their
2604 movement is much slower than which of the electrons. The current induced by n_{Cl} clusters of $N_j(t)$
2605 charge carriers drifting at velocities $\vec{v}_{Dj}(t) = \vec{x}_j(t)$ at a time t is given by Formula 4.22 in which e_0
2606 is the unit charge and \vec{E}_w is the *weighting field*.

$$(4.22) \quad i(t) = \sum_{j=1}^{n_{Cl}} \vec{E}_{wj}(\vec{x}_j(t)) \cdot \vec{v}_{Dj}(t) e_0 N_j(t)$$

2607 The weighting field, that has been schematised in Figure 4.42, corresponds to the electric field
2608 that would be observed in the gas gap if a readout electrode is placed at a potential of 1 V while
2609 keeping all the other electrodes grounded. Then the induced charge in the readout can be simply
2610 obtained by integrating Formula 4.22 over the duration T of the signal, as given by Formula 4.23.

$$(4.23) \quad Q(t) = \int_0^T \sum_{j=1}^{n_{Cl}} \vec{E}_{wj}(\vec{x}_j(t)) \cdot \vec{v}_{Dj}(t) e_0 N_j(t)$$

2611 The signal induced in the readout of RPCs operated in avalanche mode is then sent into Front-
2612 End Electronics in which they will be pre-amplified and discriminated. The discrimination and
2613 digitization of signals in CMS FEE is described through Figure 4.43. On a first stage, analogic sig-
2614 nals are amplified, following the curve given on Figure 4.44, and then sent to the Constant Fraction

2615 Discriminator (CFD) described in Figure 4.45. At the end of the chain, 100 ns long pulses are sent
 2616 in the LVDS output. The digital signals are both used as trigger for CMS and to evaluate the per-
 2617 formance of the detectors. The performance will depend on the applied HV, i.e. on the electric field
 2618 inside of the gas volume, but also on the threshold applied on the CFDs. Indeed, in order to reduce
 2619 the probability to measure noise, the threshold is set to a level where the noise is strongly suppressed
 2620 while the signals are not too affected. Typically, CMS FEEs are set to a threshold of 215 mV after
 2621 pre-amplification, corresponding to an input charge of about 140 fC.

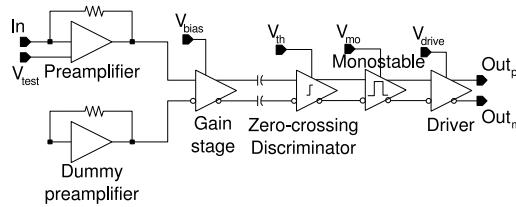


Figure 4.43: Schematics of CMS RPC FEE logic.

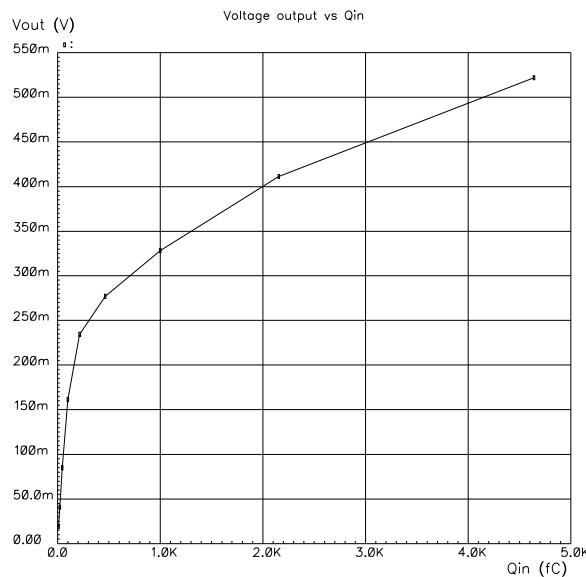


Figure 4.44: Equivalence in between the charge of the induced signal in input of the CMS FEE and the signal strength on the output of the pre-amplifier.

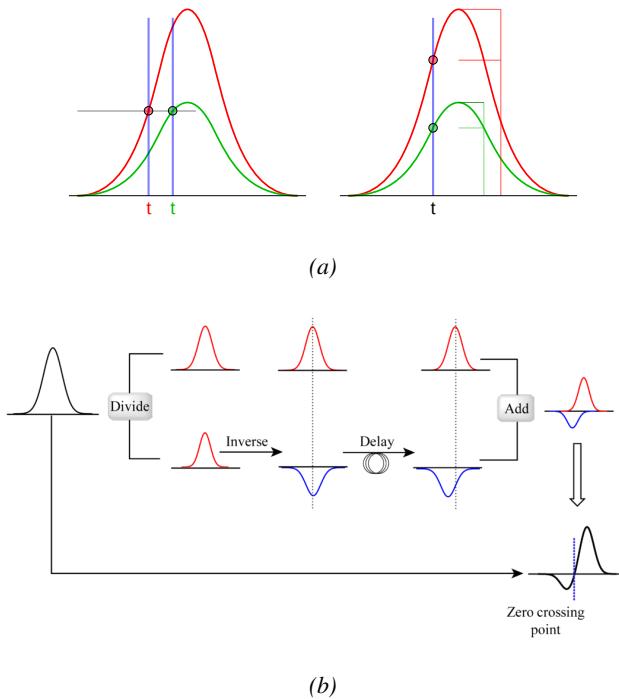


Figure 4.45: Description of the principle of a CFD. A comparison of threshold triggering (left) and constant fraction triggering (right) is shown in Figure 4.45a. Constant fraction triggering is obtained thanks to zero-crossing technique as explained in Figure 4.45b. The signal arriving at the input of the CFD is split into three components. A first one is delayed and connected to the inverting input of a first comparator. A second component is connected to the noninverting input of this first comparator. A third component is connected to the noninverting input of another comparator along with a threshold value connected to the inverting input. Finally, the output of both comparators is fed through an AND gate.

The performance of a detector is then simply measured relatively to which of a reference detector used as trigger as the ratio in between the number of events recorded in coincidence in the detector and the reference and the total amount of trigger events, $\epsilon = n_{events}/n_{triggers}$. An example of efficiency measured as a function of the effective voltage HV_{eff} is given in Figure 4.46 and can be fitted thanks to a sigmoidal function described as in Formula 4.24 and where ϵ_{max} is the maximal efficiency of the detector, λ is proportional to the slope at half maximum and HV_{50} is the value of the voltage when the efficiency reaches half of the maximum.

$$(4.24) \quad \epsilon(HV_{eff}) = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50})}}$$

CMS RPC also define two points on this sigmoid that called *knee* and *working point*. The corresponding voltages HV_{knee} is defined as the voltage at 95% of the maximum efficiency, and HV_{WP} is defined as in Formula 4.25.

$$(4.25) \quad HV_{WP} = HV_{knee} + \begin{cases} 100V & (\text{barrel}) \\ 150V & (\text{endcap}) \end{cases}$$

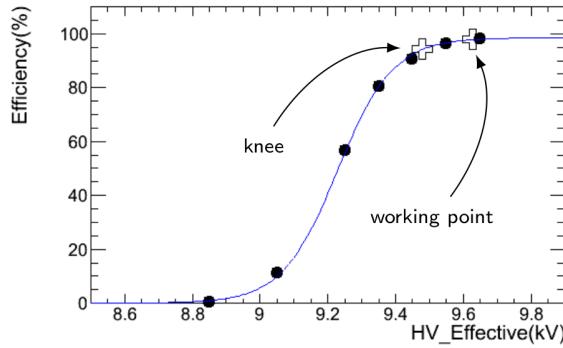


Figure 4.46: Typical efficiency sigmoid of a CMS RPC detector. The black dots correspond to the data, the blue line to the sigmoid fit and the opened cross to the knee and working extracted from the fit line.

Nevertheless, the voltage applied on a detector may vary due to a change in environmental conditions. Indeed, the variation of temperature and/or pressure will have effects on the gas density and the electrodes' resistivity which can be overcome by changing the electric field accordingly. The variation in temperature and pressure are depicted respectively in Figure 4.47 and Figure 4.48. A standard procedure to correct for temperature and pressure variations is to keep the factor $HV \cdot T/P$ constant using Formula 4.26 [84, 85] with reference values for T_0 and P_0 . For example, CMS uses $T_0 = 293.15$ K and $P_0 = 965$ hPa.

$$(4.26) \quad HV_{app} = HV_{eff} \frac{P_0}{P} \frac{T}{T_0}$$

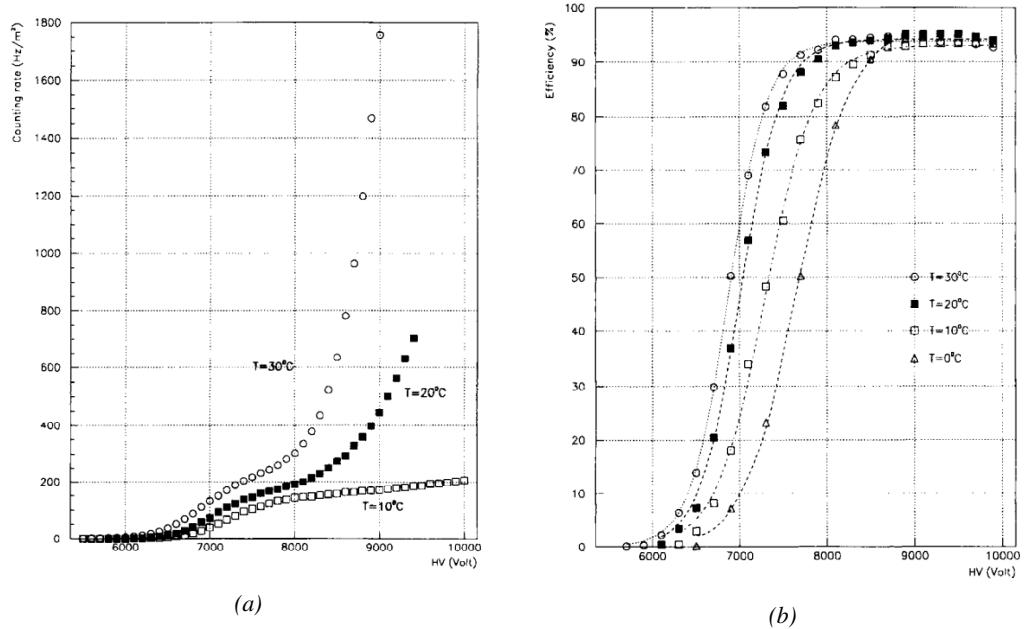


Figure 4.47: Effect of the temperature variation on the rate (Figure 4.47a) and the efficiency (Figure 4.47b) of a RPC [84].

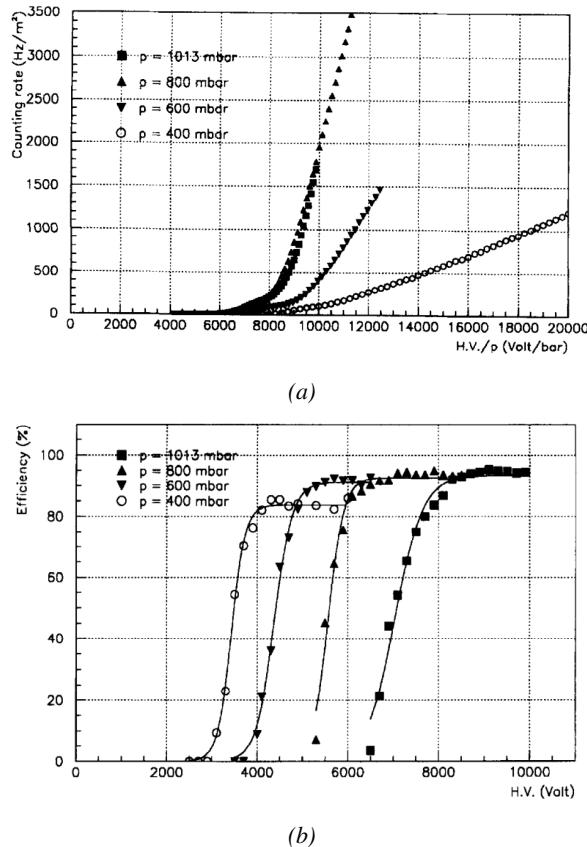


Figure 4.48: Effect of the pressure variation on the rate (Figure 4.48a) and the efficiency (Figure 4.48b) of a RPC [85].

It was actually found that such a simple procedure would overcorrect the applied voltage in the case the variations of temperature or pressure were too important [86–89]. CMS, considering that the temperature variations in the detector cavern were very small, decided only to improve the pressure correction, giving rise to Formula 4.27 [86] while on the other hand, ATLAS decided to have a more robust correction for both parameters and uses Formula 4.28 instead [89]. The coefficients α , in the case of CMS, and α, β , in the case of ATLAS, are extracted from fit on available dataset obtained during the operation of the detectors.

$$(4.27) \quad HV_{app} = HV_{eff} \left(1 - \alpha + \alpha \frac{P_0}{P} \right) \frac{T}{T_0}, \quad \alpha = 0.8$$

$$(4.28) \quad HV_{eff} = HV_{app} \left(1 + \alpha \frac{\Delta T}{T_0} \right) \left(1 - \beta \frac{\Delta P}{P_0} \right), \quad \alpha = 0.5, \beta = 0.71$$

5

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2648

Longevity studies and Consolidation of the present CMS RPC subsystem

2649 The RPC system, located in both barrel and endcap regions, provides a fast, independent muon trigger
2650 with a looser p_T threshold over a large portion of the pseudo-rapidity range ($|\eta| < 1.6$). During
2651 HL-LHC operations the expected conditions in terms of background and pile-up will make the iden-
2652 tification and correct p_T assignment a challenge for the muon system. The goal of RPC upgrade is to
2653 provide additional hits to the Muon System with more precise timing. All this information will be
2654 elaborated by the Trigger System in a global way enhancing the performance of the trigger in terms
2655 of efficiency and rate control. The RPC Upgrade is based on two projects: an improved Link Board
2656 System and the extension of the RPC coverage up to $|\eta| = 2.4$.

2657 The Link Board System is responsible for the processing, the synchronization and the zero-
2658 suppression the signals coming from the RPC FEBs. The Link Board components have been pro-
2659 duced between 2006 and 2007 and will be subjected to ageing and failure on a long term scale. An
2660 upgraded Link Board System will overcome the ageing problems and will allow for a more precise
2661 timing information to the RPC hits from 25 to 1.5 ns.

2662 In order to develop an improved RPC that fulfills CMS requirements, an extensive R&D program is
2663 being conducted. The benefits of adding two new RPC layers in the innermost ring of stations 3 and
2664 4 will be mainly observed in the neutron-induced background reduction and efficiency improvement
2665 for both trigger and offline reconstruction.

2666 The coverage of the RPC System up to higher pseudo-rapidity $|\eta| = 2.1$ was part of the original
2667 CMS TDR. Nevertheless, the expected background rates being higher than the certified rate capabili-
2668 ty of the present CMS RPCs in that region and the budget being limited, RPCs were restricted to a
2669 shorter range. Even though the iRPC technology that will equip the extension of the Muon System
2670 will be different than the current CMS RPC technology, it is necessary to certify the rate capability
2671 and longevity of the existing detectors as the radiation level will increase together with the increase
2672 of instantaneous luminosity of the LHC. For this purpose, spare RPC detectors built but not installed
2673 in CMS have been installed in different irradiation facilities, first of all, to certify the detectors to the

new levels of irradiation they will be subjected to and, finally, to study their ageing and certify their good operation throughout the HL-LHC program.

5.1 Testing detectors under extreme conditions

The upgrade from LHC to HL-LHC will increase the peak luminosity from $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to reach $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, increasing in the same way the total expected background to which the RPC System will be subjected to. Mainly composed of low energy gammas, neutrons, and electrons and positrons from p - p collisions, but also of low momentum primary and secondary muons, punch-through hadrons from calorimeters, and particles produced in the interaction of the beams with collimators, the background will mostly affect the regions of CMS that are the closest to the beam line, i.e. the RPC detectors located in the endcaps.

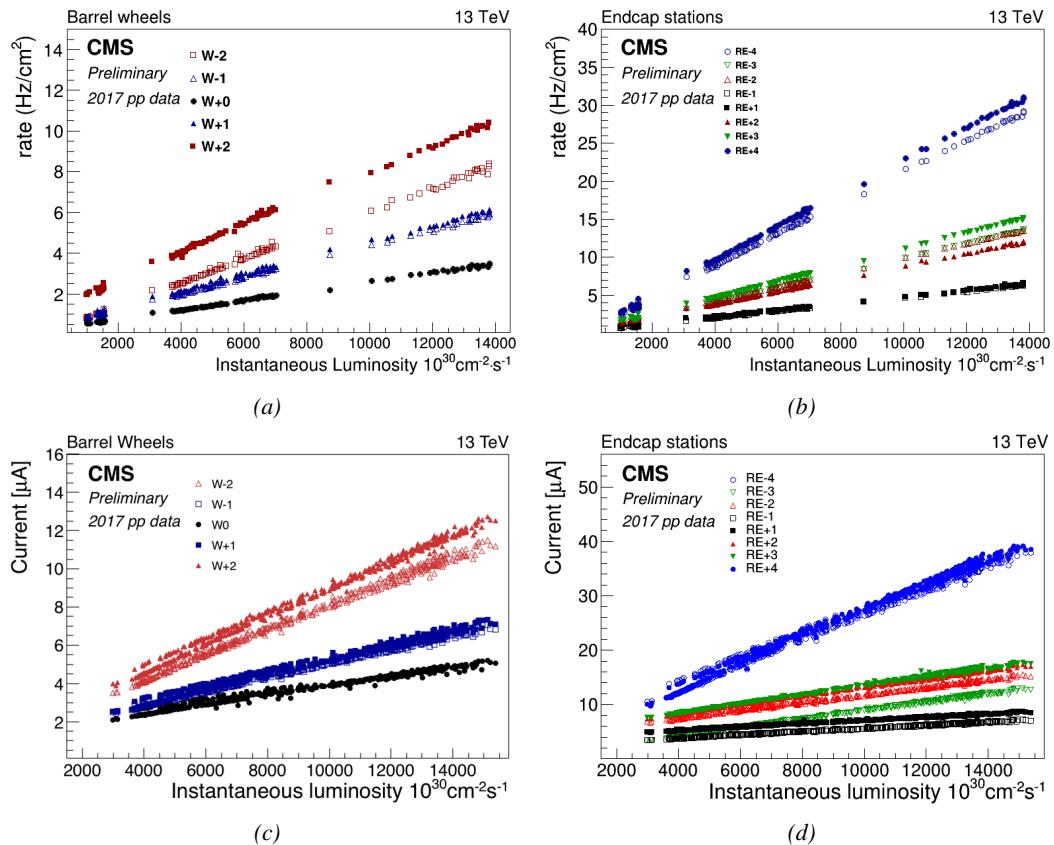


Figure 5.1: Mean RPC Barrel (left column) and Endcap (right column) rate (top row) and current (bottom row) as a function of the instantaneous luminosity as measured in 2017 p - p collision data.

Data collected over 2017, presented through Figure 5.1, allows to study the values of the background rate in all the RPC System. This was achieved thanks to a monitoring of the rates in each RPC rolls, where rolls correspond to the pseudo-rapidity partitioning of the readout electronics, and of the current in each HV channel. A linear dependence is observed between the mean rate or current

with instantaneous luminosity is showed in selected runs with identical LHC running parameters. In Figure 5.2, a linear extrapolation of the distribution of the background hit rate per unit area as well as the integrated charge is showed at a HL-LHC condition. The maximum rate per unit area in the endcap detectors at HL-LHC conditions is expected to be of the order of 600 Hz/cm^2 while the charge deposition should reach approximately 800 mC/cm^2 . These extrapolations are provided with a required safety factor 3 for the certification study.

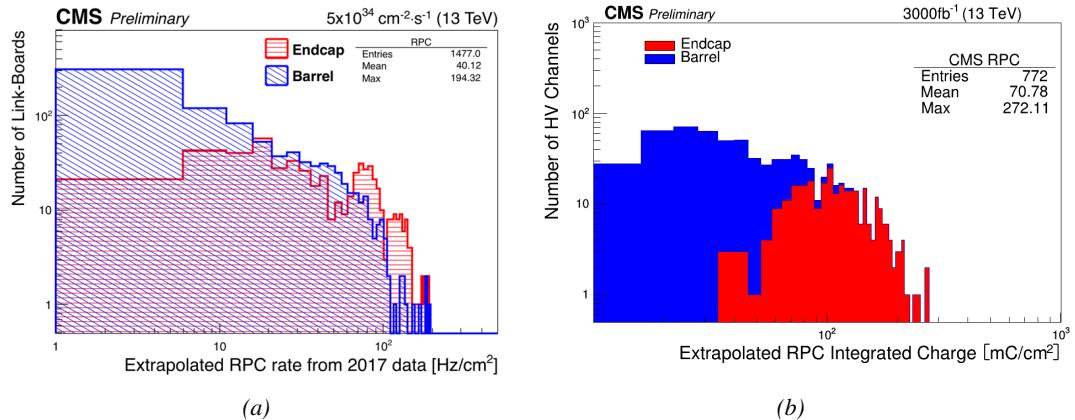


Figure 5.2: Figure 5.2a: The hit rate per region (Barrel, Endcap) is linearly extrapolated to HL-LHC highest instantaneous luminosity ($5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) using the rate as a function of instantaneous luminosity recorded by RPCs in 2017 showing a linear dependence. Figure 5.2b: The integrated charge per region (Barrel, Endcap) is extrapolated to HL-LHC integrated luminosity (3000 fb^{-1}) using the data accumulated in 2016 in every HV channels.

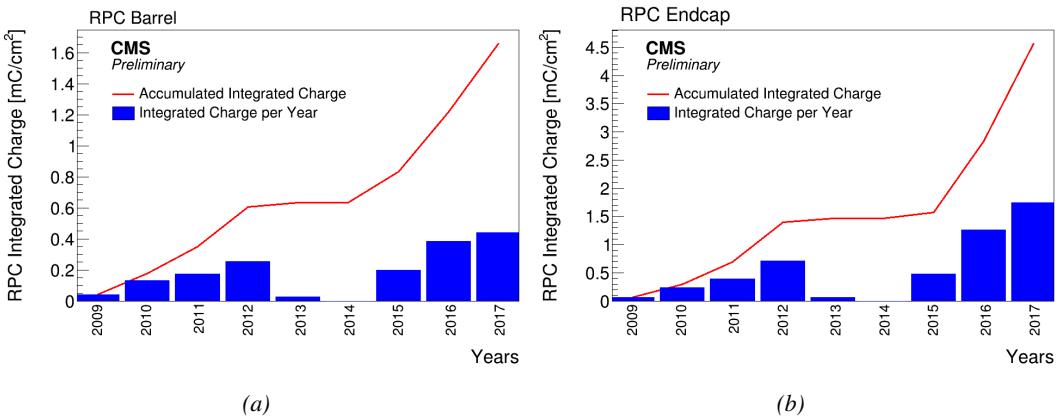


Figure 5.3: CMS RPC mean integrated charge in the Barrel region (Figure 5.3a) and the Endcap region (Figure 5.3b). The integrated charge per year is shown in blue. The red curve shows the evolution of the accumulated integrated charge through time. The blank period in 2013 and 2014 corresponds to LS1. The total integrated charge for the entire operation period (Oct.2009 - Dec.2017) is estimated to be about 1.66 mC/cm^2 in the Barrel and 4.58 mC/cm^2 in the Endcap.

In the past, extensive long-term tests were carried out at several gamma and neutron facilities certifying the detector performance. Both full size and small prototype RPCs have been irradiated

with photons up to an integrated charge of $\sim 0.05 \text{ C/cm}^2$ and $\sim 0.4 \text{ C/cm}^2$ respectively and were certified for rates reaching 200 Hz/cm^2 [90, 91]. Since the beginning of Run-I until December 2017, the RPC system provided stable operation and excellent performance and did not show any ageing effects for a maximum integrated charge in a detector of the order of 0.01 C/cm^2 - the average being of the order of 2 mC/cm^2 in the Barrel and 5 mC/cm^2 in the Endcap, closer to the beam line, as can be seen from Figure 5.3 - and a peak luminosity reaching $1.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during 2017 data taking period.

To perform the necessary studies on the present CMS RPC detectors, facilities offering the possibility to irradiate the chambers are necessary in order to recreate HL-LHC conditions or stronger and study their performance through time. Such facilities exist at CERN and were exploited to conduct this study. A first series of preliminary studies were conducted in the former gamma facility of CERN (GIF) before its dismantlement. This preliminary study was used as a stepping stone towards the building of a more powerful irradiation fully dedicated to longevity studies of CMS and ATLAS subsystems in the perspective of HL-LHC. The period of preliminary work has also been a key moment in the elaboration and improvement of data acquisition, offline analysis and online monitoring tools that are extensively used in the new gamma irradiation facility.

5.1.1 GIF

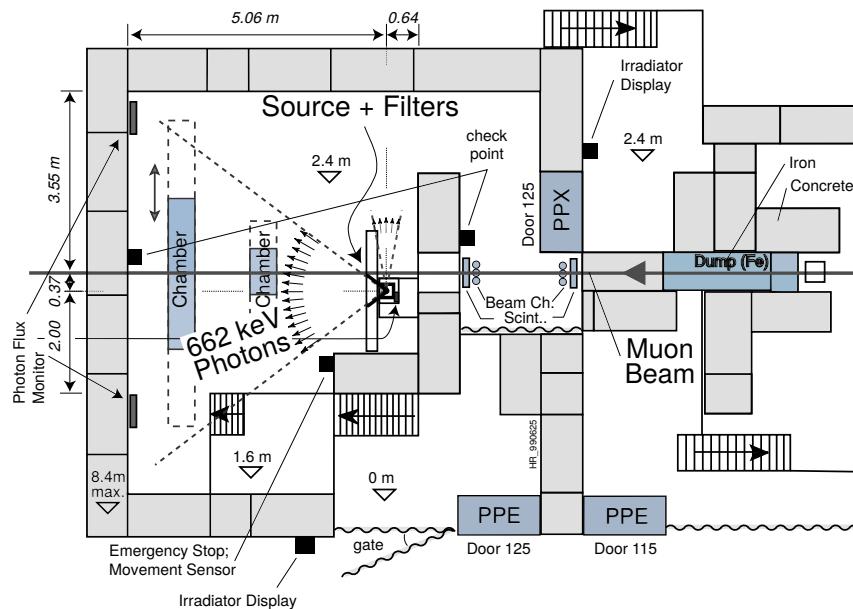


Figure 5.4: Layout of the test beam zone called X5c GIF at CERN. Photons from the radioactive source produce a sustained high rate of random hits over the whole area. The zone is surrounded by 8 m high and 80 cm thick concrete walls. Access is possible through three entry points. Two access doors for personnel and one large gate for material. A crane allows installation of heavy equipment in the area.

Located in the SPS West Area at the downstream end of the X5 test beam, the Gamma Irradiation Facility (GIF) was a test area in which particle detectors were exposed to a particle beam in presence of an adjustable gamma background [92]. Its goal was to reproduce background conditions these detectors would suffer in their operating environment at LHC. GIF layout is showed in Figure 5.4.

2717 Gamma photons are produced by a strong ^{137}Cs source installed in the upstream part of the zone
 2718 inside a lead container. The source container includes a collimator, designed to irradiate a $6 \times 6 \text{ m}^2$
 2719 area at 5 m maximum to the source. A thin lens-shaped lead filter helps providing with a uniform
 2720 out-coming flux in a vertical plane, orthogonal to the beam direction. The photon rate is controlled
 2721 by further lead filters allowing the maximum rate to be limited and to vary within a range of four
 2722 orders of magnitude. Particle detectors under test are then placed within the pyramidal volume in
 2723 front of the source, perpendicularly to the beam line in order to profit from the homogeneous photon
 2724 flux. Adjusting the background flux of photons can then be done by using the filters and choosing
 2725 the position of the detectors with respect to the source.

2726 As described on Figure 5.5, the ^{137}Cs source emits a 662 keV photon in 85% of the decays.
 2727 An activity of 740 GBq was measured on the 5th of March 1997. To estimate the strength of the
 2728 flux in 2014, was considered the nuclear decay through time associated to the Cesium source whose
 2729 half-life is well known ($t_{1/2} = (30.05 \pm 0.08) \text{ y}$). The GIF tests were done in between the 20th and
 2730 the 31st of August 2014, i.e. at a time $t = (17.47 \pm 0.02) \text{ y}$ resulting in an attenuation of the activity
 2731 from 740 GBq in 1997 to 494 GBq in 2014.

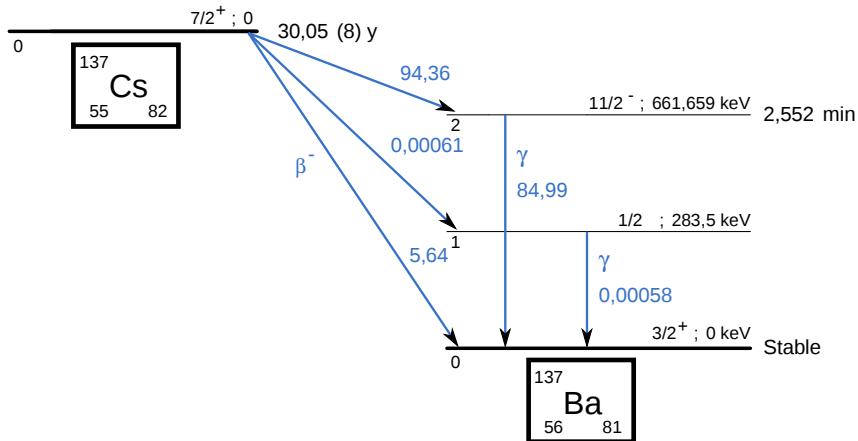


Figure 5.5: ^{137}Cs decays by β^- emission to the ground state of ^{137}Ba (BR = 5.64%) and via the 662 keV isomeric level of ^{137}Ba (BR = 94.36%) whose half-life is 2.55min.

5.1.2 Gif++

2732 The new Gamma Irradiation Facility (GIF++), located in the SPS North Area at the downstream end
 2733 of the H4 test beam, has replaced its predecessor during LS1 and has been operational since spring
 2734 2015 [93]. Like GIF, GIF++ features a ^{137}Cs source of 662 keV gamma photons, their fluence being
 2735 controlled with a set of filters of various attenuation factors. The source provides two separated
 2736 large irradiation areas for testing several full-size muon detectors with continuous homogeneous
 2737 irradiation, as presented in Figure 5.6.

2738 The source activity was measured to be about 13.5 TBq in March 2016. The photon flux being
 2739 far greater than HL-LHC expectations, GIF++ provides an excellent facility for accelerated ageing
 2740 tests of muon detectors. The source is situated in a bunker designed to perform irradiation test along
 2741 a muon beam line, the muon beam being available during selected periods throughout the year.
 2742 The H4 beam, providing the area with muons with a maximum momentum of about 150 GeV/c,
 2743 passes through the GIF++ zone and is used to periodically study the performance of the detectors

placed under continuous irradiation. Its flux is of $104 \text{ particles/s/cm}^2$ focused in an area similar to $10 \times 10 \text{ cm}^2$. Therefore, with properly adjusted filters, one can simulate the background expected at HL-LHC and study the performance and ageing of muon detectors in HL-LHC environment.

2748

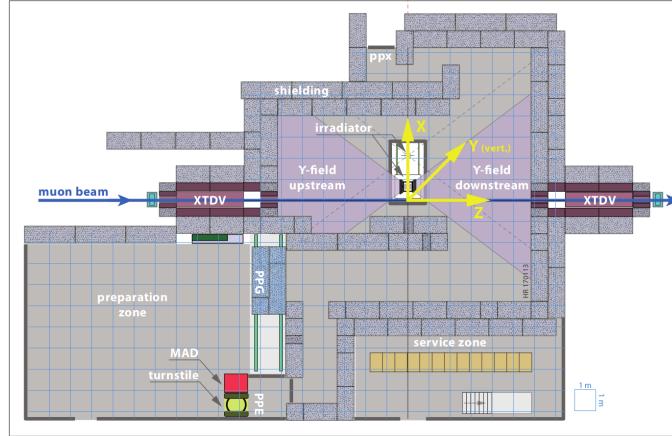


Figure 5.6: Floor plan of the GIF++ facility. When the facility downstream of the GIF++ takes electron beam, a beam pipe is installed along the beam line (z -axis). The irradiator can be displaced laterally (its center moves from $x = 0.65 \text{ m}$ to 2.15 m), to increase the distance to the beam pipe.

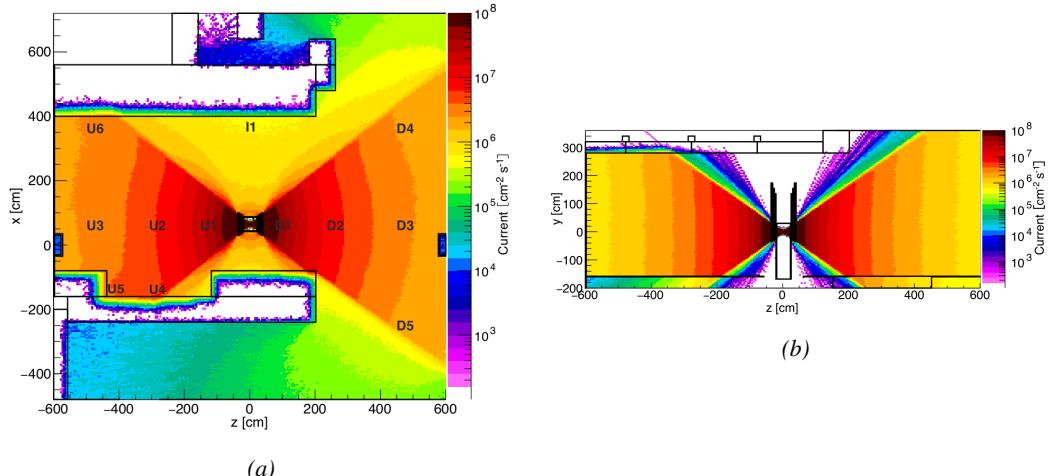
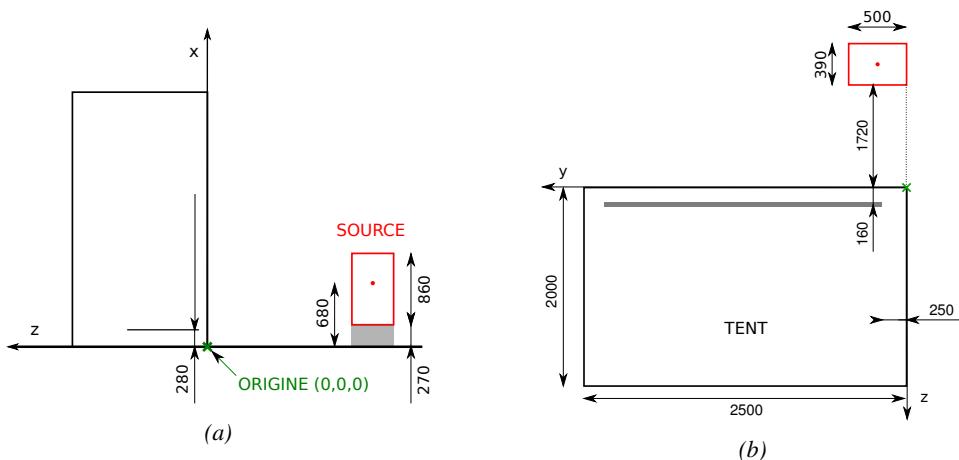


Figure 5.7: Simulated unattenuated current of photons in the xz plane (Figure 5.7a) and yz plane (Figure 5.7b) through the source at $x = 0.65 \text{ m}$ and $y = 0 \text{ m}$. With angular correction filters, the current of 662 keV photons is made uniform in xy planes.

2749 5.2 Preliminary studies at GIF

2750 5.2.1 RPC test setup

2751 During summer 2014, preliminary tests have been conducted in the GIF area on an endcap chamber
 2752 of type RE4/2 and labeled RE-4-2-BARC-161 produced for the extension of the endcap with a
 2753 fourth disk in 2013. This chamber has been placed into a trolley covered with a tent. The position
 2754 of the RPC inside the tent and of the tent with respect to the source in the bunker are described in
 2755 Figure 5.8. The goal of the study were to have a preliminary understanding of the rate capability
 2756 of the present technology used in CMS. It was decided to measure the efficiency of the RPC under
 2757 irradiation at detecting cosmic muons as, at the time of the tests, the beam not operational anymore.
 2758 Three different absorber settings were used and compared to the case where the detector was not
 2759 irradiated in order to study the evolution of the performance of the detector with increasing exposition
 2760 to gamma radiation. First of all, measurements were done with fully opened source. To complete
 2761 this preliminary study, the gamma flux has been attenuated by a factor 2, a factor 5 and finally the
 2762 source was shut down. Was measured the efficiency of the RPC at detecting the cosmic muons in
 2763 coincidence with a cosmic trigger as well as the background rate as seen by the detectors.



2764 *Figure 5.8: Description of the RPC setup. Dimensions are given in mm. A tent containing RPCs is placed
 2765 at 1720 mm from the source container. The source is situated in the center of the container. RE-4-2-BARC-
 2766 161 chamber is 160 mm inside the tent. This way, the distance between the source and the chambers plan
 2767 is 2060 mm. Figure 5.8a provides a side view of the setup in the xz plane while Figure 5.8b shows a top view in
 2768 the yz plane.*

2769 The trigger system was composed of 2 plastic scintillators and was placed in front of the setup
 2770 with an inclination of 10° with respect to the detector plane in order to look at cosmic muons. Using
 2771 this particular trigger layout, showed in Figure 5.9, leads to a cosmic muon hit distribution into the
 2772 chamber similar to the one of Figure 5.10. Measured without gamma irradiation, two peaks can
 2773 be seen on the profile of readout partition B, centered on strips 52 and 59. Section 5.2.2 will help
 2774 us understand that these two peaks are due respectively to forward and backward coming cosmic
 2775 particles where forward coming particles are first detected by the scintillators and then the RPC
 2776 while the backward coming muons are first detected in the RPC.



Figure 5.9: RE-4-2-BARC-161 chamber is inside the tent as described in Figure 5.8. In the top right, the two scintillators used as trigger can be seen. This trigger system has an inclination of 10° relative to horizontal and is placed above half-partition B2 of the RPCs. PMT electronics are shielded thanks to lead blocks placed in order to protect them without stopping photons from going through the scintillators and the chamber.

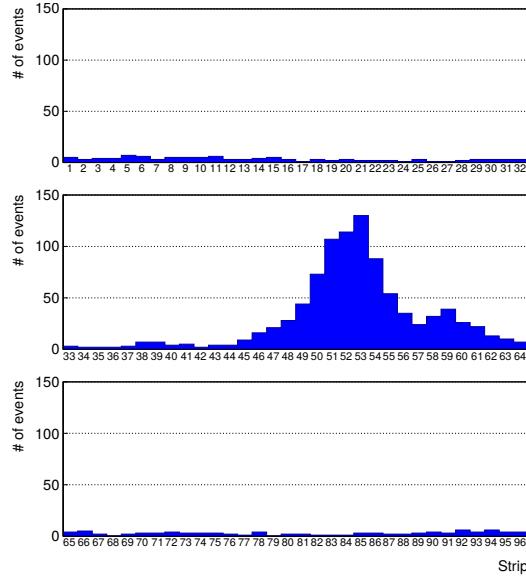


Figure 5.10: Hit distributions over all 3 partitions of RE-4-2-BARC-161 chamber is showed. Top, middle and bottom figures respectively correspond to partitions A, B, and C. The profiles show that some events still occur in other half-partitions than B2, which corresponds to strips 49 to 64, in front of which the trigger is placed, contributing to the inefficiency of detection of cosmic muons. In the case of partitions A and C, the very low amount of data can be interpreted as noise. On the other hand, it is clear that a little portion of muons reach the half-partition B1, corresponding to strips 33 to 48.

2772 The data taking is then performed thanks to a CEAN TDC module of type V1190A [94] to which
 2773 is connected the digitized output of the RPC Front-End Board, as described in Figure 5.11a and the

trigger signal from the telescope. The communication with the computer is performed thanks to a CAEN communication module of type V1718 [95]. In order to control the rates recorded by the detector, the digitized RPC signals are also sent to scalers as described in Figure 5.11b. The C++ DAQ software used in GIF was developed as an early attempt towards the understanding of the CAEN libraries and the data collected by the TDCs was saved into .dat files is analysed with an algorithm computing parameters such as efficiency, hit profile, cluster size, or gamma and noise rates which was developed with C++ as well. Finally, histograms and curves are produced using ROOT.

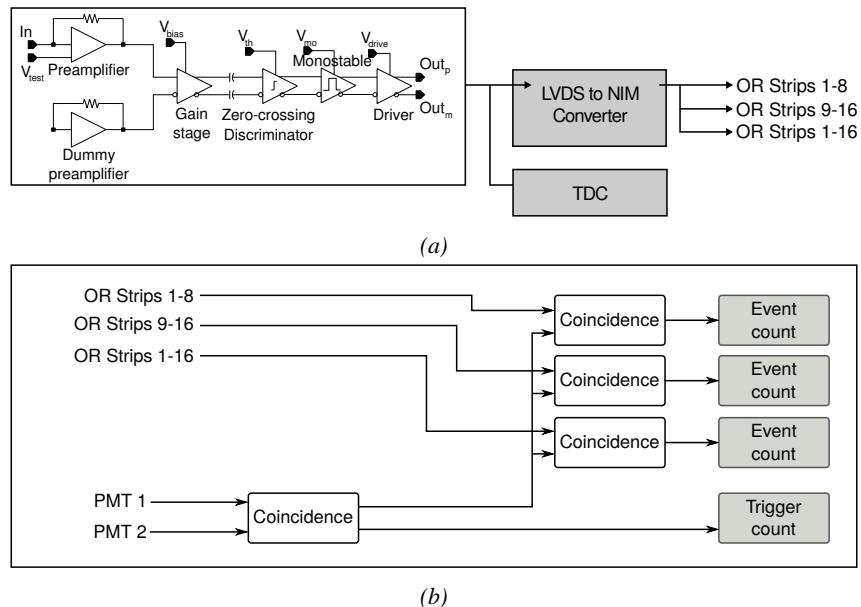


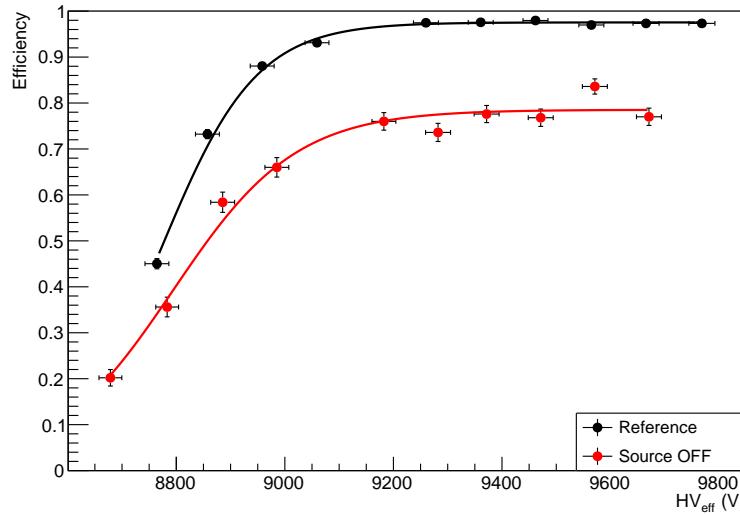
Figure 5.11: Signals from the RPC strips are shaped by the FEE described on Figure 5.11a. Output LVDS signals are then read-out by a TDC module connected to a computer or converted into NIM and sent to scalers. Figure 5.11b describes how these converted signals are put in coincidence with the trigger.

5.2.2 Geometrical acceptance of the setup layout to cosmic muons

In order to profit from a constant gamma irradiation, the detectors inside of the GIF bunker need to be placed in a plane orthogonal to the beam line. The muon beam that used to be available was meant to test the performance of detectors under test. This beam not being active anymore, an other solution to test detector performance had to be used. Thus, it has been decided to use cosmic muons detected through a telescope composed of two scintillators. Lead blocks were used as shielding to protect the photomultipliers from gammas as can be seen from Figure 5.9.

An inclination of $\sim 10^\circ$ has been given to the cosmic telescope to maximize the muon flux. A good compromise had to be found between good enough muon flux and narrow enough hit distribution to be sure to contain all the events into only one half partitions as required from the limited available readout hardware. It was then foreseen to detect muons and read them out only from half-partition B2, the last 16 channels of readout partition B (i.e. strips 49 to 64). Nevertheless, a consequence of the misplaced trigger, that can be seen as a loss of events in half-partition B1 (strips 33 to 48) in Figure 5.10, is an inefficiency. The observed inefficiency of approximately 20% highlighted in Figure 5.12 by comparing the performance of chamber RE-4-2-BARC-161 as mea-

2796 sured prior to the study at GIF and at GIF without irradiation seems too important, compared to the
 2797 12.7% of data contained into the first 16 strips observed on Figure 5.10, to only be explained by the
 2798 geometrical acceptance of the setup itself. Simulations have been conducted to show how the setup
 2799 brings inefficiency.



2800 *Figure 5.12: Results are derived from data taken on half-partition B2 only. On the 18th of June 2014, data
 has been taken on chamber RE-4-2-BARC-161 at CERN building 904 (Prevessin Site) with cosmic muons
 providing us a reference efficiency plateau of $(97.54 \pm 0.15)\%$ represented by a black curve. A similar mea-
 surement has been done at GIF on the 21st of July with the same chamber giving a plateau of $(78.52 \pm 0.94)\%$
 represented by a red curve.*

2801 5.2.2.1 Description of the simulation layout

2802 The layout of GIF setup has been reproduced, only roughly using Figure 5.9 due to the lack of
 2803 measures, and incorporated into a C++ Monte Carlo (MC) simulation to study the geometrical ac-
 2804 ceptance of the telescope projected onto the readout strips [96]. A 3D view of the simulated layout
 2805 is given into Figure 5.13. Muons are generated randomly in a horizontal plane located at a height
 2806 corresponding to the lowest point of the PMTs. This way, the needed size of the plane in order to
 2807 simulate events happening at very large azimuthal angles (i.e. $\theta \approx \pi$) can be kept relatively small
 2808 while the total number of muon tracks to propagate is kept relatively small. The muon flux is de-
 2809 signed to follow the usual $\cos^2\theta$ distribution for cosmic particles. The goal of the simulation is to
 2810 look at muons that pass through the telescope composed of the two scintillators and define their dis-
 2811 tribution onto the RPC read-out plane. During the reconstruction, the read-out plane is then divided
 2812 into read-out strips and each muon track is assigned to a strip.

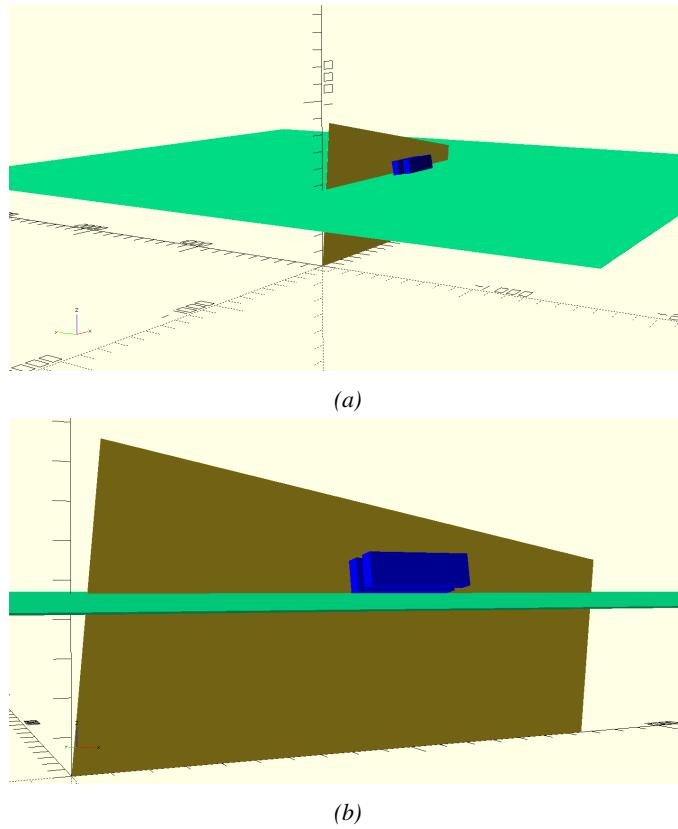


Figure 5.13: Representation of the layout used for the simulations of the test setup. The RPC read-out plane is represented as a yellow trapezoid while the two scintillators as blue cuboids looking at the sky. The green plane corresponds to the muon generation plane within the simulation. Figure 5.8a shows a global view of the simulated setup. Figure 5.8b shows a zoomed view that allows to see the 2 scintillators as well as the full RPC plane.

5.2.2.2 Simulation procedure

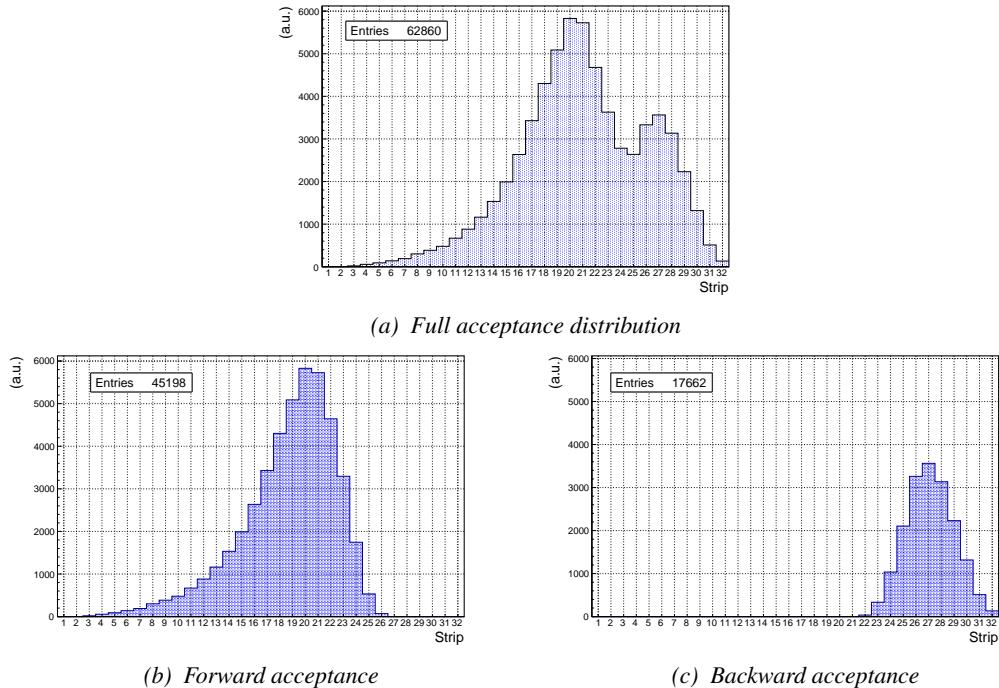
$N_\mu = 10^8$ muons are randomly generated inside the muon plane with an azimuthal angle θ chosen to follow a $\cos^2\theta$ distribution. Infinite planes are associated to each surface of the scintillators. Knowing the muon position into the muon generation plane and its direction allows, by assuming that muons travel in a straight line, to compute the intersection of the muon track with these planes. Applying conditions to the limits on the contours of the scintillators' faces then gives an answer to whether or not the muon passed through the scintillators. In the case the muon was not *detected* into both scintillators, the simulation discards the muon and generates a new one.

On the contrary, if the muon is labeled as good, its position within the RPC read-out plane is computed and the corresponding strip, determined through geometrical tests, gets a *hit*. Muon hits fill different histograms whether they are associated to forward or backward coming muons. A discrimination is performed according to their direction components. An (x, y, z) position into the generation plane as well as a $(\theta; \phi)$ pair are associated to each generated muon providing with information on the direction the track follows. This way, muons satisfying the condition $0 \leq \phi < \pi$ are labeled as *backward* coming muons while muons satisfying $\pi \leq \phi < 2\pi$ as *forward* coming

2827 muons.

2828 5.2.2.3 Results and limitations

2829 The output from the simulation is given in Figure 5.14 in which the distribution is showed for all
 2830 muons but also for the separate contributions of forward and backward coming muons. The strip
 2831 number is here given in a range of 1 to 32 corresponding to the 32 strips contained in each RPC
 2832 read-out partition, without taking into account the fact that partition B of an RPC correponds, by
 2833 convention, to strips 33 to 64. Comparing the number of muons recorded respectively in the first 16
 2834 strips and the in all of the 32 strips of the RPC read-out panel, it can be established than, out of the
 2835 total amount of muons that have passed through the telescope and reached the RPC, 16.8% where to
 2836 be detected in the 16 first strip of the read-out plane corresponding to half partition B1. This brings
 2837 a geometrical inefficiency of the same amount that can then be used to correct the data by scaling up
 2838 by a factor $c_{geo} = 1/(1 - 0.168)$ the maximum efficiency measured during data taking.



2839 *Figure 5.14: Geometrical acceptance distribution as provided by the Monte Carlo simulation.*

2840 Nevertheless, it is difficult to evaluate a systematical uncertainty on this geometrical correction
 2841 for different reasons. First of all, eventhough the dimensions of the scintillators and of the RPC are
 2842 well known, the position of each element of the setup with respect to one another was not measured.
 2843 It was then necessary, using known dimensions, to extract the positions of each element from Fig-
 2844 ure 5.9 with unknown uncertainty. The inclination is also roughly measured to be 10° and even if
 2845 the position of each peak, distant in the simulation of 7 strips, tends to confirm this assumption, the
 2846 geometrical inefficiency would be affected by a variation of the inclination angle. Introducing in the
 2847 simulation an error of $\pm 2^\circ$ would lead to a correction factor $c_{geo} = 1.20^{+0.04}_{-0.03}$ that allows for a good

improvement of the efficiency measured in GIF, as can be seen from Figure 5.15. GIF measurement is in agreement

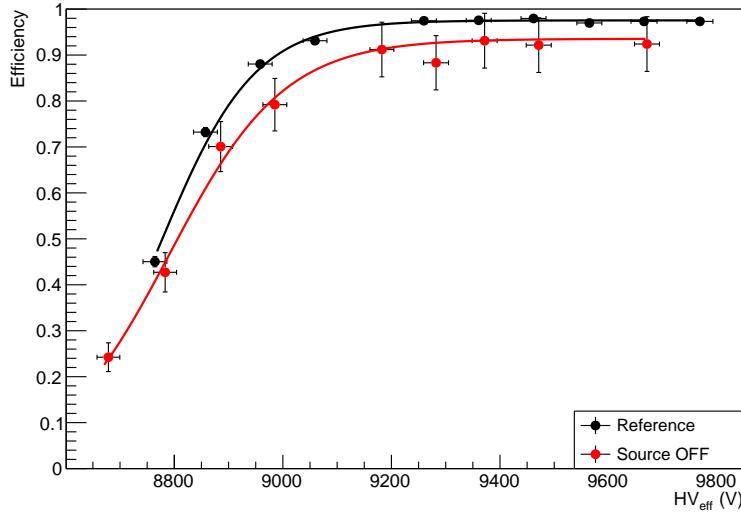


Figure 5.15: Correction of the efficiency without source. The efficiency after correction gets much closer to the Reference measurement performed before the study in GIF by reaching a plateau of $(93.52 \pm 2.64)\%$.

Further corrections could be also be brought as it can easily be understood that the distribution showed through Figure 5.14a differs from the measured hit profile showed in Figure 5.10. The contributions of forward and backward muon indicate that 28.1% of the total geometrical acceptance should contribute to detecting backward muons whereas it is measured that the hit profile contains 22.0% of backward data only. This estimation of the backward versus forward content in the data was done through a fit using a sum of two skew distribution, one acting on the forward muon peak while the other acts on the backward muon fit, as showed in Figure 5.16. Although a skew distribution lacks physical interpretation, it allows to easily fit such kind of data. A description of a skew distribution, as the product of a gaussian and a sigmoid (Formula 5.1), is given through Formula 5.2.

$$(5.1) \quad g(x) = A_g e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}, \quad s(x) = \frac{A_s}{1 + e^{-\lambda(x-x_i)}}$$

$$(5.2) \quad sk(x) = g(x) \times s(x) = A_{sk} \frac{e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}}{1 + e^{-\lambda(x-x_i)}}$$

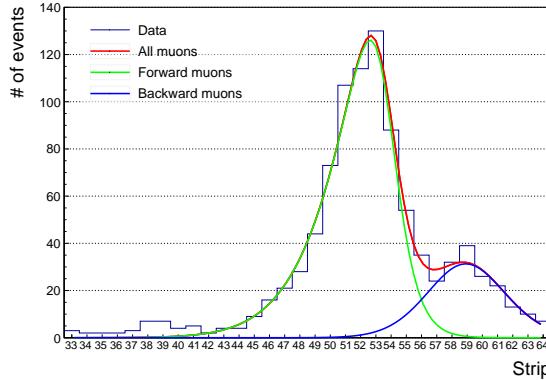


Figure 5.16: Hit distributions over read-out partition B of RE-4-2-BARC-161 chamber together with skew distribution fits corresponding to forward and backward coming muons.

From the obvious difference in between geometrical simulation and data, it is necessary to realize that the geometrical acceptance and the hit profile are two distinct information. When the geometrical acceptance only provides with the information about what the detector can expect to see in a perfect world where all muons are detected in the exact same way independently from their energy, angle of incidence, fluctuation of the detector gain due to complexe avalanche development, thresholds applied on the scintillators and on the RPC FEEs to reduce the noise, the cross-talk and corresponding spread of the induced charge observed on the read-out strips, the hit profile provides the final product of all the previously mentioned contributions and can greatly differ from purely geometrical considerations. A full physics analysis involving softwares such as GEANT would be required to further refine the correction on the measured efficiency at GIF.

5.2.3 Photon flux at GIF

In order to understand and evaluate the γ flux in the GIF area, simulations had been conducted at the time GIF was opened for research purposes [92]. Table 5.1 presented in this article gives the γ flux for different distances D to the source. The simulation was done using GEANT and a Monte Carlo N-Particle (MCNP) transport code, and the flux F is given with the estimated error from these packages expressed in %.

Nominal ABS	Photon flux F [$\text{cm}^{-2} \text{s}^{-1}$]			
	at $D = 50 \text{ cm}$	at $D = 155 \text{ cm}$	at $D = 300 \text{ cm}$	at $D = 400 \text{ cm}$
1	$0.12 \times 10^8 \pm 0.2\%$	$0.14 \times 10^7 \pm 0.5\%$	$0.45 \times 10^6 \pm 0.5\%$	$0.28 \times 10^6 \pm 0.5\%$
2	$0.68 \times 10^7 \pm 0.3\%$	$0.80 \times 10^6 \pm 0.8\%$	$0.25 \times 10^6 \pm 0.8\%$	$0.16 \times 10^6 \pm 0.6\%$
5	$0.31 \times 10^7 \pm 0.4\%$	$0.36 \times 10^6 \pm 1.2\%$	$0.11 \times 10^6 \pm 1.2\%$	$0.70 \times 10^5 \pm 0.9\%$

Table 5.1: Total photon flux ($E\gamma \leq 662 \text{ keV}$) with statistical error predicted considering a ^{137}Cs activity of 740 GBq at different values of the distance D to the source along the x-axis of irradiation field [92].

The simulation does not provide with an estimated flux at the level of the RPC under test. First of all, it is necessary to extract the value of the flux from the available data contained in the original paper and then to estimate the flux in 2014 at the time the experimentation took place. In the case of a pointlike source emitting isotropic and homogeneous gamma radiations, the gamma flux F at a

2878 distance D from the source with respect to a reference point situated at D_0 where a known flux F_0
 2879 is measured will be expressed like in Formula 5.3, assuming that the flux decreases as $1/D^2$, where
 2880 c is a fitting factor that can be written from Formula 5.3 as Formula 5.4. Finally, using Equation 5.4
 2881 and the data of Table 5.1, with $D_0 = 50$ cm as reference point, Table 5.2 can be built. It is interesting
 2882 to note that c for each value of D doesn't depend on the absorption factor.

$$(5.3) \quad F^{ABS} = F_0^{ABS} \times \left(\frac{cD_0}{D} \right)^2$$

$$(5.4) \quad c = \frac{D}{D_0} \sqrt{\frac{F^{ABS}}{F_0^{ABS}}} , \quad \Delta c = \frac{c}{2} \left(\frac{\Delta F^{ABS}}{F^{ABS}} + \frac{\Delta F_0^{ABS}}{F_0^{ABS}} \right)$$

Nominal ABS	Correction factor c		
	at $D = 155$ cm	at $D = 300$ cm	at $D = 400$ cm
1	$1.059 \pm 0.70\%$	$1.162 \pm 0.70\%$	$1.222 \pm 0.70\%$
2	$1.063 \pm 1.10\%$	$1.150 \pm 1.10\%$	$1.227 \pm 0.90\%$
5	$1.056 \pm 1.60\%$	$1.130 \pm 1.60\%$	$1.202 \pm 1.30\%$

Table 5.2: Correction factor c is computed thanks to Formula 5.4 taking as reference $D_0 = 50$ cm and the associated flux F_0^{ABS} for each absorption factor available in table 5.1.

2883 For the range of D/D_0 values available, it is possible to use a simple linear fit to get the evolution
 2884 of c that can be expressed as $c(D/D_0) = aD/D_0 + b$. Using Formula 5.5, but neglecting the
 2885 uncertainty on D that will only be used when extrapolating the values for the position of the RPC
 2886 under test whose position is not perfectly known, the results showed in Figure 5.17 is obtained.
 2887 Figure 5.17b confirms that using only a linear fit to extract c is enough as the evolution of the rate
 2888 that can be obtained superimposes well on the simulation points.

$$(5.5) \quad F^{ABS} = F_0^{ABS} \left(a + \frac{bD_0}{D} \right)^2 , \quad \Delta F^{ABS} = F^{ABS} \left[\frac{\Delta F_0^{ABS}}{F_0^{ABS}} + 2 \frac{\Delta a + \Delta b \frac{D_0}{D} + \Delta D \frac{bD_0}{D^2}}{a + \frac{bD_0}{D}} \right]$$

2889 In the context of the 2014 GIF tests, the RPC read-out plane is located at a distance $D = 206$ cm
 2890 from the source. Moreover, to estimate the strength of the flux in 2014 it is necessary to consider the
 2891 nuclear decay through time assiciated to the Cesium source whose half-life is well known ($t_{1/2} =$
 2892 (30.05 ± 0.08) y). The very first source activity measurement has been done on the 5th of March
 2893 1997 while the GIF tests where done in between the 20th and the 31th of August 2014, i.e. at a time
 2894 $t = (17.47 \pm 0.02)$ y resulting in an attenuation of the activity from 740 GBq in 1997 to 494 GBq in
 2895 2014. All the needed information to extrapolate the expected flux through the detector at the moment
 2896 of GIF preliminary tests has now been assembled, leading to Table 5.3. By assuming a sensitivity of
 2897 the RPC to γ of 2×10^{-3} , the order of magnitude of the expected hit rate per unit area would be of
 2898 the order of the kHz for the fully opened source, as reported in the last column of the table.

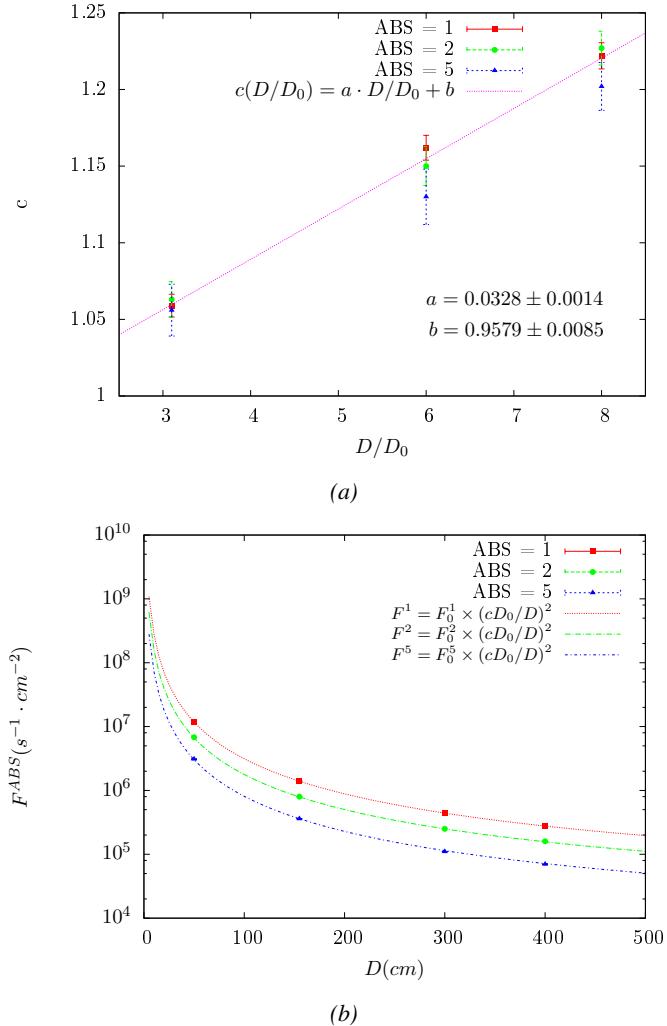


Figure 5.17: Figure 5.17a shows the linear approximation fit performed on data extracted from table 5.2. Figure 5.17b shows a comparison of Formula 5.5 with the simulated flux using a and b given in figure 5.17a in formulae 5.3 and the reference value $D_0 = 50$ cm and the associated flux for each absorption factor F_0^{ABS} from table 5.1

Nominal ABS	Photon flux F [$cm^{-2} s^{-1}$]			Rate [Hz/cm^2] at $D^{2014} = 206$ cm
	at $D_0^{97} = 50$ cm	at $D^{97} = 206$ cm	at $D^{2014} = 206$ cm	
1	$0.12 \times 10^8 \pm 0.2\%$	$0.84 \times 10^6 \pm 1.2\%$	$0.56 \times 10^6 \pm 1.2\%$	1129 ± 14
2	$0.68 \times 10^7 \pm 0.3\%$	$0.48 \times 10^6 \pm 1.2\%$	$0.32 \times 10^6 \pm 1.2\%$	640 ± 8
5	$0.31 \times 10^7 \pm 0.4\%$	$0.22 \times 10^6 \pm 1.2\%$	$0.15 \times 10^6 \pm 1.2\%$	292 ± 4

Table 5.3: The data at D_0 in 1997 is taken from [92]. Using Formula 5.5, the flux at D , including an error of 1 cm, can be estimated in 1997. Then, taking into account the attenuation of the source activity, the flux at D can be estimated at the time of the tests in GIF in 2014. Assuming a sensitivity of the RPC to γ s = 2×10^{-3} , an estimation of the hit rate per unit area is obtained.

2899 The goal of the study will be to have a good measurement of the intrinsic performance without
 2900 source irradiation. Then, taking profit of the two working absorbers, at absorbtion factors 5 (300 Hz)
 2901 and 2 (~ 600 Hz) the goal will be to show that the detectors fulfill the performance certification of
 2902 CMS RPCs. Finally, a first idea of the performance of the detectors at higher background will be
 2903 provided with absorbtion factor 1 (no absorbtion and >1 kHz)).

2904 5.2.4 Results and discussions

2905 The data taking at GIF has been conducted in between the 21st and the 31st of August, 2014. Data
 2906 has been collected with both source OFF and ON using three different absorber settings (ABS 5, 2
 2907 and 1) in order to vary the irradiation on the RPC. For each source setting, two HV scans have been
 2908 performed with two different trigger settings. During a first scan the trigger sent to the TDC module
 2909 was the coincidence of the two scintillators composing the telescope while during a second scan the
 2910 trigger was a pulse coming from a pulse generator in order to measure the noise or gamma rate seen
 2911 by the chamber. Indeed, using a pulse allows to trigger at moments not linked to any physical event
 2912 and, hence, to obtain a *RANDOM* trigger on noise and gamma events to measure the associated rates,
 2913 the probability to have a pulse in coincidence with a cosmic muon being negligible.

2914 From the cosmic trigger scans, a summary of the efficiencies and corresponding cluster sizes is
 2915 showed in Figure 5.18. The efficiency curves with Source ON show a shift with respect to the case
 2916 without irradiation. With ABS 5, the general shape of the efficiency curve stays unchanged whereas
 2917 a clear alteration of the performance is observed at ABS 2 and ABS 1. From the cluster size results,
 2918 a reduction of the cluster size under irradiation can be oberved at equivalent efficiency. This effect
 2919 can be due to the perturbation of the electric field by the strong rate of gamma particles starting
 2920 avalanches in the gas volume of the detector.

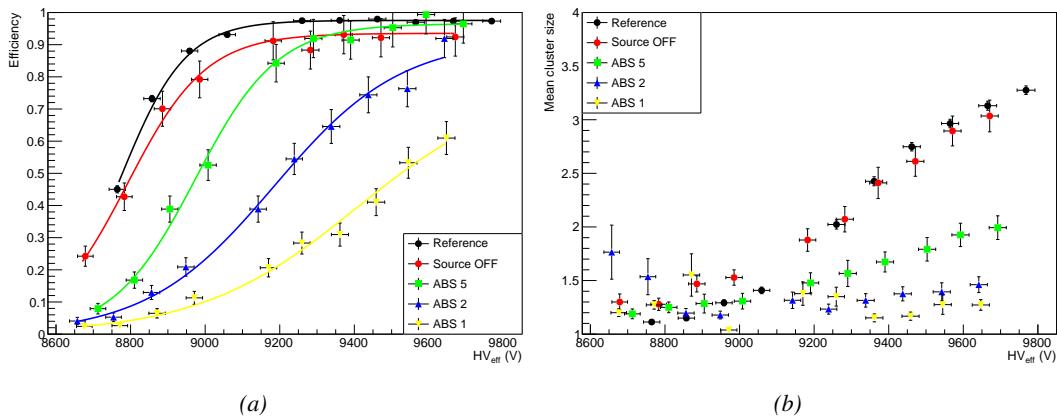


Figure 5.18: Efficiency (Figure 5.18a) and cluster size (Figure 5.18b) of chamber RE-4-2-BARC-161 measured at GIF with Source OFF (red) and Source ON using different absorber settings: ABS 5 (green), ABS 2 (blue) and ABS 1 (yellow). The results are compared to the Reference values obtained with cosmics.

2921 It is necessary to study the evolution of the performance of the chamber with the increasing rate.
 2922 In Figure 5.19a, the noise rate when the source is OFF stays low but increases at voltages above
 2923 9500 V. The rise of the noise rate in the detector can be related to the increased streamer probability
 2924 observed with such a large electric field. The rates with source ON measured at GIF all show a

similar behaviour until a high voltage of approximately 9400 V at which the rate of ABS 5 saturates, corresponding to the chamber reaching full efficiency. It is important to note that, even though the rates look similar independently from the gamma flux, relatively to the efficiency of the chamber, the rate actually increases with increasing flux at equivalent efficiency. A rough way to measure the rate effectively observed by the detector for each source setting would be to normalize the measured rates to the efficiency of the detector. This exercise was done with Figure 5.19b from which constant fits were done on Source ON data in order to extract the rate the chamber was subjected to.

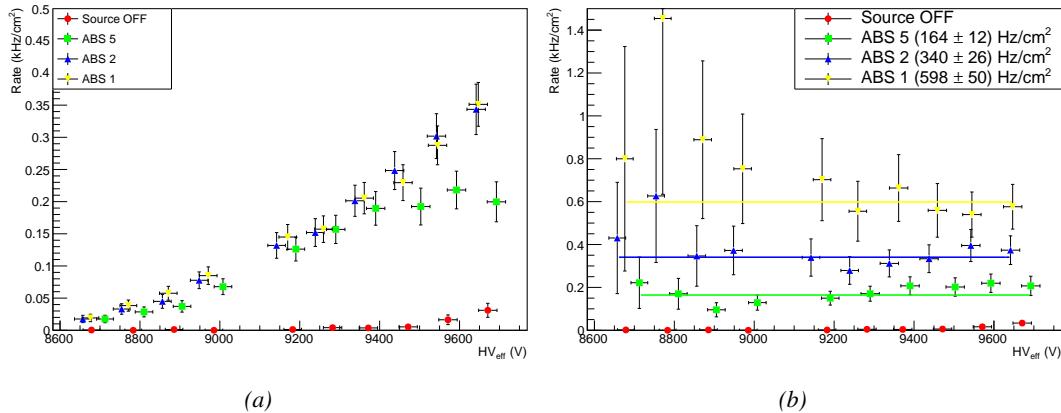


Figure 5.19: Rates in chamber RE-4-2-BARC-161 measured at GIF with Source OFF (red) and Source ON using different absorber settings: ABS 5 (green), ABS 2 (blue) and ABS 1 (yellow). On Figure 5.19b, the rates of Figure 5.19a were normalized to the measured efficiency and constant fits are performed on Source ON data showing the gamma rate in the chamber.

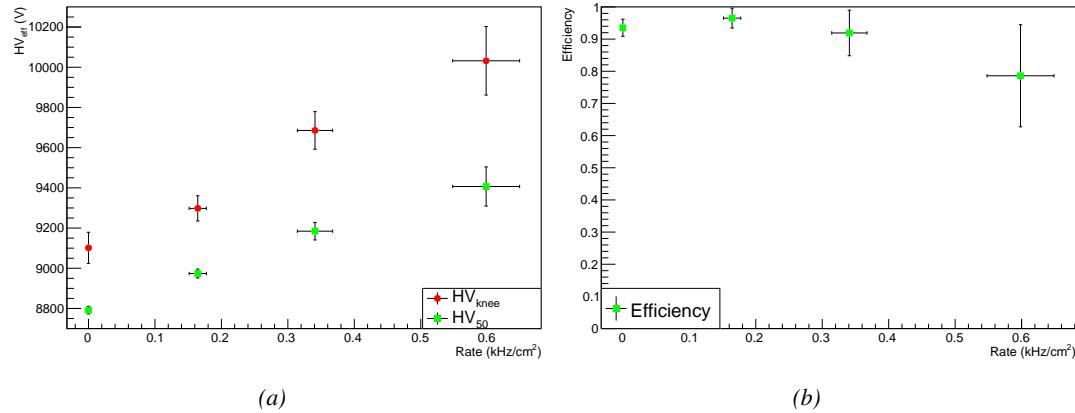


Figure 5.20: Evolution of the voltages at half maximum and at 95% of the maximum efficiency (Figure 5.20a), and of the maximum efficiency (Figure 5.20b) as a function of the rate in chamber RE-4-2-BARC-161. The data is extracted from the fits in Figures 5.18a and 5.19b.

The results need to be taken with care as a better estimation of the rate would have been to push the detector towards higher voltages to reach the efficiency plateau for each absorber configuration

and only then extract the measured rate at working voltage, defined as in Formula 4.25. Nevertheless, using this method to estimate the rate the chamber is subjected to, it is possible to look at the evolution of the HV_{50} and HV_{knee} (the working voltage being defined to be 150 V above the knee in the endcap) as a function of the increasing rate as showed in Figure 5.20. The results from GIF suggest that at a rate of 600 Hz/cm^2 the working voltage of the chamber is increased by a thousand V while the efficiency is reduced to approximately 80%, although the result still is consistent with an efficiency better than 90% due to the large error on the measurement. Moreover, it is likely that the rates obtained through fitting on normalized values is underestimated. Indeed, monitoring the current in the 3 gaps composing a CMS endcap RPC (Figure 5.21) while knowing the rate, the charge deposition per avalanche q_γ can be computed.

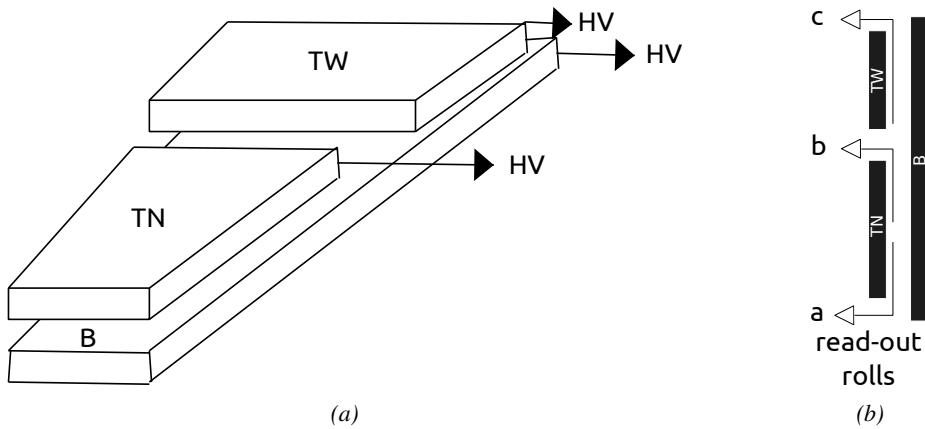


Figure 5.21: Presentation of a double-gap endcap RPC with its 3 RPC gaps. Due to the partitioning of the read-out strips into 3 rolls, the TOP layer of gap is divided into 2 gaps: TOP NARROW (TN) and TOP WIDE (TW). The BOTTOM (B) only consists in 1 gap.

A charge is expressed in C which is consistent with a current density, expressed in A/cm^2 , divided by a rate per unit area, expressed in Hz/cm^2 . The current driven by the RPC is assumed to be due to the irradiation, hence, to the avalanches developing in the gas volume due to the photons of the Cesium source. On the other hand, the rate is supposed to be a measure of the number of photons interacting with the detector. This way, it comes that the charge deposition per avalanche is expressed like $q_\gamma = J_{mon}/R_\gamma$, J_{mon} being the monitored current density and R_γ the measured γ rate. The current density is computed as the sum of the current density measured on the top gap layer and of which measured in the bottom gap layer, $J_{mon} = (I_{mon}^{TW} + I_{mon}^{TN})/(A_{TW} + A_{TN}) + I_{mon}^B/A_B$, $A_{B,TN,TW}$ being the active area and $I_{mon}^{B,TN,TW}$ the monitored currents of the gaps. According to Figure 5.22, the charge deposition per avalanche consistently converges to a value of the order of 50 pC for each absorber setting which corresponds to a value more than twice greater than what reported in litterature for CMS detectors [97, 98] indicating that the rates could have been wrongly evaluated during the short study performed at GIF. An increase of the γ rate by a factor 2 would be consistent with the expected rates calculated in Table 5.3, assuming the sensitivity to γ to be of the order of 2×10^{-3} .

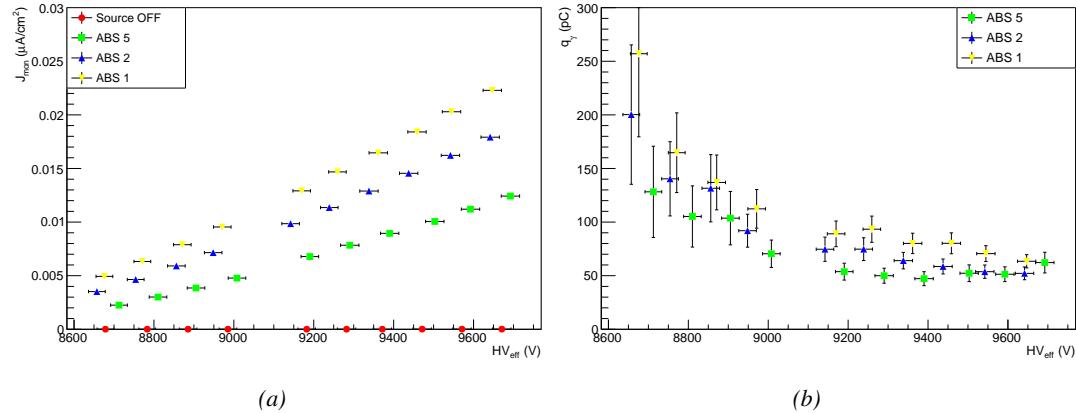


Figure 5.22: Current density and charge deposition per gamma avalanche, defined as the current density normalized to the measured rate taken from Figure 5.19a as a function of the effective high voltage in chamber RE-4-2-BARC-161 measured at GIF with Source ON using different absorber settings: ABS 5 (green), ABS 2 (blue) and ABS 1 (yellow).

Overall, working at GIF has been a rewarding experience as it offered CMS RPC R&D team the possibility to start developing the necessary skills and tools that would become the core of GIF++ experiment. The quality of the results can be argued both due to the little robustness of the experimental setup and the lack of available statistics to draw conclusions from, bringing large errors on the final result. The confrontation of the data to known results pointed to a failure in correctly measuring the γ rate at working voltage and, hence, to an overestimation of the charge per avalanche and of the drift of working voltage with increasing rate. Nevertheless, the prototypes of DAQ and offline analysis tools proved to be reliable.

5.3 Longevity tests at GIF++

5.3.1 Selection and characterization of CMS RPCs for longevity at GIF++

First proposed in 2009 [99], the new Gamma Irradiation Facility of CERN was thought in the perspective of future upgrades of PHC that would bring detectors to be operated in a high irradiation environment. GIF++ would thus provide all LHC R&D teams working on behalf of the different LHC experiment with a facility to perform longevity studies using a very intense Cesium gamma source.

In the specific case of CMS RPC, the longevity studies imply a constant irradiation of selected detectors in order to accumulate a charge equivalent to what is expected during HL-LHC, i.e. a charge of $0.8 \text{ C}/\text{cm}^2$ according to Figure 5.2 including a safety factor 3, while other detectors are left non irradiated to be used as references. Throughout the irradiation campaign, the performance of the irradiated and reference detectors will be periodically probed using the high intensity H4 muon beam. Dedicated test beam periods will be used to measure the efficiency and γ rate at the level of the detectors with different source absorber settings to have access to the rate capability of CMS RPCs, that needs to be certified above $600 \text{ Hz}/\text{cm}^2$, and to identify signs of ageing in the case the performance of the irradiated detectors diverges from those of the reference detectors with increasing accumulated charge. Other than the performance of the detectors, signs of ageing could come from

increasing dark current that would be related to local ageing of the electrodes. A close monitoring of the current driven by the detectors will then be necessary as well as dedicated periodical electrode resistivity measurement.

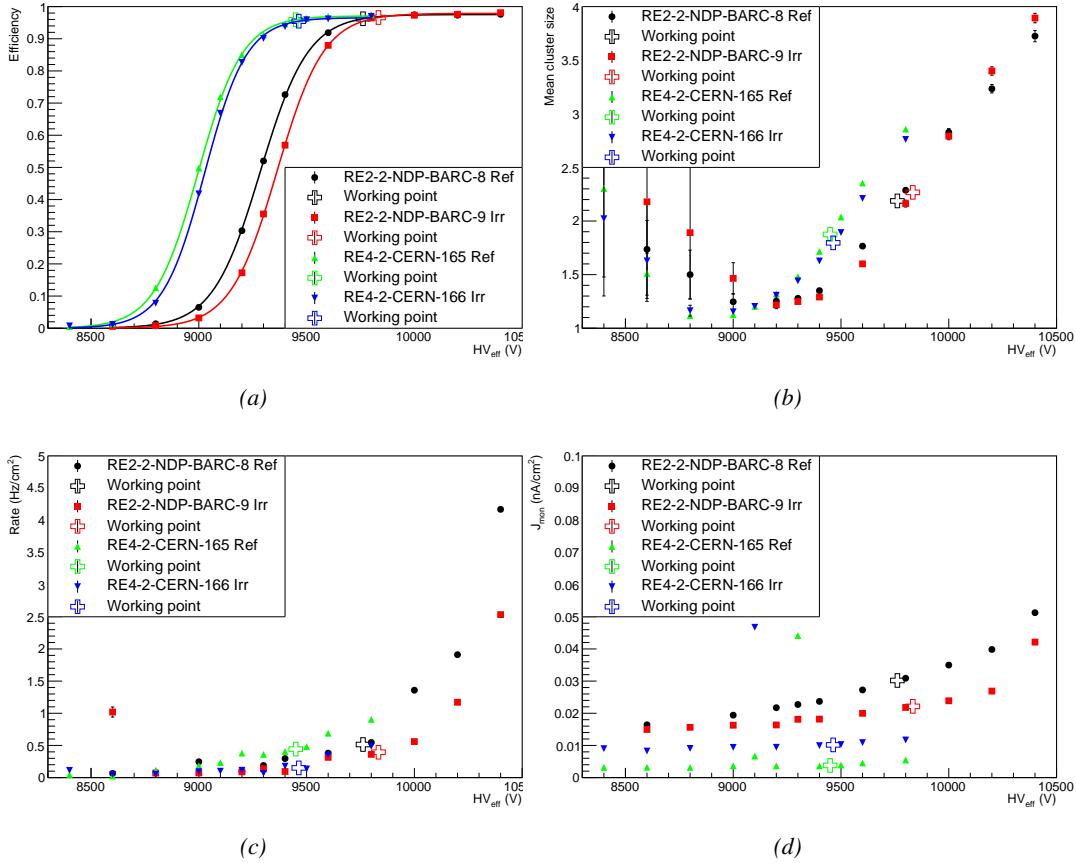


Figure 5.23: Characterization of CMS RPC detectors foreseen to be used at Gif++ for longevity studies of the present system. Using cosmic muons, efficiency (Figure 5.23a) and cluster size (Figure 5.23b) were measured as well as noise rate (Figure 5.23c) and current density (Figure 5.23d). For each detector, the working voltage, defined as in Formula 4.25, was extracted from sigmoid fits performed in Figure 5.23a and the values of efficiency, cluster size, noise rate and current density at this voltage are reported using open crosses.

As the maximum background is found in the endcap, the choice naturally was made to focus the Gif++ longevity studies on endcap chambers. Most of the RPC system was installed in 2007. Nevertheless, the large chambers in the fourth endcap (RE4/2 and RE4/3) have been installed during LS1 in 2014. The Bakelite of these two different productions having different properties, four spare chambers of the present system were selected. From the original CMS RPC system, two RE2/2 spares were selected along two RE4/2 spares from the newest detectors. Having two chambers of each type allows to always keep one of them non irradiated as reference. Due to the limited gas flow in Gif++, the RE4 chamber remained non-irradiated until end of November 2016 where the longevity studies could finally be started on those chambers.

The performance of the chambers prior to the start of the longevity campaign has been char-

acterized in Ghent before being shipped to CERN to be installed in GIF++. The results of the characterization are showed in Figure 5.23 and summarized in Table 5.4. A clear difference in performance for both types of chambers is observed as the working voltages of the newest chambers, of type RE4, are 300 to 400 V lower to the older chambers indicating that the gap thickness of RE4 detectors could be thinner. This conclusion could as well be supported by the lower cluster size at working voltages that also are smaller in RE4 chambers. Even though the measured currents are low, RE4 detectors draw less current without irradiation than RE2 detectors pointing to a difference in electrode resistivity that were produced at different moments. Efficiency and noise rate levels are of the same order of magnitude for both type of RPCs.

RPC	RE2-2-NDP-BARC-08	RE2-2-NDP-BARC-09	RE4-2-CERN-165	RE4-2-CERN-166
Used as	Reference	Irradiation	Reference	Irradiation
HV_{WP} [V]	(9762 \pm 6)	(9833 \pm 6)	(9449 \pm 5)	(9464 \pm 5)
Efficiency at WP	(96.2 \pm 0.3)	(96.6 \pm 0.3)	(95.9 \pm 0.3)	(95.5 \pm 0.3)
Cluster size at WP	(2.19 \pm 0.04)	(2.27 \pm 0.05)	(1.88 \pm 0.04)	(1.80 \pm 0.04)
Noise at WP [Hz/cm ²]	(0.51 \pm 0.01)	(0.39 \pm 0.01)	(0.44 \pm 0.00)	(0.15 \pm 0.01)
J^{WP} [pA/cm ²]	(30.1 \pm 0.1)	(22.2 \pm 0.1)	(3.8 \pm 0.0)	(10.2 \pm 0.0)

Table 5.4: Summary of the characterization measurement performed in Ghent on CMS RPC detectors foreseen to be used at GIF++ for longevity studies of the present system. For each detector, the working voltage, defined as in Formula 4.25, was extracted from sigmoid fits performed in Figure 5.23a and the values of efficiency, cluster size, noise rate and current density at this voltage are reported.

5.3.2 RPC test setup

For an easy manipulation of the detectors, a trolley with a structure containing slots in which the RPCs can be slid vertically and referred to as T1 was used. In this position described in Figure ??, each chamber is in a plane perpendicular to the beam line and the source flux as can be seen through Figure ??, receiving a uniform irradiation. Moreover the trolley allows for easy movement of the system. Indeed, the position of trolley varies according to the period of the year.

During the dedicated test beam periods during which GIF++ longevity experiments are in control of the muon beam, the trolley is placed in the upstream region of the bunker, in the beam line. The CMS RPC detectors are the ones being further away from the source on this side of the source as other detectors need to be certified at higher background rates. An additional trolley, referred to as T3, containing iRPCs and tracking RPCs is placed in between the source and the trolley containing present CMS RPCs. Indeed, iRPCs need to be certified at higher rates and thus need to be placed closer to the source to receive a stronger irradiation using the same absorber settings. The space on T1 being limited, the tracking RPCs used for extra offline information during the analysis are placed on the same trolley than iRPCs and are kept at full efficiency at all time to reconstruct muon tracks in correlate them with hits recorded in T1 chambers. The beam trigger system is composed of 2 scintillators placed outside on each side of the bunker and of a third scintillator placed in between T1 and the wall of the bunker along the beam line.

However, most of the year, T1 is placed in the so called *ageing position* corresponding to the furthest position from the source outside of the beam line, which needs to stay clear during periods where GIF++ doesn't have the control of the beam so that a beam tube can be installed through the bunker. The reason for placing the chambers as far as possible from the source comes from the too high irradiation delivered by the source during the continuous irradiation periods where all the other

3029 experiment having placed detectors into the bunker requires to integrate as much charge as possible.
3030 Hence, the source is operated with any absorbers. On the contrary, during the test beam periods, all
3031 the groups working in GIF++ are interested in operating the source using various absorber settings
3032 to study the performance of their detectors under different irradiation conditions. The time spent
3033 with a source fully opened and during which the RPCs of T1 are kept at a standby voltage of 6500 V
3034 much lower than what necessary to grow avalanches in the gas is then small compared to the time
3035 spent with other source settings and during which data can be taken.

3036 From the bunker area, the detectors are connected to the service area, visible in Figure 5.6, through
3037 the wooden floor thanks to long cable. The service area hosts all the high and low voltage power
3038 supplies, the TDCs and computers used for data acquisition and preliminary offline analysis used
3039 to fill the Detector Control Software (DCS) webpage, referred to as WebDCS, with Data Quality
3040 Monitoring (DQM) histograms useful for the shifters on duty in the control room located further in
3041 the building, away from the beam lines, as well as the gas system required for the gaseous detectors
3042 installed in GIF++ [100]. The detectors read-out is, as in the case of GIF, connected to V1190A
3043 VME TDCs communicating with the DAQ computer thanks to a V1718 VME bridge manufactured
3044 by CAEN. Moreover, a constant monitoring of all the environmental parameters, in different points
3045 of the bunker area, gas parameters, to control its composition, temperature and pressure, and of the
3046 voltages and currents delivered by the power supplies is performed and displayed on the homepage
3047 of the WebDCS interface.

3048 **5.3.3 GIF++ data flow**

3049 At GIF++, the CMS RPC R&D experiment collects different types of data coming from the detectors
3050 monitored parameters, such as voltage and currents, the gas, source, and environmental parameters,
3051 and, of course, the TDC data in which are collected the actual muon and gamma physics. These
3052 different data source compose 3 different data flows.

3053 A first, called *DIP flow*, DIP being the name of the database in which the data is retrieved from,
3054 concerns all the data coming from the gas composition, temperature and humidity, the environmental
3055 temperature and pressure, the source settings and the radiation monitoring sensors. The experimen-
3056 tal area is in charge of measuring, storing and distributing the data of interest for all of the users of
3057 the facility (source settings, radiation monitoring, gas composition at the exit of the gas mixer and
3058 general environmental information). Retrieving this data is done by accessing to the database of the
3059 experimental hall in which GIF++ is located. More specific data such as gas flow, temperature and
3060 humidity at the level of the detectors (upstream and downstream of the detectors) as well as environ-
3061 mental parameters are at the charge of the users. For this reason, several pressure, temperature and
3062 humidity sensors were installed on the gas distribution system of the RPC trolleys. The correspond-
3063 ing flow of data is saved into the local CMS RPC database and displayed on the front page of the
3064 WebDCS together with alerts in the case the values measured are out of optimal working range.

3065 The data flow related to the monitoring of detector high voltages and currents, referred to as
3066 *CAEN flow* as a reference to the manufacturer of power supplies, is retrieved thanks to computer to
3067 main frame communications. Indeed, during the operations (continuous irradiation or measurement
3068 with beam), these values can be accessed directly through the bus of the main frame hosting the high
3069 voltage supplies. The way this data articulates with the physics data flow, also called *DAQ flow*, will
3070 be described further after giving more details about this third data flow. As previously described,
3071 two types of measurement are performed on the chambers using the TDCs. On one hand, during the
3072 beam period, it is interesting to measure the efficiency of the RPCs with increasing voltage and, thus,

3073 data containing muon information will be recorded into ROOT files during what is called a HV scan.
 3074 The data is collected during several runs, each corresponding to a different HV setting. In this case,
 3075 the trigger is provided by the 3 scintillators placed along the beam line (upstream of the bunker, in
 3076 the bunker near T1 and downstream of the bunker) and extra information for the reconstruction of the
 3077 muon tracks is provided by the two tracking chambers that are constantly operated a full efficiency.
 3078 Every time a trigger is sent to the TDCs, i.e. every time a muon is detected, knowing the time delay
 3079 in between the trigger and the RPC signals, signals located in the right time window are extracted
 3080 from the buffers and saved for later analysis. Signals are taken in a time window of 400 ns centered
 3081 on the muon peak.

3082 On the other hand, during the irradiation period but also during muon time, the goal is to measure
 3083 the gamma background to have an idea of the strength of the irradiation recorded by the chamber.
 3084 This way, during the irradiation, the data is used to control any change of sensibility of the detectors,
 3085 the appearance of any hot channels that could be correlated to the appearance of hot spots, regions
 3086 of a detector leaking current while during test beam periods, the gamma background is measured
 3087 to correlate the evolution of rate capability at different stages of irradiation, hence, monitoring any
 3088 degradation of the performance due to ageing. In the absence of other signs of ageing, a reduction
 3089 of the rate capability could be related to an increase of the electrodes resistivity. These background
 3090 measurement are performed thanks to a trigger provided by a pulse generator at a rate of 300 Hz,
 3091 similarly to what was already done at GIF. Moreover, the data acquisition procedure is the same
 3092 than in the case of efficiency measurements, as a HV scan composed of several runs taken each at
 3093 a different HV setting will be taken. The HV scan in test beam period will be taken following the
 3094 same HV settings than the efficiency measurements in order to correlate both results while during
 3095 irradiation time, only key high voltage points will be taken: standby voltage and working voltage
 3096 and this not only for the RPCs operated in double-gap mode but also single-gap, by keeping one
 3097 of the two RPC layers in standby, in order to spot ageing at the gap level. To rapidly integrate an
 3098 as great as possible time, all signals contained within a time window of 10 μ s prior to the random
 3099 trigger signal are extracted form the TDC buffers and saved for further analysis.

3100 In parallel to the DAQ flow is the CAEN flow, monitoring the values of high voltage and currents
 3101 during the duration of each runs of the HV scans. In the GIF++ RPC data base, the CAEN data is
 3102 then saved into a ROOT file associated to every DAQ ROOT file. But the CAEN flow doesn't
 3103 necessary need to be correlated to the DAQ flow. Indeed, during continuous irradiation, the DAQ
 3104 only is a secondary process. The high voltage and current need to be recorded at all time while the
 3105 rates only are measured once a day for a short period. Thus, CAEN data is continuously saved into
 3106 the GIF++ database and displayed online thanks to a JS script. The data is then used to calculate
 3107 and update the integrated charge on a daily basis. When a short HV scan at standby and working
 3108 voltage is started every night to monitor once a day the gamma background, a CAEN ROOT file is
 3109 created for each DAQ ROOT file just as explained earlier. Finally, the slow DIP flow is continuously
 3110 accessed by the CAEN flow in order to correct the high voltage for pressure and temperature during
 3111 data taking, preventing for environment related performance variations.

3112 **5.3.4 RPC current, environmental and operation parameter monitoring**

3113 **5.3.5 Measurement procedure**

3114 Insert a short description of the online tools (DAQ, DCS, DQM).

3115 Insert a short description of the offline tools : tracking and efficiency algorithm.

3116 Identify long term aging effects we are monitoring the rates per strip.

3117 5.3.6 Results and discussions

3118 Figures 5.24 and 5.25 give us for different test beam periods, and thus for increasing integrated
 3119 charge through time, a comparison of the maximum efficiency, obtained using a sigmoid-like func-
 3120 tion, and of the working point of both irradiated and non irradiated chambers [55]. No aging is yet
 3121 to see from this data, the shifts in γ rate per unit area in between irradiated and non irradiated detec-
 3122 tors and RE2 and RE4 types being easily explained by a difference of sensitivity due to the various
 3123 Bakelite resistivities of the HPL electrodes used for the electrode production.

3124 Collecting performance data at each test beam period allows us to extrapolate the maximum effi-
 3125 ciency for a background hit rate of $300 \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to the expected HL-LHC condi-
 3126 tions. Aging effects could emerge from a loss of efficiency with increasing integrated charge over
 3127 time, thus Figure 5.26 helps us understand such degradation of the performance of irradiated de-
 3128 tectors in comparison with non irradiated ones. The final answer for an eventual loss of efficiency
 3129 is given in Figure 5.27 by comparing for both irradiated and non irradiated detectors the efficiency
 3130 sigmoids before and after the longevity study. Moreover, to complete the performance information,
 3131 the Bakelite resistivity is regularly measured thanks to Ag scans (Figure 5.28) and the noise rate is
 3132 monitored weekly during irradiation periods (Figure 5.29). At the end of 2016, no signs of aging
 3133 were observed and further investigation is needed to get closer to the final integrated charge require-
 3134 ments proposed for the longevity study of the present CMS RPC sub-system.

3135

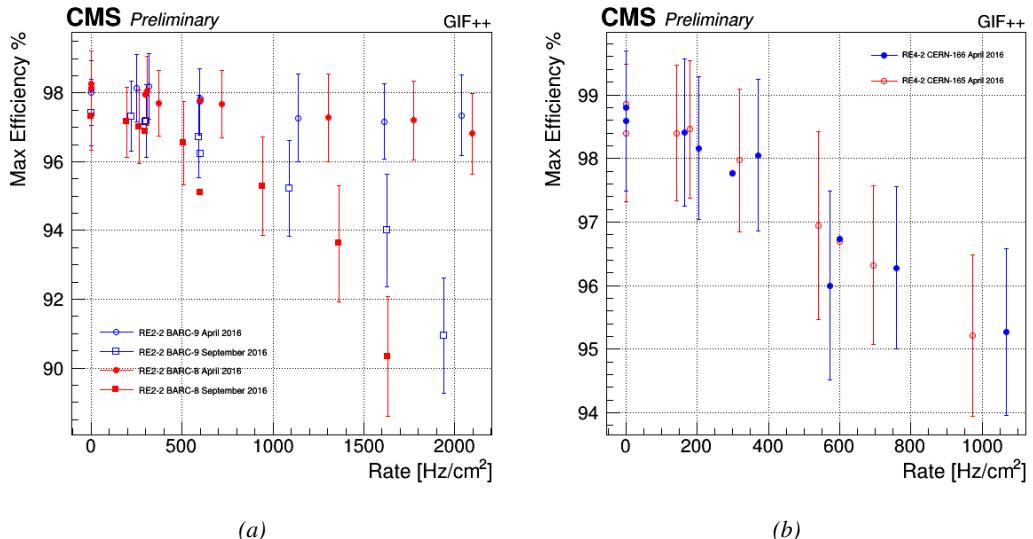


Figure 5.24: Evolution of the maximum efficiency for RE2 (5.24a) and RE4 (5.24b) chambers with increasing extrapolated γ rate per unit area at working point. Both irradiated (blue) and non irradiated (red) chambers are shown.

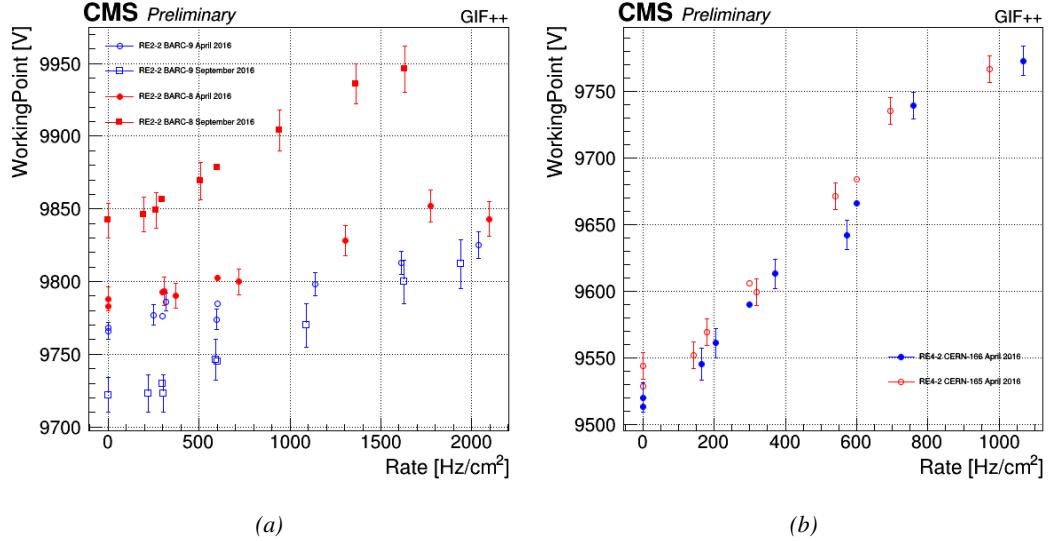


Figure 5.25: Evolution of the working point for RE2 (5.25a) and RE4 (5.25b) with increasing extrapolated γ rate per unit area at working point. Both irradiated (blue) and non irradiated (red) chambers are shown.

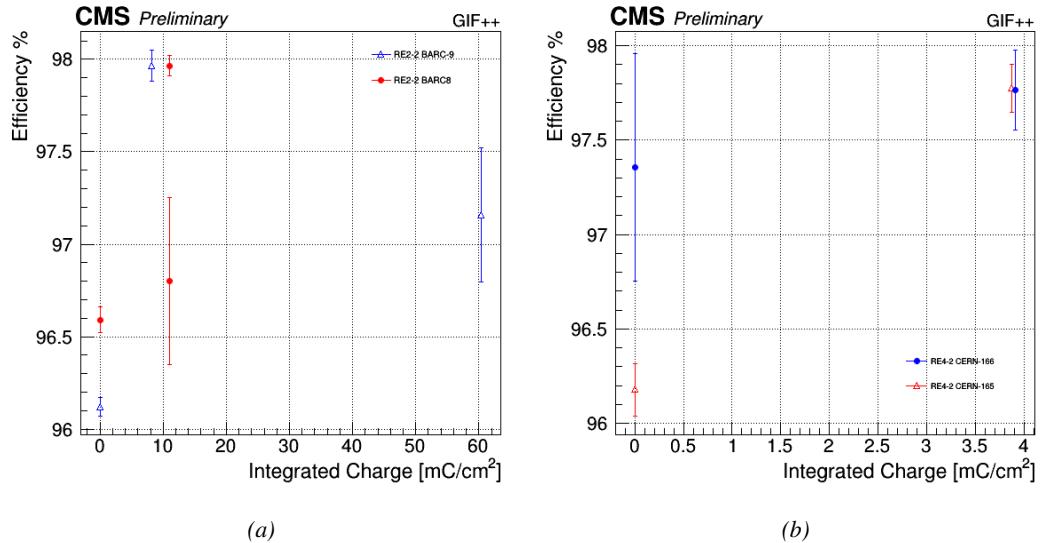


Figure 5.26: Evolution of the maximum efficiency at HL-LHC conditions, i.e. a background hit rate per unit area of 300 Hz/cm², with increasing integrated charge for RE2 (5.26a) and RE4 (5.26b) detectors. Both irradiated (blue) and non irradiated (red) chambers are shown. The integrated charge for non irradiated detectors is recorded during test beam periods and stays small with respect to the charge accumulated in irradiated chambers.

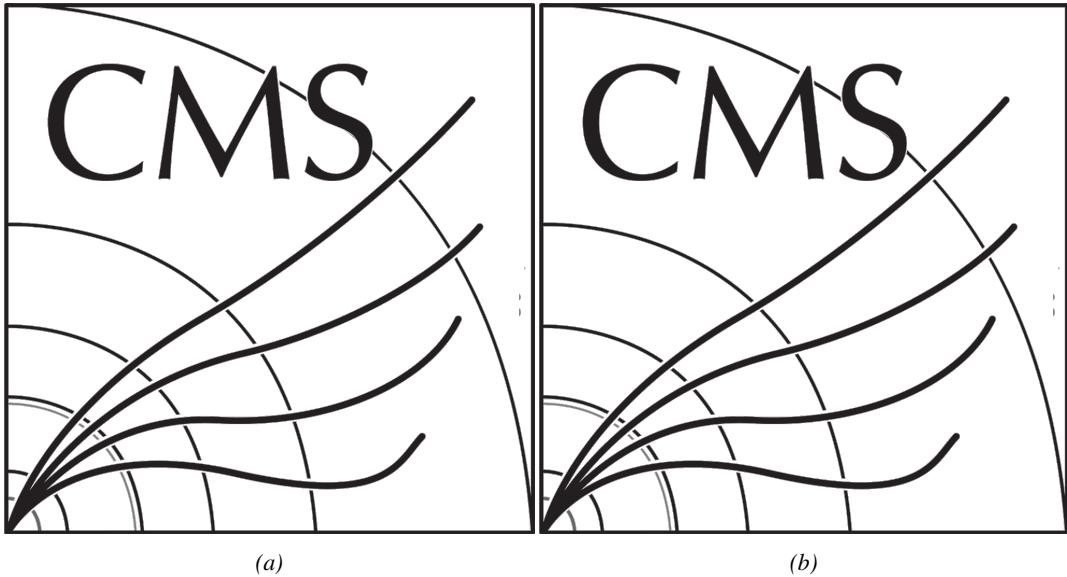


Figure 5.27: Comparison of the efficiency sigmoid before (triangles) and after (circles) irradiation for RE2 (5.27a) and RE4 (5.27b) detectors. Both irradiated (blue) and non irradiated (red) chambers are shown.

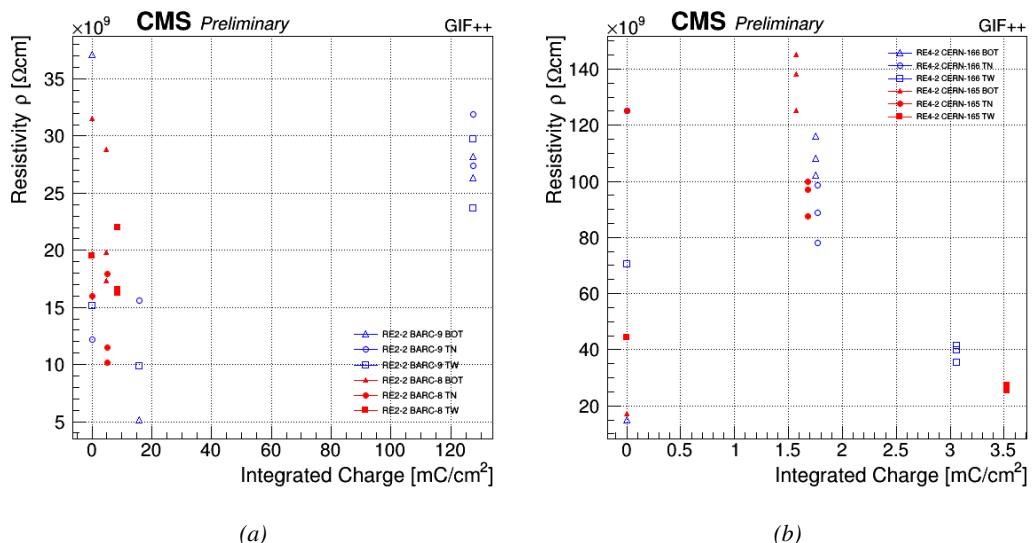


Figure 5.28: Evolution of the Bakelite resistivity for RE2 (5.28a) and RE4 (5.28b) detectors. Both irradiated (blue) and non irradiated (red) chambers are shown.

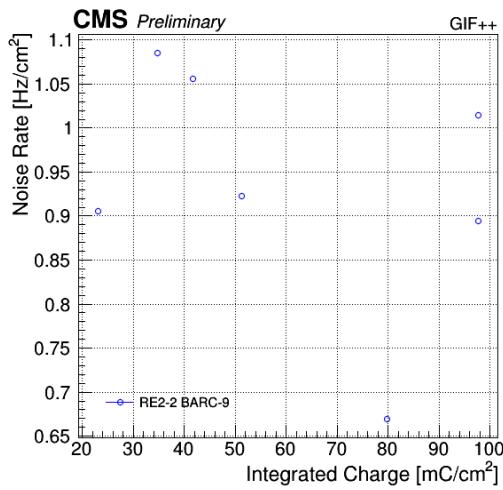


Figure 5.29: Evolution of the noise rate per unit area for the irradiated chamber RE2-2-BARC-9 only.

6

3136

3137

Conclusions and outlooks

3138 **6.1 Conclusions**

3139 **6.2 Outlooks**

A

3140

3141

A data acquisition software for CAEN VME TDCs

3142

3143 Certifying detectors in the perspective of HL-LHC required to develop tools for the GIF++ experiment.
3144 Among them was the C++ Data Acquisition (DAQ) software that allows to make the communications
3145 in between a computer and TDC modules in order to retrieve the RPC data [101]. In this
3146 appendix, details about this software, as of how the software was written, how it functions and how
3147 it can be exported to another similar setup, will be given.

3148 A.1 GIF++ DAQ file tree

3149 GIF++ DAQ source code is fully available on github at https://github.com/afagot/GIF_DAQ. The software requires 3 non-optional dependencies:

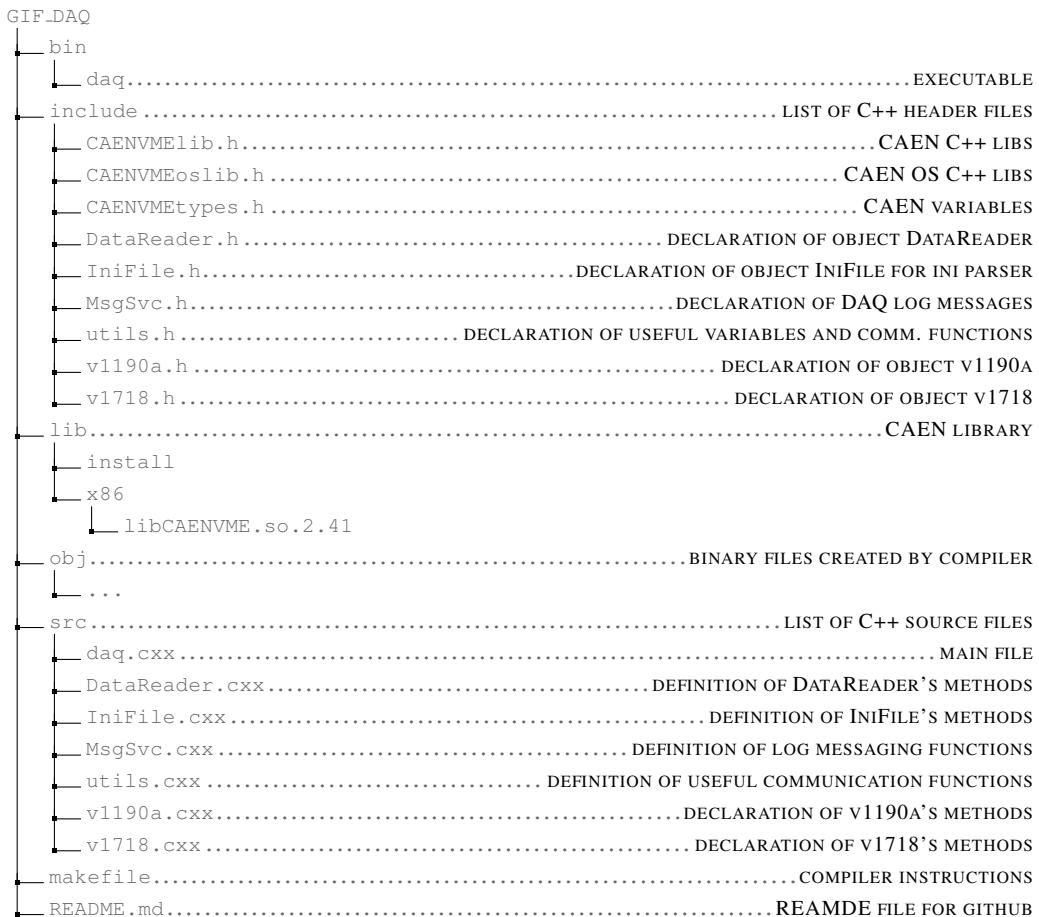
- 3151 • CAEN USB Driver, to mount the VME hardware,
3152 • CAEN VME Library, to communicate with the VME hardware, and
3153 • ROOT, to organize the collected data into a TTree.

3154 The CAEN VME library will not be packaged by distributions and will need to be installed man-
3155 ually. To compile the GIF++ DAQ project via a terminal, from the DAQ folder use the command:

3156
3157 `make`

3158 The source code tree is provided below along with comments to give an overview of the files' con-
3159 tent. The different objects created for this project (`v1718`, `v1190a`, `IniFile` & `DataReader`) will be
3160 described in details in the following sections.

3161



3162 A.2 Usage of the DAQ

3163 GIF++ DAQ, as used in GIF++, is not a standalone software. Indeed, the system being more complexe,
 3164 the DAQ only is a sub-layer of the software architecture developped to control and monitor
 3165 the RPCs that are placed into the bunker for performance study in an irradiated environment. The top
 3166 layer of GIF++ is a Web Detector Control System (webDCS) application. The DAQ is only called
 3167 by the webDCS when data needs to be acquired. The webDCS operates the DAQ through command
 3168 line. To start the DAQ, the webDCS calls:

3169
 3170 bin/daq /path/to/the/log/file/in/the/output/data/folder

3171 where /path/to/the/log/file/in/the/output/data/folder is the only argument required. This
 3172 log file is important for the webDCS as this file contains all the content of the communication of the
 3173 webDCS and the different systems monitored by the webDCS. Its content is constantly displayed
 3174 during data taking for the users to be able to follow the operations. The communication messages
 3175 are normally sent to the webDCS log file via the functions declared in file MsgSvc.h, typically
 3176 MSG_INFO(string message).

3177

3178 A.3 Description of the readout setup

3179 The CMS RPC setup at GIF++ counts 5 V1190A Time-to-Digital Converter (TDC) manufactured
 3180 by CAEN [94]. V1190A are VME units accepting 128 independent Multi-Hit/Multi-Event TDC
 3181 channels whose signals are treated by 4 100 ps high performance TDC chips developed by CERN
 3182 / ECP-MIC Division. The communication between the computer and the TDCs to transfer data is
 3183 done via a V1718 VME master module also manufactured by CAEN and operated from a USB
 3184 port [95]. These VME modules are all hosted into a 6U VME 6021 powered crate manufactured by
 3185 W-Ie-Ne-R than can accommodate up to 21 VME bus cards [102]. These 3 components of the DAQ
 3186 setup are shown in Figure A.1.

3187

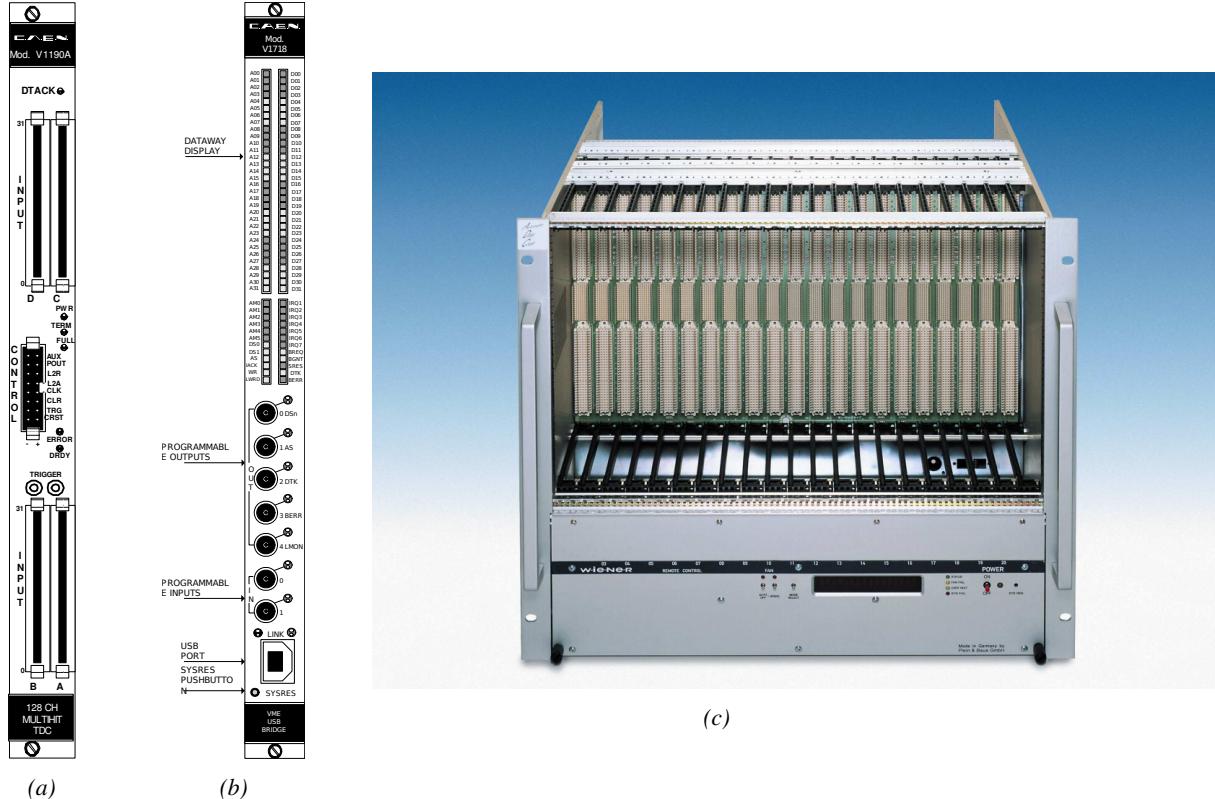


Figure A.1: (A.1a) View of the front panel of a V1190A TDC module [94]. (A.1b) View of the front panel of a V1718 Bridge module [95]. (A.1c) View of the front panel of a 6U 6021 VME crate [102].

3188

A.4 Data read-out

3189 To efficiently perform a data readout algorithm, C++ objects to handle the VME modules (TDCs
 3190 and VME bridge) have been created along with objects to store data and read the configuration file

3191 that comes as an input of the DAQ software.

3192

3193 A.4.1 V1190A TDCs

3194 The DAQ used at GIF takes profit of the *Trigger Matching Mode* offered by V1190A modules.
 3195 This setting is enabled through the method `v1190a::SetTrigMatching (int ntdcs)` where `ntdcs`
 3196 is the total number of TDCs in the setup this setting needs to be enabled for (Source Code A.1). A
 3197 trigger matching is performed in between a trigger time tag, a trigger signal sent into the TRIGGER
 3198 input of the TDC visible on Figure A.1a, and the channel time measurements, signals recorded from
 3199 the detectors under test in our case. Control over this data acquisition mode, explained through
 3200 Figure A.2, is offered via 4 programmable parameters:

- 3201 • **match window:** the matching between a trigger and a hit is done within a programmable time
 3202 window. This is set via the method
`void v1190a::SetTrigWindowWidth(Uint windowHeight, int ntdcs)`
- 3204 • **window offset:** temporal distance between the trigger tag and the start of the trigger matching
 3205 window. This is set via the method
`void v1190a::SetTrigWindowWidth(Uint windowHeight, int ntdcs)`
- 3207 • **extra search margin:** an extended time window is used to ensure that all matching hits are
 3208 found. This is set via the method
`void v1190a::SetTrigSearchMargin(Uint searchMargin, int ntdcs)`
- 3210 • **reject margin:** older hits are automatically rejected to prevent buffer overflows and to speed
 3211 up the search time. This is set via the method
`void v1190a::SetTrigRejectionMargin(Uint rejectMargin, int ntdcs)`

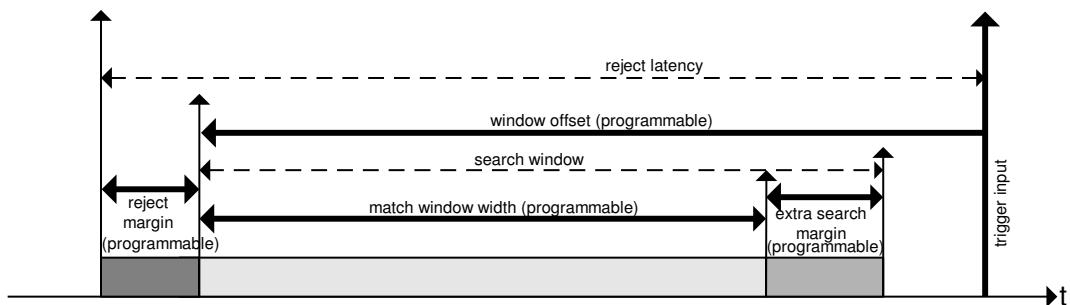


Figure A.2: Module V1190A Trigger Matching Mode timing diagram [94].

3213 Each of these 4 parameters are given in number of clocks, 1 clock being 25 ns long. It is easy to
 3214 understand at this level that there are 3 possible functioning settings:

- 3215 • **1:** the match window is entirely contained after the trigger signal,
- 3216 • **2:** the match window overlaps the trigger signal, or
- 3217 • **3:** the match window is entirely contained before the trigger signal as displayed on Figure A.2.

3218 In both the first and second cases, the sum of the window width and of the offset can be set to
3219 a maximum of 40 clocks, which corresponds to 1 μ s. Evidently, the offset can be negative, allowing
3220 for a longer match window, with the constraint of having the window ending at most 1 μ s after the
3221 trigger signal. In the third case, the maximum negative offset allowed is of 2048 clocks (12 bit) cor-
3222 responding to 51.2 μ s, the match window being strictly smaller than the offset. In the case of GIF++,
3223 the choice has been made to use this last setting by delaying the trigger signal. During the studies
3224 performed in GIF++, both the efficiency of the RPCs, probed using a muon beam, and the noise or
3225 gamma background rate are monitored. The extra search and reject margins are left unused.
3226 To probe the efficiency of RPC detectors, the trigger time tag is provided by the coïncidence of
3227 scintillators when a bunch of muons passes through GIF++ area is used to trigger the data acquisi-
3228 tion. For this measurement, it is useful to reduce the match window width only to contain the muon
3229 information. Indeed, the delay in between a trigger signal and the detection of the corresponding
3230 muon in the RPC being very contant (typically a few tens of ns due to jitter and cable length), the
3231 muon signals are very localised in time. Thus, due to a delay of approximalety 325 ns in between
3232 the muons and the trigger, the settings where chosen to have a window width of 24 clocks (600 ns)
3233 centered on the muon peak thanks to a negative offset of 29 clocks (725 ns).
3234 On the otherhand, monitoring the rates don't require for the DAQ to look at a specific time window.
3235 It is important to integrate enough time to have a robust measurement of the rate as the number of
3236 hits per time unit. The triggerring signal is provided by a pulse generator at a frequency of 300 Hz
3237 to ensure that the data taking occurs in a random way, with respect to beam physics, to probe only
3238 the irradiation spectrum on the detectors. The match window is set to 400 clocks (10 μ s) and the
3239 negative offset to 401 clocks as it needs to exceed the value of the match window.

```

3240
class v1190a
{
    private :
        long Handle;
        vector<Data32> Address;
        CVDataWidth DataWidth;
        CVAddressModifier AddressModifier;

    public:

        v1190a(long handle, IniFile *inifile, int ntdcs);
        ~v1190a();
        Data16 write_op_reg(Data32 address, int code, string error);
        Data16 read_op_reg(Data32 address, string error);
        void Reset(int ntdcs);
        void Clear(int ntdcs);
        void TestWR(Data16 value,int ntdcs);
        void CheckTDCStatus(int ntdcs);
        void CheckCommunication(int ntdcs);
        void SetTDCTestMode(Data16 mode,int ntdcs);
        void SetTrigMatching(int ntdcs);
        void SetTrigTimeSubtraction(Data16 mode,int ntdcs);
        void SetTrigWindowWidth(Uint windowHeight,int ntdcs);
        void SetTrigWindowOffset(Uint windowOffset,int ntdcs);
        void SetTrigSearchMargin(Uint searchMargin,int ntdcs);
        void SetTrigRejectionMargin(Uint rejectMargin,int ntdcs);
        void GetTrigConfiguration(int ntdcs);
        void SetTrigConfiguration(IniFile *inifile,int ntdcs);
        void SetTDCDetectionMode(Data16 mode,int ntdcs);
        void SetTDCResolution(Data16 lsb,int ntdcs);
        void SetTDCDeadTime(Data16 time,int ntdcs);
        void SetTDCHeadTrailer(Data16 mode,int ntdcs);
        void SetTDCEventSize(Data16 size,int ntdcs);
        void SwitchChannels(IniFile *inifile,int ntdcs);
        void SetIRQ(Data32 level, Data32 count,int ntdcs);
        void SetBlockTransferMode(Data16 mode,int ntdcs);
        void Set(IniFile *inifile,int ntdcs);
        void CheckStatus(CVErrorCodes status) const;
        int ReadBlockD32(Uint tdc, const Data16 address,
                           Data32 *data, const Uint words, bool ignore_berr);
        Uint Read(RAWData *DataList,int ntdcs);
};

3241

```

3242 *Source Code A.1: Description of C++ object v1190a.*

3243 The v1190a object, defined in the DAQ software as in Source Code A.1, offers the possibility to
 3244 concatenate all TDCs in the readout setup into a single object containing a list of hardware addresses
 3245 (addresses to access the TDCs' buffer through the VME crate) and each constructor and method acts
 3246 on the list of TDCs.

3247

3248 A.4.2 DataReader

3249 Enabled thanks to v1190a::SetBlockTransferMode(Data16 mode, **int** ntdcs), the data transfer
 3250 is done via Block Transfer (BLT). Using BLT allows to tranfer a fixed number of events called a
 3251 *block*. This is used together with an Almost Full Level (AFL) of the TDCs' output buffers, defined

3252 through `v1190a::SetIRQ(Data32 level, Data32 count, int ntdcs)`. This AFL gives the maximum amount of 32735 words (16 bits, corresponding to the depth of a TDC output buffer) that can
 3253 written in a buffer before an Interrupt Request (IRQ) is generated and seen by the VME Bridge,
 3254 stopping the data acquisition to transfer the content of each TDC buffers before resuming. For each
 3255 trigger, 6 words or more are written into the TDC buffer:

- 3257 • a **global header** providing information of the event number since the beginning of the data
 acquisition,
- 3259 • a **TDC header**,
- 3260 • the **TDC data** (*if any*), 1 for each hit recorded during the event, providing the channel and the
 time stamp associated to the hit,
- 3262 • a **TDC error** providing error flags,
- 3263 • a **TDC trailer**,
- 3264 • a **global trigger time tag** that provides the absolute trigger time relatively to the last reset,
 and
- 3266 • a **global trailer** providing the total word count in the event.

3267 As previously described in Section ??, CMS RPC FEEs provide us with 100 ns long LVDS output
 3268 signals that are injected into the TDCs' input. Any avalanche signal that gives a signal above the
 3269 FEEs threshold is thus recorded by the TDCs as a hit within the match window. Each hit is assigned
 3270 to a specific TDC channel with a time stamp, with a precision of 100 ps. The reference time, $t_0 = 0$,
 3271 is provided by the beginning of the match window. Thus for each trigger, coming from a scintillator
 3272 coïncidence or the pulse generator, a list of hits is stored into the TDCs' buffers and will then be
 3273 transferred into a ROOT Tree.

3274 When the BLT is used, it is easy to understand that the maximum number of words that have
 3275 been set as ALF will not be a finite number of events or, at least, the number of events that would
 3276 be recorded into the TDC buffers will not be a multiple of the block size. In the last BLT cycle to
 3277 tranfer data, the number of events to transfer will most propably be lower than the block size. In that
 3278 case, the TDC can add fillers at the end of the block but this option requires to send more data to the
 3279 computer and is thus a little slower. Another solution is to finish the transfer after the last event by
 3280 sending a bus error that states that the BLT reached the last event in the pile. This method has been
 3281 chosen in GIF++.

3283 Due to irradiation, an event in GIF++ can count up to 300 words per TDC. A limit of 4096 words
 3284 (12 bits) has been set to generate IRQ which represent from 14 to almost 700 events depending on
 3285 the average of hits collected per event. Then the block size has been set to 100 events with enabled
 3286 bus errors. When an AFL is reached for one of the TDCs, the VME bridge stops the acquisition by
 3288 sending a BUSY signal.

3289

```

3290     The data is then transferred one TDC at a time into a structure called RAWData (Source Code A.2).
3291
3292     struct RAWData{
3293         vector<int>           *EventList;
3294         vector<int>           *NHitsList;
3295         vector<int>           *QFlagList;
3296         vector<vector<int> >   *Channellist;
3297         vector<vector<float> > *TimeStampList;
3298     };

```

3293 *Source Code A.2: Description of data holding C++ structure `RAWData`.*

3294 In order to organize the data transfer and the data storage, an object called `DataReader` was
 3295 created (Source Code A.3). On one hand, it has `v1718` and `v1190a` objects as private members for
 3296 communication purposes, such as VME modules settings via the configuration file `*iniFile` or data
 3297 read-out through `v1190a::Read()` and on the other hand, it contains the structure `RAWData` that allows
 3298 to organise the data in vectors reproducing the tree structure of a ROOT file.

```

3299
3300     class DataReader
3301     {
3302         private:
3303             bool      StopFlag;
3304             IniFile *iniFile;
3305             Data32  MaxTriggers;
3306             v1718   *VME;
3307             int       nTDCs;
3308             v1190a  *TDCs;
3309             RAWData TDCData;
3310
3311         public:
3312             DataReader();
3313             virtual ~DataReader();
3314             void      SetIniFile(string inifilename);
3315             void      SetMaxTriggers();
3316             Data32  GetMaxTriggers();
3317             void      SetVME();
3318             void      SetTDC();
3319             int       GetQFlag(Uint it);
3320             void      Init(string inifilename);
3321             void      FlushBuffer();
3322             void      Update();
3323             string  GetFileName();
3324             void      WriteRunRegistry(string filename);
3325             void      Run();
3326     };

```

3301 *Source Code A.3: Description of C++ object `DataReader`.*

3302 Each event is transferred from `TDCData` and saved into branches of a ROOT `TTree` as 3 integers
 3303 that represent the event ID (`EventCount`), the number of hits read from the TDCs (`nHits`), and the
 3304 quality flag that provides information for any problem in the data transfer (`qflag`), and 2 lists of
 3305 `nHits` elements containing the fired TDC channels (`TDCCh`) and their respective time stamps (`TDCTS`),
 3306 as presented in Source Code A.4. The ROOT file file is named using information contained into
 3307 the configuration file, presented in section A.5.2. The needed information is extracted using method
 3308 `DataReader::GetFileName()` and allow to build the output filename format `ScanXXXXXX_HVX_DAQ.root`

3309 where ScanXXXXXX is a 6 digit number representing the scan number into GIFT++ database and HVX
 3310 the HV step within the scan that can be more than a single digit. An example of ROOT data file is
 3311 provided with Figure A.3.

```
3312
RAWData TDCData;
TFile *outputFile = new TFile(outputFileName.c_str(),"recreate");
TTree *RAWDataTree = new TTree("RAWData","RAWData");

int EventCount = -9;
int nHits = -8;
int qflag = -7;
vector<int> TDCCh;
vector<float> TDCTS;

RAWDataTree->Branch("EventNumber",&EventCount, "EventNumber/I");
RAWDataTree->Branch("number_of_hits",&nHits,"number_of_hits/I");
RAWDataTree->Branch("Quality_flag",&qflag,"Quality_flag/I");
RAWDataTree->Branch("TDC_channel",&TDCCh);
RAWDataTree->Branch("TDC_TimeStamp",&TDCTS);

3313
//...
//Here read the TDC data using v1190a::Read() and place it into
//TDCData for as long as you didn't collect the requested amount
//of data.
//...

for(Uint i=0; i<TDCData.EventList->size(); i++){
    EventCount = TDCData.EventList->at(i);
    nHits = TDCData.NHitsList->at(i);
    qflag = TDCData.QFlagList->at(i);
    TDCCh = TDCData.ChannelList->at(i);
    TDCTS = TDCData.TimeStampList->at(i);
    RAWDataTree->Fill();
}
```

3314 *Source Code A.4: Highlight of the data transfer and organisation within DataReader::Run() after the data has been collected into TDCData.*

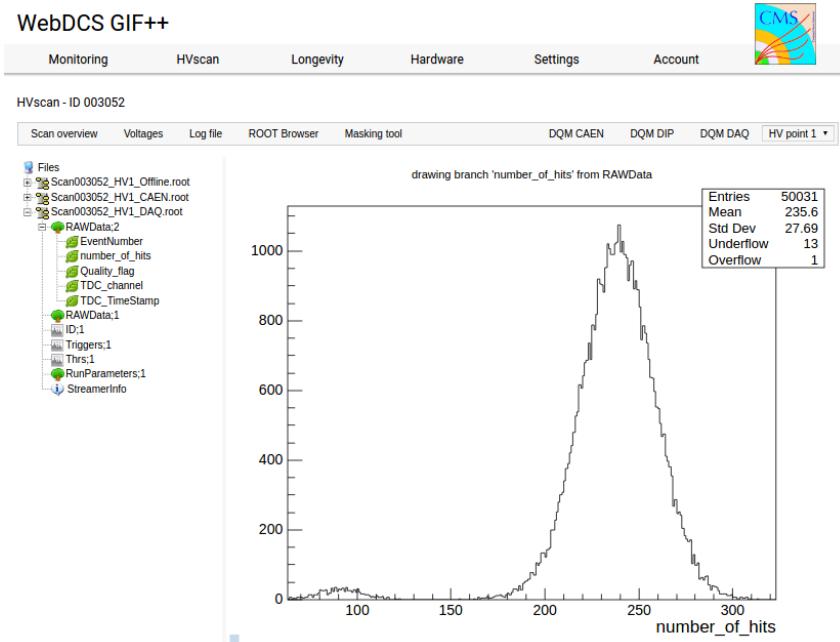


Figure A.3: Structure of the ROOT output file generated by the DAQ. The 5 branches (EventNumber, number_of_hits, Quality_flag, TDC_channel and TDC_TimeStamp) are visible on the left panel of the ROOT browser. On the right panel is visible the histogram corresponding to the variable nHits. In this specific example, there were approximately 50k events recorded to measure the gamma irradiation rate on the detectors. Each event is stored as a single entry in the TTree.

3315 A.4.3 Data quality flag

3316 Among the parameters that are recorded for each event, the quality flag, defined in Source Code A.5,
 3317 is determined on the fly by checking the data recorded by every single TDC. From method `v1190a::Read()`,
 3318 it can be understood that the content of each TDC buffer is readout one TDC at a time. Entries are
 3319 created in the data list for the first TDC and then, when the second buffer is readout, events corre-
 3320 sponding to entries that have already been created to store data for the previous TDC are added to
 3321 the existing list element. On the contrary, when an event entry has not been yet created in the data
 3322 list, a new entry is created.

```
3323
typedef enum _QualityFlag {
 3324   GOOD      = 1,
   CORRUPTED = 0
} QualityFlag;
```

3325 *Source Code A.5: Definition of the quality flag `enum`.*

3326 It is possible that each TDC buffer contains a different number of events. In cases where the first
 3327 element in the buffer list is an event for corresponds to a new entry, the difference in between the
 3328 entry from the buffer and the last entry in the data list is recorded and checked. If it is greater than 1,
 3329 what should never be the case, the quality flag is set to CORRUPTED for this TDC and an empty entry
 3330 is created in the place of the missing ones. Missing entries are believe to be the result of a bad hold

3331 on the TDC buffers at the moment of the readout. Indeed, the software hold is effective only on 1
 3332 TDC at a time and no solution as been found yet to completely block the writting in the buffers when
 3333 an IRQ is received.

3334 At the end of each BLT cycle, the ID of the last entry stored for each TDC buffer is not recorded.
 3335 When starting the next cycle, if the first entry in the pile corresponds to an event already existing
 3336 in the list, the readout will start from this list element and will not be able to check the difference
 3337 in between this entry's ID and the one of the last entry that was recorded for this TDC buffer in
 3338 the previous cycle. In the case events were missing, the flag stays at its initial value of 0, which is
 3339 similar to CORRUPTED and it is assumed that then this TDC will not contribute to `number_of_hits`,
 3340 `TDC_channel` or `TDC_TimeStamp`.

3341 Finally, since there will be 1 `RAWData` entry per TDC for each event (meaning `nTDCs` entries,
 3342 referring to `DataReader` private attribute), the individual flags of each TDC will be added together.
 3343 The final format is an integer composed `nTDCs` digits where each digit is the flag of a specific TDC.
 3344 This is constructed using powers of 10 like follows:

```
3345     TDC 0: QFlag = 100 × _QualityFlag
3346     TDC 1: QFlag = 101 × _QualityFlag
3347     ...
3348     TDC N: QFlag = 10N × _QualityFlag
```

3349 and the final flag to be with N digits:

```
3350     QFlag = n....3210
```

3351 each digit being 1 or 0. Below is given an example with a 4 TDCs setup.

```
3352     If all TDCs were good : QFlag = 1111,
3353     but if TDC 2 was corrupted : QFlag = 1011.
```

3354 When data taking is over and the data contained in the dynamical `RAWData` structure is transferred
 3355 to the ROOT file, all the 0s are changed into 2s by calling the method `DataReader::GetQFlag()`.
 3356 This will help translating the flag without knowing the number of TDCs beforehand. Indeed, a flag
 3357 111 could be due to a 3 TDC setup with 3 good individual TDC flags or to a more than 3 TDC setup
 3358 with TDCs those ID is greater than 2 being CORRUPTED, thus giving a 0.

3359 The quality flag has been introduced quite late, in October 2017 only, to the list of GIFT++ DAQ
 3360 parameters to be recorded into the output ROOT file. Before this addition, the missing data, corrupting
 3361 the quality for the offline analysis, was contributing to artificially fill data with lower multiplicity.
 3362 Looking at `TBranch number_of_hits` provides an information about the data of the full GIFT++
 3363 setup. When a TDC is not able to transfer data for a specific event, the effect is a reduction of the
 3364 total number of hits recorded in the full setup, this is what can be seen from Figure A.4. After offline
 3365 reconstruction detector by detector, the effect of missing events can be seen in the artificially filled
 3366 bin at multiplicity 0 shown in Figure A.5. Nonetheless, for data with high irradiation levels, as it is
 3367 the case for Figure A.5a, discarding the fake multiplicity 0 data can be done easily during the offline
 3368 analysis. At lower radiation, the missing events contribution becomes more problematic as the multi-
 3369 tiplicity distribution overlaps the multiplicity 0 and that in the same time the proportion of missing

3370 events decreases. Attempts to fit the distribution with a Poisson or skew distribution function were
 3371 not conclusive and this very problem has been at the origin of the quality flag that allows to give a
 3372 non ambiguous information about each event quality.

3373

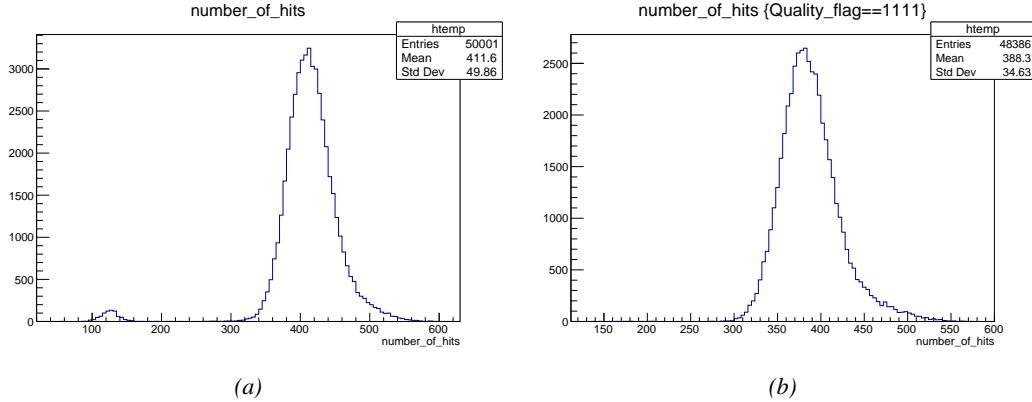


Figure A.4: The effect of the quality flag is explained by presenting the content of TBranch `number_of_hits` of a data file without `Quality_flag` in Figure A.4a and the content of the same TBranch for data corresponding to a `Quality_flag` where all TDCs were labelled as `GOOD` in Figure A.4b taken with similar conditions. It can be noted that the number of entries in Figure A.4b is slightly lower than in Figure A.4a due to the excluded events.

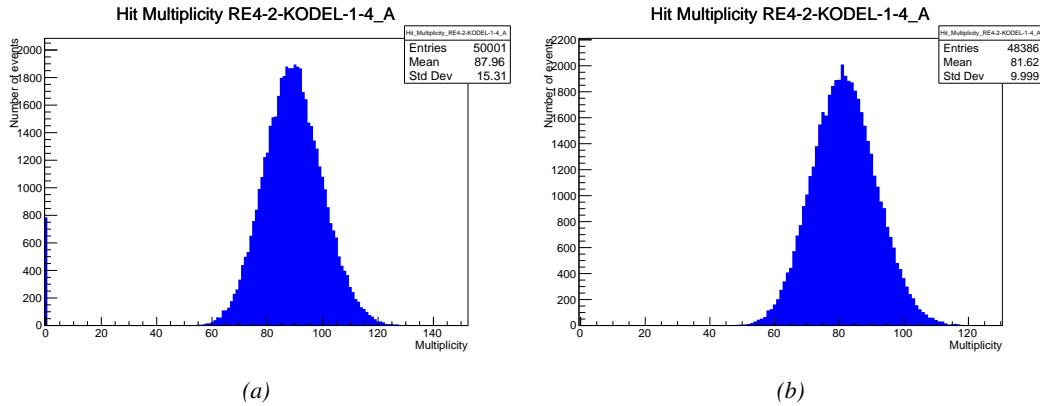


Figure A.5: Using the same data as previously showed in Figure A.4, the effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without `Quality_flag` in Figure A.5a and the reconstructed content of the same RPC partition for data corresponding to a `Quality_flag` where all TDCs were labelled as `GOOD` in Figure A.5b taken with similar conditions. The artificial high content of bin 0 is completely suppressed.

A.5 Communications

3374 To ensure data readout and dialog in between the machine and the TDCs or in between the webDCS
 3375 and the DAQ, different communication solutions were used. First of all, it is important to have a

3377 module to allow the communication in between the TDCs and the computer from which the DAQ
 3378 operates. When this communication is effective, shifters using the webDCS to control data taking
 3379 can thus send instructions to the DAQ.

3380

3381 A.5.1 V1718 USB Bridge

3382 In the previous section, the data transfer has been discussed. The importance of the `v1718` object
 3383 (Source Code A.6), used as private member of `DataReader`, was not explicated. VME master
 3384 modules are used for communication purposes as they host the USB port that connects the pow-
 3385 ered crate buffer to the computer where the DAQ is installed. From the source code point of view,
 3386 this object is used to control the communication status, by reading the returned error codes with
 3387 `v1718::CheckStatus()`, or to check for IRQs coming from the TDCs through `v1718::CheckIRQ()`.
 3388 Finally, to ensure that triggers are blocked at the hardware level, a NIM pulse is sent out of one of the
 3389 5 programmable outputs (`v1718::SendBUSY()`) to the VETO of the coincidence module where the
 3390 trigger signals originate from. As long as this signal is ON, no trigger can reach the TDCs anymore.
 3391

```
3392   class v1718{
3393     private:
3394       int           Handle;
3395       Data32        Data;          // Data
3396       CVIRQLevels  Level;        // Interrupt level
3397       CVAddressModifier AM;        // Addressing Mode
3398       CVDataWidth   DataSize;      // Data Format
3399       Data32        BaseAddress;  // Base Address
3400
3401     public:
3402       v1718(IniFile *inifile);
3403       ~v1718();
3404       long          GetHandle(void) const;
3405       int           SetData(Data16 data);
3406       Data16        GetData(void);
3407       int           SetLevel(CVIRQLevels level);
3408       CVIRQLevels  GetLevel(void);
3409       int           SetAM(CVAddressModifier am);
3410       CVAddressModifier GetAM(void);
3411       int           SetDatasize(CVDataWidth datasize);
3412       CVDataWidth   GetDataSize(void);
3413       int           SetBaseAddress(Data16 baseaddress);
3414       Data16        GetBaseAddress(void);
3415       void          CheckStatus(CVErrorCodes status) const;
3416       void          CheckIRQ();
3417       void          SetPulsers();
3418       void          SendBUSY(BusyLevel level);
3419   };
3420
```

3421 *Source Code A.6: Description of C++ object v1718.*

3422 A.5.2 Configuration file

3423 The DAQ software takes as input a configuration file written using INI standard [103]. This file is
 3424 partly filled with the information provided by the shifters when starting data acquisition using the
 3425 webDCS, as shown by Figure A.6. This information is written in section [`General`] and will later

3398 be stored in the ROOT file that contains the DAQ data as can be seen from Figure A.3. Indeed,
 3399 another `TTree` called `RunParameters` as well as the 2 histograms `ID`, containing the scan number,
 3400 start and stop time stamps, and `Triggers`, containing the number of triggers requested by the shifter,
 3401 are available in the data files. Moreover, `ScanID` and `HV` are then used to construct the file name
 3402 thanks to the method `DataReader::GetFileName()`.

WebDCS GIF++

Chamber	RE2-2-NPD-BARC-8	RE4-2-CERN-106	RE2-3-NPD-BARC-9	RE4-2-CERN-105	RE4-2-KODEL-1-4	Max triggers
HV _{eff} 1	8600	8500	8600	8500	6500	
HV _{eff} 2	8700	8600	8700	8600	6600	
HV _{eff} 3	8800	8700	8800	8700	6700	
HV _{eff} 4	8900	8800	8900	8800	6800	
HV _{eff} 5	9000	8900	9000	8900	6900	
HV _{eff} 6	9100	9000	9100	9000	7000	
HV _{eff} 7	9200	9100	9200	9100	7100	
HV _{eff} 8	9300	9200	9300	9200	7200	
HV _{eff} 9	9400	9300	9400	9300	7300	
HV _{eff} 10	9500	9400	9500	9400	7400	

Start HV scan

Figure A.6: WebDCS DAQ scan page. On this page, shifters need to choose the type of scan (Rate, Efficiency or Noise Reference scan), the gamma source configuration at the moment of data taking, the beam configuration, and the trigger mode. These information will be stored in the DAQ ROOT output. Are also given the minimal measurement time and waiting time after ramping up of the detectors is over before starting the data acquisition. Then, the list of HV points to scan and the number of triggers for each run of the scan are given in the table underneath.

3403 The rest of the information is written beforehand in the configuration file template, as explicated
 3404 in Source Code A.7, and contains the hardware addresses to the different VME modules in the
 3405 setup as well as settings for the TDCs. As the TDC settings available in the configuration file are not
 3406 supposed to be modified, an improvement would be to remove them from the configuration file and
 3407 to hardcode them inside of the DAQ code itself or to place them into a different INI file that would
 3408 host only the TDC settings to lower the probability for a bad manipulation of the configuration file
 3409 that can be modified from one of webDCS' menus.

```
3410 [General]
Tdcs=4
ScanID=$scanid
HV=$HV
RunType=$runtype
MaxTriggers=$maxtriggers
Beam=$beam
[VMEInterface]
Type=V1718
BaseAddress=0xFF0000
Name=VmeInterface
[TDC0]
Type=V1190A
BaseAddress=0x00000000
Name=Tdc0
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1
[TDC1]
Type=V1190A
BaseAddress=0x11110000
Name=Tdc1
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1
3411 [TDC2]
Type=V1190A
BaseAddress=0x22220000
Name=Tdc2
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1
[TDC3]
Type=V1190A
BaseAddress=0x44440000
Name=Tdc3
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1
[TDCSettings]
TriggerExtraSearchMargin=0
TriggerRejectMargin=0
TriggerTimeSubstraction=0b1
TdcDetectionMode=0b01
TdcResolution=0b10
TdcDeadTime=0b00
TdcHeadTrailer=0b1
TdcEventSize=0b1001
TdcTestMode=0b0
BLTMode=1
```

Source Code A.7: INI configuration file template for 4 TDCs. In section [General], the number of TDCs is explicitated and information about the ongoing run is given. Then, there are sections for each and every VME modules. There buffer addresses are given and for the TDCs, the list of channels to enable is given. Finally, in section [TDCSettings], a part of the TDC settings are given.

3413 In order to retrieve the information of the configuration file, the object `IniFile` has been developed
 3414 to provide an INI parser, presented in Source Code A.8. It contains private methods returning a
 3415 boolean to check the type of line written in the file, whether a comment, a group header or a key line
 3416 (`IniFile::CheckIfComment()`, `IniFile::CheckIfGroup()` and `IniFile::CheckIfToken()`). The
 3417 key may sometimes be referred to as *token* in the source code. Moreover, the private element
 3418 `FileData` is a map of `const string` to `string` that allows to store the data contained inside the
 3419 configuration file via the public method `IniFile::GetFileData()` following the formatting (see
 3420 method `IniFile::Read()`):

```
3421
  3422     string group, token, value;
  // Get the field values for the 3 strings.
  // Then concatenate group and token together as a single string
  // with a dot separation.
  token = group + "." + token;
  FileData[token] = value;
```

3423 More methods have been written to translate the different keys into the right variable format
 3424 when used by the DAQ. For example, to get a `float` value out of the configuration file data, knowing
 3425 the group and the key needed, the method `IniFile::floatType()` can be used. It takes 3 arguments
 3426 being the group name and key name (both `string`), and a default `float` value used as exception in
 3427 the case the expected combination of group and key cannot be found in the configuration file. This
 3428 default value is then used and the DAQ continues on working after sending an alert in the log file for
 3429 further debugging.

```

3430 typedef map< const string, string > IniFileData;

class IniFile{
    private:
        bool          CheckIfComment (string line);
        bool          CheckIfGroup(string line, string& group);
        bool          CheckIfToken(string line, string& key, string& value);
        string         FileName;
        IniFileData   FileData;
        int           Error;

    public:
        IniFile();
        IniFile(string filename);
        virtual      ~IniFile();

        // Basic file operations
        void          SetFileName(string filename);
        int           Read();
        int           Write();
        IniFileData   GetFileData();

        // Data readout methods
        Data32         addressType (string groupname, string keyname, Data32
→ defaultvalue);
        long          intType     (string groupname, string keyname, long
→ defaultvalue);
        long long    longType    (string groupname, string keyname, long long
→ defaultvalue );
        string         stringType  (string groupname, string keyname, string
→ defaultvalue );
        float         floatType   (string groupname, string keyname, float
→ defaultvalue );

        // Error methods
        string         GetErrorMsg();
};

3431

```

3432 *Source Code A.8: Description of C++ object `IniFile` used as a parser for INI file format.*

3433 A.5.3 WebDCS/DAQ intercommunication

3434 When shifters send instructions to the DAQ via the configuration file, it is the webDCS itself that
 3435 gives the start command to the DAQ and then the 2 softwares use inter-process communication
 3436 through file to synchronise themselves. This communication file is represented by the variable **const**
 3437 **string** __runstatuspath.

3438 On one side, the webDCS sends commands or status that are readout by the DAQ:

- 3439 ● INIT, status sent when launching a scan and read via function `CtrlRunStatus(...)`,
- 3440 ● START, command to start data taking and read via function `CheckSTART()`,
- 3441 ● STOP, command to stop data taking at the end of the scan and read via function `CheckSTOP()`,
 3442 and
- 3443 ● KILL, command to kill data taking sent by user and read via function `CheckKILL()`

3444 and on the other, the DAQ sends status that are controled by the webDCS:

- 3445 ● DAQ_RDY, sent with `SendDAQReady()` to signify that the DAQ is ready to receive commands
 3446 from the webDCS,
- 3447 ● RUNNING, sent with `SendDAQRunning()` to signify that the DAQ is taking data,
- 3448 ● DAQ_ERR, sent with `SendDAQError()` to signify that the DAQ didn't receive the expected com-
 3449 mand from the webDCS or that the launch command didn't have the right number of argu-
 3450 ments,
- 3451 ● RD_ERR, sent when the DAQ wasn't able to read the communication file, and
- 3452 ● WR_ERR, sent when the DAQ wasn't able to write into the communication file.

3453 **A.5.4 Example of inter-process communication cycle**

3454 Under normal conditions, the webDCS and the DAQ processes exchange commands and status via
 3455 the file hosted at the address `__runstatuspath`, as explained in subsection A.5.3. An example of
 3456 cycle is given in Table A.1. In this example, the steps 3 to 5 are repeated as long as the webDCS tells
 3457 the DAQ to take data. A data taking cycle is the equivalent as what is called a *Scan* in GIFT++ jargon,
 3458 referring to a set a runs with several HV steps. Each repetition of steps 3 to 5 is then equivalent to a
 3459 single *Run*.

3460
 3461 At any moment during the data taking, for any reason, the shifter can decide that the data taking
 3462 needs to be stopped before it reached the end of the scheduled cycle. Thus at any moment on the
 3463 cycle, the content of the inter-process communication file will be changed to `KILL` and the DAQ will
 3464 shut down right away. The DAQ checks for `KILL` signals every 5s after the TDCs configuration is
 3465 over. So far, the function `CheckKILL()` has been used only inside of the data taking loop of method
 3466 `DataReader::Run()` and thus, if the shifter decides to KILL the data taking during the TDC con-
 3467 figuration phase or the HV ramping in between 2 HV steps, the DAQ will not be stopped smoothly
 3468 and a *force kill* command will be sent to stop the DAQ process that is still awake on the computer.
 3469 Improvements can be brought on this part of the software to make sure that the DAQ can safely
 3470 shutdown at any moment.

3472 **A.6 Software export**

3473 In section A.2 was discussed the fact that the DAQ as written in its last version is not a standalone
 3474 software. It is possible to make it a standalone program that could be adapted to any VME setup
 3475 using V1190A and V1718 modules by creating a GUI for the software or by printing the log mes-
 3476 sages that are normally printed in the webDCS through the log file, directly into the terminal. This
 3477 method was used by the DAQ up to version 3.0 moment where the webDCS was completed. Also, it
 3478 is possible to check branches of DAQ v2.X to have example of communication through a terminal.

3479
 3480 DAQ v2.X is nonetheless limited in it's possibilities and requires a lot of offline manual interven-
 3481 tions from the users. Indeed, there is no communication of the software with the detectors' power
 3482 supply system that would allow for a user a predefine a list of voltages to operate the detectors at

step	actions of webDCS	status of DAQ	__runstatuspath
1	launch DAQ ramp voltages ramping over wait for currents stabilization	readout of IniFile configuration of TDCs	INIT
2		configuration done send DAQ ready wait for START signal	DAQ_RDY
3	waiting time over send START		START
4	wait for run to end monitor DAQ run status	data taking ongoing check for KILL signal	RUNNING
5		run over send DAQ_RDY wait for next DCS signal	DAQ_RDY
6	ramp voltages ramping over wait for currents stabilization		DAQ_RDY
3	waiting time over send START		START
4	wait for run to end monitor DAQ run status	update IniFile information data taking ongoing check for KILL signal	RUNNING
5		run over send DAQ_RDY wait for next DCS signal	DAQ_RDY
7	send command STOP	DAQ shuts down	STOP

Table A.1: Inter-process communication cycles in between the webDCS and the DAQ through file string signals.

3483 and loop over to take data without any further manual intervention. In v2.X, the data is taken for a
3484 single detector setting and at the end of each run, the softwares asks the user if he intends on taking
3485 more runs. If so, the software invites the user to set the operating voltages accordingly to what is
3486 necessary and to manual update the configuration file in consequence. This working mode can be a
3487 very first approach before an evolution and has been successfully used by colleagues from different
3488 collaborations.

3489
3490 For a more robust operation, it is recommended to develop a GUI or a web application to inter-
3491 face the DAQ. Moreover, to limit the amount of manual interventions, and thus the probability to
3492 make mistakes, it is also recommended to add an extra feature into the DAQ by installing the HV
3493 Wrapper library provided by CAEN of which an example of use in a similar DAQ software devel-
3494 opped by a master student of UGent, and called TinyDAQ, is provided on UGent's github. Then, this
3495 HV Wrapper will help you communicating with and give instructions to a CAEN HV powered crate
3496 and can be added into the DAQ at the same level where the communication with the user was made
3497 in DAQ v2.X. In case you are using another kind of power system for your detectors, it is stringly
3498 adviced to use HV modules or crates that can be remotely controled via a using C++ libraries.
3499

B

3500

3501

Details on the offline analysis package

3502 The data collected in GIF++ thanks to the DAQ described in Appendix A is difficult to interpret by
3503 a human user that doesn't have a clear idea of the raw data architecture of the ROOT data files. In
3504 order to render the data human readable, a C++ offline analysis tool was designed to provide users
3505 with detector by detector histograms that give a clear overview of the parameters monitored during
3506 the data acquisition [104]. In this appendix, details about this software in the context of GIF++, as
3507 of how the software was written and how it functions will be given.

3508 B.1 GIF++ Offline Analysis file tree

3509 GIF++ Offline Analysis source code is fully available on github at https://github.com/aafagot/GIF_OfflineAnalysis. The software requires ROOT as non-optionnal dependency
3510 as it takes ROOT files in input and write an output ROOT file containing histograms. To compile the
3511 GIF++ Offline Analysis project is compiled with cmake. To compile, first a build/ directory must
3512 be created to compile from there:

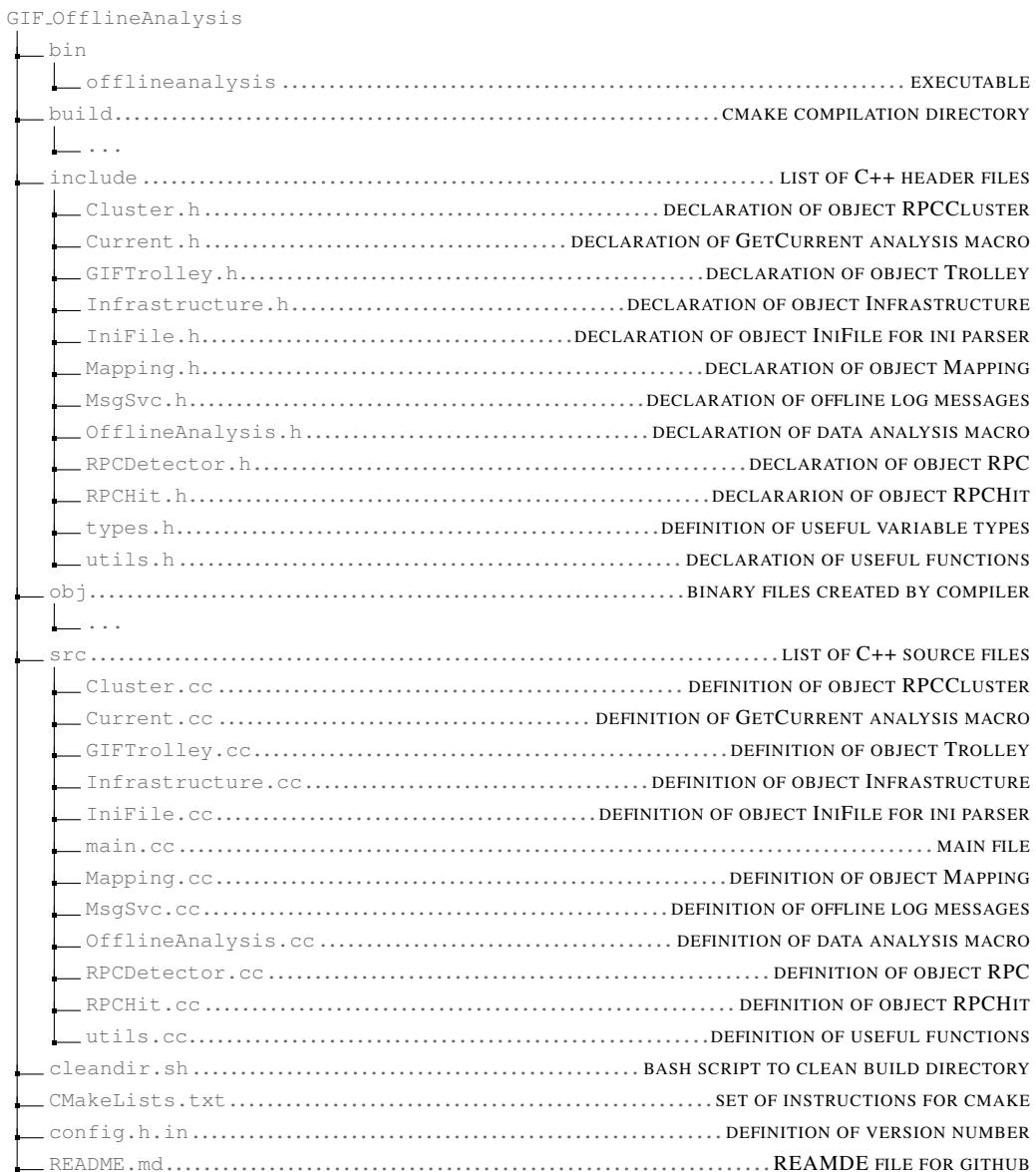
```
3514 mkdir build
3515 cd build
3516 cmake ..
3517 make
3518 make install
```

3516 To clean the directory and create a new build directory, the bash script cleandir.sh can be used:

```
3517
3518 ./cleandir.sh
```

3519 The source code tree is provided below along with comments to give an overview of the files' con-
3520 tent. The different objects created for this project (`Infrastructure`, `Trolley`, `RPC`, `Mapping`, `RPCHit`,
3521 `RPCCluster` and `Inifile`) will be described in details in the following sections.

3522



3523

B.2 Usage of the Offline Analysis

3524
3525

In order to use the Offline Analysis tool, it is necessary to know the Scan number and the HV Step of the run that needs to be analysed. This information needs to be written in the following format:

3526
3527

```
Scan00XXXX_HVY
```

3528
3529

where XXXX is the scan ID and Y is the high voltage step (in case of a high voltage scan, data will be taken for several HV steps). This format corresponds to the base name of data files in the database

3530 of the GIF++ webDCS. Usually, the offline analysis tool is automatically called by the webDCS at
 3531 the end of data taking or by a user from the webDCS panel if an update of the tool was brought.
 3532 Nonetheless, an expert can locally launch the analysis for tests on the GIF++ computer, or a user can
 3533 get the code on its local machine from github and download data from the webDCS for its own anal-
 3534 ysis. To launch the code, the following command can be used from the `GIF_OfflineAnalysis` folder:

3535
 3536 `bin/offlineanalysis /path/to/Scan00XXXX_HVY`

3537 where, `/path/to/Scan00XXXX_HVY` refers to the local data files. Then, the offline tool will by itself
 3538 take care of finding all available ROOT data files present in the folder, as listed below:

- 3539
 - 3540 ● `Scan00XXXX_HVY_DAQ.root` containing the TDC data as described in Appendix ?? (events, hit
 and timestamp lists), and
 - 3541 ● `Scan00XXXX_HVY_CAEN.root` containing the CAEN mainframe data recorded by the monitor-
 ing tool webDCS during data taking (HVs and currents of every HV channels). This file is
 created independently of the DAQ.

3544 **B.2.1 Output of the offline tool**

3545 **B.2.1.1 ROOT file**

3546 The analysis gives in output ROOT datafiles that are saved into the data folder and called using the
 3547 naming convention `Scan00XXXX_HVY_Offline.root`. Inside those, a list of `TH1` histograms can be
 3548 found. Its size will vary as a function of the number of detectors in the setup as each set of histograms
 3549 is produced detector by detector. For each partition of each chamber, can be found:

- 3550
 - 3551 ● `Time_Profile_Tt_Sc_p` shows the time profile of all recorded events (number of events per
 time bin),
 - 3552 ● `Hit_Profile_Tt_Sc_p` shows the hit profile of all recorded events (number of events per chan-
 nel),
 - 3554 ● `Hit_Multiplicity_Tt_Sc_p` shows the hit multiplicity (number of hits per event) of all recorded
 events (number of occurrences per multiplicity bin),
 - 3556 ● `Strip_Mean_Noise_Tt_Sc_p` shows noise/gamma rate per unit area for each strip in a se-
 lected time range. After filters are applied on `Time_Profile_Tt_Sc_p`, the filtered version
 of `Hit_Profile_Tt_Sc_p` is normalised to the total integrated time and active detection area
 of a single channel,
 - 3560 ● `Strip_Activity_Tt_Sc_p` shows noise/gamma activity for each strip (normalised version of
 previous histogram - strip activity = strip rate / average partition rate),
 - 3562 ● `Strip_Homogeneity_Tt_Sc_p` shows the *homogeneity* of a given partition ($\text{homogeneity} = \exp(-\text{strip rates standard deviation(strip rates in partition/average partition rate)})$),
 - 3564 ● `mask_Strip_Mean_Noise_Tt_Sc_p` shows noise/gamma rate per unit area for each masked
 strip in a selected time range. Offline, the user can control the noise/gamma rate and decide to
 mask the strips that are judged to be noisy or dead. This is done via the *Masking Tool* provided
 by the webDCS,

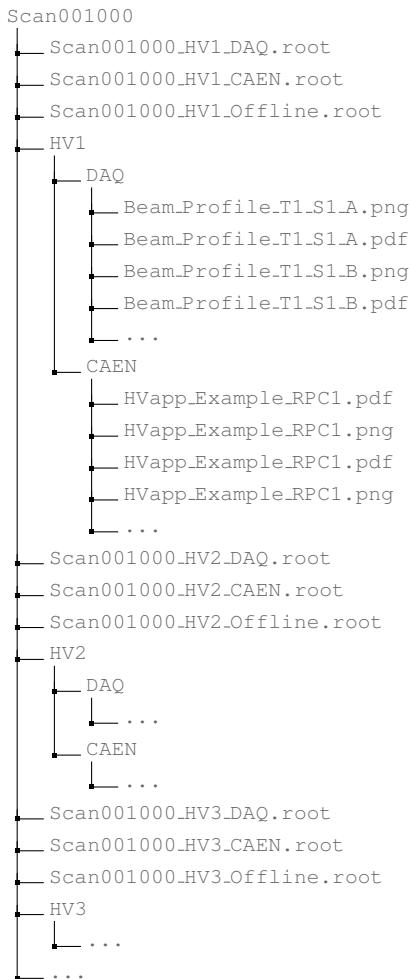
- 3568 ● `mask_Strip_Activity_Tt_Sc_p` shows noise/gamma activity per unit area for each masked
3569 strip with respect to the average rate of active strips,
- 3570 ● `NoiseCSize_H_Tt_Sc_p` shows noise/gamma cluster size, a cluster being constructed out of
3571 adjacent strips giving a signal at the *same time* (hits within a time window of 25 ns),
- 3572 ● `NoiseCMult_H_Tt_Sc_p` shows noise/gamma cluster multiplicity (number of reconstructed
3573 clusters per event),
- 3574 ● `Chip_Mean_Noise_Tt_Sc_p` shows the same information than `Strip_Mean_Noise_Tt_Scp` us-
3575 ing a different binning (1 chip corresponds to 8 strips),
- 3576 ● `Chip_Activity_Tt_Sc_p` shows the same information than `Strip_Activity_Tt_Scp` using
3577 chip binning,
- 3578 ● `Chip_Homogeneity_Tt_Sc_p` shows the homogeneity of a given partition using chip binning,
- 3579 ● `Beam_Profile_Tt_Sc_p` shows the estimated beam profile when taking efficiency scan. This
3580 is obtained by filtering `Time_Profile_Tt_Sc_p` to only consider the muon peak where the
3581 noise/gamma background has been subtracted. The resulting hit profile corresponds to the
3582 beam profile on the detector channels,
- 3583 ● `L0_Efficiency_Tt_Sc_p` shows the level 0 efficiency that was estimated **without** muon track-
3584 ing,
- 3585 ● `MuonCSize_H_Tt_Sc_p` shows the level 0 muon cluster size that was estimated **without** muon
3586 tracking, and
- 3587 ● `MuonCMult_H_Tt_Sc_p` shows the level 0 muon cluster multiplicity that was estimated **without**
3588 muon tracking.

3589 In the histogram labels, t stands for the trolley number (1 or 3), c for the chamber slot label in
3590 trolley t and p for the partition label (A, B, C or D depending on the chamber layout) as explained
3591 in Chapter 5.3.

3592 In the context of GIF++, an extra script called by the webDCS is called to extract the histograms
3593 from the ROOT files. The histograms are then stored in PNG and PDF formats into the correspond-
3594 ing folder (a single folder per HV step, so per ROOT file). the goal is to then display the histograms
3595 on the Data Quality Monitoring (DQM) page of the webDCS in order for the users to control the
3596 quality of the data taking at the end of data taking. An example of histogram organisation is given
3597 below:

3598

3599



3600 *Here can put some screens from the webDCS to show the DQM and the plots available to users.*
 3601

3602 **B.2.1.2 CSV files**

3603 Moreover, up to 3 CSV files can be created depending on which ones of the 3 input files were in the
 3604 data folder:

- 3605 • `Offline-Corrupted.csv` , is used to keep track of the amount of data that was corrupted and
 3606 removed from old data format files that don't contain any data quality flag.
- 3607 • `Offline-Current.csv` , contains the summary of the currents and voltages applied on each
 3608 RPC HV channel.
- 3609 • `Offline-L0-EffC1.csv` , is used to write the efficiencies, cluster size and cluster multiplicity
 3610 of efficiency runs. Note that `L0` refers here to *Level 0* and means that the results of efficiency and
 3611 clusterization are a first approximation calculated without performing any muon tracking in

3612 between the different detectors. This offline tool provides the user with a preliminar calculation
 3613 of the efficiency and of the muon event parameters. Another analysis software especially
 3614 dedicated to muon tracking is called on selected data to retrieve the results of efficiency and
 3615 muon clusterization using a tracking algorithm to discriminate noise or gamma from muons
 3616 as muons are the only particles that pass through the full setup, leaving hits than can be used
 3617 to reconstruct their tracks.

- 3618 ● `Offline-Rate.csv`, is used to write the noise or gamma rates measured in the detector readout
 3619 partitions.

3620 Note that these 4 CSV files are created along with their *headers* (`Offline-[...]-Header.csv`
 3621 containing the names of each data columns) and are automatically merged together when the offline
 3622 analysis tool is called from the webDCS, contrary to the case where the tool is runned locally from
 3623 the terminal as the merging bash script is then not called. Thus, the resulting files, used to make
 3624 official plots, are:

- 3625 ● `Corrupted.csv`,
 3626 ● `Current.csv`,
 3627 ● `L0-EffCl.csv`.
 3628 ● `Rate.csv`.

3629 **B.3 Analysis inputs and information handling**

3630 The usage of the Offline Analysis tool as well as its output have been presented in the previous section.
 3631 It is now important to dig further and start looking at the source code and the inputs necessary
 3632 for the tool to work. Indeed, other than the raw ROOT data files that are analysed, more information
 3633 needs to be imported inside of the program to perform the analysis such as the description of the
 3634 setup inside of `GIF++` at the time of data taking (number of trolleys, of RPCs, dimensions of the
 3635 detectors, etc...) or the mapping that links the TDC channels to the coresponding RPC channels in
 3636 order to translate the TDC information into human readable data. 2 files are used to transmit all this
 3637 information:
 3638

- 3639 ● `Dimensions.ini`, that provides the necessary setup and RPC information, and
 3640 ● `ChannelsMapping.csv`, that gives the link between the TDC and RPC channels as well as the
 3641 *mask* for each channel (masked or not?).

3642 **B.3.1 Dimensions file and InFile parser**

3643 This input file, present in every data folder, allows the analysis tool to know of the number of active
 3644 trolleys, the number of active RPCs in those trolleys, and the details about each RPCs such as
 3645 the number of RPC gaps, the number of pseudo-rapidity partitions (for CMS-like prototypes), the
 3646 number of strips per partion or the dimensions. To do so, there are 3 types of groups in the INI file
 3647 architecture. A first general group, appearing only once at the head of the document, gives information
 3648 about the number of active trolleys as well as their IDs, as presented in Source Code B.1. For

3649 each active trolley, a group similar to Source Code B.2 can be found containing information about
 3650 the number of active detectors in the trolley and their IDs. Each trolley group as a `Tt` name format,
 3651 where `t` is the trolley ID. Finally, for each detector stored in slots of an active trolley, there is a group
 3652 providing information about their names and dimensions, as shown in Source Code B.3. Each slot
 3653 group as a `TtSs` name format, where `s` is the slot ID of trolley `t` where the active RPC is hosted.

```
3654 [General]
3655 nTrolleys=2
  TrolleysID=13
```

3656 *Source Code B.1: Example of `[General]` group as might be found in `Dimensions.ini`. In Gif++, only 2 trolleys are available to hold RPCs and place them inside of the bunker for irradiation. The IDs of the trolleys are written in a single string as "13" and then read character by character by the program.*

```
3657 [T1]
  nSlots=4
  SlotsID=1234
```

3658 *Source Code B.2: Example of trolley group as might be found in `Dimensions.ini`. In this example, the file tells that there are 4 detectors placed in the holding slots of the trolley `T1` and that their IDs, written as a single string variable, are 1, 2, 3 and 4.*

```
3659 [T1S1]
  Name=RE2-2-NPD-BARC-8
  Partitions=3
  Gaps=3
  Gap1=BOT
  Gap2=TN
  Gap3=TW
  AreaGap1=11694.25
  AreaGap2=6432
  AreaGap3=4582.82
  Strips=32
  ActiveArea-A=157.8
  ActiveArea-B=121.69
  ActiveArea-C=93.03
```

3660 *Source Code B.3: Example of slot group as might be found in `Dimensions.ini`. In this example, the file provides information about a detector named `RE2-2-NPD-BARC-8`, having 3 pseudo-rapidity readout partitions and stored in slot `S1` of trolley `T1`. This is a CMS RE2-2 type of detector. This information will then be used for example to compute the rate per unit area calculation.*

3661 This information is readout and stored in a C++ object called `IniFile`, that parses the information
 3662 in the INI input file and stores it into a local buffer for later use. This INI parser is the exact same
 3663 one that was previously developed for the Gif++ DAQ and described in Appendix A.5.2.

3664 B.3.2 TDC to RPC link file and Mapping

3665 The same way the INI dimension file information is stored using `map`, the channel mapping and mask
 3666 information is stored and accessed through `map`. First of all, the mapping CSV file is organised into
 3667 3 columns separated by tabulations (and not by commas, as expected for CSV files as it is easier using
 3668 streams to read tab or space separated data using C++):

3669

3670 RPC_channel TDC_channel mask

3671 using as formatting for each field:

3672

3673	TSCCC	TCCC	M
------	-------	------	---

3674 TSCCC is a 5-digit integer where τ is the trolley ID, s the slot ID in which the RPC is held insite
 3675 the trolley τ and ccc is the RPC channel number, or *strip* number, that can take values up to
 3676 3-digits depending on the detector,

3677 TCCC is a 4 digit integer where τ is the TDC ID, ccc is the TDC channel number that can take values
 3678 in between 0 and 127, and

3679 M is a 1-digit integer indicating if the channel should be considered ($M = 1$) or discarded ($M = 0$)
 3680 during analysis.

3681 This mapping and masking information is readout and stored thanks to the object `Mapping`, pre-
 3682 sented in Source Code B.4. Similarly to `IniFile` objects, this class has private methods. The first
 3683 one, `Mapping::CheckIfNewLine()` is used to find the newline character '`\n`' or return character
 3684 '`\r`' (depending on which kind of operating system interacted with the file). This is used for the
 3685 simple reason that the masking information has been introduced only during the year 2017 but the
 3686 channel mapping files exist since 2015 and the very beginning of data taking at GIF++. This means
 3687 that in the older data folders, before the upgrade, the channel mapping file only had 2 columns, the
 3688 RPC channel and the TDC channel. For compatibility reasons, this method helps controling the
 3689 character following the readout of the 2 first fields of a line. In case any end of line character is
 3690 found, no mask information is present in the file and the default $M = 1$ is used. On the contrary, if
 3691 the next character was a tabulation or a space, the mask information is present.

3692 Once the 3 fields have been readout, the second private method `Mapping::CheckIfTDCCh()` is
 3693 used to control that the TDC channel is an existing TDC channel. Finally, the information is stored
 3694 into 3 different maps (`Link`, `ReverseLink` and `Mask`) thanks to the public method `Mapping::Read()`.
 3695 `Link` allows to get the RPC channel by knowing the TDC channel while `ReverseLink` does the op-
 3696 posite by returning the TDC channel by knowing the RPC channel. Finally, `Mask` returns the mask
 3697 associated to a given RPC channel.

```

3698 typedef map<Uint,Uint> MappingData;

3699 class Mapping {
    private:
        bool          CheckIfNewLine(char next);
        bool          CheckIfTDCCh(Uint channel);
        string         FileName;
        MappingData   Link;
        MappingData   ReverseLink;
        MappingData   Mask;
        int           Error;

3700     public:
        Mapping();
        Mapping(string baseName);
        ~Mapping();

        void SetFileName(const string filename);
        int Read();
        Uint GetLink(Uint tdcchannel);
        Uint GetReverse(Uint rpcchannel);
        Uint GetMask(Uint rpcchannel);
    };
}

```

3700 *Source Code B.4: Description of C++ object Mapping used as a parser for the channel mapping and mask file.*

3701 **B.4 Description of GIF++ setup within the Offline Analysis tool**

3702 In the previous section, the tool input files have been discussed. The dimension file information is
 3703 stored in a map hosted by the `IniFile` object. But this information is then used to create a series of
 3704 new objects that helps defining the GIF++ infrastructure directly into the Offline Analysis. Indeed,
 3705 from the `RPC`, to the more general `Infrastructure`, every element of the GIF++ infrastrucutre is
 3706 recreated for each data analysis based on the information provided in input. All this information
 3707 about the infrastructure will be used to assign each hit signal to a specific strip channel of a specific
 3708 detector, and having a specific active area. This way, rate per unit area calculation is possible.
 3709

3710 **B.4.1 RPC objects**

3711 `RPC` objects have been developped to represent physical active detectors in GIF++ at the moment
 3712 of data taking. Thus, there are as many `RPC` objects created during the analysis than there were
 3713 active RPCs tested during a run. Each `RPC` hosts the information present in the corresponding INI
 3714 slot group, as shown in B.3, and organises it using a similar architecture. This can be seen from
 3715 *Source Code B.5*.

3716 To make the object more compact, the lists of gap labels, of gap active areas and strip active
 3717 areas are stored into `vector` dynamical containers. `RPC` objects are always contructed thanks to the
 3718 dimension file information stored into the `IniFILE` and their ID, using the format `TtSs`. Using the
 3719 `RPC` ID, the constructor calls the methods of `IniFILE` to initialise the `RPC`. The other constructors
 3720 are not used but exist in case of need. Finally, some getters have been written to access the different
 3721 private parameters storing the detector information.

```

3722
class RPC{
    private:
        string      name;           //RPC name as in webDCS database
        Uint        nGaps;          //Number of gaps in the RPC
        Uint        nPartitions;    //Number of partitions in the RPC
        Uint        nStrips;         //Number of strips per partition
        vector<string> gaps;       //List of gap labels (BOT, TOP, etc...)
        vector<float>  gapGeo;        //List of gap active areas
        vector<float>  stripGeo;      //List of strip active areas

    public:
        RPC();
        RPC(string ID, IniFile* geofile);
        RPC(const RPC& other);
        ~RPC();
        RPC& operator=(const RPC& other);

        string GetName();
        Uint GetNGaps();
        Uint GetNPartitions();
        Uint GetNStrips();
        string GetGap(Uint g);
        float GetGapGeo(Uint g);
        float GetStripGeo(Uint p);
};

3723

```

3724 *Source Code B.5: Description of C++ objects RPC that describe each active detectors used during data taking.*

3725 B.4.2 Trolley objects

3726 Trolley objects have been developped to represent physical active trolleys in GIFT++ at the moment
 3727 of data taking. Thus, there are as many trolley objects created during the analysis than there were
 3728 active trolleys hosting tested RPCs during a run. Each Trolley hosts the information present in the
 3729 corresponding INI trolley group, as shown in B.2, and organises it using a similar architecture. In
 3730 addition to the information hosted in the INI file, these object have a dynamical container of RPC
 3731 objects, representing the active detectors the active trolley was hosting at the time of data taking.
 3732 This can been seen from Source Code B.6.

3733 Trolley objects are always contructed thanks to the dimension file information stored into the
 3734 IniFILE and their ID, using the format Tt. Using the Trolley ID, the constructor calls the methods
 3735 of IniFILE to initialise the Trolley. Retrieving the information of the RPC IDs via SlotsID, a new
 3736 RPC is constructed and added to the container RPCs for each character in the ID string. The other
 3737 constructors are not used but exist in case of need. Finally, some getters have been written to access
 3738 the different private parameters storing the trolley and detectors information.

```

3739
class Trolley{
    private:
        Uint          nSlots; //Number of active RPCs in the considered trolley
        string        SlotsID; //Active RPC IDs written into a string
        vector<RPC*> RPCs;   //List of active RPCs

    public:
        //Constructors, destructor and operator =
        Trolley();
        Trolley(string ID, IniFile* geofile);
        Trolley(const Trolley& other);
        ~Trolley();
        Trolley& operator=(const Trolley& other);

        //Get GIFTrolley members
        Uint  GetNSlots();
        string GetSlotsID();
        Uint   GetSlotID(Uint s);

        //Manage RPC list
        RPC*  GetRPC(Uint r);
        void  DeleteRPC(Uint r);

        //Methods to get members of RPC objects stored in RPCs
        string GetName(Uint r);
        Uint   GetNGaps(Uint r);
        Uint   GetNPartitions(Uint r);
        Uint   GetNStrips(Uint r);
        string GetGap(Uint r, Uint g);
        float  GetGapGeo(Uint r, Uint g);
        float  GetStripGeo(Uint r, Uint p);
    };

```

Source Code B.6: Description of C++ objects `Trolley` that describe each active trolley used during data taking.

3742 B.4.3 Infrastructure object

3743 The `Infrastructure` object has been developped to represent the GIFT++ bunker area dedicated to
 3744 CMS RPC experiments. With this very specific object, all the information about the CMS RPC
 3745 setup within GIFT++ at the moment of data taking is stored. It hosts the information present in the
 3746 corresponding INI general group, as shown in B.1, and organises it using a similar architecture. In
 3747 addition to the information hosted in the INI file, this object have a dynamical container of `Trolley`
 3748 objects, representing the active tolleys in GIFT++ area. This can be seen from Source Code B.7.

3749 The `Infrastructure` object is always contructed thanks to the dimension file information stored
 3750 into the `IniFILE`. Retrieving the information of the trolley IDs via `TrolleysID`, a new `Trolley` is
 3751 constructed and added to the container `Trolleys` for each character in the ID `string`. By extension,
 3752 it is easy to understand that the process described in Section B.4.2 for the construction of RPCs
 3753 takes place when a trolley is constructed. The other constructors are not used but exist in case of
 3754 need. Finally, some getters have been written to access the different private parameters storing the
 3755 infrastructure, tolleys and detectors information.

```

3756 class Infrastructure {
3757     private:
3758         Uint             nTrolleys;    //Number of active Trolleys in the run
3759         string          TrolleysID;   //Active trolley IDs written into a string
3760         vector<Trolley*> Trolleys;   //List of active Trolleys (struct)
3761
3762     public:
3763         //Constructors and destructor
3764         Infrastructure();
3765         Infrastructure(IniFile* geofile);
3766         Infrastructure(const Infrastructure& other);
3767         ~Infrastructure();
3768         Infrastructure& operator=(const Infrastructure& other);
3769
3770         //Get Infrastructure members
3771         Uint  GetNTrolleys();
3772         string GetTrolleysID();
3773         Uint   GetTrolleyID(Uint t);
3774
3775         //Manage Trolleys
3776         Trolley* GetTrolley(Uint t);
3777         void    DeleteTrolley(Uint t);
3778
3779         //Methods to get members of GIFTrolley objects stored in Trolleys
3780         Uint  GetNSlots(Uint t);
3781         string GetSlotsID(Uint t);
3782         Uint   GetSlotID(Uint t, Uint s);
3783         RPC*  GetRPC(Uint t, Uint r);
3784
3785         //Methods to get members of RPC objects stored in RPCs
3786         string GetName(Uint t, Uint r);
3787         Uint   GetNGaps(Uint t, Uint r);
3788         Uint   GetNPartitions(Uint t, Uint r);
3789         Uint   GetNStrips(Uint t, Uint r);
3790         string GetGap(Uint t, Uint r, Uint g);
3791         float  GetGapGeo(Uint t, Uint r, Uint g);
3792         float  GetStripGeo(Uint t, Uint r, Uint p);
3793     };

```

Source Code B.7: Description of C++ object Infrastructure that contains the full information about CMS RPC experiment in GIF++.

3759 B.5 Handeling of data

3760 As discussed in Appendix A.4.2, the raw data as a `TTree` architecture where every entry is related to
3761 a trigger signal provided by a muon or a random pulse, whether the goal of the data taking was to
3762 measure the performance of the detector or the noise/gamma background respectively. Each of these
3763 entries, referred also as events, contain a more or less full list of hits in the TDC channels to which
3764 the detectors are connected. To this list of hits corresponds a list of time stamps, marking the arrival
3765 of the hits within the TDC channel.

3766 The infrastructure of the CMS RPC experiment within `GIF++` being defined, combining the
3767 information about the raw data with the information provided by both the mapping/mask file and the
3768 dimension file allows to build new physical objects that will help in computing efficiency or rates.

3769 B.5.1 RPC hits

3770 The raw data stored in the ROOT file as output of the GIFT++ DAQ, is readout by the analysis tool
 3771 using the structure `RAWData` presented in Source Code B.9 that differs from the structure presented
 3772 in Appendix A.4.2 as it is not meant to hold all of the data contained in the ROOT file. In this sense,
 3773 this structure is in the case of the offline analysis tool not a dynamical object and will only be storing
 3774 a single event contained in a single entry of the `TTree`.

```
3775
3776 class RPCHit {
3777     private:
3778         Uint Channel;      //RPC channel according to mapping (5 digits)
3779         Uint Trolley;      //0, 1 or 3 (1st digit of the RPC channel)
3780         Uint Station;      //Slot where is held the RPC in Trolley (2nd digit)
3781         Uint Strip;        //Physical RPC strip where the hit occurred (last 3
3782             digits)
3783         Uint Partition;    //Readout partition along eta segmentation
3784         float TimeStamp;   //Time stamp of the arrival in TDC
3785
3786     public:
3787         //Constructors, destructor & operator =
3788         RPCHit();
3789         RPCHit(Uint channel, float time, Infrastructure* Infra);
3790         RPCHit(const RPCHit& other);
3791         ~RPCHit();
3792         RPCHit& operator=(const RPCHit& other);
3793
3794         //Get RPCHit members
3795         Uint GetChannel();
3796         Uint GetTrolley();
3797         Uint GetStation();
3798         Uint GetStrip();
3799         Uint GetPartition();
3800         float GetTime();
3801     };
3802
3803     typedef vector<RPCHit> HitList;
3804     typedef struct GIFHitList { HitList rpc[NTROLLEYS][NSLOTS][NPARTITIONS]; } →
3805         GIFHitList;
3806
3807     bool SortHitbyStrip(RPCHit h1, RPCHit h2);
3808     bool SortHitbyTime(RPCHit h1, RPCHit h2);
3809
3810 }
```

3777 *Source Code B.8: Description of C++ object RPCHit.*

```
3778
3779     struct RAWData{
3780         int iEvent;          //Event i
3781         int TDCNHits;       //Number of hits in event i
3782         int QFlag;           //Quality flag list (1 flag digit per TDC)
3783         vector<Uint> *TDCCh; //List of channels giving hits per event
3784         vector<float> *TDCTS; //List of the corresponding time stamps
3785     };
3800
3801 }
```

3779 *Source Code B.9: Description of C++ structure RAWData.*

3780 Each member of the structure is then linked to the corresponding branch of the ROOT data tree,
 3781 as shown in the example of Source Code B.10, and using the method `GetEntry(int i)` of the ROOT
 3782 class `TTree` will update the state of the members of `RAWData`.

```

3783 TTree* dataTree = (TTree*)dataFile.Get("RAWData");
3784 RAWData data;
3785
3786 dataTree->SetBranchAddress("EventNumber", &data.iEvent);
3787 dataTree->SetBranchAddress("number_of_hits", &data.TDCNHits);
3788 dataTree->SetBranchAddress("Quality_flag", &data.QFlag);
3789 dataTree->SetBranchAddress("TDC_channel", &data.TDCCh);
3790 dataTree->SetBranchAddress("TDC_TimeStamp", &data.TDCTS);

```

3785 *Source Code B.10: Example of link in between RAWData and TTree.*

3786 The data is then analysed entry by entry and to each element of the TDC channel list, a `RPCHit` is
 3787 constructed by linking each TDC channel to the corresponding RPC channel thanks to the `Mapping`
 3788 object. The information carried by the RPC channel format allows to easily retrieve the trolley and
 3789 slot from which the hit was recorded (see section B.3.2). Using these 2 values, the readout partition
 3790 can be found by knowing the strip channel and comparing it with the number of partitions and strips
 3791 per partition stored into the `Infrastructure` object.

3792 Thus `RPCHit` objects are then stored into 3D dynamical list called `GIFHitList` (Source Code B.9)
 3793 where the 3 dimensions refer to the 3 layers of the readout in `GIF++` : in the bunker there are *trolleys*
 3794 (τ) holding detectors in *slots* (s) and each detector readout is divided into 1 or more pseudo-rapidity
 3795 *partitions* (p). Using these 3 information allows to assign an address to each readout partition and
 3796 this address will point to a specific hit list.

3797

3798 **B.5.2 Clusters of hits**

3799 All the hits contained in the ROOT file have been sorted into the different hit lists through the
 3800 `GIFHitList`. At this point, it is possible to start looking for clusters. A cluster is a group of adjacent
 3801 strips getting hits within a time window of 25 ns. These strips are then assumed to be part of the same
 3802 physical avalanche signal generated by a muon passing through the chamber or by the interaction of
 3803 a gamma stopping into the electrodes of the RPCs.

3804 To keep the cluster information, `RPCCluster` objects have been defined as shown in Source
 3805 Code B.11. Using the information of each individual `RPCHit` taken out of the hit list, it stores
 3806 the cluster size (number of adjacent strips composing the cluster), the first and last hit, the center for
 3807 spatial reconstruction and finally the start and stop time stamps as well as te time spread in between
 3808 the first and last hit.

```

3809   class RPCCluster{
3810     private:
3811       Uint ClusterSize; //Size of cluster #ID
3812       Uint FirstStrip; //First strip of cluster #ID
3813       Uint LastStrip; //Last strip of cluster #ID
3814       float Center; //Center of cluster #ID ((first+last)/2)
3815       float StartStamp; //Time stamp of the earliest hit of cluster #ID
3816       float StopStamp; //Time stamp of the latest hit of cluster #ID
3817       float TimeSpread; //Time difference between earliest and latest hits
3818           //of cluster #ID
3819     public:
3820       //Constructors, destructor & operator =
3821       RPCCluster();
3822       RPCCluster(HitList List, Uint cID, Uint cSize, Uint first, Uint firstID);
3823       RPCCluster(const RPCCluster& other);
3824       ~RPCCluster();
3825       RPCCluster& operator=(const RPCCluster& other);
3826
3827       //Get Cluster members
3828       Uint GetID();
3829       Uint GetSize();
3830       Uint GetFirstStrip();
3831       Uint GetLastStrip();
3832       float GetCenter();
3833       float GetStart();
3834       float GetStop();
3835       float GetSpread();
3836   };
3837
3838   typedef vector<RPCCluster> ClusterList;
3839
3840   //Other functions to build cluster lists out of hit lists
3841   void BuildClusters(HitList &cluster, ClusterList &clusterList);
3842   void Clusterization(HitList &hits, TH1 *hcSize, TH1 *hcMult);

```

3811 *Source Code B.11: Description of C++ object Cluster.*

3812 To investigate the hit list of a given detector partition, the function `Clusterization()` defined
 3813 in `include/Cluster.h` needs the hits in the list to be time sorted. This is achieved by calling func-
 3814 tion `sort()` of library `<algorithm>` using the comparator `SortHitbyTime(RPCHit h1, RPCHit h2)`
 3815 defined in `include/RPCHit.h` that returns `true` if the time stamp of hit `h1` is lower than that of `h2`.
 3816 A first isolation of strips is made only based on time information. All the hits within the 25 ns win-
 3817 dow are taken separately from the rest. Then, this sub-list of hits is sorted this time by ascending
 3818 strip number, using this time the comparator `SortHitbyStrip(RPCHit h1, RPCHit h2)`. Finally, the
 3819 groups of adjacent strips are used to construct `RPCCluster` objects that are then stored in a temporary
 3820 list of clusters that is at the end of the process used to know how many clusters were reconstructed
 3821 and to fill their sizes into an histogram that will allows to know the mean size of muon or gamma
 3822 clusters.
 3823

3824 **B.6 DAQ data Analysis**

3825 All the ingredients to analyse GIF++ data have been defined. This section will focus on the different
 3826 part of the analysis performed on the data, from determining the type of data the tool is dealing with

3827 to calculating the rate in each detector or reconstructing muon or gamma clusters.

3828 B.6.1 Determination of the run type

3829 In GIF++, both the performance of the detectors in detecting muons in an irradiated environment and
 3830 the gamma background can be independantly measured. These corresponds to different run types
 3831 and thus, to different TDC settings giving different data to look at.

3832

3833 In the case of performance measurements, the trigger for data taking is provided by the coïncidence
 3834 of several scintillators when muons from the beam passing through the area are detected. Data
 3835 is collected in a 600 ns wide window around the arrival of muons in the RPCs. The expected time
 3836 distribution of hits is shown in Figure B.1a. The muon peak is clearly visible in the center of the
 3837 distribution and is to be extracted from the gamma background that composes the flat part of the
 3838 distribution.

3839 On the other hand, gamma background or noise measurements are focussed on the non muon
 3840 related physics and the trigger needs to be independant from the muons to give a good measurement
 3841 of the gamma/noise distribution as seen by the detectors. The trigger is then provided by a pulse
 3842 generator at a frequency of 300 Hz whose pulse is not likely to be on time with a muon. In order
 3843 to increase the integrated time without increasing the acquisition time too much, the width of the
 3844 acquisition windows are increased to 10 μ s. The time distribution of the hits is expected to be flat, as
 3845 shown by Figure B.1b.

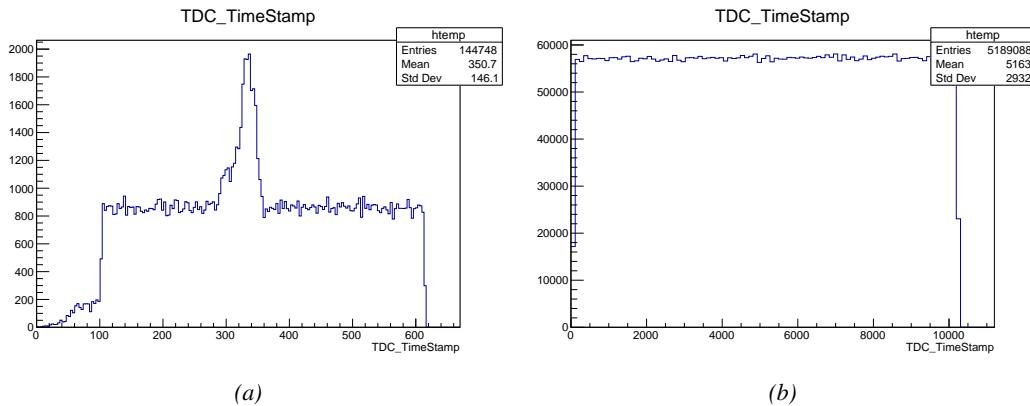


Figure B.1: Example of expected hit time distributions in the cases of efficiency (Figure B.1a) and noise/gamma rate per unit area (Figure B.1b) measurements as extracted from the raw ROOT files. The unit along the x-axis corresponds to ns. The fact that "the" muon peak is not well defined in Figure B.1a is due to the contribution of all the RPCs being tested at the same time that don't necessarily have the same signal arrival time. Each individual peak can have an offset with the ones of other detectors. The inconsistency in the first 100 ns of both time distributions is an artefact of the TDCs and are systematically rejected during the analysis.

3846 The ROOT files include a TTree called RunParameters containing, among other things, the in-
 3847 formation related to the type of run. The run type can then be accessed as described by Source
 3848 Code B.12 and the function IsEfficiencyRun() is then used to determine if the run file is an effi-
 3849 ciency run or, on the contrary, another type of run (noise or gamma measurement).

```

3850
3851     TTree* RunParameters = (TTree*)dataFile.Get("RunParameters");
3852     TString* RunType = new TString();
3853     RunParameters->SetBranchAddress("RunType", &RunType);
3854     RunParameters->GetEntry(0);

```

3852 *Source Code B.12: Access to the run type contained in TTree* RunParameters.*

3853 Finally, the data files will have a slightly different content whether it was collected before or after
 3854 October 2017 and the upgrade of the DAQ software that brought a new information into the ROOT
 3855 output. This is discussed in Appendix A.4.3 and implies that the analysis will differ a little depending
 3856 on the data format. Indeed, as no information on the data quality is stored, in older data files, the cor-
 3857 rections for missing events has to be done at the end of the analysis. The information about the type
 3858 of data format is stored in the variable **bool** `isNewFormat` by checking the list of branches contained
 3859 in the data tree via the methods `TTree::GetListOfBranches()` and `TCollection::Contains()`.

3860 **B.6.2 Beam time window calculation for efficiency runs**

3861 Knowing the run type is important first of all to know the width of the acquisition window to be used
 3862 for the rate calculation and finally to be able to seek for muons. Indeed, the peak that appears in the
 3863 time distribution for each detectors is then fitted to extract the most probable time window in which
 3864 the tool should look for muon hits. The data outside of this time window is then used to evaluate the
 3865 noise or gamma background the detector was subjected to during the data taking. Computing the
 3866 position of the peak is done calling the function `SetBeamWindow()` defined in file `src/RPCHit.cc` that
 3867 loops a first time on the data. The data is first sorted in a 3D array of 1D histograms (`GIFH1Array`, see
 3868 include/types.h). Then the location of the highest bin is determined using `TH1::GetMaximumBin()`
 3869 and is used to define a window in which a gaussian fit will be applied to compute the peak width.
 3870 This window is a 80 ns defined by Formula B.1 around the central bin.

$$(B.1a) \quad t_{center}(ns) = bin \times width_{bin}(ns)$$

$$(B.1b) \quad [t_{low}; t_{high}] = [t_{center} - 40; t_{center} + 40]$$

3871 Before the fit is performed, the average number of noise/gamma hits per bin is evaluated using
 3872 the data outside of the fit window. Excluding the first 100 ns, the average number of hits per bin
 3873 due to the noise or gamma is defined by Formula B.2 after extracting the amount of hits in the time
 3874 windows $[100; t_{low}]$ and $[t_{high}; 600]$ thanks to the method `TH1::Integral()`. This average number
 3875 of hits is then subtracted to every bin of the 1D histogram, in order to *clean* it from the noise or
 3876 gamma contribution as much as possible to improve the fit quality. Bins where $\langle n_{hits} \rangle$ is greater
 3877 than the actual bin content are set to 0.

$$(B.2a) \quad \Delta t_{noise}(ns) = 600 \overbrace{-t_{high} + t_{low}}^{-80ns} - 100 = 420ns$$

$$(B.2b) \quad \langle n_{hits} \rangle = width_{bin}(ns) \times \frac{\sum_{t=100}^{t_{low}} + \sum_{t=t_{high}}^{600}}{\Delta t_{noise}(ns)}$$

3878 Finally, the fit parameters are extracted and saved for each detector in 3D arrays of **float**
 3879 (`muonPeak`, see include/types.h), a first one for the mean arrival time of the muons, `PeakTime`,

3880 and a second one for the width of the peak, `PeakWidth`. The width is defined as 6σ of the gaussian
 3881 fit. The same settings are applied to every partitions of the same detector. To determine which one
 3882 of the detector's partitions is directly illuminated by the beam, the peak height of each partition is
 3883 compared and the highest one is then used to define the peak settings.

3884 **B.6.3 Data loop and histogram filling**

3885 3D arrays of histogram are created to store the data and display it on the DQM of G4F++ webDCS
 3886 for the use of shifters. These histograms, presented in section B.2.1.1, are filled while looping on
 3887 the data. Before starting the analysis loop, it is necessary to control the entry quality for the new
 3888 file formats featuring `QFlag`. If the `QFlag` value for this entry shows that 1 TDC or more have a
 3889 `CORRUPTED` flag, then this event is discarded. The loss of statistics is low enough to be neglected.
 3890 `QFlag` is controlled using the function `IsCorruptedEvent()` defined in `src/utils.cc`. As explained
 3891 in Appendix A.4.3, each digit of this integer represents a TDC flag that can be 1 or 2. Each 2 is
 3892 the sign of a `CORRUPTED` state. Then, the data is accessed entry by entry in the ROOT `TTree` using
 3893 `RAWData` and each hit in the hit list is assigned to a detector channel and saved in the corresponding
 3894 histograms. In the first part of the analysis, in which the loop over the ROOT file's content is
 3895 performed, the different steps are:

3896 **1- RPC channel assignment and control:** a check is done on the RPC channel extracted thanks
 3897 to the mapping via the method `Mapping::GetLink()`. If the channel is not initialised and is 0, or if
 3898 the TDC channel was greater than 5127, the hit is discarded. This means there was a problem in the
 3899 mapping. Often a mapping problem leads to the crash of the offline tool.

3900 **2- Creation of a `RPCHit` object:** to easily get the trolley, slot and partition in which the hit has
 3901 been assigned, this object is particularly helpful.

3902 **3- General histograms are filled:** the hit is filled into the time distribution and the general hit
 3903 distribution histograms, and if the arrival time is within the first 100 ns, it is discarded and nothing
 3904 else happens and the loop proceeds with the next hit in the list.

3905 **4- Multiplicity counter:** the hit multiplicity counter of the corresponding detectors incremented.

3906 **5-a- Efficiency runs - Is the hit within the peak window? :** if the peak is contained in the peak
 3907 window previously defined in section B.6.2, the hit is filled into the beam hit profile histogram of
 3908 the corresponding chamber, added into the list of muon hits and increments the counter of *in time*
 3909 hits. The term *in time* here refers to the hits that are likely to be muons by arriving in the expected
 3910 time window. If the hit is outside of the peak window, it is filled into the noise profile histogram
 3911 of the corresponding detector, added into the list of noise/gamma hits and increments the counter of
 3912 noise/gamma hits.

3913 **5-b- Noise/gamma rate runs - Noise histograms are filled:** the hit is filled into the noise profile
 3914 histogram of the corresponding detector, added into the list of noise/gamma hits and increments the
 3915 counter of noise/gamma hits.

3917 After the loop on the hit list of the entry is over, the next step is to clusterize the 3D lists filled
 3918 in the previous steps. A 3D loop is then started over the active trolley, slot and RPC partitions to
 3919 access these objects. Each `NoiseHitList` and `MuonHitList`, in case of efficiency run, are clusterized
 3920 as described in section B.5.2. There corresponding cluster size and multiplicity histograms are filled
 3921 at the end of the clustering process. Then, the efficiency histogram is filled in case of efficiency run.
 3922 The selection is simply made by checking whether the RPC detected signals in the peak window
 3923 during this event. Nevertheless, it is useful to highlight that at this level, it is not possible yet to
 3924 discriminate in between a muon hit and noise or gamma hit. Thus, `MuonCSize_H`, `MuonCMult_H`
 3925 and `Efficiency0_H` are subjected to noise and gamma contamination. This contamination will be
 3926 estimated and corrected at the moment the results will be written into output CSV files. Finally, the
 3927 loop ends on the filling of the general hit multiplicity histogram.

3928 **B.6.4 Results calculation**

3929 As mentioned in section B.2.1, the analysis of DAQ data provides the user with 3 CSV files and
 3930 a ROOT file associated to each and every ROOT data file. The fourth CSV file is provided by the
 3931 extraction of the CEAN main frame data monitored during data taking and will be discussed later.
 3932 After looping on the data in the previous part of the analysis macro, the output files are created and a
 3933 3D loop on each RPC readout partitions is started to extract the histograms parameters and compute
 3934 the final results.

3935

3936 **B.6.4.1 Rate normalisation**

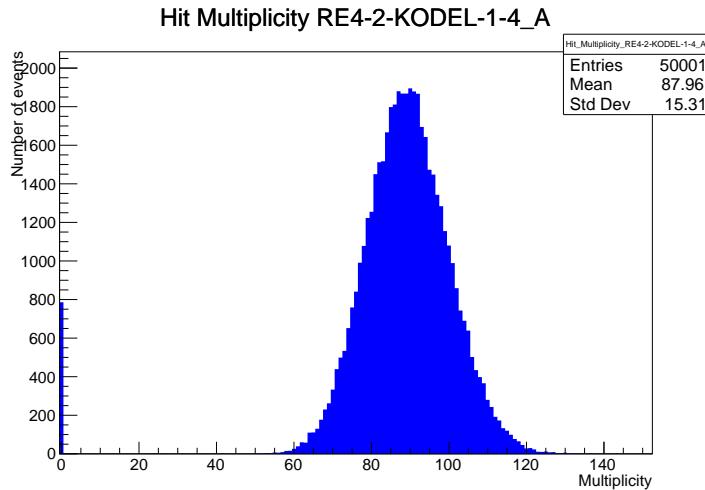


Figure B.2: The effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without `Quality_flag`. The artificial high content of bin 0 is the effect of corrupted data.

3937 To analyse old data format files, not containing any quality flag, it is needed to estimate the amount
 3938 of corrupted data via a fit as the corrupted data will always fill events with a fake "0 multiplicity".
 3939 Indeed, as no hits were stored in the DAQ ROOT files, these events artificially contribute to fill
 3940 the bin corresponding to a null multiplicity, as shown in Figure B.2. In the case the mean of the

3941 hit multiplicity distribution is high, the contribution of the corrupted data can easily be evaluated
 3942 for later correction by comparing the level of the bin at multiplicity 0 and of a skew fit curve that
 3943 should indicate a value consistent with 0. A skew fit has been chosen over a Poisson fit as it was
 3944 giving better results for lower mean multiplicity values. Nevertheless, for low irradiation cases,
 3945 as explained in Appendix A.4.3, the hit multiplicity distribution mean is, on the contrary, rather
 3946 small and the probability to record events without hits can't be considered small anymore, leading
 3947 to a difficult and non-reliable estimation of the corruption. As can be seen in Source Code B.13,
 3948 conditions have been applied to prevent bad fits and wrong corruption estimation in cases where :

3949 • The difference in between the data for multiplicity 1 and the corresponding fit value should be
 3950 lower than 1% of the total amount of data : $\frac{|n_{m=1} - sk(1)|}{N_{tot}} < 0.01$ where $n_{m=1}$ is the number
 3951 of entries with multiplicity 1, $sk(1)$ the value of the skew fit, as defined by Formula ??, for
 3952 multiplicity 1 and N_{tot} the total number of entries.

3953 • The amount of data contained in the multiplicity 0 bin should not exceed 40% : $\frac{n_{m=0}}{N_{tot}} \leq 0.4$
 3954 where $n_{m=0}$ is the number of entries with multiplicity 0. This number has been determined
 3955 to be the maximum to be able to separate the excess of data due to corruption from the hit
 3956 multiplicity distribution.

3957 Those 2 conditions need to be fulfilled to estimate the corruption of old data format files. If the
 3958 fit was successful, the level of corruption is written in `Offline-Corrupted.csv` and the number of
 3959 corrupted entries, refered as the integer `nEmptyEvent`, is subtracted from the total number of entries
 3960 when the rate normalisation factor is computed as explicit in Source Code B.13. Note that for new
 3961 data format files, the number of corrupted entries being set to 0, the definition of `rate_norm` stays
 3962 valid.

```

3963
if(!isNewFormat){
    TF1* GaussFit = new TF1("gaussfit","[0]*exp(-0.5*((x-[1])/[2])**2)",0,Xmax);
    GaussFit->SetParameter(0,100);
    GaussFit->SetParameter(1,10);
    GaussFit->SetParameter(2,1);
    HitMultiplicity_H.rpc[T][S][p]->Fit(GaussFit,"LIQR","");
    HitMultiplicity_H.rpc[T][S][p]->Fit(GaussFit,"LIQR","");
}

TF1* SkewFit = new TF1("skewfit","[0]*exp(-0.5*((x-[1])/[2])**2) / (1 +
→ exp(-[3]*(x-[4])))",0,Xmax);
SkewFit->SetParameter(0,GaussFit->GetParameter(0));
SkewFit->SetParameter(1,GaussFit->GetParameter(1));
SkewFit->SetParameter(2,GaussFit->GetParameter(2));
SkewFit->SetParameter(3,1);
SkewFit->SetParameter(4,1);
HitMultiplicity_H.rpc[T][S][p]->Fit(SkewFit,"LIQR","");
HitMultiplicity_H.rpc[T][S][p]->Fit(SkewFit,"LIQR","");
double fitValue = SkewFit->Eval(1,0,0,0);
double dataValue = (double)HitMultiplicity_H.rpc[T][S][p]->GetBinContent(2);
double difference = TMath::Abs(dataValue - fitValue);
double fitTOdataVSentries_ratio = difference / (double)nEntries;
bool isFitGOOD = fitTOdataVSentries_ratio < 0.01;

3964
double nSinglehit = (double)HitMultiplicity_H.rpc[T][S][p]->GetBinContent(1);
double lowMultRatio = nSinglehit / (double)nEntries;
bool isMultLOW = lowMultRatio > 0.4;

if(isFitGOOD && !isMultLOW){
    nEmptyEvent = HitMultiplicity_H.rpc[T][S][p]->GetBinContent(1);
    nPhysics = (int)SkewFit->Eval(0,0,0,0);
    if(nPhysics < nEmptyEvent)
        nEmptyEvent = nEmptyEvent-nPhysics;
}
}

double corrupt_ratio = 100.*(double)nEmptyEvent / (double)nEntries;
outputCorrCSV << corrupt_ratio << '\t';

float rate_norm = 0.;
float stripArea = GIFIInfra->GetStripGeo(tr,sl,p);

if(IsEfficiencyRun(RunType)){
    float noiseWindow = BMTDCWINDOW - TIMEREJECT - 2*PeakWidth.rpc[T][S][p];
    rate_norm = (nEntries-nEmptyEvent)*noiseWindow*1e-9*stripArea;
} else
    rate_norm = (nEntries-nEmptyEvent)*RDMNOISEWDW*1e-9*stripArea;

```

Source Code B.13: Definition of the rate normalisation variable. It takes into account the number of non corrupted entries and the time window used for noise calculation, to estimate the total integrated time, and the strip active area to express the result as rate per unit area.

3966 B.6.4.2 Rate and activity

3967 At this point, the strip rate histograms, StripNoiseProfile_H.rpc[T][S][p], only contain an in-
3968 formation about the total number of noise or rate hits each channel received during the data taking.
3969 As described in Source Code B.14, a loop on the strip channels will be used to normalise the content
3970 of the rate distribution histogram for each detector partitions. The initial number of hits recorded for
3971 a given bin will be extracted and 2 values will be computed:

- 3972 ● the strip rate, defined as the number of hits recorded in the bin normalised like described in
 3973 the previous section, using the variable `rate_norm`, and

- 3974 ● the strip activity, defined as the number of hits recorded in the bin normalised to the average
 3975 number of hits per bin contained in the partition histogram, using the variable `averageNhit`.
 3976 This value provides an information on the homogeneity of the detector response to the gamma
 3977 background or of the detector noise. An activity of 1 corresponds to an average response.
 3978 Above 1, the channel is more active than the average and bellow 1, the channel is less active.

```

int nNoise = StripNoiseProfile_H.rpc[T][S][p]->GetEntries();
float averageNhit = (nNoise>0) ? (float)(nNoise/nStripsPart) : 1.;

for(Uint st = 1; st <= nStripsPart; st++){
    float stripRate =
        StripNoiseProfile_H.rpc[T][S][p]->GetBinContent(st)/rate_norm;
    float stripAct =
        StripNoiseProfile_H.rpc[T][S][p]->GetBinContent(st)/averageNhit;

    StripNoiseProfile_H.rpc[T][S][p]->SetBinContent(st,stripRate);
    StripActivity_H.rpc[T][S][p]->SetBinContent(st,stripAct);
}

```

3980 *Source Code B.14: Description of the loop that allows to set the content of each strip rate and strip activity
 channel for each detector partition.*

3981 On each detector partitions, which are readout by a single FEE, all the channels are not processed
 3982 by the same chip. Each chip can give a different noise response and thus, histograms using a chip
 3983 binning are used to investigate chip related noise behaviours. The average values of the strip rate
 3984 or activity grouped into a given chip are extracted using the using the function `GetChipBin()` and
 3985 stored in dedicated histograms as described in Source Codes B.15 and B.16 respectively.

```

float GetChipBin(TH1* H, Uint chip){
    Uint start = 1 + chip*NSTRIPSCHIP;
    int nActive = NSTRIPSCHIP;
    float mean = 0.;

    for(Uint b = start; b <= (chip+1)*NSTRIPSCHIP; b++){
        float value = H->GetBinContent(b);
        mean += value;
        if(value == 0.) nActive--;
    }

    if(nActive != 0) mean /= (float)nActive;
    else mean = 0.;

    return mean;
}

```

3988 *Source Code B.15: Function used to compute the content of a bin for an histogram using chip binning.*

```

3989     for(UInt ch = 0; ch < (nStripsPart/NSTRIPSCHIP); ch++) {
3990         ChipMeanNoiseProf_H.rpc[T][S][p]->
3991             SetBinContent(ch+1,GetChipBin(StripNoiseProfile_H.rpc[T][S][p],ch));
3992         ChipActivity_H.rpc[T][S][p]->
3993             SetBinContent(ch+1,GetChipBin(StripActivity_H.rpc[T][S][p],ch));
3994     }

```

Source Code B.16: Description of the loop that allows to set the content of each chip rate and chip activity bins for each detector partition knowing the information contained in the corresponding strip distribution histograms.

The activity variable is used to evaluate the homogeneity of the detector response to background or of the detector noise. The homogeneity h_p of each detector partition can be evaluated using the formula $h_p = \exp(-\sigma_p^R / \langle R \rangle_p)$, where $\langle R \rangle_p$ is the partition mean rate and σ_p^R is the rate standard deviation calculated over the partition channels. The more homogeneously the rates are distributed and the smaller will σ_p^R be, and the closer to 1 will h_p get. On the contrary, if the standard deviation of the channel's rates is large, h_p will rapidly get to 0. This value is saved into histograms as shown in Source Code B.17 and could in the future be used to monitor through time, once extracted, the evolution of every partition homogeneity. This could be of great help to understand the apparition of eventual hot spots due to ageing of the chambers subjected to high radiation levels. The monitored homogeneity information could then be combined with a monitoring of the activity of each individual channel in order to have a finer information. Monitoring tools have been suggested and need to be developed for this purpose.

```

4003     float MeanPartSDev = GetTH1StdDev(StripNoiseProfile_H.rpc[T][S][p]);
4004     float strip_homog = (MeanPartRate==0)
4005         ? 0.
4006         : exp(-MeanPartSDev/MeanPartRate);
4007     StripHomogeneity_H.rpc[T][S][p]->Fill("exp -#left(#frac{\#sigma_{Strip}
4008         \rightarrow Rate}{\#mu_{Strip Rate}}\#right)",strip_homog);
4009     StripHomogeneity_H.rpc[T][S][p]->GetYaxis()->SetRangeUser(0.,1.);
4010
4011     float ChipStDevMean = GetTH1StdDev(ChipMeanNoiseProf_H.rpc[T][S][p]);
4012     float chip_homog = (MeanPartRate==0)
4013         ? 0.
4014         : exp(-ChipStDevMean/MeanPartRate);
4015     ChipHomogeneity_H.rpc[T][S][p]->Fill("exp -#left(#frac{\#sigma_{Chip}
4016         \rightarrow Rate}{\#mu_{Chip Rate}}\#right)",chip_homog);
4017     ChipHomogeneity_H.rpc[T][S][p]->GetYaxis()->SetRangeUser(0.,1.);

```

Source Code B.17: Storage of the homogeneity into dedicated histograms.

4006 B.6.4.3 Strip masking tool

The offline tool is automatically called at the end of each data taking to analyse the data and offer the shifter DQM histograms to control the data quality. After the histograms have been published online in the DQM page, the shifter can decide to mask noisy or dead channels that will contribute to bias the final rate calculation by editing the mask column of `ChannelsMapping.csv` as can be seen in Figure B.3.

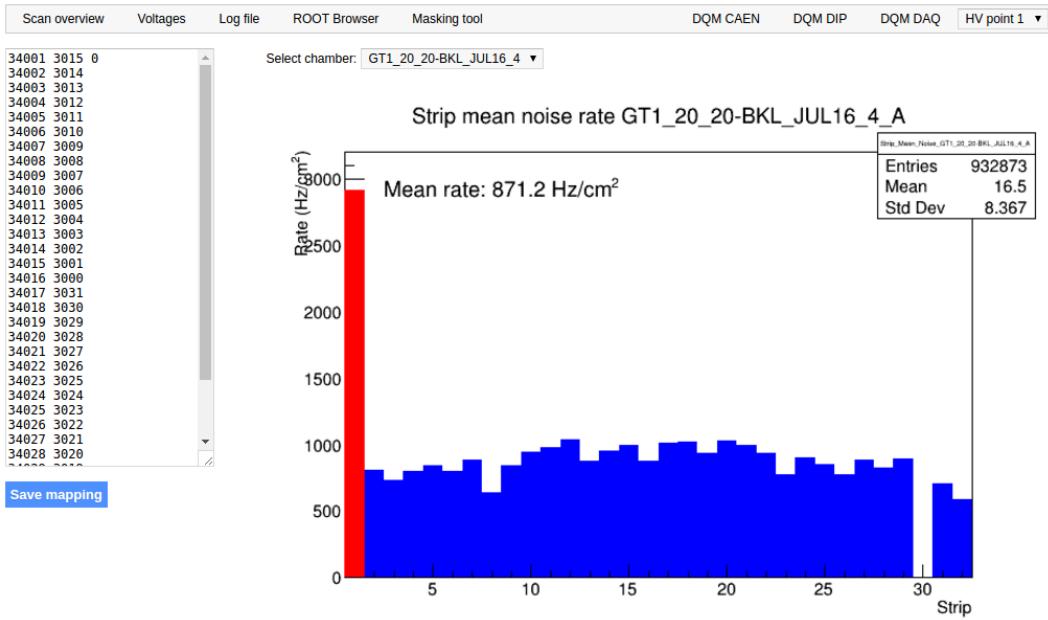


Figure B.3: Display of the masking tool page on the webDCS. The window on the left allows the shifter to edit ChannelsMapping.csv. To mask a channel, it only is needed to set the 3rd field corresponding to the strip to mask to 0. It is not necessary for older mapping file formats to add a 1 for each strip that is not masked as the code is versatile and the default behaviour is to consider missing mask fields as active strips. The effect of the mask is directly visible for noisy channels as the corresponding bin turns red. The global effect of masking strips will be an update of the rate value showed on the histogram that will take into consideration the rejected channels.

4012 From the code point of view, the function `GetTH1Mean()` is used to retrieve the mean rate par-
 4013 tition by partition after the rates have been calculated strip by strip and filled into the histograms
 4014 `StripNoiseProfile_H.rpc[T][S][p]`, as described through Source Code B.18.

4015 Once the mask for each rejected channel has been updated, the shifter can manually run the of-
 4016 fline tool again to update the DQM plots, now including the masked strips, as well the rate results
 4017 written in the output CSV file `Offline-Rate.csv`. If not done during the shifts, the strip masking
 4018 procedure needs to be carefully done by the person in charge of data analysis on the scans that were
 4019 selected to produce the final results.

```

4020
float GetTH1Mean(TH1* H) {
    int nBins = H->GetNbinsX();
    int nActive = nBins;
    float mean = 0.;

    for(int b = 1; b <= nBins; b++) {
        float value = H->GetBinContent(b);
        mean += value;
        if(value == 0.) nActive--;
    }

    if(nActive != 0) mean /= (float)nActive;
    else mean = 0.;

    return mean;
}

```

Source Code B.18: The function `GetTH1Mean()` is used to return the mean along the y-axis of TH1 histograms containing rate information. In order to take into account masked strips whose rate is set to 0, the function looks for masked channels and decrement the number of active channels for each null value found.

4023 B.6.4.4 Output CSV files filling

4024 All the histograms have been filled. Parameters will then be extracted from them to compute the
 4025 final results that will later be used to produce plots. Once the results have been computed, the very
 4026 last step of the offline macro is to write these values into the corresponding CSV outputs. Aside of
 4027 the file `Offline-Corrupted.csv`, 2 CSV files are being written by the macro `offlineAnalysis()`,
 4028 `Offline-Rates.csv` and `Offline-L0-EffCl.csv` that respectively contain information about noise
 4029 or gamma rates, cluster size and multiplicity, and about level 0 reconstruction of the detector effi-
 4030 ciency, muon cluster size and multiplicity. Details on the computation and file writing are respec-
 4031 tively given in Sources Codes B.19 and B.20.

4032 **Noise/gamma background variables** are computed and written in the output file for each detector
 4033 partitions. A detector average of the hit and cluster rate is also provided, as shown through Sources
 4034 Code B.19. The variables that are written for each partition are:

- 4035 • The mean partition hit rate per unit area, `MeanPartRate`, that is extracted from the histogram
 4036 `StripNoiseProfile_H` as the mean value along the y-axis, as described in section B.6.4.3. No
 4037 error is recorded for the hit rate as this is considered a single measurement. No statistical error
 4038 can be associated to it and the systematics are unknown.
- 4039 • The mean cluster size, `cSizePart`, is extracted from the histogram `NoiseCSize_H` and it's
 4040 statistical error, `cSizePartErr`, is taken to be 2σ of the total distribution.
- 4041 • The mean cluster multiplicity per trigger, `cMultPart`, is extracted from the histogram `NoiseCMult_H`
 4042 and it's statistical error, `cMultPartErr`, is taken to be 2σ of the total distribution. It is impor-
 4043 tant to point to the fact that this variable gives an information that is dependent on the buffer
 4044 window width used for each trigger for the calculation.
- 4045 • The mean cluster rate per unit area, `ClustPartRate`, is defined as the mean hit rate normalised

4046 to the mean cluster size and it's statistical error, `ClustPartRateErr`, is then obtained using the
 4047 relative statistical error on the mean cluster size.

```

for (UInt tr = 0; tr < GIFInfra->GetNTrolleys(); tr++){
  UInt T = GIFInfra->GetTrolleyID(tr);

  for (UInt sl = 0; sl < GIFInfra->GetNSlots(tr); sl++){
    UInt S = GIFInfra->GetSlotID(tr,sl) - 1;

    float MeanNoiseRate = 0.;
    float ClusterRate = 0.;
    float ClusterSDev = 0.;

    for (UInt p = 0; p < GIFInfra->GetNPartitions(tr,sl); p++){
      float MeanPartRate = GetTH1Mean(StripNoiseProfile_H.rpc[T][S][p]);
      float cSizePart = NoiseCSIZE_H.rpc[T][S][p]->GetMean();
      float cSizePartErr = (NoiseCSIZE_H.rpc[T][S][p]->GetEntries()==0)
        ? 0.
        : 2*NoiseCSIZE_H.rpc[T][S][p]->GetStdDev() /
          sqrt(NoiseCSIZE_H.rpc[T][S][p]->GetEntries());
      float cMultPart = NoiseCMult_H.rpc[T][S][p]->GetMean();
      float cMultPartErr = (NoiseCMult_H.rpc[T][S][p]->GetEntries()==0)
        ? 0.
        : 2*NoiseCMult_H.rpc[T][S][p]->GetStdDev() /
          sqrt(NoiseCMult_H.rpc[T][S][p]->GetEntries());
      float ClustPartRate = (cSizePart==0) ? 0.
        : MeanPartRate/cSizePart;
      float ClustPartRateErr = (cSizePart==0) ? 0.
        : ClustPartRate * cSizePartErr/cSizePart;

      outputRateCSV << MeanPartRate << '\t'
        << cSizePart << '\t' << cSizePartErr << '\t'
        << cMultPart << '\t' << cMultPartErr << '\t'
        << ClustPartRate << '\t' << ClustPartRateErr << '\t';

      RPCarea += stripArea * nStripsPart;
      MeanNoiseRate += MeanPartRate * stripArea * nStripsPart;
      ClusterRate += ClustPartRate * stripArea * nStripsPart;
      ClusterSDev += (cSizePart==0)
        ? 0.
        : ClusterRate*cSizePartErr/cSizePart;
    }

    MeanNoiseRate /= RPCarea;
    ClusterRate /= RPCarea;
    ClusterSDev /= RPCarea;

    outputRateCSV << MeanNoiseRate << '\t'
      << ClusterRate << '\t' << ClusterSDev << '\t';
  }
}

```

4049 *Source Code B.19: Description of rate result calculation and writing into the CSV output Offline-Rate.csv. Are saved into the file for each detector, the mean partition rate, cluster size and cluster mutiplicity, along with their errors, for each partition and as well as a detector average.*

4050 **Muon performance variables** are computed and written in the output file for each detector partitions as shown through Sources Code B.20. The variables that are written for each partition are:

4051

- 4052 ● The muon efficiency, `eff`, extracted from the histogram `Efficiency0_H`. It is reminded that
4053 this offline tool doesn't include any tracking algorithm to identify muons from the beam and
4054 only relies on the hits arriving in the time window corresponding to the beam time. The con-
4055 tent of the efficiency histogram is thus biased by the noise/gamma background contribution
4056 into this window and is thus corrected by estimating the muon data content in the peak re-
4057 gion knowing the noise/gamma content in the rate calculation region. Both time windows
4058 being different, the choice was made to normalise the noise/gamma background calculation
4059 window to it's equivalent beam window in order to have comparable values using the variable
4060 `windowRatio`. Finally, to estimate the data ratio in the peak region, the variable `DataRatio`
4061 is defined as the ratio in between the estimated mean cluster multiplicity of the muons in the
4062 peak region, `MuonCM`, and of the total mean cluster multiplicity in the peak region, `PeakCM`.
4063 `MuonCM` is itself defined as the difference in between the total mean cluster multiplicity in the
4064 peak region and the normalised mean noise/gamma cluster multiplicity calculated outside of
4065 the peak region. The statistical error related to the efficiency, `eff_err`, is computed using a
4066 binomial distribution, as the efficiency measure the probability of "success" and "failure" to
4067 detect muons.
- 4068 ● The mean muon cluster size, `MuonCS`, is calculated using the total mean cluster size and multi-
4069 plicity in the peak region, respectively extracted from histograms `MuonCSize_H` and `MuonCMult_H`,
4070 the noise/gamma background mean cluster size and normalised multiplicity, extracted from
4071 `NoiseCSize_H` and `NoiseCMult_H`, and of the estimated muon cluster multiplicity `MuonCM` pre-
4072 viously explicated. The associated statistical error, `MuonCM_err`, is calculated using the propa-
4073 gation of errors of the mentioned variables.
- 4074 ● The mean muon cluster multiplicity in the peak region, `MuonCM`, explicated above whose sta-
4075 tistical error, `MuonCM_err`, is the sum of statistical error associated to the total mean clus-
4076 ter multiplicity in the peak reagion, `PeakCM_err`, and of the mean noise/gamma cluster size,
4077 `NoiseCM_err`.

4078 In addition to these 2 CSV files, the histograms are saved in ROOT file `Scan00XXXX_HVY_Offline.root`
4079 as explained in section B.2.1.1.

4080

```

for (UInt tr = 0; tr < GIFInfra->GetNTrolleys(); tr++) {
    UInt T = GIFInfra->GetTrolleyID(tr);
    for (UInt sl = 0; sl < GIFInfra->GetNSlots(tr); sl++) {
        UInt S = GIFInfra->GetSlotID(tr,sl) - 1;
        for (UInt p = 0; p < GIFInfra->GetNPartitions(tr,sl); p++) {
            float noiseWindow =
                BMTDCWINDOW - TIMEREJECT - 2*PeakWidth.rpc[T][S][p];
            float peakWindow = 2*PeakWidth.rpc[T][S][p];
            float windowRatio = peakWindow/noiseWindow;

            float PeakCM = MuonCMult_H.rpc[T][S][p]->GetMean();
            float PeakCS = MuonCSize_H.rpc[T][S][p]->GetMean();
            float NoiseCM = NoiseCMult_H.rpc[T][S][p]->GetMean() *windowRatio;
            float NoiseCS = NoiseCSize_H.rpc[T][S][p]->GetMean();
            float MuonCM = (PeakCM<NoiseCM) ? 0. : PeakCM-NoiseCM;
            float MuonCS = (MuonCM==0 || PeakCM*PeakCS<NoiseCM*NoiseCS)
                ? 0.
                : (PeakCM*PeakCS-NoiseCM*NoiseCS) / MuonCM;
            float PeakCM_err = (MuonCMult_H.rpc[T][S][p]->GetEntries()==0.)
                ? 0.
                : 2*MuonCMult_H.rpc[T][S][p]->GetStdDev() /
                    sqrt(MuonCMult_H.rpc[T][S][p]->GetEntries());
            float PeakCS_err = (MuonCSize_H.rpc[T][S][p]->GetEntries()==0.)
                ? 0.
                : 2*MuonCSize_H.rpc[T][S][p]->GetStdDev() /
                    sqrt(MuonCSize_H.rpc[T][S][p]->GetEntries());
            float NoiseCM_err = (NoiseCMult_H.rpc[T][S][p]->GetEntries()==0.)
                ? 0.
                : windowRatio*2*NoiseCMult_H.rpc[T][S][p]->GetStdDev() /
                    sqrt(NoiseCMult_H.rpc[T][S][p]->GetEntries());
            float NoiseCS_err = (NoiseCSize_H.rpc[T][S][p]->GetEntries()==0.)
                ? 0.
                : 2*NoiseCSize_H.rpc[T][S][p]->GetStdDev() /
                    sqrt(NoiseCSize_H.rpc[T][S][p]->GetEntries());
            float MuonCM_err = (MuonCM==0) ? 0. : PeakCM_err+NoiseCM_err;
            float MuonCS_err = (MuonCS==0 || MuonCM==0) ? 0.
                : (PeakCS*PeakCM_err + PeakCM*PeakCS_err +
                    NoiseCS*NoiseCM_err + NoiseCM*NoiseCS_err +
                    MuonCS*MuonCM_err) / MuonCM;

            float DataRatio = MuonCM/PeakCM;
            float DataRatio_err = (MuonCM==0) ? 0.
                : DataRatio*(MuonCM_err/MuonCM + PeakCM_err/PeakCM);
            float eff = DataRatio*Efficiency0_H.rpc[T][S][p]->GetMean();
            float eff_err = DataRatio*2*Efficiency0_H.rpc[T][S][p]->GetStdDev() /
                sqrt(Efficiency0_H.rpc[T][S][p]->GetEntries()) +
                Efficiency0_H.rpc[T][S][p]->GetMean()*DataRatio_err;

            outputEffCSV << eff << '\t' << eff_err << '\t'
                << MuonCS << '\t' << MuonCS_err << '\t'
                << MuonCM << '\t' << MuonCM_err << '\t';
        }
    }
}

```

4081

Source Code B.20: Description of efficiency result calculation and writing into the CSV output Offline-L0-EffCl.csv. Are saved into the file for each detector, the efficiency, corrected taking into account the background in the peak window of the time profile, muon cluster size and muon cluster multiplicity, along with their errors, for each partition and as well as a detector average.

4082

4083 B.7 Current data Analysis

4084 Detectors under test at GIF++ are connected both to a CAEN HV power supply and to a CAEN
4085 ADC that reads the currents inside of the RPC gaps bypassing the supply cable. During data tak-
4086 ing, the webDCS records into a ROOT file called `Scan00XXXX_HVY_CAEN.root` histograms with the
4087 monitored parameters of both CAEN devices. Are recorded for each RPC channels (in most cases,
4088 a channel corresponds to an RPC gap):

- 4089 • the effective voltage, HV_{eff} , set by the webDCS using the PT correction on the CAEN power
4090 supply,
- 4091 • the applied voltage, HV_{app} , monitored by the CAEN power supply, and the statistical error
4092 related to the variations of this value through time to follow the variation of the environmental
4093 parameters defined as the RMS of the histogram divided by the square root of the number of
4094 recorded points,
- 4095 • the monitored current, I_{mon} , monitored by the CAEN power supply, and the statistical error
4096 related to the variations of this value through time to follow the variation of the environmental
4097 parameters defined as the RMS of the histogram divided by the square root of the number of
4098 recorded points,
- 4099 • the corresponding current density, J_{mon} , defined as the monitored current per unit area,
4100 $J_{mon} = I_{mon}/A$, where A is the active area of the corresponding gap,
- 4101 • the ADC current, I_{ADC} , recorded through the CAEN ADC module that monitors the dark
4102 current in the gap itself. First of all, the resolution of such a module is better than that of
4103 CAEN power supplies and moreover, the current is not read-out through the HV supply line
4104 but directly at the chamber level giving the real current inside of the detector. The statistical
4105 error is defined as the RMS of the histogram distribution divided by the square root of the
4106 number of recorded points.

4107 Once extracted through a loop over the element of GIF++ infrastructure via the C++ macro
4108 `GetCurrent()`, these parameters, organised in 9 columns per detector HV supply line, are written in
4109 the output CSV file `Offline-Current.csv`. The macro can be found in the file `Current.cc`.

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