



Universiteit Gent
Faculteit Wetenschappen
Vakgroep Fysica en Sterrenkunde

² No title yet

³ No sub-title neither, obviously...

⁴ Alexis Fagot

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Thesis to obtain the degree of
Doctor of Philosophy in Physics
Academic years 2012-2017



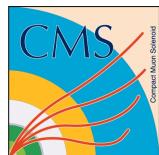


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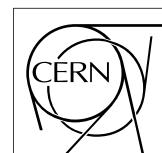
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²⁰ un bon moment

²¹ *Gent, ici la super date de la mort qui tue de la fin d'écriture*
²² *Alexis Fagot*

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List of Acronyms

A

319 **AFL**

Almost Full Level

B

324 **BARC**

Bhabha Atomic Research Centre

325 **BLT**

Block Transfer

326 **BR**

Branching Ratio

C

331 **CAEN**

Costruzioni Apparecchiature Elettroniche Nucleari S.p.A.

332 **CERN**

European Organization for Nuclear Research

333 **CFD**

Constant Fraction Discriminator

334 **CMS**

Compact Muon Solenoid

335 **CSC**

Cathode Strip Chamber

D

340 **DAQ**

Data Acquisition

341 **DCS**

Detector Control Software

342 **DQM**

Data Quality Monitoring

343 **DT**

Drift Tube

F

348	FEE	Front-End Electronics
349	FEB	Front-End Board
350		
351	G	
352		
353		
354	GE-/-	Find a good description
355	GE1/1	Find a good description
356	GE2/1	Find a good description
357	GEANT	GEometry ANd Tracking - a series of software toolkit platforms developed by CERN
358		
359	GEM	Gas Electron Multiplier
360	GIF	Gamma Irradiation Facility
361	GIF++	new Gamma Irradiation Facility
362		
363	H	
364		
365		
366	HL-LHC	High Luminosity LHC
367	HPL	High-pressure laminate
368	HV	High Voltage
369		
370	I	
371		
372		
373	iRPC	improved RPC
374	IRQ	Interrupt Request
375		
376	L	
377		
378		
379	LHC	Large Hadron Collider
380	LS1	First Long Shutdown
381	LS3	Third Long Shutdown
382	LV	Low Voltage
383	LVDS	Low-Voltage Differential Signaling
384		
385	M	
386		
387		
388	MC	Monte Carlo
389	MCNP	Monte Carlo N-Particle
390	ME-/-	Find good description

391	ME0	Find good description
392	MRPC	Multigap RPC
393		
394		
395	N	
396		
397	NIM	Nuclear Instrumentation Module logic signals
398		
399		
400	P	
401		
402	PMT	PhotoMultiplier Tube
403		
404		
405	R	
406		
407	RE-/-	Find a good description
408	RE2/2	Find a good description
409	RE3/1	Find a good description
410	RE3/2	Find a good description
411	RE4/1	Find a good description
412	RE4/2	Find a good description
413	RE4/3	Find a good description
414	RMS	Root Mean Square
415	ROOT	a framework for data processing born at CERN
416	RPC	Resistive Plate Chamber
417		
418		
419	S	
420		
421	SPS	Super Proton Synchrotron
422		
423		
424	T	
425		
426	TDC	Time-to-Digital Converter
427	ToF	Time-of-flight
428		
429		
430	W	
431		
432	webDCS	Web Detector Control System

434

Nederlandse samenvatting –Summary in Dutch–

436 Le resume en Neerlandais (j'aurais peut-être de apprendre la langue juste pour ca...).

435

English summary

⁴³⁸ Le meme résume mais en Anglais (on commencera par la hein!).

1

Introduction

439

440

⁴⁴¹ **1.1 A story of High Energy Physics**

⁴⁴² **1.2 Organisation of this study**

2

443

444

Investigating the TeV scale

445 **2.1 The Standard Model of Particle Physics**

446 **2.2 The Large Hadron Collider and the Compact Muon Solenoid**

447 **2.3 Muon Phase-II Upgrade**

448 After the more than two years lasting First Long Shutdown (LS1), the Large Hadron Collider (LHC)
449 delivered its very first Run-II proton-proton collisions early 2015. LS1 gave the opportunity to the
450 LHC and to the its experiments to undergo upgrades. The accelerator is now providing collisions
451 at center-of-mass energy of 13 TeV and bunch crossing rate of 40 MHz, with a peak luminosity
452 exceeding its design value. During the first and upcoming second LHC Long Shutdown, the Compact
453 Muon Solenoid (CMS) detector is also undergoing a number of upgrades to maintain a high system
454 performance [1].

455 From the LHC Phase-2 or High Luminosity LHC (HL-LHC) period onwards, i.e. past the Third
456 Long Shutdown (LS3), the performance degradation due to integrated radiation as well as the average
457 number of inelastic collisions per bunch crossing, or pileup, will rise substantially and become a
458 major challenge for the LHC experiments, like CMS that are forced to address an upgrade program
459 for Phase-II [2]. Simulations of the expected distribution of absorbed dose in the CMS detector
460 under HL-LHC conditions, show in figure 5.14 that detectors placed close to the beamline will have
461 to withstand high irradiation, the radiation dose being of the order of a few tens of Gy.

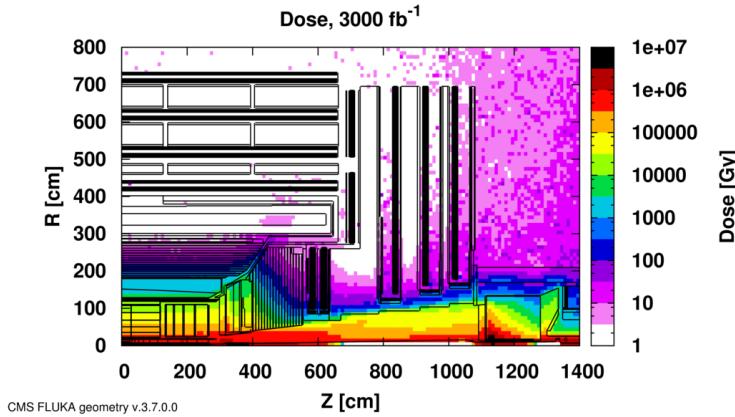


Figure 2.1: Absorbed dose in the CMS cavern after an integrated luminosity of 3000 fb^{-1} . R is the transverse distance from the beamline and Z is the distance along the beamline from the Interaction Point at $Z=0$.

The measurement of small production cross-section and/or decay branching ratio processes, such as the Higgs boson coupling to charge leptons 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 on the largest possible solid angle. To ensure proper trigger performance within the present coverage, the muon system will be completed with new chambers. In figure 2.2 one can see that the existing Cathode Strip Chambers (CSCs) will be completed by Gas Electron Multipliers (GEMs) and Resistive Plate Chambers (RPCs) in the pseudo-rapidity region $1.6 < |\eta| < 2.4$ to complete its redundancy as originally scheduled in the CMS Technical Proposal [3].

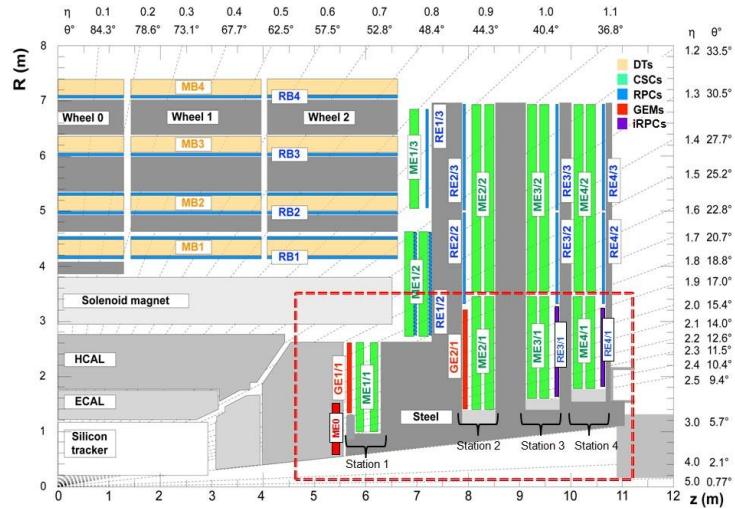


Figure 2.2: A quadrant of the muon system, showing DTs (yellow), RPCs (light blue), and CSCs (green). The locations of new forward muon detectors for Phase-II are contained within the dashed box and indicated in red for GEM stations ($ME0$, $GE1/1$, and $GE2/1$) and dark blue for improved RPC ($iRPC$) stations ($RE3/1$ and $RE4/1$).

RPCs are used by the CMS first level trigger for their good timing performances. Indeed, a very

471 good bunch crossing identification can be obtained with the present CMS RPC system, given their
 472 fast response of the order of 1 ns. In order to contribute to the precision of muon momentum mea-
 473 surements, muon chambers should have a spatial resolution less or comparable to the contribution
 474 of multiple scattering [1]. Most of the plausible physics is covered only considering muons with
 475 $p_T < 100$ GeV thus, in order to match CMS requirements, a spatial resolution of $\mathcal{O}(\text{few mm})$ the
 476 proposed new RPC stations, as shown by the simulation in figure 2.3. According to preliminary
 477 designs, RE3/1 and RE4/1 readout pitch will be comprised between 3 and 6 mm and 5 η -partitions
 478 could be considered.

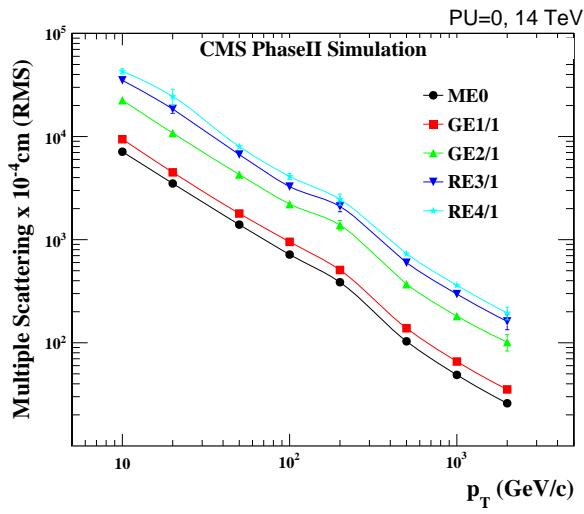


Figure 2.3: RMS of the multiple scattering displacement as a function of muon p_T for the proposed forward muon stations. All of the electromagnetic processes such as bremsstrahlung and magnetic field effect are included in the simulation.

3

479

480

Amplification processes in gaseous detectors

481

3.1 Signal formation

482

3.2 Gas transport parameters

4

483

484

Resistive Plate Chambers

485 A Resistive Plate Chamber (RPC) is a gaseous detector using the same physical processes described
486 in Chapter 3. It has been developed in 1981 by Santonico and Cardarelli [4], under the name of
487 *Resistive Plate Counter*, as an alternative to the local-discharge spark counters proposed in 1978
488 by Pestov and Fedotovich [5, 6]. Working with spark chambers implied using high-pressure gas
489 and high mechanical precision which the RPC simplified by formerly using a gas mixture of argon
490 and butane flowed at atmospheric pressure and a constant and uniform electric field propagated
491 in between two parallel electrode plates. Moreover, a significant increase in rate capability was
492 introduced by the use of electrode plate material with high bulk resistivity, preventing the discharge
493 from growing throughout the whole gas gap. Indeed, the effect of using resistive electrodes is that
494 the constant electric field is locally canceled out by the development of the discharge, limiting its
495 growth.

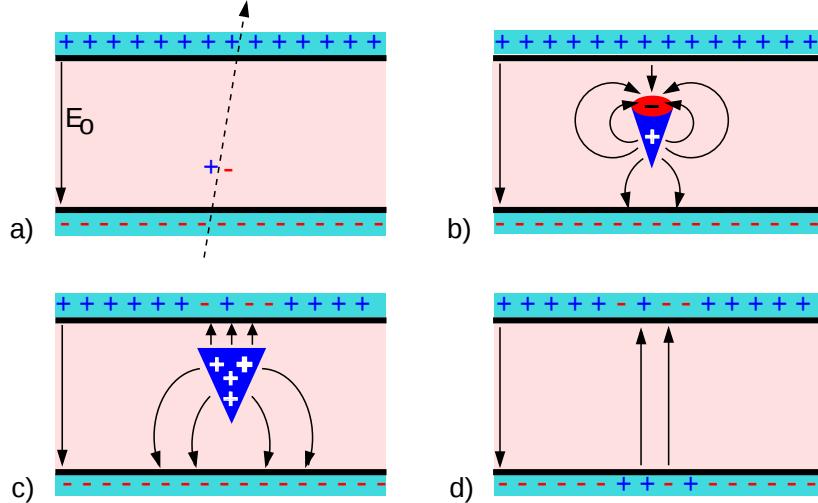
496 Through its development history, different operating modes [7–9] and new detector designs [10–
497 12] have been discovered, leading to further improvement of the rate capability of such a detector.
498 Moreover, the addition of SF_6 into the gas mix improved the stability of operation of the RPC [13,
499 14].

500 The low developing costs and easily achievable large detection areas offered by RPCs, as well
501 as the wide range of possible designs, made them a natural choice to as muon chambers and/or
502 trigger detectors in multipurpose experiments such as CMS [1] or ATLAS [15], time-of-flight detec-
503 tors in ALICE [16], calorimeter with CALICE [17] or even detectors for volcanic muography with
504 ToMuVol [18].

505 4.1 Principle

506 RPCs are ionisation detectors composed of two parallel resistive plate electrodes in between which
507 a constant electric field is set. The space in between the electrodes, referred as *gap*, is filled with a
508 dense gas that is used to generate primary ionization into the gas volume. The free charge carriers
509 (electrons and cations) created by the ionization of the gas molecules are then accelerated towards

510 the electrodes by the electric field, as shown in Figure 4.1 [19].



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

517 RPCs being passive detectors, a current on pick-up copper read-out placed outside of the gas
 518 volume is induced by the charge accumulation during the growth of the avalanche. As a result,
 519 the time resolution of the detector is substantially increased as the output signal is generated while
 520 the electrons are still in movement. The advantage of a constant electric field, over multi-wire
 521 proportional chambers, is that the electrons are being fully accelerated from the moment charge
 522 carriers are freed and feel the full strength of the electric field that doesn't depend on the distance to
 523 the readout and that the output signal doesn't need for the electrons to be physically collected.
 524

525 The typical gas mixture RPCs are operated with is generally composed of 3 gas compounds.

- 526 • Tetrafluoroethane ($C_2F_4H_2$), also referred to as *Freon*, is the principal compound of the RPC
 527 gas mixtures, with a typical fraction above 90%. It is used for it's high effective Townsend
 528 coefficient and the great average fast charge that allows to operate the detector with a high
 529 threshold with respect to argon, for example, that has similar effective Townsend coefficient
 530 but suffers from a lower fast charge. To operate with similar conditions, argon would require a
 531 higher electric field leading to a higher fraction of streamers, thus limiting the rate capability
 532 of the detector [20].
- 533 • Isobutane (i- C_4H_{10}), only present in a few percent in the gas mixtures, is used for its UV
 534 quenching properties [21] helping to prevent streamers due to UV photon emission during the
 535 avalanche growth.
- 536 • Sulfur hexafluoride, (SF_6), referred to simply as *SF6*, is used in very little quantities for its
 537 high electronegativity. Excess of electrons are being absorbed by the compound and streamers

531 are suppressed [14]. Nevertheless, a fraction of SF_6 higher than 1% will not bring any extra
 532 benefice in terms of streamer cancelation power but will lead to higher operating voltage.

533 After an avalanche developed in the gas, a time long compared to the development of a discharge
 534 is needed to recombine the charge carriers in the electrode material due to their resistivity. This
 535 property has the advantage of affecting the local electric field and avoiding sparks in the detector
 536 but, on the other hand, the rate capability is intrinsically limited by the time constant τ_{RPC} of the
 537 detector. Using a quasi-static approximation of Maxwell's equations for weakly conducting media,
 538 it can be shown that the time constant τ_{RPC} necessary to the charge recombination at the interface
 539 in between the electrode and the gas volume is given by the Formula 4.1 [22].

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

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

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

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

Material	$\rho_{electrode} (\Omega \cdot \text{cm})$	ϵ_r	$\tau_{RPC} (\text{ms})$
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.

549 4.1.1 Electron drift velocity

550 4.2 Rate capability and time resolution of Resistive Plate Cham- 551 bers

552 As already previously discussed, the electrode material plays a key role in the max intrinsic rate
 553 capability of RPCs. R&D is being done to develop at always cheaper costs material with lower
 554 resistivity. Nevertheless, the amount of charge released, i.e. the size of the discharge, if reduced
 555 leads to a smaller blind area in the detector, increasing the rate capability of the detector.

556 **4.2.1 Operation modes**

557 RPCs were developed early 1980s. At that time it was using an operating mode now referred to
 558 as *streamer mode*. Streamers are large discharges that develop in between the 2 electrodes enough
 559 to locally discharge the electrodes. If the electric field inside of the gas volume is strong enough,
 560 with electrons being fast compared to ions, a large and dense cloud of positive ions will develop
 561 nearby the anode and extend toward the cathode while the electrons are being collected, eventually
 562 leading to a streamer discharge due to the increase of field seen at the cathode. The field is then strong
 563 enough so that electrons are pulled out of the cathode. Electrodes, though they are a unique volume
 564 of resistive material, can be assimilated to capacitors. At the moment an electric field is applied in
 565 between their outer surfaces, the charge carriers inside of the volume will start moving leading to
 566 a situation where there is no voltage across the electrodes and a higher density of negative charges,
 567 i.e. electrons, on the inner surface of the cathode. Finally, when a streamer discharge occurs, these
 568 electrons are partially released in the gas volume contributing to increase the discharge strength until
 569 the formation of a conductive plasma, the streamer. This can be understood through Figure 4.2 [7].
 570 Streamer signals are very convenient in terms of read-out as no amplification is required with output
 571 pulses amplitudes of the order of a few tens to few hundreds of mV as can be seen on Figure 4.3.

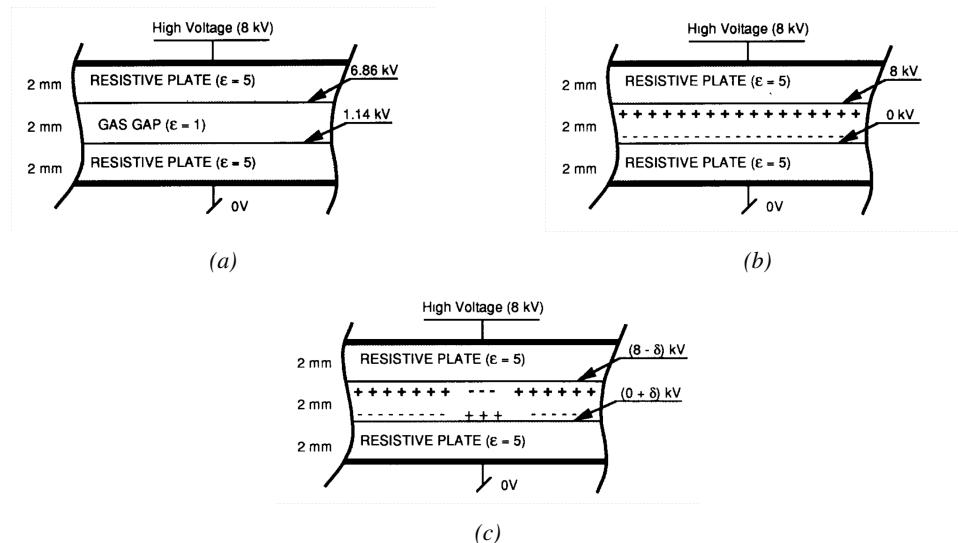


Figure 4.2: Movement of the charge carriers in an RPC. Figure 4.2a: Voltage across an RPC whose electrode have a relative permittivity of 5 at the moment the tension is applied. Figure 4.2b: After the charge carriers moved, the electrodes are charged and there is no voltage drop over the electrodes anymore. 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.

572 When the electric field is reduced though, the electronic gain is small until the electrons get close
 573 enough to the anode and the positive ion cloud is much smaller. The electric field cannot rise to the
 574 point a field emission of electrons on the cathode is possible. The resulting signal is weak, of the
 575 order of a few mv as shown on Figure 4.3, and requires amplification. This is the *avalanche mode*
 576 of RPC operation.

577 This mode offers a higher rate capability by providing smaller discharges that don't affect the
 578 electrodes charge and are more locally contained in the gas volume as was demonstrated by Crotty

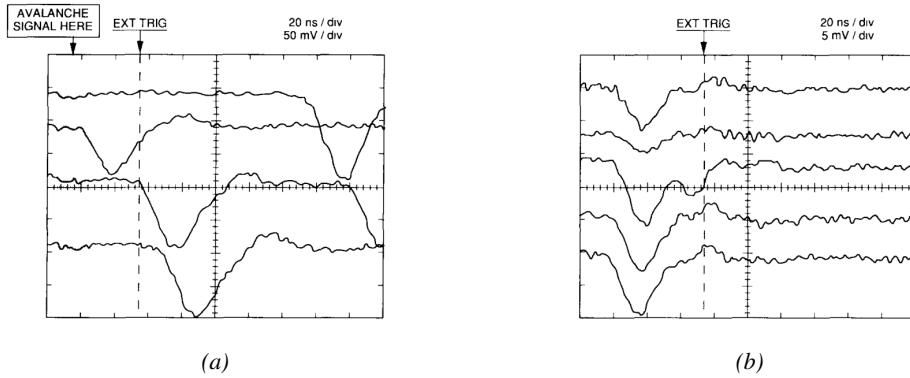


Figure 4.3: Typical oscilloscope pulses in streamer mode (Figure 4.3a) and avalanche mode(Figure 4.3b). In the case of streamer mode, the very small avalanche signal is visible.

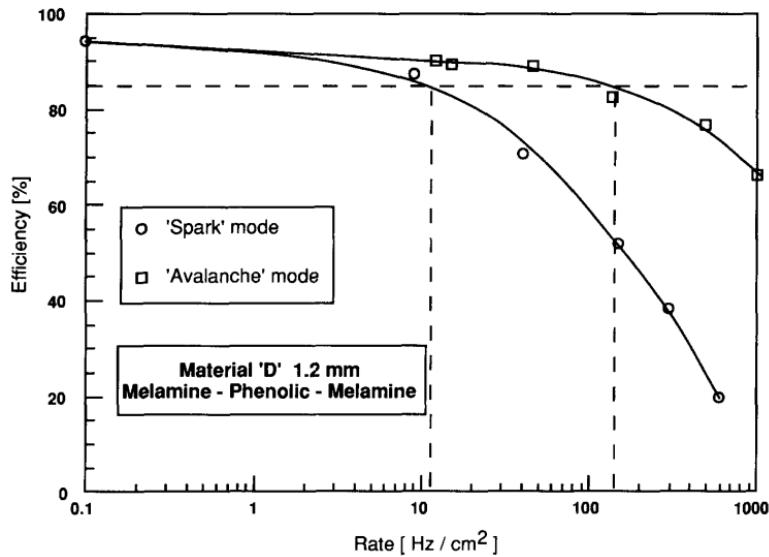


Figure 4.4: Rate capability comparison for the streamer and avalanche mode of operation. An order of magnitude in rate capability for a maximal efficiency drop of 10% is gained by using the avalanche mode over the streamer mode.

579 with Figure 4.4 [7]. The detector only stays locally blind the time the charge carriers are recombined
 580 and there is no need for electrode recharge which is a long process affecting a large portion of
 581 the detector. Another advantage of avalanche signals over streamer is the great time consistency.
 582 Figure 4.3 shows very clearly that avalanche signals have a very small time jitter. This is a natural
 583 choice for high rate experiments.

584 4.2.2 Detector design, active volume and time jitter

585 Different RPC design have been used and each of them present its own advantages. Historically, the
 586 first type of RPC to have been developed is what is referred now to *narrow gap* RPC [4, 23]. After

the avalanche mode has been discovered [7], it has been proven that increasing the width of the gas gap lead to higher rate capability, due to lower charge deposition per avalanche, and lower power dissipation [23]. 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 threshold, 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 [10]. To solve improve both the time resolution and the rate capability, different methods were used trying to get advantages of both narrow and wide gap RPCs.

Double gap RPCs are made out of 2 narrow RPC detectors. The 2 RPC gap are placed on top of each other, their anodes facing each other and placing the readout panel with the copper strips in between the 2 RPCs. This detector layout is used as an OR system in which each individual chamber participates in the ouput signal. The gain of such a detector is greatly reduced with respect to single gap RPCs with an efficiency plateau reached at lower voltage as visible on Figure 4.5.

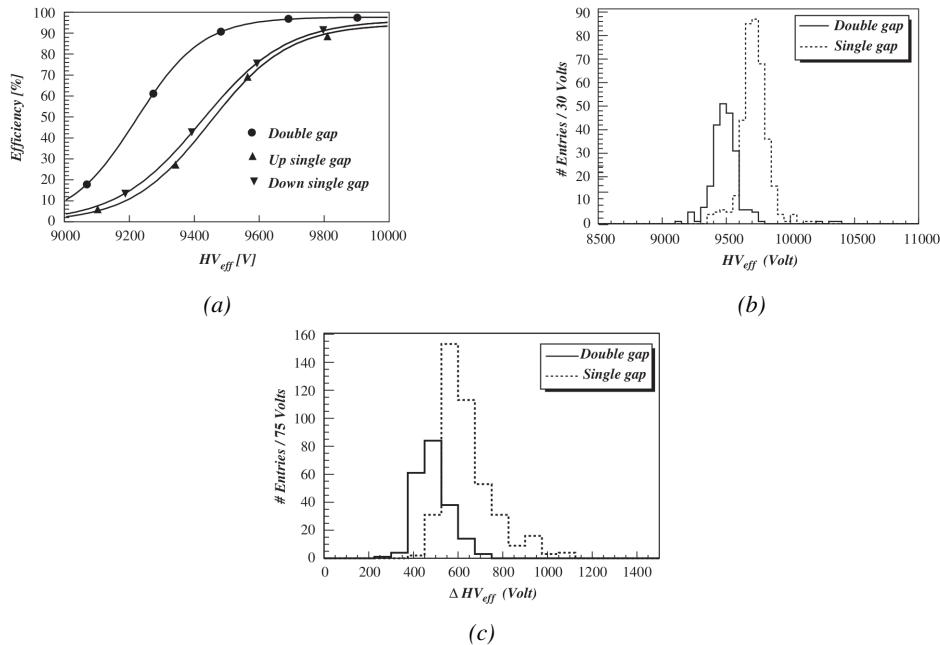


Figure 4.5: Comparison of performance of CMS double and single gap RPCs using cosmic muons [24]. Figure 4.5a: Comparison of efficiency sigmoids. Figure 4.5b: Voltage distribution at 95% of maximum efficiency. Figure 4.5c: $\Delta_{10\%}^{90\%}$ distribution.

Multigap RPC (MRPC) are layouts in which floating sub electrode plates are placed into a wide gap RPC to divide the gas volume and create a sum of narrow gaps [10, 11]. 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 shown in Figure 4.6 representing ALICE Time-of-flight (ToF) MRPCs. Sometimes used as a double multigap RPC, taking advantage of the OR of double gap RPCs, the MRPC is mainly used as ToF detector [25–29] due to its excellent timing properties that allow to perform particle identification

as explained by Williams in [30]. An example of particle identification is given for the case of STAR experiment in Figure 4.7. Another benefit of using such small gas gaps is the strong reduction of the average avalanche volume and thus of the blind spot on MRPCs leading to an improved rate capability. Multigaps can sustain backgrounds of several kHz/cm² as demonstrated in Figure 4.8.

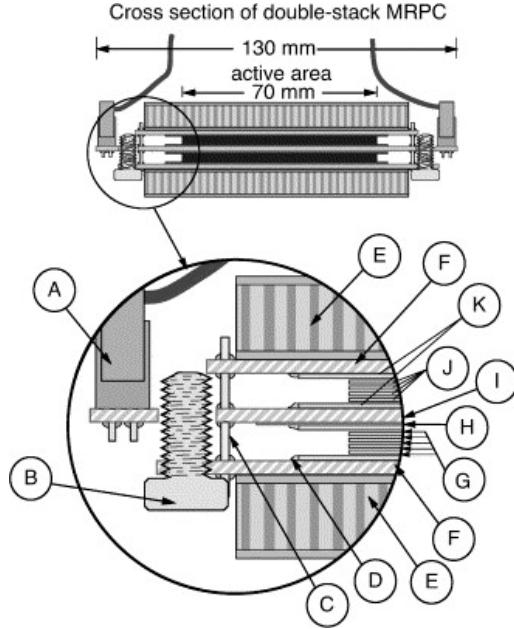


Figure 4.6: Presentation of ALICE MRPC using 250 μm gas gaps, 620 μm outer glass electrodes and 550 μm inner floating electrodes. More details on the labels are given in [25].

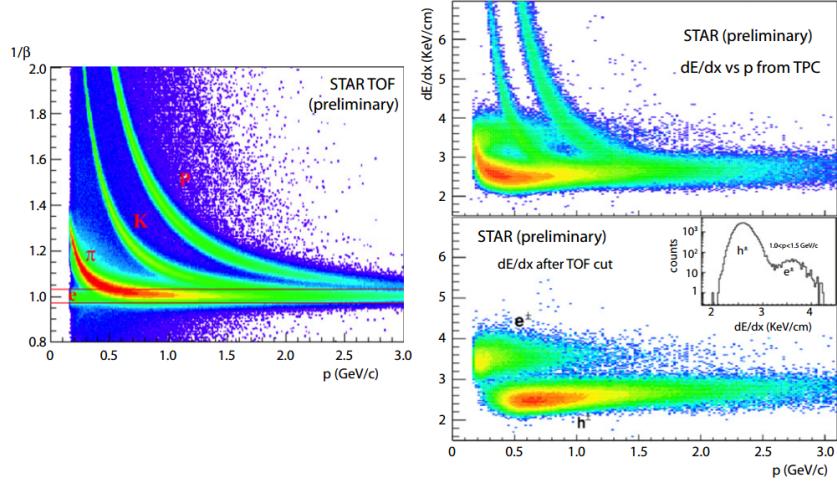


Figure 4.7: Particle identification applied to electrons in the STAR experiment. The identification is performed combining ToF and dE/dx measurements [30].

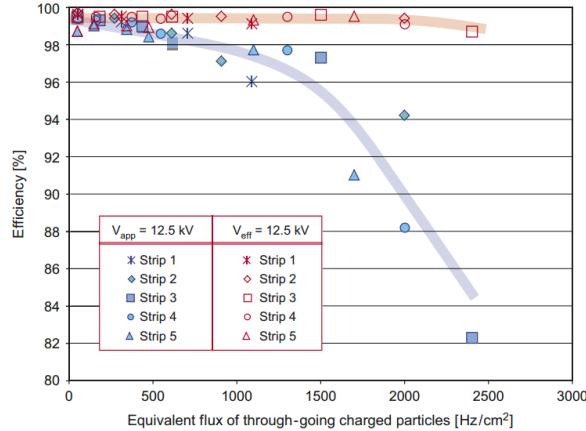


Figure 4.8: Comparison of the detector performance of ALICE ToF MRPC [31] at fixed applied voltage (in blue) and at fixed effective voltage (in red). The effective voltage is kept fixed by increasing the applied voltage accordingly to the current drawn by the detector.

611 4.3 Resistive Plate Chambers at CMS

612 4.3.1 Overview

613 The Resistive Plate Chambers (RPC) system, located in both barrel and endcap regions, provides a
 614 fast, independent muon trigger with a looser p_T threshold over a large portion of the pseudorapidity
 615 range ($|\eta| < 1.6$) [add reconstruction].

616
 617 During High-Luminosity LHC (HL-LHC) operations the expected conditions in terms of back-
 618 ground and pile-up will make the identification and correct P_T assignment a challenge for the Muon
 619 system. The goal of RPC upgrade is to provide additional hits to the Muon system with precise tim-
 620 ing. All these informations will be elaborated by the trigger system in a global way enhancing the
 621 performance of the trigger in terms of efficiency and rate control. The RPC Upgrade is based on two
 622 projects: an improved Link Board System and the extension of the RPC coverage up to $|\eta| = 2.4$.
 623 [FIXME 2.4 or 2.5?]

624 The Link Board system, that will be described in section xxx, is responsible to process, syn-
 625 chronize and zero-suppress the signals coming from the RPC front end boards. The Link Board
 626 components have been produced between 2006 and 2007 and will be subjected to aging and failure
 627 in the long term. The upgraded Link Board system will overcome the aging problems described in
 628 section xxx and will allow for a more precise timing information to the RPC hits from 25 to 1 ns [ref
 629 section xxx].

630 The extension of the RPC system up to $|\eta| = 2.1$ was already planned in the CMS TDR [ref
 631 cmstdr] and staged because of budget limitations and expected background rates higher than the rate
 632 capability of the present CMS RPCs in that region. An extensive R&D program has been done in
 633 order to develop an improved RPC that fulfills the CMS requirements. Two new RPC layers in the
 634 innermost ring of stations 3 and 4 will be added with benefits to the neutron-induced background
 635 reduction and efficiency improvement for both trigger and offline reconstruction.

636 4.3.2 The present RPC system

637 The RPC system is organized in 4 stations called RB1 to RB4 in the barrel region, and RE1 to RE4
638 in the endcap region. The innermost barrel stations, RB1 and RB2, are instrumented with 2 layers
639 of RPCs facing the innermost (RB1in and RB2in) and outermost (RB1out and RB2out) sides of the
640 DT chambers. Every chamber is then divided from the read-out point of view into 2 or 3 η partitions
641 called “rolls”. The RPC system consist of 480 barrel chambers and 576 endcap chambers. Details
642 on the geometry are discussed in the paper [ref to geo paper].

643 The CMS RPC chamber is a double-gap, operated in avalanche mode to ensure reliable operation
644 at high rates. Each RPC gap consists of two 2-mm-thick resistive High-Pressure Laminate (HPL)
645 plates separated by a 2-mm-thick gas gap. The outer surface of the HPL plates is coated with a thin
646 conductive graphite layer, and a voltage is applied. The RPCs are operated with a 3-component,
647 non-flammable gas mixture consisting of 95.2% freon ($C_2H_2F_4$, known as R134a), 4.5% isobutane
648 ($i-C_4H_{10}$), and 0.3% sulphur hexafluoride (SF_6) with a relative humidity of 40% - 50%. Readout
649 strips are aligned in η between the 2 gas gaps. [\[Add a sentence on FEBs.\]](#)

650 The discriminated signals coming from the Front End boards feed via twisted cables (10 to 20 m
651 long) the Link Board System located in UXC on the balconies around the detector. The Link System
652 consist of the 1376 Link Boards (LBs) and the 216 Control Boards (CBs), placed in 108 Link Boxes.
653 The Link Box is a custom crate (6U high) with 20 slots (for two CBs and eighteen LBs). The Link
654 Box contains custom backplane to which the cables from the chambers are connected, as well as the
655 cables providing the LBs and CBs power supply and the cables for the RPC FEBs control with use
656 of the I2C protocol (trough the CB). The backplane itself contains only connectors (and no any other
657 electronic devices).

658 The Link Board has 96 input channels (one channel corresponds to one RPC strip). The input
659 signals are the ~ 100 ns binary pulses which are synchronous to the RPC hits, but not to the LHC
660 clock (which drives the entire CMS electronics). Thus the first step of the FEB signals processing
661 is synchronization, i.e. assignment of the signals to the BXes (25 ns periods). Then the data are
662 compressed with a simple zero-suppressing algorithm (the input channels are grouped into 8 bit
663 partitions, only the partitions with at least one nonzero bit are selected for each BX). Next, the non-
664 empty partitions are time-multiplexed i.e. if there are more than one such partition in a given BX,
665 they are sent one-by-one in consecutive BXes. The data from 3 neighbouring LBs are concentrated
666 by the middle LB which contains the optical transmitter for sending them to the USC over a fiber at
667 1.6 Gbps.

668 The Control Boards provide the communication of the control software with the LBs via the
669 FEC/CCU system. The CBs are connected into token rings, each ring consists of 12 CBs of one
670 detector tower and a FEC mezzanine board placed on the CCS board located in the VME crate in
671 the USC. In total, there are 18 rings in the entire Link System. The CBs also perform automatic
672 reloading of the LB's firmware which is needed in order to avoid accumulation of the radiation
673 induced SEUs in the LBs firmware.

674 Both LBs and CB are based on the Xilinx Spartan III FPGAs, the CB additionally contains
675 radiation-tolerant (FLASH based) FPGA Actel ProAsicPlus.

676 The High Voltage power system is located in USC, not exposed to radiation and easily accessible
677 for any reparation. A single HV channel powers 2 RPC chambers both in the barrel and endcap
678 regions. The Low Voltage boards are located in UXC on the balconies and provide the voltage to the
679 front end electronics.

4.3.3 Pulse processing of CMS RPCs

681 Signals induced by cosmic particle in the RPC strips are shaped by standard CMS RPC Front-End
 682 Electronics (FEE) following the scheme of Figure 4.9. On a first stage, analogic signals are amplified
 683 and then sent to the Constant Fraction Discriminator (CFD) described in Figure 4.10. At the end of
 684 the chain, 100 ns long pulses are sent in the LVDS output. These output signal are sent on one side to
 685 a V1190A Time-to-Digital Converter (TDC) module from CAEN and on the other to an OR module
 686 to count the number of detected signals. Trigger and hit coïncidences are monitored using scalers.
 687 The TDC is used to store the data into ROOT files. These files are thus analysed to understand the
 688 detectors performance.

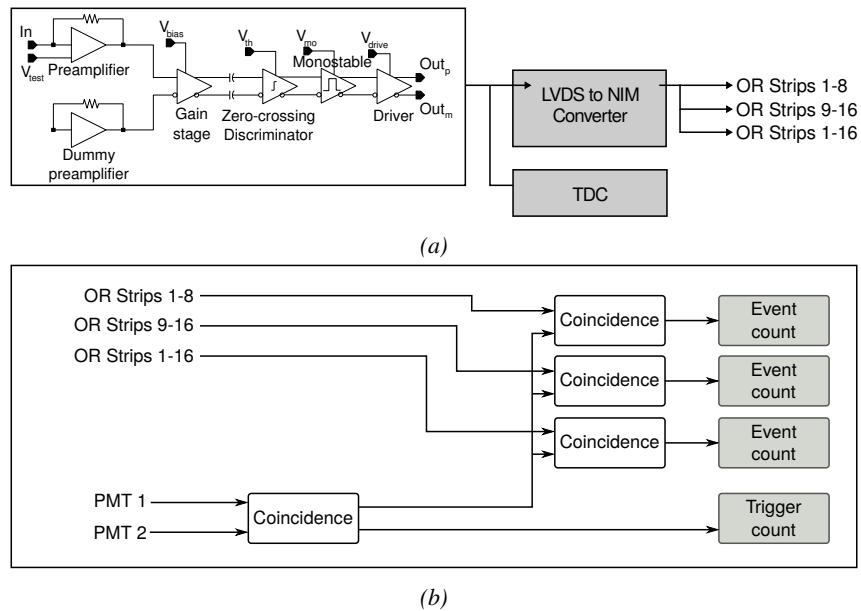


Figure 4.9: Signals from the RPC strips are shaped by the FEE described on Figure 4.9a. Output LVDS signals are then read-out by a TDC module connected to a computer or converted into NIM and sent to scalers. Figure 4.9b describes how these converted signals are put in coincidence with the trigger.

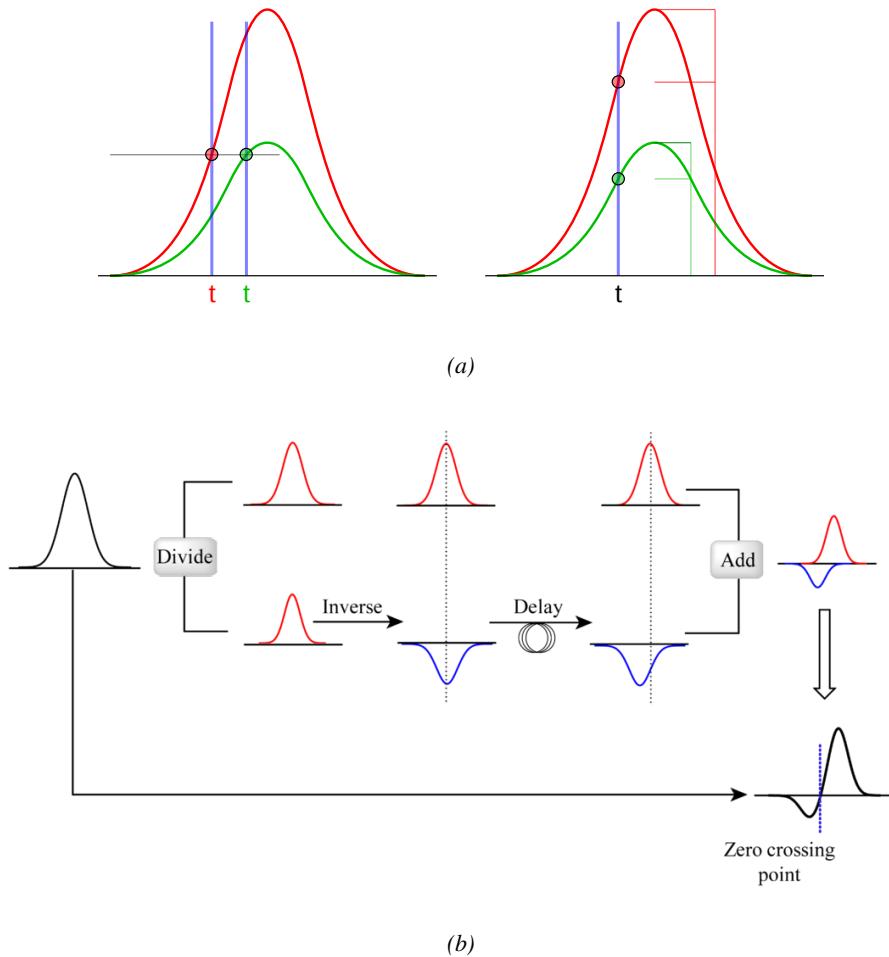


Figure 4.10: Description of the principle of a CFD. A comparison of threshold triggering (left) and constant fraction triggering (right) is shown in Figure 4.10a. Constant fraction triggering is obtained thanks to zero-crossing technique as explained in Figure 4.10b. The signal arriving at the input 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.

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Longevity studies and Consolidation of the present CMS RPC subsystem

692

5.1 Testing detectors under extreme conditions

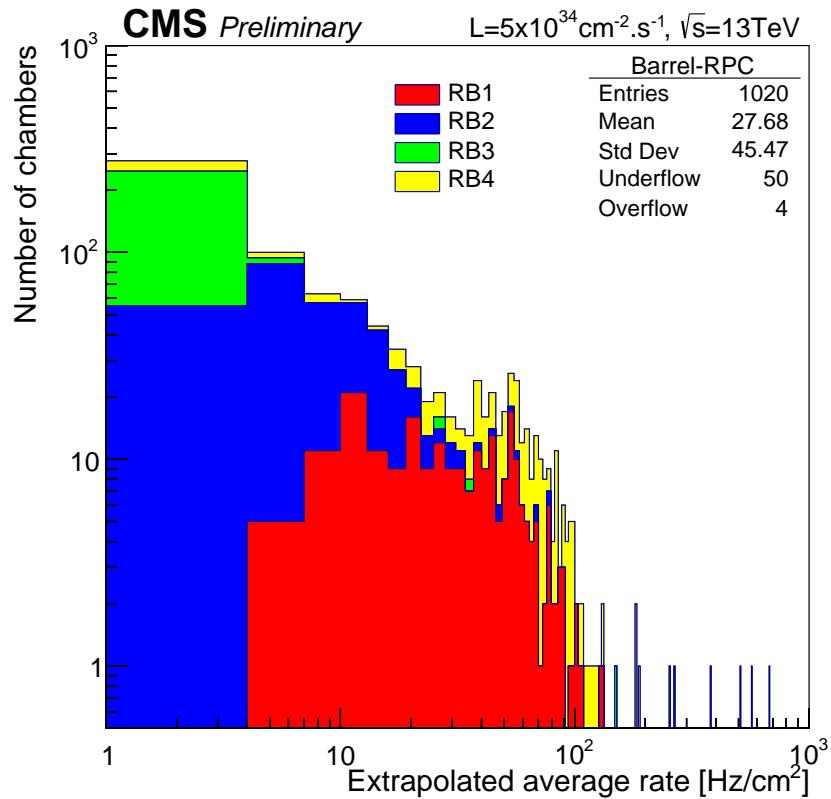
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The upgrade from LHC to HL-LHC will increase the peak luminosity from $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to reach $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, increasing in the same way the total expected background to which the RPC system will be subjected to. Composed of low energy gammas and neutrons from $p\text{-}p$ collisions, low momentum primary and secondary muons, puch-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.

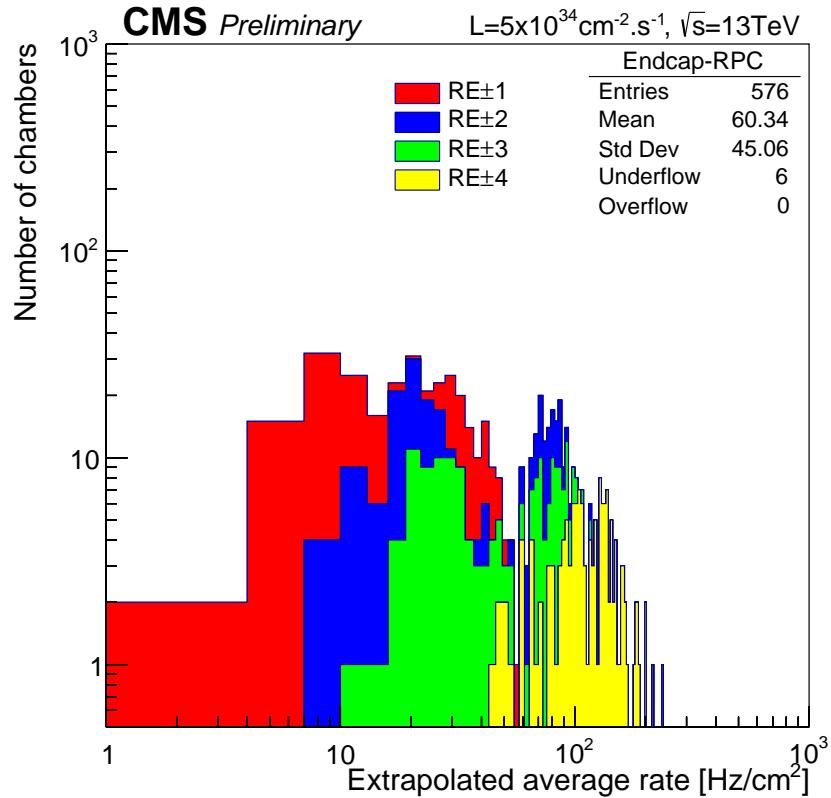
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The 2016 data allowed to study the values of the background rate in all RPC system. In Figure 5.1, the distribution of the chamber background hit rate per unit area is shown at a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ linearly extrapolating from data collected in 2016 [ref mentioning the linear dependency of rate vs lumi]. The maximum rate per unit area at HL-LHC conditions is expected to be of the order of 600 Hz/cm^2 (including a safety factor 3). Nevertheless, Fluka simulations have conducted in order to understand the background at HL-LHC conditions. The comparison to the data has shown, in Figure 5.2, a discrepancy of a factor 2 even though the order of magnitude is consistent. [Understand mismatch.]



(a)



(b)

Figure 5.1: (5.1a) Extrapolation from 2016 data of single hit rate per unit area in the barrel region. (5.1b) Extrapolation from 2016 data of single hit rate per unit area in the endcap region.

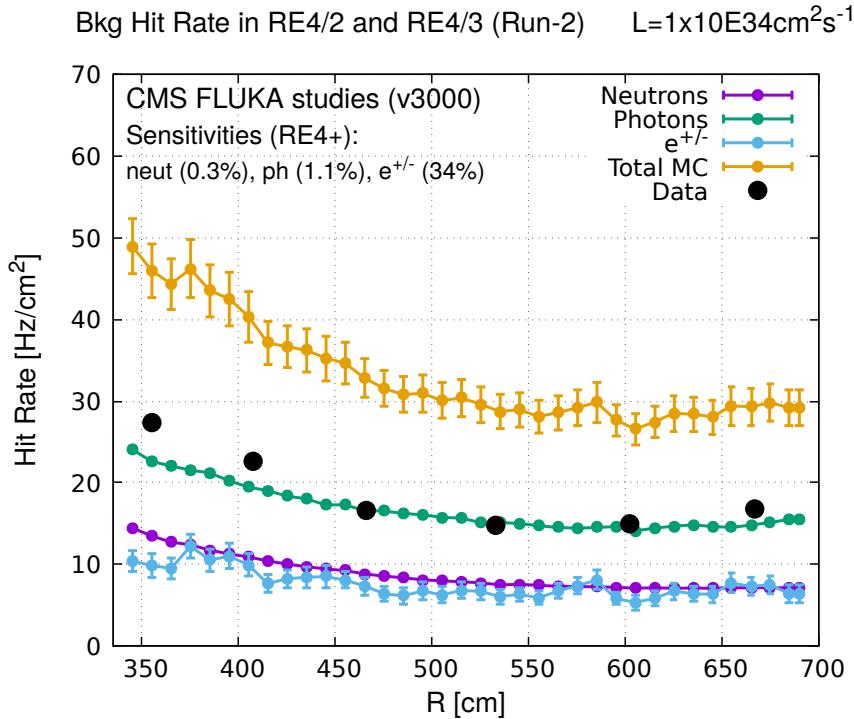


Figure 5.2: Background Fluka simulation compared to 2016 Data at $L = 10^{34}\text{cm}^{-2}\cdot\text{s}^{-1}$ in the fourth endcap disk region. A mismatch in between simulation and data can be observed. [\[To be understood.\]](#)

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 $\sim 0.05C/\text{cm}^2$ and $\sim 0.4C/\text{cm}^2$, respectively [32, 33]. During Run-I, the RPC system provided stable operation and excellent performance and did not show any aging effects for integrated charge of the order of $0.01C/\text{cm}^2$. Projections on currents from 2016 Data, has allowed to determine that the total integrated charge, by the end of HL-LHC, would be of the order of $1C/\text{cm}^2$ (including a safety factor 3). [\[Corresponding figure needed.\]](#)

717

718 5.1.1 The Gamma Irradiation Facilities

719 5.1.1.1 GIF

720 Located in the SPS West Area at the downstream end of the X5 test beam, the Gamma Irradiation
721 Facility (GIF) was a test area in which particle detectors were exposed to a particle beam in presence
722 of an adjustable gamma background [34]. Its goal was to reproduce background conditions these
723 detectors would suffer in their operating environment at LHC. GIF layout is shown in Figure 5.3.
724 Gamma photons are produced by a strong ^{137}Cs source installed in the upstream part of the zone
725 inside a lead container. The source container includes a collimator, designed to irradiate a $6 \times 6\text{ m}^2$
726 area at 5 m maximum to the source. A thin lens-shaped lead filter helps providing with a uniform
727 outcoming flux in a vertical plane, orthogonal to the beam direction. The principal collimator hole
728 provides a pyramidal aperture of $74^\circ \times 74^\circ$ solid angle and provides a photon flux in a pyramidal vol-

ume along the beam axis. The photon rate is controled by further lead filters allowing the maximum rate to be limited and to vary within a range of four orders of magnitude. Particle detectors under test are then placed within the pyramidal volume in front of the source, perpendicularly to the beam line in order to profit from the homogeneous photon flux. Adjusting the background flux of photons can then be done by using the filters and choosing the position of the detectors with respect to the source.

734

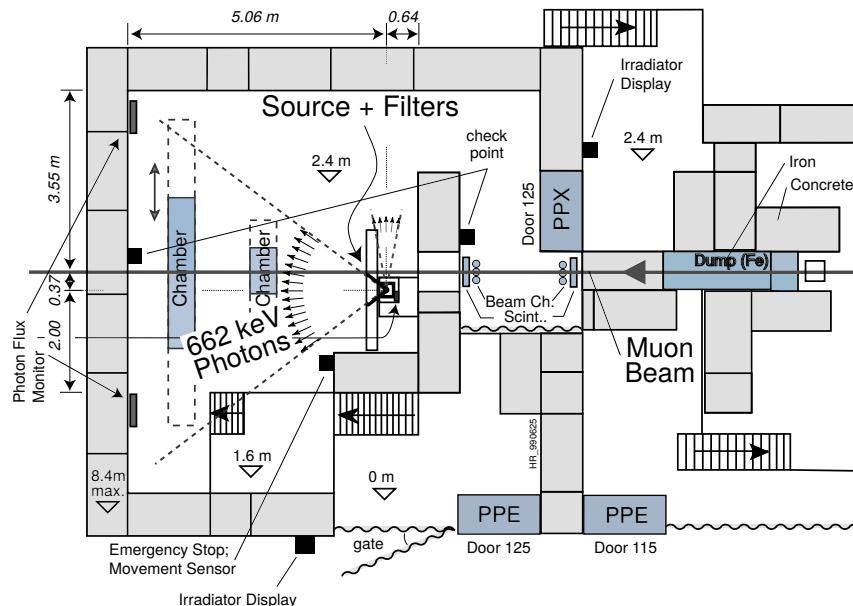


Figure 5.3: Layout of the test beam zone called X5c GIF at CERN. Photons from the radioactive source produce a sustained high rate of random hits over the whole area. The zone is surrounded by 8 m high and 80 cm thick concrete walls. Access is possible through three entry points. Two access doors for personnel and one large gate for material. A crane allows installation of heavy equipment in the area.

As described on Figure 5.4, the ^{137}Cs source emits a 662 keV photon in 85% of the decays. An activity of 740 GBq was measured on the 5th March 1997. To estimate the strength of the flux in 2014, it is necessary to consider the nuclear decay through time assiciated to the Cesium source whose half-life is well known ($t_{1/2} = (30.05 \pm 0.08)$ y). The GIF tests where done in between the 20th and the 31st of August 2014, i.e. at a time $t = (17.47 \pm 0.02)$ y resulting in an attenuation of the activity from 740 GBq in 1997 to 494 GBq in 2014.

741

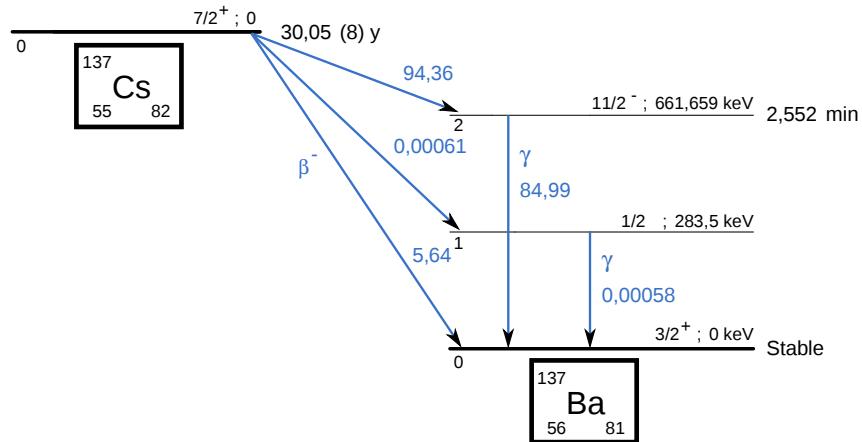


Figure 5.4: ^{137}Cs decays by β^- emission to the ground state of ^{137}Ba ($BR = 5.64\%$) and via the 662 keV isomeric level of ^{137}Ba ($BR = 94.36\%$) whose half-life is 2.55 min.

742 5.1.1.2 GIF++

743 The new Gamma Irradiation Facility (GIF++), located in the SPS North Area at the downstream end
 744 of the H4 test beam, has replaced its predecessor during LS1 and has been operational since spring
 745 2015 [35]. Like GIF, GIF++ features a ^{137}Cs source of 662 keV gamma photons, their fluence being
 746 controlled with a set of filters of various attenuation factors. The source provides two separated large
 747 irradiation areas for testing several full-size muon detectors with continuous homogeneous irradiation,
 748 as presented in Figure 5.5.

749

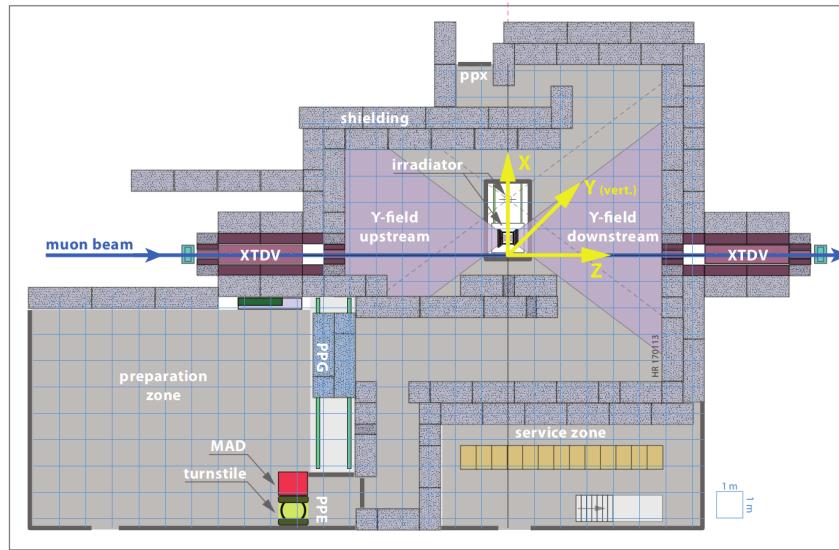


Figure 5.5: Floor plan of the GIF++ facility. When the facility downstream of the GIF++ takes electron beam, a beam pipe is installed along the beam line (z-axis). The irradiator can be displaced laterally (its center moves from $x = 0.65 \text{ m}$ to 2.15 m), to increase the distance to the beam pipe.

750 The source activity was measured to be about 13.5 TBq in March 2016. The photon flux being
 751 far greater than HL-LHC expectations, GIF++ provides an excellent facility for accelerated aging
 752 tests of muon detectors.

753

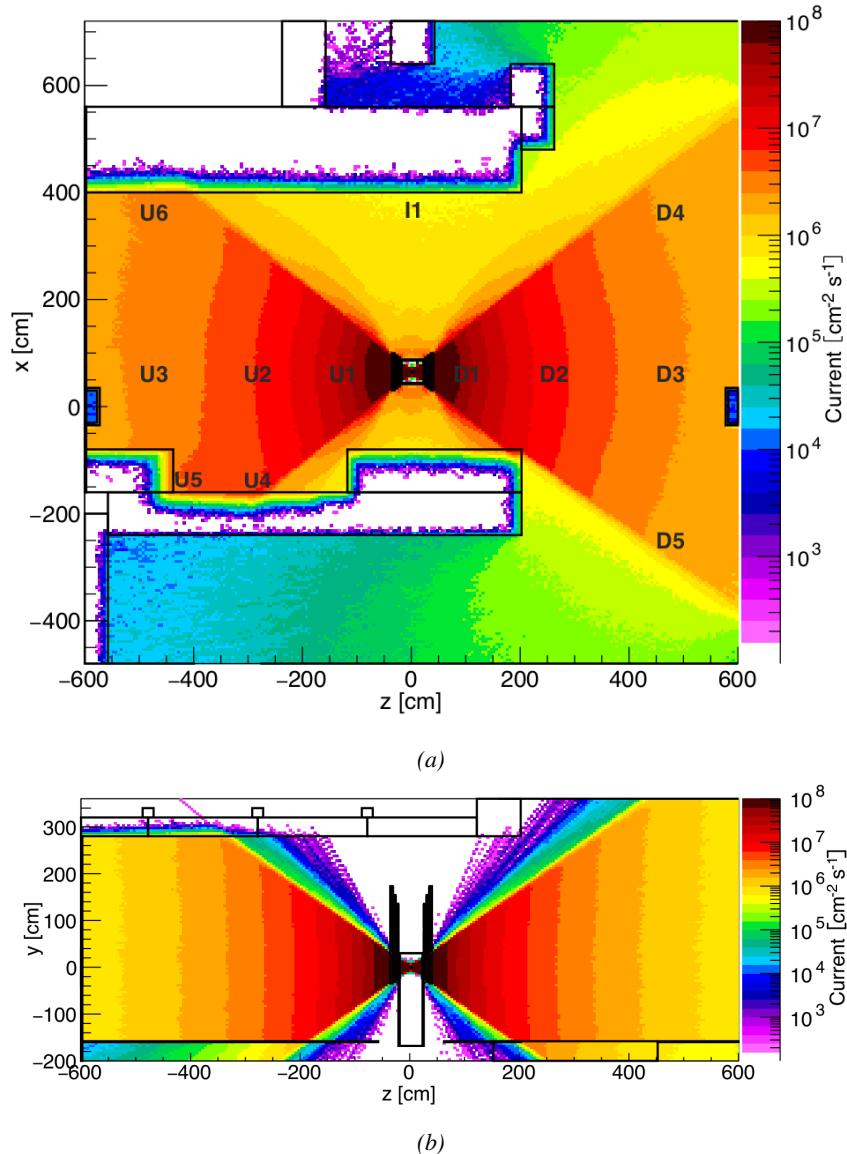


Figure 5.6: Simulated unattenuated current of photons in the xz plane (Figure 5.6a) and yz plane (Figure 5.6b) through the source at $x = 0.65 \text{ m}$ and $y = 0 \text{ m}$. With angular correction filters, the current of 662 keV photons is made uniform in xy planes.

754 The source is situated in the muon beam line with the muon beam being available a few times a
 755 year. The H4 beam, composed of muons with a momentum of about 150 GeV/c, passes through the
 756 GIF++ zone and is used to study the performance of the detectors. Its flux is of 104 particles/ s cm^2

757 focused in an area similar to $10 \times 10 \text{ cm}^2$. Therefore, with properly adjusted filters, one can imitate
 758 the HL-LHC background and study the performance of muon detectors with their trigger/readout
 759 electronics in HL-LHC environment.

760

761 5.2 Preliminary tests at GIF

762 5.2.1 Resistive Plate Chamber test setup

763 During summer 2014, preliminary tests have been conducted in the GIF area on a newly produced
 764 RE4/2 chamber labelled RE-4-2-BARC-161. This chamber has been placed into a trolley covered
 765 with a tent. The position of the RPC inside the tent and of the tent related to the source is described
 766 in Figure 5.7. To test this CMS RPC, three different absorber settings were used. First of all,
 767 measurements were done with fully opened source. Then, to complete this preliminary study, the
 768 gamma flux has been attenuated from a factor 2 and a factor 5. The expected gamma flux at the level
 769 of our detector will be discussed in subsection ??.

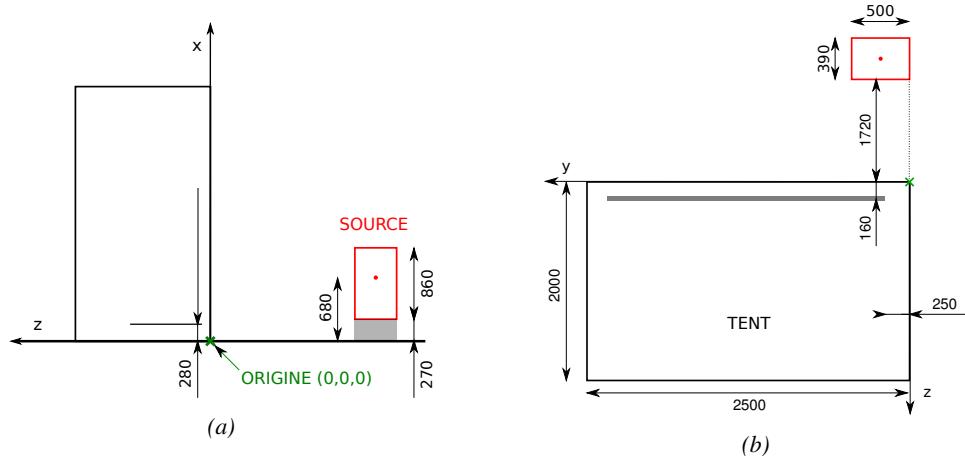


Figure 5.7: Description of the RPC setup. Dimensions are given in mm. A tent containing RPCs is placed at 1720 mm from the source container. The source is situated in the center of the container. RE-4-2-BARC-161 chamber is 160 mm inside the tent. This way, the distance between the source and the chambers plan is 2060 mm. Figure 5.7a provides a side view of the setup in the xz plane while Figure 5.7b shows a top view in the yz plane.



Figure 5.8: RE-4-2-BARC-161 chamber is inside the tent as described in Figure 5.7. 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.

770 At the time of the tests, the beam not being operational anymore, a trigger composed of 2
 771 plastic scintillators has been placed in front of the setup with an inclination of 10 deg with respect to
 772 the detector plane in order to look at cosmic muons. Using this particular trigger layout, shown on
 773 Figure 5.8, leads to a cosmic muon hit distribution into the chamber similar to the one in Figure 5.9.
 774 Measured without gamma irradiation, two peaks can be seen on the profil of partition B, centered
 775 on strips 52 and 59. Section ?? will help us understand that these two peaks are due respectively to
 776 forward and backward coming cosmic particles where forward coming particles are first detected by
 777 the scintillators and then the RPC while the backward coming muons are first detected in the RPC.

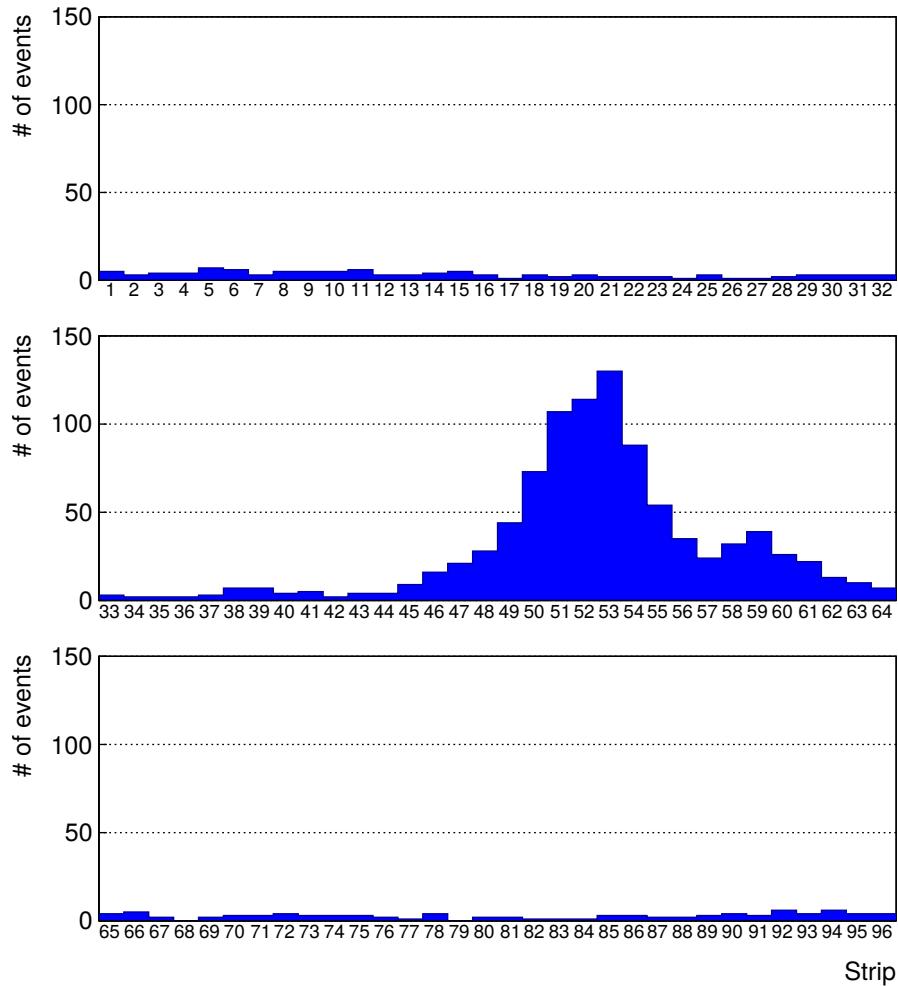


Figure 5.9: Hit distributions over all 3 partitions of RE-4-2-BARC-161 chamber is showed on these plots. Top, middle and bottom figures respectively correspond to partitions A, B, and C. These plots show that some events still occur in other half-partitions than B2, which corresponds to strips 49 to 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.

778 **5.2.2 Data Acquisition**

779 **5.2.3 Geometrical acceptance of the setup layout to cosmic muons**

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

785 protect the photomultipliers from gammas as can be seen from Figure 5.8.

786 An inclination has been given to the cosmic telescope to maximize the muon flux. A good com-
 787 promise had to be found between good enough muon flux and narrow enough hit distribution to
 788 be sure to contain all the events into only one half partitions as required from the limited available
 789 readout hardware. Nevertheless, a consequence of the misplaced trigger, that can be seen as a loss
 790 of events in half-partition B1 in Figure 5.9, is an inefficiency. Nevertheless, the inefficiency of ap-
 791 proximately 20 % highlighted in Figure 5.10 by comparing the performance of chamber BARC-161
 792 in 904 and at GIF without irradiation seems too important to be explained only by the geometri-
 793 cal acceptance of the setup itself. Simulations have been conducted to show how the setup brings
 794 inefficiency.

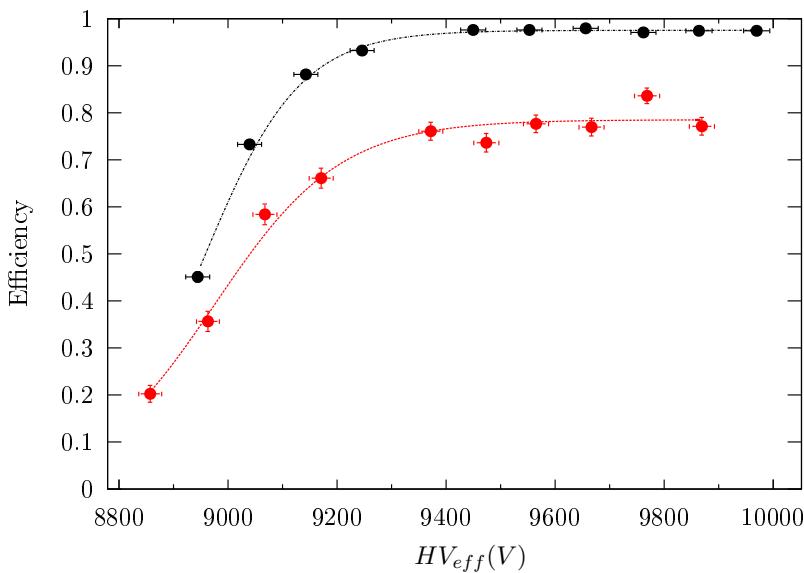


Figure 5.10: Results are derived from data taken on half-partition B2 only. On the 18th of June 2014, data has been taken on chamber RE-2-BARC-161 at building 904 (Prevessin Site) with cosmic muons providing us a reference efficiency plateau of $(97.54 \pm 0.15)\%$ represented by a black curve. A similar measurement 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.

795 **5.2.3.1 Description of the simulation layout**

796 The layout of GIF setup has been reproduced and incorporated into a Monte Carlo (MC) simulation
 797 to study the influence of the disposition of the telescope on the final distribution measured by the
 798 RPC. A 3D view of the simulated layout is given into Figure 5.11. Muons are generated randomly
 799 in a horizontal plane located at a height corresponding to the lowest point of the PMTs. This way,
 800 the needed size of the plane in order to simulate events happening at very big azimuthal angles (i.e.
 801 $\theta \approx \pi$) can be kept relatively small. The muon flux is designed to follow the usual $\cos^2\theta$ distribution
 802 for cosmic particle. The goal of the simulation is to look at muons that pass through the muon
 803 telescope composed of the two scintillators and define their distribution onto the RPC plane. During
 804 the reconstruction, the RPC plane is then divided into its strips and each muon track is assigned to a
 805 strip.

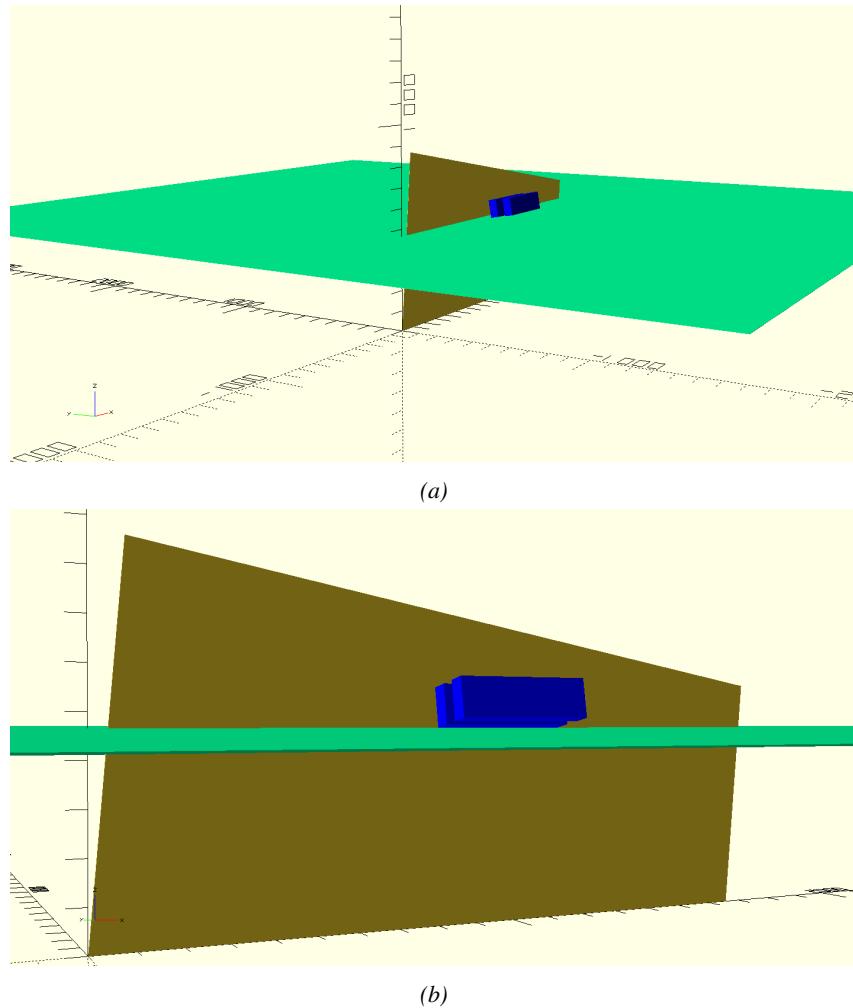


Figure 5.11: Representation of the layout used for the simulations of the test setup. The RPC is represented as a yellow trapezoid while the two scintillators as blue cuboids looking at the sky. A green plane corresponds to the muon generation plane within the simulation. Figure 5.7a shows a global view of the simulated setup. Figure 5.7b shows a zoomed view that allows to see the 2 scintillators as well as the full RPC plane.

806 In order to further refine the quality of the simulation and understand deeper the results the
 807 dependance of the distribution has been studied for a range of telescope inclinations. Moreover,
 808 the threshold applied on the PMT signals has been included into the simulation in the form of a
 809 cut. In the approximation of uniform scintillators, it has been considered that the threshold can be
 810 understood as the minimum distance particles need to travel through the scintillating material to give
 811 a strong enough signal. Particles that travel a distance smaller than the set "threshold" are thus not
 812 detected by the telescope and cannot trigger the data taking. Finally, the FEE threshold also has
 813 been considered in a similar way. The mean momentum of horizontal cosmic rays is higher than
 814 those of vertical ones but the stopping power of matter for momenta ranging from 1 GeV to 1 TeV
 815 stays comparable. It is then possible to assume that the mean number of primary e^-/ion pairs per
 816 unit length will stay similar and thus, depending on the applied discriminator threshold, muons with

817 the shortest path through the gas volume will deposit less charge and induce a smaller signal on the
 818 pick-up strips that could eventually not be detected. These two thresholds also restrain the overall
 819 geometrical acceptance of the system.

820 **5.2.3.2 Simulation procedure**

821 The simulation software has been designed using C++ and the output data is saved into ROOT
 822 histograms. Simulations start for a threshold T_{scint} varying in a range from 0 to 45 mm in steps
 823 of 5 mm, where $T_{scint} = 0$ mm corresponds to the case where there isn't any threshold apply on
 824 the input signal while $T_{scint} = 45$ mm, which is the scintillator thickness, is the case where muons
 825 cannot arrive orthogonally onto the scintillator surface. For a given T_{scint} , a set of RPC thresholds
 826 are considered. The RPC threshold, T_{RPC} varies from 2 mm, the thickness of the gas volume, to
 827 3 mm in steps of 0.25 mm. For each $(T_{scint}; T_{RPC})$ pair, $N_\mu = 10^8$ muons are randomly generated
 828 inside the muon plane described in the previous paragraph with an azimuthal angle θ chosen to follow
 829 a $\cos^2\theta$ distribution.

830 Planes are associated to each surface of the scintillators. Knowing muon position into the muon
 831 plane and its direction allows us, by assuming that muons travel in a straight line, to compute the
 832 intersection of the muon track with these planes. Applying conditions to the limits of the surfaces
 833 of the scintillator faces then gives us an answer to whether or not the muon passed through the
 834 scintillators. In the case the muon has indeed passed through the telescope, the path through each
 835 scintillator is computed and muons whose path was shorter than T_{scint} are rejected and are thus
 836 considered as having not interacted with the setup.

837 On the contrary, if the muon is labeled as good, its position within the RPC plane is computed
 838 and the corresponding strip, determined by geometrical tests in the case the distance through the
 839 gas volume was enough not to be rejected because of T_{RPC} , gets a hit and several histograms
 840 are filled in order to keep track of the generation point on the muon plane, the intersection points
 841 of the reconstructed muons within the telescope, or on the RPC plane, the path traveled through
 842 each individual scintillator or the gas volume, as well as other histograms. Moreover, muons fill
 843 different histograms whether they are forward or backward coming muons. They are discriminated
 844 according to their direction components. When a muon is generated, an (x, y, z) position is assigned
 845 into the muon plane as well as a $(\theta; \phi)$ pair that gives us the direction it's coming from. This way,
 846 muons satisfying the condition $0 \leq \phi < \pi$ are designated as backward coming muons while muons
 847 satisfying $\pi \leq \phi < 2\pi$ as forward coming muons.

848 This simulation is then repeated for different telescope inclinations ranging in between 4 and 20°
 849 and varying in steps of 2° . Due to this inclination and to the vertical position of the detector under
 850 test, the muon distribution reconstructed in the detector plane is asymmetrical. The choice as been
 851 made to chose a skew distribution formula to fit the data built as the multiplication of gaussian and
 852 sigmoidal curves together. A typical gaussian formula is given as 5.1 and has three free parameters
 853 as A_g , its amplitude, \bar{x} , its mean value and σ , its root mean square. Sigmoidal curves as given by
 854 formula 5.2 are functions converging to 0 and A_s as x diverges. The inflection point is given as x_i
 855 and λ is proportional to the slope at $x = x_i$. In the limit where $\lambda \rightarrow \infty$, the sigmoid becomes a
 856 step function.

$$g(x) = A_g e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \quad (5.1)$$

$$s(x) = \frac{A_s}{1 + e^{-\lambda(x-x_i)}} \quad (5.2)$$

Finally, a possible representation of a skew distribution is given by formula 5.3 and is the product of 5.1 and 5.2. Naturally, here $A_{sk} = A_g \times A_s$ and represents the theoretical maximum in the limit where the skew tends to a gaussian function.

$$sk(x) = g(x) \times s(x) = A_{sk} \frac{e^{\frac{-(x-\bar{x})^2}{2\sigma^2}}}{1 + e^{-\lambda(x-x_i)}} \quad (5.3)$$

5.2.3.3 Results

Influence of T_{scint} on the muon distribution

Influence of T_{RPC} on the muon distribution

Influence of the telescope inclination on the muon distribution

Comparison to data taken at GIF without irradiation

5.2.4 Photon flux at GIF

5.2.4.1 Expectations from simulations

In order to understand and evaluate the γ flux in the GIF area, simulations had been conducted in 1999 and published by S. Agosteo et al [34]. Table 5.1 presented in this article gives us the γ flux for different distances D to the source. This simulation was done using GEANT and a Monte Carlo N-Particle (MCNP) transport code, and the flux F is given in number of γ per unit area and unit time along with the estimated error from these packages expressed in %.

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

Table 5.1: Total photon flux ($E\gamma \leq 662$ 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 [34].

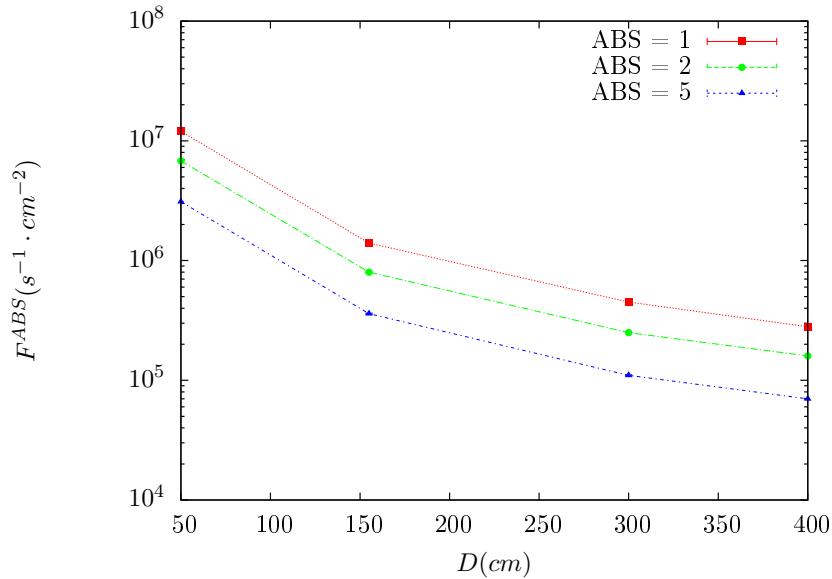


Figure 5.12: γ flux $F(D)$ is plot using values from table 5.1. As expected, the plot shows similar attenuation behaviours with increasing distance for each absorption factors.

The simulation doesn't directly provides us with an estimated flux at the level of our RPC. First of all, it is needed 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. Figure 5.12 that contains the data from Table 5.1. In the case of a pointlike source emitting isotropic and homogeneous gamma radiations, the gamma flux F at a distance D to the source with respect to a reference point situated at D_0 where a known flux F_0 is measured will be expressed like in Equation 5.4, assuming that the flux decreases as $1/D^2$, where c is a fitting factor.

$$F^{ABS} = F_0^{ABS} \times \left(\frac{cD_0}{D} \right)^2 \quad (5.4)$$

By rewriting Equation 5.4, it comes that :

$$c = \frac{D}{D_0} \sqrt{\frac{F^{ABS}}{F_0^{ABS}}} \quad (5.5)$$

$$\Delta c = \frac{c}{2} \left(\frac{\Delta F^{ABS}}{F^{ABS}} + \frac{\Delta F_0^{ABS}}{F_0^{ABS}} \right) \quad (5.6)$$

Finally, using Equation 5.5 and the data in Table 5.1 with $D_0 = 50$ cm as reference point, we can build Table 5.2. It is interesting to note that c for each value of D doesn't depend on the absorption factor.

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 formulae 5.5 taking as reference $D_0 = 50$ cm and the associated flux F_0^{ABS} for each absorption factor available in table 5.1.

883 For the range of D/D_0 values available, it is possible to use a simple linear fit to get the evolution
 884 of c . The linear fit will then use only 2 free parameters, a and b , as written in Equation 5.7. This gives
 885 us the results showed in Figure 5.13. Figure 5.13b confirms that using only a linear fit to extract c is
 886 enough as the evolution of the rate that can be obtained superimposes well on the simulation points.

$$c \left(\frac{D}{D_0} \right) = a \frac{D}{D_0} + b \quad (5.7)$$

$$F^{ABS} = F_0^{ABS} \left(a + \frac{bD_0}{D} \right)^2 \quad (5.8)$$

$$\Delta F^{ABS} = F^{ABS} \left[\frac{\Delta F_0^{ABS}}{F_0^{ABS}} + 2 \frac{\Delta a + \Delta b \frac{D_0}{D}}{a + \frac{bD_0}{D}} \right] \quad (5.9)$$

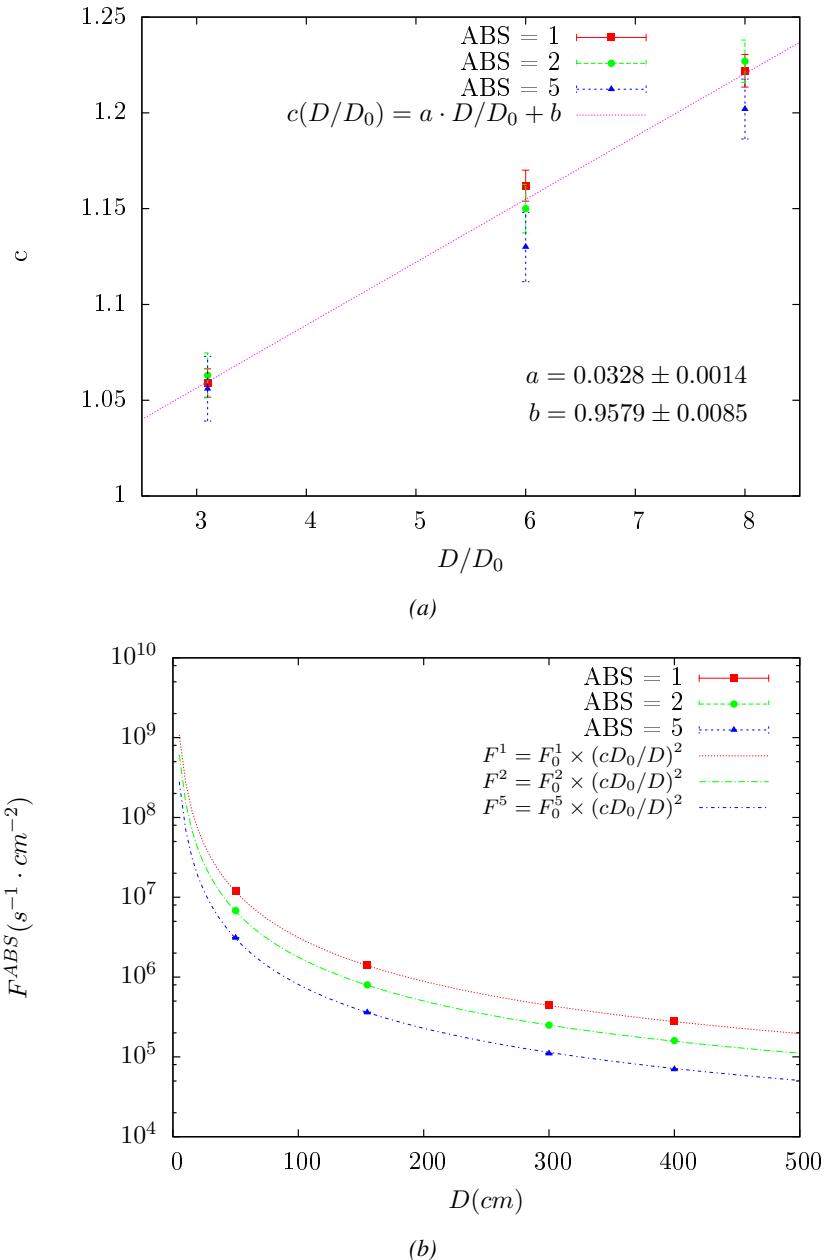


Figure 5.13: Figure 5.13a shows the linear approximation fit done via formulae 5.7 on data from table 5.2. Figure 5.13b shows a comparison of this model with the simulated flux using a and b given in figure 5.13a in formulae 5.4 and the reference value $D_0 = 50\text{cm}$ and the associated flux for each absorption factor F_0^{ABS} from table 5.1

In the case of the 2014 GIF tests, the RPC plane is located at a distance $D = 206\text{ cm}$ to the source. Moreover, to estimate the strength of the flux in 2014, it is necessary to consider the nuclear decay through time associated to the Cesium source whose half-life is well known ($t_{1/2} = (30.05 \pm 0.08)\text{ y}$). The very first source activity measurement has been done on the 5th of March 1997 while the GIF

891 tests where done in between the 20th and the 31st of August 2014, i.e. at a time $t = (17.47 \pm 0.02)$ y
 892 resulting in an attenuation of the activity from 740 GBq in 1997 to 494 GBq in 2014. All the needed
 893 information to extrapolate the flux through our detector in 2014 has now been assembled, leading
 894 to the Table 5.3. It is interesting to note that for a common RPC sensitivity to γ of $2 \cdot 10^{-3}$, the
 895 order of magnitude of the estimated hit rate per unit area is of the order of the kHz for the fully
 896 opened source. Moreover, taking profit of the two working absorbers, it will be possible to scan
 897 background rates at 0 Hz, \sim 300 Hz as well as \sim 600 Hz. Without source, a good estimate of the
 898 intrinsic performance will be available. Then at 300 Hz, the goal will be to show that the detectors
 899 fulfill the performance certification of CMS RPCs. Then a first idea of the performance of the
 900 detectors at higher background will be provided with absorption factors 2 (\sim 600 Hz) and 1 (no
 901 absorption). *[Here I will also put a reference to the plot showing the estimated background rate at
 902 the level of RE3/1 in the case of HL-LHC but this one being in another chapter, I will do it later.]*

Nominal ABS	Photon flux F [$s^{-1}cm^{-2}$]			Hit rate/unit area [$Hz cm^{-2}$] at $D^{2014} = 206$ cm
	at $D_0^{1997} = 50$ cm	at $D^{1997} = 206$ cm	at $D^{2014} = 206$ cm	
1	$0.12 \cdot 10^8 \pm 0.2\%$	$0.84 \cdot 10^6 \pm 0.3\%$	$0.56 \cdot 10^6 \pm 0.3\%$	1129 ± 32
2	$0.68 \cdot 10^7 \pm 0.3\%$	$0.48 \cdot 10^6 \pm 0.3\%$	$0.32 \cdot 10^6 \pm 0.3\%$	640 ± 19
5	$0.31 \cdot 10^7 \pm 0.4\%$	$0.22 \cdot 10^6 \pm 0.3\%$	$0.15 \cdot 10^6 \pm 0.3\%$	292 ± 9

Table 5.3: The data at D_0 in 1997 is taken from [34]. In a second step, using Equations 5.8 and 5.9, the flux at D 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. Finally, assuming a sensitivity of the RPC to γ $s = 2 \cdot 10^{-3}$, an estimation of the hit rate per unit area is obtained.

⁹⁰³ **5.2.4.2 Dose measurements**

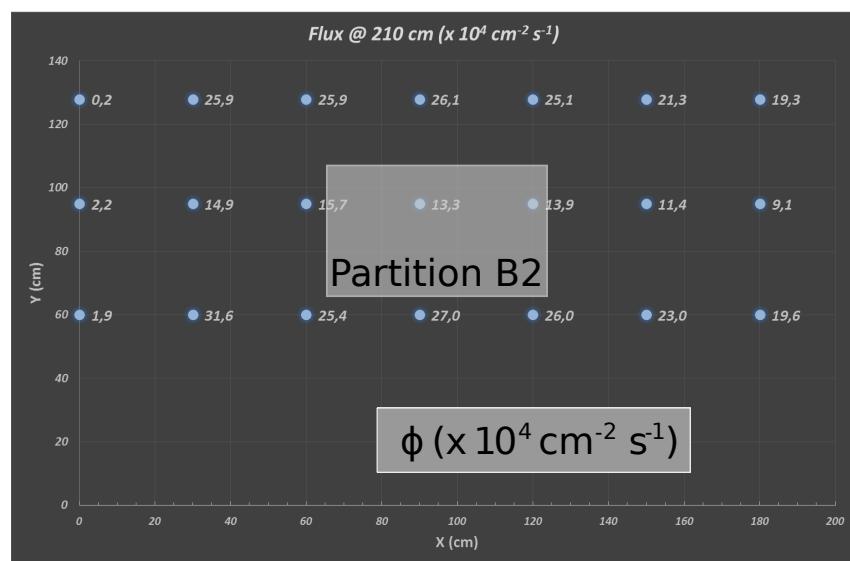


Figure 5.14: Dose measurements has been done in a plane corresponding to the tents front side. This plan is 1900 mm away from the source. As explained in the first chapter, a lens-shaped lead filter provides a uniform photon flux in the vertical plan orthogonal to the beam direction. If the second line of measured fluxes is not taken into account because of lower values due to experimental equipments in the way between the source and the tent, the uniformity of the flux is well showed by the results.

⁹⁰⁴ **5.2.5 Results and discussions**

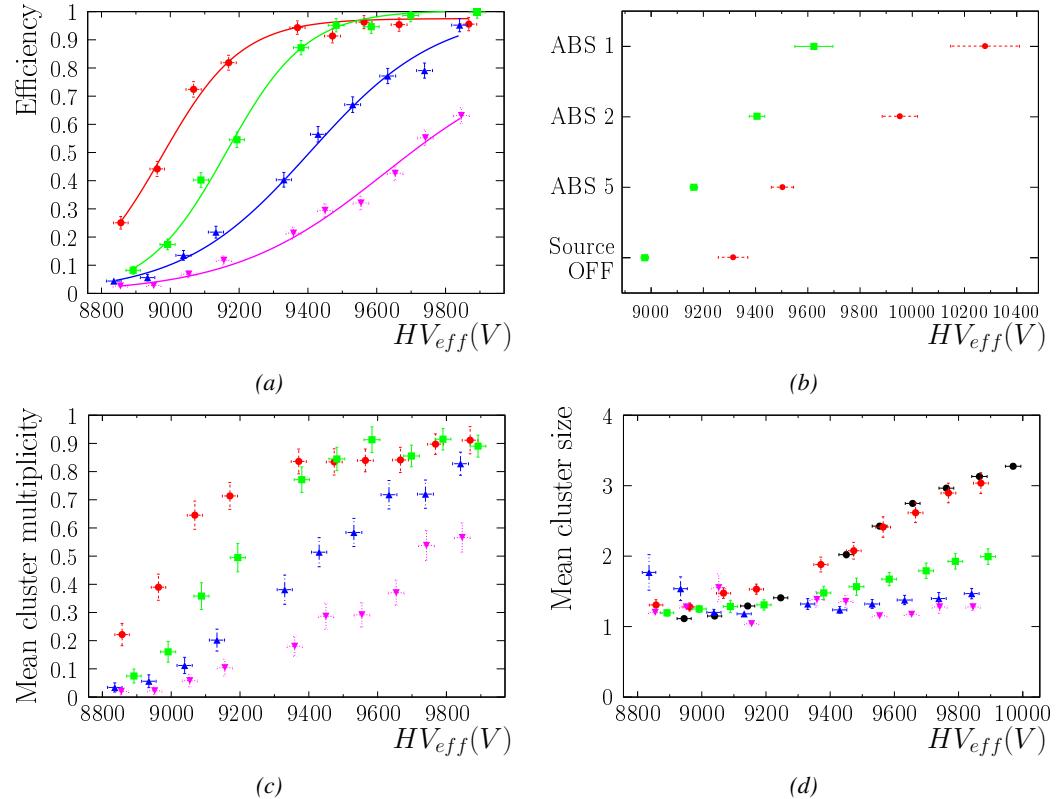


Figure 5.15

905 5.3 Longevity tests at GIF++

906 Longevity studies imply a monitoring of the performance of the detectors probed using a high inten-
907 sity muon beam in a irradiated environment by periodically measuring their rate capability, the dark
908 current running through them and the bulk resistivity of the Bakelite composing their electrodes.
909 GIF++, with its very intense ^{137}Cs source, provides the perfect environment to perform such kind
910 of tests. Assuming a maximum acceleration factor of 3, it is expected to accumulate the equivalent
911 charge in 1.7 years.

912 As the maximum background is found in the endcap, the choice naturally was made to focus the
913 GIF++ longevity studies on endcap chambers. Most of the RPC system was installed in 2007. Nev-
914 ertheless, the large chambers in the fourth endcap (RE4/2 and RE4/3) have been installed during
915 LS1 in 2014. The Bakelite of these two different productions having different properties, four spare
916 chambers of the present system were selected, two RE2,3/2 spares and two RE4/2 spares. Having
917 two chambers of each type allows to always keep one of them non irradiated as reference, the per-
918 formance evolution of the irradiated chamber being then compared through time to the performance
919 of the non irradiated one.

920 The performance of the detectors under different level of irradiation is measured periodically dur-
921 ing dedicated test beam periods using the H4 muon beam. In between these test beam periods, the
922 two RE2,3/2 and RE4/2 chambers selected for this study are irradiated by the ^{137}Cs source in order
923 to accumulate charge and the gamma background is monitored, as well as the currents. The two
924 remaining chambers are kept non-irradiated as reference detectors. Due to the limited gas flow in
925 GIF++, the RE4 chamber remained non-irradiated until end of November 2016 where a new mass
926 flow controller has been installed allowing for bigger volumes of gas to flow in the system.

927 Figures 5.16 and 5.17 give us for different test beam periods, and thus for increasing integrated
928 charge through time, a comparison of the maximum efficiency, obtained using a sigmoid-like func-
929 tion, and of the working point of both irradiated and non irradiated chambers [**SIGMOID2005**]. No
930 aging is yet to see from this data, the shifts in γ rate per unit area in between irradiated and non
931 irradiated detectors and RE2 and RE4 types being easily explained by a difference of sensitivity due
932 to the various Bakelite resistivities of the HPL electrodes used for the electrode production.

933 Collecting performance data at each test beam period allows us to extrapolate the maximum effi-
934 ciency for a background hit rate of $300\text{ Hz}/\text{cm}^2$ corresponding to the expected HL-LHC conditions.
935 Aging effects could emerge from a loss of efficiency with increasing integrated charge over time,
936 thus Figure 5.18 helps us understand such degradation of the performance of irradiated detectors in
937 comparison with non irradiated ones. The final answer for an eventual loss of efficiency is given in
938 Figure 5.19 by comparing for both irradiated and non irradiated detectors the efficiency sigmoids
939 before and after the longevity study. Moreover, to complete the performance information, the Bake-
940 lite resistivity is regularly measured thanks to Ag scans (Figure 5.20) and the noise rate is monitored
941 weekly during irradiation periods (Figure 5.21). At the end of 2016, no signs of aging were observed
942 and further investigation is needed to get closer to the final integrated charge requirements proposed
943 for the longevity study of the present CMS RPC sub-system.

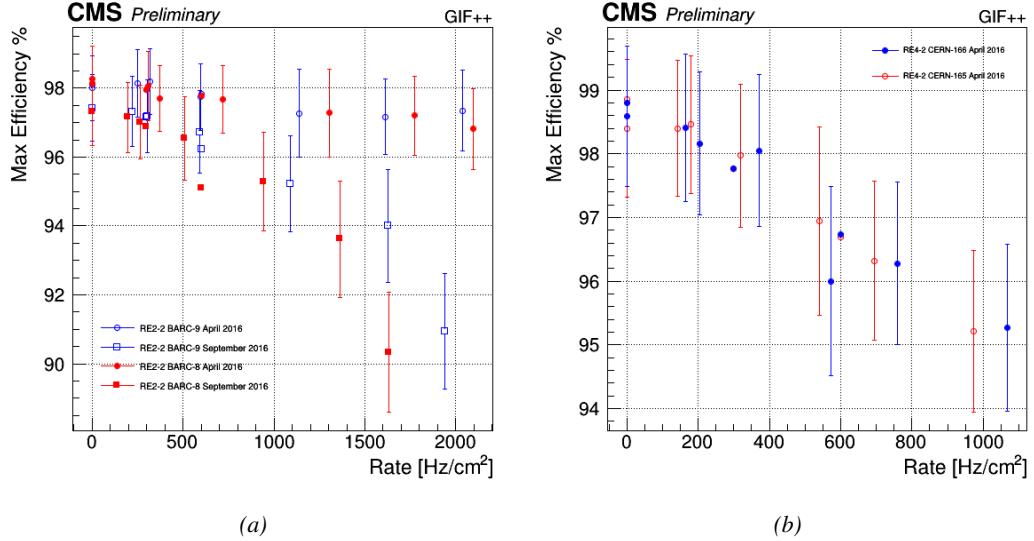


Figure 5.16: Evolution of the maximum efficiency for RE2 (5.16a) and RE4 (5.16b) chambers with increasing extrapolated γ rate per unit area at working point. Both irradiated (blue) and non irradiated (red) chambers are shown.

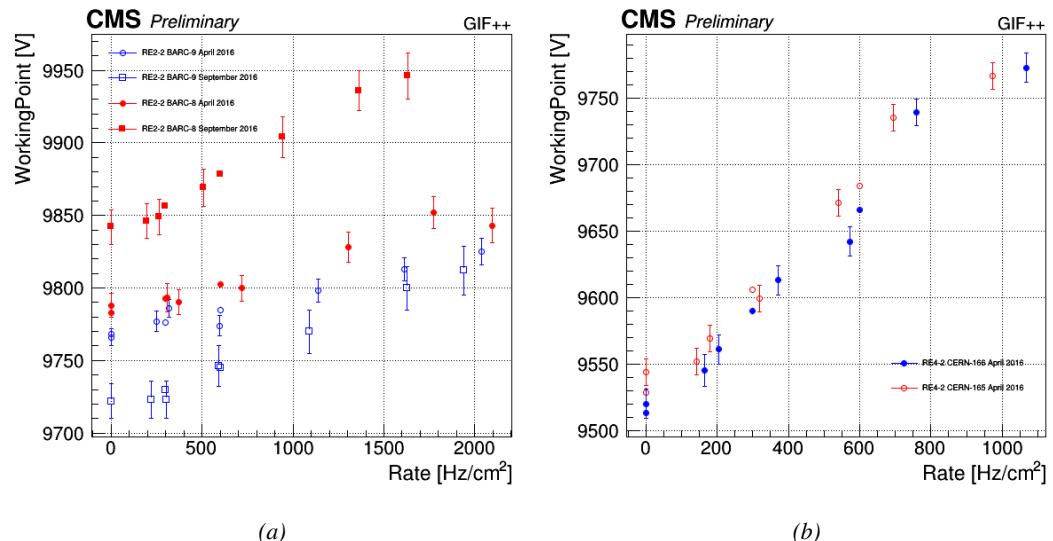


Figure 5.17: Evolution of the working point for RE2 (5.17a) and RE4 (5.17b) with increasing extrapolated γ rate per unit area at working point. Both irradiated (blue) and non irradiated (red) chambers are shown.

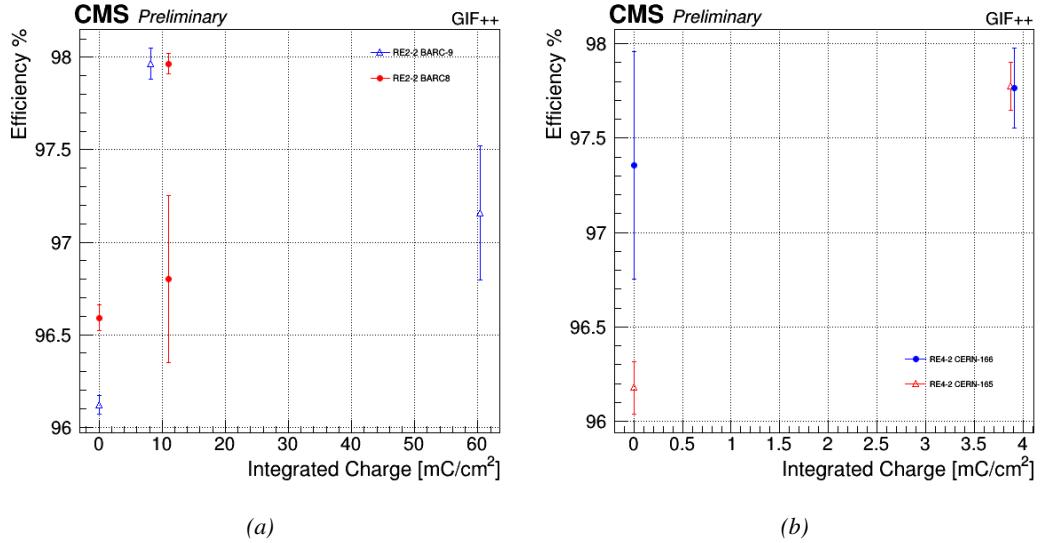


Figure 5.18: Evolution of the maximum efficiency at HL-LHC conditions, i.e. a background hit rate per unit area of 300 Hz/cm², with increasing integrated charge for RE2 (5.18a) and RE4 (5.18b) detectors. Both irradiated (blue) and non irradiated (red) chambers are shown. The integrated charge for non irradiated detectors is recorded during test beam periods and stays small with respect to the charge accumulated in irradiated chambers.

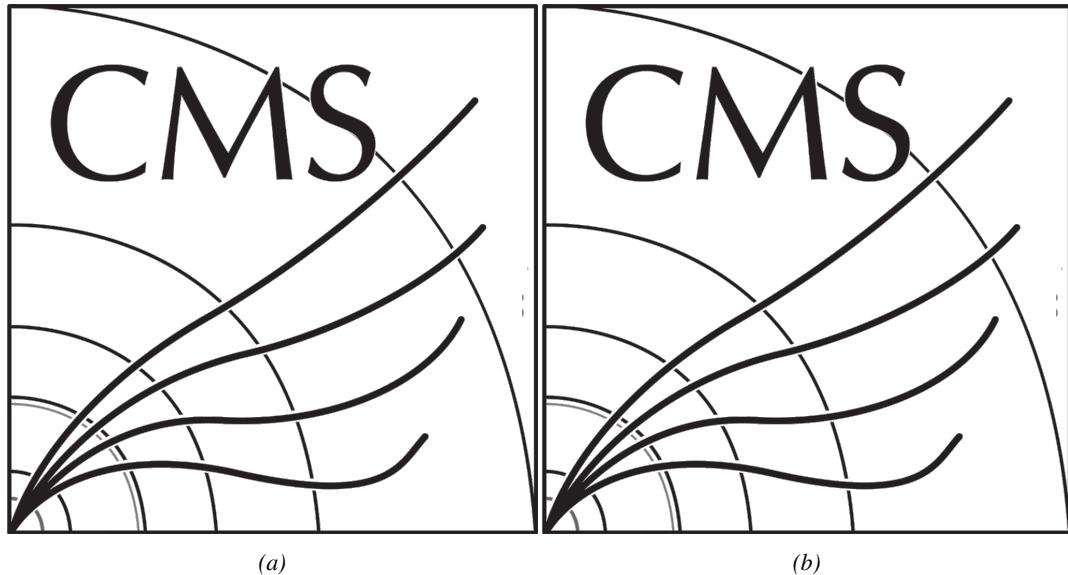


Figure 5.19: Comparison of the efficiency sigmoid before (triangles) and after (circles) irradiation for RE2 (5.19a) and RE4 (5.19b) detectors. Both irradiated (blue) and non irradiated (red) chambers are shown.

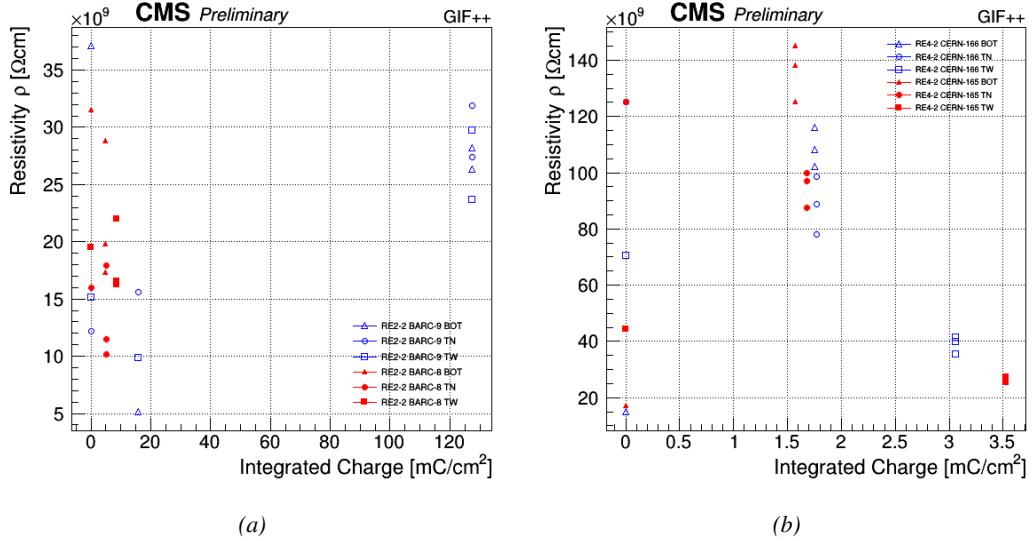


Figure 5.20: Evolution of the Bakelite resistivity for RE2 (5.20a) and RE4 (5.20b) detectors. Both irradiated (blue) and non-irradiated (red) chambers are shown.

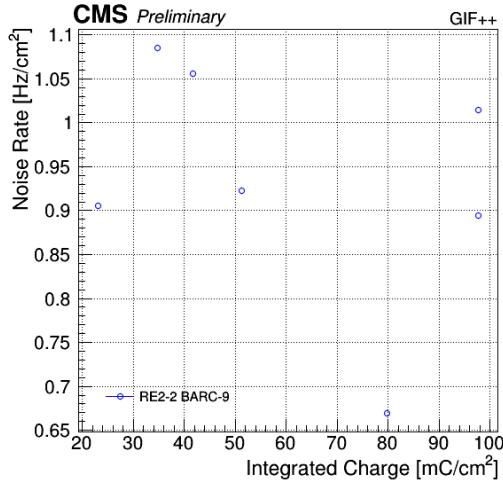


Figure 5.21: Evolution of the noise rate per unit area for the irradiated chamber RE2-2-BARC-9 only.

945 5.3.1 Description of the Data Acquisition

946 For the longevity studies, four spare chambers of the present system are used. Two spare RPCs of
 947 the RE2,3 stations as well as two spare RPCs from the new RE4 stations have been mounted in a
 948 Trolley. Six RE4 gaps are also placed in the trolley. The trolley is placed inside the GIFT++ in the
 949 upstream region of the bunker, taking the cesium source as a reference. The trolley is oriented for
 950 the detection surface of the chambers to be orthogonal to the beam line. The system can be moved
 951 along the orthogonal plane in order to have the beam in all η -partitions. For the aging the trolley is

952 moved outside the beam line and is placed in a distance of 5.2 m to the source, which irradiates the
 953 bunker using an attenuation filter of 2.2 which corresponds to a fluence of 10^7 gamma/cm^2 .

954 During GIF++ operation, the data collected can be divided into different categories as several
 955 parameters are monitored in addition to the usual RPC performance data. On one hand, to know
 956 the performance of a chamber, it is need to measure its efficiency and to know the background
 957 conditions in which it is operated. To do this, the hit signals from the chamber are recorded and
 958 stored in a ROOT file via a Data Acquisition (DAQ) software. On the other hand, it is also very
 959 important to monitor parameters such as environmental pressure and temperature, gas temperature
 960 and humidity, RPC HV, LV, and currents, or even source and beam status. This is done through the
 961 GIF++ web Detector Control Software (DCS) that stores this information in a database.

962 Two different types of tests are conducted on RPCs via the DAQ. Indeed, the performance of the
 963 detectors is measured periodically during dedicated test beam periods using the H4 muon beam. In
 964 between these test beam periods, when the beam is not available, the chambers are irradiated by the
 965 ^{137}Cs in order to accumulate deposited charge and the gamma background is measured.

966 RPCs under test are connected through LVDS cables to V1190A Time-to-Digital Converter
 967 (TDC) modules manufactured by CAEN. These modules, located in the rack area outside of the
 968 bunker, get the logic signals sent by the chambers and save them into their buffers. Due to the
 969 limited size of the buffers, the collected data is regularly erased and replaced. A trigger signal is
 970 needed for the TDC modules to send the useful data to the DAQ computer via a V1718 CAEN USB
 971 communication module.

972 In the case of performance test, the trigger signal used for data acquisition is generated by the
 973 coincidence of three scintillators. A first one is placed upstream outside of the bunker, a second one
 974 is placed downstream outside of the bunker, while a third one is placed in front of the trolley, close by
 975 the chambers. Every time a trigger is sent to the TDCs, i.e. every time a muon is detected, knowing
 976 the time delay in between the trigger and the RPC signals, signals located in the right time window
 977 are extracted from the buffers and saved for later analysis. Signals are taken in a time window of
 978 400 ns centered on the muon peak (here we could show a time spectrum). On the other hand, in the
 979 case of background rate measurement, the trigger signal needs to be "random" not to measure muons
 980 but to look at gamma background. A trigger pulse is continuously generated at a rate of 300 Hz using
 981 a dual timer. To integrate an as great as possible time, all signals contained within a time window of
 982 10us prior to the random trigger signal are extracted form the buffers and saved for further analysis
 983 (here another time spectrum to illustrate could be useful, maybe even place both spectrum together
 984 as a single Figure).

985 The signals sent to the TDCs correspond to hit collections in the RPCs. When a particle hits
 986 a RPC, it induce a signal in the pickup strips of the RPC readout. If this signal is higher than the
 987 detection threshold, a LVDS signal is sent to the TDCs. The data is then organised into 4 branches
 988 keeping track of the event number, the hit multiplicity for the whole setup, and the time and channel
 989 profile of the hits in the TDCs.

990 5.3.2 RPC current, environmental and operation parameter monitoring

991 In order to take into account the variation of pressure and temperature between different data taking
 992 periods the applied voltage is corrected following the relationship :

$$993 \quad HV_{eff} = HV_{app} \times \left(0.2 + 0.8 \cdot \frac{P_0}{P} \times \frac{T}{T_0} \right) \quad (5.10)$$

993 where T_0 (=293 K) and P_0 (=990 mbar) are the reference values.

994 **5.3.3 Measurement procedure**

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

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

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

998 **5.3.4 Longevity studies results**

6

999

1000

Investigation on high rate RPCs

1001 **6.1 Rate limitations and ageing of RPCs**

1002 **6.1.1 Low resistivity electrodes**

1003 **6.1.2 Low noise front-end electronics**

1004 **6.2 Construction of prototypes**

1005 **6.3 Results and discussions**

7

1006

1007

Conclusions and outlooks

1008 **7.1 Conclusions**

1009 **7.2 Outlooks**

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A

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1089

A data acquisition software for CAEN VME TDCs

1090 Certifying detectors in the perspective of HL-LHC required to develop tools for the GIF++ experiment.
1091 Among them was the C++ Data Acquisition (DAQ) software that allows to make the communications
1092 in between a computer and TDC modules in order to retrieve the RPC data [36]. In this
1093 appendix, details about this software, as of how the software was written, how it functions and how
1094 it can be exported to another similar setup, will be given.

1095 A.1 GIF++ DAQ file tree

1096 GIF++ DAQ source code is fully available on github at https://github.com/afagot/GIF_DAQ. The software requires 3 non-optional dependencies:

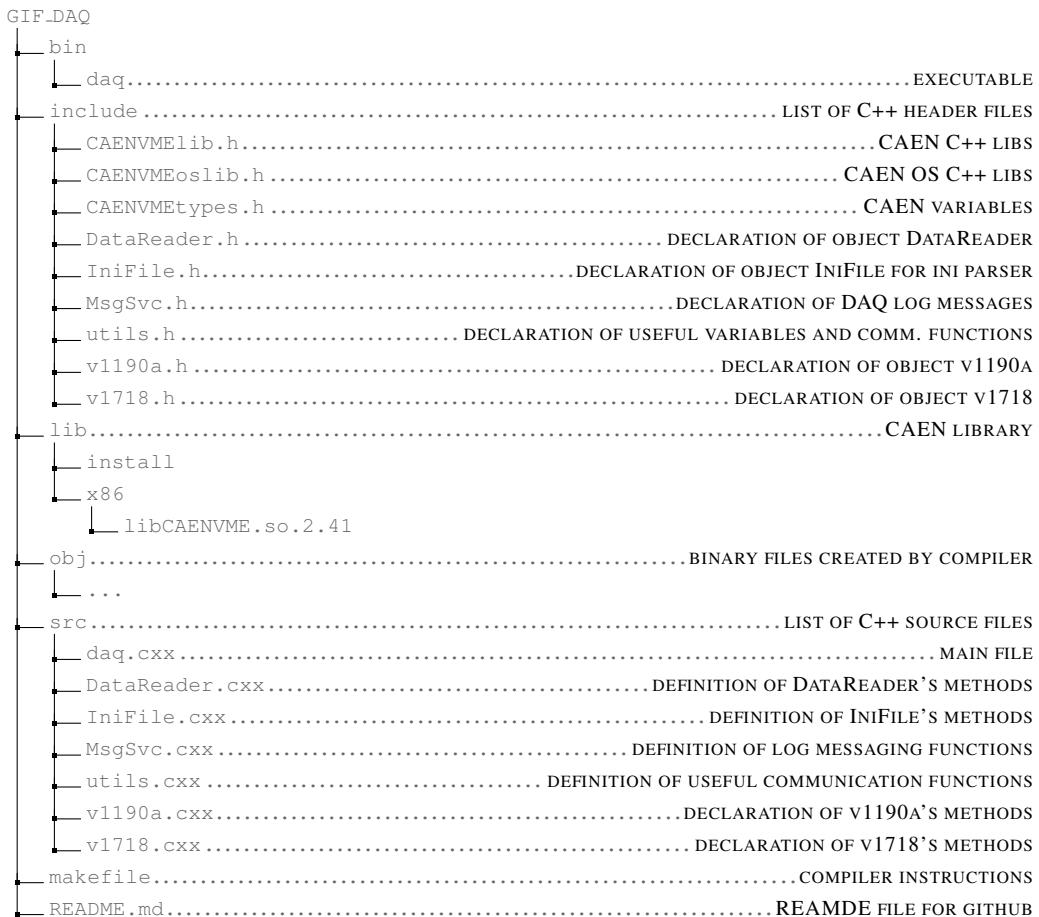
- 1098 • CAEN USB Driver, to mount the VME hardware,
- 1099 • CAEN VME Library, to communicate with the VME hardware, and
- 1100 • ROOT, to organize the collected data into a TTree.

1101 The CAEN VME library will not be packaged by distributions and will need to be installed man-
1102 ually. To compile the GIF++ DAQ project via a terminal, from the DAQ folder use the command:

1103 1104 `make`

1105 The source code tree is provided below along with comments to give an overview of the files' con-
1106 tent. The different objects created for this project (`v1718`, `v1190a`, `IniFile` & `DataReader`) will be
1107 described in details in the following sections.

1108



1109 A.2 Usage of the DAQ

1110 GIF++ DAQ, as used in GIF++, is not a standalone software. Indeed, the system being more complexe,
 1111 the DAQ only is a sub-layer of the software architecture developped to control and monitor
 1112 the RPCs that are placed into the bunker for performance study in an irradiated environment. The top
 1113 layer of GIF++ is a Web Detector Control System (webDCS) application. The DAQ is only called
 1114 by the webDCS when data needs to be acquired. The webDCS operates the DAQ through command
 1115 line. To start the DAQ, the webDCS calls:

1116
 1117 bin/daq /path/to/the/log/file/in/the/output/data/folder

1118 where /path/to/the/log/file/in/the/output/data/folder is the only argument required. This
 1119 log file is important for the webDCS as this file contains all the content of the communication of the
 1120 webDCS and the different systems monitored by the webDCS. Its content is constantly displayed
 1121 during data taking for the users to be able to follow the operations. The communication messages
 1122 are normally sent to the webDCS log file via the functions declared in file MsgSvc.h, typically
 1123 MSG_INFO(string message).

1124

1125 A.3 Description of the readout setup

1126 The CMS RPC setup at GIF++ counts 5 V1190A Time-to-Digital Converter (TDC) manufactured
 1127 by CAEN [37]. V1190A are VME units accepting 128 independent Multi-Hit/Multi-Event TDC
 1128 channels whose signals are treated by 4 100 ps high performance TDC chips developed by CERN
 1129 / ECP-MIC Division. The communication between the computer and the TDCs to transfer data is
 1130 done via a V1718 VME master module also manufactured by CAEN and operated from a USB
 1131 port [38]. These VME modules are all hosted into a 6U VME 6021 powered crate manufactured by
 1132 W-Ie-Ne-R than can accommodate up to 21 VME bus cards [39]. These 3 components of the DAQ
 1133 setup are shown in Figure A.1.

1134

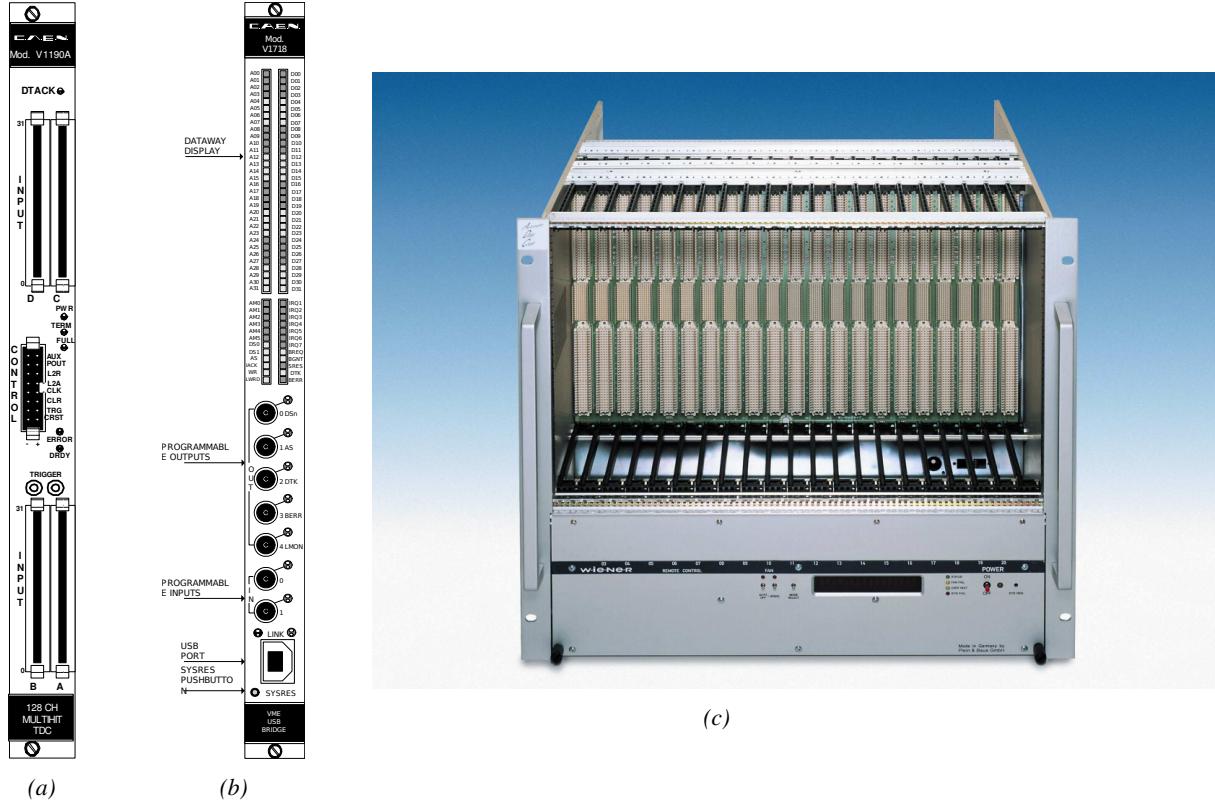


Figure A.1: (A.1a) View of the front panel of a V1190A TDC module [37]. (A.1b) View of the front panel of a V1718 Bridge module [38]. (A.1c) View of the front panel of a 6U 6021 VME crate [39].

1135

A.4 Data read-out

1136 To efficiently perform a data readout algorithm, C++ objects to handle the VME modules (TDCs
 1137 and VME bridge) have been created along with objects to store data and read the configuration file

1138 that comes as an input of the DAQ software.

1139

1140 A.4.1 V1190A TDCs

1141 The DAQ used at GIF takes profit of the *Trigger Matching Mode* offered by V1190A modules.
 1142 This setting is enabled through the method `v1190a::SetTrigMatching (int ntdcs)` where `ntdcs`
 1143 is the total number of TDCs in the setup this setting needs to be enabled for (Source Code A.1). A
 1144 trigger matching is performed in between a trigger time tag, a trigger signal sent into the TRIGGER
 1145 input of the TDC visible on Figure A.1a, and the channel time measurements, signals recorded from
 1146 the detectors under test in our case. Control over this data acquisition mode, explained through
 1147 Figure A.2, is offered via 4 programmable parameters:

- 1148 • **match window:** the matching between a trigger and a hit is done within a programmable time
 1149 window. This is set via the method

1150 `void v1190a::SetTrigWindowWidth(Uint windowHeight, int ntdcs)`

- 1151 • **window offset:** temporal distance between the trigger tag and the start of the trigger matching
 1152 window. This is set via the method

1153 `void v1190a::SetTrigWindowWidth(Uint windowHeight, int ntdcs)`

- 1154 • **extra search margin:** an extended time window is used to ensure that all matching hits are
 1155 found. This is set via the method

1156 `void v1190a::SetTrigSearchMargin(Uint searchMargin, int ntdcs)`

- 1157 • **reject margin:** older hits are automatically rejected to prevent buffer overflows and to speed
 1158 up the search time. This is set via the method

1159 `void v1190a::SetTrigRejectionMargin(Uint rejectMargin, int ntdcs)`

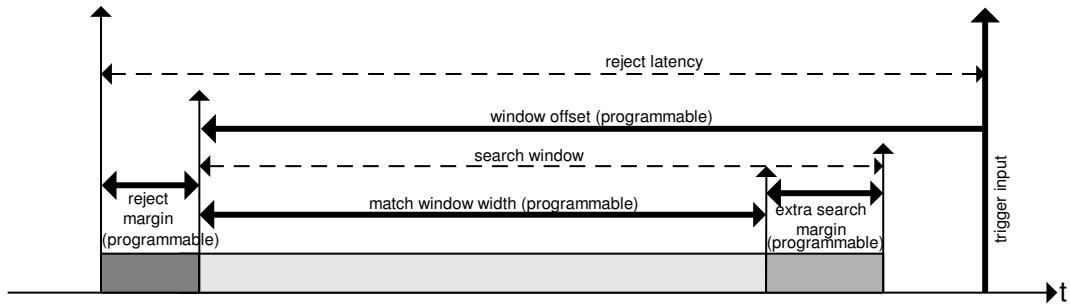


Figure A.2: Module V1190A Trigger Matching Mode timing diagram [37].

1160 Each of these 4 parameters are given in number of clocks, 1 clock being 25 ns long. It is easy to
 1161 understand at this level that there are 3 possible functioning settings:

- 1162 • **1:** the match window is entirely contained after the trigger signal,

- 1163 • **2:** the match window overlaps the trigger signal, or

- 1164 • **3:** the match window is entirely contained before the trigger signal as displayed on Figure A.2.

1165 In both the first and second cases, the sum of the window width and of the offset can be set to
1166 a maximum of 40 clocks, which corresponds to 1 μ s. Evidently, the offset can be negative, allowing
1167 for a longer match window, with the constraint of having the window ending at most 1 μ s after the
1168 trigger signal. In the third case, the maximum negative offset allowed is of 2048 clocks (12 bit) cor-
1169 responding to 51.2 μ s, the match window being strictly smaller than the offset. In the case of GIF++,
1170 the choice has been made to use this last setting by delaying the trigger signal. During the studies
1171 performed in GIF++, both the efficiency of the RPCs, probed using a muon beam, and the noise or
1172 gamma background rate are monitored. The extra search and reject margins are left unused.
1173 To probe the efficiency of RPC detectors, the trigger time tag is provided by the coïncidence of
1174 scintillators when a bunch of muons passes through GIF++ area is used to trigger the data acquisi-
1175 tion. For this measurement, it is useful to reduce the match window width only to contain the muon
1176 information. Indeed, the delay in between a trigger signal and the detection of the corresponding
1177 muon in the RPC being very contant (typically a few tens of ns due to jitter and cable length), the
1178 muon signals are very localised in time. Thus, due to a delay of approximalety 325 ns in between
1179 the muons and the trigger, the settings where chosen to have a window width of 24 clocks (600 ns)
1180 centered on the muon peak thanks to a negative offset of 29 clocks (725 ns).
1181 On the otherhand, monitoring the rates don't require for the DAQ to look at a specific time window.
1182 It is important to integrate enough time to have a robust measurement of the rate as the number of
1183 hits per time unit. The triggerring signal is provided by a pulse generator at a frequency of 300 Hz
1184 to ensure that the data taking occurs in a random way, with respect to beam physics, to probe only
1185 the irradiation spectrum on the detectors. The match window is set to 400 clocks (10 μ s) and the
1186 negative offset to 401 clocks as it needs to exceed the value of the match window.

```

1187
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);
};

1188

```

1189 *Source Code A.1: Description of C++ object v1190a.*

1190 The v1190a object, defined in the DAQ software as in Source Code A.1, offers the possibility to
 1191 concatenate all TDCs in the readout setup into a single object containing a list of hardware addresses
 1192 (addresses to access the TDCs' buffer through the VME crate) and each constructor and method acts
 1193 on the list of TDCs.

1194

1195 A.4.2 DataReader

1196 Enabled thanks to v1190a::SetBlockTransferMode(Data16 mode, int ntdcs), the data transfer
 1197 is done via Block Transfer (BLT). Using BLT allows to tranfer a fixed number of events called a
 1198 *block*. This is used together with an Almost Full Level (AFL) of the TDCs' output buffers, defined

1199 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
 1200 written in a buffer before an Interrupt Request (IRQ) is generated and seen by the VME Bridge,
 1201 stopping the data acquisition to transfer the content of each TDC buffers before resuming. For each
 1202 trigger, 6 words or more are written into the TDC buffer:

- 1204 • a **global header** providing information of the event number since the beginning of the data
 acquisition,
- 1206 • a **TDC header**,
- 1207 • the **TDC data** (*if any*), 1 for each hit recorded during the event, providing the channel and the
 time stamp associated to the hit,
- 1209 • a **TDC error** providing error flags,
- 1210 • a **TDC trailer**,
- 1211 • a **global trigger time tag** that provides the absolute trigger time relatively to the last reset,
 and
- 1213 • a **global trailer** providing the total word count in the event.

1214 As previously described in Section 4.3.3, CMS RPC FEEs provide us with 100 ns long LVDS
 1215 output signals that are injected into the TDCs' input. Any avalanche signal that gives a signal above
 1216 the FEEs threshold is thus recorded by the TDCs as a hit within the match window. Each hit is
 1217 assigned to a specific TDC channel with a time stamp, with a precision of 100 ps. The reference
 1218 time, $t_0 = 0$, is provided by the beginning of the match window. Thus for each trigger, coming from
 1219 a scintillator coïncidence or the pulse generator, a list of hits is stored into the TDCs' buffers and
 1220 will then be transferred into a ROOT Tree.

1221 When the BLT is used, it is easy to understand that the maximum number of words that have
 1222 been set as ALF will not be a finite number of events or, at least, the number of events that would
 1223 be recorded into the TDC buffers will not be a multiple of the block size. In the last BLT cycle to
 1224 transfer data, the number of events to transfer will most probably be lower than the block size. In that
 1225 case, the TDC can add fillers at the end of the block but this option requires to send more data to the
 1226 computer and is thus a little slower. Another solution is to finish the transfer after the last event by
 1227 sending a bus error that states that the BLT reached the last event in the pile. This method has been
 1228 chosen in GIF++.

1230 Due to irradiation, an event in GIF++ can count up to 300 words per TDC. A limit of 4096 words
 1231 (12 bits) has been set to generate IRQ which represent from 14 to almost 700 events depending on
 1232 the average of hits collected per event. Then the block size has been set to 100 events with enabled
 1233 bus errors. When an AFL is reached for one of the TDCs, the VME bridge stops the acquisition by
 1234 sending a BUSY signal.

1236

1237 The data is then transferred one TDC at a time into a structure called `RAWData` (Source Code A.2).

```
1238
1239 struct RAWData{
1240     vector<int>           *EventList;
1241     vector<int>           *NHitsList;
1242     vector<int>           *QFlagList;
1243     vector<vector<int>>   *Channellist;
1244     vector<vector<float>>  *TimeStampList;
1245 };
1246
```

1240 *Source Code A.2: Description of data holding C++ structure `RAWData`.*

1241 In order to organize the data transfer and the data storage, an object called `DataReader` was
1242 created (Source Code A.3). On one hand, it has `v1718` and `v1190a` objects as private members for
1243 communication purposes, such as VME modules settings via the configuration file `*iniFile` or data
1244 read-out through `v1190a::Read()` and on the other hand, it contains the structure `RAWData` that allows
1245 to organise the data in vectors reproducing the tree structure of a ROOT file.

```
1246
1247 class DataReader
1248 {
1249     private:
1250     bool      StopFlag;
1251     IniFile  *iniFile;
1252     Data32    MaxTriggers;
1253     v1718    *VME;
1254     int       nTDCs;
1255     v1190a   *TDCs;
1256     RAWData  TDCData;
1257
1258     public:
1259     DataReader();
1260     virtual ~DataReader();
1261     void      SetIniFile(string inifilename);
1262     void      SetMaxTriggers();
1263     Data32    GetMaxTriggers();
1264     void      SetVME();
1265     void      SetTDC();
1266     int       GetQFlag(Uint it);
1267     void      Init(string inifilename);
1268     void      FlushBuffer();
1269     void      Update();
1270     string   GetFileName();
1271     void      WriteRunRegistry(string filename);
1272     void      Run();
1273 };
1274
```

1248 *Source Code A.3: Description of C++ object `DataReader`.*

1249 Each event is transferred from `TDCData` and saved into branches of a ROOT `TTree` as 3 integers
1250 that represent the event ID (`EventCount`), the number of hits read from the TDCs (`nHits`), and the
1251 quality flag that provides information for any problem in the data transfer (`qflag`), and 2 lists of
1252 `nHits` elements containing the fired TDC channels (`TDCCh`) and their respective time stamps (`TDCTS`),
1253 as presented in Source Code A.4. The ROOT file file is named using information contained into
1254 the configuration file, presented in section A.5.2. The needed information is extracted using method
1255 `DataReader::GetFileName()` and allow to build the output filename format `ScanXXXXXX_HVX_DAQ.root`

1256 where ScanXXXXXX is a 6 digit number representing the scan number into GIFT++ database and HVX
 1257 the HV step within the scan that can be more than a single digit. An example of ROOT data file is
 1258 provided with Figure A.3.

```
1259
1260 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);

1261 //...
//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();
}
```

1261 *Source Code A.4: Highlight of the data transfer and organisation within DataReader::Run() after the data has been collected into TDCData.*

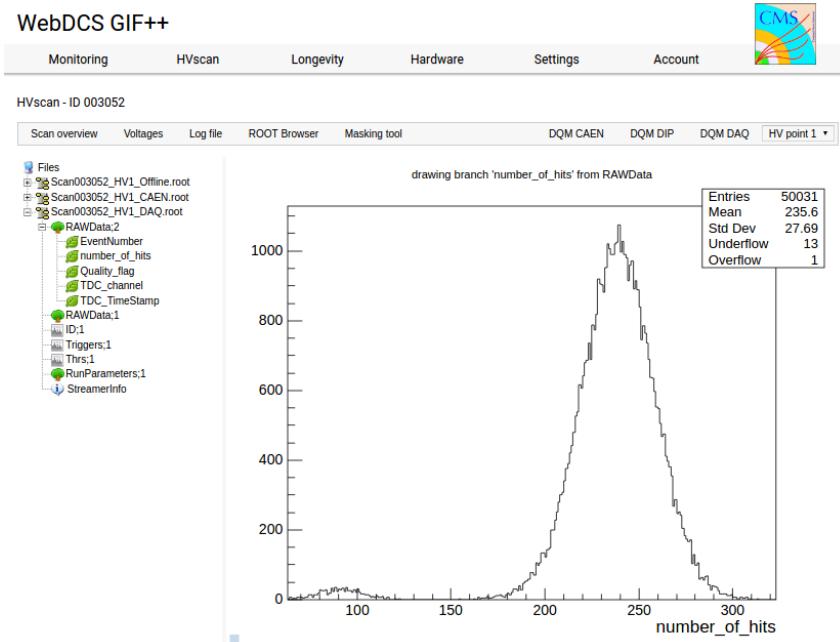


Figure A.3: Structure of the ROOT output file generated by the DAQ. The 5 branches (EventNumber, number_of_hits, Quality_flag, TDC_channel and TDC_TimeStamp) are visible on the left panel of the ROOT browser. On the right panel is visible the histogram corresponding to the variable nHits. In this specific 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.

1262 A.4.3 Data quality flag

1263 Among the parameters that are recorded for each event, the quality flag, defined in Source Code A.5,
 1264 is determined on the fly by checking the data recorded by every single TDC. From method `v1190a::Read()`,
 1265 it can be understood that the content of each TDC buffer is readout one TDC at a time. Entries are
 1266 created in the data list for the first TDC and then, when the second buffer is readout, events corre-
 1267 sponding to entries that have already been created to store data for the previous TDC are added to
 1268 the existing list element. On the contrary, when an event entry has not been yet created in the data
 1269 list, a new entry is created.

```
1270
 1271 typedef enum _QualityFlag {
 1272     GOOD      = 1,
 1273     CORRUPTED = 0
 1274 } QualityFlag;
```

1272 *Source Code A.5: Definition of the quality flag `enum`.*

1273 It is possible that each TDC buffer contains a different number of events. In cases where the first
 1274 element in the buffer list is an event for corresponds to a new entry, the difference in between the
 1275 entry from the buffer and the last entry in the data list is recorded and checked. If it is greater than 1,
 1276 what should never be the case, the quality flag is set to CORRUPTED for this TDC and an empty entry
 1277 is created in the place of the missing ones. Missing entries are believe to be the result of a bad hold

1278 on the TDC buffers at the moment of the readout. Indeed, the software hold is effective only on 1
 1279 TDC at a time and no solution as been found yet to completely block the writting in the buffers when
 1280 an IRQ is received.

1281 At the end of each BLT cycle, the ID of the last entry stored for each TDC buffer is not recorded.
 1282 When starting the next cycle, if the first entry in the pile corresponds to an event already existing
 1283 in the list, the readout will start from this list element and will not be able to check the difference
 1284 in between this entry's ID and the one of the last entry that was recorded for this TDC buffer in
 1285 the previous cycle. In the case events were missing, the flag stays at its initial value of 0, which is
 1286 similar to CORRUPTED and it is assumed that then this TDC will not contribute to `number_of_hits`,
 1287 `TDC_channel` or `TDC_TimeStamp`.

1288 Finally, since there will be 1 `RAWData` entry per TDC for each event (meaning `nTDCs` entries,
 1289 referring to `DataReader` private attribute), the individual flags of each TDC will be added together.
 1290 The final format is an integer composed `nTDCs` digits where each digit is the flag of a specific TDC.
 1291 This is constructed using powers of 10 like follows:

```
1292     TDC 0: QFlag = 100 × _QualityFlag
1293     TDC 1: QFlag = 101 × _QualityFlag
1294     ...
1295     TDC N: QFlag = 10N × _QualityFlag
```

1296 and the final flag to be with N digits:

```
1297     QFlag = n....3210
```

1298 each digit being 1 or 0. Below is given an example with a 4 TDCs setup.

```
1299     If all TDCs were good : QFlag = 1111,
```

```
1300     but if TDC 2 was corrupted : QFlag = 1011.
```

1301 When data taking is over and the data contained in the dynamical `RAWData` structure is transferred
 1302 to the ROOT file, all the 0s are changed into 2s by calling the method `DataReader::GetQFlag()`.
 1303 This will help translating the flag without knowing the number of TDCs beforehand. Indeed, a flag
 1304 111 could be due to a 3 TDC setup with 3 good individual TDC flags or to a more than 3 TDC setup
 1305 with TDCs those ID is greater than 2 being CORRUPTED, thus giving a 0.

1306 The quality flag has been introduced quite late, in October 2017 only, to the list of GIFT++ DAQ
 1307 parameters to be recorded into the output ROOT file. Before this addition, the missing data, corrupting
 1308 the quality for the offline analysis, was contributing to artificially fill data with lower multiplicity.
 1309 Looking at `TBranch number_of_hits` provides an information about the data of the full GIFT++
 1310 setup. When a TDC is not able to transfer data for a specific event, the effect is a reduction of the
 1311 total number of hits recorded in the full setup, this is what can be seen from Figure A.4. After offline
 1312 reconstruction detector by detector, the effect of missing events can be seen in the artificially filled
 1313 bin at multiplicity 0 shown in Figure A.5. Nonetheless, for data with high irradiation levels, as it is
 1314 the case for Figure A.5a, discarding the fake multiplicity 0 data can be done easily during the offline
 1315 analysis. At lower radiation, the missing events contribution becomes more problematic as the mul-
 1316 tiplicity distribution overlaps the multiplicity 0 and that in the same time the proportion of missing

1317 events decreases. Attempts to fit the distribution with a Poisson or skew distribution function were
 1318 not conclusive and this very problem has been at the origin of the quality flag that allows to give a
 1319 non ambiguous information about each event quality.

1320

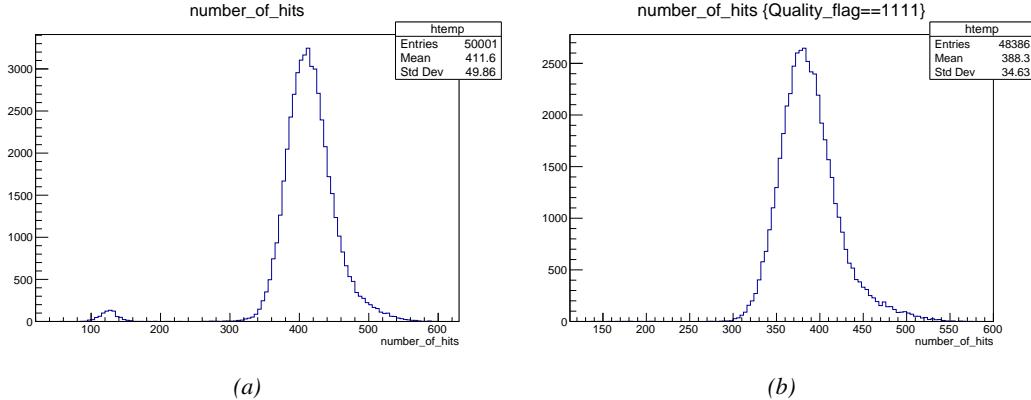


Figure A.4: The effect of the quality flag is explained by presenting the content of TBranch `number_of_hits` of a data file without `Quality_flag` in Figure A.4a and the content of the same TBranch for data corresponding to a `Quality_flag` where all TDCs were labelled as `GOOD` in Figure A.4b taken 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.

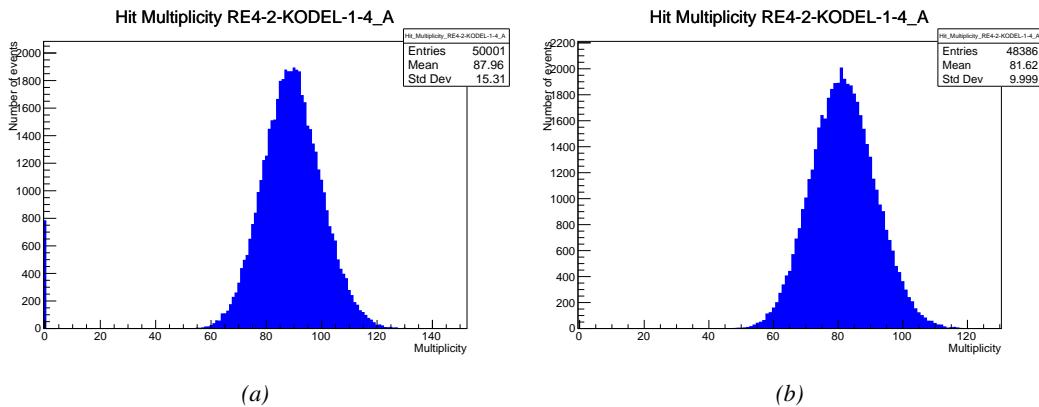


Figure A.5: Using the same data as previously showed in Figure A.4, the effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without `Quality_flag` in Figure A.5a and the reconstructed content of the same RPC partition for data corresponding to a `Quality_flag` 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

1321 To ensure data readout and dialog in between the machine and the TDCs or in between the webDCS
 1322 and the DAQ, different communication solutions were used. First of all, it is important to have a
 1323

1324 module to allow the communication in between the TDCs and the computer from which the DAQ
 1325 operates. When this communication is effective, shifters using the webDCS to control data taking
 1326 can thus send instructions to the DAQ.

1327

1328 A.5.1 V1718 USB Bridge

1329 In the previous section, the data transfer has been discussed. The importance of the `v1718` object
 1330 (Source Code A.6), used as private member of `DataReader`, was not explicated. VME master
 1331 modules are used for communication purposes as they host the USB port that connects the pow-
 1332 ered crate buffer to the computer where the DAQ is installed. From the source code point of view,
 1333 this object is used to control the communication status, by reading the returned error codes with
 1334 `v1718::CheckStatus()`, or to check for IRQs coming from the TDCs through `v1718::CheckIRQ()`.
 1335 Finally, to ensure that triggers are blocked at the hardware level, a NIM pulse is sent out of one of the
 1336 5 programmable outputs (`v1718::SendBUSY()`) to the VETO of the coincidence module where the
 1337 trigger signals originate from. As long as this signal is ON, no trigger can reach the TDCs anymore.
 1338

```
1339
  class v1718{
    private:
      int Handle;
      Data32 Data;           // Data
      CVIRQLevels Level;    // Interrupt level
      CVAddressModifier AM;  // Addressing Mode
      CVDataWidth dataSize; // Data Format
      Data32 BaseAddress;   // Base Address

    public:
      v1718(IniFile *inifile);
      ~v1718();
      long GetHandle(void) const;
      int GetData(Data16 data);
      Data16 GetData(void);
      int SetLevel(CVIRQLevels level);
      CVIRQLevels GetLevel(void);
      int SetAM(CVAddressModifier am);
      CVAddressModifier GetAM(void);
      int SetDatasize(CVDataWidth datasize);
      CVDataWidth GetDataSize(void);
      int SetBaseAddress(Data16 baseaddress);
      Data16 GetBaseAddress(void);
      void CheckStatus(CVErrorCodes status) const;
      void CheckIRQ();
      void SetPulsers();
      void SendBUSY(BusyLevel level);
  };

```

1340

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

1341 A.5.2 Configuration file

1342 The DAQ software takes as input a configuration file written using INI standard [40]. This file is
 1343 partly filled with the information provided by the shifters when starting data acquisition using the
 1344 webDCS, as shown by Figure A.6. This information is written in section [`General`] and will later

1345 be stored in the ROOT file that contains the DAQ data as can be seen from Figure A.3. Indeed,
 1346 another `TTree` called `RunParameters` as well as the 2 histograms `ID`, containing the scan number,
 1347 start and stop time stamps, and `Triggers`, containing the number of triggers requested by the shifter,
 1348 are available in the data files. Moreover, `ScanID` and `HV` are then used to construct the file name
 1349 thanks to the method `DataReader::GetFileName()`.

Chamber	RE2-2-NPD-BARC-8	RE2-2-CERN-106	RE2-3-NPD-BARC-9	RE4-2-CERN-165	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	

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.

1350 The rest of the information is written beforehand in the configuration file template, as explicated
 1351 in Source Code A.7, and contains the hardware addresses to the different VME modules in the
 1352 setup as well as settings for the TDCs. As the TDC settings available in the configuration file are not
 1353 supposed to be modified, an improvement would be to remove them from the configuration file and
 1354 to hardcode them inside of the DAQ code itself or to place them into a different INI file that would
 1355 host only the TDC settings to lower the probability for a bad manipulation of the configuration file
 1356 that can be modified from one of webDCS' menus.

1357

```
[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
[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
TriggerTimeSubtraction=0b1
TdcDetectionMode=0b01
TdcResolution=0b10
TdcDeadTime=0b00
TdcHeadTrailer=0b1
TdcEventSize=0b1001
TdcTestMode=0b0
BLTMode=1
```

1358

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.

1359 In order to retrieve the information of the configuration file, the object `IniFile` has been developed
 1360 to provide an INI parser, presented in Source Code A.8. It contains private methods returning a
 1361 boolean to check the type of line written in the file, whether a comment, a group header or a key line
 1362 (`IniFile::CheckIfComment()`, `IniFile::CheckIfGroup()` and `IniFile::CheckIfToken()`). The
 1363 key may sometimes be referred to as *token* in the source code. Moreover, the private element
 1364 `FileData` is a map of `const string` to `string` that allows to store the data contained inside the
 1365 configuration file via the public method `IniFile::GetFileData()` following the formatting (see
 1366 method `IniFile::Read()`):

```
1368
  1369     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;
```

1370 More methods have been written to translate the different keys into the right variable format
 1371 when used by the DAQ. For example, to get a `float` value out of the configuration file data, knowing
 1372 the group and the key needed, the method `IniFile::floatType()` can be used. It takes 3 arguments
 1373 being the group name and key name (both `string`), and a default `float` value used as exception in
 1374 the case the expected combination of group and key cannot be found in the configuration file. This
 1375 default value is then used and the DAQ continues on working after sending an alert in the log file for
 1376 further debugging.

```

1377 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();
};

1378

```

1379 *Source Code A.8: Description of C++ object `IniFile` used as a parser for INI file format.*

1380 A.5.3 WebDCS/DAQ intercommunication

1381 When shifters send instructions to the DAQ via the configuration file, it is the webDCS itself that
 1382 gives the start command to the DAQ and then the 2 softwares use inter-process communication
 1383 through file to synchronise themselves. This communication file is represented by the variable **const**
 1384 **string** __runstatuspath.

1385 On one side, the webDCS sends commands or status that are readout by the DAQ:

- 1386 ● INIT, status sent when launching a scan and read via function `CtrlRunStatus(...)`,
- 1387 ● START, command to start data taking and read via function `CheckSTART()`,
- 1388 ● STOP, command to stop data taking at the end of the scan and read via function `CheckSTOP()`,
 1389 and
- 1390 ● KILL, command to kill data taking sent by user and read via function `CheckKILL()`

1391 and on the other, the DAQ sends status that are controled by the webDCS:

- 1392 ● `DAQ_RDY`, sent with `SendDAQReady()` to signify that the DAQ is ready to receive commands
1393 from the webDCS,
- 1394 ● `RUNNING`, sent with `SendDAQRunning()` to signify that the DAQ is taking data,
- 1395 ● `DAQ_ERR`, sent with `SendDAQError()` to signify that the DAQ didn't receive the expected com-
1396 mand from the webDCS or that the launch command didn't have the right number of argu-
1397 ments,
- 1398 ● `RD_ERR`, sent when the DAQ wasn't able to read the communication file, and
- 1399 ● `WR_ERR`, sent when the DAQ wasn't able to write into the communication file.

1400 **A.5.4 Example of inter-process communication cycle**

1401 Under normal conditions, the webDCS and the DAQ processes exchange commands and status via
1402 the file hosted at the address `__runstatuspath`, as explained in subsection A.5.3. An example of
1403 cycle is given in Table A.1. In this example, the steps 3 to 5 are repeated as long as the webDCS tells
1404 the DAQ to take data. A data taking cycle is the equivalent as what is called a *Scan* in GIFT++ jargon,
1405 referring to a set a runs with several HV steps. Each repetition of steps 3 to 5 is then equivalent to a
1406 single *Run*.

1407

1408 At any moment during the data taking, for any reason, the shifter can decide that the data taking
1409 needs to be stopped before it reached the end of the scheduled cycle. Thus at any moment on the
1410 cycle, the content of the inter-process communication file will be changed to `KILL` and the DAQ will
1411 shut down right away. The DAQ checks for `KILL` signals every 5s after the TDCs configuration is
1412 over. So far, the function `CheckKILL()` has been used only inside of the data taking loop of method
1413 `DataReader::Run()` and thus, if the shifter decides to KILL the data taking during the TDC con-
1414 figuration phase or the HV ramping in between 2 HV steps, the DAQ will not be stopped smoothly
1415 and a *force kill* command will be sent to stop the DAQ process that is still awake on the computer.
1416 Improvements can be brought on this part of the software to make sure that the DAQ can safely
1417 shutdown at any moment.

1418

1419 **A.6 Software export**

1420 In section A.2 was discussed the fact that the DAQ as written in its last version is not a standalone
1421 software. It is possible to make it a standalone program that could be adapted to any VME setup
1422 using V1190A and V1718 modules by creating a GUI for the software or by printing the log mes-
1423 sages that are normally printed in the webDCS through the log file, directly into the terminal. This
1424 method was used by the DAQ up to version 3.0 moment where the webDCS was completed. Also, it
1425 is possible to check branches of DAQ v2.X to have example of communication through a terminal.

1426

1427 DAQ v2.X is nonetheless limited in it's possibilities and requires a lot of offline manual interven-
1428 tions from the users. Indeed, there is no communication of the software with the detectors' power
1429 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	<code>__runstatuspath</code>
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.

1430 and loop over to take data without any further manual intervention. In v2.X, the data is taken for a
1431 single detector setting and at the end of each run, the softwares asks the user if he intends on taking
1432 more runs. If so, the software invites the user to set the operating voltages accordingly to what is
1433 necessary and to manual update the configuration file in consequence. This working mode can be a
1434 very first approach before an evolution and has been successfully used by colleagues from different
1435 collaborations.

1436
1437 For a more robust operation, it is recommended to develop a GUI or a web application to inter-
1438 face the DAQ. Moreover, to limit the amount of manual interventions, and thus the probability to
1439 make mistakes, it is also recommended to add an extra feature into the DAQ by installing the HV
1440 Wrapper library provided by CAEN of which an example of use in a similar DAQ software devel-
1441 opped by a master student of UGent, and called TinyDAQ, is provided on UGent's github. Then, this
1442 HV Wrapper will help you communicating with and give instructions to a CAEN HV powered crate
1443 and can be added into the DAQ at the same level where the communication with the user was made
1444 in DAQ v2.X. In case you are using another kind of power system for your detectors, it is stringly
1445 adviced to use HV modules or crates that can be remotely controled via a using C++ libraries.

1446

B

1447

1448

Details on the offline analysis package

1449 The data collected in GIF++ thanks to the DAQ described in Appendix A is difficult to interpret by
1450 a human user that doesn't have a clear idea of the raw data architecture of the ROOT data files. In
1451 order to render the data human readable, a C++ offline analysis tool was designed to provide users
1452 with detector by detector histograms that give a clear overview of the parameters monitored during
1453 the data acquisition [41]. In this appendix, details about this software in the context of GIF++, as of
1454 how the software was written and how it functions will be given.

1455 B.1 GIF++ Offline Analysis file tree

1456 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
1457 as it takes ROOT files in input and write an output ROOT file containing histograms. To compile the
1458 GIF++ Offline Analysis project is compiled with cmake. To compile, first a build/ directory must
1459 be created to compile from there:

```
1461 mkdir build
1462 cd build
1463 cmake ..
1464 make
1465 make install
```

1463 To clean the directory and create a new build directory, the bash script cleandir.sh can be used:

```
1464
1465 ./cleandir.sh
```

1466 The source code tree is provided below along with comments to give an overview of the files' con-
1467 tent. The different objects created for this project (`Infrastructure`, `Trolley`, `RPC`, `Mapping`, `RPCHit`,
1468 `RPCCluster` and `Inifile`) will be described in details in the following sections.

1469

```

GIF_OfflineAnalysis
├── bin
│   └── offlineanalysis ..... EXECUTABLE
├── build..... CMAKE COMPILATION DIRECTORY
└── ...
    ├── include..... LIST OF C++ HEADER FILES
    │   ├── Cluster.h..... DECLARATION OF OBJECT RPCCLUSTER
    │   ├── Current.h..... DECLARATION OF GETCURRENT ANALYSIS MACRO
    │   ├── GIFTrolley.h..... DECLARATION OF OBJECT TROLLEY
    │   ├── Infrastructure.h..... DECLARATION OF OBJECT INFRASTRUCTURE
    │   ├── IniFile.h..... DECLARATION OF OBJECT INI FILE FORINI PARSER
    │   ├── Mapping.h..... DECLARATION OF OBJECT MAPPING
    │   ├── MsgSvc.h..... DECLARATION OF OFFLINE LOG MESSAGES
    │   ├── OfflineAnalysis.h..... DECLARATION OF DATA ANALYSIS MACRO
    │   ├── RPCTracker.h..... DECLARATION OF OBJECT RPC
    │   ├── RPCHit.h..... DECLARATION OF OBJECT RPCHIT
    │   ├── types.h..... DEFINITION OF USEFUL VARIABLE TYPES
    │   └── utils.h..... DECLARATION OF USEFUL FUNCTIONS
    ├── obj..... BINARY FILES CREATED BY COMPILER
    └── ...
        ├── src..... LIST OF C++ SOURCE FILES
        │   ├── Cluster.cc..... DEFINITION OF OBJECT RPCCLUSTER
        │   ├── Current.cc..... DEFINITION OF GETCURRENT ANALYSIS MACRO
        │   ├── GIFTrolley.cc..... DEFINITION OF OBJECT TROLLEY
        │   ├── Infrastructure.cc..... DEFINITION OF OBJECT INFRASTRUCTURE
        │   ├── IniFile.cc..... DEFINITION OF OBJECT INI FILE FORINI PARSER
        │   ├── main.cc..... MAIN FILE
        │   ├── Mapping.cc..... DEFINITION OF OBJECT MAPPING
        │   ├── MsgSvc.cc..... DECLARATION OF OFFLINE LOG MESSAGES
        │   ├── OfflineAnalysis.cc..... DECLARATION OF DATA ANALYSIS MACRO
        │   ├── RPCTracker.cc..... DECLARATION OF OBJECT RPC
        │   ├── RPCHit.cc..... DECLARATION OF OBJECT RPCHIT
        │   └── utils.cc..... DEFINITION OF USEFUL FUNCTIONS
        ├── cleandir.sh..... BASH SCRIPT TO CLEAN BUILD DIRECTORY
        ├── CMakeLists.txt..... SET OF INSTRUCTIONS FOR CMAKE
        ├── config.h.in..... DEFINITION OF VERSION NUMBER
        └── README.md..... README FILE FOR GITHUB

```

1470

B.2 Usage of the Offline Analysis

1471

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:

1473

1474

```
Scan00XXXX_HVY
```

1475

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

1476

1477 of the GIF++ webDCS. Usually, the offline analysis tool is automatically called by the webDCS at
 1478 the end of data taking or by a user from the webDCS panel if an update of the tool was brought.
 1479 Nonetheless, an expert can locally launch the analysis for tests on the GIF++ computer, or a user can
 1480 get the code on its local machine from github and download data from the webDCS for its own anal-
 1481 ysis. To launch the code, the following command can be used from the `GIF_OfflineAnalysis` folder:

1482
 1483 `bin/offlineanalysis /path/to/Scan00XXXX_HVY`

1484 where, `/path/to/Scan00XXXX_HVY` refers to the local data files. Then, the offline tool will by itself
 1485 take care of finding all available ROOT data files present in the folder, as listed below:

- 1486
 - 1487 ● `Scan00XXXX_HVY_DAQ.root` containing the TDC data as described in Appendix ?? (events, hit
 and timestamp lists), and
 - 1488 ● `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.

1491 **B.2.1 Output of the offline tool**

1492 **B.2.1.1 ROOT file**

1493 The analysis gives in output ROOT datafiles that are saved into the data folder and called using the
 1494 naming convention `Scan00XXXX_HVY_Offline.root`. Inside those, a list of `TH1` histograms can be
 1495 found. Its size will vary as a function of the number of detectors in the setup as each set of histograms
 1496 is produced detector by detector. For each partition of each chamber, can be found:

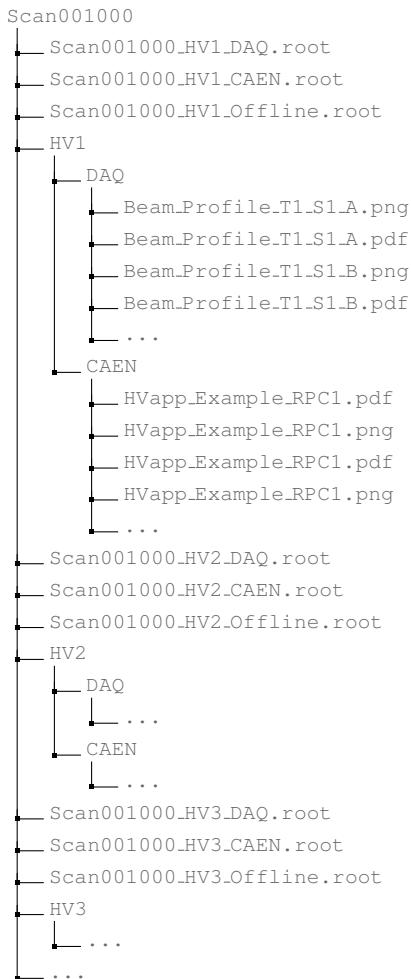
- 1497
 - 1498 ● `Time_Profile_Tt_Sc_p` shows the time profile of all recorded events (number of events per
 time bin),
 - 1499 ● `Hit_Profile_Tt_Sc_p` shows the hit profile of all recorded events (number of events per chan-
 nel),
 - 1501 ● `Hit_Multiplicity_Tt_Sc_p` shows the hit multiplicity (number of hits per event) of all recorded
 events (number of occurrences per multiplicity bin),
 - 1503 ● `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,
 - 1507 ● `Strip_Activity_Tt_Sc_p` shows noise/gamma activity for each strip (normalised version of
 previous histogram - strip activity = strip rate / average partition rate),
 - 1509 ● `Strip_Homogeneity_Tt_Sc_p` shows the *homogeneity* of a given partition ($\text{homogeneity} = \exp(-\text{strip rates standard deviation(strip rates in partition/average partition rate)})$),
 - 1511 ● `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,

- 1515 ● `mask_Strip_Activity_Tt_Sc_p` shows noise/gamma activity per unit area for each masked
1516 strip with respect to the average rate of active strips,
- 1517 ● `NoiseCSize_H_Tt_Sc_p` shows noise/gamma cluster size, a cluster being constructed out of
1518 adjacent strips giving a signal at the *same time* (hits within a time window of 25 ns),
- 1519 ● `NoiseCMult_H_Tt_Sc_p` shows noise/gamma cluster multiplicity (number of reconstructed
1520 clusters per event),
- 1521 ● `Chip_Mean_Noise_Tt_Sc_p` shows the same information than `Strip_Mean_Noise_Tt_Scp` us-
1522 ing a different binning (1 chip corresponds to 8 strips),
- 1523 ● `Chip_Activity_Tt_Sc_p` shows the same information than `Strip_Activity_Tt_Scp` using
1524 chip binning,
- 1525 ● `Chip_Homogeneity_Tt_Sc_p` shows the homogeneity of a given partition using chip binning,
- 1526 ● `Beam_Profile_Tt_Sc_p` shows the estimated beam profile when taking efficiency scan. This
1527 is obtained by filtering `Time_Profile_Tt_Sc_p` to only consider the muon peak where the
1528 noise/gamma background has been subtracted. The resulting hit profile corresponds to the
1529 beam profile on the detector channels,
- 1530 ● `L0_Efficiency_Tt_Sc_p` shows the level 0 efficiency that was estimated **without** muon track-
1531 ing,
- 1532 ● `MuonCSize_H_Tt_Sc_p` shows the level 0 muon cluster size that was estimated **without** muon
1533 tracking, and
- 1534 ● `MuonCMult_H_Tt_Sc_p` shows the level 0 muon cluster multiplicity that was estimated **without**
1535 muon tracking.

1536 In the histogram labels, *t* stands for the trolley number (1 or 3), *c* for the chamber slot label in
1537 trolley *t* and *p* for the partition label (A, B, C or D depending on the chamber layout) as explained
1538 in Chapter 5.3.

1539 In the context of GIF++, an extra script called by the webDCS is called to extract the histograms
1540 from the ROOT files. The histograms are then stored in PNG and PDF formats into the correspond-
1541 ing folder (a single folder per HV step, so per ROOT file). the goal is to then display the histograms
1542 on the Data Quality Monitoring (DQM) page of the webDCS in order for the users to control the
1543 quality of the data taking at the end of data taking. An example of histogram organisation is given
1544 below:

1545



1547 Here can put some screens from the webDCS to show the DQM and the plots available to users.

1548

1549 B.2.1.2 CSV files

1550 Moreover, up to 3 CSV files can be created depending on which ones of the 3 input files were in the

1551 data folder:

- 1552 • Offline-Corrupted.csv , is used to keep track of the amount of data that was corrupted and**
- 1553 removed from old data format files that don't contain any data quality flag.**
- 1554 • Offline-Current.csv , contains the summary of the currents and voltages applied on each**
- 1555 RPC HV channel.**
- 1556 • Offline-L0-EffC1.csv , is used to write the efficiencies, cluster size and cluster multiplicity**
- 1557 of efficiency runs. Note that L0 refers here to *Level 0* and means that the results of efficiency and**
- 1558 clusterization are a first approximation calculated without performing any muon tracking in**

1559 between the different detectors. This offline tool provides the user with a preliminar calculation
 1560 of the efficiency and of the muon event parameters. Another analysis software especially
 1561 dedicated to muon tracking is called on selected data to retrieve the results of efficiency and
 1562 muon clusterization using a tracking algorithm to discriminate noise or gamma from muons
 1563 as muons are the only particles that pass through the full setup, leaving hits than can be used
 1564 to reconstruct their tracks.

- 1565 ● `Offline-Rate.csv`, is used to write the noise or gamma rates measured in the detector readout
 1566 partitions.

1567 Note that these 4 CSV files are created along with their *headers* (`Offline-[...]-Header.csv`
 1568 containing the names of each data columns) and are automatically merged together when the offline
 1569 analysis tool is called from the webDCS, contrary to the case where the tool is runned locally from
 1570 the terminal as the merging bash script is then not called. Thus, the resulting files, used to make
 1571 official plots, are:

- 1572 ● `Corrupted.csv`,
 1573 ● `Current.csv`,
 1574 ● `L0-EffCl.csv`.
 1575 ● `Rate.csv`.

1576 **B.3 Analysis inputs and information handling**

1577 The usage of the Offline Analysis tool as well as its output have been presented in the previous section.
 1578 It is now important to dig further and start looking at the source code and the inputs necessary
 1579 for the tool to work. Indeed, other than the raw ROOT data files that are analysed, more information
 1580 needs to be imported inside of the program to perform the analysis such as the description of the
 1581 setup inside of GIFT++ at the time of data taking (number of trolleys, of RPCs, dimensions of the
 1582 detectors, etc...) or the mapping that links the TDC channels to the coresponding RPC channels in
 1583 order to translate the TDC information into human readable data. 2 files are used to transmit all this
 1584 information:
 1585

- 1586 ● `Dimensions.ini`, that provides the necessary setup and RPC information, and
 1587 ● `ChannelsMapping.csv`, that gives the link between the TDC and RPC channels as well as the
 1588 *mask* for each channel (masked or not?).

1589 **B.3.1 Dimensions file and InFile parser**

1590 This input file, present in every data folder, allows the analysis tool to know of the number of active
 1591 trolleys, the number of active RPCs in those trolleys, and the details about each RPCs such as
 1592 the number of RPC gaps, the number of pseudo-rapidity partitions (for CMS-like prototypes), the
 1593 number of strips per partion or the dimensions. To do so, there are 3 types of groups in the INI file
 1594 architecture. A first general group, appearing only once at the head of the document, gives information
 1595 about the number of active trolleys as well as their IDs, as presented in Source Code B.1. For

1596 each active trolley, a group similar to Source Code B.2 can be found containing information about
 1597 the number of active detectors in the trolley and their IDs. Each trolley group as a `Tt` name format,
 1598 where `t` is the trolley ID. Finally, for each detector stored in slots of an active trolley, there is a group
 1599 providing information about their names and dimensions, as shown in Source Code B.3. Each slot
 1600 group as a `TtSs` name format, where `s` is the slot ID of trolley `t` where the active RPC is hosted.

```
1601 [General]
1602 nTrolleys=2
1603 TrolleysID=13
```

1603 *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.*

```
1604 [T1]
1605 nSlots=4
      SlotsID=1234
```

1605 *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.*

```
1606 [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
```

1607 *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.*

1608 This information is readout and stored in a C++ object called `IniFile`, that parses the information
 1609 in the INI input file and stores it into a local buffer for later use. This INI parser is the exact same
 1610 one that was previously developed for the Gif++ DAQ and described in Appendix A.5.2.

1611 B.3.2 TDC to RPC link file and Mapping

1612 The same way the INI dimension file information is stored using `map`, the channel mapping and mask
 1613 information is stored and accessed through `map`. First of all, the mapping CSV file is organised into
 1614 3 columns separated by tabulations (and not by commas, as expected for CSV files as it is easier using
 1615 streams to read tab or space separated data using C++):

1616

1617 RPC_channel TDC_channel mask

1618 using as formatting for each field:

1619
1620 TSCCC TCCC M

1621 TSCCC is a 5-digit integer where T is the trolley ID, s the slot ID in which the RPC is held insite
1622 the trolley T and CCC is the RPC channel number, or *strip* number, that can take values up to
1623 3-digits depending on the detector,

1624 TCCC is a 4 digit integer where T is the TDC ID, CCC is the TDC channel number that can take values
1625 in between 0 and 127, and

1626 M is a 1-digit integer indicating if the channel should be considered (M = 1) or discarded (M = 0)
1627 during analysis.

1628 This mapping and masking information is readout and stored thanks to the object `Mapping`, pre-
1629 sented in Source Code B.4. Similarly to `IniFile` objects, this class has private methods. The first
1630 one, `Mapping::CheckIfNewLine()` is used to find the newline character '`\n`' or return character
1631 '`\r`' (depending on which kind of operating system interacted with the file). This is used for the
1632 simple reason that the masking information has been introduced only during the year 2017 but the
1633 channel mapping files exist since 2015 and the very beginning of data taking at GIF++. This means
1634 that in the older data folders, before the upgrade, the channel mapping file only had 2 columns, the
1635 RPC channel and the TDC channel. For compatibility reasons, this method helps controling the
1636 character following the readout of the 2 first fields of a line. In case any end of line character is
1637 found, no mask information is present in the file and the default M = 1 is used. On the contrary, if
1638 the next character was a tabulation or a space, the mask information is present.

1639 Once the 3 fields have been readout, the second private method `Mapping::CheckIfTDCCh()` is
1640 used to control that the TDC channel is an existing TDC channel. Finally, the information is stored
1641 into 3 different maps (`Link`, `ReverseLink` and `Mask`) thanks to the public method `Mapping::Read()`.
1642 `Link` allows to get the RPC channel by knowing the TDC channel while `ReverseLink` does the op-
1643 posite by returning the TDC channel by knowing the RPC channel. Finally, `Mask` returns the mask
1644 associated to a given RPC channel.

```

1645 typedef map<Uint,Uint> MappingData;

1646 class Mapping {
    private:
        bool          CheckIfNewLine(char next);
        bool          CheckIfTDCCh(Uint channel);
        string         FileName;
        MappingData   Link;
        MappingData   ReverseLink;
        MappingData   Mask;
        int           Error;

    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);
};


```

1647 *Source Code B.4: Description of C++ object Mapping used as a parser for the channel mapping and mask file.*

1648 B.4 Description of GIF++ setup within the Offline Analysis tool

1649 In the previous section, the tool input files have been discussed. The dimension file information is
 1650 stored in a map hosted by the `IniFile` object. But this information is then used to create a series of
 1651 new objects that helps defining the GIF++ infrastructure directly into the Offline Analysis. Indeed,
 1652 from the `RPC`, to the more general `Infrastructure`, every element of the GIF++ infrastrucutre is
 1653 recreated for each data analysis based on the information provided in input. All this information
 1654 about the infrastructure will be used to assign each hit signal to a specific strip channel of a specific
 1655 detector, and having a specific active area. This way, rate per unit area calculation is possible.
 1656

1657 B.4.1 RPC objects

1658 `RPC` objects have been developped to represent physical active detectors in GIF++ at the moment
 1659 of data taking. Thus, there are as many `RPC` objects created during the analysis than there were
 1660 active `RPCs` tested during a run. Each `RPC` hosts the information present in the corresponding INI
 1661 slot group, as shown in B.3, and organises it using a similar architecture. This can be seen from
 1662 `Source Code B.5`.

1663 To make the object more compact, the lists of gap labels, of gap active areas and strip active
 1664 areas are stored into `vector` dynamical containers. `RPC` objects are always contructed thanks to the
 1665 dimension file information stored into the `IniFILE` and their ID, using the format `TtSs`. Using the
 1666 `RPC` ID, the constructor calls the methods of `IniFILE` to initialise the `RPC`. The other constructors
 1667 are not used but exist in case of need. Finally, some getters have been written to access the different
 1668 private parameters storing the detector information.

```

1669 class RPC{
1670     private:
1671         string      name;           //RPC name as in webDCS database
1672         Uint        nGaps;          //Number of gaps in the RPC
1673         Uint        nPartitions;    //Number of partitions in the RPC
1674         Uint        nStrips;        //Number of strips per partition
1675         vector<string> gaps;       //List of gap labels (BOT, TOP, etc...)
1676         vector<float>  gapGeo;        //List of gap active areas
1677         vector<float>  stripGeo;      //List of strip active areas
1678
1679     public:
1680         RPC();
1681         RPC(string ID, IniFile* geofile);
1682         RPC(const RPC& other);
1683         ~RPC();
1684         RPC& operator=(const RPC& other);
1685
1686         string GetName();
1687         Uint GetNGaps();
1688         Uint GetNPartitions();
1689         Uint GetNStrips();
1690         string GetGap(Uint g);
1691         float GetGapGeo(Uint g);
1692         float GetStripGeo(Uint p);
1693     };

```

¹⁶⁷¹ *Source Code B.5: Description of C++ objects RPC that describe each active detectors used during data taking.*

¹⁶⁷² B.4.2 Trolley objects

¹⁶⁷³ Trolley objects have been developed to represent physical active trolleys in GIFT++ at the moment
¹⁶⁷⁴ of data taking. Thus, there are as many trolley objects created during the analysis than there were
¹⁶⁷⁵ active trolleys hosting tested RPCs during a run. Each Trolley hosts the information present in the
¹⁶⁷⁶ corresponding INI trolley group, as shown in B.2, and organises it using a similar architecture. In
¹⁶⁷⁷ addition to the information hosted in the INI file, these objects have a dynamical container of RPC
¹⁶⁷⁸ objects, representing the active detectors the active trolley was hosting at the time of data taking.
¹⁶⁷⁹ This can be seen from Source Code B.6.

¹⁶⁸⁰ Trolley objects are always constructed thanks to the dimension file information stored into the
¹⁶⁸¹ IniFILE and their ID, using the format Tt. Using the Trolley ID, the constructor calls the methods
¹⁶⁸² of IniFILE to initialise the Trolley. Retrieving the information of the RPC IDs via SlotsID, a new
¹⁶⁸³ RPC is constructed and added to the container RPCs for each character in the ID string. The other
¹⁶⁸⁴ constructors are not used but exist in case of need. Finally, some getters have been written to access
¹⁶⁸⁵ the different private parameters storing the trolley and detectors information.

```

1686
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.

1689 B.4.3 Infrastructure object

1690 The `Infrastructure` object has been developped to represent the GIFT++ bunker area dedicated to
 1691 CMS RPC experiments. With this very specific object, all the information about the CMS RPC
 1692 setup within GIFT++ at the moment of data taking is stored. It hosts the information present in the
 1693 corresponding INI general group, as shown in B.1, and organises it using a similar architecture. In
 1694 addition to the information hosted in the INI file, this object have a dynamical container of `Trolley`
 1695 objects, representing the active tolleys in GIFT++ area. This can be seen from Source Code B.7.

1696 The `Infrastructure` object is always contructed thanks to the dimension file information stored
 1697 into the `IniFILE`. Retrieving the information of the trolley IDs via `TrolleysID`, a new `Trolley` is
 1698 constructed and added to the container `Trolleys` for each character in the ID `string`. By extension,
 1699 it is easy to understand that the process described in Section B.4.2 for the construction of RPCs
 1700 takes place when a trolley is constructed. The other constructors are not used but exist in case of
 1701 need. Finally, some getters have been written to access the different private parameters storing the
 1702 infrastructure, tolleys and detectors information.

```

1703
class Infrastructure {
    private:
        Uint             nTrolleys;   //Number of active Trolleys in the run
        string          TrolleysID; //Active trolley IDs written into a string
        vector<Trolley*> Trolleys; //List of active Trolleys (struct)

    public:
        //Constructors and destructor
        Infrastructure();
        Infrastructure(IniFile* geofile);
        Infrastructure(const Infrastructure& other);
        ~Infrastructure();
        Infrastructure& operator=(const Infrastructure& other);

        //Get Infrastructure members
        Uint  GetNTrolleys();
        string GetTrolleysID();
        Uint   GetTrolleyID(Uint t);

1704
        //Manage Trolleys
        Trolley* GetTrolley(Uint t);
        void     DeleteTrolley(Uint t);

        //Methods to get members of GIFTrolley objects stored in Trolleys
        Uint  GetNSlots(Uint t);
        string GetSlotsID(Uint t);
        Uint   GetSlotID(Uint t, Uint s);
        RPC*  GetRPC(Uint t, Uint r);

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

```

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

1706 B.5 Handeling of data

1707 As discussed in Appendix A.4.2, the raw data as a `TTree` architecture where every entry is related to
 1708 a trigger signal provided by a muon or a random pulse, whether the goal of the data taking was to
 1709 measure the performance of the detector or the noise/gamma background respectively. Each of these
 1710 entries, referred also as events, contain a more or less full list of hits in the TDC channels to which
 1711 the detectors are connected. To this list of hits corresponds a list of time stamps, marking the arrival
 1712 of the hits within the TDC channel.

1713 The infrastructure of the CMS RPC experiment within `GIF++` being defined, combining the
 1714 information about the raw data with the information provided by both the mapping/mask file and the
 1715 dimension file allows to build new physical objects that will help in computing efficiency or rates.

1716 B.5.1 RPC hits

1717 The raw data stored in the ROOT file as output of the GIFT++ DAQ, is readout by the analysis tool
 1718 using the structure `RAWData` presented in Source Code B.9 that differs from the structure presented
 1719 in Appendix A.4.2 as it is not meant to hold all of the data contained in the ROOT file. In this sense,
 1720 this structure is in the case of the offline analysis tool not a dynamical object and will only be storing
 1721 a single event contained in a single entry of the `TTree`.

```
1722
1723 class RPCHit {
1724     private:
1725         Uint Channel;      //RPC channel according to mapping (5 digits)
1726         Uint Trolley;      //0, 1 or 3 (1st digit of the RPC channel)
1727         Uint Station;      //Slot where is held the RPC in Trolley (2nd digit)
1728         Uint Strip;        //Physical RPC strip where the hit occurred (last 3
1729             digits)
1730         Uint Partition;    //Readout partition along eta segmentation
1731         float TimeStamp;   //Time stamp of the arrival in TDC
1732
1733     public:
1734         //Constructors, destructor & operator =
1735         RPCHit();
1736         RPCHit(Uint channel, float time, Infrastructure* Infra);
1737         RPCHit(const RPCHit& other);
1738         ~RPCHit();
1739         RPCHit& operator=(const RPCHit& other);
1740
1741         //Get RPCHit members
1742         Uint GetChannel();
1743         Uint GetTrolley();
1744         Uint GetStation();
1745         Uint GetStrip();
1746         Uint GetPartition();
1747         float GetTime();
1748     };
1749
1750     typedef vector<RPCHit> HitList;
1751     typedef struct GIFHitList { HitList rpc[NTROLLEYS][NSLOTS][NPARTITIONS]; } →
1752         GIFHitList;
1753
1754     bool SortHitbyStrip(RPCHit h1, RPCHit h2);
1755     bool SortHitbyTime(RPCHit h1, RPCHit h2);

```

1724 *Source Code B.8: Description of C++ object RPCHit.*

```
1725
1726     struct RAWData{
1727         int iEvent;          //Event i
1728         int TDCNHits;       //Number of hits in event i
1729         int QFlag;           //Quality flag list (1 flag digit per TDC)
1730         vector<Uint> *TDCCh; //List of channels giving hits per event
1731         vector<float> *TDCTS; //List of the corresponding time stamps
1732     };

```

1726 *Source Code B.9: Description of C++ structure RAWData.*

1727 Each member of the structure is then linked to the corresponding branch of the ROOT data tree,
 1728 as shown in the example of Source Code B.10, and using the method `GetEntry(int i)` of the ROOT
 1729 class `TTree` will update the state of the members of `RAWData`.

```

1730 TTree* dataTree = (TTree*)dataFile.Get("RAWData");
1731 RAWData data;
1732
1733 dataTree->SetBranchAddress("EventNumber", &data.iEvent);
1734 dataTree->SetBranchAddress("number_of_hits", &data.TDCNHits);
1735 dataTree->SetBranchAddress("Quality_flag", &data.QFlag);
1736 dataTree->SetBranchAddress("TDC_channel", &data.TDCCh);
1737 dataTree->SetBranchAddress("TDC_TimeStamp", &data.TDCTS);

```

1732 *Source Code B.10: Example of link in between RAWData and TTree.*

1733 The data is then analysed entry by entry and to each element of the TDC channel list, a `RPCHit` is
 1734 constructed by linking each TDC channel to the corresponding RPC channel thanks to the `Mapping`
 1735 object. The information carried by the RPC channel format allows to easily retrieve the trolley and
 1736 slot from which the hit was recorded (see section B.3.2). Using these 2 values, the readout partition
 1737 can be found by knowing the strip channel and comparing it with the number of partitions and strips
 1738 per partition stored into the `Infrastructure` object.

1739 Thus `RPCHit` objects are then stored into 3D dynamical list called `GIFHitList` (Source Code B.9)
 1740 where the 3 dimensions refer to the 3 layers of the readout in `GIF++` : in the bunker there are *trolleys*
 1741 (τ) holding detectors in *slots* (s) and each detector readout is divided into 1 or more pseudo-rapidity
 1742 *partitions* (p). Using these 3 information allows to assign an address to each readout partition and
 1743 this address will point to a specific hit list.

1744

1745 **B.5.2 Clusters of hits**

1746 All the hits contained in the ROOT file have been sorted into the different hit lists through the
 1747 `GIFHitList`. At this point, it is possible to start looking for clusters. A cluster is a group of adjacent
 1748 strips getting hits within a time window of 25 ns. These strips are then assumed to be part of the same
 1749 physical avalanche signal generated by a muon passing through the chamber or by the interaction of
 1750 a gamma stopping into the electrodes of the RPCs.

1751 To keep the cluster information, `RPCCluster` objects have been defined as shown in Source
 1752 Code B.11. Using the information of each individual `RPCHit` taken out of the hit list, it stores
 1753 the cluster size (number of adjacent strips composing the cluster), the first and last hit, the center for
 1754 spatial reconstruction and finally the start and stop time stamps as well as te time spread in between
 1755 the first and last hit.

```

1756
class RPCCluster{
    private:
        Uint ClusterSize; //Size of cluster #ID
        Uint FirstStrip; //First strip of cluster #ID
        Uint LastStrip; //Last strip of cluster #ID
        float Center; //Center of cluster #ID ((first+last)/2)
        float StartStamp; //Time stamp of the earliest hit of cluster #ID
        float StopStamp; //Time stamp of the latest hit of cluster #ID
        float TimeSpread; //Time difference between earliest and latest hits
                           //of cluster #ID

    public:
        //Constructors, destructor & operator =
        RPCCluster();
        RPCCluster(HitList List, Uint cID, Uint cSize, Uint first, Uint firstID);
        RPCCluster(const RPCCluster& other);
        ~RPCCluster();
        RPCCluster& operator=(const RPCCluster& other);

        //Get Cluster members
        Uint GetID();
        Uint GetSize();
        Uint GetFirstStrip();
        Uint GetLastStrip();
        float GetCenter();
        float GetStart();
        float GetStop();
        float GetSpread();
};

typedef vector<RPCCluster> ClusterList;

//Other functions to build cluster lists out of hit lists
void BuildClusters(HitList &cluster, ClusterList &clusterList);
void Clusterization(HitList &hits, TH1 *hcSize, TH1 *hcMult);

```

Source Code B.11: Description of C++ object cluster.

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

1771 B.6 DAQ data Analysis

1772 All the ingredients to analyse GIF++ data have been defined. This section will focus on the different
1773 part of the analysis performed on the data, from determining the type of data the tool is dealing with

¹⁷⁷⁴ to calculating the rate in each detector or reconstructing muon or gamma clusters.

¹⁷⁷⁵ B.6.1 Determination of the run type

¹⁷⁷⁶ In GIF++, both the performance of the detectors in detecting muons in an irradiated environment and
¹⁷⁷⁷ the gamma background can be independantly measured. These corresponds to different run types
¹⁷⁷⁸ and thus, to different TDC settings giving different data to look at.

¹⁷⁷⁹

¹⁷⁸⁰ In the case of performance measurements, the trigger for data taking is provided by the coïncidence
¹⁷⁸¹ of several scintillators when muons from the beam passing through the area are detected. Data
¹⁷⁸² is collected in a 600 ns wide window around the arrival of muons in the RPCs. The expected time
¹⁷⁸³ distribution of hits is shown in Figure B.1a. The muon peak is clearly visible in the center of the
¹⁷⁸⁴ distribution and is to be extracted from the gamma background that composes the flat part of the
¹⁷⁸⁵ distribution.

¹⁷⁸⁶ On the other hand, gamma background or noise measurements are focussed on the non muon
¹⁷⁸⁷ related physics and the trigger needs to be independant from the muons to give a good measurement
¹⁷⁸⁸ of the gamma/noise distribution as seen by the detectors. The trigger is then provided by a pulse
¹⁷⁸⁹ generator at a frequency of 300 Hz whose pulse is not likely to be on time with a muon. In order
¹⁷⁹⁰ to increase the integrated time without increasing the acquisition time too much, the width of the
¹⁷⁹¹ acquisition windows are increased to 10 μ s. The time distribution of the hits is expected to be flat, as
¹⁷⁹² shown by Figure B.1b.

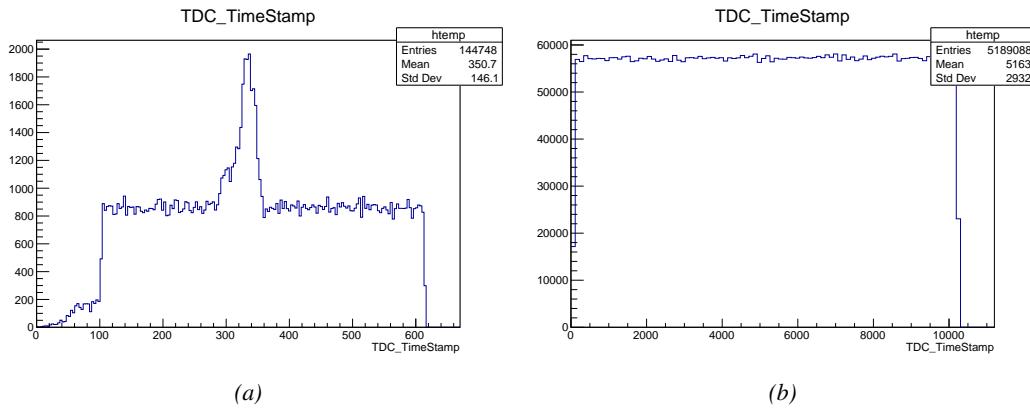


Figure B.1: Example of expected hit time distributions in the cases of efficiency (Figure B.1a) and noise/gamma rate per unit area (Figure B.1b) measurements as extracted from the raw ROOT files. The unit along the x-axis corresponds to ns. The fact that "the" muon peak is not well defined in Figure 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.

¹⁷⁹³ The ROOT files include a TTree called RunParameters containing, among other things, the in-
¹⁷⁹⁴ formation related to the type of run. The run type can then be accessed as described by Source
¹⁷⁹⁵ Code B.12 and the function IsEfficiencyRun() is then used to determine if the run file is an effi-
¹⁷⁹⁶ ciency run or, on the contrary, another type of run (noise or gamma measurement).

```

1797
1798     TTree* RunParameters = (TTree*)dataFile.Get("RunParameters");
1799     TString* RunType = new TString();
1800     RunParameters->SetBranchAddress("RunType", &RunType);
1801     RunParameters->GetEntry(0);

```

1799 *Source Code B.12: Access to the run type contained in TTree* RunParameters.*

1800 Finally, the data files will have a slightly different content whether it was collected before or after
1801 October 2017 and the upgrade of the DAQ software that brought a new information into the ROOT
1802 output. This is discussed in Appendix A.4.3 and implies that the analysis will differ a little depending
1803 on the data format. Indeed, as no information on the data quality is stored, in older data files, the cor-
1804 rections for missing events has to be done at the end of the analysis. The information about the type
1805 of data format is stored in the variable **bool** `isNewFormat` by checking the list of branches contained
1806 in the data tree via the methods `TTree::GetListOfBranches()` and `TCollection::Contains()`.

1807 **B.6.2 Beam time window calculation for efficiency runs**

1808 Knowing the run type is important first of all to know the width of the acquisition window to be used
1809 for the rate calculation and finally to be able to seek for muons. Indeed, the peak that appears in the
1810 time distribution for each detectors is then fitted to extract the most probable time window in which
1811 the tool should look for muon hits. The data outside of this time window is then used to evaluate the
1812 noise or gamma background the detector was subjected to during the data taking. Computing the
1813 position of the peak is done calling the function `SetBeamWindow()` defined in file `src/RPCHit.cc` that
1814 loops a first time on the data. The data is first sorted in a 3D array of 1D histograms (`GIFH1Array`, see
1815 `include/types.h`). Then the location of the highest bin is determined using `TH1::GetMaximumBin()`
1816 and is used to define a window in which a gaussian fit will be applied to compute the peak width.
1817 This window is a 80 ns defined by Formula B.1 around the central bin.

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

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

1818 Before the fit is performed, the average number of noise/gamma hits per bin is evaluated using
1819 the data outside of the fit window. Excluding the first 100 ns, the average number of hits per bin
1820 due to the noise or gamma is defined by Formula B.2 after extracting the amount of hits in the time
1821 windows $[100; t_{low}]$ and $[t_{high}; 600]$ thanks to the method `TH1::Integral()`. This average number
1822 of hits is then subtracted to every bin of the 1D histogram, in order to *clean* it from the noise or
1823 gamma contribution as much as possible to improve the fit quality. Bins where $\langle n_{hits} \rangle$ is greater
1824 than the actual bin content are set to 0.

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

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

1825 Finally, the fit parameters are extracted and saved for each detector in 3D arrays of **float**
1826 (`muonPeak`, see `include/types.h`), a first one for the mean arrival time of the muons, `PeakTime`,

1827 and a second one for the width of the peak, `PeakWidth`. The width is defined as 6σ of the gaussian
 1828 fit. The same settings are applied to every partitions of the same detector. To determine which one
 1829 of the detector's partitions is directly illuminated by the beam, the peak height of each partition is
 1830 compared and the highest one is then used to define the peak settings.

1831 **B.6.3 Data loop and histogram filling**

1832 3D arrays of histogram are created to store the data and display it on the DQM of G4F++ webDCS
 1833 for the use of shifters. These histograms, presented in section B.2.1.1, are filled while looping on
 1834 the data. Before starting the analysis loop, it is necessary to control the entry quality for the new
 1835 file formats featuring `QFlag`. If the `QFlag` value for this entry shows that 1 TDC or more have a
 1836 `CORRUPTED` flag, then this event is discarded. The loss of statistics is low enough to be neglected.
 1837 `QFlag` is controlled using the function `IsCorruptedEvent()` defined in `src/utils.cc`. As explained
 1838 in Appendix A.4.3, each digit of this integer represent a TDC flag that can be 1 or 2. Each 2 is
 1839 the sign of a `CORRUPTED` state. Then, the data is accessed entry by entry in the ROOT `TTree` using
 1840 `RAWData` and each hit in the hit list is assigned to a detector channel and saved in the corresponding
 1841 histograms. In the first part of the analysis, in which the loop over the ROOT file's content is
 1842 performed, the different steps are:

1843 **1- RPC channel assignment and control:** a check is done on the RPC channel extracted thanks
 1844 to the mapping via the method `Mapping::GetLink()`. If the channel is not initialised and is 0, or if
 1845 the TDC channel was greater than 5127, the hit is discarded. This means there was a problem in the
 1846 mapping. Often a mapping problem leads to the crash of the offline tool.

1847 **2- Creation of a `RPCHit` object:** to easily get the trolley, slot and partition in which the hit has
 1848 been assigned, this object is particularly helpful.

1849 **3- General histograms are filled:** the hit is filled into the time distribution and the general hit
 1850 distribution histograms, and if the arrival time is within the first 100 ns, it is discarded and nothing
 1851 else happens and the loop proceeds with the next hit in the list.

1852 **4- Multiplicity counter:** the hit multiplicity counter of the corresponding detectors incremented.

1853 **5-a- Efficiency runs - Is the hit within the peak window? :** if the peak is contained in the peak
 1854 window previously defined in section B.6.2, the hit is filled into the beam hit profile histogram of
 1855 the corresponding chamber, added into the list of muon hits and increments the counter of *in time*
 1856 hits. The term *in time* here refers to the hits that are likely to be muons by arriving in the expected
 1857 time window. If the hit is outside of the peak window, it is filled into the noise profile histogram
 1858 of the corresponding detector, added into the list of noise/gamma hits and increments the counter of
 1859 noise/gamma hits.

1860 **5-b- Noise/gamma rate runs - Noise histograms are filled:** the hit is filled into the noise profile
 1861 histogram of the corresponding detector, added into the list of noise/gamma hits and increments the
 1862 counter of noise/gamma hits.

1864 After the loop on the hit list of the entry is over, the next step is to clusterize the 3D lists filled
 1865 in the previous steps. A 3D loop is then started over the active trolley, slot and RPC partitions to
 1866 access these objects. Each `NoiseHitList` and `MuonHitList`, in case of efficiency run, are clusterized
 1867 as described in section B.5.2. There corresponding cluster size and multiplicity histograms are filled
 1868 at the end of the clustering process. Then, the efficiency histogram is filled in case of efficiency run.
 1869 The selection is simply made by checking whether the RPC detected signals in the peak window
 1870 during this event. Nevertheless, it is useful to highlight that at this level, it is not possible yet to
 1871 discriminate in between a muon hit and noise or gamma hit. Thus, `MuonCSize_H`, `MuonCMult_H`
 1872 and `Efficiency0_H` are subjected to noise and gamma contamination. This contamination will be
 1873 estimated and corrected at the moment the results will be written into output CSV files. Finally, the
 1874 loop ends on the filling of the general hit multiplicity histogram.

1875 **B.6.4 Results calculation**

1876 As mentioned in section B.2.1, the analysis of DAQ data provides the user with 3 CSV files and
 1877 a ROOT file associated to each and every ROOT data file. The fourth CSV file is provided by the
 1878 extraction of the CEAN main frame data monitored during data taking and will be discussed later.
 1879 After looping on the data in the previous part of the analysis macro, the output files are created and a
 1880 3D loop on each RPC readout partitions is started to extract the histograms parameters and compute
 1881 the final results.

1882

1883 **B.6.4.1 Rate normalisation**

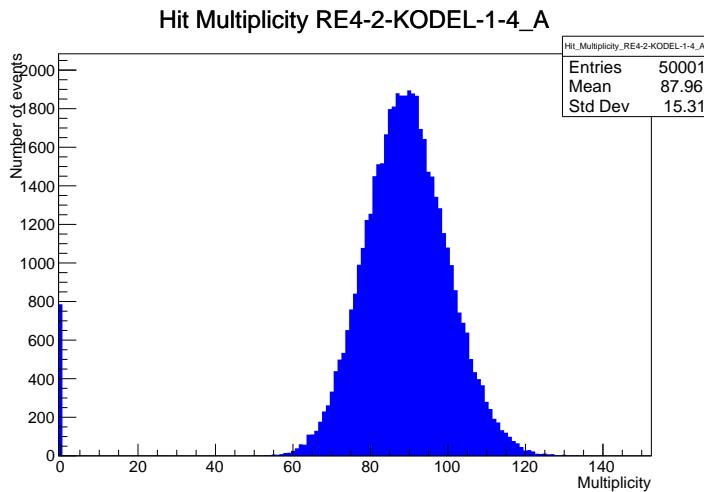


Figure B.2: The effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without `Quality_flag`. The artificial high content of bin 0 is the effect of corrupted data.

1884 To analyse old data format files, not containing any quality flag, it is needed to estimate the amount
 1885 of corrupted data via a fit as the corrupted data will always fill events with a fake "0 multiplicity".
 1886 Indeed, as no hits were stored in the DAQ ROOT files, these events artificially contribute to fill
 1887 the bin corresponding to a null multiplicity, as shown in Figure B.2. In the case the mean of the

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

- The difference in between the data for multiplicity 1 and the corresponding fit value should be 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 of entries with multiplicity 1, $sk(1)$ the value of the skew fit, as defined by Formula 5.3, for multiplicity 1 and N_{tot} the total number of entries.

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

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

```

1910
    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","",0.5,Xmax);

        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","",0.5,Xmax);

        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;

1911
        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.

1913 B.6.4.2 Rate and activity

1914 At this point, the strip rate histograms, StripNoiseProfile_H.rpc[T][S][p], only contain an in-
1915 formation about the total number of noise or rate hits each channel received during the data taking.
1916 As described in Source Code B.14, a loop on the strip channels will be used to normalise the content
1917 of the rate distribution histogram for each detector partitions. The initial number of hits recorded for
1918 a given bin will be extracted and 2 values will be computed:

- 1919 ● the strip rate, defined as the number of hits recorded in the bin normalised like described in
 1920 the previous section, using the variable `rate_norm`, and

- 1921 ● the strip activity, defined as the number of hits recorded in the bin normalised to the average
 1922 number of hits per bin contained in the partition histogram, using the variable `averageNhit`.
 1923 This value provides an information on the homogeneity of the detector response to the gamma
 1924 background or of the detector noise. An activity of 1 corresponds to an average response.
 1925 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);
}

```

1927 *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.*

1928 On each detector partitions, which are readout by a single FEE, all the channels are not processed
 1929 by the same chip. Each chip can give a different noise response and thus, histograms using a chip
 1930 binning are used to investigate chip related noise behaviours. The average values of the strip rate
 1931 or activity grouped into a given chip are extracted using the using the function `GetChipBin()` and
 1932 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;
}

```

1935 *Source Code B.15: Function used to compute the content of a bin for an histogram using chip binning.*

```
1936   for(Uint ch = 0; ch < (nStripsPart/NSTRIPSCHIP); ch++) {
        ChipMeanNoiseProf_H.rpc[T][S][p]-
            SetBinContent(ch+1,GetChipBin(StripNoiseProfile_H.rpc[T][S][p],ch));
        ChipActivity_H.rpc[T][S][p]-
            SetBinContent(ch+1,GetChipBin(StripActivity_H.rpc[T][S][p],ch));
    }
```

1937 *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.

```

1950 float MeanPartSDev = GetTH1StdDev(StripNoiseProfile_H.rpc[T][S][p]);
float strip_homog = (MeanPartRate==0)
? 0.
: exp(-MeanPartSDev/MeanPartRate);
StripHomogeneity_H.rpc[T][S][p]->Fill("exp -#left (#frac{\sigma_{Strip}
-> Rate}){\mu_{Strip Rate}}#right)",strip_homog);
StripHomogeneity_H.rpc[T][S][p]->GetYaxis()->SetRangeUser(0.,1.);

1951 float ChipStDevMean = GetTH1StdDev(ChipMeanNoiseProf_H.rpc[T][S][p]);
float chip_homog = (MeanPartRate==0)
? 0.
: exp(-ChipStDevMean/MeanPartRate);
ChipHomogeneity_H.rpc[T][S][p]->Fill("exp -#left (#frac{\sigma_{Chip}
-> Rate}){\mu_{Chip Rate}}#right)",chip_homog);
ChipHomogeneity_H.rpc[T][S][p]->GetYaxis()->SetRangeUser(0.,1.);
```

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

1953 B.6.4.3 Strip masking tool

1954 The offline tool is automatically called at the end of each data taking to analyse the data and offer
1955 the shifter DQM histograms to control the data quality. After the histograms have been published
1956 online in the DQM page, the shifter can decide to mask noisy or dead channels that will contribute
1957 to bias the final rate calculation by editing the mask column of `ChannelsMapping.csv` as can be seen
1958 in Figure B.3.

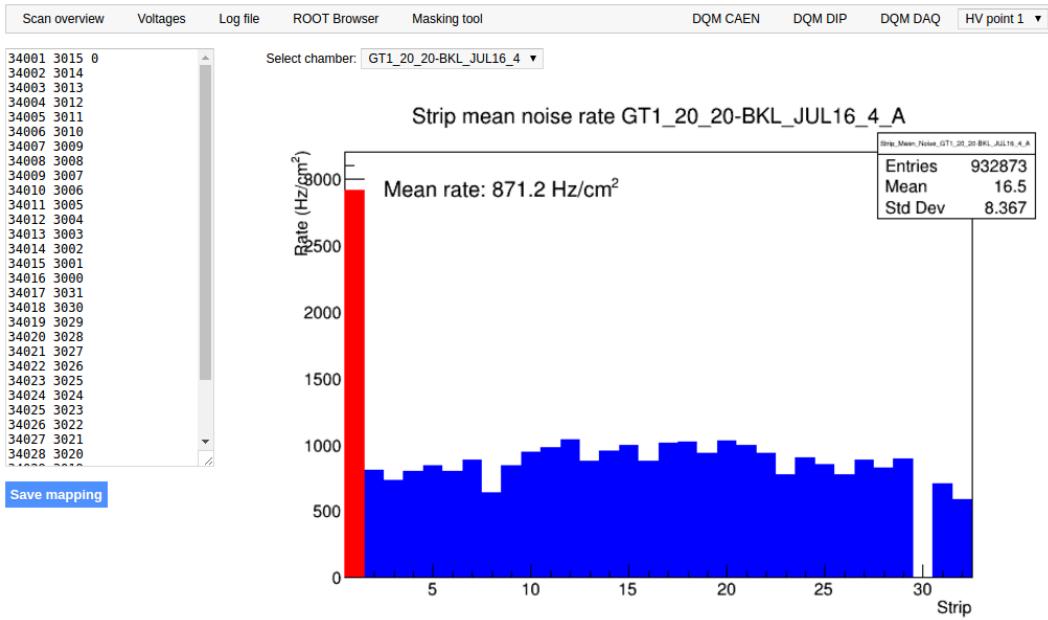


Figure B.3: Display of the masking tool page on the webDCS. The window on the left allows the shifter to edit ChannelsMapping.csv. To mask a channel, it only is needed to set the 3rd field corresponding to the strip to mask to 0. It is not necessary for older mapping file formats to add a 1 for each 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.

1959 From the code point of view, the function `GetTH1Mean()` is used to retrieve the mean rate par-
 1960 tition by partition after the rates have been calculated strip by strip and filled into the histograms
 1961 `StripNoiseProfile_H.rpc[T][S][p]`, as described through Source Code B.18.

1962 Once the mask for each rejected channel has been updated, the shifter can manually run the of-
 1963 fline tool again to update the DQM plots, now including the masked strips, as well the rate results
 1964 written in the output CSV file `Offline-Rate.csv`. If not done during the shifts, the strip masking
 1965 procedure needs to be carefully done by the person in charge of data analysis on the scans that were
 1966 selected to produce the final results.

```

1967
1968   float GetTH1Mean(TH1* H) {
1969     int nBins = H->GetNbinsX();
1970     int nActive = nBins;
1971     float mean = 0.;

1972     for(int b = 1; b <= nBins; b++) {
1973       float value = H->GetBinContent(b);
1974       mean += value;
1975       if(value == 0.) nActive--;
1976     }

1977     if(nActive != 0) mean /= (float)nActive;
1978     else mean = 0.;

1979     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.

1970 B.6.4.4 Output CSV files filling

1971 All the histograms have been filled. Parameters will then be extracted from them to compute the
 1972 final results that will later be used to produce plots. Once the results have been computed, the very
 1973 last step of the offline macro is to write these values into the corresponding CSV outputs. Aside of
 1974 the file `Offline-Corrupted.csv`, 2 CSV files are being written by the macro `offlineAnalysis()`,
 1975 `Offline-Rates.csv` and `Offline-L0-EffCl.csv` that respectively contain information about noise
 1976 or gamma rates, cluster size and multiplicity, and about level 0 reconstruction of the detector effi-
 1977 ciency, muon cluster size and multiplicity. Details on the computation and file writing are respec-
 1978 tively given in Sources Codes B.19 and B.20.

1979 **Noise/gamma background variables** are computed and written in the output file for each detector
 1980 partitions. A detector average of the hit and cluster rate is also provided, as shown through Sources
 1981 Code B.19. The variables that are written for each partition are:

- 1982 • The mean partition hit rate per unit area, `MeanPartRate`, that is extracted from the histogram
 1983 `StripNoiseProfile_H` as the mean value along the y-axis, as described in section B.6.4.3. No
 1984 error is recorded for the hit rate as this is considered a single measurement. No statistical error
 1985 can be associated to it and the systematics are unknown.
- 1986 • The mean cluster size, `cSizePart`, is extracted from the histogram `NoiseCSize_H` and it's
 1987 statistical error, `cSizePartErr`, is taken to be 2σ of the total distribution.
- 1988 • The mean cluster multiplicity per trigger, `cMultPart`, is extracted from the histogram `NoiseCMult_H`
 1989 and it's statistical error, `cMultPartErr`, is taken to be 2σ of the total distribution. It is impor-
 1990 tant to point to the fact that this variable gives an information that is dependent on the buffer
 1991 window width used for each trigger for the calculation.
- 1992 • The mean cluster rate per unit area, `ClustPartRate`, is defined as the mean hit rate normalised

1993 to the mean cluster size and it's statistical error, `ClustPartRateErr`, is then obtained using the
 1994 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';
  }
}

```

1996 *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.*

1997 **Muon performance variables** are computed and written in the output file for each detector parti-
 1998 tions as shown through Sources Code B.20. The variables that are written for each partition are:

- 1999 • The muon efficiency, `eff`, extracted from the histogram `Efficiency0_H`. It is reminded that
2000 this offline tool doesn't include any tracking algorithm to identify muons from the beam and
2001 only relies on the hits arriving in the time window corresponding to the beam time. The con-
2002 tent of the efficiency histogram is thus biased by the noise/gamma background contribution
2003 into this window and is thus corrected by estimating the muon data content in the peak re-
2004 gion knowing the noise/gamma content in the rate calculation region. Both time windows
2005 being different, the choice was made to normalise the noise/gamma background calculation
2006 window to it's equivalent beam window in order to have comparable values using the variable
2007 `windowRatio`. Finally, to estimate the data ratio in the peak region, the variable `DataRatio`
2008 is defined as the ratio in between the estimated mean cluster multiplicity of the muons in the
2009 peak region, `MuonCM`, and of the total mean cluster multiplicity in the peak region, `PeakCM`.
2010 `MuonCM` is itself defined as the difference in between the total mean cluster multiplicity in the
2011 peak region and the normalised mean noise/gamma cluster multiplicity calculated outside of
2012 the peak region. The statistical error related to the efficiency, `eff_err`, is computed using a
2013 binomial distribution, as the efficiency measure the probability of "success" and "failure" to
2014 detect muons.

- 2015 • The mean muon cluster size, `MuonCS`, is calculated using the total mean cluster size and multi-
2016 plicity in the peak region, respectively extracted from histograms `MuonCSize_H` and `MuonCMult_H`,
2017 the noise/gamma background mean cluster size and normalised multiplicity, extracted from
2018 `NoiseCSize_H` and `NoiseCMult_H`, and of the estimated muon cluster multiplicity `MuonCM` pre-
2019 viously explicated. The associated statistical error, `MuonCM_err`, is calculated using the propa-
2020 gation of errors of the mentioned variables.

- 2021 • The mean muon cluster multiplicity in the peak region, `MuonCM`, explicated above whose sta-
2022 tistical error, `MuonCM_err`, is the sum of statistical error associated to the total mean clus-
2023 ter multiplicity in the peak reagion, `PeakCM_err`, and of the mean noise/gamma cluster size,
2024 `NoiseCM_err`.

2025 In addition to these 2 CSV files, the histograms are saved in ROOT file `Scan00XXXX_HVY_Offline.root`
2026 as explained in section B.2.1.1.

2027

```

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';
        }
    }
}

```

2028

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.

2029

2030 B.7 Current data Analysis

2031 Detectors under test at GIF++ are connected both to a CAEN HV power supply and to a CAEN
2032 ADC that reads the currents inside of the RPC gaps bypassing the supply cable. During data tak-
2033 ing, the webDCS records into a ROOT file called `Scan00XXXX_HVY_CAEN.root` histograms with the
2034 monitored parameters of both CAEN devices. Are recorded for each RPC channels (in most cases,
2035 a channel corresponds to an RPC gap):

- 2036 • the effective voltage, HV_{eff} , set by the webDCS using the PT correction on the CAEN power
2037 supply,
- 2038 • the applied voltage, HV_{app} , monitored by the CAEN power supply, and the statistical error
2039 related to the variations of this value through time to follow the variation of the environmental
2040 parameters defined as the RMS of the histogram divided by the square root of the number of
2041 recorded points,
- 2042 • the monitored current, I_{mon} , monitored by the CAEN power supply, and the statistical error
2043 related to the variations of this value through time to follow the variation of the environmental
2044 parameters defined as the RMS of the histogram divided by the square root of the number of
2045 recorded points,
- 2046 • the corresponding current density, J_{mon} , defined as the monitored current per unit area,
2047 $J_{mon} = I_{mon}/A$, where A is the active area of the corresponding gap,
- 2048 • the ADC current, I_{ADC} , recorded through the CAEN ADC module that monitors the dark
2049 current in the gap itself. First of all, the resolution of such a module is better than that of
2050 CAEN power supplies and moreover, the current is not read-out through the HV supply line
2051 but directly at the chamber level giving the real current inside of the detector. The statistical
2052 error is defined as the RMS of the histogram distribution divided by the square root of the
2053 number of recorded points.

2054 Once extracted through a loop over the element of GIF++ infrastructure via the C++ macro
2055 `GetCurrent()`, these parameters, organised in 9 columns per detector HV supply line, are written in
2056 the output CSV file `Offline-Current.csv`. The macro can be found in the file `Current.cc`.