

1

CAMPINAS STATE UNIVERSITY

2

DOCTORAL THESIS

3

4 **Search of Z and Higgs boson decaying into $\Upsilon + \gamma$**
5 **in pp collisions at CMS/LHC**

6

7 *Author:*

Felipe Torres da Silva de Araujo

Supervisor:

Dr. José Augusto Chinellato

Co-Supervisor:

Dr. Alberto Franco de Sá Santoro

8

*A thesis submitted in fulfillment of the requirements
for the degree of Doctor of Physics*

10

in the

11

Graduate Program of
"Gleb Wataghin" Institute of Physics

12

13

August 15, 2020

¹⁴ “Sometimes science is a lot more art than science. A lot of people don’t get that.”

¹⁵

Rick Sanchez

¹⁶ “Então, que seja doce. Repito todas as manhãs, ao abrir as janelas para deixar entrar o sol ou o
¹⁷ cinza dos dias, bem assim, que seja doce. Quando há sol, e esse sol bate na minha cara amassada do
¹⁸ sono ou da insônia, contemplando as partículas de poeira soltas no ar, feito um pequeno universo;
¹⁹ repito sete vezes para dar sorte: que seja doce que seja doce que seja doce e assim por diante. Mas,
²⁰ se alguém me perguntasse o que deverá ser doce, talvez não saiba responder. Tudo é tão vago como
²¹ se fosse nada.”

²²

Caio Fernando Abreu

23 CAMPINAS STATE UNIVERSITY

24 *Abstract*

25 "Gleb Wataghin" Institute of Physics

26 Doctor of Physics

27 **Search of Z and Higgs boson decaying into $\Upsilon + \gamma$ in pp collisions at CMS/LHC**

28 by Felipe Torres da Silva de Araujo

29 Searches for Standard Model Higgs and Z bosons decaying to a $\Upsilon(1S, 2S, 3S)$ and a photon, with
30 subsequent decay of the $\Upsilon(1S, 2S, 3S)$ to $\mu^+ \mu^-$ are presented. The analyses is performed using
31 data recorded by CMS detector from proton-proton collisions at center-of-mass energy of 13 TeV
32 corresponding to an integrated luminosity of 35.86 fb^{-1} . We put a limit, 95% confidence level, on
33 $H \rightarrow \Upsilon(1S, 2S, 3S) + \gamma$ decay branching fraction at $(6.8, 7.1, 6.0) \times 10^{-4}$ and on $Z \rightarrow \Upsilon(1S, 2S, 3S) +$
34 γ decay branching fraction at $(2.6, 2.3, 1.3) \times 10^{-6}$. Contributions to operation, maintenance and
35 R&D of Resistive Plate Chambers (RPC) of CMS are also presented. **EXPANDIR**

DRAFT

36

Acknowledgements

37 I would like to thank:

- 38 • the Campinas State University for providing the institutional support for this study;
- 39 • the Rio de Janeiro State University for the cooperation with Campinas State University in
40 their high-energy physics program. This was a key factor for this study;
- 41 • the National Council for Scientific and Technological Development (CNPq) for the financial
42 support for this work;
- 43 • the European Laboratory for Particle Physics (CERN) for the construction and operation of
44 the Large Hadron Collider (LHC);
- 45 • the Compact Muon Solenoid (CMS) collaboration for the construction, operation and provi-
46 sion of the instrumental means for this study.

DRAFT

47 Contents

48	Abstract	iii
49	Acknowledgements	v
50	1 Introduction	1
51	2 CMS Resistive Plate Chambers - RPC	3
52	2.1 Resistive Plate Chambers	3
53	2.2 CMS Resistive Plate Chambers	3
54	2.2.1 Performance	5
55	2.3 Contribution to the CMS RPC project	5
56	2.3.1 RPC Operation - Shifts and Data Certification	6
57	2.4 RPC Online Software	7
58	2.4.1 iRPC R&D	8
59	2.4.2 LS2 and the RPC Standard Maintenance	14
60	HV maintenance	14
61	LV and control maintenance	15
62	Detector commissioning	16
63	Bibliography	19

DRAFT

⁶⁴ 1 Introduction

⁶⁵ INTRODUÇÃO
⁶⁶ USAR UM PAPER DE CMS MUON PERFORMANCE PARA DIZER PORQUE
⁶⁷ TRABALHAR COM DETECTORES DE MUONS

DRAFT

⁶⁸ 2 CMS Resistive Plate Chambers - RPC

⁶⁹ In the course of this PhD study, there were a lot of opportunities to work for the RPC project, in
⁷⁰ the context of the CMS Collaboration. The main activities consists of shifts for the RPC operation
⁷¹ and data certification, upgrade and maintenance of the online software, R&D activities for the RPC
⁷² upgrade and detector maintenance during the LHC Long Shutdown 2 (2019 to 2020).

⁷³ In this chapter, it is presented a summary of the Resistive Plate Chamber technology and the
⁷⁴ contributions to the RPC project at CMS.

⁷⁵ 2.1 Resistive Plate Chambers

⁷⁶ The seminal paper on the Resistive Plate Chamber (RPC) technology was presented by R.
⁷⁷ Santonico and R. Cardarelli, in which they described a "dc operated particle detector (...) whose
⁷⁸ constituent elements are two parallel electrode Bakelite plates between" [1]. The key idea behind
⁷⁹ the RPC, with respect to other similar gaseous detectors, is the use of two resistive plates as anode
⁸⁰ an cathode, which makes possible to have a small localized region of dead time, achieving very good
⁸¹ time resolution.

⁸² The working principle for RPCs relies on the idea that a ionizing particle crossing the detector,
⁸³ tend to interact with the gas gap between the two plates and form a ionizing cascade process, in
⁸⁴ which the produced charged particle are driven by the strong uniform electrical field produced
⁸⁵ by the two plates.

⁸⁶ The gas mixture is a key component of a RPC. Even though the first RPCs were produced
⁸⁷ with a mixture of argon and butane, nowadays RPCs use a mixture of gases that would enhance an
⁸⁸ ionization caused by the incident particle and quench secondary (background) effects.

⁸⁹ Another feature of the RPCs is its construction simplicity and low cost. This allow the use RPC
⁹⁰ to cover larger at a reasonable cost.

⁹¹ A extensive review of the RPC technology and its application can be found in [2].

⁹² **DESCREVER A TECNOLOGIA DAS RPCS**

⁹³ **DESCREVER OS PRINCÍPOS DE OPERACAO - TDR**

⁹⁴ 2.2 CMS Resistive Plate Chambers

⁹⁵ At CMS, the Resistive Plate Chamber are installed in both the barrel and endcap region, forming
⁹⁶ a redundant system with the DT (barrel) and CSC (endcap). As described in the CMS Muon
⁹⁷ Technical Design Report (Muon-TDR) [3], the RPC are composed of 423 endcap chambers and
⁹⁸ XXXXXX **QUAL O NUMERO DE BARREL CHAMBERS????** barrel chambers.

99 Each chamber consists of two gas gaps (double gap), 2 mm tick each, made of Bakelite (phenolic
 100 resin) with bulk resistivity of $10^{10} - 10^{11} \Omega m$. The choice of the bulk resistivity of the electrode has
 101 high impact on the rate capability of the detector.

102 Each gap has its external surface is coated with a thin layer of graphite paint, which acts as
 103 conductive material, distributing the applied high-voltage (HV). On top of the graphite a PET
 104 film is used for isolation. A sheet of copper strips is sandwiched between the gaps. Everything is
 105 wrapped in aluminum case.

106 The double gap configuration increases the efficiency of the chamber, since the signal is picked
 107 up from the OR combination of the two gaps. A chamber with only one gap working, loses around
 108 15% of efficiency, even though, this can be recovered by increasing the HV applied during operation
 109 mode (working point - WP).

110 A characteristic that differentiate the CMS RPC from previous RPC application in HEP is
 111 the operation mode. A RPC at CMS, operates in avalanche mode, while previous experiments used
 112 the streamer mode. Both modes are related to the applied HV, in commitment with the strength of
 113 the generated signal, and are capable of generate a well localized signal, which can be picked up by
 114 the readout electronics, but the avalanche mode offer a higher rate capability around 1 kHz/cm^2 ,
 115 while the streamer mode goes up to 100 Hz/cm^2 . The high rate capability is a key factor in order
 116 to cope with requirements of the LHC luminosity, specially in the high background regions.

117 Besides the rate capability, the key factors that driven the CMS RPC design were: high effi-
 118 ciency ($> 95\%$), low cluster size (> 2) for better spatial resolution (this reflects in the momentum
 119 resolution) and good timing in order to do the readout of the signal within the 25 ns of a LHC
 120 bunch cross (BX) and provide it to the CMS trigger system. These requirements have implications
 121 in the choice of material, dimensions, electronics and gas mixture.

122 In the barrel, along the radial direction, there are 4 muon layers (called stations), MB1 to MB4.
 123 MB1 and MB2 is composed of a DT chamber sandwiched between two RPC chambers (RB1 and
 124 RB2) with rectangular shape. The stations MB3 and MB4 have only one RPC (RB3 and RB4) are
 125 composed by two RPC chambers (named - and + chambers with the increase of ϕ) attached to one
 126 DT chamber, except in sector 9 and 11, where there is only one RPC. RE4, sector 10 is a special
 127 case, since it is composed of four chambers (-, -, + and ++). These stations are replicated along
 128 the z direction in five different wheels of the CMS (W-2, W-1, W0, W+1 and W+2) and in twelve
 129 azimuthally distributed sectors (S1 to S12). Figure 2.1 show the different barrel stations and wheel.

130 **DAR AS DIMENSOES - BARREL**

131 In the endcap, the RPC chambers have a trapezoidal shape and are distributed in four disks (or
 132 stations) each side (RE ± 4 , RE ± 3 , RE ± 2 , RE ± 1), each one with 72 chambers. CMS split up its
 133 disks in 3 rings, along the radial direction, and 36 sector in the azimuthal angle. RPCs are present
 134 in the two outer rings (R2 and R3), in all 36 sectors. The RE ± 4 are special cases, since these
 135 chambers were installed only in 2014, a design choice was made the mechanically attached R2 and
 136 R3 chambers, each sector, in what is called, a super-module. Figure 2.2 show the different endcap
 137 disks.

138 **DAR AS DIMENSOES - ENDCAP**

139 The length of the strips is chosen, for both barrel and endcap, in such a way to control the area
 140 of each strip, in order to reduce the fake muons, due to random coincidence. This has to do with

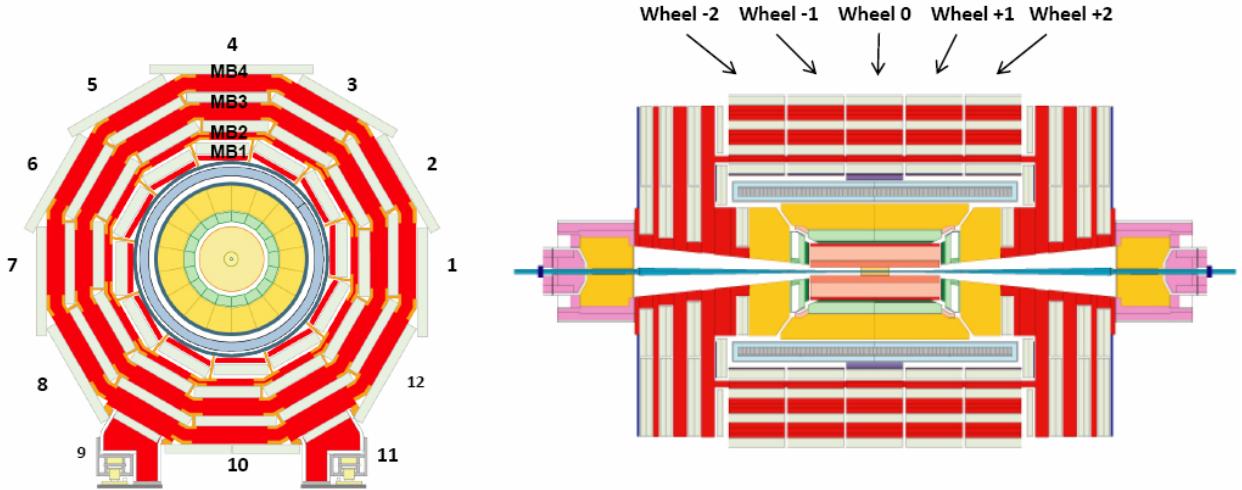


Figure 2.1: R- ϕ (left) and R-Z (right) projections of the barrel Muon System.

141 the time-of-flight and signal propagation along the strip. In the barrel, each chamber readout is
 142 divided in two regions (rolls), called forward and backward (along increasing $|\eta|$) ¹. In the endcap,
 143 the strips are divided in 3 regions, called partitions A, B and C (from inside the detector to outside).

144 The gas mixture used in the CMS RPCs is composed by C2H2F4 (Freon R-134a, tetrafluoroethane), C4H10 (isobutane), SF6 (sulphur hexafluoride) (95.2 : 4.5 : 0.3 ratio) and with controlled
 145 humidity of 40% at 20-22 °C. The Freon is used to enhance the ionization and charge multiplication
 146 that characterizes the avalanche, while the isobutane is introduced for quenching proposes, in order
 147 to reduce the secondary ionizations that could lead to formation of streamers and the SF6 is used
 148 to reduce the electron background. The choice of Freon over other gases, i.e. argon-based and
 149 helium-based, was motivated by previous studies [4, 5].

151 Since its R&D, the RPC have shown good performance over aging. This is even historical over
 152 previous RPC experiments **ADICIONAR REFERÊNCIAS 5.14, 5.15 E 5.16 DO MUON**
 153 **TDR**. Even the most recent studies of aging, taking into account future LHC conditions (High-
 154 Luminosity LHC - HL-LHC) plus a safety margin of 3 times the expected background (600 Hz/cm^2)
 155 have shown good aging hardness [6].

156 2.2.1 Performance

157 PERFORMANCE NO RUN2

158 2.3 Contribution to the CMS RPC project

159 During the curse of this study, a head collaboration of our research group and the CMS RPC
 160 project was established. Many contributions were given to the project as part of the graduation as a
 161 experimental particle physicist, with focus on getting acquaintance with a subsystem technology and

¹Some chamber are divided in three rolls, forward, middle and backward, for trigger propose.

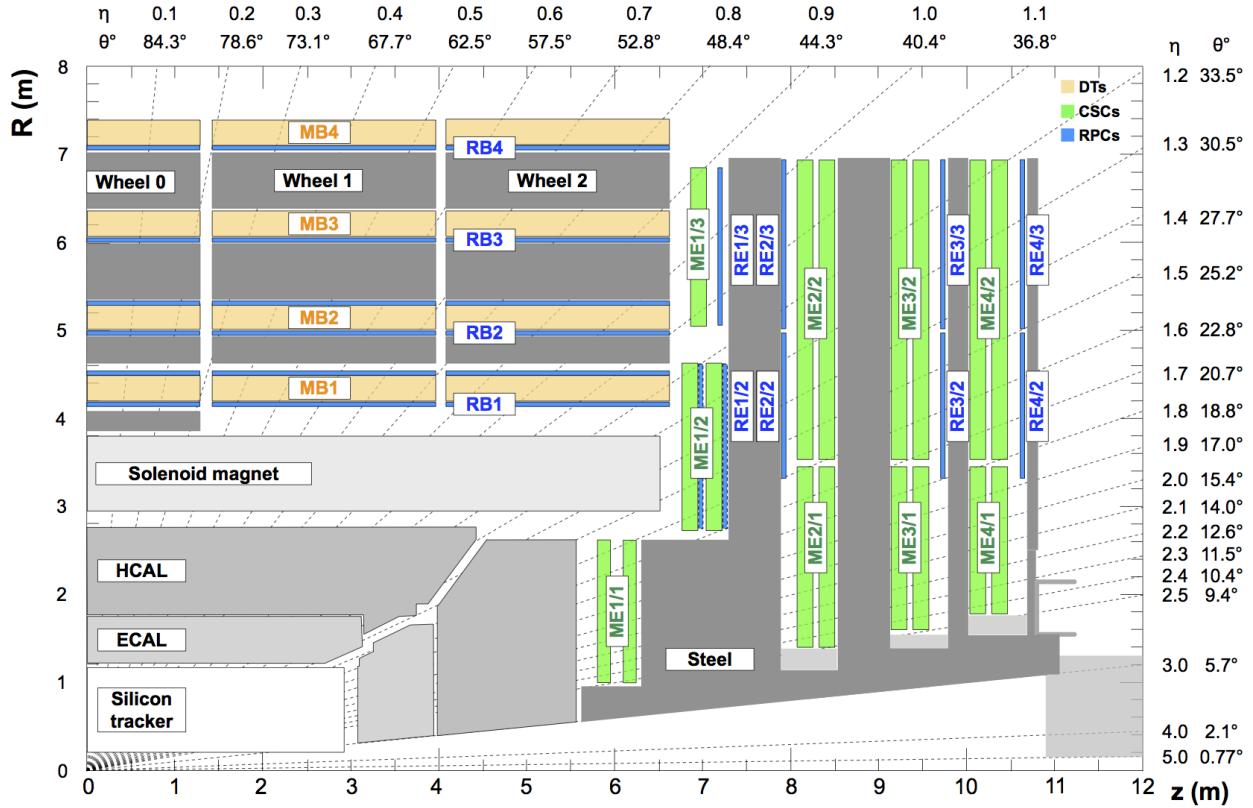


Figure 2.2: R-Z projections of the endcap Muon System (positive Z side). This is the same configuration for the 36 ϕ sectors.

give a meaningful collaboration to the detector operation. Those are considered by the community important steps on the student graduation.

Bellow it is described the contributions given to the CMS RPC project.

2.3.1 RPC Operation - Shifts and Data Certification

The first activities done for the CMS RPC project were shifts for data certification of data taken. This certification is done by specialized people for different CMS subsystems and physics objects groups².

This certification is done in order to ensure the quality of the date recorded based on the well functionality of each system during the data taking and the reconstruction of the physics objects in the expected matter. A certain collection of data (run) is said certificate when all subsystems and object experts agrees on this.

Figure 2.3 shows, as an example of the luminosity delivered by the LHC, recorded one by CMS and the certified (validated), from the 22nd of April, 2016 to the 27th of October, 2016. Only certified data is available for physics analysis.

Shifts are a continuous weekly activity (specially during the data taking period), performed in a weekly basis, in order to ensure the availability of certified data, as soon as possible.

²Groups of reconstruction and performance experts for different high-level reconstructed objects from CMS, i.e. muons, taus, jets/MET, electrons/photons

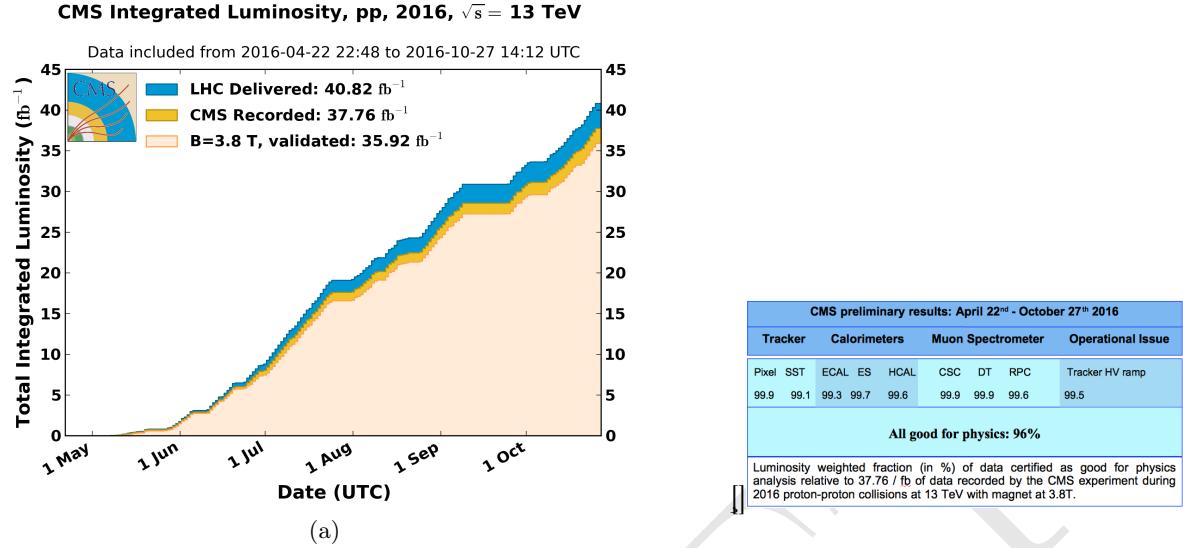


Figure 2.3: (a) Luminosity delivered by the LHC, recorded one by CMS and the certified (validated), from the 22nd of April, 2016 to the 27th of October, 2016. (b) Efficiency of the certification process for each subsystem, from the 22nd of April, 2016 to the 27th of October, 2016. Total CMS efficiency is above 90%. [7]

2.4 RPC Online Software

On what concerns the Online Software (OS) of the CMS RPC system, the main contribution given was the upgrade of the Trigger Supervisor libraries.

The Trigger Supervisor is a web-based software, which run over the xDAQ backend and provides, through a mudules organized in a tree system, called cells, a standard interface for the operation and monitoring of different system at CMS. In principle only systems which contribute directly to the L1 trigger should have a Trigger Supervisor implementation. This was the case for the RPC during the Run1. Since Run2, RPC contributes to the trigger indirectly, by providing data to the muon processors (CPPF, OMTF and TwinMux). The Trigger Supervisor implementation is a legacy from that period.

Each subsystem is responsible for its own implementation of the Trigger Supervisor, based on the functionalities that it wants to have (requirements). The xDAQ [8] is a middleware, developed by CERN and widely used at CMS, as a tool for control and monitoring of data acquisition system in a distributed environment. It is capable of providing a software layer for direct access of hardware functionalities and monitoring.

The upgrade made (figure 2.4), consists in upgrade the higher level of the RPC online software. In summary, up to 2017, the online software, was using Scientific Linux 6 as operational system, which executed xDAQ 12, in turn, servers as backend for Trigger Supervisor 2. A upgrade of the operational system to Centos 7, demanded the upgrade to xDAQ 14. On top of that, Trigger Supervisor 2 would not work and had to be updated to Trigger Supervisor 5 in order to be functional in 2018.

Between versions 2 and 5 of Trigger Supervisor, part of the source-code had to be reworked, keep the majority of the code structures. Most of the changes were made in the front-end of the system. The standard JavaScript library Dojo [9], used in version2, was deprecated in favor of

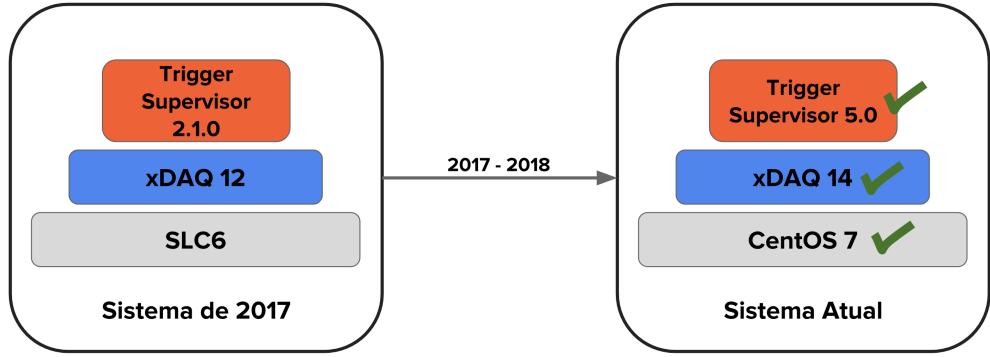


Figure 2.4: Upgrade of the RPC online software.

202 Google's Polymer[10]. The main reason for this change was to isolate C++ code from HTML, which
 203 was impossible with Dojo. This implied to rewrite all the screen of the RPC Trigger Supervisor
 204 implementation, as in figure 2.5.

205 The upgrade was done in time to ensure the control and operation of the RPC for 2018 data
 206 taking.

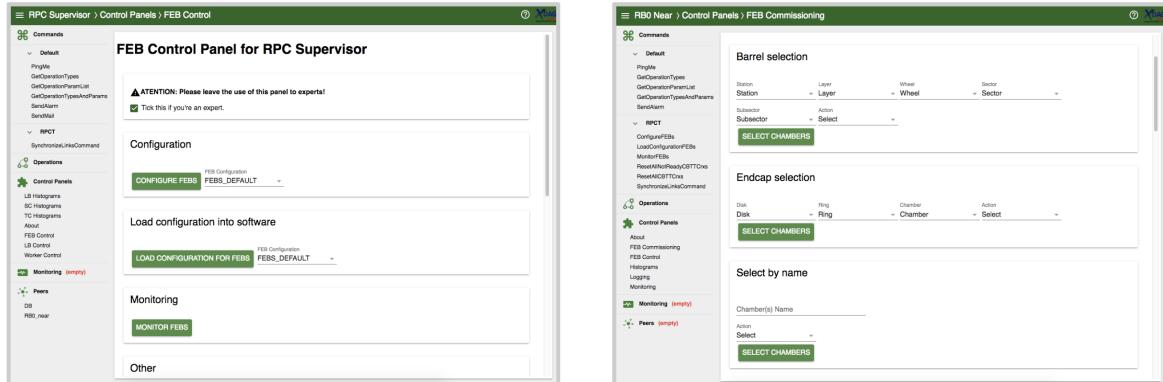


Figure 2.5: Example of the updated screens, using Trigger Supervisor 5.

207 2.4.1 iRPC R&D

208 For the next 4 year of CMS activities it is foreseen the upgrade of the the Muon Systems [3].
 209 These upgrades are planed in order to extend the pseudorapidity coverage (η) and to guarantee the
 210 operation conditions of the present system in the HL-LHC (High Luminosity LHC) era. The RPC
 211 (Resistive Plate Chambers) [3] subsystem, it will have maintenance of the present chambers and
 212 installation of new chambers in the region of $|\eta| < 1,8$ para $|\eta| < 2,4$ [11]. These new chambers
 213 (iRPC) will be added in the most internal part of the muon spectrometer, RE3/1 e RE4/1, as in
 214 Figure 2.6.

215 Even thought this region is covered by the CSC detectors CSC (Cathode Strip Chambers), there
 216 are some loss of efficiency due the the system geometry. The installation of additional chambers will
 217 mitigate this problem and potentially increase the global efficiency of the muon system. The new

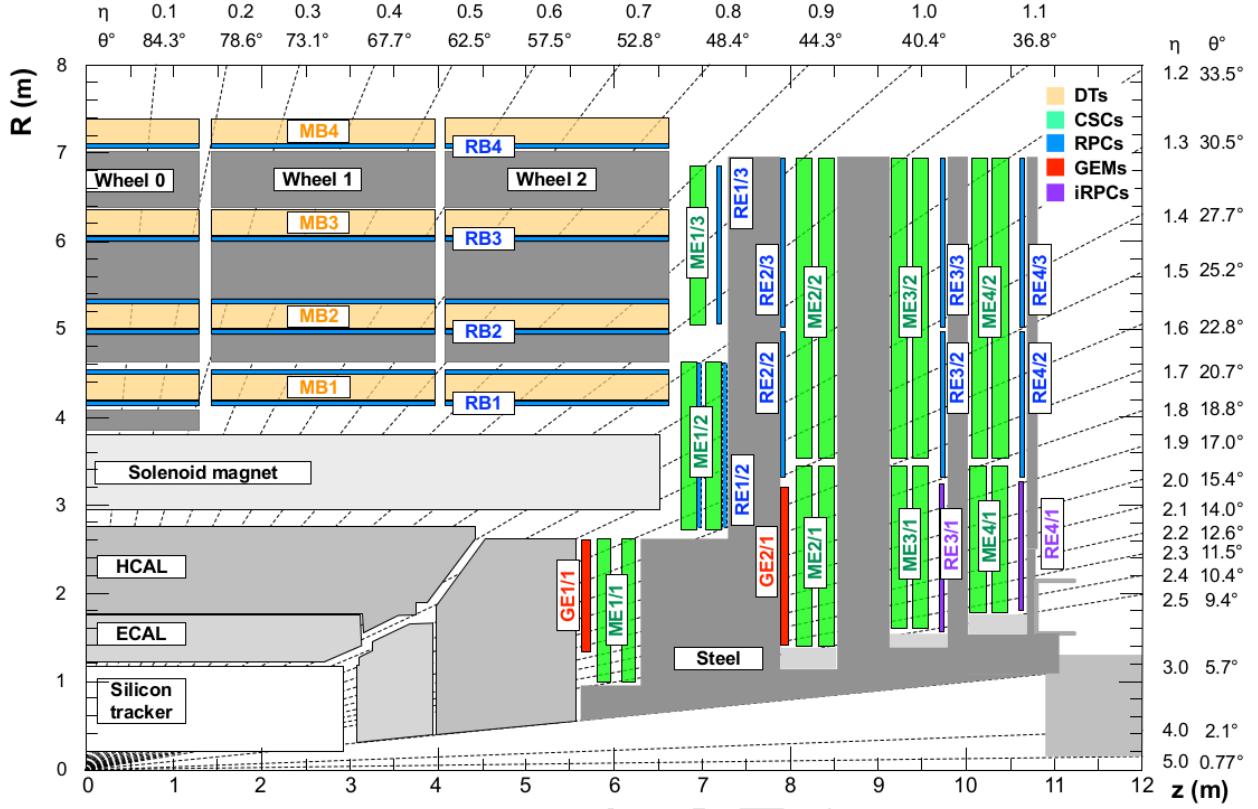


Figure 2.6: η projection of the Muon System subdetectors. In purple, is labeled the iRPCs to be installed during the CMS upgrade.

218 chamber, called iRPC (*improved RPC*), will be different them the present one. For a luminosity of
 219 $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ the neutrons, photons, electrons and positrons background in the high $|\eta|$ region
 220 is expected to by be around 700 Hz/cm^2 (for the chambers in RE3-4/1). Applying a safety factor
 221 of 3, the new chambers should support up to 2 Hz/cm^2 of gamma radiation and still keep more
 222 than 95% of efficiency. Studies indicate, so far, that the use of High Pressure Laminates (HPL) for
 223 the double gap chambers is the most suitable choice. In order to reduce the aging and increase the
 224 rate capability, the electrodes and the gap size should be reduced in comparison with the present
 225 system.

226 One of the challenges for the R&D of the iRPC chambers is measuring the their performance
 227 in a high radiation environment, as the one for HL-LHC. For this, the CMS RPC project uses the
 228 Gamma Irradiation Facility (GIF++) [12], at CERN. The GIF++ is located at the H4 beam line
 229 in EHN1 providing high energy charged particle beams (mainly muon beam with momentum up to
 230 100 GeV/c), combined with a 14 TBq 137-Cesium source. In the GIFF++ it is possible to achieve
 231 the HL-LHC total dose in a much reasonable amount of time. With the shutdown of LHC, the
 232 muon beam source is also off and will stay like this for 3 years. This means that the only muon
 233 sources for studies in GIF++ are cosmic muons.

234 In order to create a trigger system for iRPC R&D, the usual procedure is to use scintillators,
 235 on the top and on the bottom of the chamber. This is effective, but in a high gamma radiation
 236 environment, scintillators can be very sensitive which could lead to an undesirable amount of fake

triggers which can degrade the measurements. Also, if one wants to covers a large area with scintillators, this can be expensive and they will not provide any means of tracking to measuring not only the global, but also the local chamber performance.

To provide a solution, the CMS RPC got in agreement with the LHCb [13] Muon Project to use their Multiwire Proportional Chambers (MWPC) [14], which were removed from LHCb, to be replaced by new chambers, and use them as trigger and/or tracking system at GIF++. This chambers, by design, have relatively low gamma sensitivity, already have some 1-dimensional resolution ($O(\text{cm})$) and, the biggest advantage, with respect to any other gaseous particle detector option: LHCb has hundreds of vacant chambers. Any other detector would have to be build.

Not going in details of the MWPC technology nor the LHCb chamber construction [15], these chambers have a total active area of $968 \times 200 \text{ mm}^2$ divided 2 layers (top and bottom) of 24 wire pads ($40 \times 200 \text{ mm}^2$) composed of around 25 wires/channel, grouped by construction. Each chamber is equipped with 3 FEBs (Front-End Boards) with 16 pads each.

A channel is a logical combination of a top layer (pads) and a bottom layer readout. These readouts can be combined in AND or OR logics. One can have 8 channels per FEB, each channel being a logical combination of top and bottom pads. In this mode they are called AND2 and OR2. It is also possible to have the FEB configured in a 2 channels mode, each one corresponding to one sixth of the total readout pads. In this mode, all the pads can be combined in OR (called OR8) or they can be AND'ed in top and bottom pads and then group in OR (called OR4AND2). Figures 2.7 and 2.8 presents a logical diagram for each readout mode.

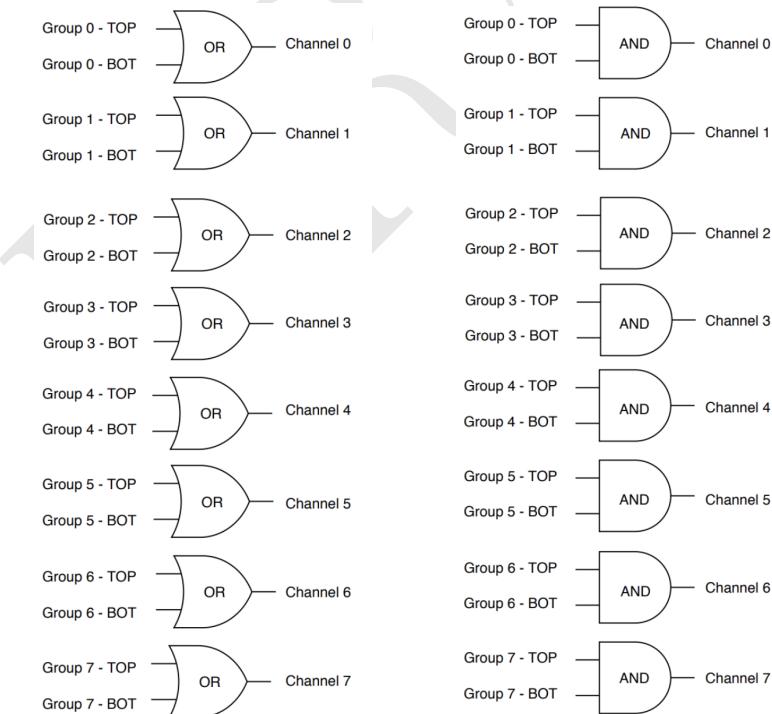


Figure 2.7: FEB configured 8 channels modes. Group should be understood as wire pad. Left: Logical diagram for OR2. Right: Logical diagram for AND2.

The nominal gas mixture for these chambers is Ar/CO₂/CF₄ (40:55:5). For a matter of simplicity, it was used an already available similar gas line in the same building, used by CMS CSC

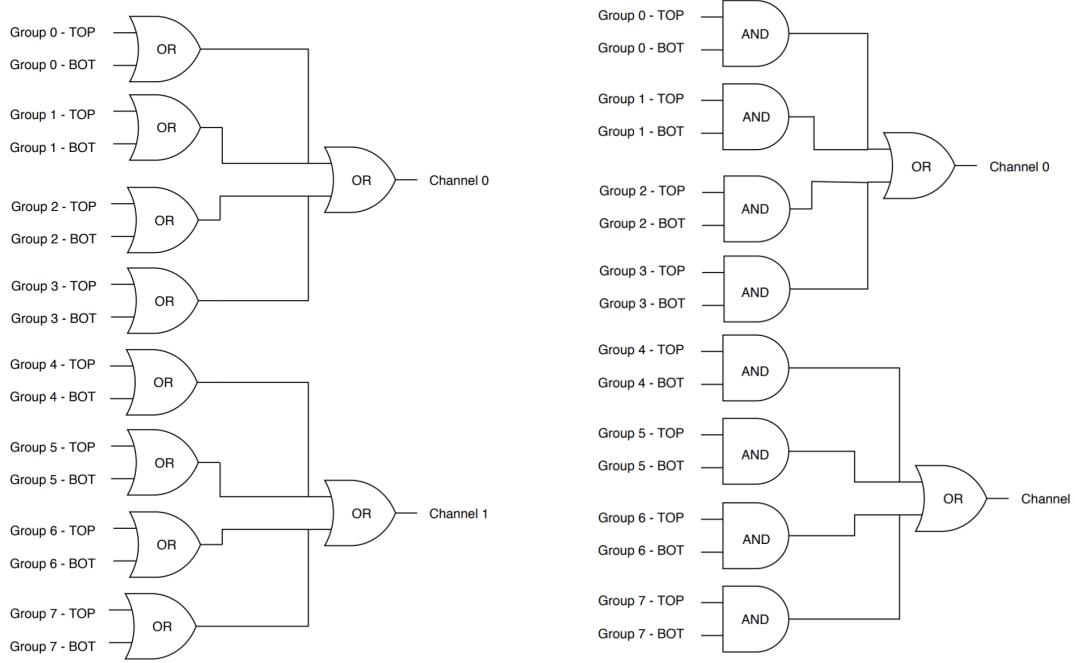


Figure 2.8: FEB configured 2 channels modes. Left: Logical diagram for OR8. Group should be understood as wire pad. Right: Logical diagram for OR4AND2.

259 (Cathode Strip Chamber) [3], which has a similar composition (40:50:10). Optimal conditions are
260 obtained with 2 to 4 liters/hour of gas flux and 2.65 kV of applied voltage.

261 Figure 2.9 shows the setup that was prepared for commissioning of this chambers. It was
262 mounted two chambers on top of another (chambers A and B) above an RPC R&D chamber and
263 two other chambers on the bottom (chambers C and D). These four MWPC will be used as telescope
264 for the RPC chamber. All the services were mounted in rack, as in Figure 2.9. This includes power
265 supply (low voltage and high voltage), distribution panel, VME crate and boards for FEB control,
266 computer for control (high voltage, and FEB control) and NIM crate and boards for LVDS to NIM
267 signal conversion, logics and counting.

268 Due to the short amount of time available for the commissioning, only two measurements mea-
269 surements were made with these chambers. They were meant to be a proof of concept for future
270 activities.

271 The first measurement was to measure the coincidence rate of two chambers as a function of
272 the distance between the two top planes (Figure 2.10). This measurements were done with nominal
273 working point, with one FEB configured in 2 channels mode with 7 pC threshold, in (160 mm x
274 160 mm) area per chamber. One can observe that, if we go for a telescope trigger in the order of
275 1 meter of separation between the chamber, the logical combination chosen has negligible effect in
276 the coincidence rate. Also, the fits can be used to estimate the rate in a configuration with chamber
277 on the roof and under the floor. This could be the case of a universal trigger, to be mounted in
278 GIF++ with these chamber.

279 The second measurement consist on evaluate the impact of γ background by placing a small
280 Cs-137 source on top of the chamber A (Figure 2.11). For this measurement, the distance between
281 top planes of each pair of chamber (A to B and C to D) is 65 mm, while the distance between the

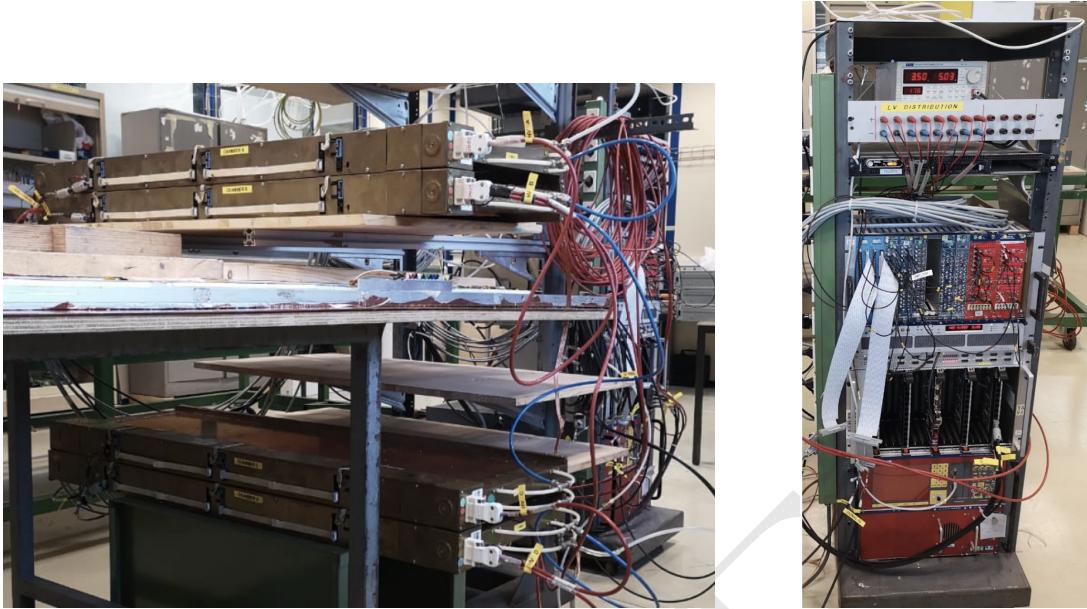


Figure 2.9: Left: Setup mounted for commissioning. Two MWPC chamber on the top (chambers A and B) and two (chambers C and D) on the bottom with a RPC R&D in the middle. Right: Rack with all the services for the operation of these chambers.

282 top planes of A and C is 570 mm. It is clear the the γ source has an impact on chamber A rate,
283 but this is negligible when we take into account the coincidence between two chambers.

284 This two measurements were enough to validate this chambers as possible trigger pro RPC R&D
285 with cosmic muons in the laboratory and at GIF++. The next steps would be use this MWPC
286 chamber to implement a tracking system from triggering. This would demand some developments,
287 since, due to bandwidth restrictions, the signal from each FEB would have to go to a programmable
288 fast electronics, i.e. a FPGA, which would reconstruct muon tracks and provide the trigger to the
289 DAQ system. This can be done by placing the two pair of chambers (AB and CD) in orthogonal
290 configuration and read the signal in a CAEN V2495 board [16].

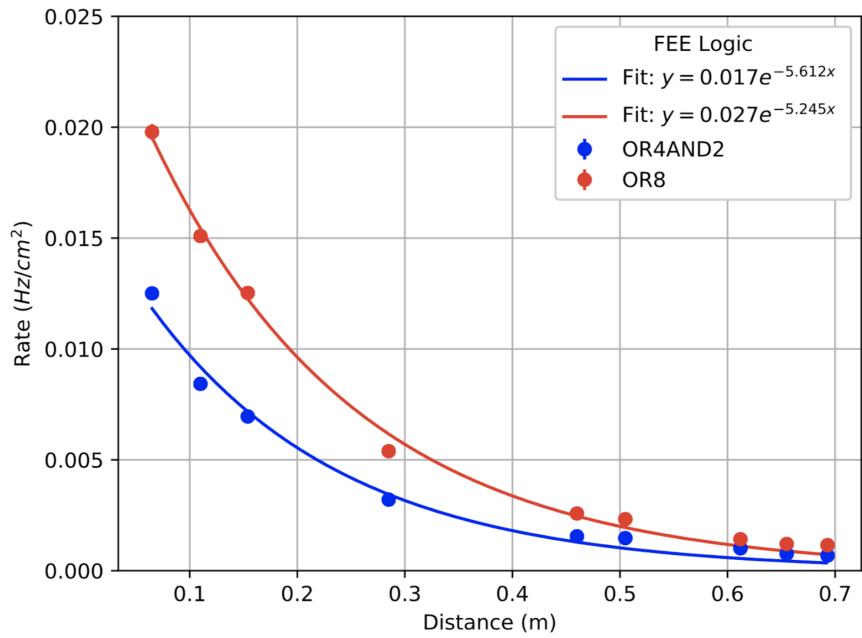


Figure 2.10: Coincidence rate of two chambers with respect to an arbitrary distance between the two top planes. Measured in 10 minutes, for 2 logical combinations (OR8 and OR4AND2). Applied high voltage: 2.65 kV. Threshold: 7 pC. Active area: readout of 160 mm x 160 mm per chamber.

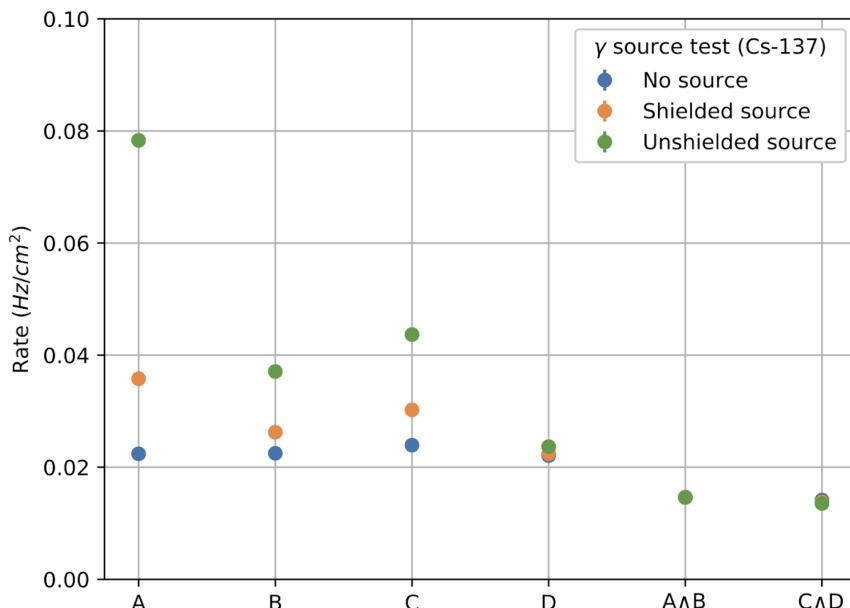


Figure 2.11: Individual rates (chambers A, B, C and D) and coincidence rates for two chambers (A AND B, C AND D), for without γ source (blue), a shielded γ source (orange) and an unshielded γ source (green). Source sitting on top of chamber A. Applied high voltage: 2.65 kV. Threshold: 7 pC. Active area: readout of 160 mm x 320 mm per chamber. Logical combination: AND2

291 2.4.2 LS2 and the RPC Standard Maintenance

292 In December 2018, the LS2 (Long Shutdown 2) was started. This a period in which the LHC
293 and its detectors (CMS included) stop their operation for maintenance and upgrade. The LS2 will
294 go up to 2021, when LHC and CMS restart the data taking with the Run3.

295 During the LS2 it is being installed services for the new chambers (gas pipes, low voltage
296 (LV), cables, signal and control optical fibers, high voltage (HV) cable and support equipment,
297 and HV/LV power supplies), as well as continuity to the to the RPC R&D studies, besides the
298 reparation of broken elements of the present system, i.e. chamber in the barrel region which present
299 gas leak problems, maintenance of the LV and HV connectivity and power system, maintenance of
300 the control system of problematic chambers (Front-Ends boards, cabling and Distribution Boards)
301 and the dismount and reinstallation of four stations in the endcap (RE4) on both sides of CMS [17].

302 What concerns the standard maintenance of the present RPC system, the main LS2 activities
303 in which the student was involved, can be divided in three main tasks: (a) HV maintenance, (b)
304 LV and control maintenance and (c) detector commissioning.

305 HV maintenance

306 A key factor of and RPC performance is the applied high voltage (HV). The CMS RPC achieve
307 their optimal performance with, around, 9.5 kV applied in each gap. This voltage is in the range
308 of the dielectric breakdown of many gases, which could lead to potential current leakages, if some
309 part of the system is damaged, poorly operated or badly installed. If the currents are high enough
310 this can make impossible the operation of the chamber. In cases like this, during the operation
311 period (data taking), the problematic HV channel is identified and turned off (each chamber has
312 two channels, one for each lawyer of gaps). Chambers in this situation are said to be operating in
313 single gap mode (SG).

314 The goal for the HV maintenance is to, now that the CMS is off and the chambers are accessible,
315 identify which part of the HV supply system is causing the current leak and fix it the best way
316 possible. Usually the problem is beyond the power supply, very often connectors or the gap itself
317 are damaged.

318 The CMS RPCs uses two kind of HV connectors, monopolar and tripolar connector. The
319 monopolar are used to connect the chamber to the power supply. If mounted properly, rarely they
320 present problems. The connection to the chamber is made by tripolar connectors, in which the
321 ground and the HV for both gaps arrives to the chamber in a single connector, for simplicity and to
322 save space in the patch panel. Unfortunately these connectors are relatively fragile, and they could
323 be a potential source of leak, specially if they were poorly mounted, badly operated or with aging
324 itself. Also, since this was a connector made exclusively for the CMS RPC system, some design
325 choices had to be improved after the installation of other chamber. Those installed with old batches
326 of tripolar connectors are sensitive ones. The reparation of this connectors consists in isolate the
327 connector from the chamber and power it up to 15 kV (maximum voltage allowed by the system). If
328 the tested connector is broken one will observe a very fast increase in the current of the HV channel.
329 The only solution to this kind of problem is to replace the connector.

On the other hand, if the connector is powered isolated and pass the test, the problem beyond the connector (assuming that the power system have already been tested), i.e. inside the chamber. When a chamber is in SG mode it means that a full layer is off, but not necessarily all the gaps in that layer are bad (a RPC can have up to three per layer). In this situation, the procedure consists in cutting the cables that comes from the gaps to the chamber side connector one by one and identify which gap of the problematic layer is the broken by powering it. Once identified, this gap should isolated and the other ones reconnected. The broken gap is unrecoverable, since it is inside the chamber, but 5% to 10 % of efficiency can be retaken, without changing the applied HV and increasing the longevity of the chamber.

Another contribution to the HV maintenance was the proposal of a procedure to replace the problematic tripolar connector by a monopolar (also called jupiter) connector, which are known for being much more stable and reliable. The figure 2.12 (left) show the designed adapter for the chamber patch panel which would made this change possible. Figure 2.12 (right) shows a tryout of a chamber in which this procedure was tested. The proposal was presented to the RPC community and approved to be used from now on. Technical drawings and instructions were provided.

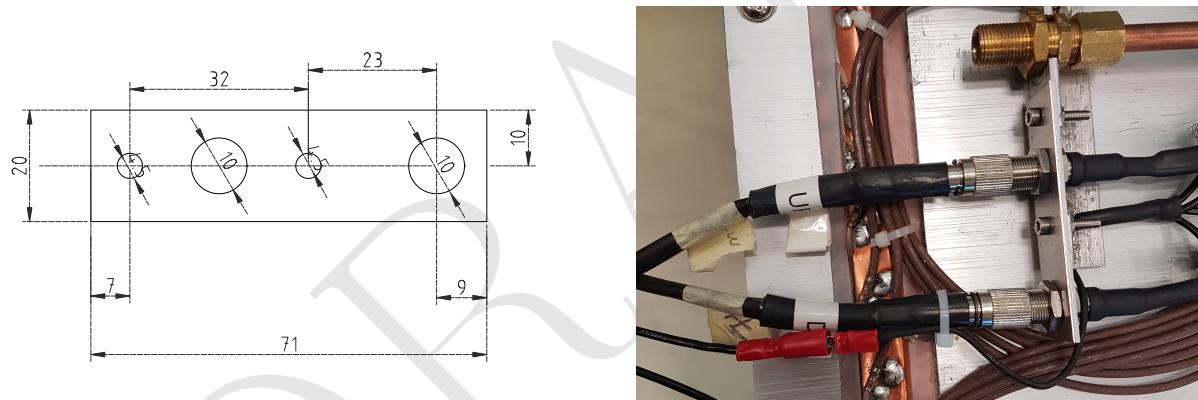


Figure 2.12: Left: Proposed adapter the chamber patch panel which make it possible to replace a tripolar by a jupiter HV connector. Right: Try out of the proposed HV connector replacement.

345 LV and control maintenance

The low voltage (LV) and control maintenance consists in make sure that the Front-End Boards (FEBs) are powered and configurable, which means that the LV power system is working from supply board to the cable, that the signal cables are in good state and properly connected to the chamber and to the link boards and that the on-detector electronics (FEBs and Distribution Boards - DBs) are working fine.

Usually, this system is very reliable. The weak point, in most of the cases, is the detector electronics. When a FEB [18] (as in Figure 2.13) is problematic it can present regions of very high noise or no signal at all (silent), which can not be recovered by the threshold control. In cases like this, when the FEB is accessible, it can be replaced in order to recover efficiency in the problematic chamber. This procedure is done by extracting the chamber from inside the detector (only for barrel chamber) and opening its cover to have access to the problematic component. Removed boards are send back to production labs for refurbishment.

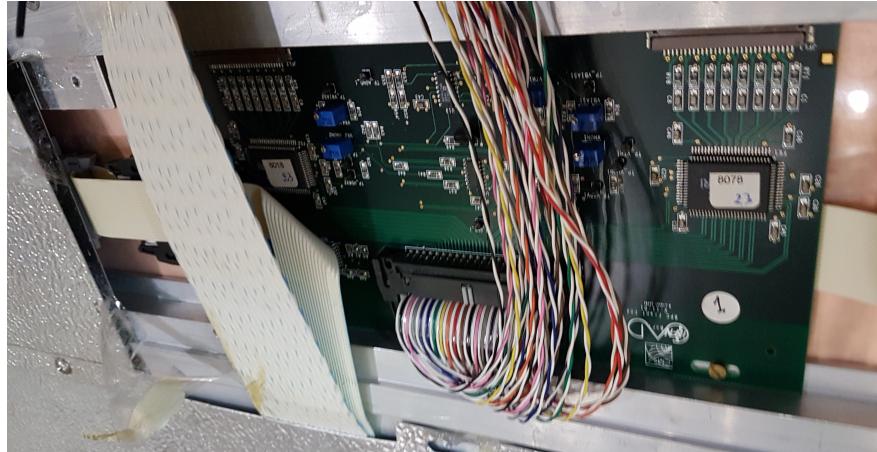


Figure 2.13: RPC Front-end board (FEB) used in the barrel chambers.

358 The most usual problem is a chamber in which the threshold control was lost. For those chamber,
 359 most probably, the problem is in the distribution board of the chamber, which is a piece of hardware
 360 responsible for distribute the LV power to the FEBs (3 to 6 per chamber) and send the threshold
 361 control signal to the FEBs via I2C line. If a chamber has no threshold control, it means that the
 362 RPC operation has no control over the signal selection, which can potentially induce performance
 363 issues.

364 For the barrel this maintenance happens concomitantly with the gas leak reparations on the
 365 barrel chamber, since both demands the chamber extraction, which is a complex procedure in terms
 366 of operation and demands specialized equipment and manpower. For technical reasons, the gas leak
 367 extractions have precedence over LV ones.

368 Detector commissioning

369 All the LS2 activities demands uncabling of the chamber to be repaired and possibly some
 370 neighbor chambers. Also, it can involve the replacement of components of the chamber. To avoid
 371 damage to the system a compromising procedure is needed after all this activities. Given the
 372 responsibilities of the commissioning it was necessary to: (a) make sure that the the RPC system
 373 keep tracks of all the interventions, (b) maintain all the algorithms used in the commissioning
 374 procedure, (c) together with the RPC Coordination, define a pool of people and a schedule to the
 375 commissioning of the system and (d) follow-up, with other CMS RPC experts, the availability of
 376 materials and resources for the commissioning operations.

377 Besides the organizational tasks, the commissioning demanded to establish procedures to ensure
 378 the connectivity and functionality of HV and LV connections. For the HV, it is needed to make sure
 379 that the chambers are properly connected, without miscabling³ and that the currents at stand-by
 380 HV and working point HV are compatible with the ones in the end of last data-taking (end of
 381 2018). This activity will start in November/2019, when the CMS RPC Standard Gas Mixture will
 382 be available again.

³Mixed cable connections.

For the LV point of view, the LV power cable and signal cables should also be properly connected, and presenting a noise profile compatible with last data-taking. One key point for this task is to make sure that there are no miscabling of signal cable. One RPC chamber can have from 6 to 18 signal cable, which are connected very close one to another. There is a good chance that a chamber, after reparation, have its signal cables mixed. In order to diagnose situations like this, it was validated a algorithm present in the RPC Online Software, but never used since LS1, which, by changing the threshold of each component of the RPC system, from very high to very low values (component by component), can spot miscabled chambers. Since the control line is independent of the signal line, a misclabel will present a different noise from what is expected.

Besides the validation of this algorithm, it was also implemented a web system (Figure 2.14), developed in Flask [19] which automatize the execution of the algorithm, making transparent to the shifter (or the one performing the commissioning) the procedure to get miscabling report.

FEB Connectivity Test - Analysis

Worker	Date (YY-MM-DD)	Time (HH:MM:SS)	Hash	
RBP2_Far	2019-06-20	23:43:19	387534dst	<button>Run Analyzer</button>
RBP1_Far	2019-06-20	20:12:20	458306dst	<button>Run Analyzer</button>
RBP1_Far	2019-06-20	20:04:46	336162dst	<button>Run Analyzer</button>
RBP1_Near	2019-06-20	19:02:00	377863dst	<button>Run Analyzer</button>
RBP1_Near	2019-06-19	18:59:00	858950dst	<button>Run Analyzer</button>
RBP1_Far	2019-06-19	18:58:26	994787dst	<button>Run Analyzer</button>
YEN3_Far	2019-05-07	10:28:23	176278dst	<button>Run Analyzer</button>
YEN3_Near	2019-05-07	10:28:08	347504dst	<button>Run Analyzer</button>
YEN1_Far	2018-12-07	15:03:24	575561	<button>Run Analyzer</button>
RBO_Far	2018-12-07	14:45:42	101463	<button>Run Analyzer</button>
RBP1_Far	2018-12-07	09:12:00	477689	<button>Run Analyzer</button>

Figure 2.14: RPC FEB Commissioning Analyzer.

The LV commissioning is ongoing, since it happens, as much as possible, right after the chamber reparation.

DRAFT

Bibliography

- [397] [1] R. Santonico and R. Cardarelli. “Development of resistive plate counters”. In: *Nuclear Instruments and Methods in Physics Research* 187.2 (1981), pp. 377–380. ISSN: 0167-5087. DOI: [https://doi.org/10.1016/0029-554X\(81\)90363-3](https://doi.org/10.1016/0029-554X(81)90363-3). URL: <http://www.sciencedirect.com/science/article/pii/0029554X81903633>.
- [402] [2] Marcello Abbrescia, Paulo Fonte, and Vladimir Peskov. *Resistive gaseous detectors: designs, performance, and perspectives*. Weinheim: Wiley-VCH, 2018. DOI: 10.1002/9783527698691.
- [404] [3] *The CMS muon project: Technical Design Report*. Technical Design Report CMS. Geneva: CERN, 1997. URL: <https://cds.cern.ch/record/343814>.
- [406] [4] P. Bernardini et al. “Precise measurements of drift velocities in helium gas mixtures”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 355.2 (1995), pp. 428–433. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/0168-9002\(94\)01144-3](https://doi.org/10.1016/0168-9002(94)01144-3). URL: <http://www.sciencedirect.com/science/article/pii/0168900294011443>.
- [411] [5] E. Gorini et al. “Drift velocity measurements in C₂H₂F₄ based mixtures”. In: *Proceedings of the 4th International Workshop on Resistive Plate Chamber and Related Detectors, in Napoli, Italy, 15-16 October* (1997).
- [414] [6] Andrea Gelmi. *Longevity studies for the CMS-RPC system*. Tech. rep. CMS-CR-2018-136. Geneva: CERN, July 2018. URL: <https://cds.cern.ch/record/2634505>.
- [416] [7] *Public CMS Data Quality Information*. twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality. Acessado em: 20/02/2018.
- [418] [8] Johannes Gutleber, Steven Murray, and Luciano Orsini. “Towards a homogeneous architecture for high-energy physics data acquisition systems”. In: *Computer Physics Communications* 153.2 (2003), pp. 155–163. ISSN: 0010-4655. DOI: [https://doi.org/10.1016/S0010-4655\(03\)00161-9](https://doi.org/10.1016/S0010-4655(03)00161-9). URL: <http://www.sciencedirect.com/science/article/pii/S0010465503001619>.
- [423] [9] *Dojo*. <https://dojotoolkit.org/>. Acessado em: 20/02/2018.
- [424] [10] *Polymer Project*. Acessado em: 20/02/2018.
- [425] [11] M. I. Pedraza-Morales. *RPC upgrade project for CMS Phase II*. 2018. arXiv: 1806.11503 [physics.ins-det].

- 427 [12] Dorothea Pfeiffer et al. “The radiation field in the Gamma Irradiation Facility Gif++ at
428 CERN”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
429 Spectrometers, Detectors and Associated Equipment* 866 (2017), pp. 91–103. ISSN: 0168-9002.
430 DOI: <https://doi.org/10.1016/j.nima.2017.05.045>. URL: <http://www.sciencedirect.com/science/article/pii/S0168900217306113>.
- 432 [13] A. Augusto Alves Jr. et al. “The LHCb Detector at the LHC”. In: *JINST* 3 (2008), S08005.
433 DOI: 10.1088/1748-0221/3/08/S08005.
- 434 [14] Georges Charpak et al. “The Use of Multiwire Proportional Counters to Select and Localize
435 Charged Particles”. In: *Nucl. Instrum. Meth.* 62 (1968), pp. 262–268. DOI: 10.1016/0029-
436 554X(68)90371-6.
- 437 [15] *LHCb Muon Group Home Page*. [Online; accessed 1-October-2019]. 2019. URL: <http://lhcb-muon.web.cern.ch/lhcb-muon/>.
- 439 [16] *CAEN Programmable Logic Unit - V2495*. [Online; accessed 1-October-2019]. 2019. URL:
440 <https://www.caen.it/products/v2495/>.
- 441 [17] *Resistive Plate Chambers are getting dolled up*. <https://cms.cern/news/resistive-plate-chambers-are-getting-dolled>. Acessado em: 20/09/2019.
- 443 [18] C. Binetti et al. “A new Front-End board for RPC detector of CMS”. In: (Sept. 1999).
- 444 [19] *Flask (web framework)*. [Online; accessed 1-October-2019]. 2019. URL: <https://palletsprojects.com/p/flask/>.