New eco-friendly gas mixture for Resistive Plate Chambers in CMS in the framework of HL-LHC (CERN Summer Student Project report).

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The Compact Muon Solenoid (CMS) experiment at CERN is a multi purpose particle detector designed to make accurate measurements on a wide range of physics topics. Within the coming framework of High Luminosity-LHC an increased amount of background events are expected to be recorded with the normal operation of the machine. In order to keep the high accuracy and precision of the recorded measurements, a general upgrade to the systems has been going on since the last couple of years. The Resistive Plate Chambers are part of the general Muon Detector which works with a standard gas mixture of 95.2% $C_2H_2F_4$ which accounts for the number of primary ion-electron pairs, 4.5% iC_2H_{10} that allows to avoid photon feedback effects and 0.3% SF_6 which is an electron quencher. $C_2H_2F_4$ and SF_6 are very well known Greenhouse gases with Global Warming Potential (GWP) of 1430 and 22600, respectively. During the Run 2 of LHC major leakages were produced at detector level, and due to the increasing costs of the Freon in the EU, CERN has actively started a search for alternatives to replace the main active medium, identifying based CO_2 gas mixtures as the main possible candidate for a short-mid term solution. On this report an analysis is presented for the results obtained for four different CO_2 based gas mixtures with different concentrations of SF_6 in the presence of both a muon beam accounting for the signal and a gamma background radiation source. The results showed a good performance for all four candidates, but the selection of a final candidate is not yet presented as more studies are currently on their way to investigate the aging effects of each one of them.

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1. INTRODUCTION

The Compact Muon Solenoid (CMS) experiment [1] operating at the Large Hadron Collider (LHC) at CERN is a multi-purpose particle detector designed to make accurate measurements on a wide range of physics topics. The CMS detector is formed by various layers of material and subdetectors, each of them capable of measuring different types of particles. At the heart of CMS sits a superconducting solenoid capable of providing a magnetic field of 4 T for the bending of the charged particles. Along with the Hadronic Calorimeter (HCAL) and the Electromagnetic Calorimeter (ECAL), these devices allow us to properly reconstruct the energy of charged particles. At the closest interaction point, a set of pixel detectors form the inner tracking system of CMS while the muon detector system is located at the farthest point. The High Luminosity LHC [2] or Phase II is an upgrade project for the LHC which aims to achieve higher luminosities than the nominal value, thus allowing the experiments at CERN to enlarge their data samples by an order of magnitude.

Resistive Plate Chambers (RPC) are gaseous ionization detectors that are widely used as triggers in the muon systems of the LHC experiments such as Alice, LHCb, ATLAS and CMS. Within the latter, the RPCs constitute one of the main features of the muon detector along with the Drift Tubes (DT) and the Cathode Strip Chambers (CSC).These detectors are made out of two high pressure laminates with high resistivity. For the current model of RPCs in the CMS experiment, the electrodes have a thickness of 2 mm with a 2 mm gas gap between them. For the Phase II of LHC, a new generation of improved RPC detectors (iRPCs) is already being developed with a set of new features and changes to the original layout. The iRPCs are envisioned to be a double 1.4 mm Bakelite gap array with a gas gap of 1.4 mm and readout electronics of 32 copper strips and Front-End Board (FEB) threshold of 16 fC. The assembly and quality control tests have been going on during this year and performed at the 904 Building at CERN as part of the updates for the High Luminosity LHC era.

The standard mixture used in the RPCs system is made out of 95.2% of $C_2H_2F_4$, 4.5% iC_2H_{10} and 0.3% SF_6. The main component, also known as Freon or R-134a in the industry, gives the necessary amount of primary ion-electron pairs that will help to generate the signal when a muon passes through the medium. A small amount of isobuthane is also included in order to reduce photon-feedback effects as well as some SF_6 which is introduced in the mixture as an electron quencher to ensure the operation of the detector on an avalanche mode. Both Freon and SF_6 are well known Greenhouse gases with a Global Warming Potential (GWP) of 1430 and 22600, respectively. During the Run 2 of LHC, major leakages of the gases were produced at the detector level. In order to reduce the emissions generated by gaseous detectors, CERN has implemented various strategies to solve this problem: the first one with the implementation of a recirculation system with an 80% efficiency that is already on commissioning phase and a second one consisting on various tests to change the standard mixture for an eco-friendly alternative. In previous CMS analyses made by the Gas Group at CERN [3, 4], CO_2 based gas mixtures were identified as a short-mid term solution to reduce the amount of Freon by replacing it with CO_2 in the standard mixture, as it best reproduces the results obtained for the production of primary ion-electron pairs and muon efficiency. Other studies are trying to completely replace Freon by the usage of CO_2 and HFO, which represent the current long term idea to solve this issue but these will not be reviewed in here.

On this report an analysis is made for four different CO_2 based gas mixtures with different concentrations of SF_6. The gas mixtures tested had the concentrations of 30% CO_2 + 1% SF_6, 40% CO_2 + 1% SF_6, 30% CO_2 + 0.5% SF_6 and the standard one. These studies were conducted at the Gammma Irradiation Facility (GIF++) at CERN with the usage of a muon beam accounting for the signal and a gamma background source to mimic HL-LHC conditions.

2. RESISTIVE PLATE CHAMBERS IN CMS

A Resistive Plate Chamber consist mainly on two large electrodes made out of High Laminate materials, usually referred to as *Bakelite*, with a gas acting as the active medium between them. The readout electronics for the nominal model of RPCs are mainly made out of copper strips usually placed at the top (or bottom) panels of the detector, which allow us to collect data and have a good time and space resolution estimation of the ionizing particles that pass through the detector. Once a high energy particle passes through the RPC, the gas ionizes and the effect is thus measured by the applying of a potential difference between the electrodes. The estimation of the passage of a particle can then be measured in the form of an electrical current by the copper strips.

The choosing of the gas mixture cannot be done randomly, but it usually takes into account a list of features and characteristics needed for the proper functionality of the detectors. According to the original design these main specifications are required:

- High density of primary ion-electron clusters
- Relevant quenching properties
- It should not be dangerous to the human health
- Low GWP

With this last property, the primary goal is to reduce emissions when using an RPC, however, with the natural use of a detector another problem arises, as it can start the production of chemical elements that can potentially endanger the inner structure of the gap and thus the performance of the detector. In order to assure the proper functionality of the RPC the selection of the active medium must consider the possible subproducts that can be generated due to the chemical reactions within it.

In CMS, the RPC system is one of the main features of the Muon detector. It covers both the endcap and barrel regions and contributes to the trigger, identification and reconstruction of muons, in particular in the regions where the other subdetectors (CSCs and DTs) can not reach. During the HL-LHC future operation, the RPC system is envisioned to be extending its coverage range from $|\eta| = 1.9$ up to 2.4, thus allowing for more precise measurements in physical regions that were not possible to study before. In addition to the extended angular range, an upgraded version of RPCs will be also located there instead of the nominal model. These are known simply as iRPCs (see Fig. 1). Details about their design will be briefly described in the next subsection, where a summary of the assembly process will be taken into account for the present report.

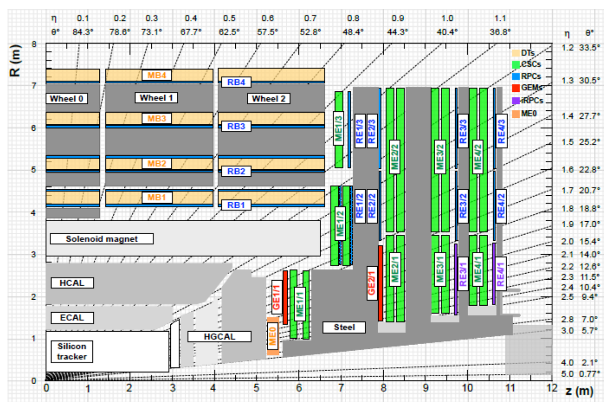

Fig. 1. Transversal cut of the CMS detector showing only one quarter of it. The location of the extended muon system can be appreciated with the purple labels identifying the iRPC detectors.

A. Assembly of iRPCs

Within the coming framework of High Luminosity LHC, the experimental data samples of the CERN experiments are expected to be increased by an order of magnitude, allowing the scientists working at CERN to study phenomena and physics that could challenge or validate the Standard Model of Particle Physics. Along with this upgrade a new problem arises, as the expected amount of background events will also be tremendously increased, thus creating a problem for the current measurement systems and detectors installed at the CERN experiments. That is why, a general update in the detection system is mandatory in order to keep the high accuracy, good performance and excellence of results for the coming years.

One of these sub-detection systems is the Muon system of the CMS experiment, which is composed of three main features: the RPCs, CSCs and DTs. The first of them represents the cornerstone for this study and we will focus on it, but the rest of the detectors are also being updated by other collaborations and groups within CERN.

For the current nominal model of RPCs installed at CMS, the Bakelite electrodes have a thickness of 2 mm with a gas gap of 2 mm between them. This array is also made out of a double gap RPC instead of the original model with a single gap. On the other hand, the new generation of RPCs or iRPCs are envisioned to be a double gap 1.4 mm Bakelite gap array with a gas gap of 1.4 mm instead of the original 2 mm design. Additionally, the iRPCs count with double readout electronics formed by 32 copper strips located between the gaps and a FEB threshold of 60 fC.

As part of the Summer Student Project made at CERN and the feasibility studies for the detection system upgrade, an assembly operation was carried out for the first month of internship, covering from the 26th June up until 19th of July at the 904 Building in the Prevessin site at CERN. The assembly project aimed to create the next generation of detectors while keeping a good performance when subjected to different conditions.

One of the first steps in the assembly process consists in a quality control for the gas gaps produced by the Korean Detector Laboratory. The purpose of this procedure is to ensure the correct positioning and state of the spacers inside the gap, as well as the applying of a gas leak test, which would allow us to verify the proper functionality of the gas system for the RPC. In order to do this, a series of pipes are connected to the gap under study and a constant flux of Argon is then injected through the gas openings located at four points in the gap with a total pressure of 60 mBar. At the same time, a measurement device is connected to the system in order to register the rate of change of pressure as a function of time inside the gap giving us an output plot that allows us to better picture this behaviour. A gap presented a leak whenever it showed a decrease of 4 mBar or more in 10 minutes or less. If a leak was identified the gap was then discarded and separated from the rest for reparations and/or for recycling.

Once a gap passed the gas leak test, the detector was then taken into another area to conduct the Dark Current test. This examination was done to ensure that no big currents were generated inside the gap due to the applying of the high voltage alone. Whenever a current exceeded the 4 mA a problem was considered to be happening within the system and the gap was discarded to use. All the measurements for this test were recorded at WebDCS, which is a software designed for and by CERN users that allow to take data without the user to do it manually. More details about this will be described in future sections.

Naturally, for the cases when the gap presented no leakages and the dark current test was correctly passed, the gap was taken to the next assembly area. On this next part, the gap was stored and the assembly of the top and bottom panels started with cleaning procedures for the surfaces. Once this was done, a set of long spacers was then screwed on each side of the bottom panel and some internal L-shape spacers were also put there to guarantee that the gas gap would not move too much when it was placed in the middle of it. After that, a copper foil previously designed was placed on top of the bottom panel and the gas gap was carefully put above it. A plastic coverage was then placed above the gap and the next gap was put in the array with a second copper foil covering both of them, creating a Faraday cage to ensure that no external signal would be generated inside the detector. The assembly finished with the placing of the top pannel, the screwing of all the system and the instalation of the gas copper pipes at the end of it. An iRPC fully assembled is shown in Fig. 2.

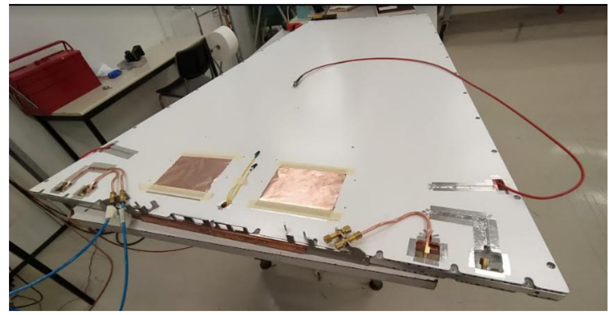

Fig. 2. Assembled iRPC showing the top and bottom white panels, the copper gas pipes and two copper foils that will be directly connected to the FEB electronics.

3. EXPERIMENTAL SETUP

During the 2023 July Test Beam a proton beam is generated by the Super Proton Synchrotron (SPS) Accelerator at CERN, which is then deviated and passed through a series of filters that create muons as a collision subproduct. These muons are then selected and manipulated by the usage of magnets which allows to generate a stable muon beam. This beam is generated for special measurements and feature testing of the different gaseous detectors used by the collaborations currently working at site, like CMS and ATLAS. SPS can operate accelerating charged particles, like protons, at a center of mass energy of 250 GeV and the overall array of accelerators can ensure the proper deviation of the muon beam directly to the Gamma Irradiation Facility (GIF++) in the North Area of CERN for recording, analysis and testing of the detectors.

A. Gamma Irradiation Facility

Located at the Prevessin Site in CERN, the GIF++ Facility [5] is a building specially designed for the testing of gaseous detectors within a bunker that contains a radioactive source that allows us to recreate the extreme conditions expected during the Phase-II of LHC while keeping the personnel safe during the process and able to record the data for every chamber put into test. At the same time, the muon beam is also directed into it to account for the signal part of the experiment.

The RPCs, CSCs and DTs, as well as other gaseous detectors for the CMS experiment were all tested to verify their proper functionality under these conditions.

The experimental array consists only on a set of a carefully placed RPCs located between two scintillators and a random pulse generator that will serve as a crosscheck device. Additionally to the muon beam a gamma source of Cs-137 is also used to simulate almost three times the high background rate expected during the Phase-II of the LHC upgrade; this device being located a few meters away from the detectors and at the center of the bunker.

There are currently two operation modes for the muon beam: one with beam ON and another one with the beam OFF. Both of them depend mostly in the availability and repairs made by the staff at the SPS accelerator as the muon beam is generated there. Despite this one can always work under the effect of the radioactive source tested for this and a set of different filters that can be applied in order to control the amount of radiation received by the detectors.

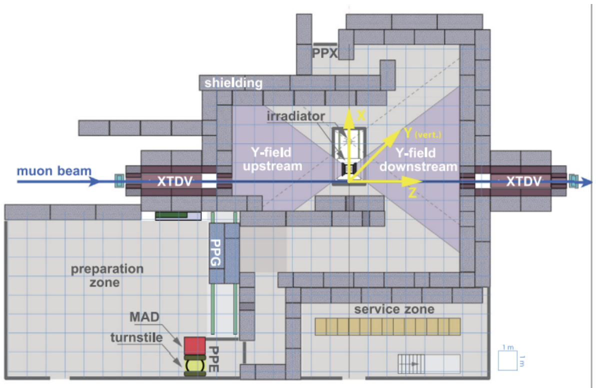

Fig. 3. Gamma Irradiation Facility (GIF++). Taken from [5]

As it is observed from figure 3 there are two areas in the bunker: upstream and downstream, each one of them indicating only the spacial location of the RPCs. For this setup, the detectors located at the upstream and downstream zones have a set of absorption (ABS) filters that can be simultaneously different, thus allowing various configurations at the same time. All the studies for the RPCs were conducted in the upstream zone using source OFF and source ON with ABS filters: 3.3, 4.6, 6.9, 10 and 22, each one of them corresponding to a certain background rate which will be summarized later on this report. The smaller (higher) the ABS value is, the major (lesser) amount of radiation is impinging on the detector. One can easily see that the background rate is proportional to the amount of radiation. For these tests, the highest background rate achieved was that of 1.6 kHz/cm^2 for the 3.3 ABS filter, which corresponds with almost three times the expected amount for HL-LHC.

B. RPCs and gas mixtures under study

In the already established framework a type E Korean Detector Laboratory double gap RPC (KODEL-E) with a total area of 50x50 cm^2 is under study. The readout electronics are made out of 16 copper strips with a FEB threshold of 60 fC, while the gas gap and the electrodes have a thickness of 1.4 mm each.

The standard gas mixture employed by the CMS collaboration for its detectors is composed mainly by 95.2% $C_2H_2F_4$, 4.5% iC_2H_{10} and 0.3% SF_6, with relative humidity of 40%. In order to lower the GWP and reduce costs, CERN has identified the usage of CO_2 as a possible candidate to substitute Freon as the active medium in the mixture, with a possibility to keep using it while reducing the percentage of R-134a into the total gas. The aim of the current work is to test the feasibility and operation of the RPCs under the applying of 4 different gas mixtures with varying percentages of CO_2 and SF_6 which are enlisted below in the form of a table to summarize its main properties.

C. Data taking and DAQ

As it has already been established, the data readout process is made via a 16 channel FEB with a threshold of 60 fC. For the measurements made for all RPC detectors a software designed at CERN called WebDCS is used for recording and storage of

Mixture	Freon	$iC_2H_{1}0$	CO_2	SF_6	GWP
STD	95.2	4.5	0	0.3	1490
Mixture 1	64	5.0	30	1.0	1530
Mixture 2	54	5.0	40	1.0	1450
Mixture 3	64.5	5.0	30	0.5	1380

Table 1. Gas mixtures summarized and their different configurations of gases in percentages. The GWP is included not considering the 80% recirculation system in CMS.

data, which is directly connected to the readout electronics and the copper strips. This page allows the user to select the detector to be tested and initialize the number of high voltage points required for the analysis, as well as the conditions under which we are testing the RPC, such as the muon beam status (ON and OFF) and the gamma background source filter. The data collections are stored online for user retrieval with their respective labels and commentaries for each run. At the end of each measurement process, an output ROOT file is generated with all the raw data containing the number of strips, time stamps, fired channels, and other basic features.

Inside WebDCS an analyzer can also be run in order to obtain high level features such as the cluster size, cluster multiplicity and gamma background rate, that will be explained on the next section. All of these characteristics will be fundamental to determine the muon reconstruction efficiency and thus to obtain the final plots for the gas mixtures efficiency studies.

The whole data recording process took place during the first two weeks of July 2023 at the Gamma Irradiation Facility with shifts of eight hours each per available person at site concluding at July 19th with a successful recording for all the RPC detectors types and gas mixtures.

4. ANALYSIS STRATEGY

Once the data taking process was completed at the GIF++ Facility, the next step consists on an offline analysis for the recorded performance of the detectors.

For this, an offline local WebDCS analyzer is run so the ROOT file produced can be read and with it we can extract all the necessary data needed to conduct the studies for the muon reconstruction efficiency and the overall feasibility of the RPC detector as a whole. In this section we will briefly discuss each of these characteristics for the KODEL-E chamber and describe the steps applied to obtain these results.

A. Clusterization algorithm

As a starting point of the offline reconstruction analysis we first have to take a look at what does a raw event looks like. When a muon passes through the RPC, it generates a set of primary ion-electron clusters that can be then measured by the copper strips as current when the high voltage is applied between the electrodes. Naturally, secondary clusters can be generated via the interaction of the ions and electrons with their surrounding medium thus creating an avalanche-like effect. A problem then arises when the avalanche keeps growing until the point where it is large enough to cover a big area of the TDC channels readout system, which ends up resulting in an overestimation in the muon's energy. This last mode is commonly known as **streamer** mode. However, the avalanches are necessary for the signal formation and represent a good element in the signal readout process as long as one is able to control their size. The avalanches can be managed up to certain point thanks to the electron-quenching properties of the SF_6 and the RPC operational mode known simply as *avalanche mode*.

Once an RPC has been properly set, a raw digitalized event displays in the form of a collection of fired Time Digital Converter (TDC) channels that when plotted against time can perfectly give us a schematic view of the signals obtained by each strip during a certain time window. In order to determine each of the possible time windows, one first needs to plot the total number of hits against time.

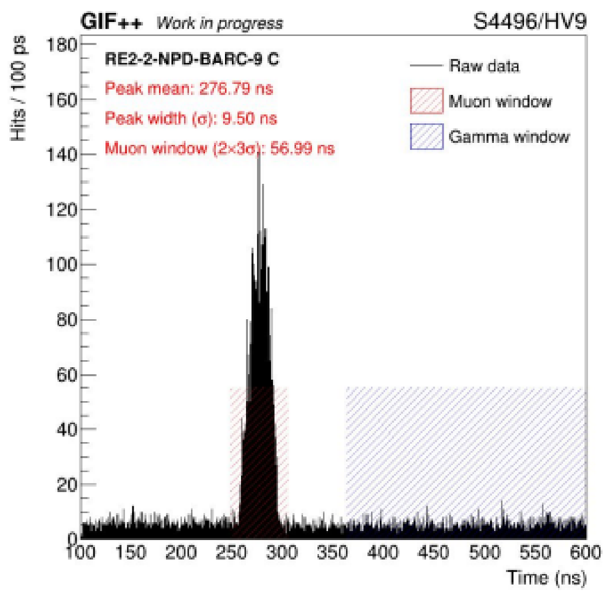

Fig. 4. Time profile for the number of hits on the RPC for a situation with source ON at a certain high voltage point. The selected gamma and muon windows are included as well as the fitted parameters. Here, the consideration of avoiding the first 100 ns has already being made.

For the measurements done with source ON, there are two main time windows: one when only gammas are recorded and the second one when both the muon beam and the gammas are impinging on the detector. The physical reason for this behaviour is due to the nature of the muon beam, as it is not a continuous flux of particles, but rather a set of particle bunches that came with a delay time between them. The first one represents the time zone in which the number of hits has an average constant behaviour with respect of time and it can be parametrized as a constant function. On the other hand, the muon time window is the easiest to recognize as it is represented by the appearing peak in the time profile, thus making it easy to parametrize by a gaussian function. A construction of a nominal model can then be made in order to extract the value for the width σ, which will allow us to define the muon window as the region with three sigmas to the right and the left from the mean value of the gaussian function.

For the case with source OFF the situation is slightly different. As there is no gamma source active, there is no definition of the gamma window, but the muon window is still obtained from the gaussian fit and defined as the time stamp with three sigmas to the right and the left with respect of its mean value.

For both cases with source ON or OFF, the first 100 ns are discarded on the analysis due to bad TDC data transfer that can occur.

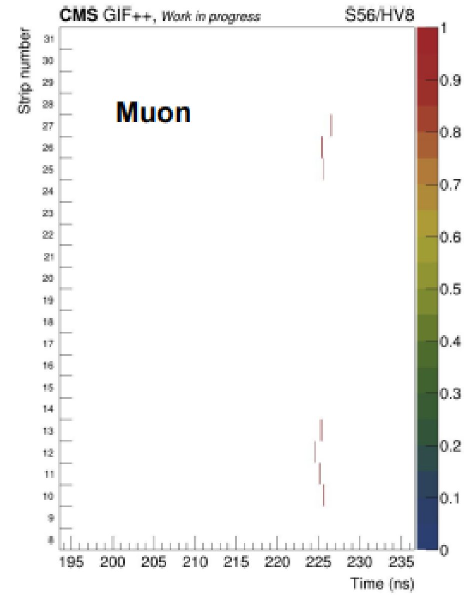

Fig. 5. Raw event containing two sets of fired TDC channels corresponding with two measured muons inside the muon time window for an experimental array with no active gamma source (source OFF).

As can be seen in Fig. 5, a single event might contain one or more strip signals corresponding to one or more ionizing particles. A set of fired TDC channels can correspond to the measurement of a cluster generated by a single particle and a certain estimation could be made about whether some of them in the vicinity correspond to the same event or not. The task ahead now consists on trying to determine the size of the total cluster and which strips signals are related to a single signal. This is what is called the *clusterization* algorithm.

First, one must select the events which are in the same time window, as this is only a way to properly select the clusters generated by a single signal. In order to do this, the fired TDC channels must be adjacent with one another and must not exceed a time window labeled as ΔT, which is different than the muon and gamma time windows. For every single group of paired strips, the cluster multiplicity is computed simply as the amount of clusters and the muon cluster size as the average size of all formed clusters.

The clusterization method is applied for the muon and gamma windows. This study allows us to know how the cluster size evolves in time once an ionizing radiation passes through the chamber.

B. Efficiency curve

Following the clusterization algorithm results, an efficiency curve is now built for the different set of high voltages and efficiencies recorded for the reconstructed muons within the RPC detector. In order to obtain the efficiency, we must first take into account the two situations that can appear: one with source OFF, that is, without gammas impinging on the detector, and the second one when the source is ON.

For the first scenario, the muon reconstruction efficiency is computed simply as the number of muons reconstructed by the RPC divided by the number of events recorded by the trigger system (the array of scintillators), both of them being extracted in the muon time window. This can be described by a mathematical model as follows:

$$\epsilon = \frac{N_{RPC}}{N_{Trigger}} \quad \textbf{(1)}$$

As it has been discussed in subsection A, having a radioactive source active while the measurements are done directly affects the muon reconstruction of events, as it induces a background signal coming from the particles emitted by such source impinging on the detector, thus a correction in the raw efficiency is mandatory. This extra effect is well pictured in Fig. 4, where the gamma particles behave as a constant number of hits in the time profile. In order to purify the signal and discard the contributions made by the background, the efficiency correction is made via the Bayesian probability theory.

Due to the existence of gammas even on the muon time window, the total efficiency $P(tot)$ measured within it already includes both: the muon $P(\mu)$ and the gamma $P(\gamma)$ efficiency. The latter contribution can be calculated by taking a time interval outside the time window, equal in length to the muon window, and evaluating the gamma efficiency directly. Once the components are obtained, the Bayesian probability formula for non independent measurements estipulates that:

$$P(tot) = P(\mu) + P(\gamma) - P(\mu)P(\gamma) \quad \textbf{(2)}$$

so that the muon efficiency is corrected simply as:

$$P(\mu) = \frac{P(tot) - P(\gamma)}{1 - P(\gamma)} \quad \textbf{(3)}$$

Under this circumstances, the $P(tot)$ describes the raw efficiency obtained without the gamma correction, that is, the efficiency described by Eq. (1). This algorithm is implemented for each scan and a set of efficiencies is obtained for every high voltage point. With all of this one is now able to plot an efficiency curve for the recorded data.

In any case, the functional form of the data could be parametrized by a sigmoid function (S-curve) which takes into account three different parameters: the maximum efficiency ϵ_{max} at the plateau, which describes the highest value achieved once the detector is at its maximum performance, the high voltage at 50% of the efficiency $HV_{50\%}$ and the value λ which is a constant with dimensions of inverse voltage. The nominal model is then written simply as,

$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50\%})}} \quad \textbf{(4)}$$

The data extraction and fitting process is done for each of the 4 gas mixtures tested. The usage of a python script was needed and done via the `scipy.optimize.fit` function which allowed to us to introduce the three main parameters as well as the dataset. As an output, this function returns the optimized parameters after the fitting process and the uncertainties in the form of the covariance matrix.

From Fig. (4) the working point (WP) is defined as the knee plus 150 V, which represents the point where the detector reaches 95% of efficiency in the absence of other contributions. In order to determine this, we follow the formula:

$$WP = HV_{95\%} + 150V = \frac{\log 19}{\lambda} + HV_{50\%} + 150V \quad \textbf{(5)}$$

At the end, the total minimized function is plotted along the experimental data and the calculated WP for each ABS filter. A normal efficiency curve for a single scan looks like the one in figure 6. One important thing to notice is that without a plateau, the WP can not be appropriately defined. If an efficiency profile does not reach a plateau eventually, the scan, and more importantly, the detector, is discarded and could be a sign of bad functionality.

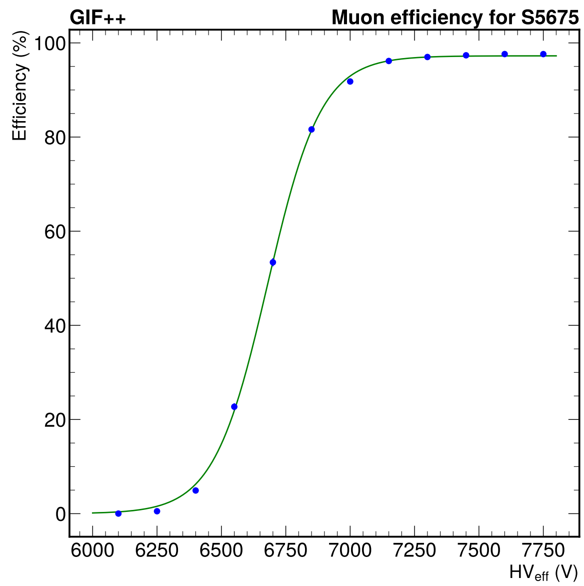

Fig. 6. Muon efficiency behaviour for data collected during a normal scan performed with the software WebDCS.

C. Gamma background rate

As the final step in the analysis procedure, and in order to better picture a physical quantity that can give us the amount of radiation impinging on the RPCs during the data taking, the usage of the ABS filters labels is discarded from now on and instead the gamma background rate is computed as the noise background rate on the RPC divided by the gamma cluster size. All of this will allow us to compare the different background rates at which the RPCs are currently being subjected to with the maximum background rate foreseen in the CMS RPC Endcap Region for the High Luminosity LHC Phase, which has a value of 0.6 kHz/cm^2 [6]. Needless to say is that this is the location where the new generation of detectors will be installed in the future. In addition to all of this, the gamma background rate will help us to understand the overall performance of the detectors under these extreme conditions.

The equivalence of the gamma background rates with their corresponding ABS filters is reported in table 2. This calculations are only approximations to the real values, but will be useful to illustrate how the muon reconstruction efficiency evolves.

That is, for the 3.3 ABS filter, an amount of almost three times the expected gamma rate for Phase II of LHC is recorded. The

ABS Filters	Background rate (kHz/cm^2)
Source OFF	0.00
3.3	1.60
4.6	0.90
6.9	0.60
10	0.50
22	0.20

Table 2. Equivalence table between the ABS filters and gamma background rates. These are just approximations to the real values.

6.9 ABS filter corresponds to the radiation region which we are aiming to be working with and the filters of 10 and 22 are crosschecks for the radiation region with less than the foreseen amount. The usage of the ABS labels will be included once again in only one plot just to illustrate the evolution of the efficiency at the WP for the gas mixtures with all of the ABS filters, but one can always refer to Table 2 in case the conversion is needed.

5. RESULTS AND DISCUSSION

In the present work a measurement and comparison of the muon reconstruction efficiency is made for Resistive Plate Chambers with four different CO_2 based gas mixtures and varying concentrations of SF_6 as an electron quencher. As the aim of this work is to lower the GWP of the gas mixture, as well as reducing costs by maintaining similar detector performance for the HL-LHC phase, individual analyses are developed for each one of them under an experimental array consisting of a muon beam accounting for the signal part and a ^{137}Cs radioactive source with multiple absorption filters, reaching and surpassing the expected background gamma rate of 0.6 kHz/cm^2 for certain measurements.

Every result obtained here has also been computed and stored within the Technical Report in the twiki page of CERN, which will allow other collaborators from around the world to see this analysis on detail.

As a first step, the results on the S-curve fitting process will be presented for each gas mixture under different background rates available. The clusterization algorithm parts are purposefully avoided and not reported in here as they were only tools that allowed us to build the muon efficiency plots but not of interest for the general study. The working point and the efficiency at the WP were extracted directly from the fitting procedure. In order to visualize the entire behaviour for each gas mixture, all the S-curves for different background rates are included in the same plot with their respective uncertainties and labels.

On this particular report only a single plot is included for one selected candidate, which is the one with 30% CO_2 and 1% SF_6. Further commentaries as to why this mixture is the only one pictured in here will be made in the future sections.

From the data extraction, the WP for different gas mixtures at different background rates (ABS filters) can then be summarized simply as the table below. For simplicity all of them will be labeled as follows: STD for the standard, Mixture 1 for 30% CO_2 + 1% SF_6, Mixture 2 for 40% CO_2 + 1% SF_6 and Mixture 3 for 30% CO_2 + 0.5% SF_6.

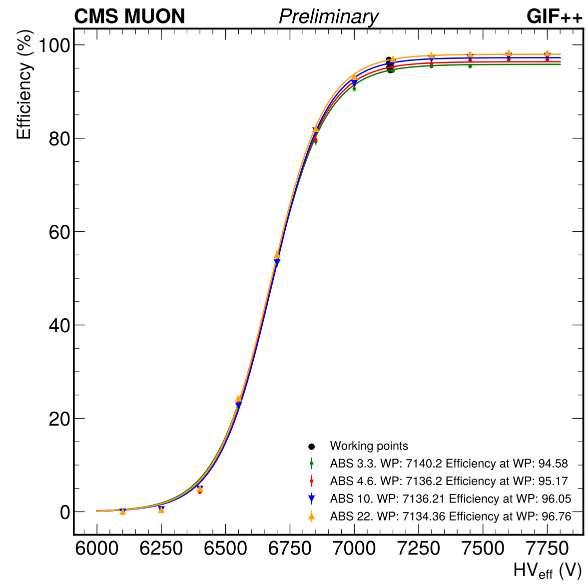

Fig. 7. S-curve for different filters and with a mixture made out of 30% CO_2 and 1% SF_6. The uncertainty bars for the efficiency points are included but they can not be distinguished due to the scale.

Gamma rate	STD (V)	Mix 1(V)	Mix 2 (V)	Mix 3 (V)
0.0 kHz/cm^2	–	7246.00	6998.97	6697.26
1.6 kHz/cm^2	7246.00	7126.62	–	6691.83
0.9 kHz/cm^2	7260.14	7120.48	7007.31	–
0.6 kHz/cm^2	7243.20	–	7002.51	6694.90
0.5 kHz/cm^2	7261.31	7131.27	6999.88	6727.30
0.2 kHz/cm^2	7253.93	–	–	–

Table 3. Comparison of the WP evolution for different ABS filters and gas mixtures.

From Table 3 and Table 4, one is able to see that results can only be compared in general for the 10 ABS filter as it is the only one in which the 4 mixtures have been properly measured. Despite this fact, certain conclusions can be made for the general behaviour of the gases in the presence of different CO_2 and SF_6 concentrations. In order to better picture the conclusions of this work, one extra plot is included for the evolution of the efficiency at WP comparing all gas mixtures and filters used.

First of all, a small shift in the WP is recorded with respect to the standard one for all the gas mixtures tested, as it is naturally expected from other CMS Muon and Gas Group collaborations. Following this fact, a drop in the muon efficiency at the WP is also observed for the three gas mixture candidates when comparing to the results of the standard one, as can be seen in fig 8. The smallest value recorded for this parameter was of 92.88% which was obtained for the gas mixture with 30% CO_2 + 1% SF_6 (red bar) corresponding to a background gamma rate of 1.6 kHz/cm^2, which is beyond the well established limit of 0.6kHz/cm^2 for HL-LHC.

Gamma rate	STD	Mix 1	Mix 2	Mix 3
0.0 kHz/cm^2	–	97.62%	97.48%	96.28%
1.6 kHz/cm^2	94.00%	93.47%	–	92.88%
0.9 kHz/cm^2	95.25%	94.54%	94.43%	–
0.6 kHz/cm^2	95.71%	–	95.12%	94.27%
0.5 kHz/cm^2	96.37%	96.08%	95.54%	95.24%
0.2 kHz/cm^2	97.14%	–	–	–

Table 4. Efficiency at the WP for different ABS filters and gas mixtures.

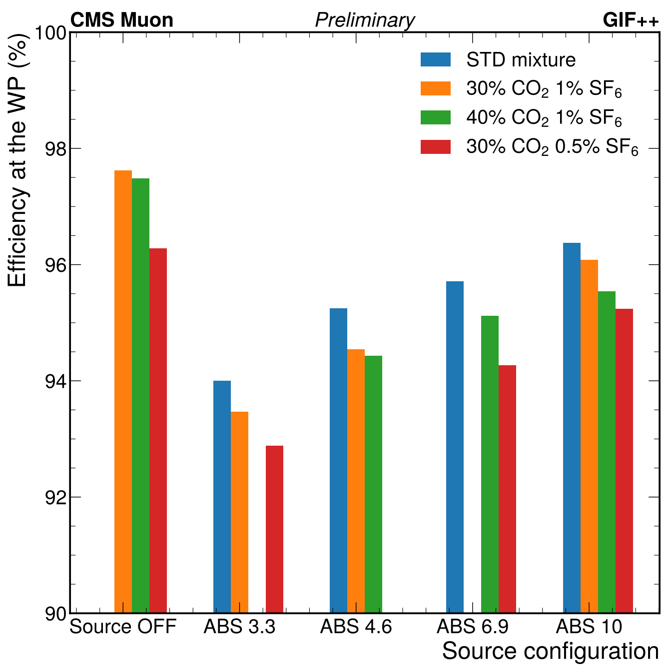

Fig. 8. Comparison of the efficiency at the WP evolution for the available set of ABS filters and gas mixtures.

This fact tells us that even though the RPCs are reconstructing less muon events, the overall performance of the detector is good enough to keep CO_2 based gas mixtures on the test as none of them present a reconstruction efficiency dropping below 90% even for the cases with more than two times the HL-LHC limit.

On the other hand, for the cases of different CO_2 concentrations and same SF_6 (Mix 1 and Mix 2), the efficiency at the WP presents a drop when increasing CO_2, while for the same amount of CO_2 and different SF_6 (Mix 1 and Mix 3) the exact opposite phenomena is recorded, as the lowering of this last component resulted into worse results for the muon efficiency.

6. CONCLUSIONS AND PERSPECTIVES FOR THE FUTURE

A study on the feasibility of four CO_2 based gas mixtures for the Resistive Plate Chambers in the CMS experiment was conducted during the 2023 July and April Test Beam at the Gamma Irradiation Facility at CERN. The RPCs were subjected to a muon beam produced at the SPS accelerator and a ^{137}Cs radioactive source that reproduced the high luminosity expected for the Phase-II of LHC. A set of filters were also applied to study the behaviour of the mixtures under different background rates.

The shape of the reconstructed efficiency curves followed a sigmoid function which were then fitted and with which we could obtain the working point for each analysis curve and gas mixture. As it was expected, a drop in the muon efficiency is recorded for increasing background rates, which is physically consistent with other results, but not relevant enough to discard the usage of CO_2 as a partial replacement for the Freon on the mid term solution to the emission problem. In particular, the increase of CO_2 on the gas mixtures exhibit a decreasing behaviour for the muon efficiency, while the mixtures with 1% SF_6 showed better results as the ones with 0.5%. Even though the SF_6 has a very high GWP, the 1% concentration mixture represents a good balance between performance and emission reduction for RPCs.

Although the preliminary results obtained during the Test beam were shown to be satisfactory, the selection of a final candidate is not yet presented on this report, as it has been already determined by the CMS RPC group that more studies need to be made in order to reach a final solution. Due to the Freon recirculation system already in commissioning phase for CMS, the reduction of the Greenhouse Gases emission does not represent a high level priority right now and the studies on eco-friendly gas alternatives can still be investigated for a while. However, collaborations like the RPC group at ATLAS do need a quick solution, as the RPCs are the only trigger system that they have within their muon detector and no recirculation system is currently existing nor in commissioning way. It is due to this fact, that both ATLAS and CMS have agreed to keep working with the gas mixture that showed better results during this Test Beam, that is, the one with 30% CO_2 + 1% SF_6, which will allow ATLAS to solve their problem and at the same time giving some more time to CMS to continue with many other studies for CO_2.

Once the results have been completely approved by the CMS Muon Group, the next natural step is to keep investigating the aging effects of CO_2 based gas mixtures within the iRPC detectors as well as to determine in the near future which is the best candidate for the mid-short term solution to the GHG emission problems at CERN. As a way to verify and compare the performance of the iRPC wih the nominal model currently installed at CMS, some more studies on the muon reconstruction efficiency will also be conducted at the Gamma Irradiation Facility at CERN for old double gap RPCs with 2 mm thickness and a FEB threshold of 130 fC. The data taking will take place during the last weeks of August 2023, corresponding to the next scheduled Test Beam, when we expect to obtain encouraging results for the matters already discussed before. In addition to this, timing resolution analyses are also on the way.

REFERENCES

1. R. Adolphi *et al.*, "The CMS experiment at the CERN LHC," Jinst **803**, S08004 (2008).
2. G. Apollinari, I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, and L. Tavian, "High-luminosity large hadron collider (hl-lhc). technical design report v. 0.1," (2017).
3. G. Rigoletti, R. Guida, and B. Mandelli, "Performance studies of rpc detectors operated with c2h2f4 and co2 gas mixtures," Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip. **1049**, 168088 (2023).
4. M. Capeans, R. Guida, and B. Mandelli, "Strategies for reducing the environmental impact of gaseous detector operation at the cern lhc experiments," Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip. **845**, 253–256 (2017).

5. D. Pfeiffer, G. Gorine, H. Reithler, B. Biskup, A. Day, A. Fabich, J. Germa, R. Guida, M. Jaekel, and F. Ravotti, “The radiation field in the gamma irradiation facility gif++ at cern,” Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip. **866**, 91–103 (2017).
6. “The Phase-2 Upgrade of the CMS Muon Detectors,” Tech. rep., CERN, Geneva (2017). This is the final version, approved by the LHCC.