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Study of environment-friendly gas mixtures for Resistive Plate Chambers in view of future applications

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*To my father, mother and brother...
thank you for teaching me to face life
armed with my dreams*

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Abstract

The purpose of this thesis is the search of an environment-friendly gas mixture for the Resistive Plate Chambers (RPC) for present and future applications.

The standard gas mixture, composed of $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$, is currently used in the RPCs at the Large Hadron Collider (LHC) experiments because it ensures good rate capability and long-term operation in a high-radiation background environment.

This gas mixture has a high Global Warming Potential (GWP) ~ 1430 due to the presence of $\text{C}_2\text{H}_2\text{F}_4$ and SF_6 . European Union regulations have imposed a progressive phase down in the production and use of the F-gases in industry, thus reducing their availability and increasing their price.

For this reason, the search for an environment-friendly gas mixture that can maintain the excellent performance of the standard one is crucial for the usage of RPCs in present and future experiments.

In this thesis alternative gases to both $\text{C}_2\text{H}_2\text{F}_4$ and SF_6 have been studied, with an ATLAS RPC already in operation during Run-2 and with a new RPC (thinner gas gap) foreseen the High-Luminosity phase of the LHC.

The $\text{C}_2\text{H}_2\text{F}_4$ has been substituted with a proper mixture of CO_2 (GWP = 1) and Tetrafluoropropene ($\text{C}_3\text{H}_2\text{F}_4$, GWP ~ 6), while the Chloro-Trifluoropropene ($\text{C}_3\text{H}_2\text{ClF}_3$, GWP ~ 5), never tested before in the RPC detectors, has been chosen to substitute the SF_6 .

In chapter 1 a brief introduction to the HL-LHC upgrade project is given, focusing on the description of the ATLAS Muon Spectrometer and the RPC system. Examples of the ATLAS Physics goals for the HL-LHC are also described.

The RPC operating principle and its main characteristics are presented in chapter 2.

The search for alternative low-GWP gas mixtures is introduced in chapter 3 with the description of the standard gas mixture properties and the possibility of using new environment-friendly gas mixtures. The new gas components are presented along with the description of the so called "transition events", a new category of signals having intermediate properties between avalanche and streamer, occurring in the eco-gases analyzed.

In chapter 4 the results of the tests performed with cosmic rays on an ATLAS RPC (2 mm gas gap) using new gas mixtures composed of $\text{C}_3\text{H}_2\text{F}_4/\text{CO}_2/\text{i-C}_4\text{H}_{10}/\text{SF}_6$ are presented. Moreover, the possibility to replace the SF_6 with the new gas $\text{C}_3\text{H}_2\text{ClF}_3$ is also studied. The detection efficiency, streamer probability and electronic and ionic charges as a function of the high voltage are studied together with the timing properties and the time resolution. For the first time, an alternative gas mixture composed of $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{C}_3\text{H}_2\text{ClF}_3$, with a GWP = 10, has been studied, paving the way for the possibility of operating the RPCs with a totally eco-friendly gas mixture.

In chapter 5 and chapter 6 the results of the test performed with a muon beam and under the irradiation from a strong photon source (CERN GIF++ facility) are presented, with the aim to certify that both an ATLAS RPC (2 mm gas gap) and the new ATLAS

BIS78 RPC (1 mm gas gap) can operate with good performance using the new gas mixture composed of $\text{C}_3\text{H}_2\text{F}_4/\text{CO}_2/\text{i-C}_4\text{H}_{10}/\text{SF}_6$ in the high HL-LHC environmental background.

The last chapter, Chapter 7, is dedicated to muon performance studies. The measurement of muon isolation efficiency and scale factors in a busy environment using $t\bar{t}$ events is described, to give a complementary approach to extract these quantities to the one currently used in the analysis.

Chapter 1

The High-Luminosity Large Hadron Collider and the ATLAS experiment

The Large Hadron Collider (LHC) [1] has reached energies almost up to 14 TeV, offering a wide range of physics researches. Proton bunches circulate along the 27 Km ring of superconducting magnets, interacting in four points, where the main LHC experiments are located. The beams travel in opposite directions in separate beams pipe kept at ultra high vacuum and guided through the accelerator ring by a strong magnetic field of 8.5 T.

The design luminosity is $10^{34}\text{cm}^{-2}\text{s}^{-1}$ with a bunch spacing of 25 ns (bunch crossing), a bunch intensity of $\sim 10^{11}$ and 13-14 TeV of center of mass energy.

The proton-proton interactions are studied by ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid) and LHC-b (dedicated exclusively to b-physics) experiments. A fourth experiment, ALICE (A Large Ion Collider Experiment) is optimized to study the collisions of nuclei at the ultra-relativistic energies, thus the physics of strongly interacting matter in the quark-gluon plasma environment.

The High-Luminosity phase of the Large Hadron Collider (HL-LHC) [2] will provide a unique opportunity to study electroweak symmetry breaking in detail and explore the nature of physics beyond the Standard Model.

In order to fully exploit the physics potential of the LHC, two upgrades have been planned: the first one consists in the injectors upgrade leading to an increase of the LHC peak luminosity up to $3 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ with the aim of delivering an integrated luminosity of 300fb^{-1} . A further upgrade includes the installation of new elements like focusing magnets and crab cavities.

The HL-LHC phase 2 upgrade is expected to provide peak luminosity of $5\text{-}7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, and a total expected integrated luminosity of 3000fb^{-1} . The increase of luminosity by almost an order of magnitude with respect to the original LHC design, will lead to an increase of particle flux by the same amount, as well as an increase of the integrated radiation and particle rate.

Therefore, the HL-LHC will have a much harsher environment in terms of background radiation along with a higher pile-up.

A major upgrade of the experiments is then required in order to address these new and harsher conditions and to fully exploit the HL-LHC physics potential.

The upgrade program, divided in two phases, is shown in Figure 1.1: the phase-1 started in 2019, with the LHC reaching a center-of-mass energy of 13.7 TeV and the experiments collecting 300fb^{-1} (Run-3). The phase 2, starting in 2026, with the collider reaching a center-of-mass energy of 14 TeV and a collection of 3000fb^{-1} of

integrated luminosity.

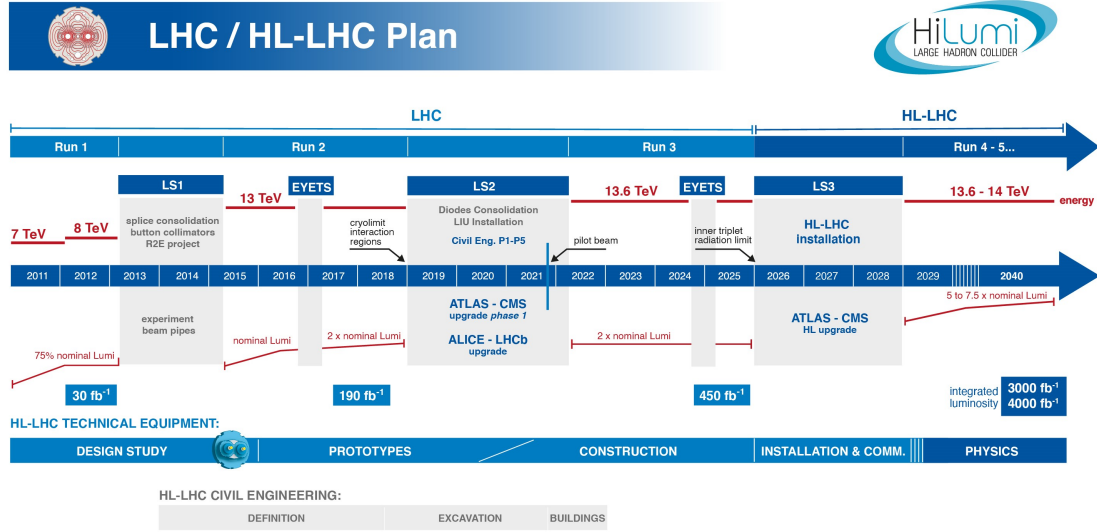


Figure 1.1: The High-Luminosity Large Hadron Collider (HL-LHC) program.

1.1 The ATLAS experiment

The ATLAS (A Toroidal LHC Apparatus) detector [3] is a multi-purpose experiment at the LHC which discovered, together with CMS, the Higgs boson in 2012. ATLAS is located 100 m below ground at Point 1 at the LHC and is the largest volume detector ever constructed for a particle collider, being 46 m long, 25 m in diameter and 7000 tons weight. The experiment, shown in Figure 1.2, has a cylindrical shape and is a many-layer instrument. It is composed of six different detecting subsystem, built concentrically around the collision point to record the trajectory, momentum and energy of particles. The particles are bent under the action of a huge magnet system so that their momentum can be measured as precisely as possible. The detector tracks and identifies particles to investigate a wide range of physics, from the study of the Higgs boson and top quark to the search for Physics Beyond the Standard Model.

The layer of the ATLAS detector nearest to the collision point is the Inner Tracker detector (ID) [4]-[5] and is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. The ID consists of silicon pixel [6], silicon microstrip, and transition radiation tracker detectors and covers the pseudorapidity range $|\eta| < 2.5$. The second layer, surrounding the ID, is made of lead/liquid-argon (LAr) sampling calorimeters [7]-[8] that measure the energy and position of electromagnetic showers with high granularity. In the central region, $|\eta| < 1.7$ the steel/scintillator-tile calorimeter [9] is used to provide hadronic energy measurements. In the endcap and forward regions LAr calorimeters with copper and tungsten absorbers are used for electromagnetic and hadronic showers measurements up to $|\eta| = 4.9$. The outermost layer of the ATLAS detector is the muon spectrometer [10] and will be further described in Section 1.1.1. It consists of separate trigger and high-precision

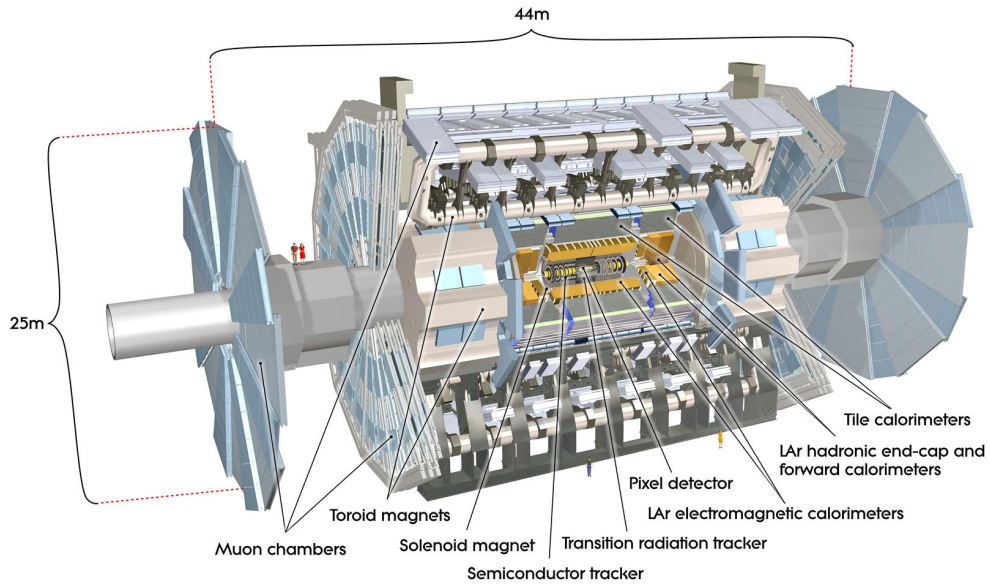


Figure 1.2: The ATLAS experiment

tracking chambers, operating in a magnetic field generated by three large air-core toroidal superconducting magnets with eight coils each. In order to select and record events of interest, a two-level trigger system is used. The level-1 trigger is implemented in custom hardware. It uses information from the calorimeters and the muon spectrometer to reduce the event rate below 100 kHz. Then a fully software-based trigger, the high-level trigger (HLT), is used to further reduce the event rate to 1 kHz on average.

1.1.1 Muon spectrometer

The ATLAS Muon Spectrometer (MS), shown in Figure 1.3, is designed to reconstruct muons, to trigger on them and to measure their momentum either as a stand-alone system or in combination with the Inner Detector. It covers the pseudorapidity range $|\eta| \leq 2.7$ with a small hole at $|\eta| = 0$, where cables and services belonging to the Inner Detector and to the Calorimeter systems are located.

Precision-tracking chambers in the barrel region are located between and on the eight coils of the superconducting barrel toroid magnet, while the end-cap chambers are in front and behind the two end-cap toroid magnets.

The ϕ symmetry of the toroids is reflected in the symmetric structure of the muon chamber system, consisting of eight octants. Each octant is subdivided in the azimuthal direction in two sectors with slightly different lateral extensions, a large and a small sector, leading to a region of overlap in ϕ . This overlap of the chamber boundaries minimises holes in detector coverage and also allows for the relative alignment of adjacent sectors using tracks recorded by both a large and a small detector.

It is composed of four types of muons chambers:

- Monitored Drift Tubes (MDT), covering the region $|\eta| \leq 2.7$, provide position measurement in the bending plane over most of the MS acceptance region;
- Cathode Strip Chambers (CSC), covering the region $2 \leq |\eta| \leq 2.7$, provide position measurement both in the bending and in the non-bending plane in the

innermost detector layer of the forward regions;

- Thin Gap Chambers (TGC) cover $1.05 \leq |\eta| \leq 2.4$ and are used for trigger information and non-bending plane position measurement in the endcap regions;
- Resistive Plate Chambers (RPC) covering $|\eta| \leq 1.05$ are used for trigger information and for non-bending plane position measurement in the barrel region

In the barrel region, the precision MDT chambers are arranged in three layers with cylindrical symmetry around the beam axis providing the three track position measurements needed for momentum determination: The inner (I) layer at $R=5$ m, the middle (M) layer at $R=7.5$ m and the outer (O) layer at $R=10$ m. In the endcaps, the layers are located at 7 m (I), 14 m (M) and 21-23 m (O) from the nominal interaction point. The muon trigger and the precision coordinate are provided in the barrel by three layers of Resistive Plate Chambers and in the endcaps by the Thin Gap Chambers. The muon first-level hardware trigger is based on hit coincidence between different RPC or TGC detector layers inside programmed geometrical windows which define the muon p_T .

Monitored Drift Tubes A MDT chamber is composed of drift tubes, with a length of 1-6 m, organized in two multi-layers separated by a spacer. Each multi-layer is composed of 3 or 4 layers of tubes. It operates with $\text{Ar}/\text{CO}_2(93/7)$ gas mixture at a pressure of 3 bar. The MDTs provide a precision measurement of the track coordinates in the bending direction of the magnetic field over most of the $|\eta|$ -range. The maximum drift time is ~ 700 ns and the single-wire resolution is $\sim 80 \mu\text{m}$.

In order to measure track sagittas as low as $500 \mu\text{m}$, an optical alignment system monitors the alignment of the chambers along the tracks, detecting the detectors relative displacement with an accuracy of $30 - 40 \mu\text{m}$.

The MDTs can operate up to background rates of $500 \text{ Hz}/\text{cm}^2$ without compromising the spatial resolution and tracking efficiency.

Cathode Strip Chamber Cathode Strip Chambers (CSC) are multi-wire proportional chambers with readout cathode strips parallel and orthogonal to the wires and are used in the innermost layer of the MS, where the high background radiation rate would degrade too much the performance of the MDT chambers.

CSC chambers operate with a $\text{Ar}/\text{CO}_2/\text{CF}_4$ (30%/50%/20%) gas.

The precision coordinate is determined as the mean of the orthogonal strip cathode coordinates weighted by the charge signals induced on them, with a resolution of about $60 \mu\text{m}$ for a single CSC plane. Each chamber is composed of 4 planes. The transverse coordinate is measured with a resolution of about 5 mm by the cathode strips oriented parallel to the wires, which have larger pitch.

The CSC chambers are designed to operate with a background radiation level up to $1 \text{ kHz}/\text{cm}^2$, which is sufficient to cope with the working conditions of the inner part of the forward spectrometer region. They guarantee high spatial accuracy, good two-tracks separation (40% of the pitch), short electron drift time (30 ns), a time resolution of ~ 7 ns and low neutron sensitivity.

Thin Gap Chambers Thin Gap Chambers (TGC) are multi-wire proportional chambers with anode wire pitch larger than the anode-cathode distance.

They operate with a highly quenching gas mixture composed of $\text{CO}_2/\text{n-C}_5\text{H}_{12}$ (55%/45%). The wires provide the coordinate measurement in the bending direction, while the transverse coordinate measurement is provided by the cathode strips orthogonal to the wires.

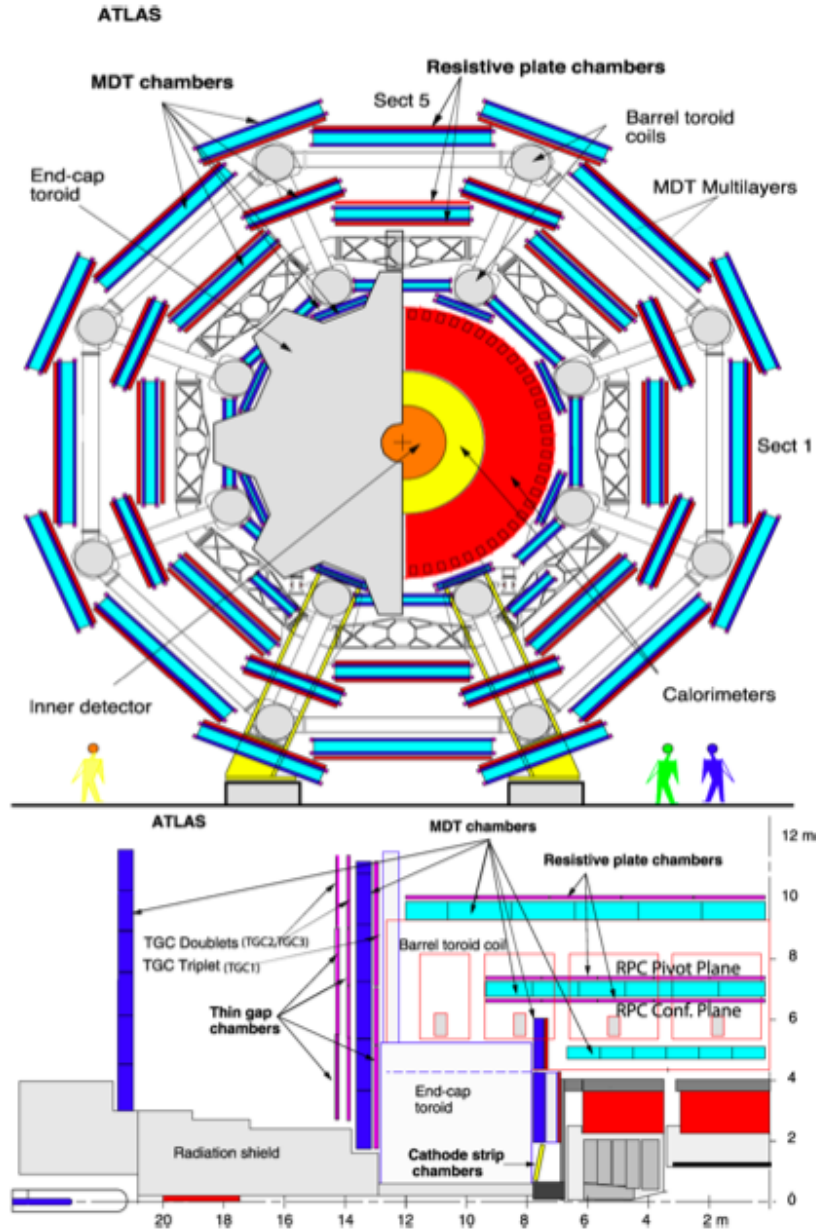


Figure 1.3: The ATLAS Muon Spectrometer

The system is composed of three stations in each endcap, called Big Wheels, with 12 m radius each.

The first station is made of three layers, while the other are assembled in a two-layers structure.

They are used to provide the LVL1 muon trigger in the end cap and the non-bending plane coordinate measurement.

Resistive Plate Chamber The Resistive Plate Chambers (RPC) are composed of two independent detector layers, each providing two-dimensional coordinate measurement.

The layers consist of two Bakelite plates of 1.8 mm thickness, separated by a 2 mm wide gap filled with $C_2/H_2F_4/i - C_4H_{10}/SF_6$ (94.7%/5%/0.3%) gas mixture.

The induced signal is amplified by a Front End electronics based on GaAs technology. The 2D readout is provided by two panels of orthogonal strips, in η and ϕ directions, providing both the bending and non-bending plane measurements.

The system consists in three concentric layers around the beam axis, providing six independent measurements along the muon track with 1 cm of spatial resolution and an intrinsic time resolution of ~ 1 ns.

Two of the three layers are mounted on both sides of the middle MDT chambers in the Barrel Middle Region (BM), while the third one is on the outer side of the MDT chambers in the Barrel Outer region (BO).

The RPC system provides the hardware muon trigger in the barrel. The low- p_T trigger, used for muon signature, requires the coincidence between the innermost two RPC doublets and can select muons with p_T thresholds between 4 and 10 GeV.

The high- p_T trigger, used in coincidence with other objects to select multi-object signature, requires an additional coincidence with the third layer and can select muons with p_T thresholds between 11 and 20 GeV.

The ATLAS RPCs were certified for 10 years of operation at the LHC luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$) with an efficiency of 96 % at a maximum counting rate of 100 Hz/cm². The actual rate capability of RPCs reaches several hundreds of Hz/cm², but the long-term sustainable rate is limited to 100 Hz/cm² due to ageing effects.

The intrinsic RPC time resolution for a 2 mm gas gap is 1 ns [13], but the time resolution of the ATLAS RPC system is 2 ns, obtained from a global fit that takes into account the analogue-to-digital coupling, time walk, and the TDC precision (3.125 ns/bin) [14]. The spatial resolution is limited by the strip pitch of 26–35 mm and the digital strip readout.

The RPC LVL1 Muon Trigger The LVL1 trigger [11] must uniquely identify the bunch-crossing of interest. The LHC bunch-crossing period of 25 ns is much shorter than the maximum drift time of the MDTs. Bunch-crossing identification is thus essential to reconstruct the muon trajectory correctly, and to correlate the muon trigger to triggers from other subdetectors.

The trigger scheme is therefore based on coincidences with a time resolution smaller than the bunch-crossing interval. At high luminosity, each bunch crossing contains an average of 23 proton-proton collisions, thus requiring a LVL1 trigger selectivity of $\sim 10^4$. The LVL1 trigger decision is based on combinations of objects required in coincidence or veto. The trigger schemes, shown in Figure 1.4, uses RPCs in the barrel covering $|\eta| \leq 1.05$, and TGCs in the end-caps covering $1.05 \leq |\eta| \leq 2.4$.

In the barrel region ($|\eta| \leq 1.05$) the LVL1 trigger is provided by Resistive Plate Chambers, exploiting the bending power of the large air-core superconducting toroidal magnet in the $|\eta|$ coordinate. The time measurement provided by the RPCs is primarily used to associate hits in the Monitored Drift Tube (MDT) chambers to the correct bunch crossing. Also the rejection of the cosmic muons is achievable with the time measurement, allowing the research for delayed signals from high-mass long-lived particles predicted in certain extensions of the Standard Model [18].

There are two types of muon trigger:

- The low- p_T trigger selects muons with p_T thresholds between 4 and 10 GeV, requiring a coincidence between the innermost two RPC doublets (Figure 1.4);
- The high- p_T trigger selects muons with thresholds between 11 and 20 GeV by requiring an additional coincidence with the third RPC layer (Figure 1.4)

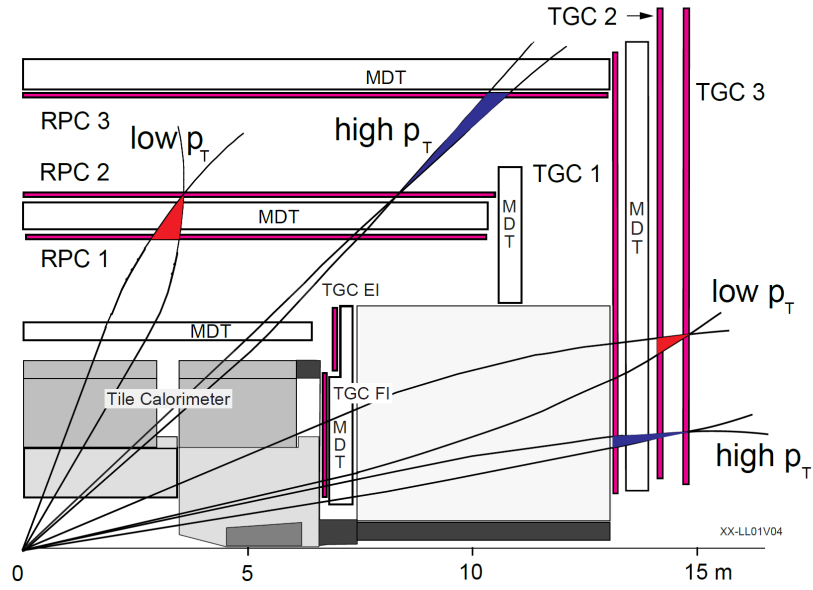


Figure 1.4: Muon trigger scheme of low- p_T and high- p_T muons in the barrel (RPC) and endcaps (TGC). The low- p_T trigger in the barrel is based on the coincidence between two BM RPCs, while the high- p_T trigger requires an additional coincidence with a BO RPC chamber.

The high- p_T triggers are used for muon signature while low p_T triggers are used in coincidence with other objects to select multi-object signatures, including muon pairs.

1.1.2 The ATLAS muon spectrometer at the High-Luminosity LHC

In sight of High-Luminosity LHC program, the ATLAS Muon Spectrometer [12] must be able to operate at instantaneous luminosity L of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and at a pile-up $\langle \mu \rangle = 200$.

The muon trigger should be able to trigger on single muons with high efficiency with a rate of less than 40 kHz for a p_T threshold greater than 20 GeV. On the other hand, lower p_T threshold ($> 4 \text{ GeV}$) should be viable for multi-muon and combined triggers. Moreover, the trigger and readout system should work a Level-0 trigger rates of 1 MHz and a latency of 10 μs .

The main goal is to maintain the performance in a very-high-pile-up scenario, in terms of muon trigger, identification and momentum resolution (reached in combination with the Inner Detector upgrade).

The Muon Spectrometer upgrade consists in the installation of new detectors, the improvement of the detector already installed and the replacement of the trigger and readout electronics in order to maintain the MS performance as in Run-2, keeping low trigger thresholds and trigger rates at a manageable level in a higher radiation environment. The scheme of the MS including the new chambers is shown in Figure 1.5.

New Small Wheels The Small Wheels have been replaced with the New Small Wheels (NSWs) during phase-I upgrade. The NSWs are composed by MicroMegas (MM) and small-strip TGC chambers (sTGC), which have replaced the Cathode Strip Chambers (CSC) and the MDT chambers of the innermost endcap wheels. These de-

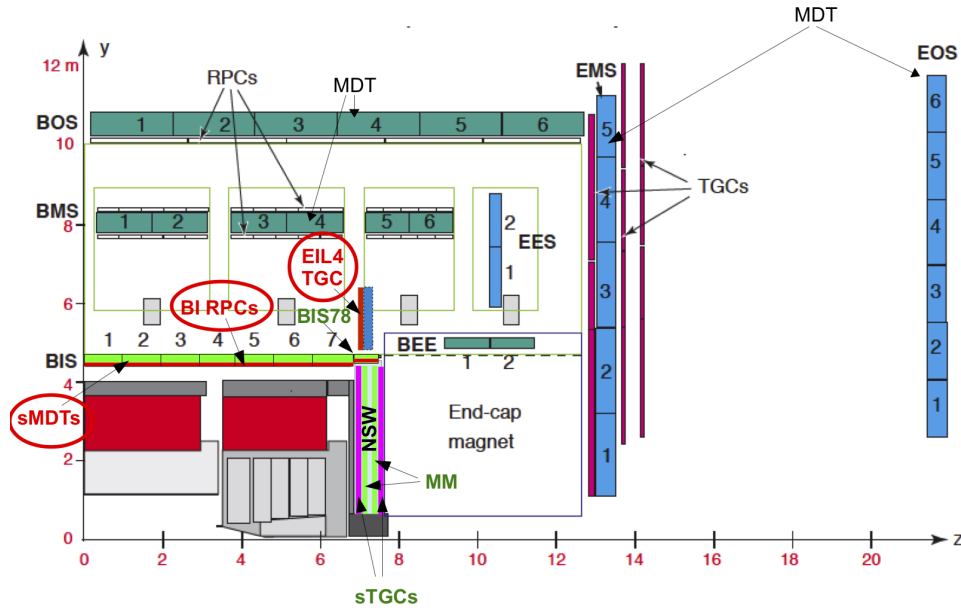


Figure 1.5: Scheme of the Muon Spectrometer including the new detectors

tectors can provide the muon Level-1 trigger system with online track segments of good angular resolution, in order to confirm that muon tracks originate from the IP. In this way the end-cap fake triggers will be considerably reduced.

Thin Gap Chambers The current EIL4 TGC doublet chambers will be replaced during phase-2 upgrade by TGC triplets with finer readout granularity in order to obtain a uniform level of purity for triggered muons over all the regions covered by the endcap trigger. In this way a more robust 2/3 majority logic and smaller coincidence windows can be used for confirmation of muons detected by the TGC trigger chambers, reducing considerably the rate of fake trigger in the acceptance of EIL4.

Monitored Drift Tubes and Resistive Plate Chambers In order to maintain a high trigger efficiency, triplets of new RPC chambers with increased rate capability will be installed on the inner (BI) MDT chambers of the barrel. Due to the reduced space available, in the small sectors MDT chambers will be replaced with sMDT chambers with reduced overall thickness, in order to be coupled in the same envelope, as the original MDT chambers, with the BI RPCs. The RPC upgrade has started during phase-1 (BIS78 project) and will be completed during phase-2 (BI project). The detailed description of this upgrade will be given in Section 1.1.4

Trigger and read out electronics The trigger system, as well as the data acquisition, will be redesigned to have a Level-0 trigger working at a rate of 1 MHz, to maintain similar trigger thresholds as in Run-2 but at higher luminosity. Most of the present components have hard limits on the maximum first-level trigger latency and rate

they can operate at, and therefore they have to be replaced. The trigger logic will be moved from on-detector custom ASICs to off-detector boards based on programmable FPGAs, allowing for more complex and flexible algorithms. MDT hits will be used in the first level trigger to refine candidates based on RPC, TGC and NSW data.

1.1.3 The RPCs at the Large Hadron Collider: limits of the present system

In the HL-LHC upgrade a luminosity increase up to $7.5 \times 10^{34} \text{cm}^2 \text{s}^{-1}$ is expected, as discussed at the beginning of this Chapter. The RPC muon trigger system should undergo an improvement in order to maintain a high detection efficiency for muons with $p_T > 20 \text{ GeV}$ while keeping the rate of fake triggers under control and to maintain low trigger thresholds to be sensitive to the search of Physics beyond the Standard Model.

One of the limitations of the RPC present system concerns the rate capability. The RPC counting rate capability, described in detail in Section 2.3, is limited by the voltage drop on the resistive electrodes, reducing the effective voltage across the gap and thus the efficiency. The ATLAS RPCs working conditions allow an average charge per converted photon of 30 pC. Under these conditions the rate capability of an ATLAS-type RPC is above 1 kHz/cm², but the need to maintain long-term stable detector conditions introduces constraints on the working rate.

The ATLAS-legacy RPCs, used during Run-1 and Run-2, are certified to operate up to an integrated charge of 0.3 C/cm², which corresponds to ten years LHC operation at counting rate of 100 Hz/cm². Irradiation test results and the experience from ATLAS operation show that the RPC chambers can be maintained in good working conditions, without an increase of the ohmic resistance of the resistive layers, thus without any performance deterioration, if they are operated below a maximum current density, corresponding to an integrated charge less than 30 mC/cm² per year. These working conditions are considered adequate for providing a stable performance over ten years of standard LHC operation at a maximum luminosity of $10^{34} \text{cm}^2 \text{s}^{-1}$ and an LHC duty cycle of about 33%.

The rates extrapolated from Run-1 data to HL-LHC for the middle layer chambers, shown in Figure 1.6, reach up to 340 Hz/cm² in chambers near $|\eta|=1$, therefore the integrated dose over 30 years will exceed the design specification by more than a factor of ten in some chambers.

In order to maintain the RPCs in good working condition, the current must be lowered below the stable operation limits. The reduction of the charge per count can be reached by lowering the operating voltage, resulting in a reduction of the single-hit efficiency of about 15% up to 35% in chambers at large η . This affects the trigger performance and makes necessary to loose the trigger requirements to compensate the loss in efficiency.

Moreover, the high- p_T trigger requires hits on the three layers of RPCs, limiting the acceptance to only about the 80% in the region that are covered by these layers ($|\eta| < 1.05$), mainly due to the barrel toroid coils and their support structures (see Figure 1.7).

In addition, the electronics on the Pad boards must be replaced because they have been designed for a maximum Level-1 readout latency of 6.4 μs and a maximum Level-1 trigger rate of 100 kHz, and they don't fulfill the Phase-II requirements of the trigger.

Moreover, the current gas mixture for RPCs, composed by $\text{C}_2\text{H}_2\text{F}_4$, C_4H_{10} and SF_6 has a high-environment impact and must be replaced. This is the main topic of this thesis and will be further discussed in Chapter 3.

Sector Φ _{id}	RPC unit Id. along Z direction																					Average
	-6.2	-6.1	-5.0	-4.0	-3.2	-3.1	-2.2	-2.1	-1.2	-1.1	1.1	1.2	2.1	2.2	3.1	3.2	4.0	5.0	6.1	6.2		
01.01	342	280	301	225	145	114	128	101		61	61	71	113	122	127	136	214	276	269	285	180	
01.02	293	281	303	218	159	133	129	143		76	71	75	127	143	140	148	215	295	278	297	188	
2	168	204	188	138	109	90	77	63	55	56	45	48	61	79	94	104	140	207	196	152	115	
03.01	297	296	281	198	148	128	119	119	68	67	65	71	131	125	114	125	207	329	268	290	177	
03.02	300	243	277	210	151	129	155	122	85	75	75	70	122	127	152	132	207	315	243	299	179	
4	112	166	158	151	101	83	65	77	41	53	46	41	73	68	92	108	160	196	175	112	101	
05.01	171	173	263	138	105	102	140	127	68	60	60	69	124	177	102	137	185	290	173	171	149	
05.02	227	198	237	158	109	105	136	143	77	61	63	71	111	136	108	141	200	267	255	282	159	
6	175	186	208	163	105	95	90	95	77	59	52	59	84	81	106	124	189	200	227	167	131	
07.01	305	263	288	191	154	129	131	114		76	78		122	139	124	148	185	261	268	305	183	
07.02	327	258	216	203	141	112	129	108		74	77		105	114	112	152	184	278	276	279	175	
8	146	196	195	161	103	85	80	70	50	57	54	54	67	74	85	108	168	196	194	156	118	
09.01	319	246	301	206	155	117	149	119		46	64		106	134	124	135	197	283	262	297	181	
09.02	347	258	287	205	143	95	107	103		58	67		99	112	95	137	188	285	265	292	174	
10	174	201	207	147	99	86	68	71	46	43	41	50	64	69	80	103	148	193	201	170	115	
11.01	308	244	237	157	97	84	81	87		40	43		83	94	92	94	148	227	215	278	132	
11.02	196	193	157	105	78	66	55	57		33	31		50	62	58	71	98	151	160	185	98	
12					80	81	66	51	36	36	51	75	87	80							64	
13.01	291	278	253		140	102	96	84	43	41	47	50	87	95	99	123		249	263	319	149	
13.02	299	264	262		104	97	105	86	49	48	50	56	93	103	97	110		252	227	294	146	
14					142	68	64	52	41	40	49	63	68	136							76	
15.01	196	221	148	113	76	71	67	49		38	36		50	59	86	87	104	156	173	196	104	
15.02	183	159	246	164	116	98	103	75		44	43		75	106	112	107	158	248	159	183	133	
16	173	214	216	173	108	89	54	75	56	59	50	50	77	54	87	103	177	209	208	154	124	
Average	229	223	234	167	118	101	96	88	56	52	51	56	86	97	103	118	171	240	221	221	137	

Figure 1.6: Average RPC hit rates in BM chambers extrapolated from Run-1 data to the HL-LHC luminosity of $7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, including the safety factor, the extension of the LHC running time to 30 years and a reduction of the NSW shielding that is expected to affect chambers in the vicinity of the $|\eta| = 1$.

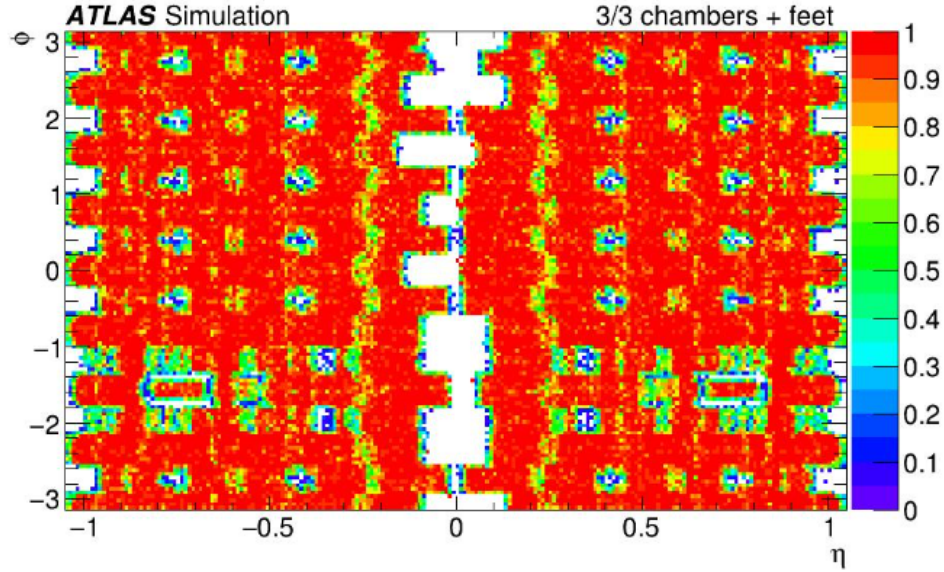


Figure 1.7: Geometrical acceptance in the $\eta - \phi$ plane of the Run-2 (2017) single-muon trigger in the barrel with respect to reconstructed combined muons. The current trigger is based on requiring hits in the three layers of RPC chambers (two in BM and one in BO) plus special two-chamber triggers added to cover approximately 3% of the acceptance in the feet regions (at $\phi = 1.1$ and $\phi = 2.0$). The acceptance limitations in the small sectors related to the toroid coils and their supports are visible at $|\eta| = 0.4, 0.75$, and 1.0 .

1.1.4 The BI project at the HL-LHC

In order to face the problems discussed in Section 1.1.3, an additional layer of new generation of high-performance RPCs operating at full efficiency will be installed during the phase-2 upgrade in the inner layer (BI) of the muon spectrometer, where currently

there are no RPCs. The overall RPC phase-2 upgrade program consists of the following three sub-projects:

- The installation of new generation of RPCs in the inner layer of the barrel providing a full trigger coverage (from 80% to 95%) to increase by 50% the number of measured track points and to measure the muon momentum based on a three-point sagitta measurement, improving the trigger momentum resolution and selectivity;
- The replacement of the trigger and readout electronics, to be compatible with the phase-2 ATLAS TDAQ scheme;
- The retrofitting with new front-end electronics of a limited and targeted set of RPCs in the Barrel Outer (BO) where the highest rate expected ($|\eta| = 1$).

Each BI RPC station is composed of three independent singlets of RPCs mounted all together in the same envelope in a triplet configuration, each equipped with an improved and very sensitive Front-End electronics. Each singlet is composed by a 1 mm gas gap with 1.3 mm thick electrodes. The signal is readout by two panels of parallel strips, both in the η direction.

The ϕ coordinate in this case will be measured with the difference in time between signals read-out on the parallel strips.

The layout of these detectors leads to several intrinsic advantages:

- The reduction of the gas gap width allows to work approximately at half of the currently high voltage and improves the time resolution from 1 ns to 0.4 ns, as discussed in Section 2.1;
- The thinner electrodes allow to reduce the total thickness and the total weight and to improve the signal to noise ratio, increasing the charge fraction transferred to the pick-up electrodes;
- The minimum threshold of the new Front End electronics, 0.3 mV corresponding to a detectable signal of 1-4 fC, provides a reduction of about a factor ten in the charge produced inside the gas gap, resulting in an increase of the rate capability of the same amount;
- The reduction of the gas gap, the thinner electrodes and the new Front End electronics allow to reduce the total charge per hit generated inside the gas for a given efficiency, resulting in an improvement of the rate capability and of the detector lifetime;

The installation of the BI chambers will improve the geometrical acceptance and the robustness of the barrel muon trigger, allowing to compensate the effects derived from the decrease of the high voltage of the present RPC, necessary to ensure their longevity. Indeed, the installation of the BI will improve the redundancy of the trigger, using nine measurement planes instead of six, provided by four layers of RPCs as shown in Figure 1.8 : one BI triplet (RPC0), two BM doublets (RPC1 and RPC2) and one BO doublet (RPC3).

The current high- p_T trigger is based on the 3/3 chambers logic, shown in Figure 1.8, which requires hits in at least two-out-of-four planes of the RPC1 and RPC2 chambers and at least in one-out-of-two planes of RPC3. To take advantage from the improved redundancy of the trigger, new trigger logic schemes, in addition to the 3/3 logic, have

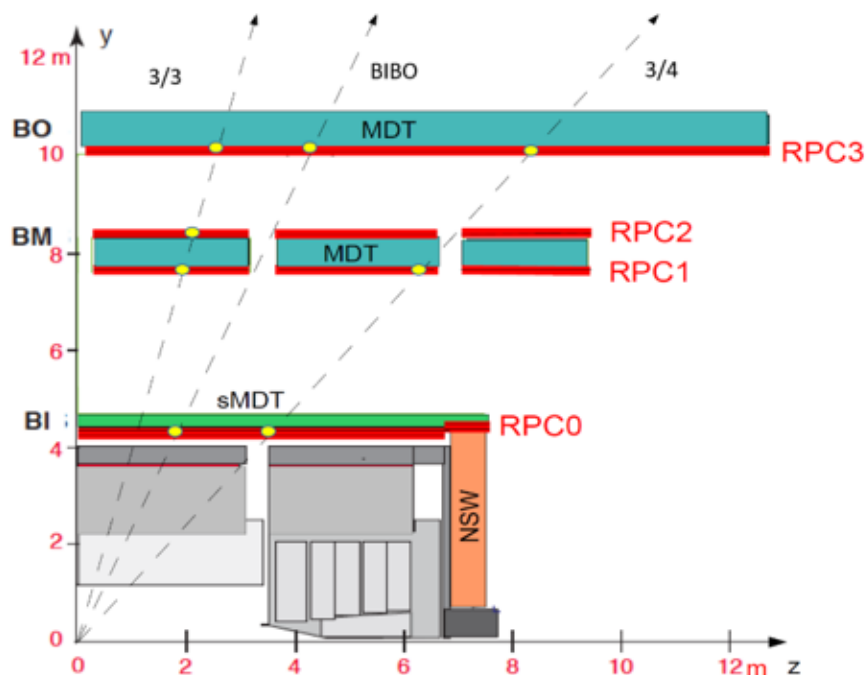


Figure 1.8: Scheme of the four layers of RPCs in a small sector. The different trigger logic are also shown.

been developed and are shown in Figure 1.8.

The first one is the 3/4 majority which consists in the 3/3 logic in a logical OR with the requirement of hits in at least 2/3 planes in RPC0 and in at least 3/6 in RPC1+RPC2+RPC3. In this way all combinations of three chambers coincidence are accepted.

The second one is the 3/4 majority + BI-BO and consists in the 3/4 majority in a logical OR with the requirements of at least two hits in BI RPCs and at least one hit in BO RPCs.

The development of these new trigger logics will balance the effect of the efficiency reduction of the old chambers, as can be seen in Figure 1.9 (b), which shows that the installation of the BI allows to work at trigger efficiency times acceptance more than 90% even in the worst case scenario, with the old RPCs at the lowest voltage. In addition, the geometrical acceptance is improved and most of the holes mainly due to the feet and rails of the calorimeter and the toroidal magnets supports are covered, as can be seen in Figure 1.9 (a).

The trigger efficiency times acceptance as a function of the muon p_T , for $p_T > 10$ GeV and $p_T > 20$ GeV rises of 10% including BI, as shown in Figure 1.10, resulting in an improvement of the trigger selectivity.

The installation of the BI will give also further benefits. The transverse momentum of the muons which cross all the three stations can be calculated using a 3-point sagitta measurement, resulting in an improvement of the momentum selectivity.

In addition, there will be the possibility to measure the Φ coordinate in the Inner Barrel region, which is not available from MDT chambers, gaining in terms of pattern recognition and track finding in a high-background conditions.

Moreover, thanks to the better time resolution, it will be possible to perform time-of-flight measurements. This is very useful for instance in the search of long lived particles, giving the possibility to measure their velocity β and to distinguish a New Physics signal

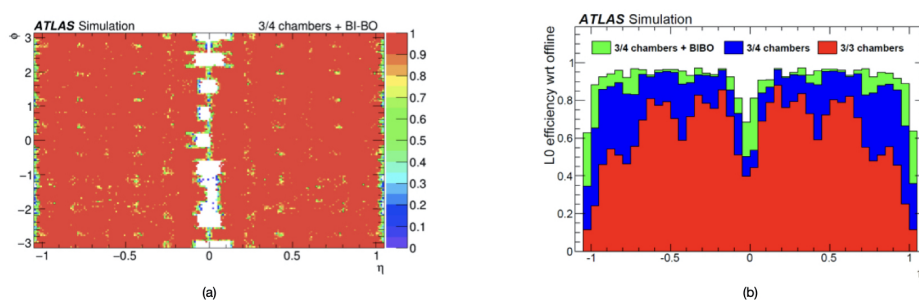


Figure 1.9: (a) Geometrical acceptance of the L0 barrel trigger with respect to the reconstructed muons with $p_T=25$ GeV in the η - Φ plane for the 3/4 chambers + BI-BO trigger scheme. (b) Efficiency times acceptance of the Level-0 barrel trigger with respect to the reconstructed muons with $p_T=20$ GeV as a function of η assuming the worst case scenario, which represents the limit in which the old RPCs operate at very low voltage.

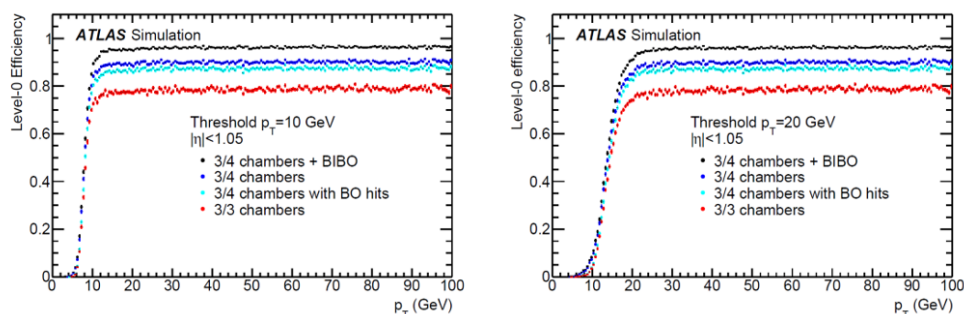


Figure 1.10: Trigger efficiency times acceptance as a function of the p_T for a threshold of 10 GeV (left) and 20 GeV (right).

from the Standard Model one.

The BIS78 project of RPC phase-1 upgrade

During phase-1 upgrade a new generation of RPCs coupled with small-MDTs have been installed in the sectors 7 and 8 of the Barrel Inner region (BIS78) of the MS, where the highest rate of fake triggers is expected ($1.0 < |\eta| < 1.3$).

The BIS78 project [15] is considered the pilot project for the phase-2 BI upgrade, since the BIS78 chambers are designed to be compatible with HL-LHC conditions and the BI RPCs will inherit most of their design.

The estimated total rate of the Level-1 single-muon trigger with $p_T > 20$ GeV is expected to rise during Run-3 up to 57.6 kHz, while the allocable rate is 25 kHz for muon triggers out of a total bandwidth of 100 kHz.

In Figure 1.11 the abundance of ROIs in the $|\eta| > 1$ region with respect to the flat distribution of the constructed muons are reported: most of ROIs are background mainly due to low- p_T protons generated in toroids and in the shielding of the MS.

In order to address this problem the pseudorapidity region $1.3 < |\eta| < 2.5$ will be covered by the New Small Wheels that will solve the problems of fake triggers mainly coming from secondary charged particles generated inside the cryostats and will improve the muon selectivity and the discrimination of low- p_T muons.

The EIL4 TGCs informations combined with the Tile-Calorimeter allow both fake rejection and detector granularity in about 50% of the transition region.

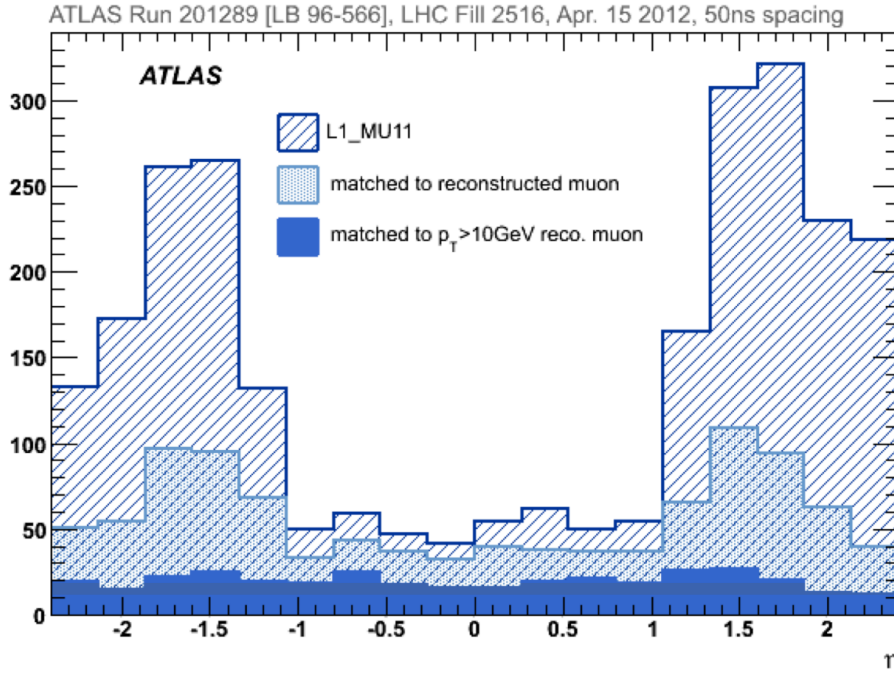


Figure 1.11: η distribution of Level-1 muon ROIs with $p_T > 10$ GeV with the distribution of the subset matched to an offline reconstructed muon with $p_T > 3$ GeV or $p_T > 10$ GeV

The BIS78 RPCs cover the region at $1.0 < |\eta| < 1.3$, which corresponds to the barrel-endcap transition region, completing the coverage provided by the New Small Wheels, thus leading to a total coverage of the trigger of $\sim 83.5\%$ of the transition region as shown in Figure 1.12.

The background rejection and the drastic reduction of the number of fake events in the transition region is reported in Figure 1.13.

Defining:

- The efficiency as the ratio between the reconstructed muons triggered by the End-Cap associated with segments in the chambers and all reconstructed muons triggered by End-Cap,
- The rate fraction as the ratio between the ROIs in the End Cap associated with segments in the chambers and all the ROIs in the End-cap,
- The background fraction as the ratio between the ROIs in the End Cap associated with segments in the chambers but not to any reconstructed muons and all the ROIs in the End Cap,

it is possible to evaluate them for different cases and different requests.

These three quantities are reported in Table 1.1, requiring the association between ROIs and segments of the BIS+EI chambers for all the ROIs in the transition region, with the association between ROIs and segments of the EI chambers only in EI acceptance and making no requests on other ROIs, and requiring the association between ROIs and segments of the BIS+EI chambers only in their acceptance and making no request on other ROIs.

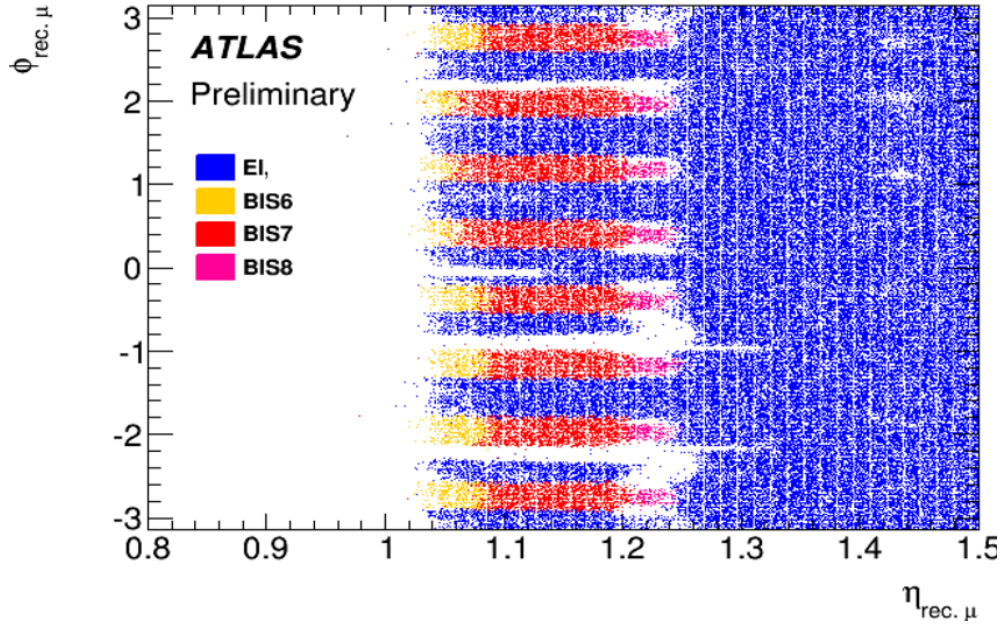


Figure 1.12: $\eta - \phi$ distribution of reconstructed muons with $p_T > 20$ GeV associated with the segments in the inner End Cap chambers (EI) and in the BIS chambers.

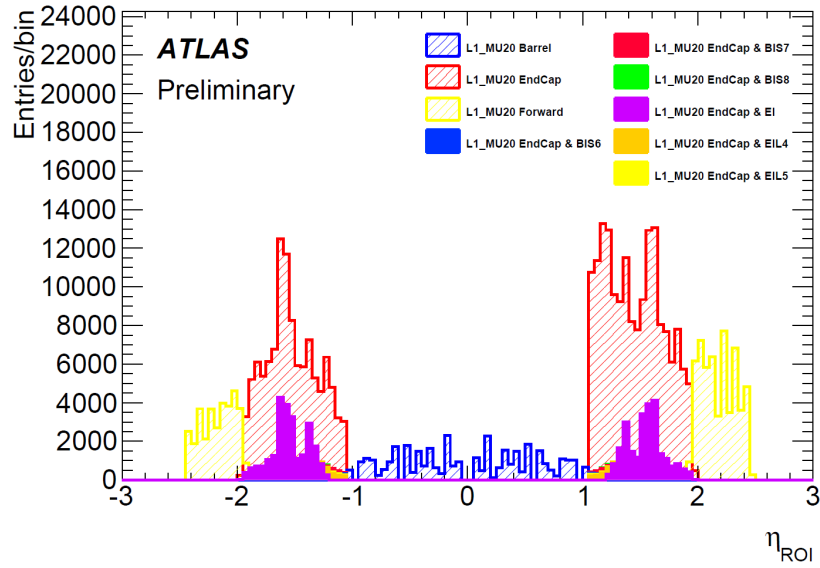


Figure 1.13: η distribution of ROIs with $p_T > 20$ GeV. The hatched distribution is obtained with the current End Cap trigger, while the fully colored one is obtained requiring the passage through the EI or the BIS chambers.

	BIS+EI everywhere	EI EI acceptance	BIS+EI BIS+EI acceptance
Efficiency	80.1%	99.8%	98.9%
Rate Fraction	6.8%	54.5%	35.2%
Background Fraction	5.5%	53.5%	34.1%

Table 1.1: Efficiency, Rate Fraction and Background Fraction calculated with three different requests

The combination of Tile, BIS and EIL chambers could lead to an high detection efficiency $\sim 97\%$, higher robustness against pile-up effects and will reduce the total trigger rate from 57 kHz to 10 kHz.

A single BIS78 station consists of two triplets of RPCs, which is the minimal requirement for an efficient stand-alone trigger coincidence in both the η and ϕ coordinates, coupled to a multi-layer of s-MDTs in the same envelope, without making any contact between the two systems, preserving their electrical and mechanical integrity.

The BIS78 RPC system consists of 16 BIS7 and 16 BIS8 triplets, covering a total area of 94 m². The available space for the installation of the BIS78 in the inner barrel layer is very limited, keeping many constraint on the detectors dimensions, making the reduction of the thickness of all the RPC detector components necessary.

The new RPCs have a gas gap width of 1 mm. This choice allows to reduce the total thickness of the system and leads to other benefits: since the RPC time resolution scales with the gas gap width (see Section 2.1), this reduction leads to an improvement of the time resolution up to ~ 0.4 ns [16].

The electrodes thickness also has been reduced to 1.3 mm. This reduction takes the advantage of increasing the charge fraction transferred to the pick-up electrodes, resulting in an improvement of the Signal-to-Noise ratio. The graphite resistivity is 500 k Ω /□, allowing the operation with very low-threshold, as discussed in Section 2.1.

Each detector is readout on both sides by two panels of orthogonal strips, with strip pitches of 24-26 mm depending on the chamber type, providing both η and ϕ coordinates.

The challenge of making the chambers compatible with operation at higher hit rates is addressed by a proportional reduction of charge per count, while simultaneously increasing the sensitivity and signal-to-noise ratio of the Front-End electronics without degrading the fast timing features of the RPCs.

In order to improve the rate capability a new Front End electronics [17] has also been developed together with new Faraday cage design, suitable for low-threshold operation to shield the more sensitive Front-End electronics.

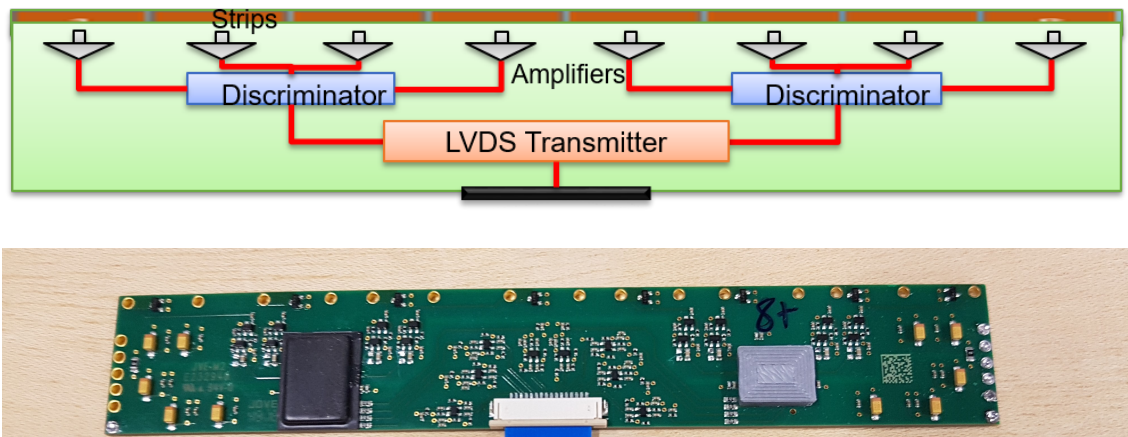


Figure 1.14: Front-End electronics

This new electronics, shown in Figure 1.14, is radiation hard, has low power consumption, improved discriminator performance and allow to improve the time-of-flight capability. A low-noise charge amplifier allows lower charge produced by the avalanches

and consequently to work at lower current at the same hit rate, resulting in a slower detector ageing. The main features of the amplifier are listed in Table 1.2.

Parameter	Value
Voltage Supply	3-5 V
Sensitivity	2-4 mV/fC
Noise(up to 10 pF input capacitance)	1700 e^- r.m.s
Input Impedance	50-100 Ω
Bandwidth	10-100 MHz
Power Consumption	10 mW/ch
Rise Time $\delta(t)$ input	300-600 ps
Radiation Hardness	10 kGy, 10^{13} n/cm ²
Gain	0.2-0.4 mV/fC

Table 1.2: Main features of the new fast charge amplifier implemented in Si BJT technology

The Front-End boards have eight channels, eight of the new discrete-components amplifiers based on Si BJT and eight discriminators in two ASIC chips based on SiGe Technology. The main parameter of the discriminator are listed in Table 1.3.

Parameter	Value
Voltage Supply	2-3 V
Threshold	3-200 mV
Input Impedance	100 Ω
Bandwidth	500 MHz
Power Consumption	10 mW/ch
Rise Time $\delta(t)$ output	300 ps
Radiation Hardness	10 kGy, 10^{13} n/cm ²
Gain	0.2-0.4 mV/fC
Minimum duration input pulse	0.5 ns
Double-pulse separation	1 ns
Channels per chip	4

Table 1.3: Main features of the new discriminator ASIC implemented in SiGe BiCMOS technology.

A pull up resistance is used to ensure a known state for a signal produced by an external devices at high impedance.

The advantage in using an LVDS transmitter is the reduction of the electromagnetic noise and a lower sensitivity to the electromagnetic interferences.

In fact an LVDS transmitter works with the difference between two tensions, which does not change when the same value is summed at both terminals.

The minimum threshold of 0.3 mV and the detectable signal of 1-2 fC provide a reduction of a factor ten in the charge produced inside the gas gap, resulting in an increase of the rate capability up to 10 kHz/cm².

Table 1.4 summarizes the difference between BIS78 RPC and ATLAS legacy RPC.

Detector parameters	Legacy-RPC	BIS78 RPC
Gap Width	2 mm	1 mm
Electrode Thickness	1.8 mm	1.2 mm
Time Resolution	1 ns	0.4 ns
Space Resolution	6 mm	1 mm
FE Amplifier	GaAs	BJT Si
FE Discriminator	GaAs	HJT SiGe
FE effective threshold	2-3 mV	0.2-0.3 mV
Power Consumption	30 mW/ch	10 mW/ch
Readout	2D orthogonal	2D orthogonal

Table 1.4: Comparison between the detector parameters of the ATLAS standard RPCs and the BIS78

1.1.5 ATLAS Physics goals in High-Luminosity LHC

The discovery of the Higgs boson has marked the start of a new era of physics discovery at LHC and opens a new chapter in the study of the electroweak symmetry-breaking mechanism. The increase of luminosity provided with HL-LHC will allow to study in details the Higgs physics thanks to the higher statistics that will be collected from the physics channels that are less likely in the present condition.

The relevant Branching Ratios for a Standard Model Higgs are listed in Table 1.5.

$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	WW^*	ZZ^*
56.9	6.2	0.02	2.9	8.5	0.2	0.16	22.3	2.8

Table 1.5: SM branching ratios, in %, for various Higgs decay channels and at $m_H = 125.5$ GeV

One of the primary goals of the future LHC programme is therefore to greatly extend the range and precision of Higgs studies, improving the accuracy of the measurements, searching for yet unobserved decay modes, and probing in more detail the mechanism of electroweak symmetry breaking, with a precision in the range of a few percent.

Thanks to the HL-LHC it will be possible to be more sensitive to particles expected from Supersymmetry Models, being able to study not only particles with higher mass but also final states that are harder to distinguish from the Standard Model background. A Higgs mechanism is defined by the spectrum of the Higgs states, and by the dynamics that leads the Higgs field to acquire a non-zero vacuum expectation value, resulting in the Electroweak symmetry breaking (EWSB).

In the SM version of the Higgs mechanism, there is a single complex SU(2) doublet, corresponding to four real degrees of freedom and the symmetry breaking is driven by the minimization of the mexican-hat-shaped potential. Alternatives to the SM Higgs mechanism include theories with a more extended spectrum and/or with a different EWSB dynamic.

For example, several theories have two doublets instead of one, where one doublet is used to give mass to the up-type quarks, while the other doublet to the down-type quarks and to the charged leptons.

In these models, there is a total of five Higgs particles (the 2×4 states of 2 complex $SU(2)$ doublets, minus the 3 states absorbed by $W^\pm$ and Z^0), three of them neutral (typically labeled h^0 , H^0 , A^0), the other two being the opposite-charge states of a charged $H^\pm$ Higgs.

Other SM extensions include the possibility of further doublets, or of different $SU(2)$ representations, including singlets, or vectors or doubly charged Higgs fields.

In other scenarios, EWSB may arise from an underlying strong dynamics, the Higgs field emerging as a composite particle, a bound state of elementary fermions confined together.

In some theories with extra-space dimensions, the Higgs scalar could be a component of vector fields living in higher dimensions.

In the SM, the production and decay properties of the Higgs boson are completely determined by its mass and by the masses of the SM particles.

In BSM theories those properties can change, whether because of a richer Higgs spectrum, or of a different EWSB dynamics, or because the other new BSM particles can influence the Higgs couplings: additional decay channels can be opened, or new intermediate virtual states can modify the loop-mediated Higgs effective couplings, such as those to gluons and photons.

While the available experimental information is sufficient to claim with complete confidence that the discovered particle is a Higgs boson, the quantitative determination of its consistency with the SM predictions is limited by the statistical and systematics accuracy of the measurements.

The Higgs has been searched, and detected, in a combination of different production and decay modes.

The production and decay cross sections are shown in Figure 1.15.

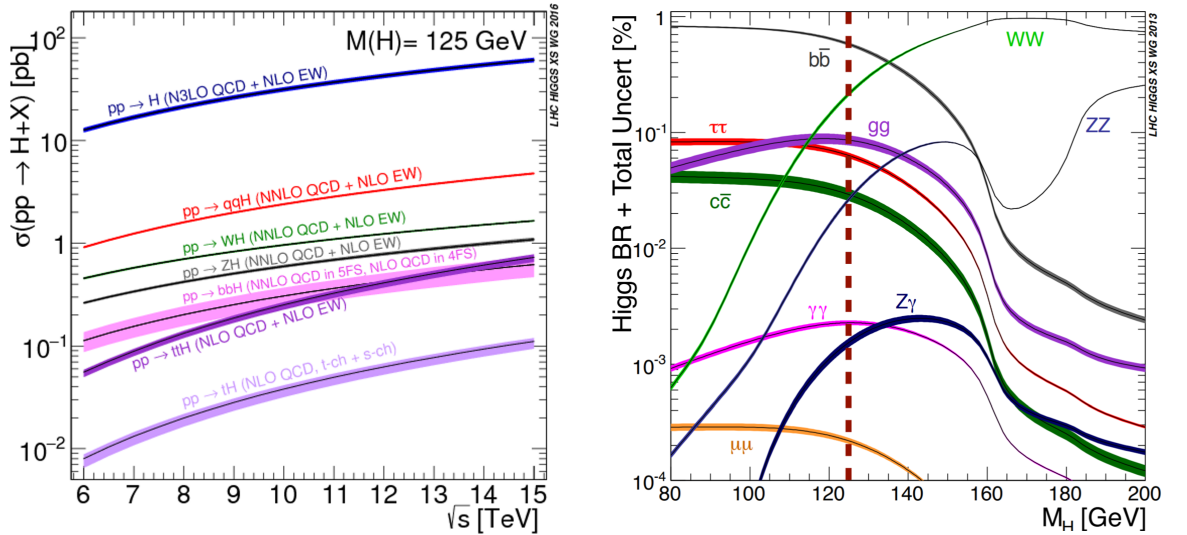


Figure 1.15: Cross section for Higgs production modes (Left) and BR for Higgs decay modes (Right)

For both ATLAS and CMS, the measurement of production rates times branching ratios, averaged over all channels, agrees with the SM expectations to within 15–20%,

consistent with the current statistical and systematic uncertainty.

All the individual channels are also consistent with the SM prediction, with varying degrees of significance.

Higgs decays to the $\mu^+\mu^-$ and $Z\gamma$ final states have been searched, but no signal was found, as expected from the very small branching ratios predicted by the SM.

Likewise, there are no signals of decays that are forbidden in the SM, such as $H \rightarrow \mu^\pm e^\mp$, or indications of BSM Higgs-like states, over a mass range extending up to several hundreds GeV.

The goal of the HL-LHC is therefore to extend the measurements of the Higgs properties, and to reach a precision in the range of few percent, in order to match the sensitivity to direct manifestations of New Physics appearing at the TeV scale. The luminosity of the HL-LHC will provide substantially improved statistical precision for already established channels and allow rare Higgs boson production and decay modes to be studied.

From the combination of the observed rates in all channels, detailed measurements of the Higgs boson coupling strength can then be extracted.

We can cite two of the decay channels that can be studied in the new conditions to underline the potential of HL-LHC machine:

- WH/ZH, $H \rightarrow \gamma\gamma$ and $t\bar{t}H, H \rightarrow \gamma\gamma$: these channels have a low signal rate at the LHC, but one can expect to observe more than 100 signal events with the HL-LHC. The $t\bar{t}$ initial state gives the cleanest signal with a signal-to-background ratio of $\approx 20\%$, to be compared to $\approx 10\%$ for ZH and $\approx 2\%$ for WH.

The $t\bar{t}$ initial state is of special interest, as it yields a precise measurement of the square of the top-Yukawa coupling, which is otherwise not directly accessible.

Figure 1.16 shows the expected signal in the $t\bar{t}$ 1-lepton final state and Figure 1.18 the expected measurement precision.

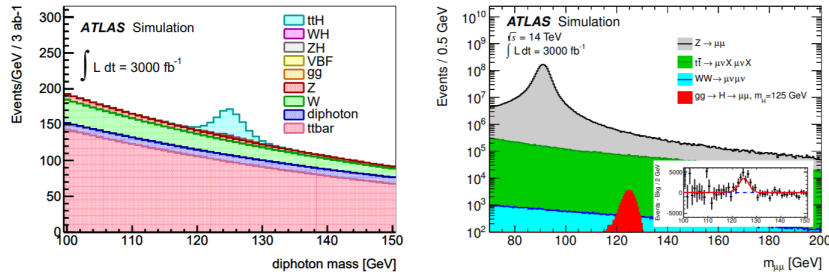


Figure 1.16: Expected $\gamma\gamma$ invariant mass distribution for the $t\bar{t}H, H \rightarrow \gamma\gamma$ channel in 1-lepton selection for an assumed integrated luminosity of 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ (left). Expected invariant mass distribution for the inclusive $H \rightarrow \mu\mu$ for an integrated luminosity of 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$. The inset shows the expectation for the $H \rightarrow \mu\mu$ signal after the subtraction of the fitted background

- $H \rightarrow \mu\mu$ [20]: this channel has also a low signal rate at the LHC with a signal-to-background ratio of only $\approx 0.2\%$.

However, the expected narrow signal peak allows a signal extraction at very high luminosities, resulting in an expected signal significance larger than 6σ with 3000 fb^{-1} for the inclusive channel.

The analysis in Figure 1.16 (right) shows the expected signal compared to the large continuous background. Also the exclusive $t\bar{t}H, H \rightarrow \mu\mu$ channel was studied.

While the expected signal rate is only ≈ 30 events at 3000 fb^{-1} , a signal-to-

background ratio of better than unity can be achieved and hence this channel gives information on both the top and μ -Yukawa couplings with a precision on the total signal strength of $\approx 25\%$.

In Figure 1.17 there are the invariant mass distributions of the signal+background corresponding to 139 and 3000 fb^{-1} .

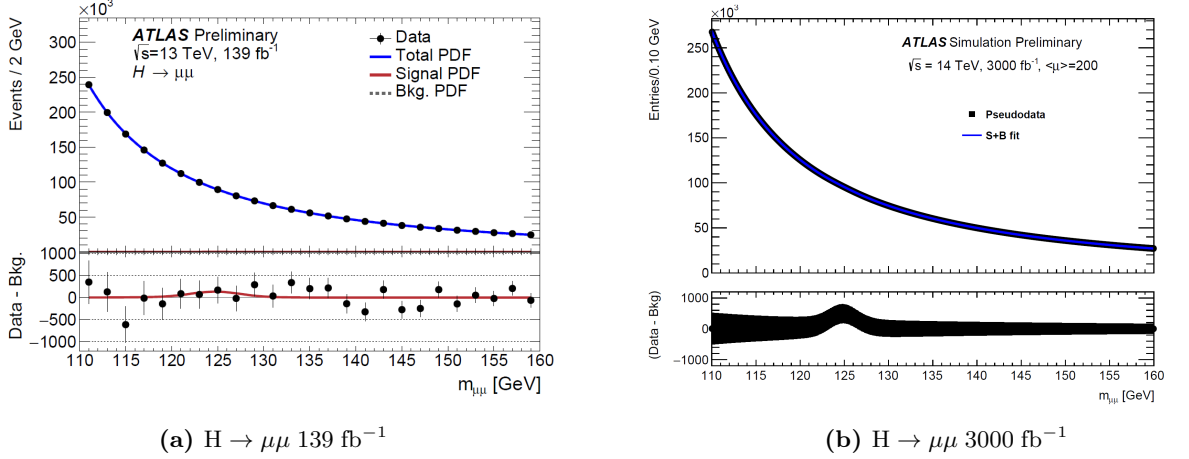


Figure 1.17: Di-muon invariant mass spectrum in all the analysis categories observed in data corresponding to 139 fb^{-1} (a) and 3000 fb^{-1} (b)

An overview of the expected measurement precision in each channel for the signal strength μ with respect to the Standard Model Higgs boson expectation for a mass of 125 GeV is given in Figure 1.18 for assumed integrated luminosities of 3000 and 300 fb^{-1} .

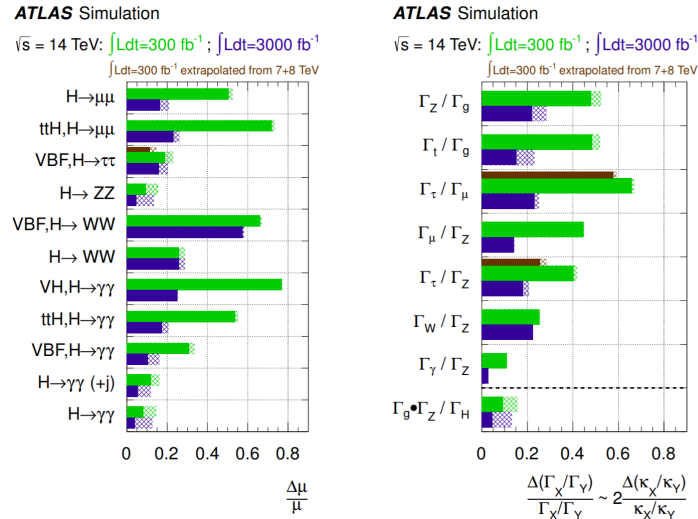


Figure 1.18: Expected precision measurements on the signal strength (left) and on ratios of Higgs boson partial widths

In order to establish the Higgs mechanism as being responsible for electroweak symmetry breaking, the measurement of the Higgs self-couplings [21]-[22] and subsequent

reconstruction of the Higgs potential are crucial.

A direct analysis of the Higgs boson trilinear self-coupling λ_{HHH} can be done via the detection of Higgs boson pair production.

At hadron colliders, the dominant production mechanism is gluon-gluon fusion and selecting the decay channel $HH \rightarrow b\bar{b}W^+W^-$ for its clean signature and high branching ratio, a precision of 30% can be achieved at HL-LHC.

In Figure 1.19 is shown the expected 95 % CL upper limit on the cross section $\sigma(HH \rightarrow b\bar{b}\gamma\gamma)$ in HL-LHC as a function of the Higgs self-coupling constant.

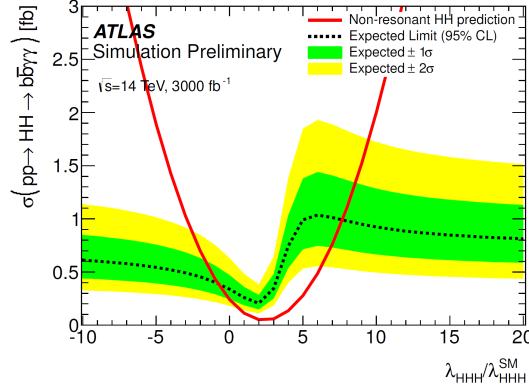


Figure 1.19: Expected 95% CL upper limit on the cross-section $\sigma(HH \rightarrow b\bar{b}\gamma\gamma)$ with 3000 fb^{-1} of data and neglecting systematic uncertainties, as a function of the Higgs self-coupling constant λ in units of λ_{SM} . The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands are shown in green and yellow. The cross-section exclusion limit grows less stringent in the range $3 < \lambda/\lambda_{\text{SM}} < 5$ due to the shift of the number of expected HH events towards lower values where the cross section is smaller.

Along with the Higgs sector, the discovery (or exclusion) of weak scale SuperSymmetry (SUSY) remains among the highest priorities for the LHC experiments.

SUSY removes the quadratic divergences that accompany a fundamental scalar Higgs boson, by introducing supersymmetric partners to all SM particles.

In the framework of generic R-parity conserving supersymmetric extensions of the SM, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable.

The LSP can provide the massive thermal relic required to explain the cosmological dark matter. The lightest neutralino is often assumed as LSP, where neutralinos ($\tilde{\chi}_j^0, j = 1, 2, 3, 4$) and charginos ($\tilde{\chi}_i^\pm, i = 1, 2$) are the mass eigenstates originating from the mixture of the SUSY partners of Higgs and electroweak gauge bosons (higgsinos and gauginos).

The scalar partners of right-handed and left-handed fermions can mix to form two mass eigenstates.

The sensitivity to heavy SUSY particles will be increased significantly when the full LHC energy of $\sqrt{s} = 14\text{TeV}$. An example that can be done is the *Direct stop pair production*.

Naturalness arguments suggest that the light top squark mass eigenstate to be below 1-1.5 TeV. At $\sqrt{s} = 14\text{ TeV}$ the direct stop pair production cross section for 600 GeV (1 TeV) stops is 240 (10) fb.

The HL-LHC integrated luminosity will increase the sensitivity to stop or, if stop candidates are found, will allow their properties to be measured.

In Figure 1.20-1.21 is shown the discovery and exclusion potential as a function of the $\tilde{t}$ and $\tilde{\chi}_1^0$ masses in two different decay mode for 300, 3000 and 20 fb^{-1} .

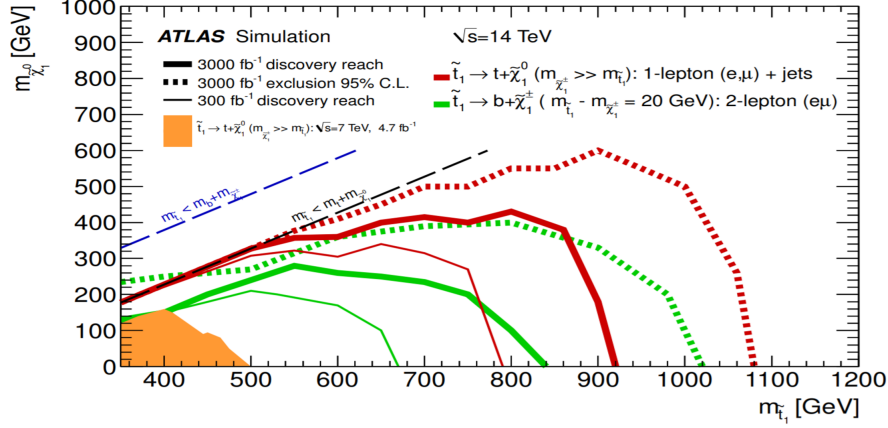


Figure 1.20: The 95% CL exclusion limits for 3000 fb^{-1} (dashed) and 5 σ discovery reach (solid) for 300 and 3000 fb^{-1} in the $\tilde{t}, \tilde{\chi}_1^0$ mass plane assuming the $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ (red) or the $\tilde{t} \rightarrow b + \tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W + \tilde{\chi}_1^0$ (green) decay mode

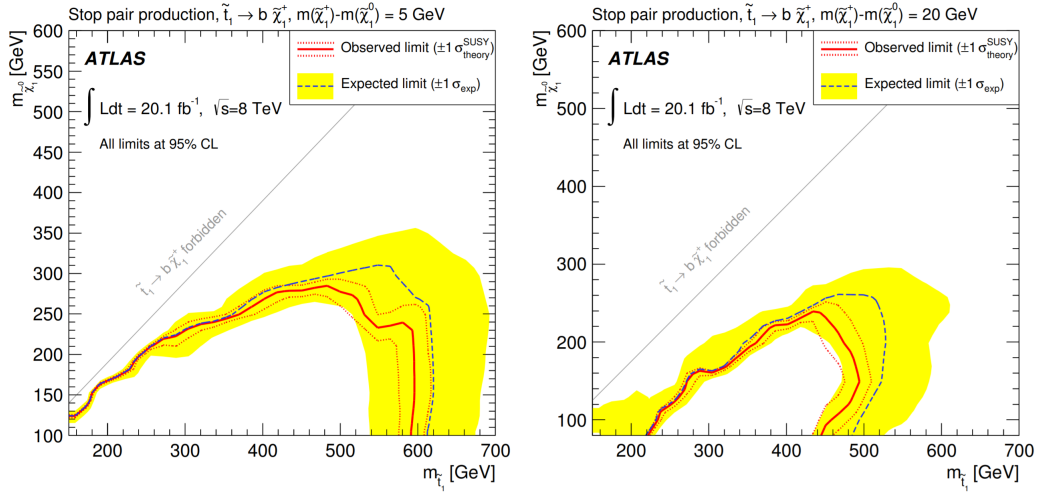


Figure 1.21: The 95% CL exclusion limits for the different stop pair production scenarios. Left: $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane with $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 5$ GeV. Right: $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane with $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 20$ GeV. The dashed (solid) lines show the expected (observed) limits, including all uncertainties except for the theoretical signal cross-section uncertainty (PDF and scale). The bands around the expected limits show the $\pm 1\sigma$ uncertainties. The dotted lines around the observed limits represent the results obtained when moving the nominal signal cross section up or down by the $\pm 1\sigma$ theoretical uncertainty. The excluded regions are below the curves. The lower bound of the vertical axis corresponds to the LEP limit of the lightest chargino mass: 103.5 GeV.

The High Luminosity upgrade will give also the possibility to be sensitive to the discovery of Long Lived Particles which are predicted from some extension of the Standard Model.

Both in the Standard Model and in New Physics Models, particles can acquire discernible lifetimes from a variety of mechanisms, including weak effective couplings to the final state due to heavy intermediate particles, which can arise in models with mass hierarchies, or due to small coupling constants, which can arise from conserved or nearly-conserved symmetries.

Long lifetimes can also manifest due to decays that are phase-space suppressed or from new particles which interact only weakly with the SM particles via mediators.

If a new long-lived particle decays within the detector but at an observable distance from the proton-proton interaction point, and if its decay products include multiple charged particles reconstructed as tracks, it can produce a distinctive signature of an event containing at least one displaced vertex (DV).

The replacement of the existing tracking detector with a full-silicon inner tracker (ITk) significantly changes the search sensitivity, which is estimated using extrapolations of the reconstruction capabilities for displaced tracks and displaced vertices from a combination of the performance of the current detector and a simulation of the upgraded detector. As an example the gluino R-hadron production in the ATLAS Experiment can be considered. For long-lived gluinos which decay to SM quarks and a 100 GeV stable neutralino, ATLAS should have the sensitivity to discover R-hadrons with lifetimes from 0.1 to 10 ns with masses up to 2.8 TeV.

In the absence of long-lived gluino production, the 95% CL upper limit on gluino masses will reach 3.4 TeV.

In Figure 1.22-1.23 are shown the simulation results for this research.

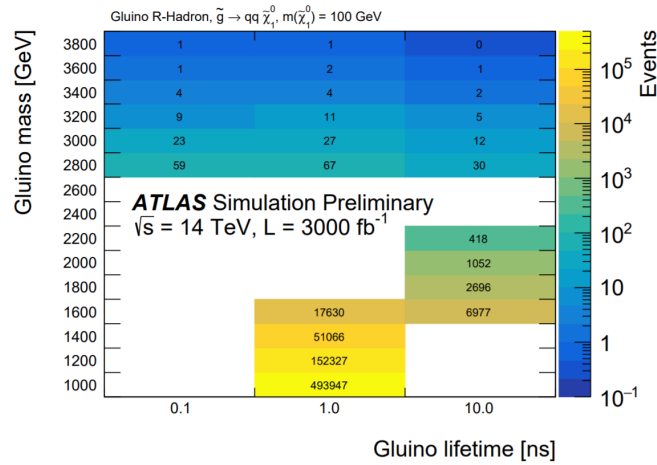


Figure 1.22: The number of expected R-hadron events selected for 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ as a function of the gluino lifetime and gluino mass for gluinos which decay to SM quarks and a neutralino with a mass of 100 GeV

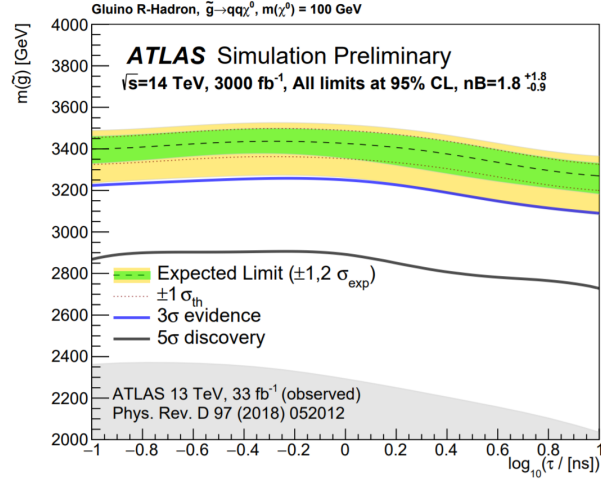


Figure 1.23: The projected sensitivity for the upper limit on the mass of a gluino R-hadron that can be observed with 3σ and 5σ confidence or excluded at 95 % CL, as a function of the gluino lifetime, for a background of $1.8^{+1.8}_{-0.9}$ events. This result is valid for a gluino which decays to SM quarks and a stable neutralino with a mass of 100 GeV. Results assume 3000 fb^{-1} of collisions at $\sqrt{s} = 14 \text{ TeV}$ collected with the upgraded ATLAS detector, and are compared to the observed ATLAS exclusion limits for a dataset of 33 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$

Chapter 2

The Resistive Plate Chambers

The Resistive Plate Chambers [23]-[24] are gaseous detectors characterized by the uniform electric field generated by two parallel electrode plates of high bulk resistivity. They can reveal charged particles using the so called standard gas mixture ($\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$) as active target for the ionization. The applied field is strong enough to produce the avalanche multiplication process as soon as the free electron is produced by the gas ionization. This feature leads to the absence of any drift time, making the RPC detector suitable for timing measurements and for triggering. In the ATLAS experiment they are used for triggering on muons, due to their excellent timing performance and low-cost materials.

2.1 Description

The Resistive Plate Chamber (RPC) detector, shown in Figure 2.1, is a planar detector composed of a gap in the millimeter range size filled with a proper gas mixture, which defines the detector active area and works simultaneously as target for the ionizing particle and as signal amplifier.

The gas mixture used in RPC which works in avalanche mode is the so called "standard gas mixture", composed of $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$. The properties of this gas will be further described in Section 3.1.

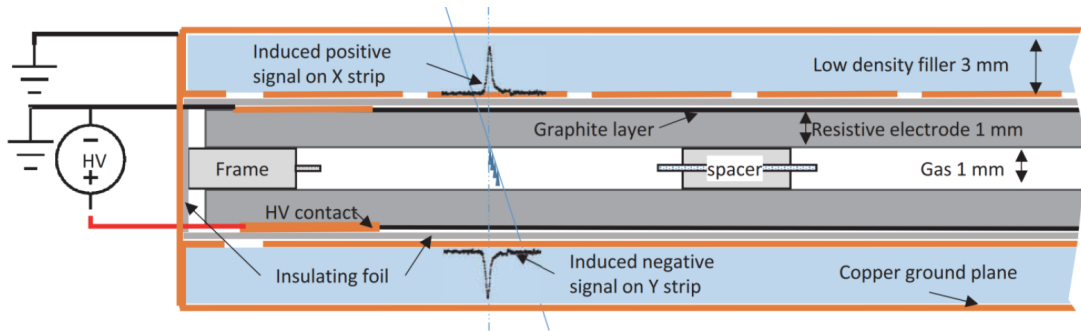


Figure 2.1: Scheme of the Resistive Plate Chamber (RPC) detector.

The gas is confined between two parallel resistive electrodes made of phenolic plastic material at high resistivity ($\rho \sim 10^{10} \div 10^{12} \Omega\text{cm}$). Thanks to the resistive material, the discharge due to the passage of charged particles involves only a limited region around the incidence point with a dead time τ of the order of ms, keeping active the remaining area of the detector.

The electrode are taken at fixed distance by polycarbonate spacers, guaranteeing the gas gap thickness uniformity in the whole detector area. The choice of the shape, dimension, number and location of the spacers is very important because they constitute blind areas, being a source of geometrical inefficiency.

The outer surfaces of the electrodes are painted with a layer of graphite, with surface resistivity which allows at the same time the production of a uniform electric field and the inductive pick-up of the charge created within the gas. The graphite resistivity can vary from 100 to 1000 $\text{k}\Omega/\square$, depending on the application. The graphite resistivity is one of the components defining the coupling between strips and the diffusion of the induced signal: a too low value of the resistivity results in a huge increase in the cross-talk between strips, leading to bigger cluster sizes on the readout panels, when a very low threshold is used. Therefore, a higher graphite resistivity is preferred when very low-thresholds are used.

The inner surface of the electrodes is covered by a thin layer of linseed oil in order to avoid inhomogeneity in the electric field which leads to sparks and increases the detector noise.

The read-out and the transmission of the signal is made by one or more panels of conductive strips that are separated from the graphite by a layer of polyethylene terephthalate (PET).

The front-end electronics and the readout panels are then integrated with the gas gap within a Faraday cage structure, which suppresses most of the external noise.

Many gaseous detectors have the ionization region separated from the multiplication one. In this case the field close to the cathode of the detector is weak, thus guaranteeing better stability and very low noise. On the other hand, the time needed to produce the avalanche is strongly dependent on the impact position of the incoming particle and on longer primary electrons drift time in the detector drift region. Hence, a delay of few tens to hundreds of nanoseconds is introduced before the signal is generated inside the sensor. Moreover, the time resolution worsens due to the statistical fluctuation on the path in the drift region.

In the RPC case, the field is uniform and perpendicular to the electrodes. When a sufficient high voltage is applied, the electrons created by the ionizing particle are accelerated to the anode creating avalanches along the path. The avalanches grow until a maximum size, depending on the distance between the primary cluster and the anode. The induced signal will be the sum of all these simultaneous contributions and its duration is of the order of few ns, depending on the gas gap width.

The total ionization depends on the length of the travel path inside the gas: events with the same energy produce signals with different delivered charges depending on the first ionization point. On the other hand, the overlapping between the drift and the ionization regions, allows a very fast response to the particle passage, of the order of few ns. Due to the absence of any drift time, the RPC detectors are characterized by an excellent time resolution, which depends on the gas gap width and on the gas mixture.

One of the parameters affecting the time resolution is the contribution given by the statistics of the saturated avalanche development and can be reduced lowering the signal induction time. The experimental observation shows that the most direct approach to decrease the avalanche formation time is the reduction of the gas gap thickness [25]: the current for a given charge produced inside a thinner gap is double, following the Shockley-Ramo's theorem [26].

Moreover, with a smaller gap, the detector must be operated at a higher electric field

without incurring in streamer transition. Hence, the Townsend coefficient gets higher as well. The net result is a reduction in the avalanche formation time.

The 2 mm gas gap of the ATLAS RPC ensures 1 ns of time resolution, allowing the correct identification of the LHC bunch crossing for each detected particle. Reducing the gap width to 1 mm, like in the case of the RPC of the ATLAS upgrade, allows improving the time resolution to ~ 400 ps. In the latter case, since the gas gap reduction comes along with a decrease of the pulse duration, a more sensitive and high performing Front-End electronics is required to exploit the best performance.

2.1.1 Operating principle

When no gas ionization occurs, the RPC could be described as two capacitors filled with a dielectric, as shown in the left part of Figure 2.2. Here, C and R refer to the capacitance and resistance of the electrodes, while C_g and R_g represent the same quantity related to the gas gap [27]. In this case, the resistance of the gas, R_g , is infinite and all the voltage applied to the electrodes drops totally on the gas gap.

When the particle ionizes the gas, the electric discharge could be well described as a current generator which discharge the capacitor C_g , as shown in the right part of Figure 2.2. In this case the voltage applied is transferred to the resistive plates, represented by C .

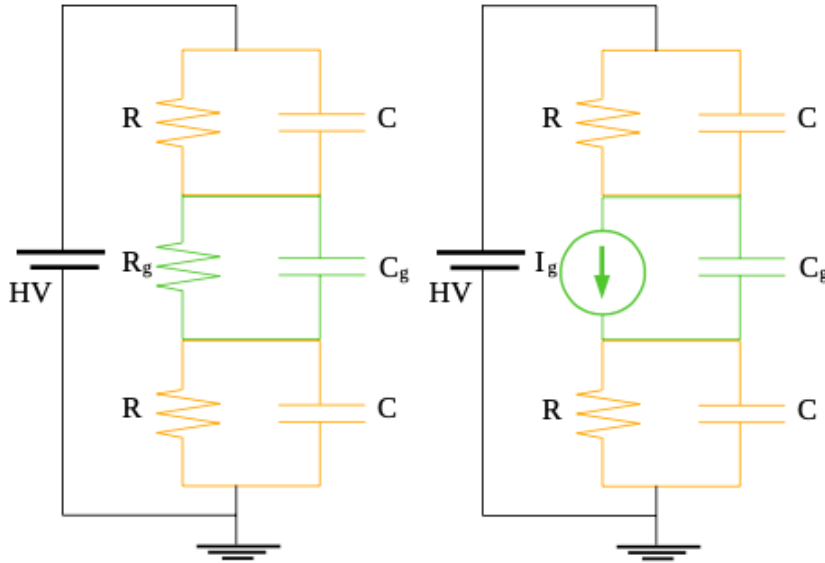


Figure 2.2: Equivalent circuit of an RPC in absence of ionization (left) and after the ionization (right).

The system will go back to the initial condition with the following exponential law:

$$\frac{dq_C}{q_C} = \frac{dt}{R(C + C_g)} \quad (2.1)$$

with a characteristic time τ :

$$\tau = R(C + C_g) = \rho \epsilon_0 \left(\epsilon_r + \frac{2d}{g} \right) \quad (2.2)$$

where d is the thickness of the electrodes, g is the width of the gas gap, ϵ_r is the dielectric constant and ρ is the electrodes resistivity.

Considering $\rho \sim 10^{10} \Omega\text{cm}$, τ is of the order of 10 ms while the discharge inside the RPC is around 10 ns $\ll \tau$. During this time the electrodes appear as an insulator and the discharge could not be supplied anymore. This "quenching" mechanism is the main operating principle of the RPC detector, where τ represents the dead time of the detector.

The dead area is very small due to the electrodes resistive material, and is related to the front of the avalanche, thus to the total ionic charge Q produced inside the gas (see Section 2.2).

The induced charge on the readout strips from a single couples of electron-ion is:

$$q = \frac{-e\Delta x_e + e\Delta x_I}{g} \quad (2.3)$$

where $\Delta x_e = v_d t$ and $\Delta x_I = V_d t$ are respectively the electron and the ion displacements after a time t from the ionization. V_d and v_d are the electron and the ion drift speed respectively. After a sufficient time, the whole charge developed inside the gap is induced on the reading strips and:

$$\Delta x_e + \Delta x_I = g \rightarrow q = e \quad (2.4)$$

The current induced by a single electron-ion couple is:

$$\frac{dq}{dt} = \frac{e(V_d + v_d)}{g} \sim \frac{ev_d}{g} \quad (2.5)$$

This means that only the electrons give a relevant contribution to the observable signal induced on the pick-up electrodes (prompt signal), while the ions contribute to a slower signal of the order of μs (ionic signal).

The ionic signal could be read as a current signal on a shunt resistance placed on the power supply line.

The induced current on the read-out strip at the time t for N electrons is:

$$i(t) = eN(t) \frac{v_d}{g} = \frac{ev_d}{\Lambda} \left(1 - \frac{v_d t}{g}\right) e^{\alpha v_d t} \quad (2.6)$$

being α the first Townsend coefficient and Λ^{-1} the number of primary ionizations. The prompt signal charge, q , is the integral of the current until the maximum drift time $t_{\text{max}} = g/v_d$:

$$q = \int_0^{t_{\text{max}}} i(t) dt \sim \frac{I_p}{(\alpha g)^2} e^{\alpha g} \quad (2.7)$$

The ionic charge, Q , represents almost the 90% of the total charge delivered inside the detector:

$$Q = \frac{e}{\Lambda} \int_0^g e^{\alpha x} dx = \frac{e}{\Lambda \alpha} (e^{\alpha g} - 1) \sim \frac{I_p}{\alpha g} e^{\alpha g} \quad (2.8)$$

where the approximation is valid in the saturated avalanche regime in which $\alpha g \sim 20$. The ionic to prompt ratio is given by:

$$\frac{q}{Q} = \frac{1}{2\alpha g \left(1 + \frac{2d}{\epsilon_r g}\right)} \quad (2.9)$$

where the approximation is valid if an exponential model for the avalanche growth is taken into account, therefore only for low detector efficiency (see Section 2.2).

2.2 The avalanche working mode

When a charged particle crosses the sensitive active volume releases energy according to the Bethe-Bloch formula and ionizes the gas molecules producing electron-ion couples. The RPC detector can be considered as a thin material thickness with low density, therefore the particle loses a negligible fraction of its energy in a small number of interactions.

The number of primary ionization follows the Poisson statistics and is completely determined by the mean free path of primary ionization λ . The primary ionization I_p can be written as the electric charge e multiplied by the number of ionization per unit length λ^{-1} and the gas gap width g :

$$I_p = e \frac{g}{\lambda} = en_p \quad (2.10)$$

being n_p the number of primary ionizations. The probability for a particle to do k ionizing interactions is then:

$$P(n_p, k) = \frac{n_p^k}{k!} e^{-n_p} \quad (2.11)$$

For a 2 mm gas gap RPC filled with only tetrafluoroethane ($\lambda^{-1} \sim 75$ ions/cm) the mean number of primary ionization is $n_p \sim 15$.

During its passage through the gas gap, the particle ionizes the gas in several points, producing many primary clusters. Not all primary clusters have the same probability to give a detectable signal: those generated near the anode give a small number of electrons, which could not go above the discriminator threshold.

We can imagine to divide the gas gap into two regions: the one nearest to the cathode, which represents the effective gas gap available for the ionization, and that nearest to the anode, where the generated clusters are inefficient.

When a higher voltage is applied, the effective region widens, including more clusters. If we interpret the detector inefficiency as the probability to have zero effective primary ionization, we can write:

$$1 - \epsilon_{\text{intr}} = P(0) = e^{-\langle n_p \rangle_{\text{effective}}} \quad (2.12)$$

where $\langle n_p \rangle_{\text{effective}}$ is the average number of effective primary ionization and ϵ_{intr} is the detector intrinsic efficiency. From Equation 2.12:

$$1 - \epsilon_{\text{intr}} = e^{-\langle n_p \rangle_{\text{eff}}} = \ln\left(\frac{1}{1 - \epsilon_{\text{intr}}}\right) \quad (2.13)$$

which represents the number of primary clusters which are detected.

In an RPC the electric field is such that the electron released from the primary ionization has enough energy to ionize again the gas, triggering a multiplication process which leads to the formation of an avalanche charge.

The avalanche has a drop shape, as shown in Figure 2.3, due to the different electron and ion speeds. The electrons have a higher speed velocity, 100 times higher than the ions, which depends on the gas mixture and electric field and are therefore located on

the front of the drop.

The ions, whose velocity depends linearly on $E/P \sim \text{constant}$, are located on the tail of the drop.

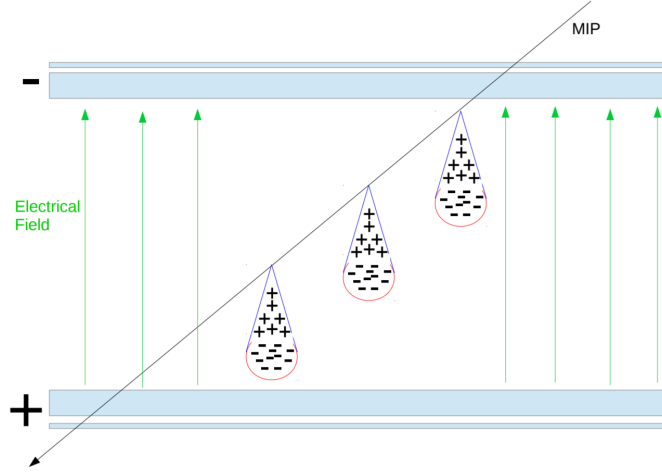


Figure 2.3: Scheme of the avalanche charge development in the RPC.

Considering now a single avalanche, $\alpha = \lambda^{-1}$ is the first Townsend coefficient and represents the ionization probability per unit length. If at a certain time there are n electrons inside the avalanche, then in a length dx they will increase of:

$$dn = n\alpha dx \quad (2.14)$$

At the time t after the gas ionization, the cluster displacement toward the anode is $\Delta x = v_d t$, being v_d the electrons drift speed. Integrating Equation 2.14 we obtain the gain factor of the avalanche:

$$\frac{n(t)}{n(0)} = e^{\alpha \Delta x} \quad (2.15)$$

The avalanches generated at $x > v_d t$ have the same gain, while the others are absorbed by the anode.

A simplified model of the avalanche growth can be built, assuming that:

- the mean free path of primary ionization, Λ , depends only on the gas mixture;
- the first primary electron is released at the beginning of the gap and all the electrons are at distance Λ ;
- $\alpha = \lambda^{-1}$ is independent from the electric field;

in this way the space available for a secondary ionization for each primary electron is given by:

$$S_i = g - i\Lambda \quad (2.16)$$

and the number of produced electron is:

$$n_i = n_s e^{\frac{S_i}{\lambda}} \quad (2.17)$$

Assuming that each primary electron gives rise to an avalanche, the total charge produced is given by:

$$\frac{q}{e} \approx n e^{\frac{g}{\lambda}} \frac{1}{1 - e^{-\frac{\Delta}{\lambda}}} \quad (2.18)$$

where n_s is the mean number of secondary ionization.

In this way, the total charge produced can be measured as the sum over all the primary electrons n_p :

$$\frac{q}{e} = N = \sum_{i=1}^{n_p} n_i = \sum_{i=1}^{n_p} n_s e^{\frac{g-i\Delta}{\lambda}} \quad (2.19)$$

and, for a large number of primary ionization ($n_p \rightarrow \infty$), we obtain:

$$\frac{q}{e} \approx n_s e^{\frac{g}{\lambda}} \frac{1}{1 - e^{-\frac{\Delta}{\lambda}}} \quad (2.20)$$

This model describes the growth of the avalanche as a pure exponential function. Here, the gain increases with the tension V applied on the electrodes because α is an increasing function of the electric field:

$$\alpha = \lambda^{-1} e^{-\frac{\epsilon_i}{eE\lambda}} \quad (2.21)$$

where the mean free path λ is inversely proportional to the cross section σ and the gas electron density ρ . If also the attachment is taken into account, α could be redefined as $\alpha - \gamma$ where γ is the attachment probability per unit length.

Figure 3.4 reported in Section 3.1, shows how the charge distribution of a sample of triggered cosmic avalanche induced signals depends on the applied electric field.

In the hypothesis of a standard exponential law, an approximately $1/Q$ distribution is expected. On the contrary, the Figure shows a gradual transition from exponential to a peaked distribution while the field, thus the average avalanche size, is increasing.

This saturation effect [28]-[29] suggests that the avalanche does not grow indefinitely and can be explained imagining that two charged zones are established inside the avalanche: one positive, due to ions, and one negative, due to the electrons.

An electric field, opposite to the applied one, is thus established in the region where the electrons and ions are closer, due to this space-charge effect.

While the electric field gets stronger, the avalanche can reach increasing values of the total charge in the same drift space, until the space charge effect is strong enough to leave back a certain fraction of the multiplying electrons.

These electrons keep on moving about at the same average speed (until attached), but they are subtracted from any further multiplication process.

This process finds a dynamical equilibrium status when the number of electrons left behind is equal to the number of the newly generated one. The equilibrium is stable because the space charge acts as a negative feedback on the fluctuations: an over-production increases the space charge field that pushes backward more electrons and viceversa.

The saturation of the avalanche suggests that the avalanche front reaches a stable maximum population and we can imagine it like a cluster of moving charge that propagates in the gas dissipating energy along the lines of the electric field, leaving a tail of inactive electrons.

The consequence of the growth mechanism of the avalanche is that the electron prompt

charge induced on the readout strips is only a small fraction of the total charge produced in the gas gap, because most of electrons are produced in the final stage of the avalanche, when they are closer to the anode.

The total induced charge is approximately

$$Q_{\text{induced}} \approx Q_{\text{tot}} \frac{\Delta x}{g} \quad (2.22)$$

where Δx is the average drift length of the electrons and g is the gap width.

2.2.1 From avalanche to streamer

When the avalanche reaches an electron multiplicity of 10^6 electrons, it slows down the exponential growth due to the space charge effects, and the saturated regime is established.

The electric field associated with the space charge distribution can increase a lot until it neglects the one applied, triggering recombination phenomena with consequent emission of photons in the UV.

This photons interact with the electrodes and produce additional electrons which ionize again the gas, giving rise to secondary delayed avalanches.

For extremely high values of the electronic charge (established by Meek to be 10^8 electrons for noble gases, corresponding to $\alpha g > 20$), the secondary avalanches merge together generating a plasma pillar, where the electron and ions are uniformly distributed, that interconnects the electrodes and is called streamer.

This plasma filament produces an extremely intense current pulse in the gas, about 100 times larger than the typical avalanche (100 pC vs 1 pC). The streamer is prevented to evolve in a spark thanks to the electrodes resistivity, and to propagate laterally, due to emission of UV ionizing photons by the slowed recombining electrons, by an opportune photon quencher in the gas mixture (like $i\text{-C}_4\text{H}_{10}$ and SF_6).

It is important to stress that the streamer is not an evolution of the avalanche, but a subsequent effect due to photo-ionization phenomena when the avalanche is extinguished. Indeed, streamer appearance is independent from the total charge of the precursor and the streamer signal follows the avalanche one with a time delay that decreases with the increase of the electric field.

The signal associated to the avalanche in a 2 mm gas gap filled with the standard gas mixture has an amplitude of about 1 mV, a duration of 4-5 ns and an average charge of 1 pC, while the streamer has an amplitude of 100 mV, a duration of tens of ns and an average charge of 100 pC.

The RPC can work both in avalanche and streamer mode. The avalanche mode is used in the experiments operating in presence of a high flux of ionizing particles (as LHC), because it guarantees a good rate capability and a slow detector ageing if compared to the streamer mode.

2.2.2 Ionic signal

The ionic signal is the signal induced on the graphite electrodes after a discharge inside the gap and, though mostly given by the contribution of ions, it contains also the contribution of the electrons.

The behaviour of the potential developed on the graphite electrodes is of fundamental importance for the study of the detector, because this signal includes all the information

released by the passage of the particle inside the gas.

In the limit of negligible inductive effect, justified by the high surface resistivity of the graphite electrodes ($\sigma \approx 100 \text{ k}\Omega/\square$), the electrode coupled with its ground reference can be considered as a distributed capacitive-resistive system.

In the uni-dimensional case, this system can be described as a transmission line in which the inductive impedance has been neglected, as shown in Figure 2.4.

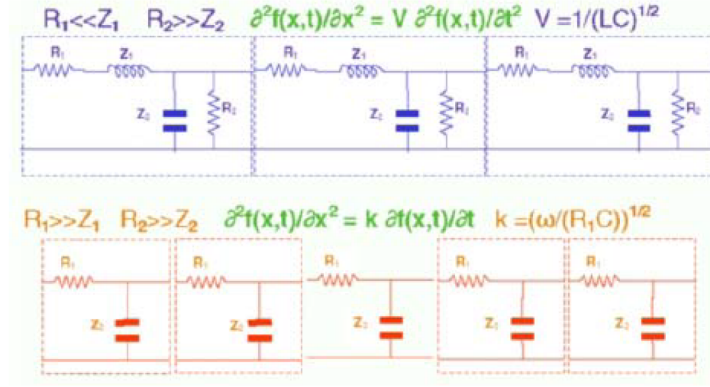


Figure 2.4: Uni-dimensional Model for the case of transmission line with $R_1 \ll Z_1$ (propagation equation) and for the case of a distributed capacitive-resistive system with $R_1 \gg Z_1$.

The ideal transmission line, where there is not dissipation ($R_1 \ll Z_1$), is the case of a capacitive-inductive system where the signal follows the propagation equation, while in the case of a capacitive-resistive system ($R_1 \gg Z_1$) the signal follows the diffusion equation.

The behaviour of the potential distribution through time on the graphite plane is described by the two-dimensional diffusion equation:

$$\frac{\partial V}{\partial t} = a^2 \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) \quad (2.23)$$

where $V=V(x,y,t)$, $a^2 = 1/\sigma C^*$ and C^* is the capacitance per surface unit of the resistive electrode, which takes its main contribution from the capacity between the electrode and his ground reference.

If we imagine that the electric discharge produces a point perturbation of the potential on the graphite electrodes, it will diffuse on the electrode as a time-dependent Gaussian:

$$V(r,t) = \frac{1}{4\pi a^2 t} e^{-\frac{r^2}{4a^2 t}} \quad (2.24)$$

where r is the distance from the ionization point (x_0, y_0) .

This is a particular solution that is valid for an infinite electrode, neglecting the edge effects. The evolution of the signal is given by a Gaussian with time-dependent variance, widening with increasing t and remaining centered in (x_0, y_0) because in the graphite we have only diffusion and no propagation. (Figure 2.5).

The potential assumes its maximum value at:

$$t = \frac{r^2}{4a^2} \quad (2.25)$$

The signal on the graphite depends on the distance from the ionization point. In particular the signal is degraded when the distance increases.

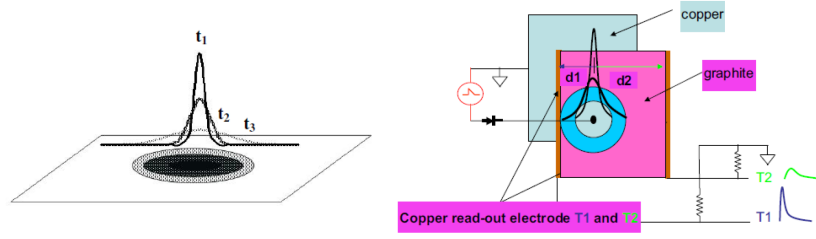


Figure 2.5: Left: time evolution of the potential on the graphite represented by a two-dimensional time-dependent gaussian; Right: Scheme of the signal pick-up developed on the graphite.

The amplitude of the maximum of the signal and the width of the peak depend strongly on r :

$$V(t = \frac{r^2}{4a^2}) \propto \frac{1}{\pi r^2} \frac{\partial^2 V}{\partial t^2}(t = \frac{r^2}{4a^2}) \propto \frac{16a^4}{\pi r^6} \quad (2.26)$$

In order to optimize the signal read-out, copper electrodes can be introduced on the graphite, to minimize the distance from the incidence point.

The electrodes are connected to ground with a shunt resistance where the tension can be read. Therefore, the signal on the graphite, or ionic signal, is read-out as a current signal.

Historically the RPCs are used as *trigger* detector, fast and with excellent time-resolution, using only the prompt signal. The information given by the ionic signal are of fundamental importance because its charge is related to the ageing of the detector.

It has been demonstrated that the ageing of the detector depends on the integrated charge during its operation, thus with the average charge per count Q .

An RPC that works under irradiation by very intensive sources (as at the LHC) shows, after a long period of time, a gradual reduction of the rate capability that can be explained as an effect due to a progressive increase of the electrodes resistivity.

2.3 The RPC rate capability

The experiments which work in high-radiation environment, therefore under a strong flux of incident particles, require the RPC operation in avalanche mode in order to ensure long-term operation and a good rate capability.

The RPC rate capability is mainly limited by the current flowing through the high resistivity electrodes.

For a uniform irradiation density, a working current I flowing across the electrodes with a total resistance R , produces a voltage drop V_{el} on them. The voltage drop on the electrodes (V_{el}) can be expressed as:

$$V_{el} = V_a - V_{gas} = IR \quad (2.27)$$

being V_a and V_{gas} the voltages applied on the detector and the drop on the gas respectively.

In order to achieve a high rate capability, V_{el} must be negligible with respect to V_{gas} under heavy irradiation.

The voltage drop, V_{el} , can be written as a function of the detector parameters:

$$V_{el} = \rho d < Q > \Phi \quad (2.28)$$

where ρ is the bulk resistivity of the electrodes material, d is the total thickness of both electrodes, $\langle Q \rangle$ is the average charge per count delivered inside the gas and Φ is the counting rate per unit surface. The rate capability can be defined as the rate per unit voltage drop across the electrodes:

$$\text{Rate capability} = \frac{\Phi}{V_{\text{el}}} = \frac{1}{\rho d \langle Q \rangle} \quad (2.29)$$

The rate capability can be increased adopting several approaches:

- Increase V_{gas} , in order to compensate the voltage drop on the electrodes due to the higher Φ and keeping V_{gas} constant;
- Decrease the electrode resistivity and thickness;
- Reduce the average charge per count.

The increase of V_{gas} , causes the average charge per count $\langle Q \rangle$ increases greatly with the electric field. Therefore, if the operating current is too high, the increase of the applied potential would only increase the current, causing only a minimal fraction of the voltage to be transferred to the gas.

The decrease of the electrode resistivity would imply a corresponding increase of the operating current and of the pollutants generated inside the gas. Moreover, the spontaneous detector noise could increase as well, along with a potential acceleration of the detector ageing due to the higher operating current. As a consequence, a new robust ageing test to qualify the RPC detector would be required.

The reduction of the electrode thickness has a similar effect on the rate capability as to reduce its resistivity, being the total electrode resistance R proportional to ρd . However, a further important effect of the electrode thickness, is to attenuate the charge induced on the read out electrodes by a factor of

$$A = 1 + \frac{d}{\epsilon_r g} \quad (2.30)$$

where ϵ_r and g are the relative dielectric constant of the electrode material and the gas gap size respectively. Consequently, the amount of induced signal on the read out panel gets larger due to the thinner electrodes, thus improving the signal to noise ratio. This effect, which is particularly relevant for very thin gaps, shows that the electrode thickness should be reduced according to the gap size.

The most advantageous approach is the reduction of the average charge, which leads to the improvement of the rate with minimum or null penalization of other parameters such as the detector ageing. This approach is the most demanding in terms of technological effort, since it requires the introduction of a more sensitive Front End electronics in order to transfer part of the gas amplification to the FE electronics.

The most ambitious goal, achievable only through this method, is to obtain a rate capability improvement keeping the current constant, thus making any further ageing test unnecessary.

The electronics required for this purpose must be very sensitive, with an excellent signal to noise ratio. Moreover, it requires also a careful optimization of the chamber structure as a Faraday cage, in order to strongly suppress the noise originated both by the detector itself and by external sources.

Chapter 3

Low Global Warming Potential and Ozone Depletion Potential gases for RPCs

3.1 The standard gas mixture

The experiments which operate in high radiation environment require the RPC operation in avalanche working mode, which ensures a good rate capability and a long term operation in presence of a high-irradiation background. The avalanche working mode is achieved thanks to the standard gas mixture[29]-[31], composed of tetrafluoroethane ($C_2H_2F_4$), i-butane ($i-C_4H_{10}$) and sulfur hexafluoride (SF_6).

The chemical structures of the gas components are shown in Figure 3.1.

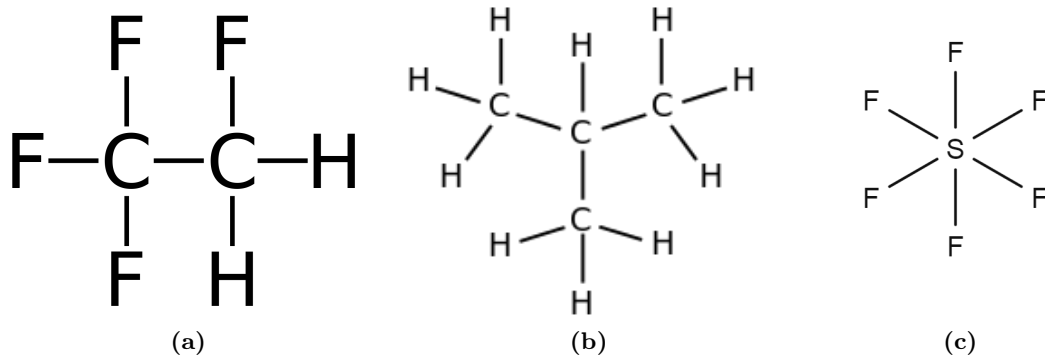


Figure 3.1: (a) $C_2H_2F_4$, (b) $i-C_4H_{10}$ and (c) SF_6 molecular structures.

The $C_2H_2F_4$ is a high-density gas with a modest electronegativity and represents the major part of the detector active target, being the 94.7% of the gas mixture. The gas density and the ionization potential (12.1 eV) ensure a sufficient production of primary electron-ion couples when the particle crosses the active area, resulting in a high detection efficiency.

The $i-C_4H_{10}$ plays the role of *quencher*, absorbing part of the UV photons coming from electron-ion recombination processes and re-emitting them in the form of radiation to which the detector is transparent. This feature makes it efficient in delaying the streamer formation and in reducing the photo-electron discharges which can damage the

electrode surfaces. For this reason this component results very suitable in reducing the ageing effects in long term operation. Its concentration in the mixture is 4.7%, limited by its flammability.

The SF_6 is a very electronegative gas which captures low-energy electrons, limiting the spatial growth of the avalanche, thus retarding the streamer formation: it has good insulation properties due to the large electron scattering and attachment cross sections at low (thermal) energies (see Figure 3.2). A small amount of this gas, only 0.3%, ensures a good streamerless operation.

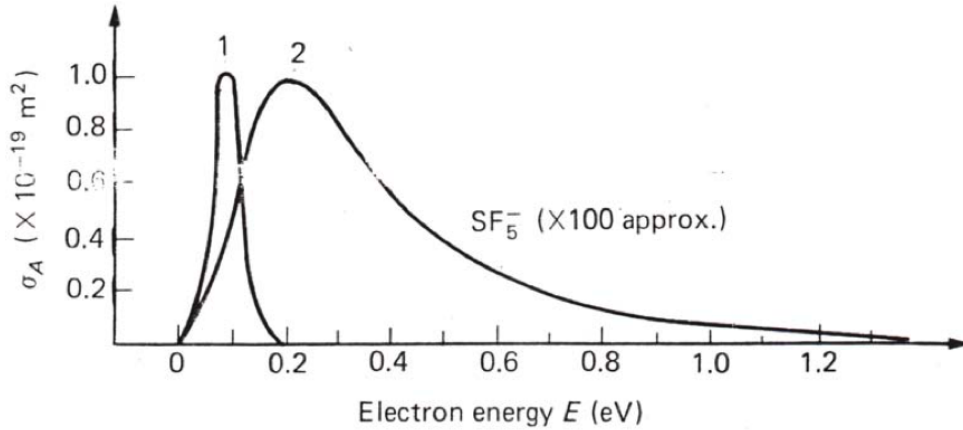


Figure 3.2: SF_6 Radiative attachment (1) and dissociative attachment (2) cross sections as a function of the electron energy.

The standard gas mixture is the result of a relevant R&D investment and its properties make it suitable to work in avalanche mode, as required by the high-luminosity collider experiments.

The high gas density ensures sufficient primary ionization even for gas gaps in the millimeter range size, while the electronegativity gives a large separation between avalanche and streamer appearance.

The detection efficiency and the streamer probability as a function of the high voltage for a 2 mm gas gap RPC is shown in Figure 3.3(a). The efficiency reaches 99.9% at 10.1 kV and the separation between the two regimes is ~ 1 kV, well above the uncertainties in the high voltage spread in the experiments (for ATLAS is 150 V).

The prompt and ionic charges as a function of the high voltage are shown in Figure 3.3(b). The ionic charge represents almost the 90% of the total charge delivered inside the gas and it is strictly correlated with the detector rate capability: the lower is the ionic charge, the higher is the rate capability [32]. The ionic charge slowly increases with the high voltage, varying from 20 pC at the first high voltage value of the efficiency plateau (10 kV) to 30 pC at 10.8 kV. Above this HV value, the charge increases because streamer events start to occur.

The prompt charge, dominated by the electron drift motion, slowly increases with the high voltage and is high enough to overcome the front-end electronics threshold. The prompt charge distribution for several efficiency values is shown in Figure 3.4.

The charges are well peaked around a modest main value also for high efficiency. As soon as the streamers occur, the avalanche charge contribution stays in a well defined peak at lower mean values (within 10 pC), while the streamers appear as a well separated

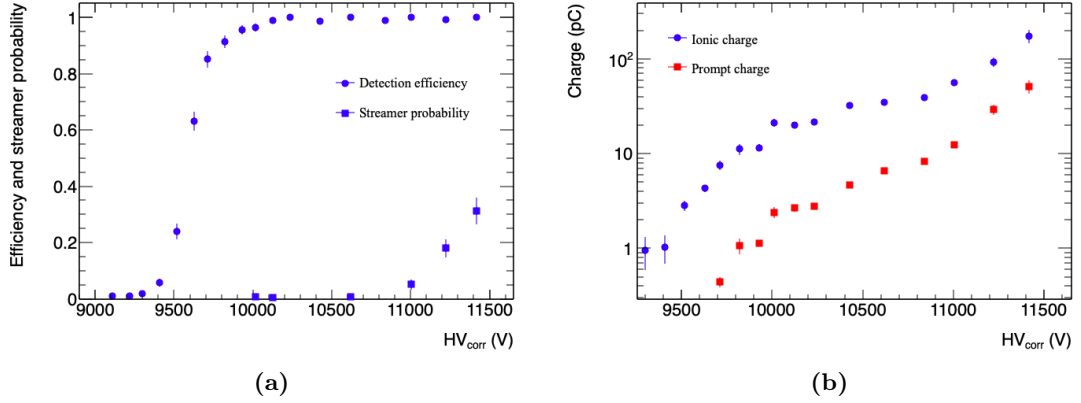


Figure 3.3: (a) Efficiency and streamer probability and (b) ionic and prompt charges as a function of the high voltage for a 2 mm gas gap RPC operated using the standard gas mixtures.

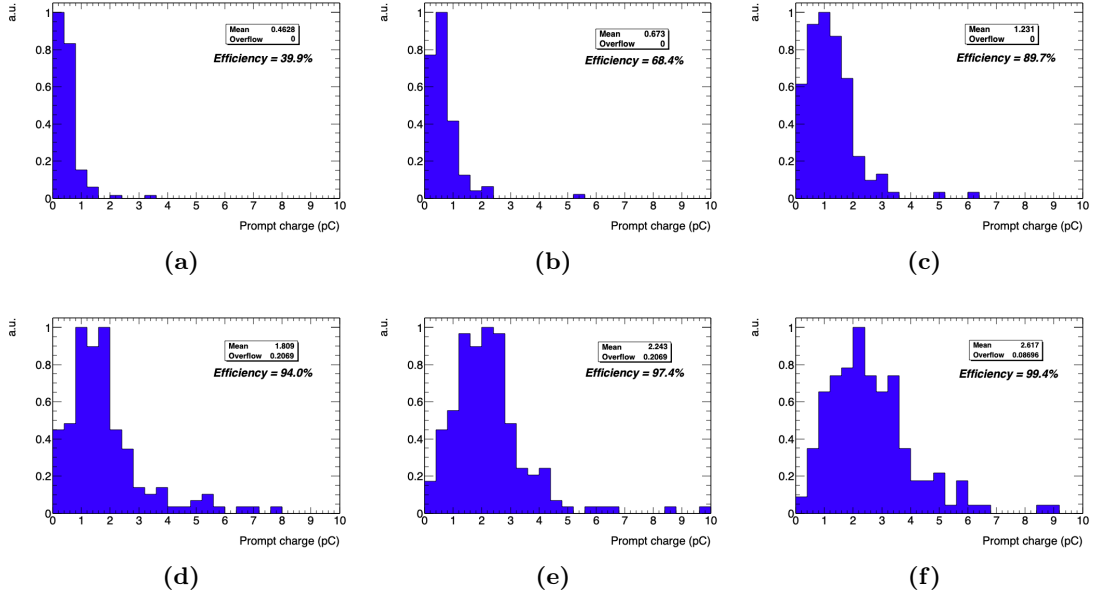


Figure 3.4: Total prompt charge distribution at different efficiencies for the standard gas mixture.

peak at higher charge ~ 100 pC higher (see Figure 3.5).

The high electron *drift* velocity in Tetrafluoroethane results in an excellent detector time resolution, as shown in Figure 3.6:

$$\sigma_t^{\text{Standard}} = (1.09 \pm 0.07) \text{ ns} \quad (3.1)$$

The standard gas mixture is non-flammable, no toxic and made of industrial components as required for very large size detectors, also operating in underground laboratories.

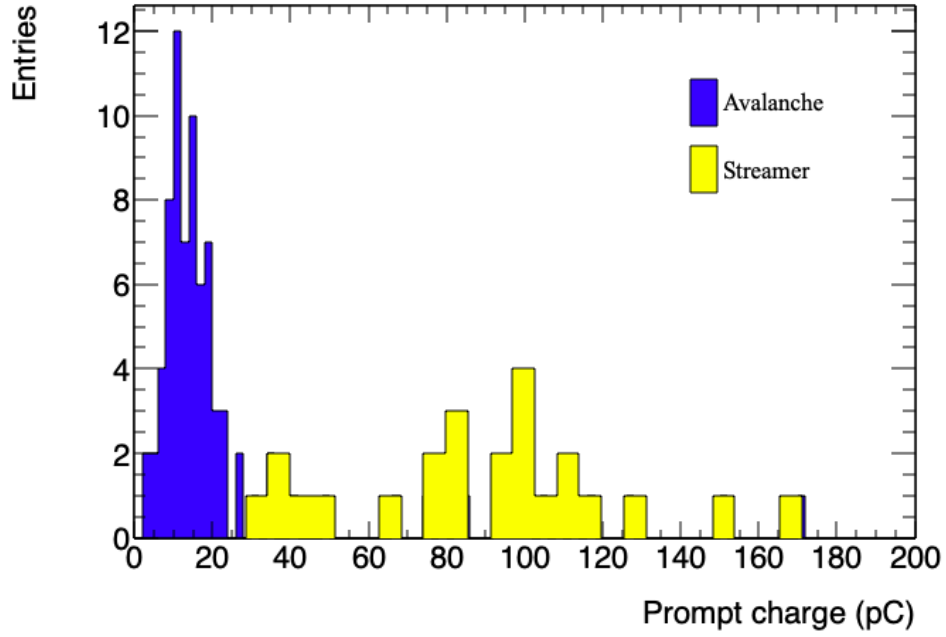


Figure 3.5: Prompt charge distribution for the standard gas mixture at $HV = 11.4$ kV. The avalanche (blue) and streamer (yellow) events appear as two well separated peaks in the distribution.

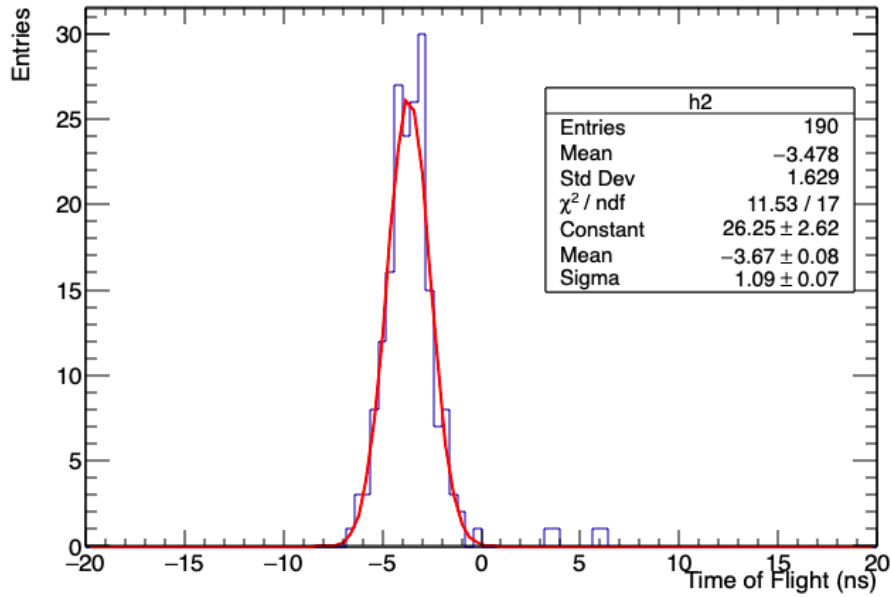


Figure 3.6: Time resolution of a 2 mm gas gap RPC operating with the standard gas mixture.

3.2 Search of an environment-friendly gas mixture

The standard RPC gas mixture is mostly based on Hydrofluorocarbons, HFCs, extensively used in the refrigeration industry. The Hydrofluorocarbons are now considered to be non-eco-friendly gases for their high Global Warming Potential (GWP) [33]-[34]-

[35]. These greenhouse gases warm the Earth by absorbing energy and slowing the rate at which it escapes to space, depending on their ability to absorb energy and how long they stay in the atmosphere.

The GWP measures how much energy the emissions of 1 ton of a gas will absorb over a given period of time, compared to the emission of the same amount of CO_2 . The larger the GWP, the more a given gas warms the Earth compared to the CO_2 over that time period (usually 100 years are taken as a reference).

European Union regulations for the Earth protection take into account also the Ozone Depletion Potential (ODP), defined as the amount of ozone degradation a gas causes, taken the trichlorofluoromethane as reference ($\text{ODP} = 1$). High-ODP gases dissociate the ozone molecules, reducing it, resulting in the increase of the radiation that can reach the Earth's surface and causes climate change.

The standard gas mixture has a GWP of 1430 and a null ODP. The SF_6 has the largest GWP, 22900, but, due to its low concentration, it contributes only with few tens of units to the total value. The major contribution comes from the main standard gas mixture component, the $\text{C}_2\text{H}_2\text{F}_4$ (TFE), which has a GWP of 1400. The $\text{i-C}_4\text{H}_{10}$ does not give contribution, being its GWP only few units.

These F-gases have been phased-out from industry, therefore their availability will be increasingly difficult over time and all the institutes, like CERN, are pursuing a campaign toward the reduction of their greenhouse gas emission with the aim of substitute these gas components in the RPC detectors.

In this framework the search of an alternative gas mixture, which can maintain the excellent performance of the standard one but with lower GWP, plays a crucial role in the usage of RPC in present and future experiments.

Alternative gases are searched looking at their use in industry, due to their easy availability and low cost. In the refrigeration industry the $\text{C}_2\text{H}_2\text{F}_4$ is replaced by Hydrofluorolefins, unsaturated organic compounds comprising of hydrogen, fluorine and carbon and characterized by a double carbon-carbon bond.

Due to the $\text{C}=\text{C}$ bond faster reactivity, they have a short lifetime in the atmosphere and are thus classified as low-GWP and low-ODP molecules.

Among them, the most similar to the $\text{C}_2\text{H}_2\text{F}_4$ is the Tetrafluoropropene (Figure 3.7), $\text{C}_3\text{H}_2\text{F}_4$, being the only difference an extra carbon and the $\text{C}=\text{C}$ bond.

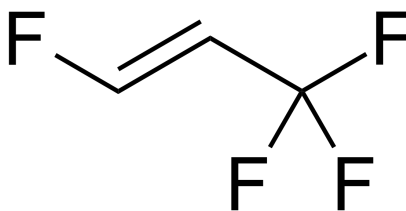


Figure 3.7: 1,3,3,3-Tetrafluoropropene molecule (HFO1234ze).

In this thesis a suitable alternative to the bigger-GWP molecule, the SF_6 , has been studied: the 1-Chlorine-3,3,3-trifluoropropene, $\text{C}_3\text{H}_2\text{ClF}_3$, shown in Figure 3.8. This gas has null-ODP and $\text{GWP} \sim 1$.

The gas mixtures with this new component as SF_6 substitute, have a $\text{GWP} \sim 10$, therefore totally environment-friendly.

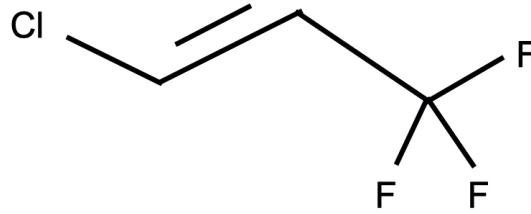


Figure 3.8: 1-Chlorine-3,3,3-trifluoropropene molecule (HFO1233zd).

3.3 Operating Resistive Plate Chambers with eco-gases

Union European regulation on greenhouse gases emission does not recommend the use of F-gases, like HFCs and SF_6 , with the aim of limiting or stopping at all the use of these non-eco-friendly gases in industry.

As a consequence, the availability of $\text{C}_2\text{H}_2\text{F}_4$ and SF_6 will be increasingly difficult over time and for RPC detectors the lack of TFE will be more critical, representing the main gas component of the standard gas mixture. Moreover, the development of a proper recirculation system to preserve this gases in the large experiments (for example ATLAS and CMS) is hampered by detector leaks which let the major part of the gas disperse in the surrounding area and make very difficult its recovery. In the ATLAS experiment the RPC gas system releases ~ 700 l/h in the atmosphere, which corresponds to 4 tons of CO_2 per hour.

Studies on the research of an environment-friendly gas mixture are on going for many years with the purpose of replacing the HFC components without losing the excellent properties of the standard gas.

For what concerns the LHC experiments, which operate in high radiation environment, the alternative gas mixture should guarantee high particle detection efficiency with modest currents and charge delivered inside the gas, in order to reach a good rate capability and ensure long term operation.

This replacement is more critical for the RPCs already working at the LHC with respect to the new RPCs to be conceived and installed during phase-2 upgrade.

In the latter case the new chamber setup, gap size, front-end electronics etc can be optimized to account for the new gas properties. This upgrade was not possible so far for the chambers already installed, which have not been replaced before LHC Run-3. On the other hand, the new generation of RPCs developed for the ATLAS phase-2 upgrade have a smaller gas gap size, 1 mm with respect to 2 mm of the legacy one, therefore a higher density gas is needed in order to preserve a high detection efficiency.

The efficiency depends on the gas density, ionization potential and cross section and scales with the gas gap width. The efficiency plateau value for RPCs with different gas gap sizes working with the standard mixture are summarized in Table 3.1.

The drop in efficiency due to the smaller gas gap active area is around 1% and 15% for 1 mm gap and 0.5 mm gap respectively with respect to the 2 mm RPC.

Even if the drop in efficiency with 1 mm RPC working with the standard gas mixture is not much big, eco-gases could show a different behaviour due to the different molecular properties cited before.

Therefore, an alternative gas mixture less dense than the standard one could be suitable for legacy RPCs but a heavier active target could be needed for 1 mm RPCs.

In conclusion, an alternative gas mixture for RPC detectors should maintain the prop-

Table 3.1: Intrinsic detection efficiency with the standard gas mixture for different gas gap widths

Gas gap width	HV (V)	Efficiency
2 mm	10290	99%
1 mm	6560	98.5%
0.5 mm	3900	85%

erties of the standard gas which can be summarized as follows:

- high gas density in order to achieve high detection efficiency;
- prompt charge slowly increasing with the applied voltage and high enough to easily overcome the front-end electronics threshold;
- low total charge delivered to ensure modest working current and good rate capability, as required by high-luminosity collider experiments;
- comfortable avalanche-streamer separation;
- non-flammable and made of industrial components.

The alternative gases, as discussed before, have been selected among the hydrofluoroolefins molecules (HFOs). The HFO gases, when used in RPC [36]-[37]-[38]-[39]-[40]-[41], exhibit important differences in comparison with the $C_2H_2F_4$ -based gas mixture used so far. In particular, they require much higher electric fields, due to their stronger electronegativity.

Working with higher electric field leads to the increase of the detector current and charge delivered, resulting in a lower rate capability and also in a faster detector ageing. Moreover, the operating high voltage moves near the instrumentation limits.

For these reasons, a gas mixture totally based on HFO could be suitable only for cosmic-ray experiments and not for those which require a good rate capability.

In the latter case, the HFO is always mixed with the CO_2 , which is a very simple molecule with low electronegativity, used to reduce the detector operating voltage.

The mixture composed of $C_3H_2F_4/CO_2/i-C_4H_{10}/SF_6$ has a GWP ~ 200 , totally due to the SF_6 , whose concentration is increased up to 1%.

A suitable substitute of SF_6 is needed in order to obtain a totally eco-friendly gas.

Previous tests suggest that HFC molecules with two different halogen atoms, like CF_3Br and CF_3I , have a strong quenching effect reducing the avalanche and streamer charges [42]. None of these molecules is suitable for very large size RPC systems, which require no flammable and no toxic gases. A relevant exception is found in the Hydrofluoroolefins series, the 1-Chlorine-3,3,3-trifluoropropene (HFO1233zd). This gas could represent a good alternative to SF_6 (see section 4.4).

The choice of an alternative gas mixture is based on the balance of the experiment requirements. On one side, the request to work with high particle detection efficiency suggests that the gas mixture main component should be a high-density gas with an ionization potential low enough to ensure a sufficient primary ionization, like the HFO. On the other side, the high operating electric field along with the copious presence of fluorine molecules and the weakness of the double C-C bond, could premature trigger streamers and dissociation processes which lead to the production of fluorine pollutants,

damaging the electrode surfaces and resulting in a too fast detector ageing. These effects suggest that the HFO concentration must be taken as low as possible. For these reasons, in this thesis the CO_2 is used as the main gas mixture component and the HFO concentration is chosen as the minimum amount enough to fully benefit from its properties both as quencher and primary target. In CO_2 -based gas mixtures the signal classification in avalanche and streamer is not sufficient anymore: a new category of signals occurs, showing properties between avalanche and streamer. We will refer to them as "transition events", due to their properties which will be discussed in section 3.4.

3.4 The transition events

The RPC working with the standard gas mixture shows a large plateau of operation in avalanche mode, as discussed in Section 3.1.

An avalanche signal, shown in Figure 3.9.a, is defined as an event with short duration and low charge content (see Section 2.2.1). In a 2 mm gas gap RPC the avalanche amplitude is of the order of 1 mV, the signal lasts 4-5 ns and it carries a charge of the order of 1 pC. The operating HV range in pure avalanche mode before the first streamer occurs is 1 kV, as previously shown in Figure 3.3.a.

A streamer event is not correlated with the avalanche growth, being a physics process independent from the avalanche formation and interpreted as a thin plasma column interconnected the electrodes. It is generated at high field by electrons extracted from the cathode by photo-ionization processes by photons coming from electron-ion recombination.

It appears as a wide signal with an amplitude of the order of 100 mV, a duration of tens of ns and a charge content of 100 pC. A streamer signal occurs after an avalanche precursor with a time delay depending on the gas properties and the field intensity, as shown in Figure 3.9.c.

These categories of signals, avalanche and streamer, belonging to different physics processes, are independently well defined and classified.

The transition between the two regimes can be defined as a "threshold process", where the field intensity plays the crucial role in the generation of these unwanted events: at high field, above 11 kV in a 2 mm gas gap, the avalanche and streamers coexist, while below this value only avalanche events can be observed.

In HFO/ CO_2 -based gas mixtures the scenario is slightly different: the transition between avalanche and streamer regime passes through a transition regime characterized by signals with intermediate properties between avalanche and streamer.

These signals appear as multi-peaks events and/or wide avalanches followed by a long tail, as shown in Figure 3.9.b. Their charge content is above 1 pC and their duration is longer than the classical avalanche one. On the other hand, the charge content and duration are well below those typical of streamers. Therefore they can not be interpreted neither as avalanche nor as streamer. This new category occurs only in eco-gases, while in the standard gas they are negligible or absent. In this thesis they will be defined as "transition signals", due to their intermediate characteristics.

Due to the presence of these events, the HFO/ CO_2 -based gas mixtures don't show a pure-avalanche efficiency plateau before the streamer appearance, but they are characterized by the overlapping between avalanches and transition events.

These events can be interpreted as streamer precursors, representing those events in

which the delayed avalanches produced by photo-ionization processes don't merge together to form the streamer but they ionize the gas molecules.

This can be due to the combination of the CO_2 , which produces many photons, and a very electronegative gas as $\text{C}_3\text{H}_2\text{F}_4$: the photons are much more with respect to the standard gas mixture and interact with the electrodes, producing many secondary electrons. These electrons ionize the gas but they are not able to trigger the streamer because they are restrained by the HFO. At high HV, these events gradually turn into streamers because the HFO can not be efficient anymore in presence of too much high electric field. In terms of RPC performance, the impact of this new category of events must be carefully studied. Concerning the application in the LHC experiments, in principle working in a regime characterized by avalanche and transition events is not problematic. The two parameters of major interest are the charge content and the time-over-threshold, because they are strictly correlated to the rate capability, aging and timing performance. The higher charge content of the transition events could increase the total charge delivered, thus worsening both rate capability and ageing. Moreover, their longer duration could affect the FE discriminator performances, leading to the misidentification of the correct bunch crossing associated to the triggered particle.

As long as these parameters are within the requirements of the experiment, an RPC can work also in presence of transition events. The impact of these signals in terms of these parameters will be deeply studied in section 4.4.

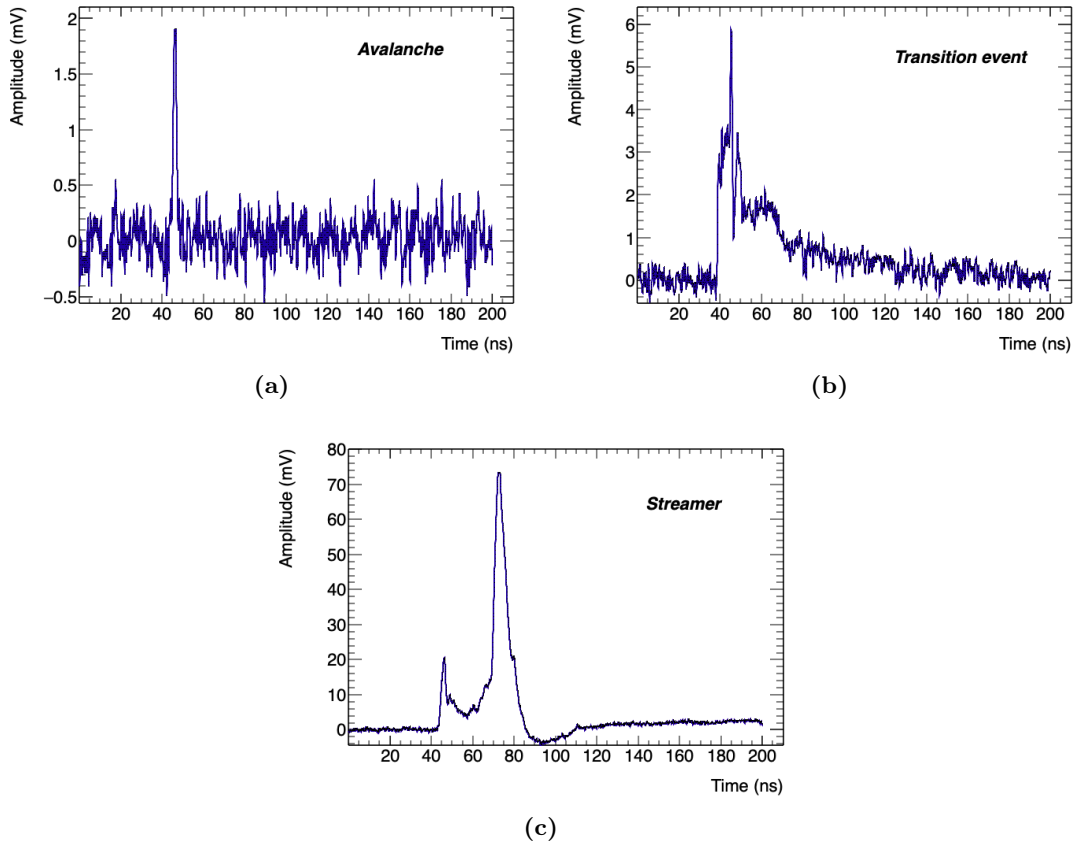


Figure 3.9: (a) Avalanche, (b) transition and (c) streamer signals.

Chapter 4

Test with cosmic rays

The tests with cosmic rays have been performed at the PP1 laboratory at the University of Roma Tor Vergata, on a 2 mm RPC operating with gas mixtures composed of $\text{C}_3\text{H}_2\text{F}_4/\text{CO}_2/\text{i-C}_4\text{H}_{10}$ and SF_6 or $\text{C}_3\text{H}_2\text{ClF}_3$.

For simplicity, in the following the $\text{C}_3\text{H}_2\text{F}_4$ (HFO1234ze) and the $\text{C}_3\text{H}_2\text{ClF}_3$ (HFO1233zd) will be labeled as "F-HFO" and "Cl-HFO" respectively.

The studies on gas mixtures containing the SF_6 have been organized in two sets:

- Measurements on the F-HFO percentage: the RPC performance have been studied varying the F-HFO/ CO_2 ratio, while taken $\text{i-C}_4\text{H}_{10}/\text{SF}_6$ concentrations fixed at 5/1;
- Measurements on the $\text{i-C}_4\text{H}_{10}$ percentage: the F-HFO/ SF_6 ratio is fixed at 5/1, while the $\text{i-C}_4\text{H}_{10}/\text{CO}_2$ proportions vary;

The mixtures under study have a GWP of 200, totally due to the presence of SF_6 , whose concentration has been increased up to 1% in order to compensate the weak quenching power of these gas mixtures.

Moreover, mixtures composed of F-HFO/ $\text{CO}_2/\text{i-C}_4\text{H}_{10}/\text{Cl-HFO}$ have been studied in order to understand the effect of the new Chlorine molecule as SF_6 substitute in the RPC performance. These gas mixtures have a GWP of ~ 10 , therefore totally environment-friendly.

4.1 Experimental apparatus

In this section the experimental apparatus built for the tests with cosmic rays, shown in Figure 4.1, is described. It is composed of:

- RPC detector under test;
- Trigger system;
- Gas system;
- Data Acquisition system (DAQ)

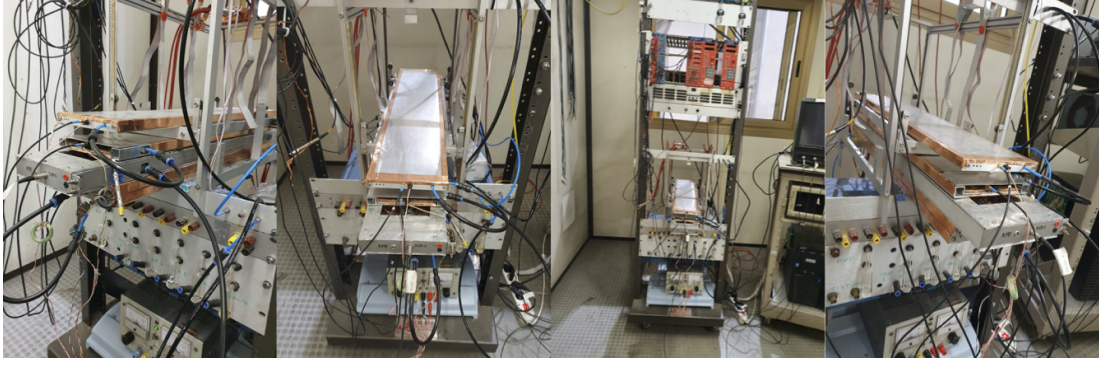
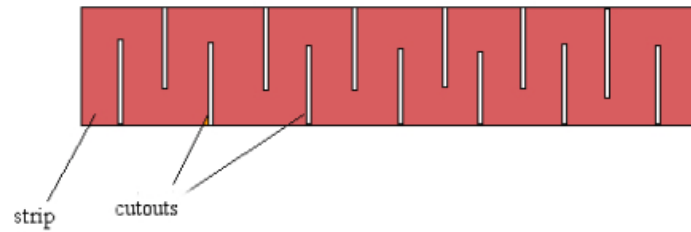
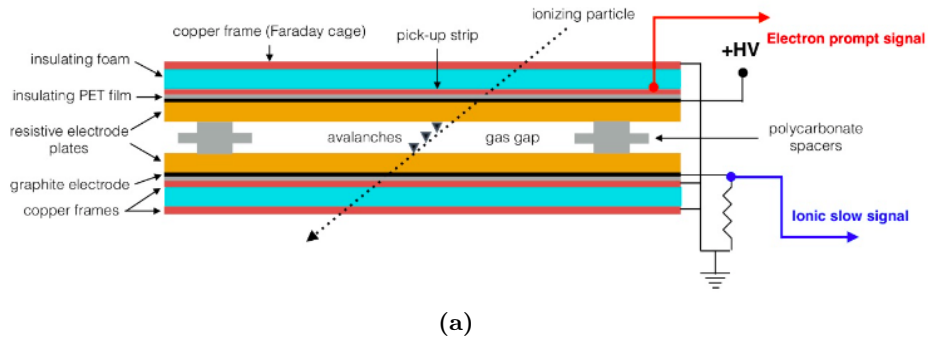


Figure 4.1: Picture of the experimental setup.

4.1.1 Trigger and RPC tested

The test chamber, schematized in Figure 4.2.a, is a small-size RPC, (55×10) cm² area, with 2 mm gas gap and 1.8 mm thick electrode made of phenolic resin based High Pressure Laminate (HPL). Both the gas gap and the electrode thickness reproduce the layout of the RPCs already operating in the ATLAS experiment during Run-2. The graphite electrodes have surface resistivity of 100 k Ω /□. The one connected to ground is used for detecting the ionic signal, by sampling the voltage across a 10 k Ω resistor connecting the graphite electrode to ground.



(b)

Figure 4.2: Schemes of the test chamber(a) and (b) of the readout strip).

The prompt-signal pick-up is made with a single strip, shaped as shown in Figure 4.2.b, of 30 Ω line impedance covering a pick-up area 35 mm wide, which fully intercepts the solid angle covered by the trigger system. The particular shape with cutouts reduces the effective width of the transmission line with respect to 35 mm, in order not to lower

its characteristic impedance substantially below $30\ \Omega$. No Front-End electronics has been used for this test.

The trigger system consists of four RPC detectors selecting cosmic-ray tracks. One of them has a 0.5 mm gas gap (the others are 2 mm wide) and provides a precise time reference ($\sigma_{\text{time}} < 0.5\ \text{ns}$) for the acquired data. In the offline analysis, the signal of the 0.5 mm gas gap is required as fourth trigger chamber and used as confirmation for the efficiency measurement. The trigger signals are amplified and discriminated. Then, a logical unit performs the logic AND of the 4 trigger signals. The trigger rate is 0.5 Hz, which is compatible with the expected rate on the acceptance area ($50 \times 35\ \text{cm}^2$) and covered solid angle.

4.1.2 Gas system

The gas mixtures are obtained with a standard gas system, composed by mass flow meters (MFM) and mass flow controllers (MFC). A special attention was dedicated to the flow measurement of the Cl-HFO whose boiling point, $T=19\ ^\circ\text{C}$, is very close to the room temperature. In order to avoid any risk of gas liquefaction, a small Cl-HFO glass bottle and the relative MFC were kept at the controlled temperature of $T=33\ ^\circ\text{C}$ inside a climate chamber. The scheme of the gas system is shown in Figure 4.3.

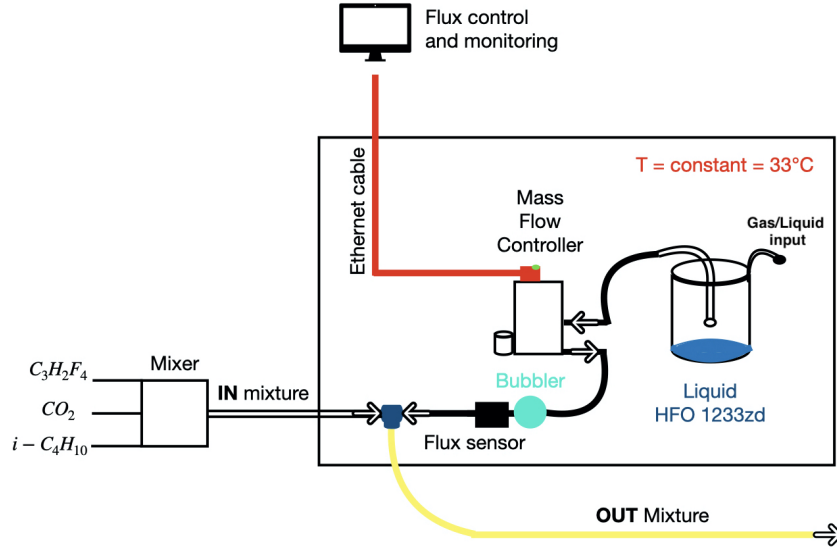


Figure 4.3: Gas system scheme.

The gas pressure inside the bottle, about 1.7 atm, is sufficient to keep a constant flow. Outside the MFM the gas flows through a bubbler and an independent flow sensor. The Cl-HFO is mixed with the other three components (F-HFO/ CO_2 / $i\text{-C}_4\text{H}_{10}$) inside the climate chamber. The resulting gas mixture, once outside of the climatic chamber, can be cooled without liquefaction risk due to the low Cl-HFO partial pressure inside the mixture. As an example in the mixture with 2% of Cl-HFO, liquefaction occurs at temperature much below $-10\ ^\circ\text{C}$. The absolute flux of the new component is evaluated with the flow sensor. The total flux inside the test gas volume is of the order of $\sim 60\ \text{cc/min}$.

4.1.3 DAQ

For each trigger signal, the waveforms produced by the test chamber are recorded on a 4-channel oscilloscope. The measurements described in section 4.2 have been performed with an oscilloscope with an analog bandwidth of 3 GHz and sampling rate of 10 Gs/s, while during those described in section 4.4 a scope with analog bandwidth of 4 GHz and sampling rate of 40 Gs/s has been used. This data acquisition allows storing the maximum amount of information concerning the electrical discharge occurring inside the gas. The prompt signal, generated by the electron drift motion inside the gap, is acquired on both ends of the read-out strip and recorded with different sensitivity scales of the scope. The strip is terminated on both ends with its own $30\ \Omega$ impedance which requires introducing a $75\ \Omega$ resistor in parallel to the $50\ \Omega$ cable connecting the strip to the scope input. The following signals are recorded for each triggered event:

- Prompt signal with the highest sensitivity scale of the scope, thus the best signal-to-noise ratio, in order to detect small signals as required for the detection efficiency measurement;
- Prompt signal with a variable scope scale sensitivity in order to minimize the saturation risk for very large signals generated at operating voltages near to or beyond the streamer appearance;
- Ionic signal generated by the slow drift motion of the ions inside the gas. This signal is read out on a $10\ \text{k}\Omega$ resistor connecting the graphite electrode to ground. A thin metal wire is embedded in the graphite at the electrode edges for minimizing the signal diffusion time, which would abnormally increase the ionic signal duration;
- The prompt signal of the 0.5 mm gap trigger chamber is used to confirm the trigger over a reduced covered area and is assumed as time reference for any timing analysis, due to its improved time resolution (0.5 ns instead of ~ 1 ns of the 2 mm gas gap) .

The time window acquired for the prompt signal, both with high and low-sensitivity scales, is 200 ns wide. This wide window allows detecting unwanted events like streamers if any, occurring much after the first short (few ns) avalanche signal. The acquisition window for the ionic signal is $100\ \mu\text{s}$.

These four waveforms are recorded for any off-line analysis. For each tested gas mixture a voltage scanning is carried out, from near-to-zero efficiency up to the streamer appearance in steps of 100 V, with 300 events acquired at each step. The gas properties depends on the temperature and pressure at which the data-taking is performed. Therefore, these parameters have been monitored and the absolute HV values have been corrected for T and P small variations using the relation:

$$\text{HV}_{\text{eff}} = \text{HV}_{\text{applied}} \times \frac{T}{T_0} \times \frac{P_0}{P} \quad (4.1)$$

being $T_0 = 273.15\ \text{K}$ and $P_0 = 1010\ \text{mbar}$.

For each operating voltage the acquired data allows to measure: detection efficiency, prompt and ionic charges, streamer probability and also to detect anomalous afterpulses produced in the 200 ns window. The offline data analysis has been performed using the ROOT framework [43].

4.1.4 Analysis criteria and measurement strategy

For each triggered event a waveform of 200 ns is acquired for the electron-induced prompt signal (see Figure 4.4.a). A background window of 30 ns is defined, which is supposed to be empty, together with a pulse window of 40 ns in which the signal is expected and searched. In the background interval the average amplitude of the background level is measured and subtracted to the full waveform to eliminate low-frequency noise. The standard deviation is measured in the same interval in order to set a 5-sigma threshold for the discrimination of the genuine signals. The associated avalanche charge is integrated and normalized with respect to the line impedance Z of the read-out strip, in a 10 ns time interval around the maximum. The total prompt charge, including the after-pulses and streamers, is measured by integrating the signal on a 170 ns wide window starting after the background time interval. Moreover, the charge associated with the single avalanche signal is defined as the integrated charge over 10 ns around the avalanche peak. This time window is somewhat larger than the avalanche duration to take into account the time jitter of the trigger with respect to the signal itself. Therefore, concerning the prompt charge, we can distinguish the total prompt charge, integrated on a 170 ns window, from the single avalanche charge integrated over a 10 ns window. The corresponding ionic charge is measured by integrating the ionic signal, detected on a 10 k Ω resistor connected to the ground, on a 100 μ s time window (see Figure 4.4.b).

The time over threshold, used for timing measurement and event discrimination, is defined as the difference between the time at which the signal goes below the 5-sigma threshold and the time at which it crosses the same threshold:

$$\text{TOT} = t_{\uparrow-\text{threshold}} - t_{\downarrow-\text{threshold}} \quad (4.2)$$

In order to measure the time over threshold of streamer events, the time below threshold has been chosen as the last time the signal goes below the threshold in the whole time window acquired.

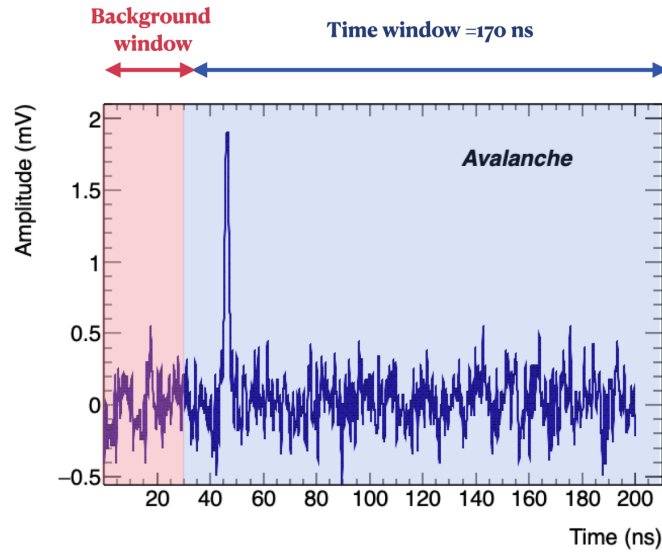
An amplitude threshold has been established for the efficiency calculation, measured with the highest signal-to-noise ratio of the scope. This threshold, constant during the whole data acquisition, has been set as the 5 Root Mean Square (RMS) of the background amplitude and is measured for each acquired waveform. Figure 4.5.a shows that the 5*RMS value during the data taking measured with the 3 GHz-scope is of the order of 1.5 mV, corresponding to almost 150 fC. Figure 4.5.b represents the 5*RMS distribution measured with the 4 GHz-scope. The set of measurements performed with this oscilloscope has a threshold of the order of 0.9 mV, corresponding to almost 90 fC.

Only the events where the confirmation chamber has been efficient have been included in this measurement.

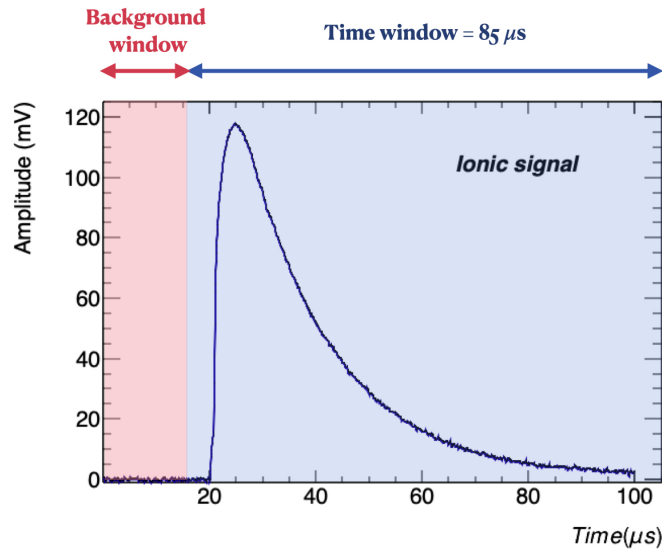
Event definition: avalanche, transition and streamer

Different types of electron prompt signals are classified as follows in order to distinguish the categories established in section 3.3 :

- Pure avalanche: it is a very short single signal, 2-3 ns FWHM in a 2 mm gap, depending on the gas mixture, which is strictly time-correlated with the trigger signal;
- Streamer: it is characterized by an avalanche signal “precursor” followed, after some very fluctuating delay, by a much larger signal lasting tens of nanosec-



(a)



(b)

Figure 4.4: Prompt (a) and (b) ionic signals. The background (red) and integration (blue) windows are shown.

onds. It can be interpreted as a thin column of conducting plasma interconnecting the two electrode surfaces. In the streamer event, the time interval between the avalanche precursor and the streamer appearance is characterized by a multiple avalanche regime and/or by a large tail of the avalanche precursor. The streamers occur usually at voltages above the “knee” of the efficiency plateau. In principle when operating in “avalanche mode”, the absence of streamers is desirable but this strongly depends on the gas-mixture properties;

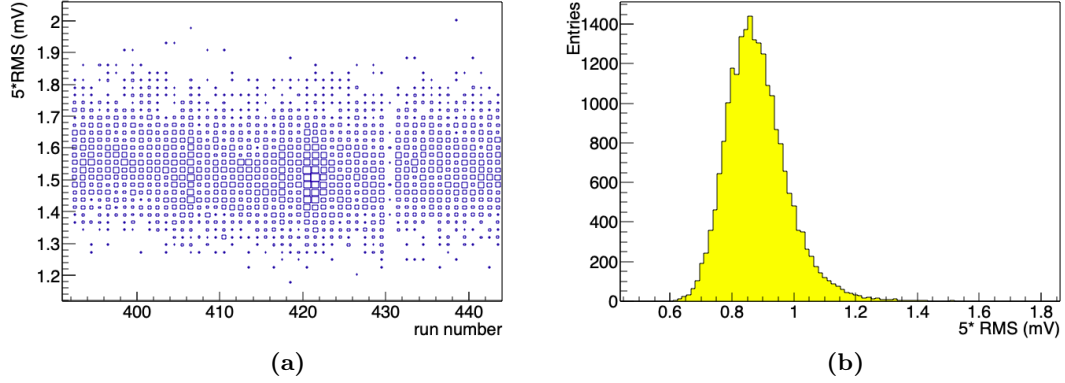


Figure 4.5: (a) 5*RMS as a function of the high voltage for the 3 GHz-scope and (b) 5*RMS distribution measured with the 4 GHz-scope.

- Transition signal: in some cases a multiple avalanche signal and/or a large tail following the precursor, which do not trigger any streamer production, are observed. These events are neither streamers nor avalanches. They are classified in the following as transition signals because they are typical of a high-voltage range where the avalanche-to-streamer transition is gradually happening. These signals are negligible for the standard gas, but relevant in the HFO-CO₂ gas mixtures.

The measured prompt-charge value and the time-over-threshold are the two parameters used for discriminating among the three kinds of events established above, as shown in Figure 4.6. For this purpose the threshold has been fixed to 15% of the maximum amplitude peak in the event. Figure 4.6 shows three well-separated bands associated to the three categories of signals.

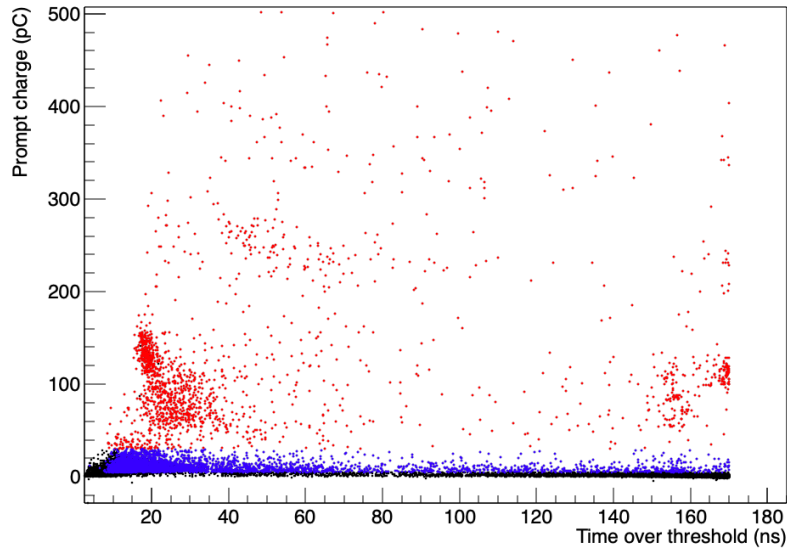


Figure 4.6: Total prompt charge as a function of the time over threshold for all gas mixtures studied. The threshold is fixed at 15% of the signal maximum amplitude. Black points represent the avalanches, the blue one the transition events and the red one the streamers.

A single avalanche is defined by a charge not exceeding 5 pC and a time-over-threshold below 12 ns, which is the typical duration of an avalanche signal in the standard mixture, increased with an adequate margin. A transition signal is defined by the logical OR of two conditions: i) a total prompt charge between 5 pC and 30 pC with a time-over-threshold exceeding 12 ns or ii) the charge integrated over the tail of the signal, excluding therefore the avalanche contribution, exceeding 21% of the total charge associated to the event (called exceeding charge below). A streamer is defined by a total prompt charge above 30 pC and a time-over-threshold exceeding 30 ns. These conditions are summarized in Table 4.1.

Table 4.1: Avalanche, streamer and transition event criteria. The exceeding charge is defined as the charge integrated over the tail of the signal, excluding therefore the avalanche contribution.

Signal type	Prompt charge	Time over threshold	exceeding charge
avalanche	≤ 5 pC	< 12	-
streamer	> 30 pC	> 30 ns	-
transition event	$5 \leq q$ (pC) < 30	≥ 12 ns	> 0.21

4.2 RPC performance with low-HFO1234ze content

The first set of measurements is dedicated to the study of the detector performance operating with F-HFO/CO₂/i-C₄H₁₀/SF₆ as a function of the variation of F-HFO concentration. The range of F-HFO low-concentration explored is (5-25)%, chosen in order to minimize ageing effects as discussed in Section 3.3.

Indeed, for our present understanding, the detector ageing is strictly correlated with the presence and formation of fluorine molecules inside the mixture. These molecules interact with the linseed-oil, producing polymers which attach to the linseed oil, damaging the electrode surface.

Even if the aging is a very more complex physics process, comprising several parameters not yet well known, the number of fluorinated pollutants is certainly one of the parameter to adjust in order to minimize this effect. Therefore, less fluorine molecules inside the gas should improve the detector ageing.

Moreover, the F-HFO is much more electronegative with respect to the C₂H₂F₄. As a consequence the operating voltage moves towards higher values, resulting in a higher operating current and a faster ageing.

Ageing studies on a mixture composed of F-HFO/CO₂/i-C₄H₁₀/SF₆ with 45% of F-HFO show that after a short period of time the current starts to derive, therefore a concentration of 25%, well below 45%, has been chosen as upper limit for this test.

The mixture studied are : F-HFO/CO₂=25/69, 20/74, 15/79, 10/84 and 5/89 with i-C₄H₁₀/SF₆ proportion fixed at 5/1.

Figure 4.7 shows the detection efficiency, the streamer probability and the transition events probability with several F-HFO concentrations. The amplitude threshold for this test is set to 1.5 mV, corresponding to ~ 150 fC. The reduction of HFO produces a decrease of the operating voltage of about 500 V every 5% of HFO reduction. The absolute detection efficiency value, measured with respect to 1.5 mV threshold, is higher than 90%, increasing of 1% with the increase of 5% of HFO content. The mixtures with F-HFO concentration above 15% shows similar efficiency plateau values, around 98%, the same separation between avalanche and streamer operation mode (300 V) and a transition event probability slowly increasing with the increase of F-HFO. Below 15%

the efficiency drops from 98% to 93% and the probability of unwanted events strongly increases.

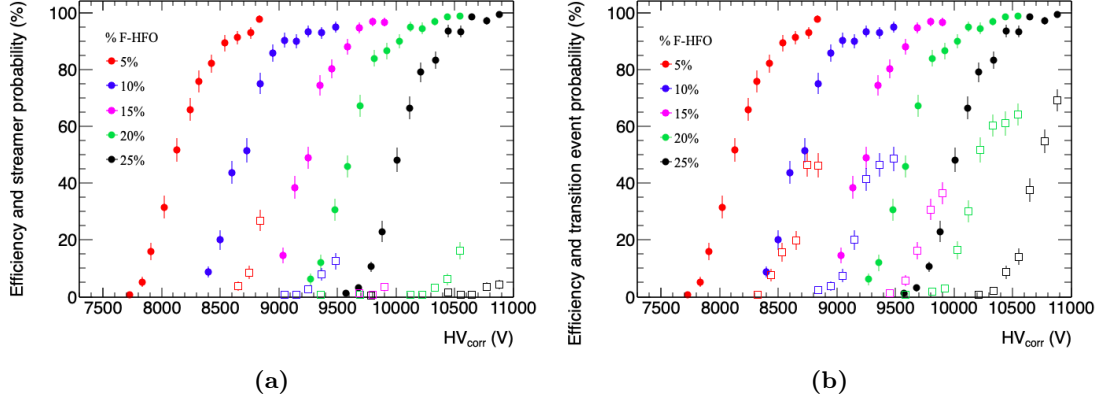


Figure 4.7: (a) Detection efficiency and streamer probability and (b) detection efficiency and transition event probability as a function of the high voltage and F-HFO concentration. The threshold for the efficiency measurement is 1.5 mV, corresponding to ~ 150 fC.

This behaviour is supported by the trend of an increasing charge, shown in Figure 4.8. Both ionic and prompt charges show the same trend above 15%. Below this value the slopes of the curves are steeper and the operating currents increase. The results are summarized in Table 4.2, where the gas mixture parameters of interest are compared at the HV value:

$$HV = V_{\text{knee}} + 200 \text{ V} \quad (4.3)$$

where V_{knee} is defined as the HV value at which the efficiency curve approaches 90%. The comparison with the standard gas mixture is reported as a reference. The eco-gases studied show the detector efficiency plateau value consistent with that of the standard gas and a good separation between avalanche and streamer regime of about 300 V is measured. The HV range streamerless is shorter with respect to the 1 kV range of the standard gas, but sufficient to ensure a comfortable avalanche working mode.

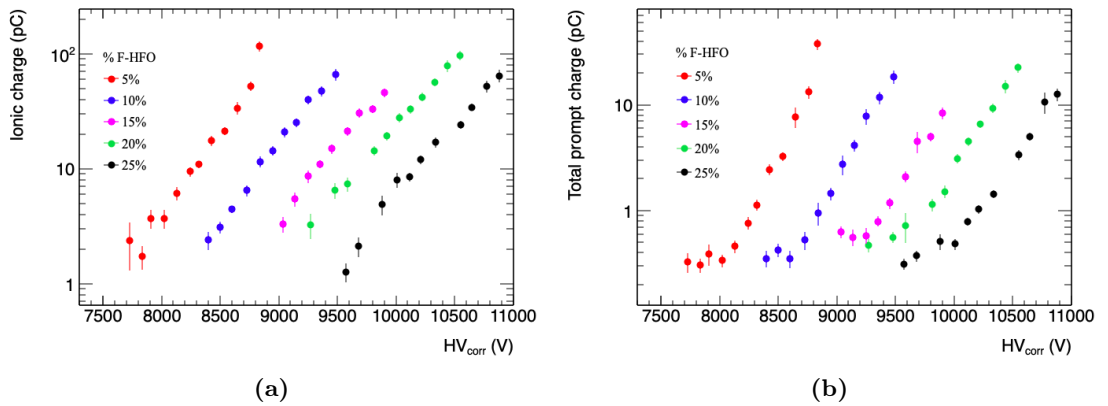


Figure 4.8: (a) Ionic charge and (b) prompt charge as a function of the high voltage and F-HFO concentration.

Table 4.2: Variables under study at the high voltage reference value which is equal to $V_{\text{knee}} + 200$ V. The i-C₄H₁₀/SF₆ ratio is fixed at the ratio 5/1 and the HFO1234ze/CO₂ fractions under study are: 5/89, 10/84, 15/79, 20/74, 25/69

F-HFO %	V_{knee} (kV)	Efficiency @plateau	streamer (%)	extra-charge (%)	prompt charge (pC)	Ionic charge (pC)
5	8.5	93%	8.5	46	11.5	50
10	9	94%	3	41	7	38
15	9.5	96%	0.6	31	4.3	32
20	9.9	97%	0.8	30	4	31
25	10.4	98%	0.7	37	5	34
STD MIX	10.3	99.9%	0	0	3	25

4.3 RPC Performance with different i-C₄H₁₀ concentrations

The aim of the second set of measurements is to study the RPC performance as a function of the i-C₄H₁₀ concentration. The mixtures tested are composed of : CO₂/i-C₄H₁₀ in the proportions (89/5), (84/10) and (79/15), while the F-HFO/SF₆ fraction is fixed at 5/1.

The i-C₄H₁₀ shows excellent properties in cleaning the detector surfaces and in reducing the photoelectron discharge, slowing down the detector aging. Its concentration in the gas mixture is limited by its flammability, not yet measured in HFO/CO₂-based mixtures. Tests with i-butane variable concentrations have been performed with the aim to study the effect of this gas in the streamer suppression and charge decrease. The results obtained varying the i-C₄H₁₀ concentration are shown in Figure 4.9 and 4.10 and summarized in Table 4.3. The increase of i-C₄H₁₀ does not change significantly the operating voltage, but it strongly decreases the streamers, moving them from 8.5% to 1%.

Moreover, the separation between avalanche and streamer/transition charge appearance improves and the prompt and ionic charge are reduced of a factor two using the mixture with the highest i-C₄H₁₀ concentration (15%). These results suggest that the maximization of the i-C₄H₁₀ is the best strategy to dump the charges and to suppress streamer formation. Further tests should be performed in order to fix the flammability threshold of this gas working with the HFOs/CO₂-based gas mixtures.

Table 4.3: Variables under study at the high voltage reference value which is equal to $V_{\text{knee}} + 200$ V. The HFO1234ze/SF₆ ratio is fixed at 5/1. The i-C₄H₁₀/CO₂ fractions under study are: 5/89, 10/84, 15/79.

i-C ₄ H ₁₀ %	V_{knee} (kV)	streamer (%)	extra-charge (%)	prompt charge (pC)	ionic charge (pC)
5	8.5	8.5	46	11.5	50
10	8.45	3.5	46	7.3	37
15	8.4	1	35	5.3	30

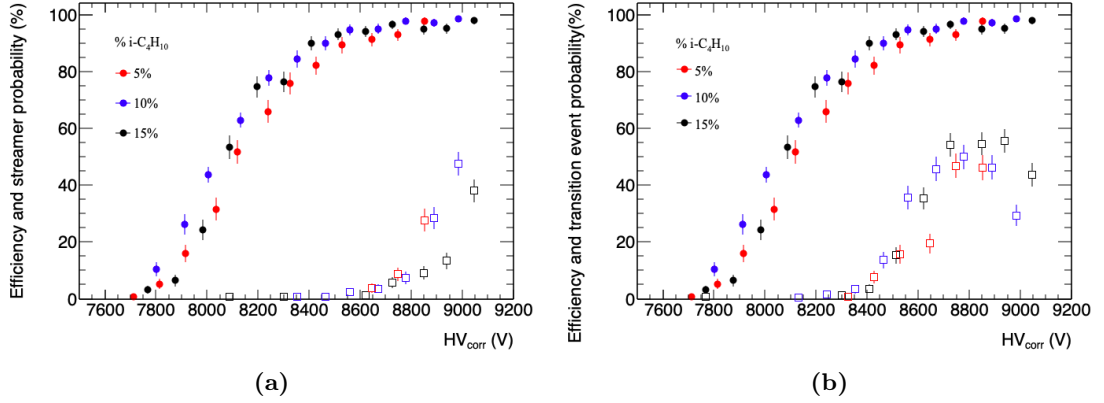


Figure 4.9: (a) Detection efficiency and streamer probability and (b) detection efficiency and transition event probability as a function of the high voltage and i-butane concentration. The threshold for the efficiency measurement is 1.5 mV.

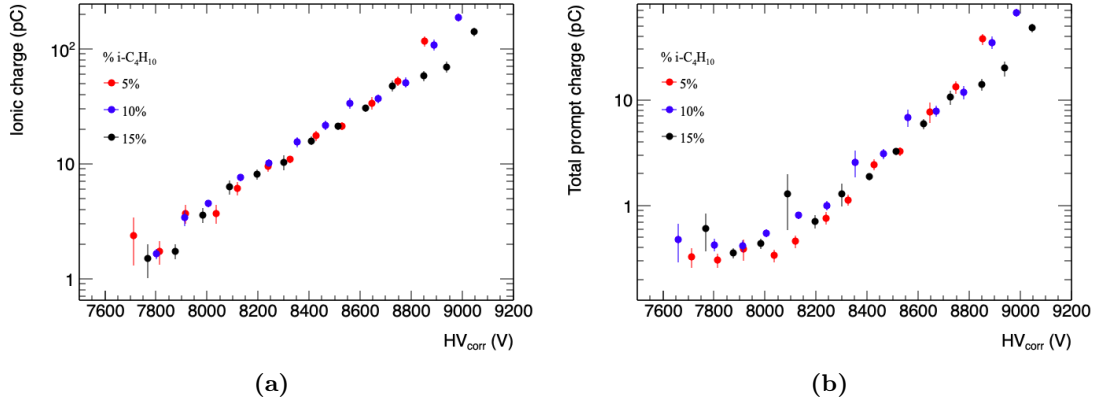


Figure 4.10: (a) Ionic charge and (b) prompt charge as a function of the high voltage. Both efficient and inefficient events are taken into account.

4.4 RPC performance with HFO1233zd

The tests described in section 4.2 suggest that a new eco-gas mixture replacing the standard one could be found according to the following criteria:

- The Tetrafluoroethane is replaced by the C₃H₂F₄/CO₂ mixture, which becomes the main component of the new gas mixture;
- The i-C₄H₁₀ should be kept at 7%. Its concentration can vary depending on the exact value of the mixture flammability without affecting the RPC performance.

In this section the possibility to replace the SF₆ with C₃H₂F₃Cl (HFO1233zd) is explored. Previous studies show that Cl-HFO concentration above 10% moves the operating voltage towards very high values, near to the instrumentation limit[39], suggesting that this gas component concentration must be only of the order of few percent. The tests are performed on an RPC working with the 4-component gas mixture of: F-HFO/CO₂/i-C₄H₁₀/Cl-HFO, with HFO/i-C₄H₁₀ kept at constant concentration of 15% and 7% respectively and CO₂/Cl-HFO ratio ranging from 77/0 to 71/6 in steps of 1%. The 15% F-HFO concentration has been chosen in order to maximize the impact

of the Cl-HFO, adding it in an environment with very low quenching power. This value can be adjusted to reach higher efficiency plateau once the ageing effect will be studied. Moreover, these results strongly depends on the threshold used for the test, therefore the current behaviour, thus the ageing and the rate capability, could be improved lowering the FE threshold, as will be shown in Section 6.

4.4.1 Efficiency studies

Detection efficiency and streamer probability as a function of the high voltage is reported in Figure 4.11 for all the mixtures with different $\text{CO}_2/\text{Cl-HFO}$ ratio. The amplitude threshold is around 0.9 mV, corresponding to ~ 90 fC.

According to Figure 4.11 the effect of Cl-HFO on the RPC performance can be summarized as follows:

- The operating voltage increases at the rate of about 400 V/1% Cl-HFO, two times the rate observed using the F-HFO;
- The detection efficiency at the knee of the plateau is at least 93% for all the gas mixtures studied;
- The mixture not containing Cl-HFO shows a substantial overlapping between the operating voltages of the avalanche and streamer modes, the streamer contamination being about 35% at the plateau knee;
- For all mixtures containing Cl-HFO the avalanche-to-streamer separation, defined as the voltage range between the plateau knee and the voltage at which the streamer probability is 10%, is about 400 V.

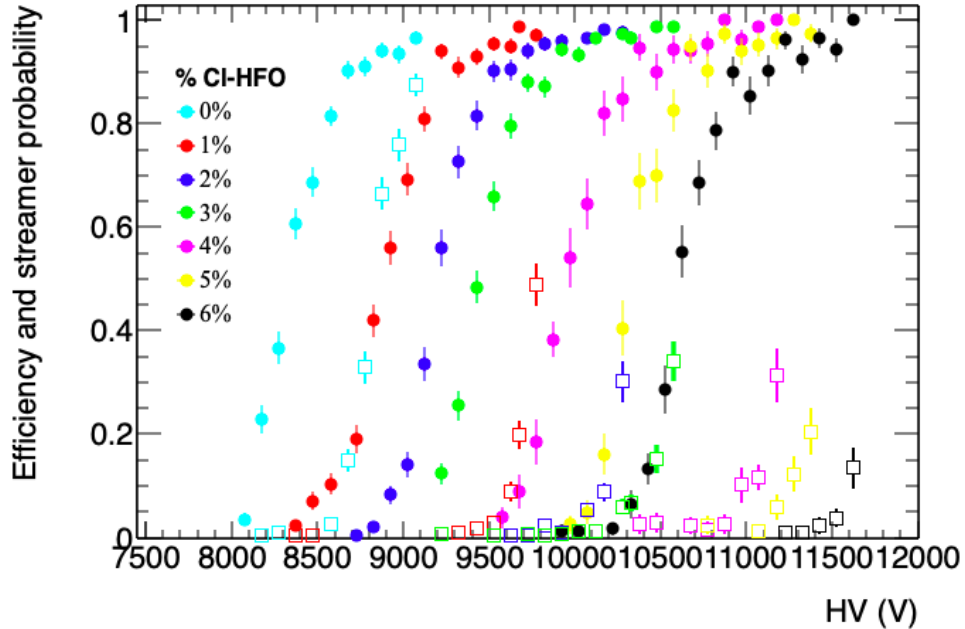


Figure 4.11: Efficiency and streamer probability as a function of the high voltage for different Cl-HFO concentrations. The blank markers are referred to the prompt efficiency, while the empty markers represent the streamer probability.

In order to evidence shape differences among different plots in Figure 4.11, all plots have been aligned at the high-voltage value corresponding to 50% detection efficiency. The results, reported in Figure 4.12, show that all efficiency plots have the same shape. The good overlapping ($\chi^2/\text{ndf} = 1.07$, see Figure 4.16) shows that the difference among different Cl-HFO concentrations is just a displacement along the high-voltage axis with zero impact on the rise of the efficiency curve and efficiency absolute value. On the contrary, the streamer probability, Figure 4.12.a, aligned with the same rule, decreases for increasing Cl-HFO concentration. This effect is very strong up to 2% concentration and much weaker above, giving comparable streamer curves. Figure 4.12.b shows the transition signal probability as a function of the high voltage. Differently from the streamers, all the plots with Cl-HFO concentration above 1% have the same behaviour. The decreasing probability indicates the transition to streamer mode. For Cl-HFO concentration equal to zero, no transition charges are observed because the transition to streamers occurs at the very beginning of the efficiency curve. Further analysis on transition events will be presented in section 4.4.3.

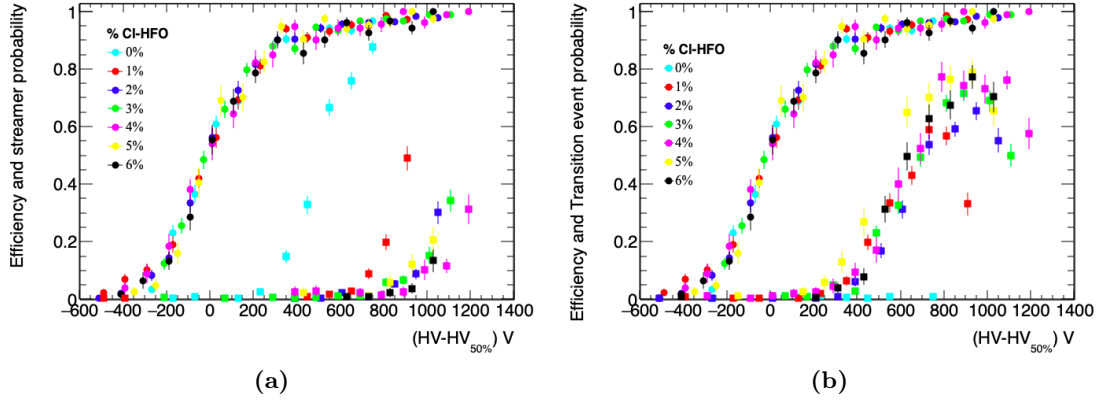


Figure 4.12: Efficiency and streamer probability (a) and transition event probability (b) as a function of the high voltage for different Cl-HFO concentrations. The curves have been aligned respect to the high voltage value which corresponds to the 50% of efficiency. The transition event probability grows until a maximum and then starts to decrease due to the transition to streamers.

4.4.2 Charge studies

In Figure 4.13 the ionic charge as a function of the high voltage is shown, using the same HV shift as in the previous plots. The results can be summarized as follows:

- The ionic charge of the mixture without Cl-HFO reaches very high values (~ 75 pC) at low efficiency due to premature streamer appearance;
- The mixtures with Cl-HFO concentration in the range (1%-4%) show a total charge between 20 and 30 pC up to 300 V above the operating voltage and a slower rise;
- The gas mixtures with 5% and 6% of Cl-HFO content have a ionic charge exceeding 30 pC at the first plateau point and reach very high values at the operating voltage, due to the much higher operating field;

- The mixture with 1% of Cl-HFO shows the lowest ionic charge in the first three plateau points, but has a fast rise due to the premature streamer appearance.

These results suggests that the mixture with about 2%-3% of Cl-HFO should be the best one regarding both avalanche-streamer separation and total charge delivered inside the detector considering the charge threshold chosen for the efficiency measurements.

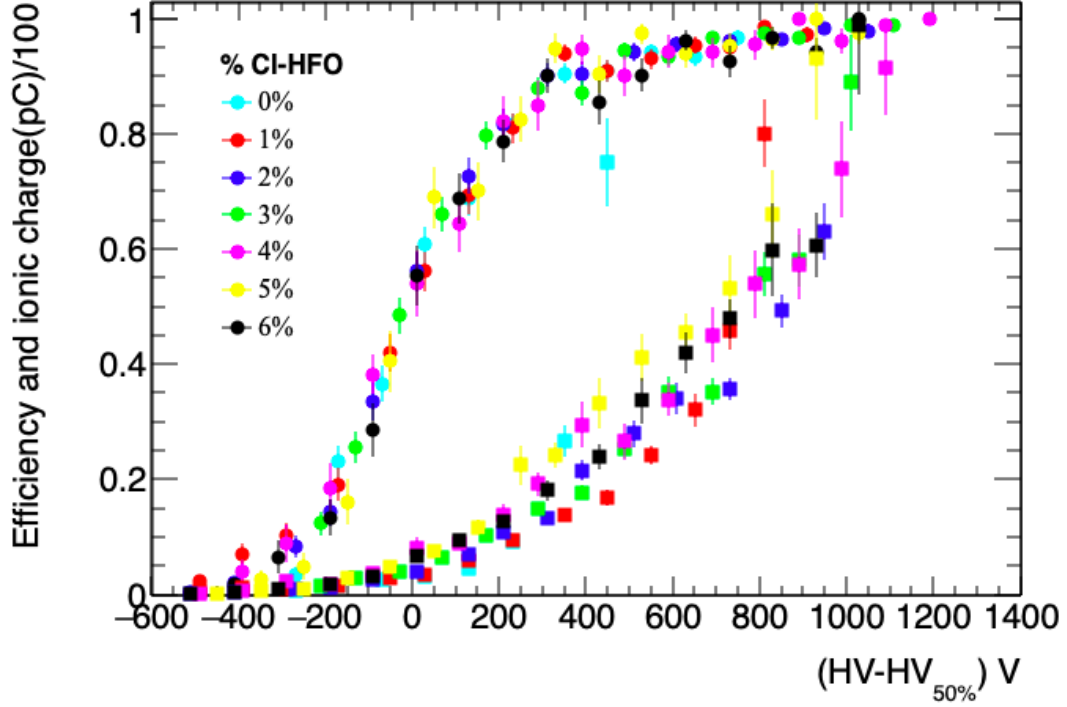


Figure 4.13: Efficiency and ionic charge as a function of the high voltage for different Cl-HFO concentrations. The curves have been aligned respect to the high voltage value which corresponds to the 50% of efficiency.

4.4.3 Study of the transition events

In Section 3.4 the transition events have been interpreted as streamer precursors, thus associated to the very first step of the physics process evolution which leads to streamer formation. This implies that transition events must share well defined properties typically of that specific physics process and solely related to it. Therefore, there must be physics observables which confirm this hypothesis and remark the separation between avalanche, streamer and transition events classification. The total prompt charge as a function of the time-over-threshold, previously shown in Figure 4.6, is one of them. In that case three well-separated bands have been observed, corresponding to the different shapes of these three categories. In this way the criteria for defining these events typical of the HFO/CO₂-based gas mixtures has been experimentally established, merging the results obtained with about 100 different gas mixtures.

Another discriminant between these three categories can be found in the correlation between the total charge delivered inside the gas associated to each event (ionic charge) and the total electronic induced charge that is detected and recorded in the three cases. Figure 4.14 shows the distributions of the ionic-to-prompt charge ratio of avalanche, streamer and transition signals for different Cl-HFO concentrations. These plots strongly

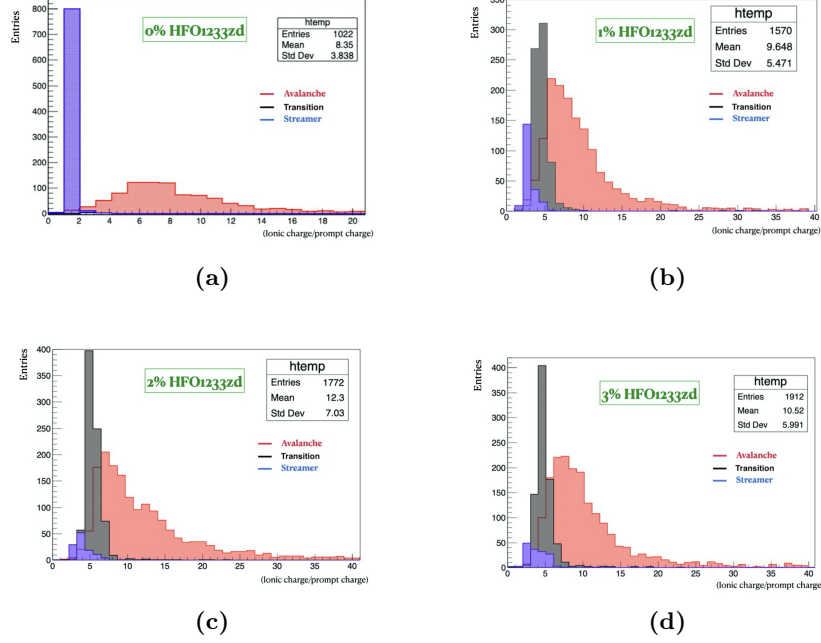


Figure 4.14: Ionic/prompt ratio of avalanches, streamers and extra charges for different Cl-HFO percentages: (a) 0%, (b) 1%, (c) 2% and (d) 3%.

support the classification of the observed waveforms as avalanches, streamers, and transition signals, showing that it is not arbitrary but based on different physical properties of each category. Indeed, purely exponential models of the avalanche growth give:

$$q_{\text{ionic}}/q_{\text{prompt}} = \alpha g \sim 10 \div 12 \quad (4.4)$$

being α and g the Townsend coefficient and the gas gap size respectively. The interpretation of the streamer as a plasma column where electrons and ions are uniformly distributed gives $q_{\text{ionic}}/q_{\text{prompt}} = 1$. The addition of an electronegative quenching, like Cl-HFO or F-HFO, generates the category of the transition signals as a mixing of avalanche and streamer properties. Moreover, it also reduces, to some extent, the difference between avalanches and streamers increasing the ionic/prompt value from 1 to few units.

This interpretation is supported also by the trend of the transition and streamer events probability as a function of the voltage applied, previously shown in Figure 4.12. The trend of the transition event probability is a function which increases with the high voltage until a maximum is reached. Above this value, it starts to decrease at higher field. The inversion point, thus the maximum probability value, corresponds to the last operation point streamer-free. Above this value, a fraction of the transition events turns into streamers. As a consequence, the mixture with 1% of Cl-HFO fraction shows an anticipated decrease of transition events, being the rise of the streamer curve steeper with respect to the other gas mixtures. Moreover, the mixture with zero Cl-HFO does not show any transition event but the overlapping between avalanche and streamer regime just above 80% efficiency, due to the lack of any "streamer-quencher" gas.

In sight of RPC operation in high radiation environment, the impact of these additional signals on the performance in terms of time properties and charge content has been studied. For what concerns the charge, the contribution of these events is totally taken

into account in the ionic charge measurement, reported in Figure 4.13. The total charge value at the operating voltage comprises avalanche, transition and streamer contributions and has been already discussed. The other point to stress concerns the duration of these events, which could be problematic in terms of timing performance and FE electronics operation. In order to discuss this point, the mixture with 2%Cl-HFO has been taken as a reference, but the results can be extended to all gas mixtures containing this gas.

Figure 4.15 shows the efficiency and transition probability curve of this gas mixture, together with the time-over-threshold distribution of the transition events within the plateau of operation of the RPC (red area). The distribution shows that most of the transition events have a time-over-threshold less than 20 ns, below the LHC bunch crossing (25 ns). This result, together with the observation that the probability to observe a transition event in coincidence in a system composed by more than one RPC (as ATLAS) strongly decreases, suggests that the correct identification of the bunch crossing and the timing performance won't be affected by these events. As a conclusion, the RPC can operate also in presence of these events without showing any worsening of the performance.

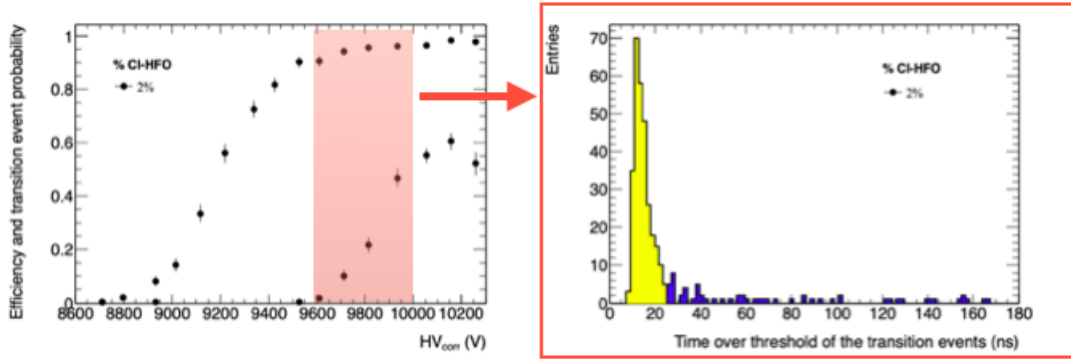


Figure 4.15: Time-over-threshold of transition events in the HV range of RPC operation with the gas mixture containing 2% Cl-HFO.

4.4.4 Fit analysis

The results described in section 4.4.1 show that, after aligning the high voltage scale to the 50% efficiency point for all plots, the efficiency curves have the same profile. The plot summarizing all experimental data contains 97 points and offers therefore an excellent opportunity to find an adequate fitting function.

The data analysis requires indeed interpolating functions that allow correlating with continuity different quantities without the constraint of limiting the correlation to the values of the experimental points.

It should be stressed that the functions used to fit the several physics observable are not based on physical models. They are just suggested by the similarity between the shape of the fitting function and the experimental plot. The following fitting functions are used:

- The detection efficiency as a function of the high voltage is usually fitted with the Fermi function. In this case the trend of the efficiency plateau shows a systematic slow rise after the knee. Therefore a "double-Fermi" function fit is used :

$$f(x) = \frac{p_0}{1 + e^{\frac{p_1 - x}{p_2}}} + \frac{1 - p_0}{1 + e^{\frac{p_3 - x}{p_4}}}; \quad (4.5)$$

- The streamer probability vs HV curve has been fitted single Fermi function fit:

$$f(x) = \frac{p_0}{1 + e^{\frac{p_1 - x}{p_2}}}; \quad (4.6)$$

- Transition events vs HV: Landau-type fit. This fit reproduces the fact that the transition-event probability grows, reaching a maximum at the first streamer appearance, and then slowly decreases as the streamer probability increases;
- Prompt and ionic charge vs HV: multi-degree polynomial fit.

The quality of the double-Fermi function fit is shown in Figure 4.16 where a 5-parameter function can fit 97 experimental points with an excellent χ^2/ndf (1.07).

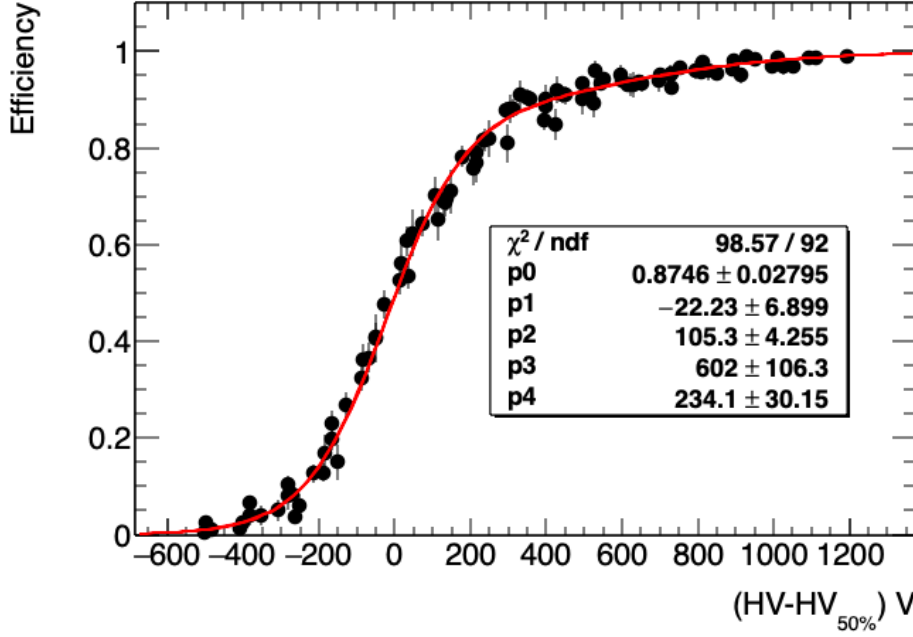


Figure 4.16: Fit result on the global efficiency curve using the double-Fermi function.

4.4.5 Comparison of gas mixtures with different Cl-HFO concentrations

The choice among mixtures fulfilling the crucial prerequisites of non-flammability and environment-friendship is mainly based on the total charge/pulse delivered in the gas. Indeed, the lower this charge the lower the operating current and therefore the higher the rate capability. This is subject anyway to the condition that the signal has to pass the front-end electronics discrimination threshold in order to be detected.

The optimal choice of the Cl-HFO fraction is based on the criteria of minimizing both streamer fraction and total delivered charge per pulse, at efficiency $\geq 95\%$.

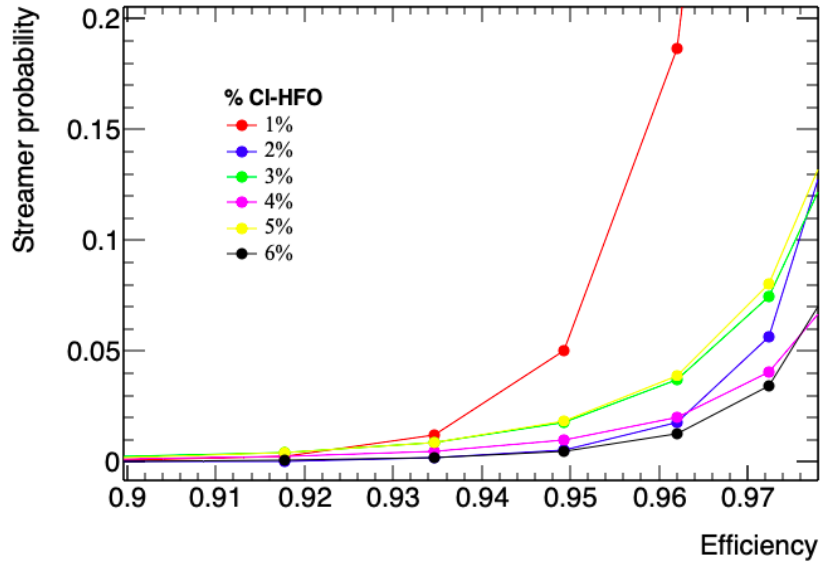


Figure 4.17: Streamer probability as a function of the efficiency and Cl-HFO concentration.

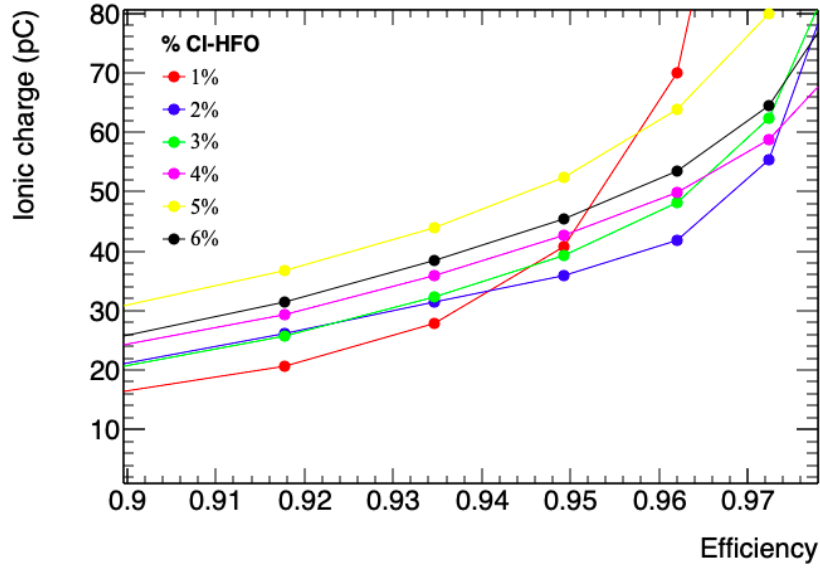


Figure 4.18: Ionic charge as a function of the efficiency.

These data are reported in detail in Figure 4.17 and Figure 4.18 respectively and summarized in Table 4.4 and Table 4.5. The values are extrapolated from fit results. According to these tables the optimal concentration is about 2%. However, the range (3-6)% gives good performance anyway taking also into account that the final choice has to include other parameters, like for example the aging, that are not yet measured.

4.5 Comparison with the standard gas mixture

From the previous section the mixture with 2%-Cl-HFO appears to be the most suitable in terms of avalanche-streamer high-voltage separation and total charge delivered inside the detector.

Table 4.4: Streamer and transition events probability for the tested mixtures at different efficiency values.

	% Cl-HFO	0	1	2	3	4	5	6
Efficiency 90%	streamer(%)	20	0	0	0	0	0	0
	transition event (%)	0	11	5	5	7	25	9
Efficiency 95%	%streamer	86	5	0	2	1	2	0
	%transition event	0	50	45	54	57	74	60
Efficiency 96%	%streamer	92	20	2	4	2	4	1
	%transition event	0	51	57	65	70	77	70

Table 4.5: Ionic and prompt charges of the tested mixtures at different efficiency values.

	% Cl-HFO	0	1	2	3	4	5	6
Efficiency 90%	Ionic charge (pC)	45	15	20	20	23	30	24
	Prompt charge (pC)	27	2.4	2	2.2	2.7	4	2.5
Efficiency 95%	Ionic charge (pC)	240	40	36	39	42	52	45
	Prompt charge (pC)	209	10	6	7	7	9	7
Efficiency 96%	Ionic charge (pC)	270	70	42	48	50	62	53
	Prompt charge (pC)	241	19	8	9	9	11	9

The performance comparison between the gas mixture composed of F-HFO/CO₂/i-C₄H₁₀/2%Cl-HFO and the standard gas mixture (C₂H₂F₄/i-C₄H₁₀/SF₆) is shown in Figure 4.19.

The two gas mixtures have the same HV working point value, but the standard gas mixture shows a steeper rise of the efficiency curve.

The avalanche-streamer separation of this eco gas mixture, shown in Figure 4.19.a, even if not at the same level of the standard one, allows anyway an efficient streamerless operation in avalanche mode (400 V).

Figure 4.19.b shows the transition event probability as a function of the high voltage. This plot suggests that in the standard gas mixture the transition events represent only a very small negligible fraction (below 5%) at high field, supporting the hypothesis previously made about the origin of these events. It also confirms that the transition regime is typical of the mixtures with high CO₂ value and low-quenching power.

The ionic charge, shown in Figure 4.19.c, has a steeper rise in the ecogas, but its absolute value, at the working point, is only few pC greater than that measured with the standard gas (30 pC vs 25 pC).

The total prompt charge distribution of the eco mixture with 2% Cl-HFO is shown in Figure 4.20 for different efficiency values, and compared to Figure 3.4. These distributions show a clear peak up to 90% efficiency. For higher efficiencies the distributions become much broader due to the appearance of the transition events.

The time resolution has been measured with the time-of-flight (TOF) method, using the 0.5 mm gas gap as time reference. The time of flight is the difference between the threshold crossing time in the reference chamber and the signal peak time in the test chamber. The TOF distribution with the eco gas mixture is shown in Figure 4.21, to be compared with that of the standard gas previously shown in Figure 3.6. The corresponding time resolutions are:

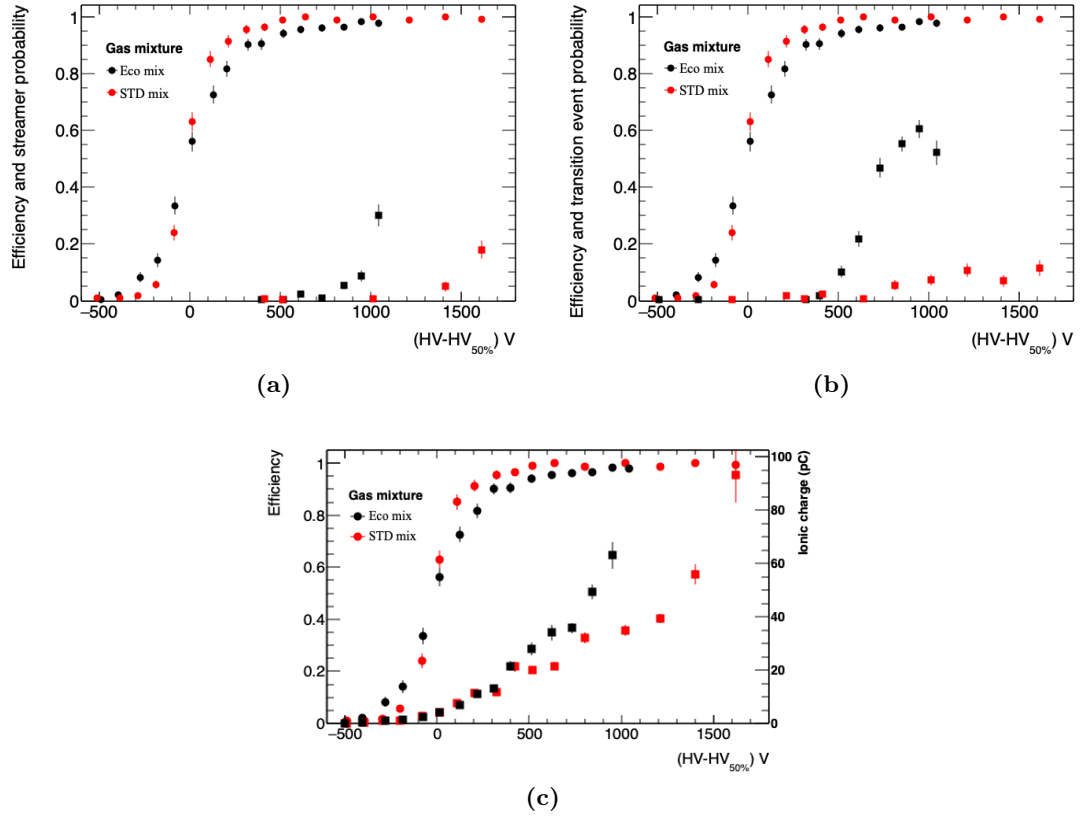


Figure 4.19: Efficiency and (a) streamer probability, (b) transition event probability and (c) ionic charge as a function of the high voltage for the standard and eco gas mixtures.

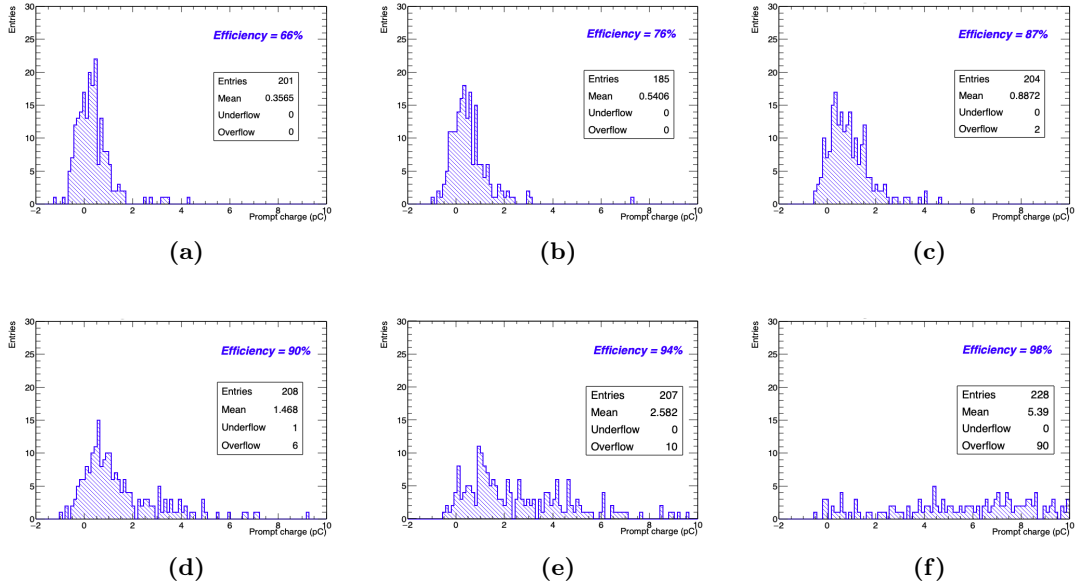


Figure 4.20: Total prompt charge distributions at different efficiencies for the eco-gas mixture composed of $\text{CO}_2/\text{F-HFO}/\text{i-C}_4\text{H}_{10}/\text{Cl-HFO}=76/15/7/2$.

$$\sigma_t^{\text{Eco}} = (0.83 \pm 0.03)\text{ns}$$

$$\sigma_t^{\text{Standard}} = (1.09 \pm 0.07)\text{ns}$$

These TOF distributions do not contain any kind of corrections for systematic effects due to :

- Contribution of the reference chamber time resolution;
- Different propagation time of the signal in the confirm and test chamber due to the angular distribution of the cosmic rays;
- Presence of multiple peaks merged together which might broaden the signal waveform.

The comparison between the two distributions shows a time resolution improvement of the new gas, of about 24% better than that obtained with the standard mixture. This is explained with the higher drift velocity of the CO_2 with respect to the $\text{C}_2\text{H}_2\text{F}_4$.

The better timing properties of the new gas are confirmed by the signal rise time comparison shown in Figure 4.22. The rise time is defined as 20% to 50% of the maximum amplitude and is 0.3 ns shorter in the ecogas mixture. For fraction of the maximum amplitude $> 50\%$, the rise time could be affected by multi-peak events.

These results show, for the first time, that an RPC detector has excellent performance with a totally eco-friendly gas mixture.

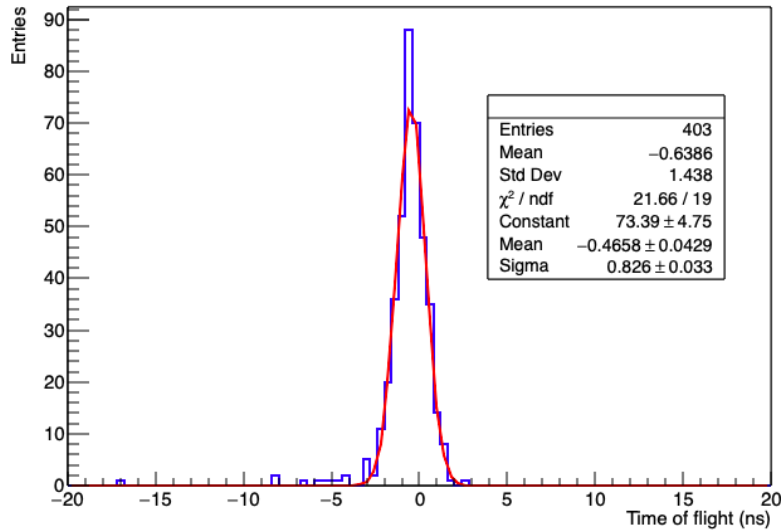


Figure 4.21: Time resolution for the eco mixture ($\text{CO}_2/\text{F-HFO}/\text{i-C}_4\text{H}_{10}/\text{Cl-HFO}=76/15/7/2$)

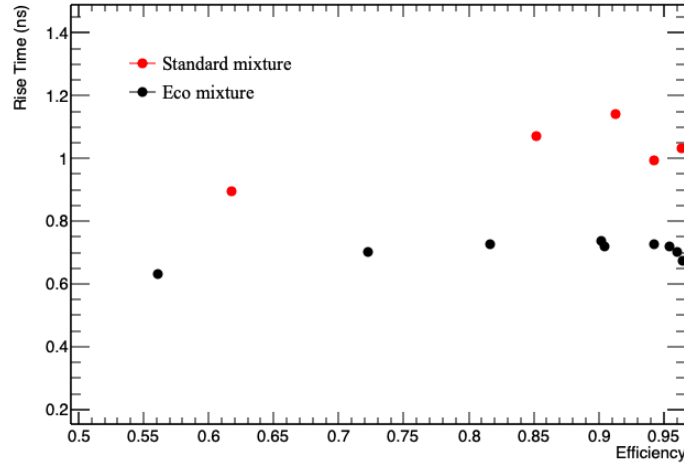


Figure 4.22: Rise time as a function of the efficiency for the standard and eco mixture. The eco mixture rise time is about 0.3 ns shorter.

4.6 Performance comparison between HFO1233zd and SF₆

The experimental results suggest that Cl-HFO is a very high electronegative gas and has properties suitable for streamer suppression. In the standard mixture and in the eco-friendly gas mixture already tested, the SF₆ plays the role of streamer suppressor. This component has a GWP=23900, while the Cl-HFO has a GWP ~ 7 . In this section a detailed comparison between the SF₆ and the Cl-HFO properties is made. Mixtures composed of F-HFO/i-C₄H₁₀ = 15/7 and i) CO₂/SF₆ = 77/1 or ii) CO₂/Cl-HFO = 76/2 are compared.

The efficiency as a function of the high voltage is shown in Figure 4.23.a. The operating voltage of the mixture with Cl-HFO is 450 V higher than the one applied with SF₆. Both efficiency curves show a plateau knee at 90% efficiency followed by a slow efficiency increase up to 96% where the first streamer appears.

The difference between the voltage knee and the streamer appearance is about ~ 400 V for both mixtures and the streamer growth is steeper in the mixture with SF₆.

The efficiency curves as a function of the ionic charge (Figure 4.23.b) show that the two mixtures have the same ionic charge at the same efficiency value.

This result suggests that the Cl-HFO can substitute the SF₆ in these gas mixtures, leading to the possibility to work with a totally environment-friendly gas mixture.

4.7 Conclusions

In this chapter performance studies carried on an ATLAS-like RPC(2 mm gas gap wide and 1.8 mm thick electrode) operating with several eco-friendly gas mixtures are summarized.

The gas mixtures tested are composed of CO₂/C₃H₂F₄(HFO1234ze)/i-C₄H₁₀/SF₆ and have a GWP ~ 229 , totally due to the SF₆. The composition of the mixtures has been chosen in order to minimize the HFO1234ze concentration and maximize the i-butane percentage. Less HFO in the gas mixture results in a smaller production of fluorine pollutants that can damage the detector surfaces and accelerate the aging process. The

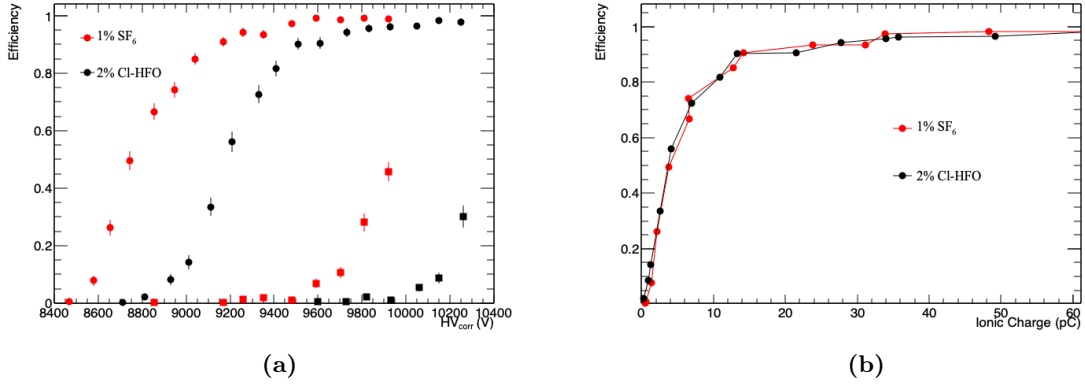


Figure 4.23: Efficiency as a function of (a) the high voltage and (b) of the ionic charge for gas mixtures composed of 77%CO₂/15%C₃H₂F₄(HFO1234ze)/7%i-C₄H₁₀/1%SF₆ (red) and 76%CO₂/15%C₃H₂F₄/7%i-C₄H₁₀/2%C₃H₂ClF₃(black).

ATLAS experience showed that the i-butane has a very good effect in cleaning the electrode surfaces, suggesting that its concentration should be increase as much as possible. This possibility is currently limited on the gas flammability, not yet measured in these eco-gas mixtures.

The results show that the composition of the new mixtures is not critical with respect to its components and can be summarized as follows:

- The RPC performance are not degraded using a C₃H₂F₄ content in the range (25-15)% in terms of detection efficiency (> 90%), avalanche-streamer separation (~350 V) and charge delivered inside the gas (< 30 pC). The final choice of the C₃H₂F₄ content in this range depends on the ageing properties that are not yet measured;
- The i-butane has a strong effect in dumping the charge and delaying the streamer appearance. Its concentration, limited by its flammability, must be optimize to be as large as possible. However, a small change of its concentration, around few percents, does not affect the detector performances;

An alternative gas to the SF₆, the C₃H₂ClF₃, has also been studied. Gas mixtures composed of CO₂/C₃H₂F₄/i-C₄H₁₀/C₃H₂ClF₃ have a GWP of few units and a ODP near to zero, therefore totally environment-friendly. Performance tests using this gas mixture show the following main results:

- The efficiency is above 93% using 15% F-HFO concentration. The possibility to increase the F-HFO concentration must be evaluated after the results from aging studies;
- The operating voltage interval separating the avalanche from the streamer working mode, ~ 350 V, is sufficient to ensure a streamerless operation in avalanche mode;
- This new component has a boiling point of 19 °C, very close to the room temperature, and its use requires therefore some precautions. However, its low concentration, around 2%, does not produce any constraint for the mixture temperature: once this gas is mixed with the other components, the temperature can be lowered down to -10 °C without any risk of liquefaction;

- The ecogas mixture shows a better time resolution than the one measured using the standard gas.

These new gas mixtures show a new category of signals, the transition signals, which are negligible in the standard gas mixture and have intermediate characteristics between avalanche and streamer. These events carries higher charge and have longer duration with respect to the avalanche ones, but do not represent a critical issue for the RPC performances.

Chapter 5

Results: Test with muon beam and under irradiation on ATLAS legacy RPC

5.1 The Gamma Irradiation Facility++

In this section the experimental setup built for the test with the muon beam and under photon irradiation, shown in Figure 5.1, is described. The tests are performed

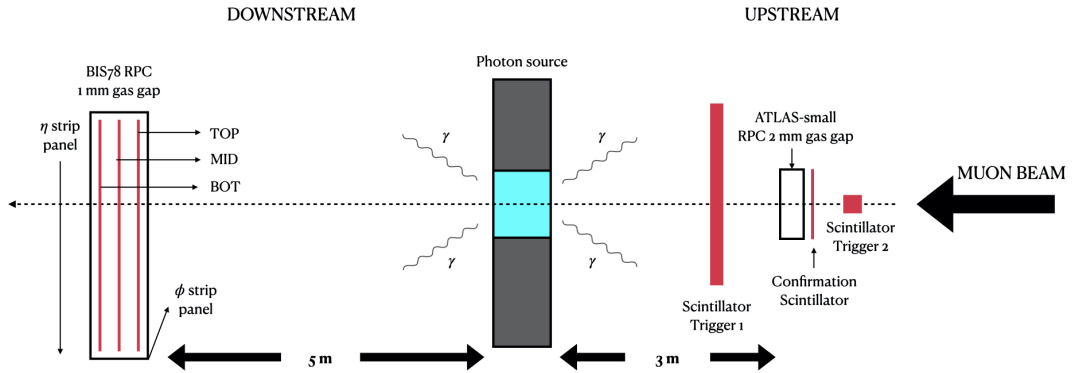


Figure 5.1: Scheme of the experimental setups at the GIF++ (lateral view).

at the Gamma Irradiation Facility (GIF++) [44], located at CERN Preveessin site. The GIF++, shown in Figure 5.2, is a 100 m² bunker located near the end of the H4 beam line, which combines a 14 TBq ¹³⁷Cs source and a high-energy muon beam (100 GeV/c²) coming from the secondary SPS beam line. It was built to study the performance of the detectors under high particles flux and their ageing, which are crucial parameters for the certification to work in the LHC cavern.

The irradiator provides two large radiation fields with individual attenuation system and defines two separate areas, upstream and downstream the irradiator with respect to the beam direction. Large and small-size detectors are located in these zones and are tested in presence of different background radiation levels up to HL-LHC-like irradiation.

The muon beam is mainly generated by pions and kaons decays that are produced in the primary target. The muon momentum can vary from 10 GeV/c up to the maximum SPS momentum of 450 GeV/c and the core of the beam, containing half of the entire

beam, covers a surface of $S \sim (10 \times 10) \text{ cm}^2$. The beam halo is spread over a footprint of about 1 m^2 .

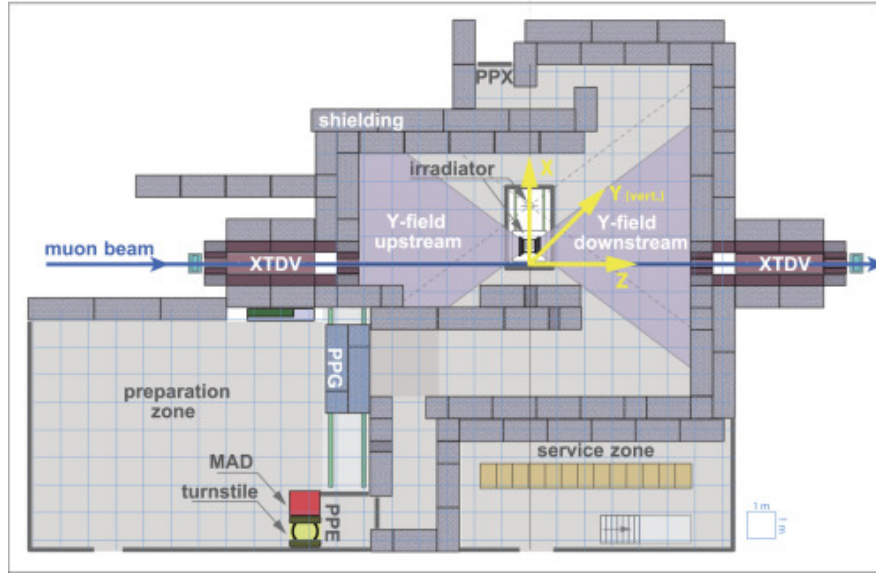


Figure 5.2: The Gamma Irradiation Facility (GIF++).

5.1.1 The photon source

The ^{137}Cs source, shown in Figure 5.3, is embedded between two Tungsten blocks and has two collimators ($\pm 37^\circ$) covering both downstream and upstream areas and produces photons with energy of 662 keV. Both outlets are equipped with an Aluminium

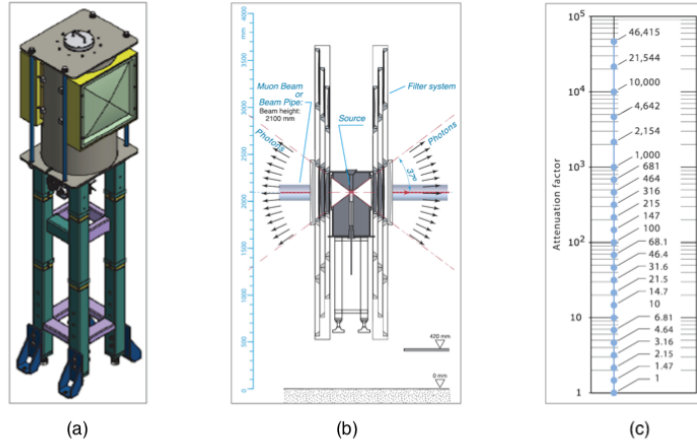


Figure 5.3: (a) The ^{137}Cs source, (b) the filter system and (c) nominal attenuation factors.

angular correction lens to provide a uniform photon flux distribution. The flux can be modulated independently in the upstream and downstream areas, using two attenuation systems made of an array of lead attenuation filters. The filters are mounted on aluminium support plates and are positioned inside steel frames used as collimators, and are connected to counterweights moving on the sides of the irradiator.

The filter system consists of three planes of filters, with three filters per plane which can

provide 24 different nominal attenuation factors. The factors are chosen to be nearly equidistant, on a logarithmic scale, over the first three order of magnitude (Figure 5.3.c). The irradiator and the filter system are mounted on rails, so that the whole assembly can be moved in the muon beam transverse direction. The convex shape of the attenuation filters let the photons go through the same material thickness and thus undergo the same attenuation at each position of the filter.

The effective total attenuation over the whole spectral range is lower than the nominal attenuation because of the presence of lower energy photons and it will depend on the spectral sensitivity of the detector used, as well as on the presence of other objects in the bunker.

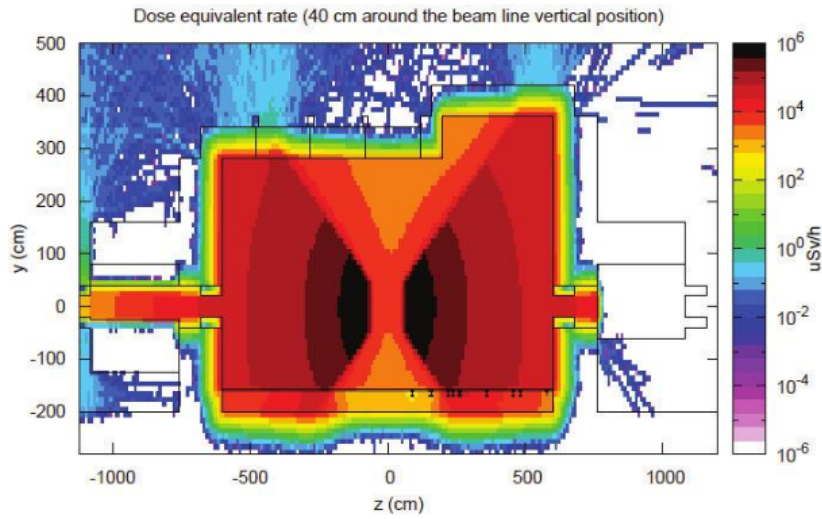


Figure 5.4: Simulation of the equivalent dose rate in $\mu\text{Sv/h}$ in the GIF++ bunker.

Figure 5.4 shows the simulated dose equivalent rate in $\mu\text{Sv/h}$ for the irradiation without angular correction lenses or attenuation filters. In the direct irradiation zones, 1 Sv/h is reached at a distance of one meter from the source. Due to multiple scattering of photons in the bunker area, the dose rate stays above several mSv/h throughout the whole centre zone. In the main access path, 0.1 mSv/h can be expected.

5.2 ATLAS RPC legacy : experimental apparatus

The ATLAS-RPC legacy setup is located in the upstream area (see Figure 5.1) at 3 m from the photon source.

5.2.1 Trigger and RPC under test

The RPC detector under test is the 2 mm gas gap RPC described in Section 4.1.1. The trigger consists of five scintillators coincidence. Two scintillators, provided by the GIF++, are used to build the rough trigger and are located outside the bunker. Two large-area scintillators ($10 \times 40 \text{ cm}^2$), orthogonal to each other, are located inside the bunker, upstream and downstream of the test chamber and are used to focalize the trigger beam in a smaller area. Another scintillator, with the same RPC strip dimension of $(3.5 \times 55) \text{ cm}^2$, is mounted on the RPC mechanics and is aligned with the readout strip. In this way the acceptance is improved, being the RPC strip lateral dimension

much smaller than the beam spot. The estimated geometrical inefficiency is of the order of 2%.

5.2.2 DAQ

For each triggered event a time window of 500 ns is acquired using a digitizer (14 bit @ 500 Ms/s). The signals acquired and used for the further analysis are:

- Coincidences between the external and internal scintillators (hardware trigger), used as input trigger of the digitizer;
- Signals of the small-size scintillator, used as trigger confirmation for the offline analysis;
- RPC signals, read on one side of the strip line without amplification.

For each gas mixture an HV scan from zero efficiency to full efficiency (~ 13 HV values) at different irradiation intensities is performed. The absorption factors (ABS) used varies from zero source shielding, corresponding to the highest irradiation (ABS = 1), to zero photon irradiation (source off). For each ABS and gas mixture the current, efficiency and high-charge contamination as a function of the high voltage are studied. The charge distribution is also reported. The HV parameters are corrected for temperature and pressure as in Equation 4.1. HV readjustment to account for larger pressure variation typical of this area were not considered.

The analysis has been performed using ROOT framework.

5.2.3 Analysis criteria and measurement strategy

For each triggered event a waveform of 500 ns is acquired for the RPC and scintillator signals.

A signal is defined efficient if it crosses an amplitude threshold equal to five times the RMS of the background amplitude distribution and is measured in a time window of 30 ns after the background time. The background amplitude is measured in a time window of 100 ns which anticipates the RPC signal. The background amplitude distribution is shown in Figure 5.5 for HV = 10400 V when the detector is operated with the standard gas mixture. Its average value during the whole scan is constant, as shown in Figure 5.6, and equal to ~ 1.3 mV corresponding to ~ 130 fC. The small-scintillator signal is also required to discriminate an efficient signal. The scintillator efficiency is measured with the same algorithm and the $5 \times \text{rms}$ as a function of the run number is shown in Figure 5.6. The scintillator efficiency is $\sim 14\%$ and was constant during the entire test, as shown in Figure 5.7.

Since the time window for the acquisition is much larger than the RPC signal, a non-negligible contribution from the instrument baseline after it can affect the charge measurements due to low frequency noise. In order to correct the measurement for this effect, the prompt charge is integrated in well defined time windows and not always on the entire window acquired. The time at which the integration starts is defined as the nearest point to the threshold time at which the signal goes to zero. The end of the integration is the first point which crosses zero after the signal goes below the threshold. The threshold set is the same used for the efficiency. An example of this integration interval is shown in Figure 5.8.

In order to include also high-charge contribution characterized by multi-avalanche events or streamers, this method is repeated on other efficient signals, if any, in the

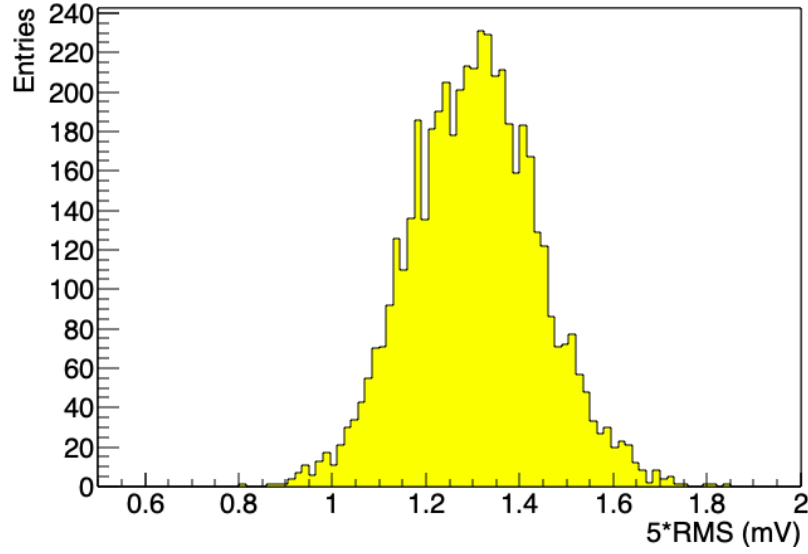


Figure 5.5: 5*RMS distribution at HV = 10400 V for the RPC operating with the standard gas mixture.

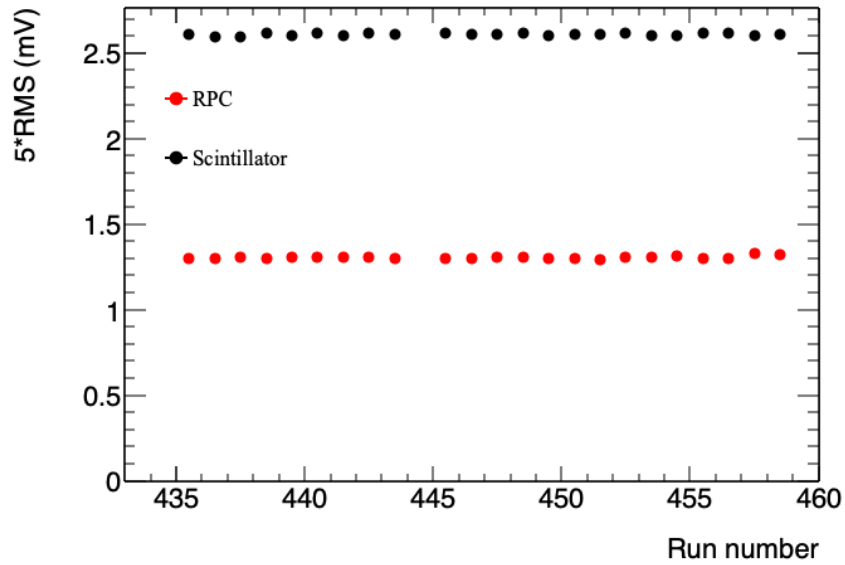


Figure 5.6: 5*RMS as a function of the run number for the RPC operating with the standard gas mixture and for the scintillator measured at source off.

same event considering the entire time window acquired. The total charge is the sum of these integration intervals normalized to the strip line impedance (50Ω). The definition of avalanche, streamer and transition events are the same described in Table 4.1, but the error on this measurement is larger due to the lower sampling rate. The mixtures tested are :

- Standard gas mixture : $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$, taken as a reference point to compare the performance with eco-gases;
- $\text{ECO2} = \text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 60/35/4/1$;

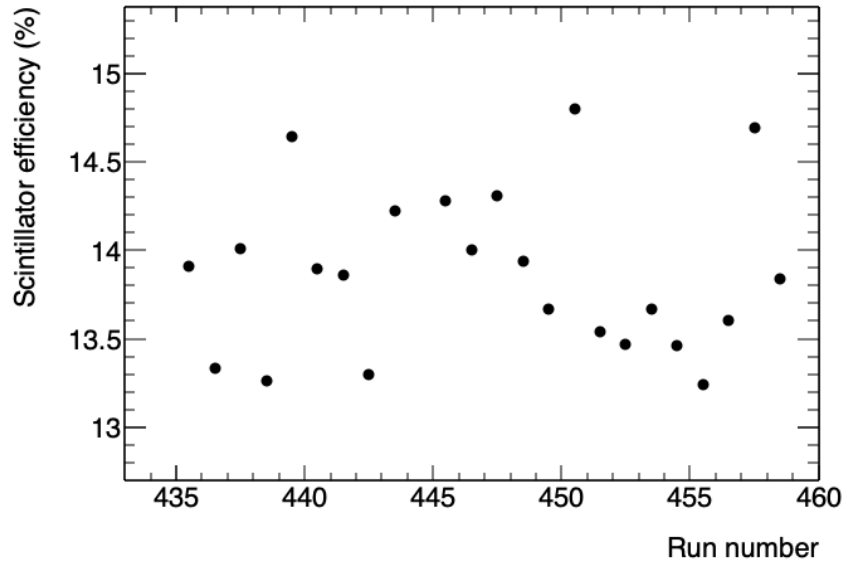


Figure 5.7: Scintillator efficiency as a function of the run number.

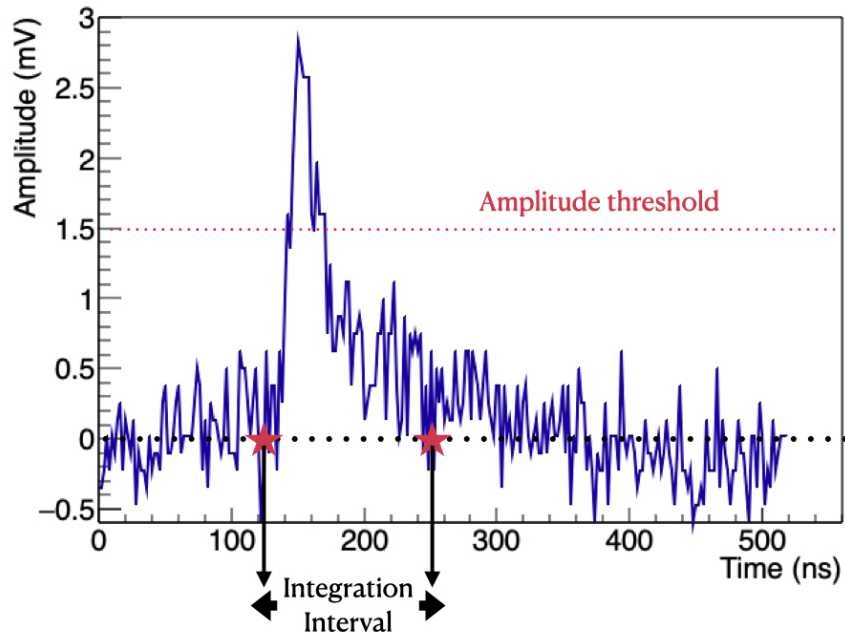


Figure 5.8: Example of the integration interval for the charge measurement.

- $\text{ECO3} = \text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 70/25/4/1$;

5.3 ATLAS legacy results at the GIF++: Source OFF

In this section the results with only muon beam and no photon irradiation on the 2 mm gas gap RPC operating with the standard gas mixture, ECO2 and ECO3 are reported. These results are taken as a reference for the measurements performed under irradiation.

5.3.1 Efficiency study

The detection efficiency times acceptance as a function of the high voltage obtained with the gas mixtures under test is reported in Figure 5.9.

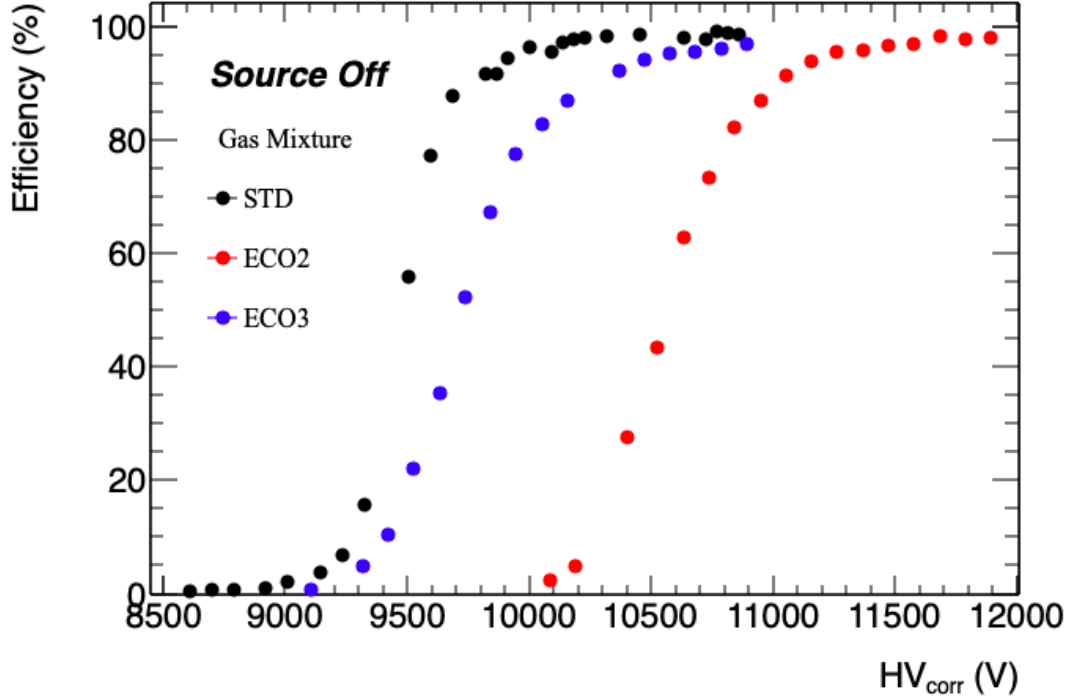


Figure 5.9: RPC efficiency as a function of the high voltage with the standard gas (black), ECO3 (blue) and ECO2 (red) measured with no photon irradiation (source off).

The amplitude threshold used for this test corresponds to ~ 130 fC, thus smaller than the one used for the test with cosmic rays, equal to 150 fC. For this reason, the working points obtained in this test assume lower values with respect to those of the test described in Section 4.2. The gain in high voltage due to the reduction of the threshold is not linear with the threshold itself, because the shape of the charge distribution changes with the high voltage, as shown in Figure 5.10. This means that the halving of the average charge in principle does not correspond to the halving of the threshold, which should be reduced even more than a factor 2 to reach the same efficiency value, due to the different charge distribution on which it is operating.

Therefore, we can not know the trend and the gain due to the decrease of the threshold a priori if the effective charge distribution is not known. Using the 130 fC threshold, the operating voltages obtained in this test with ECO2, ECO3 and the standard gas anticipate of about 200 V if compared to 150 fC threshold.

The overall results are comparable with the previous tests and can be summarized as follows:

- The efficiency curve obtained with the standard gas shows a steeper rise;
- The efficiency plateau value obtained with the standard gas mixture is $\sim 98\%$, while for ECO3 and ECO2 are 96% and 97% respectively, slightly below the one of the standard gas. These values are comparable with those obtained in the test

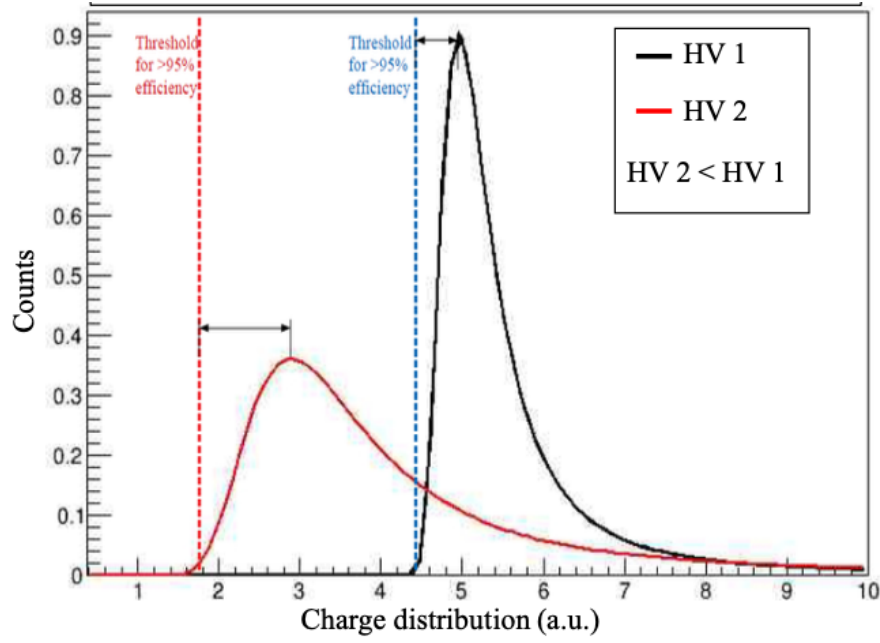


Figure 5.10: RPC Charge distribution as a function of the HV together with the threshold set to operate at $\epsilon > 95\%$.

with cosmic rays, considering the 2% of inefficiency due to the misalignment of the scintillator with the readout strip discussed before;

- The shift in operating voltage between ECO2 and ECO3 is 900 V corresponding to ~ 450 V/5% F-HFO;

The HV values at 50% and 90% efficiency along with the efficiency values at plateau are summarized in Table 5.1.

Table 5.1: Efficiency plateau, HV at 50% and 90% efficiency and currents at 90% and 96% efficiency measured with muon beam and with the photon source switched off, for the standard, ECO3 and ECO2 gas mixtures.

Gas mixture	Efficiency plateau (%)	HV _{50%} (kV)	HV _{90%} (kV)	I _{90%} (μ A)	I _{96%} (μ A)
STD	98	9.5	9.85	0.8	1
ECO3	96	9.7	10.2	1.9	2.4
ECO2	97	10.6	11	1.6	2

The parameters used for the analysis are compared at the high voltage values corresponding to 90% and 96% (maximum efficiency reached using ECO3). One of the most important parameter used to compare the gas mixtures is the current measured at the same efficiency value. The currents as a function of the efficiency are shown in Figure 5.11 and their values at HV_{90%} and HV_{96%} are summarized in Table 5.1.

At 90% efficiency:

$$I_{\text{ECO3}} \sim 1.2 I_{\text{ECO2}} \sim 2 I_{\text{STD}}. \quad (5.1)$$

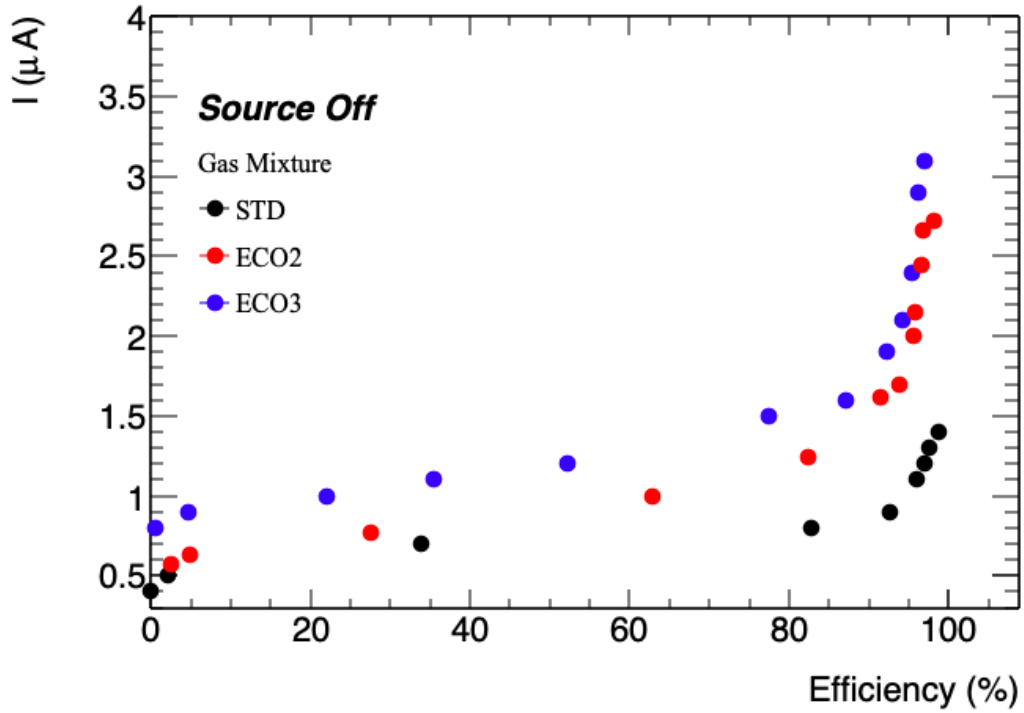


Figure 5.11: Current as a function of the efficiency with the standard gas (black), ECO3 (blue) and ECO2 (red) measured with no photon irradiation (source off).

5.3.2 Charge study

The prompt charge as a function of the high voltage is shown in Figure 5.12 and the values measured at $HV_{90\%}$ and $HV_{96\%}$ are summarized in Table 5.2.

Table 5.2: Prompt charge at $HV_{90\%}$ and $HV_{96\%}$ for the standard gas, ECO3 and ECO2 measured with no photon irradiation (source off).

Gas mixture	q at $HV_{90\%}$ (pC)	q at $HV_{96\%}$ (pC)
STD	0.5	1
ECO3	2	8
ECO2	1.2	4

The ECO2 and ECO3 prompt charges at 90% of efficiency are respectively two and three times higher than the one of the standard gas. Moreover, the prompt charge curves with eco-gases show a steeper rise above this value, with ECO2 being the one with a slower rise. This is due to the premature appearance of high-charge events in ecogases, as shown in the prompt charge distributions at different efficiency values, reported in Figure 5.13, 5.14 and 5.15.

The standard gas mixture prompt charge distribution, Figure 5.13, is peaked around a mean value which slightly increases with the high voltage, moving from ~ 0.5 pC at 90% to ~ 1 pC at 98%. At full efficiency, 98%, there is no contamination from high-charge events. Figure 5.14 shows ECO2 prompt charge distribution at approximately the same efficiency values taken as a reference for the standard one. At 91% efficiency

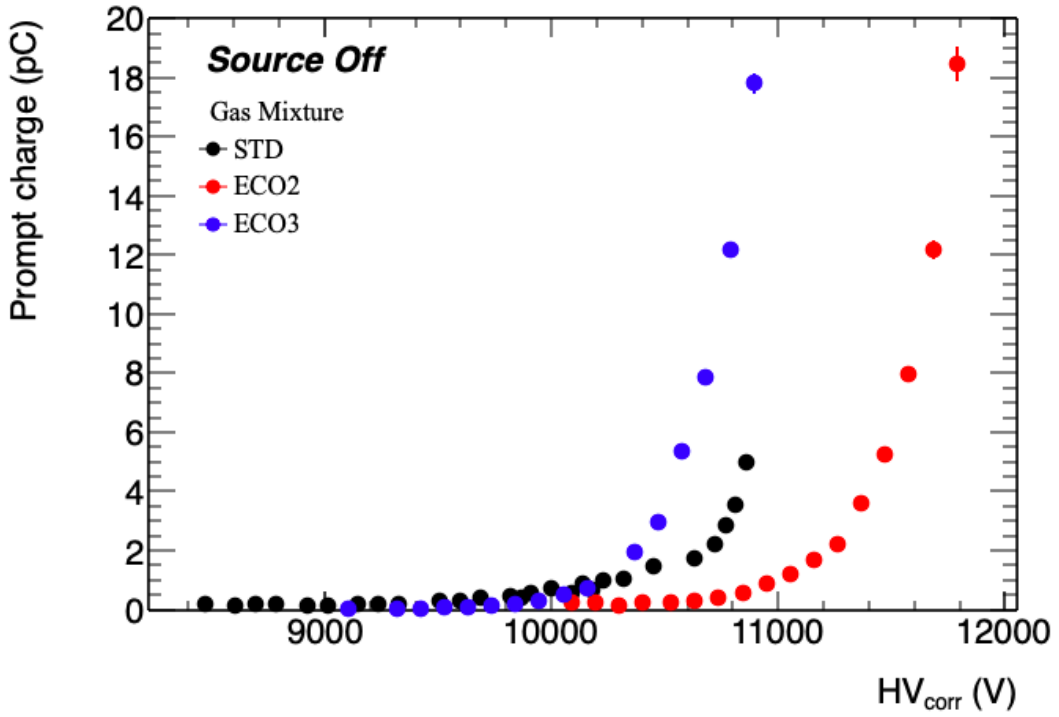


Figure 5.12: Prompt charge as a function of the high voltage with the standard gas (black), ECO3 (blue) and ECO2 (red) measured with no photon irradiation (source off).

the distribution is peaked around a mean value (~ 1 pC) and the charge shape is typical of the pure avalanche saturated regime. At higher efficiency the mean value rises up to 4 pC and high-charge events start to appear as a second broadened peak well separated from the avalanche one. The contamination at full efficiency, 97%, is around 22%. The charge distributions with ECO3 gas mixture show the same trend of ECO2 gas mixture, with a higher mean value, rising from 2 pC to 8 pC.

High-charge events start to appear at 95% of efficiency and their contamination at full efficiency, 97%, is around 24%. The differences between the high voltage corresponding to approximately 90% and the one corresponding to the full efficiency are 400 V, 450 V and 500 V for the standard gas, ECO2 and ECO3 respectively showing that the three gas mixtures have different rises of the efficiency curve.

The transition event and streamer probability are shown in Figure 5.16.

The transition event probability shows a maximum at approximately 25% for both gas mixtures at almost 98% of the maximum plateau value. Above this value, they start to decrease, in correspondence to a streamer probability higher than 25%.

These results strongly confirm those obtained in Section 4.2 and they are taken as a reference for the performance measurements under photon irradiation.

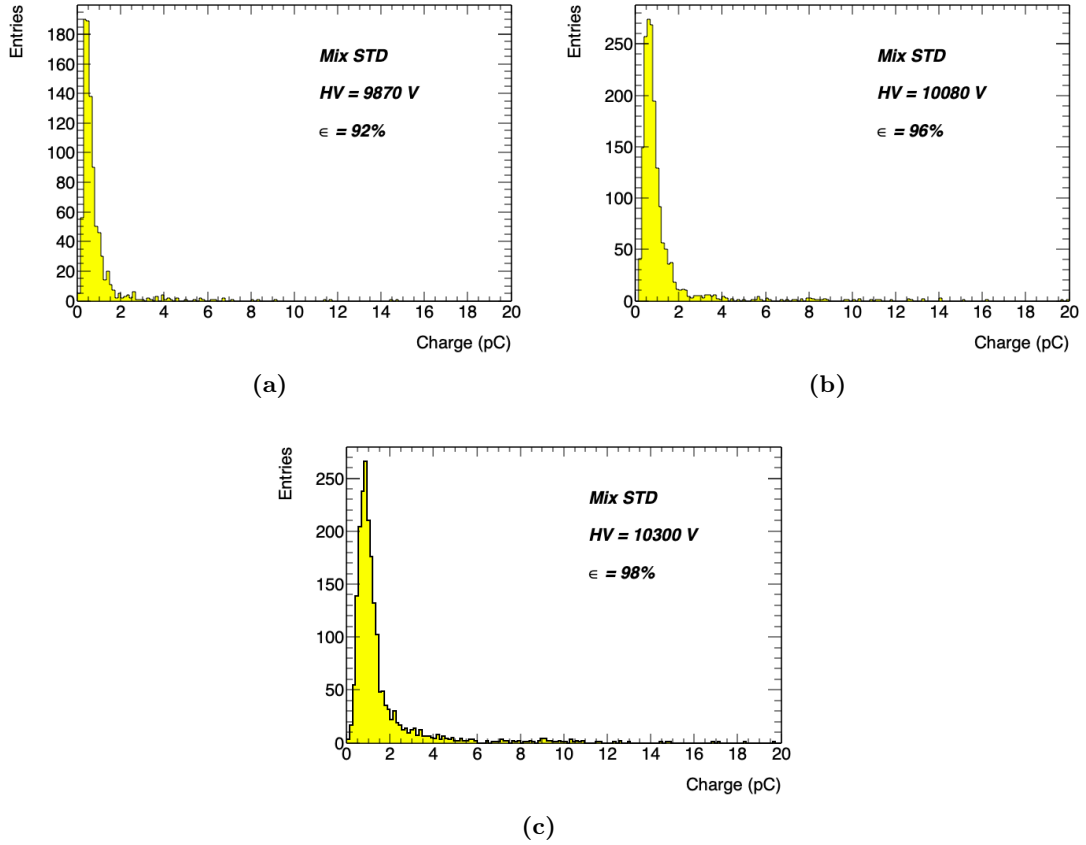


Figure 5.13: Prompt charge distributions at source off with the standard gas mixture at (a) 92%, (b) 94% and (c) 98% efficiency.

5.4 ATLAS legacy results at the GIF++: test under irradiation

In this section the results with the muon beam and under photon irradiation on the 2 mm gas gap RPC operating with the standard gas mixture, ECO2 and ECO3 are reported. The ABS factors studied are: 6.9 and 22.

The performance with source off previously discussed are also reported and taken for reference.

5.4.1 Rate measurement

The rate of converted photons corresponding to each ABS factor is calculated as follow:

$$\text{Rate}(\text{Hz}/\text{cm}^2) = \frac{n_{\text{peaks}}}{n_{\text{events}}} \times \frac{1}{t} \times \frac{1}{A} \quad (5.2)$$

where n_{peaks} is the number of peaks measured in $n_{\text{events}} = 4000$ events in a time window t of 100 ns which is not-in-time with the trigger signal. This value, divided to the strip area $A = (3.5 \times 55) \text{ cm}^2$, gives the rate of converted photons inside the detector. The RPC efficiency to photons is around 0.3%. Each gas mixture has its own photon efficiency, therefore the rate has been calculated for each ABS and gas mixture

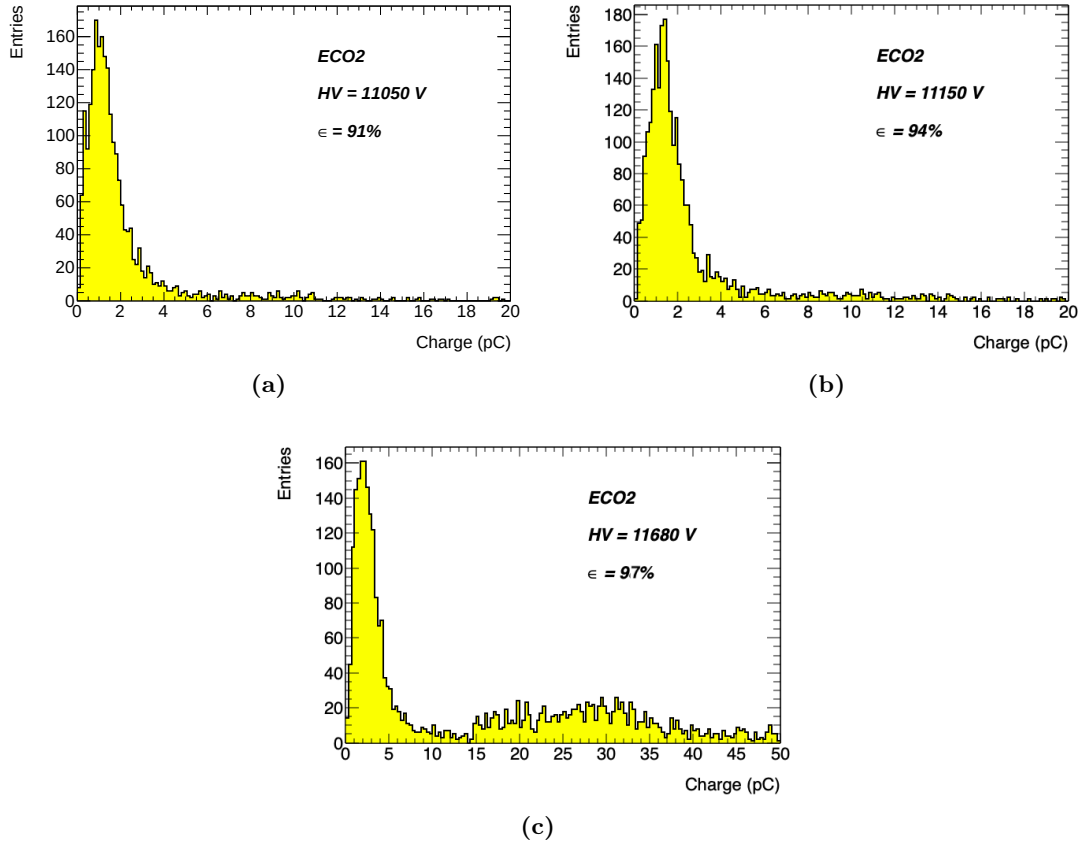


Figure 5.14: Prompt charge distributions at source off with the ECO2 gas mixture at (a) 91%, (b) 94% and (c) 97% efficiency.

at the same efficiency value, showing that it is independent from the gas mixture used. The relative rates are summarized in Table 5.3.

Table 5.3: ABS values and corresponding rates.

ABS	6.9	22
Rate (Hz/cm ²)	500	200

The rate of 500 and 200 Hz/cm² have been chosen for this test because they are correlated with the RPC operation at the HL-LHC.

The main source of background present in the barrel region of the ATLAS experiment mainly consists of photons and neutrons. The rate in the ATLAS experiment during Run-2 is around 100 Hz/cm², including a safety factor of 10. If the same safety factor is applied to the rate expected during the High-Luminosity phase, the rate is around 200 Hz/cm². For this reason the RPC performance at 200 Hz/cm² of converted photons has been studied in order to give an estimation of their future operation in Run-4.

The rate of 500 Hz/cm² has been taken as upper limit on the rate capability achievable with this system. It is important to stress that these measurements are strictly correlated with the threshold used, therefore the performance could be improved with a system working with a lower threshold.

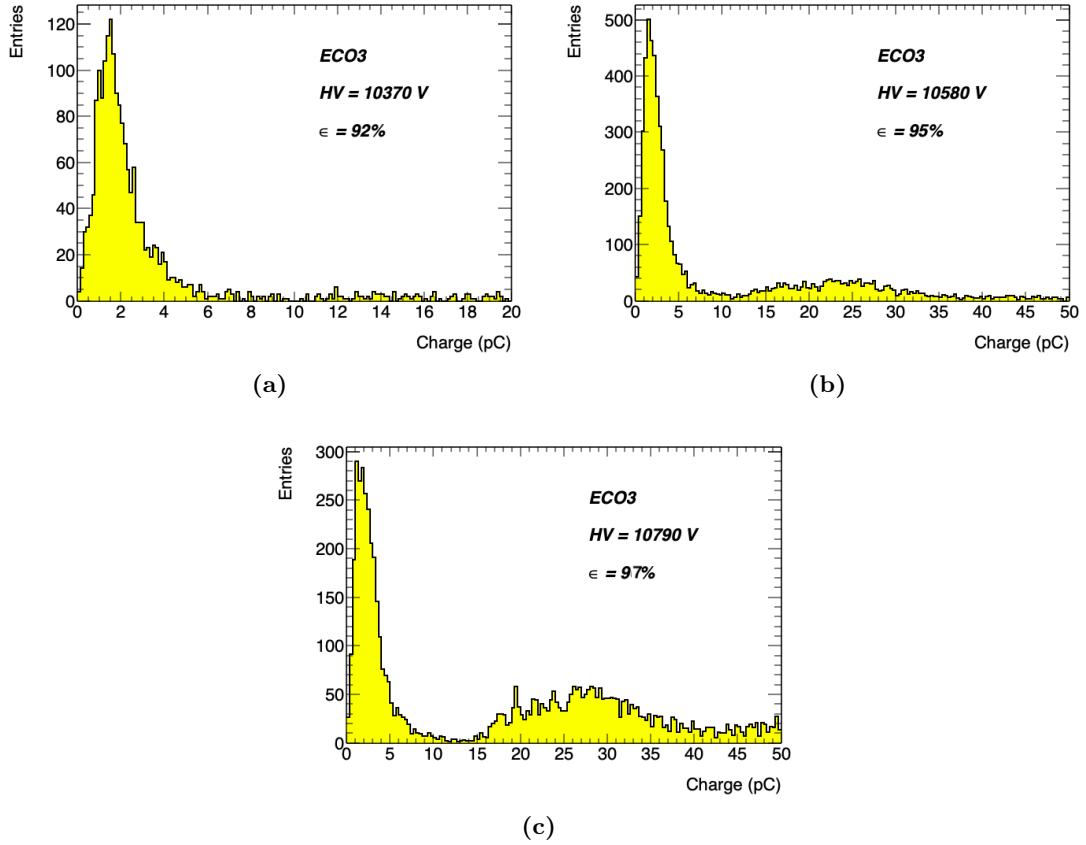


Figure 5.15: Prompt charge distributions at source off with the ECO3 gas mixture at (a) 92%, (b) 95% and (c) 97% efficiency.

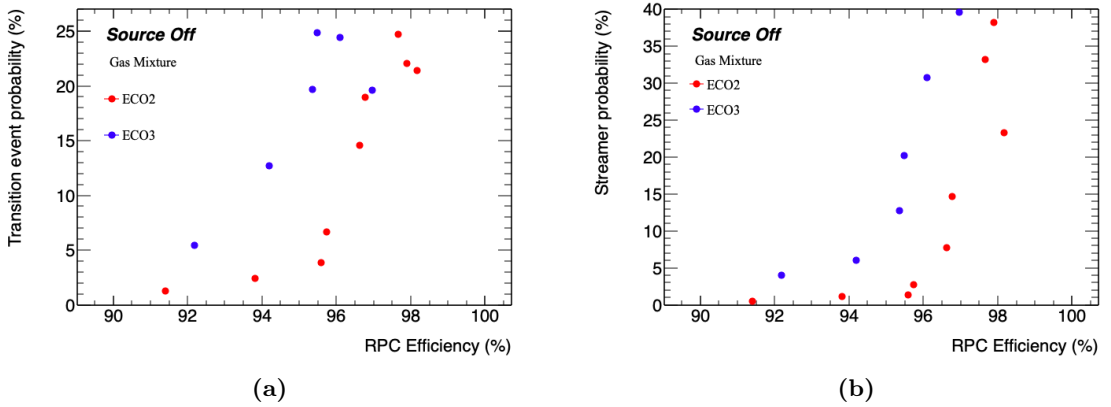


Figure 5.16: (a) Transition event probability and (b) streamer probability as a function of the efficiency for the ECO3 (blue) and ECO2 (red) gas mixtures measured with no photon irradiation (source off).

This possibility will be further studied in Chapter 6.

5.4.2 Efficiency study

The efficiencies as a function of the high voltage are shown in Figure 5.17. The efficiency curve of the standard gas mixture, Figure 5.17.a, does not show a shift in the high voltage up to $\sim 200 \text{ Hz/cm}^2$. At $\sim 500 \text{ Hz/cm}^2$, the shift measured at $\text{HV}_{50\%}$ is around 100 V and the efficiency curve has a slower rise, being the $\text{HV}_{90\%}$ 250 V higher than that calculated at source off.

At $\sim 200 \text{ Hz/cm}^2$, the ECO3 gas mixture efficiency curve, Figure 5.17.b, shows a voltage shift of 50 V at $\text{HV}_{50\%}$ and of 100 V at $\text{HV}_{90\%}$. At 500 Hz/cm^2 the shift is of 150 V at $\text{HV}_{50\%}$ with respect to the situation without photon irradiation and the efficiency does not reach 90% efficiency, being 88% the maximum efficiency value.

For what concerns ECO2, Figure 5.17.c, the voltage shift at 50% is around 100 V at 200 Hz/cm^2 . The 90% efficiency is reached up to $\sim 500 \text{ Hz/cm}^2$, with a shift of $\sim 140 \text{ V}$ with respect to the measurement at source off.

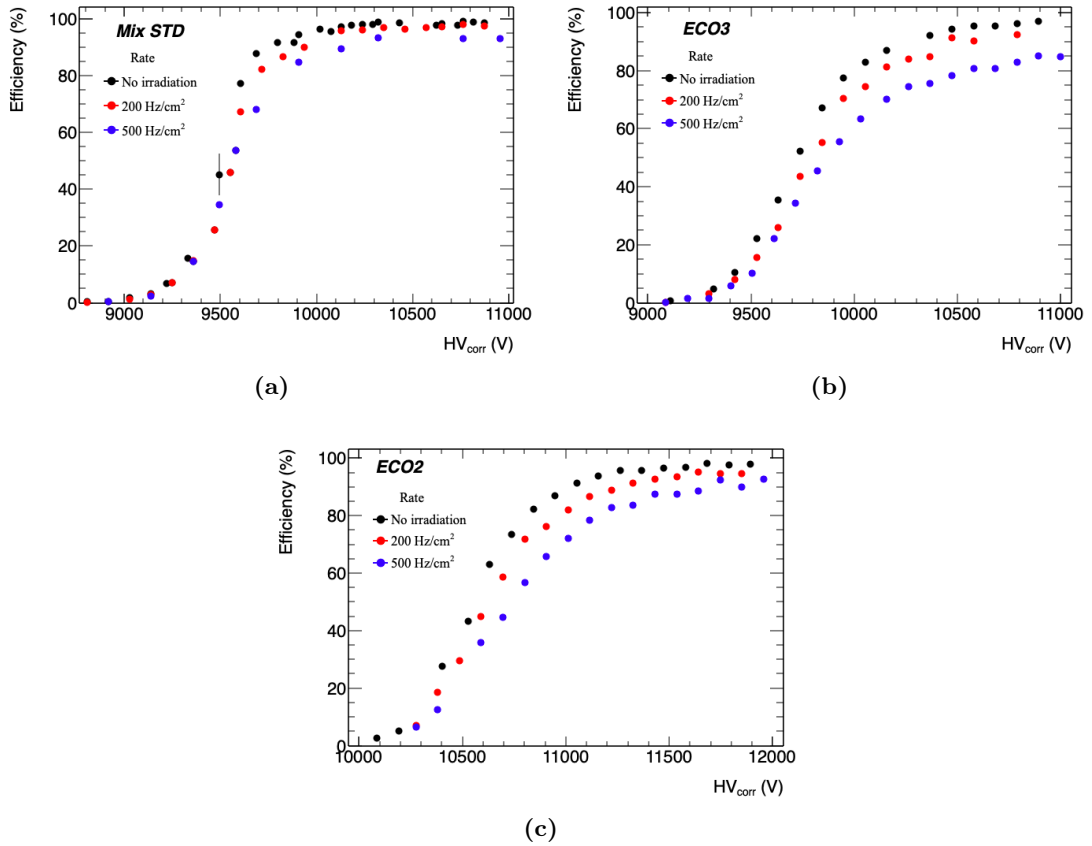


Figure 5.17: Efficiency as a function of the high voltage under different photon irradiation for the (a) standard, (b) ECO3 and (c) ECO2 gas mixtures.

5.4.3 Current study

The currents as a function of the efficiency and rate are shown in Figure 5.18 and the currents measured at 90% efficiency considering the rate of 200 Hz/cm^2 are summarized in Table 5.4.

The efficiency-current curves have been fitted with an exponential function, in order to compare the currents at the same efficiency, even if an experimental point is missing.

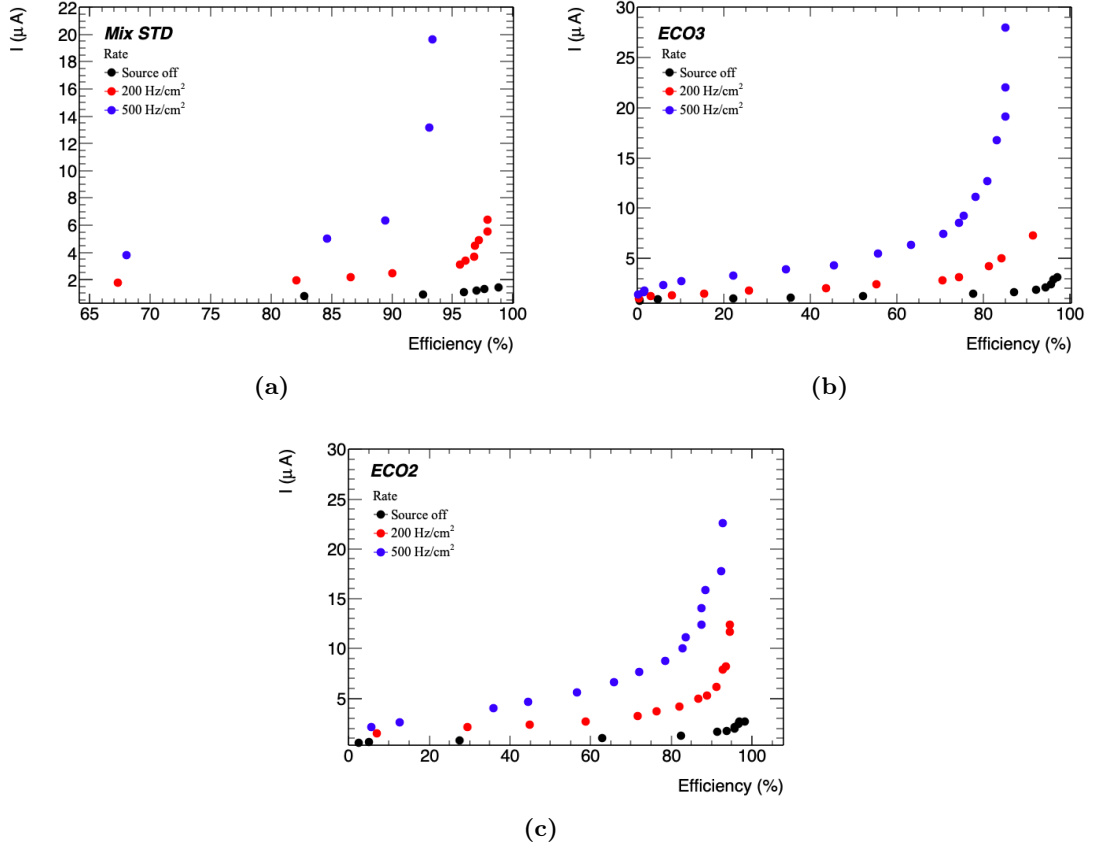


Figure 5.18: Currents as a function of the efficiency for several ABS values with the (a) standard, (b) ECO3 and (c) ECO2 gas mixtures.

Table 5.4: Currents measured at 90% with 200 Hz/cm^2 of converted photons.

Gas Mixture	$I_{90\%}$ (μA)
STD	2.1
ECO3	6
ECO2	5

The standard gas shows an increase in the current measured at 90% efficiency of 5 μA moving from zero irradiation to 500 Hz/cm^2 .

The current measured at the same rate with ECO2 gas mixture is $\sim 15 \mu\text{A}$, three times higher. If we compare the gas mixtures at the same rate and efficiency, 200 Hz/cm^2 and 90%, we obtain:

$$I_{\text{ECO3}} \sim 1.2 I_{\text{ECO2}} \sim 3 I_{\text{STD}}; \quad (5.3)$$

The currents of the eco-gas mixtures under High-Luminosity-like irradiation environment are three times higher if compared to the condition with no irradiation. The current of the standard one instead is 2.4 times higher. As a general conclusion, the currents measured with ecogases are higher than those obtained with the standard gas. However, their absolute values are not critical for the RPC performances. The gas mix-

tures tested show very encouraging performance results in sight of their possible usage at the HL-LHC. Along with these tests, the aging test will be performed in order to accept or discard a gas mixture. Currently, an ageing campaign using ECO2 is on going at the GIF++.

5.4.4 Resistivity measurement

The detector aging is strictly correlated with the integrated charge during its operation, thus the average charge per count. The reduction of the rate capability after a long period of operation under strong gamma irradiation can be explained with a progressive increase of the electrodes resistivity, which is correlated to the current flowed across the electrode plates [45]. The monitoring of the electrode resistance is therefore a measurement that can highlight the start of the aging process. The resistivity measurement taken as a reference was performed flushing the detector with Argon and is:

$$\rho_{\text{Argon}} = 5.5 \times 10^{10} \Omega\text{cm} \quad (5.4)$$

The measurement has been periodically performed during the year giving the same average number, thus not showing any aging effect.

In order to confirm this result and to obtain a more precise resistivity value, during the test beam the same measurement has been performed using the efficiency and currents measured at different irradiation and repeated with the detector flushing with the standard, ECO2 and ECO3 gas mixtures.

In this case the difference between the voltages and currents at 50% efficiency measured with no photon irradiation and at 200 Hz/cm² have been considered and, following the Ohm law:

$$\Delta V = R \Delta I \quad (5.5)$$

the resistance, thus resistivity, has been derived. The reference values are summarized in Table 5.5.

Table 5.5: Difference of Voltages and Currents measured at 50% efficiency with standard, ECO2 and ECO3 gases at source off and at 200 Hz/cm² of converted photons.

Gas Mixture	$\Delta I_{50\%}$ (μA)	$\Delta V_{50\%}$ (V)
STD	100	2.8
ECO3	150	3.7
ECO2	140	4.35

The corresponding resistance are:

$$\begin{aligned}
 R_{\text{STD}} &= 36 \text{ M}\Omega; \\
 R_{\text{ECO3}} &= 38 \text{ M}\Omega \\
 R_{\text{ECO2}} &= 34 \text{ M}\Omega
 \end{aligned}
 \tag{5.6}$$

The average resistivity is:

$$\rho_{\text{source}} = 5 \times 10^{10} \text{ }\Omega\text{cm} \tag{5.7}$$

showing that the two methods are equivalent and confirming that the detector does not show any resistivity increase after one year of irradiation.

5.4.5 Conclusions

In this Chapter an ATLAS-like RPC with 2 mm wide gas gap has been tested with a muon beam and under photon irradiation with the following gas mixtures :

- Standard gas mixture = $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$;
- $\text{ECO2} = \text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 60/35/4/1$;
- $\text{ECO3} = \text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 70/25/4/1$;

The results can be summarized in the following points:

- The results obtained with the muon beam and with the photon source switched off confirm those obtained in Chapter 4 using cosmic ray tracks;
- The currents at 90% efficiency are $I_{\text{ECO3}} \sim 2.4 \text{ }\mu\text{A} \sim 1.2I_{\text{ECO2}} \sim 2I_{\text{STD}}$. At the rate of 200 Hz/cm^2 of converted photons are: $I_{\text{ECO3}} \sim 6 \text{ }\mu\text{A} \sim 1.2I_{\text{ECO2}} \sim 3I_{\text{STD}}$;
- Both ECO2 and ECO3 gas mixtures show good performance up to 200 Hz/cm^2 (HL-LHC background), having efficiencies above 90% and modest currents at the working point;
- The electrodes resistivity has been measured using two techniques: flushing the RPC with Argon and measuring the voltage/current shift under irradiation using the standard, ECO2 and ECO3 gas mixtures. The resistivity is the same using the two methods and is $\rho = 5 \times 10^{10} \text{ }\Omega\text{cm}$;
- The detector does not show any resistivity increase after one year of irradiation.

Chapter 6

Test on the new RPCs for the ATLAS upgrade with eco-gases

6.1 ATLAS BIS78 upgrade apparatus

The ATLAS BIS78 experimental setup is located at 5 m from the source in the downstream area at the GIF++ facility at CERN, as shown in Figure 5.1. The detector under test, shown in Figure 6.1, is the BIS78 RPC prototype-0, therefore it has the same layout and electronics of the detectors installed in the ATLAS experiment during the phase-1 upgrade described in Section 1.1.4.



Figure 6.1: Picture of the BIS78 RPC at the GIF++.

The detectors have the dimension of $(1.82 \times 1.18) \text{ m}^2$. We will refer to the BIS78 singlet detectors as TOP, MID and BOT chambers, being the TOP and BOT the nearest and the farther from the source respectively. The estimated geometrical inefficiency, due to spacers, is 2%. The Front end electronics parameters set for the tests are the same for both η and ϕ panels and are listed in Table 6.1. The FE threshold varies from an estimated equivalent threshold of 4 fC (1.8 V) to 1 fC (2.1 V).

Table 6.1: Setting of the Front end parameters.

$V_{\text{threshold}}$ (V)	$V_{\text{amplifier}}$ (V)	$V_{\text{discriminator}}$ (V)	V_{lvds} (V)	$V_{\text{pull-up}}$ (V)
1.8-2.1	1.3	2.5	2.4	0.35

6.1.1 DAQ

The FE RPC signal is read with 9 High Performance Time to Digital Converter (HPTDC) [46], based on a series of 32-channels TDCs developed at CERN. The HPTDC measures the time-over-threshold (TOT), giving the leading edge time of the hit and its duration, with a resolution of 200 ps and 400 ps respectively. The digital information from the TDC is serialized by means of the Gigabit Optical Link (GOL) [47] chip and sent to the RPC PAD board. The Pad board, based on Field Programmable Gate Array (FPGA) [48], collects the RPC hits and performs the trigger coincidence. It can also receive the trigger from an external source, i.e. the scintillators coincidence used for this test. The trigger coincidence is based on timing requirements: a clock at 40 MHz is provided to the PAD (or the scintillator coincidence signal) and the trigger is accepted if 2/3 chambers have recorded one hit with a time distance to each other within 25 ns (LHC bunch crossing). The RPC data are stored in the FPGA in free running mode and, when a trigger signal is accepted, a 800 ns time window is acquired and the data are sent through the optical link to the Felix System [49]. The data recorded are further analyzed using ROOT framework.

6.1.2 Analysis criteria and measurement strategy

For each triggered event a time window of 800 ns, containing the RPC hit leading time and the duration of the signal, is acquired. For each gas mixture, an HV scan is performed on the TOP chamber, using different FE thresholds and photon backgrounds, starting from zero efficiency to full efficiency. The HV parameters are corrected for temperature and pressure as in Equation 4.1. During the scan the BOT and MID RPCs are taken at the fixed voltage corresponding to their full efficiency and are used as trigger. The TOP chamber has been chosen as detector under test, in sight of the tests under high irradiation with eco-gases, due to its lowest current, as shown in Figure 6.2.

The physics object used for the offline analysis are reconstructed by means of the leading time and the width of the signal. The number of HPTDCs allows to read 288 strips, 32 in η panel and 64 in ϕ panel for the three detectors. The beam spot, including both core and halo, is included within strips 42-52 in ϕ and 22-32 in η , as shown in Figure 6.3.

The performance of the RPC are provided considering the hits in the entire chamber and not only the area covered by the beam spot.

Clusterization

The clusterization is performed discriminating the hits in terms of their distance in space and time. Two or more hits belong to the same cluster if they are within 15 ns from each other and if they belong to neighbourhood strips. The average number of clusters in the η panel of the TOP chamber at the working point (HV = 5800 V) operating with the standard gas mixture is shown in Figure 6.4.

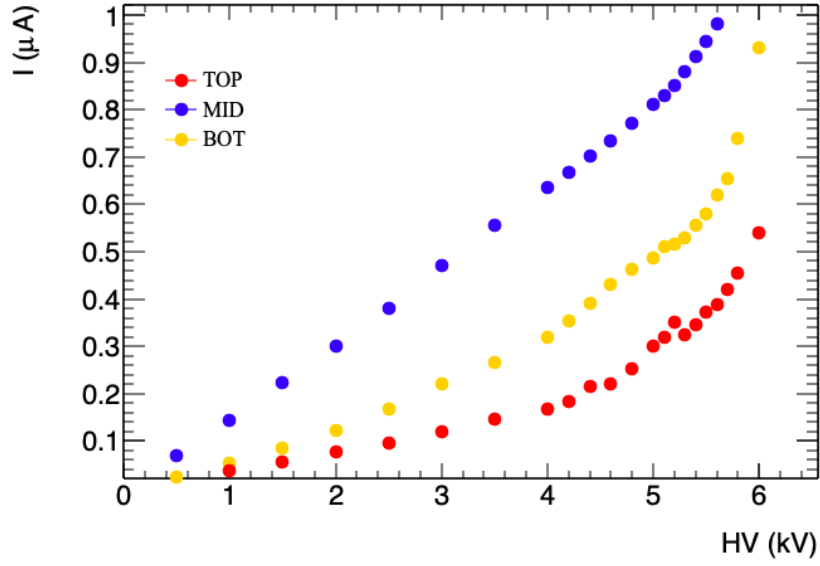


Figure 6.2: Volt-ampere curves of the TOP (red), MID (blue) and BOT (yellow) BIS78 singlets operating with standard gas mixture.

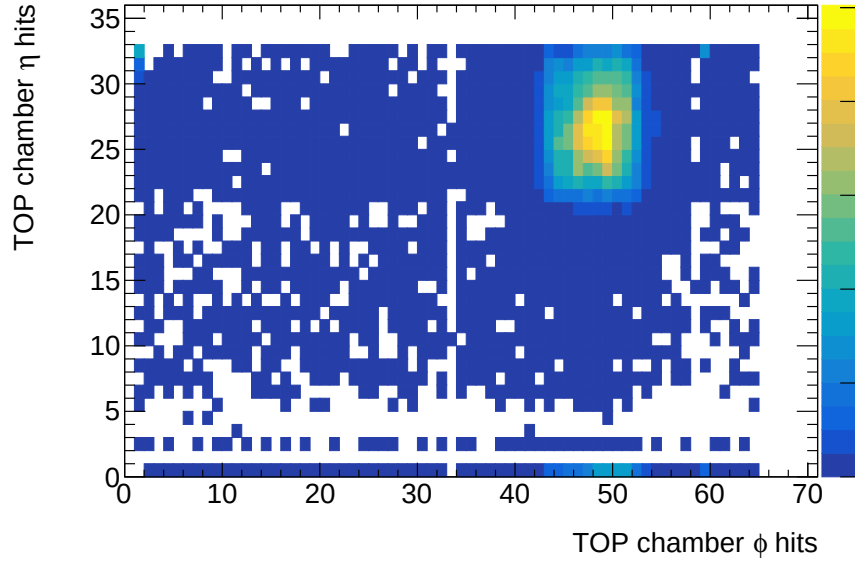


Figure 6.3: Beam Spot measured in the TOP chamber at HV= 5800 V.

Three parameters are extracted from the clusterization: the time, center and width of the cluster. The center of the cluster is defined as the strip which fires first in time and belongs to that cluster. The arriving time of the center of the cluster defines its time leading. The difference between the trailing and leading time of the center of the cluster defines its width. These parameters are shown in Figure 6.5.

The cluster size of the event is defined as the number of contiguous strips which fires in one cluster. The event in Figure 6.5 represents one cluster with cluster size equal to three. The physical cluster size, considering this specific strip readout, is about 1.2 considering both cases in which the muon crosses the strip and passes in the middle between two strips. Cluster size above this value represents a cross talk among strips

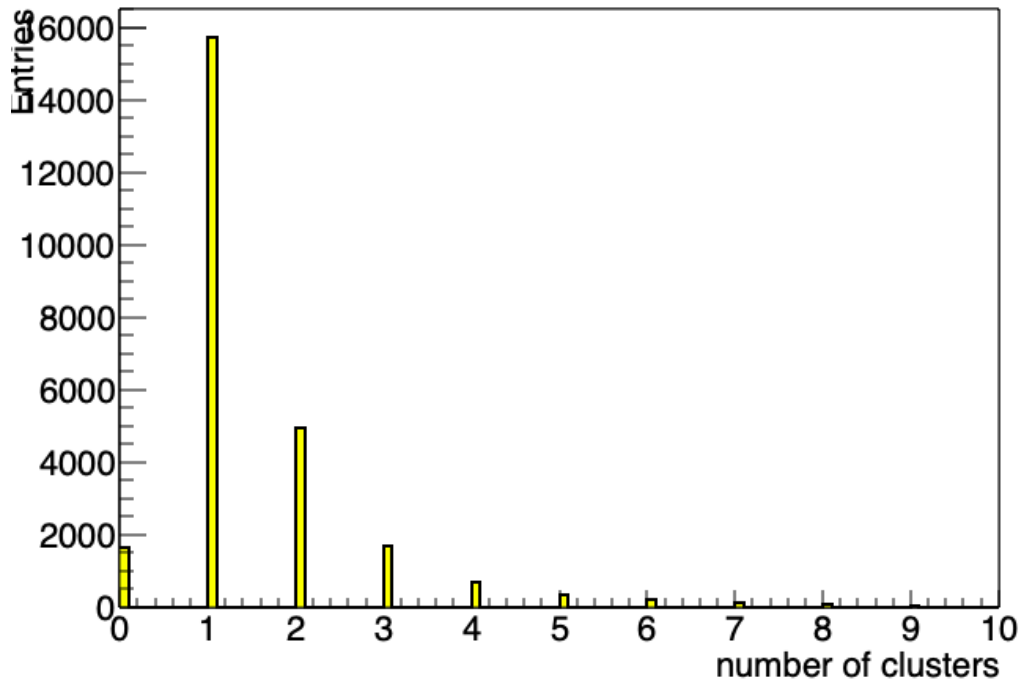


Figure 6.4: Distribution of the number of clusters at the working point (HV = 5800 V) for the TOP chamber operating with the standard gas mixture.

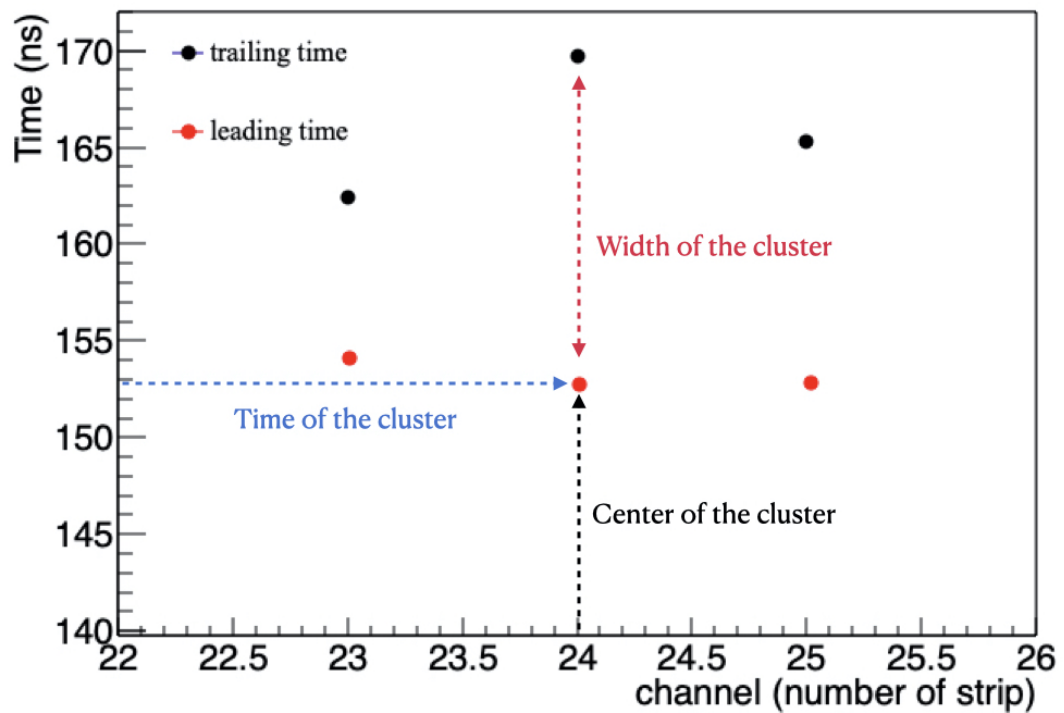


Figure 6.5: Leading and trailing time of a cluster as a function of the strip channel. The center (black line), time (blue line) and width (red line) of the cluster are also shown.

or auto-induction noise.

Efficiency

The efficiency algorithm is performed independently for η and ϕ panels. It requires the following stringent cuts on the trigger chambers:

- The time distance between the two clusters must be less than 5 ns ;
- The space distance between the two clusters must be less than 3 strips;
- The width of the two clusters must be between 5 ns and 30 ns;

These three conditions allow to obtain a clean and pure sample of muons to define a triggered event. Hits on the entire test chamber are searched and the efficiency is measured. This method has the advantage that the whole test chamber behaviour can be studied, thus additional hits or noise located in strips far from the beam spot can be taken into account in a single event. Figure 6.6 shows the η and Φ panels efficiencies as a function of the high voltage. Since the two curves have the same trend (as expected) and the detector performance and characteristics do not change selecting one of the two readout panels, only the physics quantities measured in η will be shown in the following, but the results can be extended to Φ strip panels.

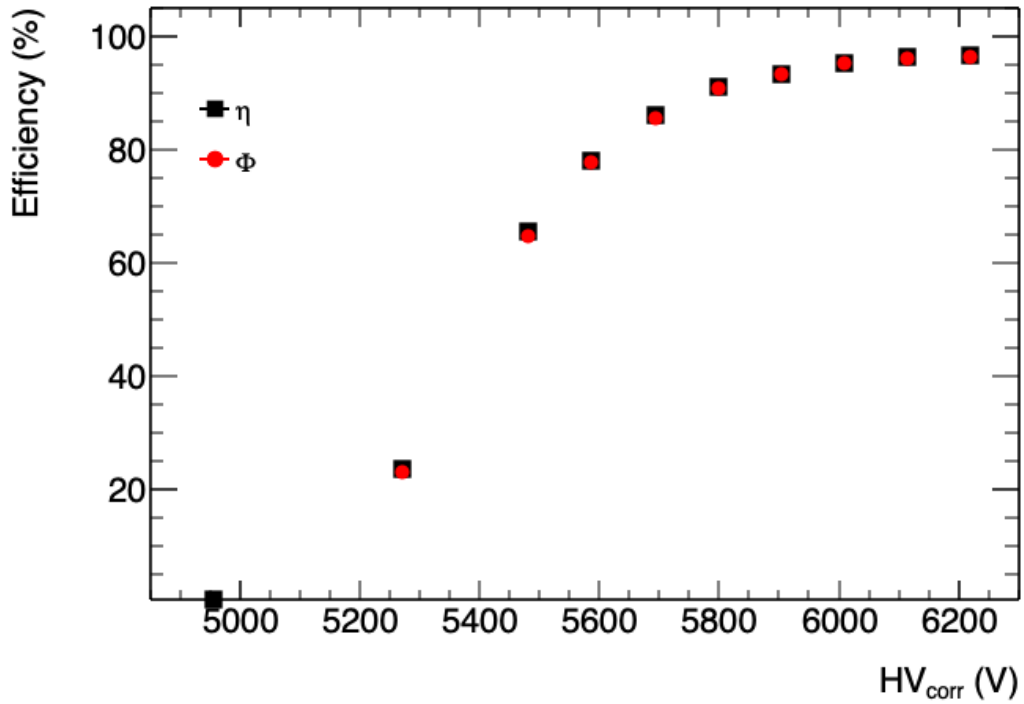


Figure 6.6: η (black) and Φ (red) efficiencies of the BIS78 TOP singlet operated with the standard gas mixture.

Time of flight measurement

The time resolution is measured using the time-of-flight method (TOF) between TOP and MID chambers flushed with the same gas mixture. The sigma of the TOF is equal to:

$$\sigma_{\text{TOF}}^2 = \sigma_{\text{TOP}}^2 + \sigma_{\text{MID}}^2; \quad (6.1)$$

The time resolution depends on the gas mixture and gas gap width. Since the TOP and MID chambers have the same gas gap width(1 mm) and are flushed with the same gas mixture:

$$\sigma_{\text{TOP}} = \sigma_{\text{MID}} = \sigma; \quad (6.2)$$

The time resolution is measured performing a gaussian fit on the TOF distribution at the operating voltage and is:

$$\sigma = \frac{\sigma_{\text{TOF}}}{\sqrt{2}}; \quad (6.3)$$

Equation 6.3 represents the first approximation of the time resolution measurement. This value must be corrected for time-walk effect. The time at which the signal crosses the threshold depends on the amplitude of the signal, as shown in Figure 6.7: wider is the signal, earlier it crosses the threshold.

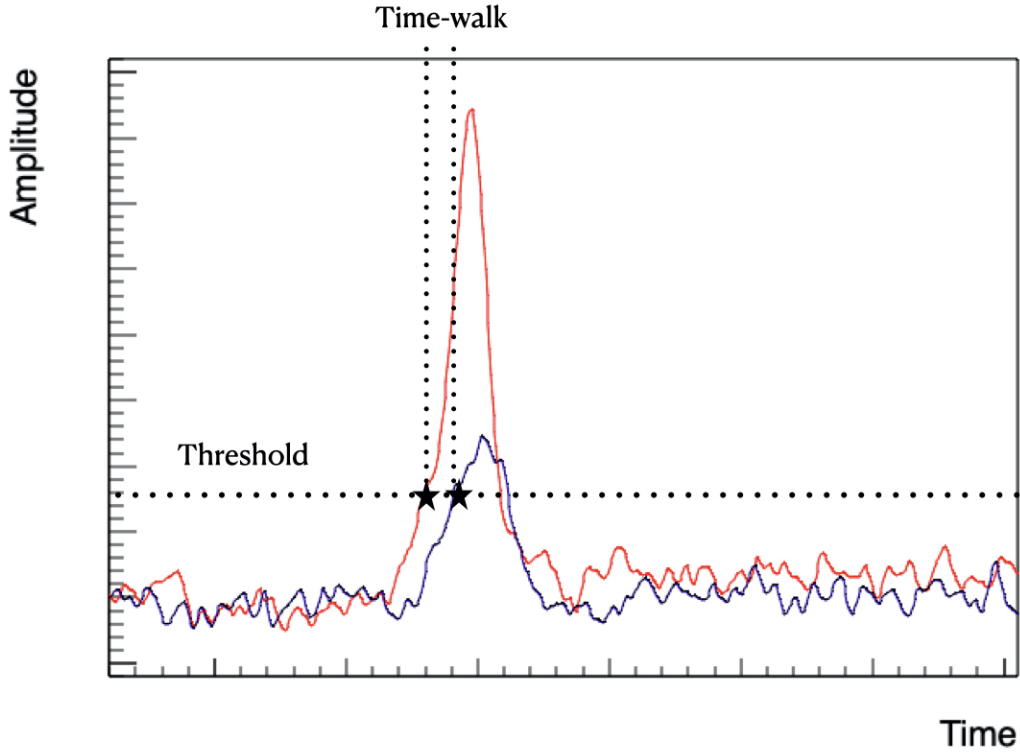


Figure 6.7: Time-walk effect due to the different signal amplitudes. The wider signal (red line) crosses the threshold before the smaller one (blue line).

In order to account for this phenomenon the function which correlates the time of flight and the time-over-threshold has been determined and the time resolution has been corrected for time-walk effect and consequently improved.

6.2 ATLAS BIS78 RPC: results with source OFF

In this section the test beam results on the 1 mm gas gap RPC (BIS78) are reported. The gas mixtures tested are :

- Standard gas mixture = $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$;
- ECO65 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 30/65/4/1$;
- ECO55 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 40/55/4/1$;
- ECO2 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 60/35/4/1$;
- ECO3 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 70/25/4/1$.

The tests have been performed varying the gas mixture and the FE threshold, exploring a range from 4 fC to 1 fC. The gas mixtures are compared taken as a reference the conservative threshold (4 fC), currently used in the BIS78 installed in the ATLAS experiment. The threshold scan allows to understand the best performance achievable with this innovative technology and to establish how far we can go down with the threshold, without losing the system stability. The optimization of the FE threshold is crucial for the characterization of the RPC detector operating with eco-gases: lower is the threshold, sooner the detector reaches the efficiency plateau, resulting in a lower current and a slower detector ageing. The possibility to work at the same efficiency with a lower current can be important to accept or discard a gas mixture.

In this section the results obtained with only muon beam and no photon irradiation on the BIS78 RPC operating with the gas mixtures listed above are reported.

6.2.1 Efficiency study

The detection efficiency curves obtained with the gas mixtures described above setting the conservative threshold of 4 fC are reported in Figure 6.8.

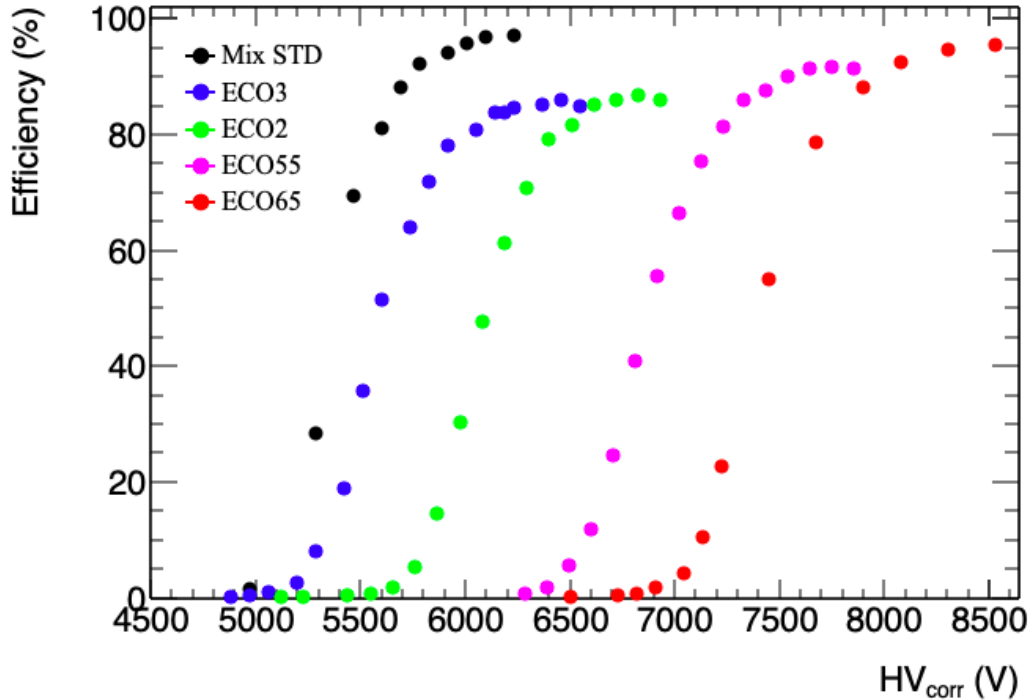


Figure 6.8: BIS78 RPC efficiency curves as a function of the high voltage operating with the standard gas (black), ECO3 (blue), ECO2 (green), ECO55 (pink) and ECO65 (red).

The results can be summarized as follows:

- The high voltage shift between the standard gas mixture and ECO3 is around 200 V;
- The operating voltage in the eco-gases increases at the rate of about 500 V/10% F-HFO, half the one obtained with the 2 mm gas gap (see Section 4.2);
- The efficiency plateau with the ECO3 and ECO2 gas mixtures is below 90%, while with ECO55 and ECO65 the efficiency plateau is above 90%;
- ECO65 reaches 96.5% efficiency, 1% less than the value obtained with the standard gas mixture.

The trend of the efficiency plateau as a function of the Hydrofluorocarbon concentration is shown in Figure 6.9.a. The low-density of the CO₂ results in a smaller active target available for the primary ionization. Consequently, the mixtures with high-CO₂ concentration, ECO3 and ECO2, have low detection efficiency, while ECO55 and ECO65 give a high-efficiency plateau due to the predominant presence of a high-density gas, like tetrafluoropropene.

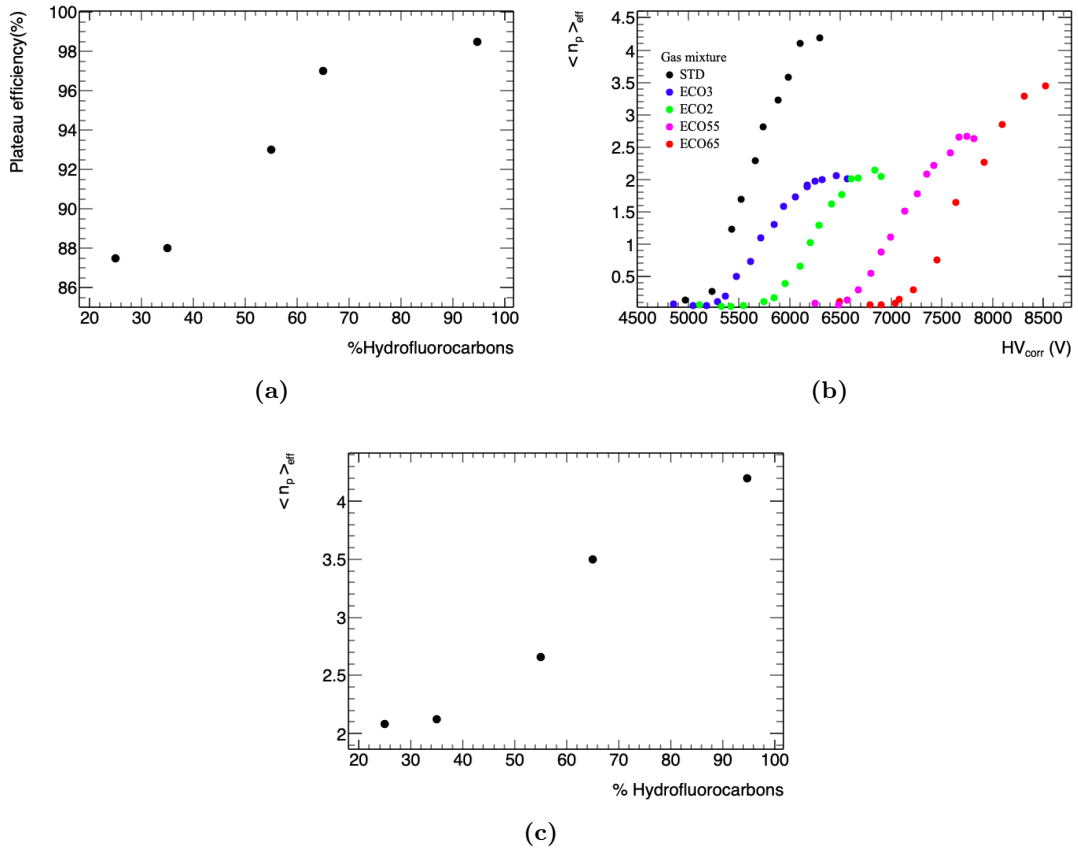


Figure 6.9: (a) Efficiency plateau as a function of the hydrofluorocarbon concentration, (b) number of effective cluster as a function of the high voltage and (c) number of effective clusters at plateau as a function of the hydrofluorocarbon percentage for the STD, ECO3, ECO2, ECO55 and ECO65 gas mixtures.

This behaviour can be explained with the lower number of primary clusters available for the multiplication, reported in Figure 6.9.b, thus the clusters which can produce a detectable signal. The number of primary clusters at the plateau, Figure 6.9.c, is below

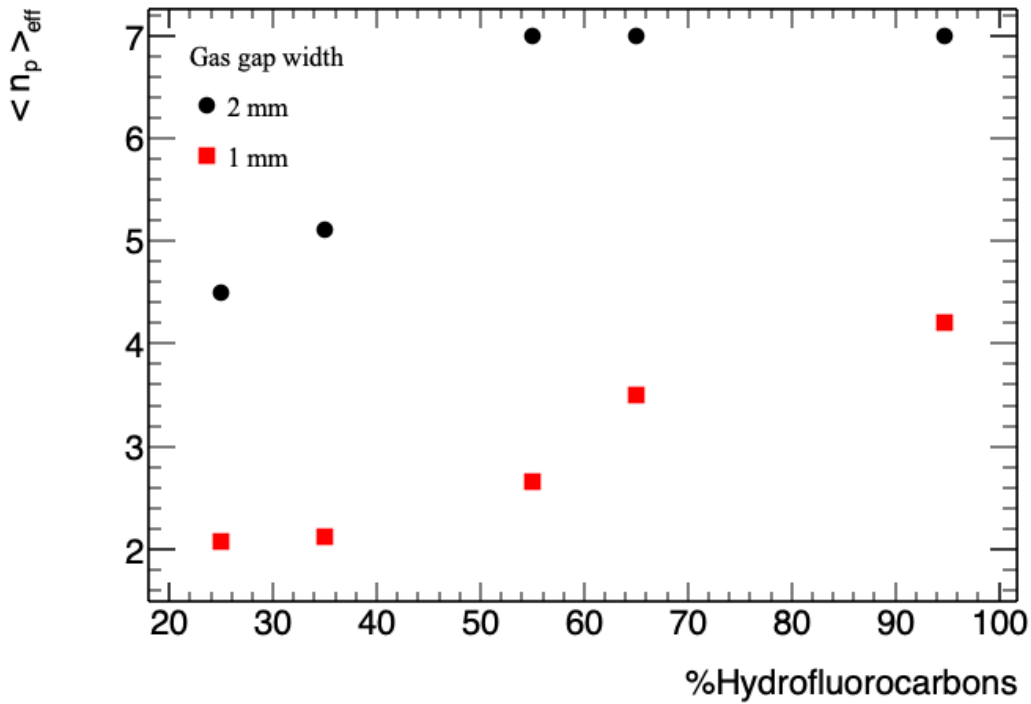


Figure 6.10: Number of effective primary clusters as a function of the hydrofluorocarbon concentration for the 2 mm gas gap (black) and 1 mm gas gap (red).

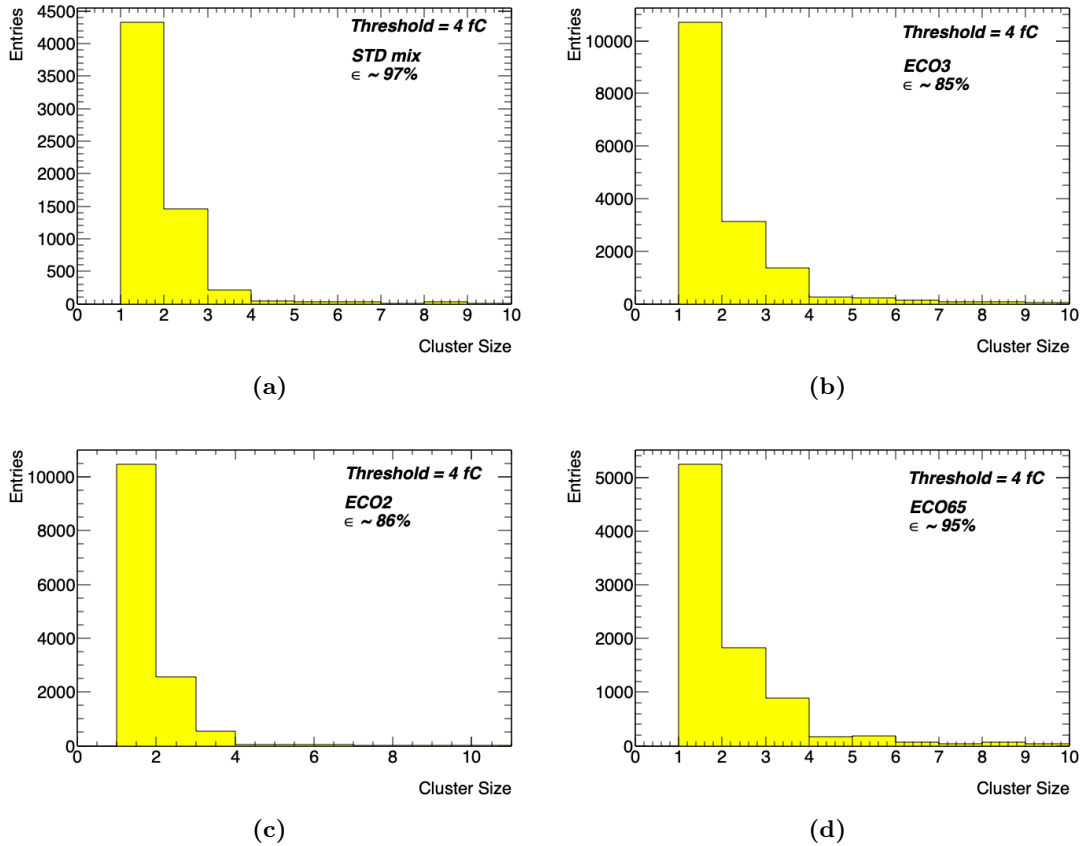
2.3 for ECO3 and ECO2, while is equal to 3.5 for ECO65 and 4.2 with the standard gas. Here, the tetrafluoroethane has been assumed equal to F-HFO in terms of hydrofluorocarbon density. The number of effective clusters has been obtained considering the intrinsic efficiency, i.e. subtracting the geometrical inefficiency due to spacers ($\sim 1.5\%$). This plot shows that above 65% of F-HFO concentration, the number of effective primary clusters reaches a saturation, approaching its maximum value, limited by the gas density and ionization energy. The thin gas gap introduces an additional degree of freedom, which delays the point of saturation with respect to larger gas gaps, as the 2 mm gas gap tested before. Figure 6.10 shows the number of effective primary clusters as a function of the hydrofluorocarbon concentration comparing the 1 mm gas gap with the 2 mm gas gap tested in Section 4.2. The larger gas gap allows to reach the saturation at 35% of F-HFO concentration, while the one 1 mm gas gap shows the same behaviour for F-HFO concentration above 65%. This suggests that the 1 mm gas gap needs a double the F-HFO concentration to exploit all the clusters available for the multiplication and detection. In the saturation plateau, the effective clusters in the 1 mm gas gap are half those available in the 2 mm gas gap (4 VS 8). It is important to stress that the number of effective clusters, n_p , used for this study is calculated using the Poisson statistics, thus considering the probability to have zero ionizations (see Equation 2.12 in Section 2.2). This implies that this number gives an estimation of only the cluster detected, but it does not give the total number of clusters generated inside the gas gap. Therefore, $n_p = 2$ does not mean that two clusters occur inside the gas gap, but that among the clusters formed in the gas gap, two of them produce a detectable signal. The results are summarized in Table 6.2.

Table 6.2: HV at 50% efficiency, efficiency plateau value, and number of effective clusters at plateau for the standard, ECO3, ECO2, ECO55 and ECO65 gas mixtures.

Gas mixture	HV _{50%} (V)	$\epsilon_{\text{plateau}}$	$\langle n_p \rangle_{\text{eff}}$
STD	5400	98.5%	4.2
ECO3	5600	87%	2.04
ECO2	6100	88%	2.15
ECO55	6900	93%	2.65
ECO65	7400	97%	3.5

6.2.2 Cluster size

Figure 6.11 shows the cluster size distribution at the efficiency plateau for the gas mixtures studied. The average cluster size is around 1.5, near to the physical value. The fraction of events with cluster size higher than four are not correlated with the passage of the particle, but are due to electronic noise far from the beam spot which has not been subtracted. Indeed, the quantities shown in these plots are obtained considering the hits in the entire detector area and not only the strips within the beam spot. The cluster size depends on the readout system, i.e. the strips layout. In this case the cluster sizes with different gas mixtures are comparable as expected.

**Figure 6.11:** Cluster size at plateau for (a) the standard gas, (b) ECO3, (c) ECO2 and (d) ECO65.

6.2.3 Time over threshold

Figure 6.12 shows the time over threshold (TOT) at full efficiency obtained with the mixtures under test. The TOT has been measured considering the difference between the trailing and leading edge of only the center of the cluster. The standard gas mixture, Figure 6.12.a, shows a TOT distribution well peaked around 16 ns. The eco-gases, Figure 6.12(b)-(c)-(d), show a broader distribution with a peak between 20 ns and 25 ns. The tails at both edges of the distribution are due to multi-avalanche events and transition events typical of these gas mixtures, as discussed in Section 3.4 and studied in details in Section 4.4.3. The time over threshold is correlated with the charge released in the gas, showing that the ecogas mixtures produce larger signals with a higher charge content. This characteristic will be further studied in Section 6.2.6.

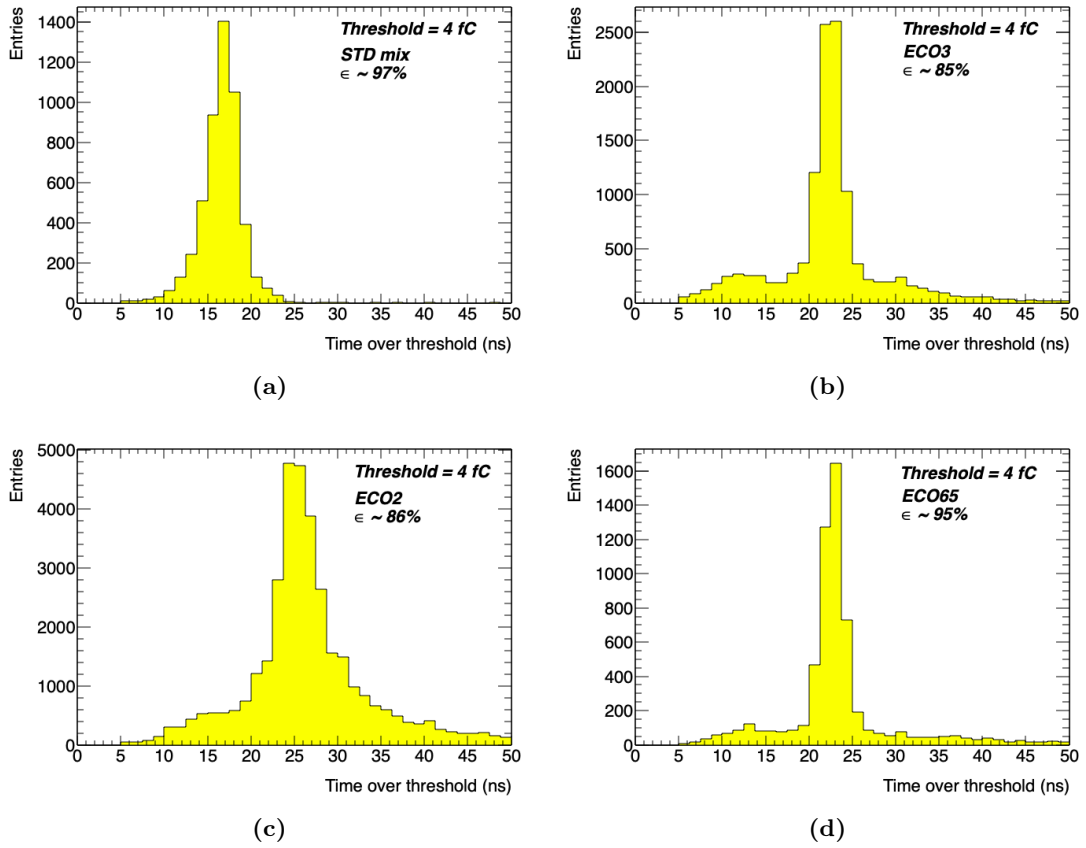


Figure 6.12: Time over threshold at plateau of the center of the cluster for the (a) standard gas, (b) ECO3, (c) ECO2 and (d) ECO65 gas mixtures.

The correlation between time over threshold and charge allows to study the charge distribution as a function of the high voltage, thus the avalanche growth, looking at the TOT variation at different high voltage values. In order to study the avalanche growth according to the model given in Section 2.2, the ECO2 and standard gas efficiencies have been normalized at their maximum plateau value (86% and 97% respectively) and their TOT distributions have been compared at the same normalized efficiency. The results are shown in Figure 6.13.

At low efficiency the standard gas mixture shows a higher shoulder for small TOT values. This shoulder disappears at higher efficiency (Figure 6.13.a), demonstrating that the development of the avalanche is the same regardless of the gas mixture.

At higher field, corresponding to $\epsilon_{\text{norm}} \sim 72\%$ (Figure 6.13.d), the ecogas shows a tail at higher charge due to transition events, as discussed before.

The trend at low electric field values, Figure 6.13.a and Figure 6.13.b, can be explained imagining that the ecogas reaches the saturation regime before the standard gas mixture, thus the CO_2 allows the growth of avalanches with higher density, causing the establishment of the electric field due to space charge effect to occur earlier. The earlier the avalanche saturates, the sooner the spatial electric field reaches a value high enough to neglect the one applied, triggering the recombination processes which leads to the generation of transition events and, at higher field, streamers.

This behaviour strongly supports the transition event model given in Section 4.4.3 and suggests that these events can really be interpreted as streamer precursors and as delayed avalanches coming from electron-ion recombination. The electron speed in eco-gases is higher if compared to the tetrafluoroethane, therefore the multi-avalanches events are much closer to each other and, in some cases, the signals merge together and appear as multi-peaks events or wider avalanches and the identification of multi-peaks and their separation is not distinguishable due to the low resolution.

The study of the saturation effect was only possible with this setup due to the very performing threshold which allows to appreciate this behaviour and be sensitive to the transition from the exponential growth to the saturation regime.

In the 2 mm gas gap case, the threshold was 150 fC to be compared to 4 fC of this FE electronics, and the resolution was too small to appreciate the passage between these two regimes.

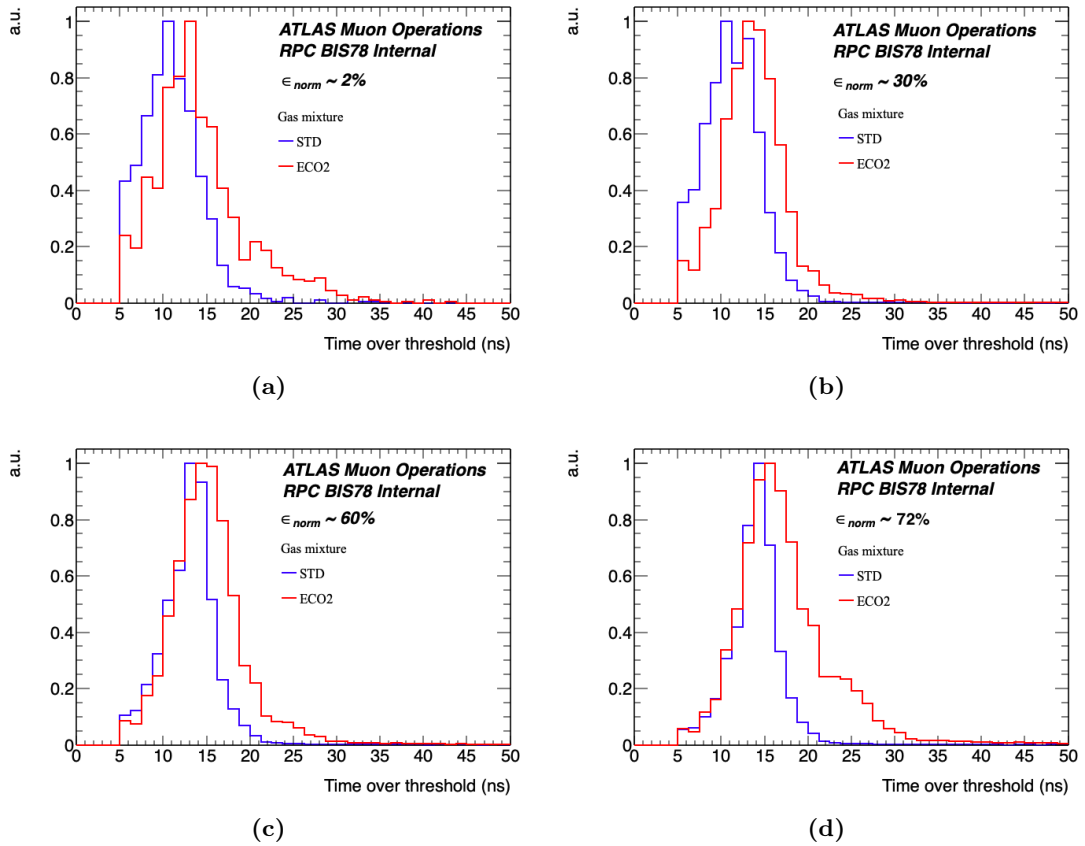


Figure 6.13: Normalized charge distributions for standard and ECO2 gas mixtures at $\epsilon_{\text{norm}} = 2\%$ (a), 30% (b), 60% (c) and 72% (d) of the maximum plateau associated to the mixture.

6.2.4 Time resolution

The time resolution depends on the gas mixture and scales with the gas gap width. In Section 4.5 we found that the higher drift velocity in CO_2 improves the detector time resolution of 300 ps in the 2 mm gas gap RPC.

The time resolution of BIS78 RPC is measured using the time of flight method (TOF) described in Section 6.1.2 in the $(\eta \times \phi)$ square corresponding to the center of the beam spot. In order not to contaminate the TOF distribution with cross-talk events and to remove the cluster size effect, only the leading edge of the first signal of each cluster is taken into account for the TOF measurement.

The time resolution of BIS78 RPC operating with ECO3 gas mixture (maximum value of CO_2 explored) is shown in Figure 6.14 and is:

$$\sigma_{\text{RAW}} = (311 \pm 0.02) \text{ ps} \quad (6.4)$$

The time resolution measurement is spoiled by primary and secondary ionization sta-

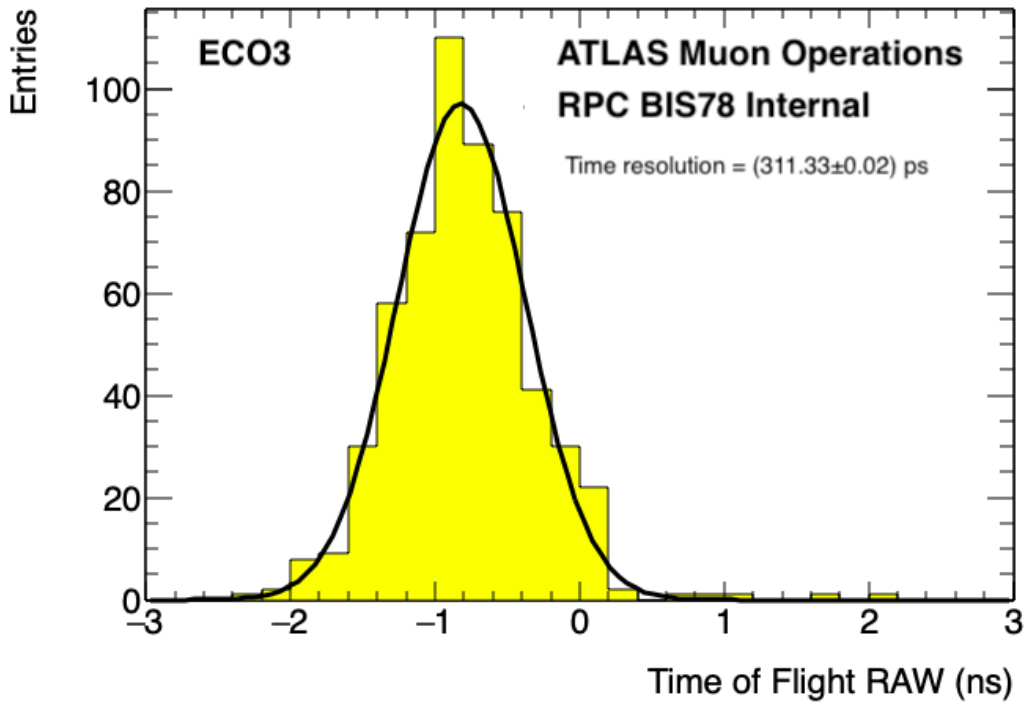


Figure 6.14: Time resolution without time-walk corrections of the BIS78 operated with ECO3 gas mixture.

tistical fluctuations and limited by the time jitter, time-walk and drift time.

The electronic skew and time propagation effect can be calibrated applying the time-walk corrections which should be very low if the threshold is low and the FE discriminator is fast.

An exponential function has been used to correct the TOF distribution.

The procedure can be summarized in the following steps:

- Exponential fit on the curve representing the time of flight as a function of the TOP chamber time-over threshold (Figure 6.15.a). The TOF of the two singlets is used for the correlation with the TOT distributions, because it allows to remove all the systematic effect, like trigger jitter and TDC jitter;

- Subtraction of the exponential fit to the time of flight distribution, correcting it by removing the dependence on the TOT of the first singlet. Figure 6.15.b shows the weight of this subtraction as a function of the TOP time over threshold. The distribution is almost-flat, showing that the dependency on the signals amplitude is already very low at this step. The only exception is in the range between 16 and 18 ns, which corresponds to the TOT range where the charge distribution moves from the first peak observed and the second (see Figure 6.12.b);
- Exponential fit on the corrected time of flight distribution as a function of the MID chamber (Figure 6.15.c);
- Subtraction of the exponential fit to the time of flight distribution. Figure 6.15.d shows the weight of this subtraction as a function of the MID time over threshold. The flat distribution shows that the method is working fine with some uncertainties in the transition region between 16 and 18 ns, as discussed above.

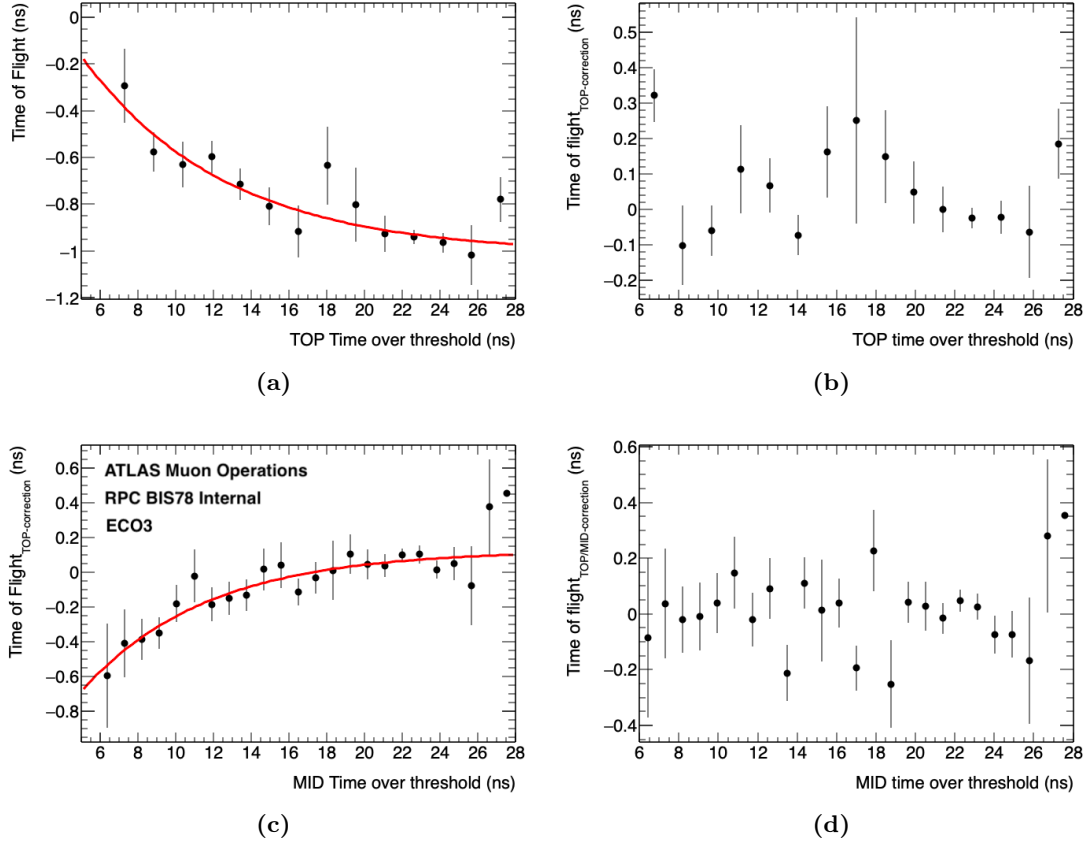


Figure 6.15: Time walk correction.

The time resolution after applying the time walk correction is shown in Figure 6.16 and is:

$$\sigma_{\text{ECO3}} = (285 \pm 0.02) \text{ ps} \quad (6.5)$$

With a systematic uncertainty estimated to be about 50 ps with the time resolution varies from 220 ps to 300 ps depending on the $(\eta \times \Phi)$ square chosen for the measurement.

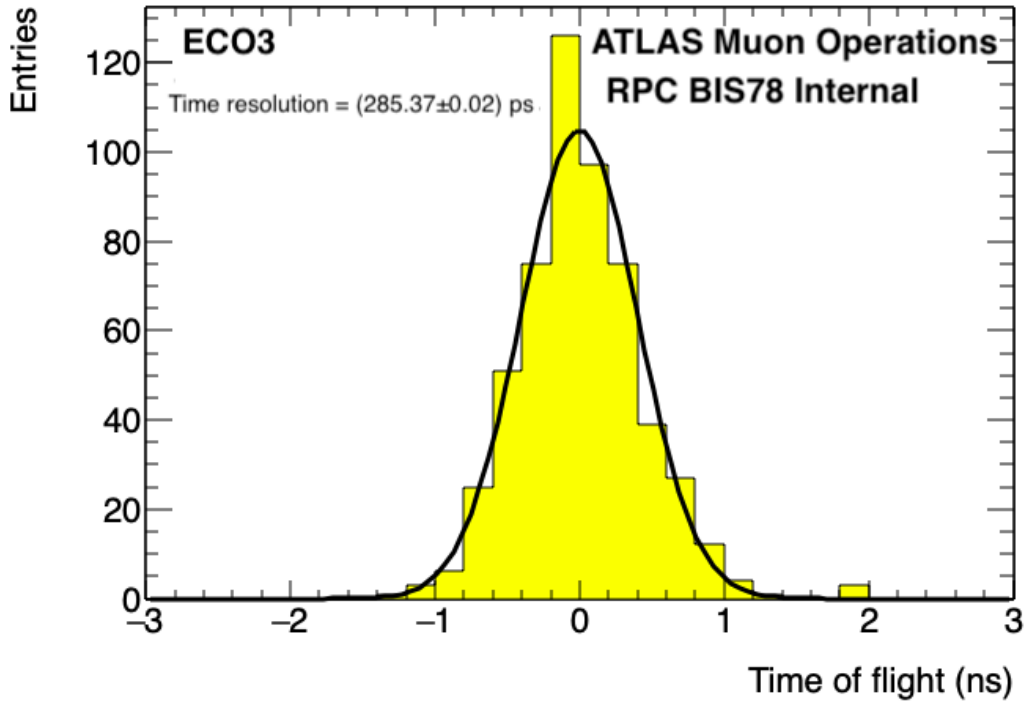


Figure 6.16: Time resolution after time-walk corrections of the BIS78 operated with ECO3 gas mixture.

The same method has been applied to measure the time resolution with ECO2, ECO55 and ECO65 gas mixtures. The results are comparable within 50 ps with the one obtained with ECO3. The systematic effects don't allow to appreciate the variation of the time resolution as a function of the HFO concentration. Indeed, the measurement is performed in a $(\eta \times \Phi)$ square which can vary within measurements depending on the position of the beam spot. The choice of different strips mainly leads to two systematic effects, not corrected in this analysis and currently under study:

- The homogeneity of the gas gap: even a very small variation of the gas gap width (around 100 μm) produces an electric field variation of hundreds of Volt, which means that the time resolution is measured at different efficiency values;
- The calibration of the FE electronics: the FE channels are not perfectly calibrated and this produces a different response for different pulses depending on the performance of their single specific component. Indeed, a faster response leads to an improved time resolution;

The average time resolution, considering the entire surface, of a BIS78 RPC operating with the standard gas mixture is [50]:

$$\sigma_{\text{STD}} = (450 \pm 50) \text{ ps} \quad (6.6)$$

Comparing this value with 6.4, we can conclude that the time resolution is improved by 30% operating the RPC with the eco gas mixture .

The best time resolution achieved with the corrections described above operating the BIS78 RPC with the standard gas is [50] :

$$\sigma_{\text{STD}} = (330 \pm 18) \text{ ps} \quad (6.7)$$

14% worst than ECO3 after applying only the time walk corrections.

This result confirms the excellent performance achievable in terms of timing properties using the CO₂ as the main gas component. Moreover, the very small correction, around 70 ps, suggests that the FE electronic is really fast, thus implicitly applies time walk corrections.

6.2.5 Threshold scans

In order to investigate the best performance achievable with the new FE electronics, a threshold scan has been performed on the standard gas, ECO3 and ECO65 with thresholds varying from 4 fC to 1 fC. The gain in high voltage obtained by decreasing

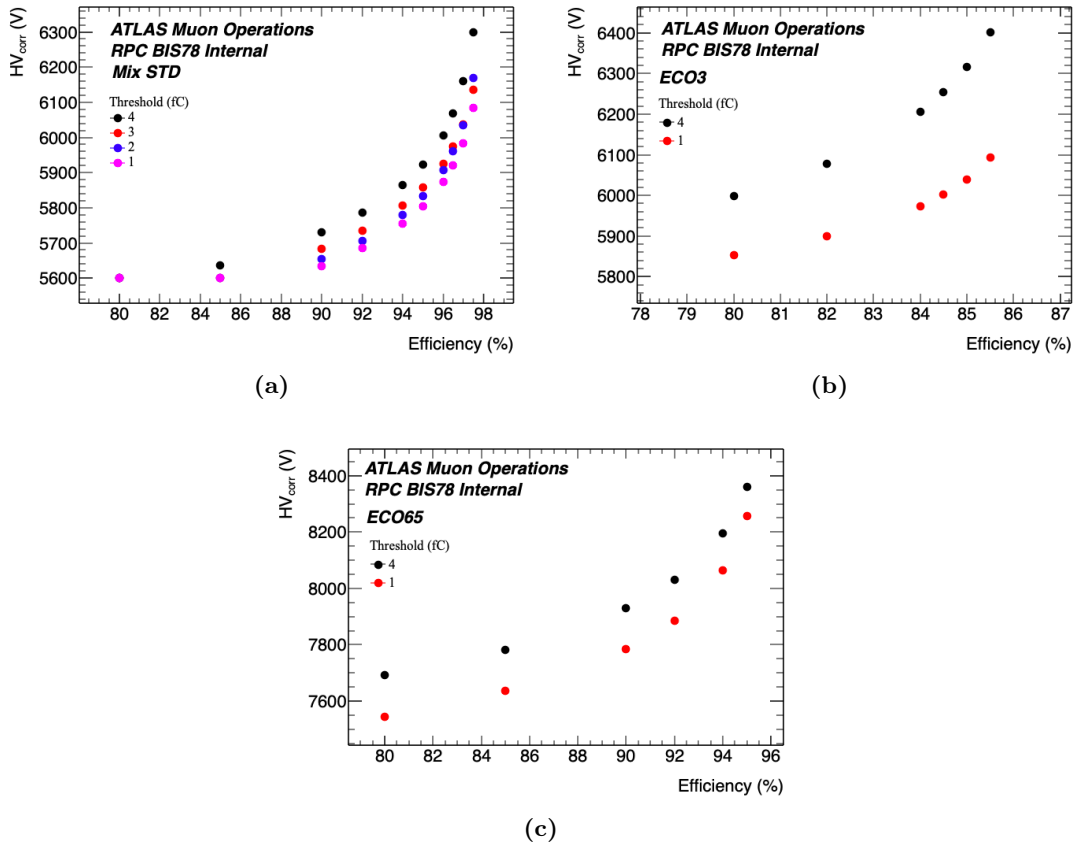


Figure 6.17: High voltage as a function of the efficiency for (a) the standard gas, (b) ECO3 and (c) ECO65 for different threshold values.

the threshold is reported in Figure 6.17 and shows the high voltage as a function of the efficiency. Figure 6.17 shows that moving the threshold from 4 fC to 1 fC the detector works at the same efficiency plateau, with the efficiency plateau value anticipated by 150 V, regardless of the gas mixture used.

The decrease of the threshold can lead to the instability of the system, affecting other detector characteristic such as the average number of cluster per event and the cluster size. Figure 6.18 and Figure 6.19 show these quantities as a function of the efficiency. The number of clusters at full efficiency with the threshold set at 1 fC is 3, while is 2 with the threshold equal to 4 fC. The cluster size does not change varying the FE

threshold.

These results suggest that the BIS78 can be operated also at lower threshold, the lowest ever achieved in RPC detectors. The decrease of the threshold at fixed current results in an improved detector ageing and rate capability, thus the minimum threshold should be carefully chosen to maximize this effect for the RPC operation with eco-gases.

Indeed, the copious Fluorine production is currently one of the main limitation of the RPC operation with ecogases, causing the deterioration of the electrode surface and the start of the accelerate aging process.

The need to decrease the Fluorine concentration inside the gas mixture using ECO2 or ECO3 allows an absolute detection efficiency of only 88% instead of 98%.

The use of a very low threshold allows to work with ECO65 without both loosing in performance and triggering an anticipate detector aging.

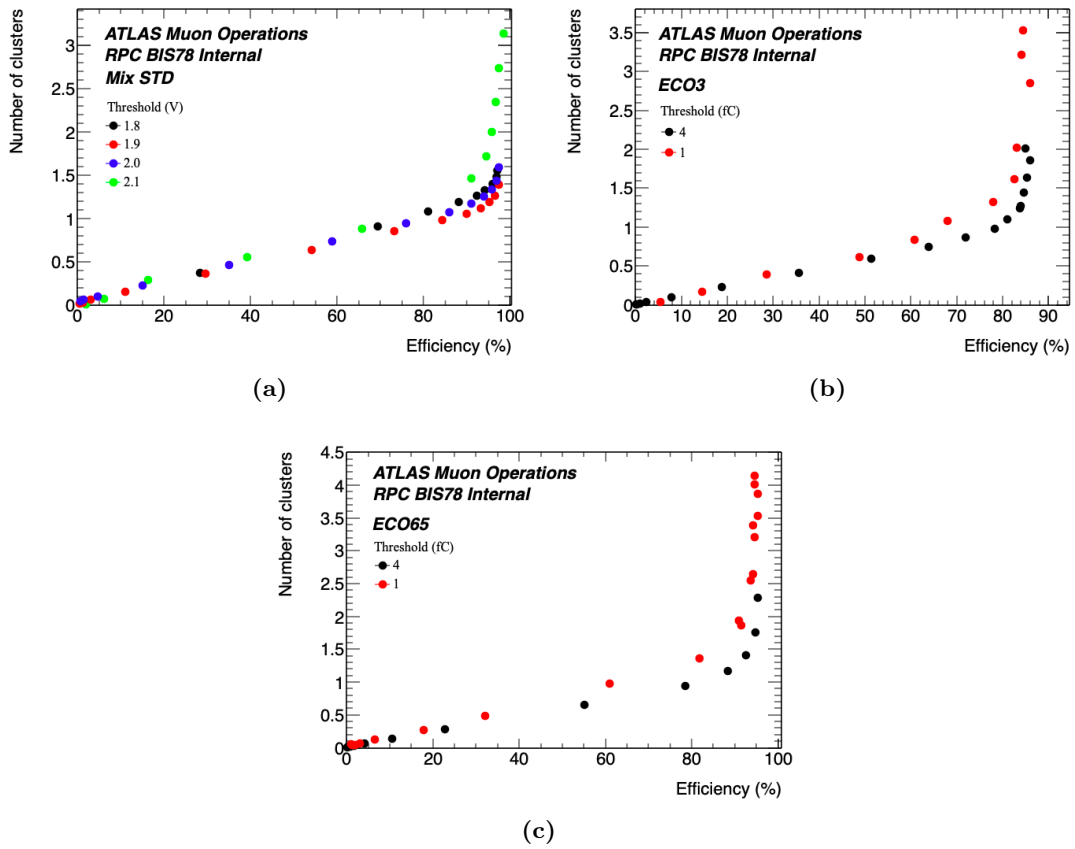


Figure 6.18: Number of clusters as a function of the efficiency or (a) the standard gas, (b) ECO3 and (c) ECO65 for different threshold values.

6.2.6 Currents

Figure 6.20.a shows the currents measured with the standard gas, ECO3 and ECO65 gas mixtures without photon irradiation as a function of the normalized efficiency. The normalized efficiency has been obtained dividing the efficiency by its maximum plateau value. The maximum plateau values of the gas mixtures studied are listed in Table 6.2. Figure 6.20.a shows that the current due to the passage of the Minimum Ionizing Particle (MIP) is higher in the eco gas mixtures with respect to the standard gas:

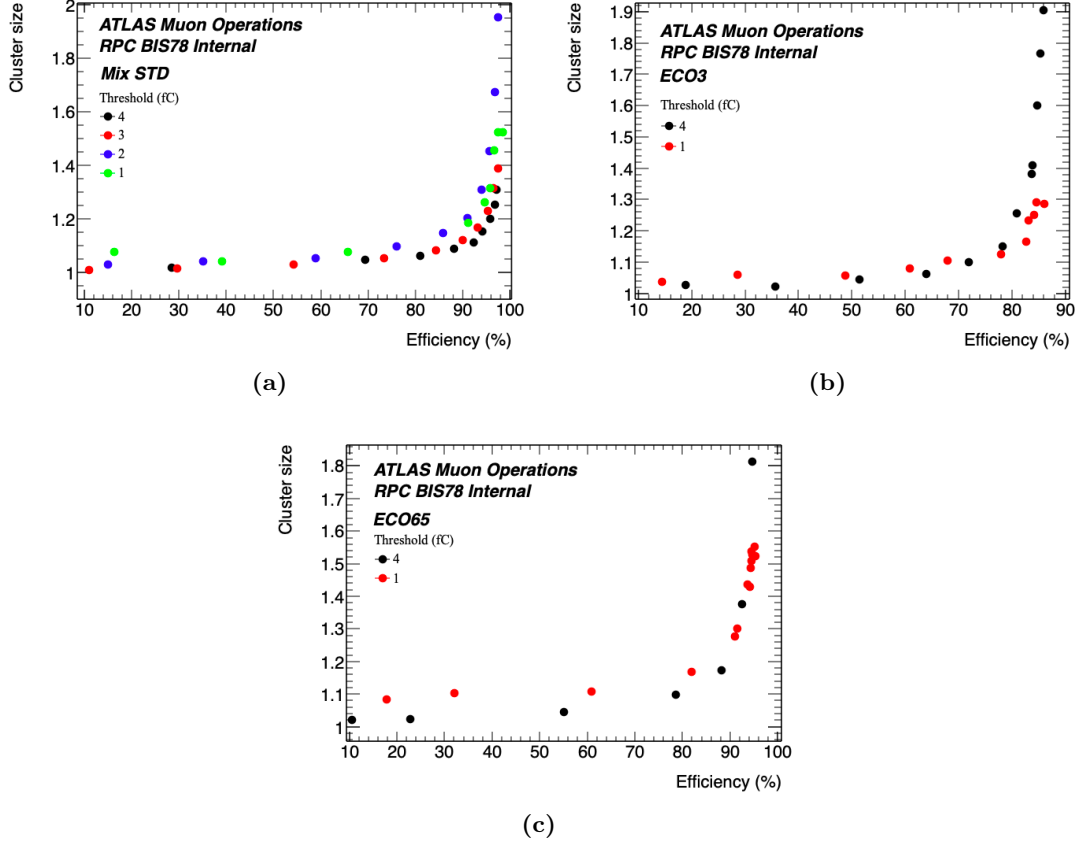


Figure 6.19: Cluster size as a function of the efficiency or (a) the standard gas, (b) ECO3 and (c) ECO65 for different threshold values.

$$\begin{aligned}
 I_{\text{STD}}(\epsilon_n = 100\%) &= 0.5 \mu\text{A}; \\
 I_{\text{ECO3}}(\epsilon_n = 100\%) &= 1.7 \mu\text{A}; \\
 I_{\text{ECO2}}(\epsilon_n = 100\%) &= 2.9 \mu\text{A}
 \end{aligned}
 \tag{6.8}$$

In the ATLAS experiment the main contribution to the current which affect the detector operation and aging, is due to the photons and neutrons backgrounds, as discussed in Section 5.4.1. The behaviour of these gas mixtures in presence of a photon background has been studied. The photon contribution to the current, shown in Figure 6.20.b, has been measured irradiating the detector with a modest intensity and measuring the current excluding the current due to muons. In this way only the contribution to the current due to photons is considered and its trend as a function of the normalized efficiency is reported in Figure 6.20.b. Figure 6.20.b shows that the three gas mixtures have the same photon current at the same normalized efficiency. This result suggests that, operating the detector with 1 fC threshold, the photon contribution to the detector current is independent from the gas mixture at the same normalized efficiency. ECO2 and the standard gas mixtures have the same photon current at the same normalized efficiency, but a different absolute MIP efficiencies, being their efficiency 88% and 98.6% respectively. On the other hand, ECO65 gas mixture reaches almost the same efficiency with the same photon current at the same normalized efficiency. This result is very promising because suggests that working with 1 fC threshold, the ecogas

mixtures can guarantee the same aging and rate capability of the standard gas.

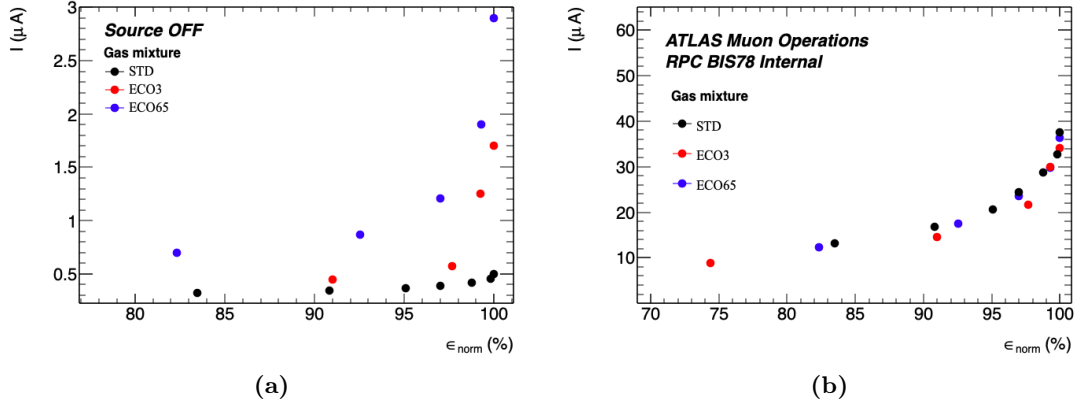


Figure 6.20: Current as a function of the normalized efficiency (a) without and (b) with photon irradiation.

6.2.7 Conclusions

In this Chapter a RPC, with 1 mm wide gas gap, has been tested with a muon beam and under strong photon irradiation, with the aim to characterize the phase-1/2 upgrade RPC with environment-friendly gas mixtures. The gas mixtures studied are:

- Standard gas mixture = $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$;
- ECO65 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 30/65/4/1$;
- ECO55 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 40/55/4/1$;
- ECO2 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 60/35/4/1$;
- ECO3 = $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 70/25/4/1$.

The measurements have been performed varying the FE threshold, exploring a range from 4 fC to 1 fC. The RPC performance have been compared using the conservative threshold, 4 fC, currently used in the RPC-BIS78 system of the ATLAS experiment and the results can be summarized as follows:

- The ECO2 and ECO3 gas mixtures do not offer a sufficient active target for the primary ionization, resulting in a detection efficiency less than 90%, while ECO55 and ECO65 show high-efficiency above 90%. In particular, ECO65 shows the best performance in terms of efficiency, 97.5%, consistent with the one measured with the standard gas;
- The ecogas mixtures show comparable performance in terms of current at the same normalized efficiency and timing properties;
- The time resolution with eco-gases improves compared to the value obtained with the standard gas ;

- The RPC filled with eco-gas mixtures can work under irradiation at the same current obtained with the standard gas mixture using a low FE thresholds (1 ÷ 4 fC), offering the possibility to work also with a high $\text{C}_3\text{H}_2\text{F}_4$ concentration, without worsening the rate capability and accelerating the aging process;

Chapter 7

Muon isolation efficiency and scale factors in $t\bar{t}$ events

In this chapter the measurement of the muon isolation efficiency in a busy environment using $t\bar{t}$ events is presented. The aim of this work is to provide a complementary measurement with respect to the current technique used to extract these quantities, i.e. the Tag & Probe method using $Z \rightarrow \mu\mu$ events. In this way it is possible to probe the reliability of the detector simulation for different processes, with a significantly different environment.

The measurement is performed using data from pp collisions at $\sqrt{s}=13$ TeV collected by the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of 36 fb^{-1} .

The muon isolation efficiency is derived from a sample of $t\bar{t}$ using the dilepton decay channel and are compared with those obtained using $Z \rightarrow \mu\mu$ sample.

7.1 Muon reconstruction and identification in the ATLAS experiment

The identification and precise measurement of processes with muons in the final state is one of the main goal of the ATLAS experiment at the LHC and HL-LHC.

Muons are produced in many important physics processes and are detected by the Muon Spectrometer (see Section 1.1.1) with almost 100%-efficiency and good momentum resolution.

The muon identification and reconstruction is performed combining information from ID, MS and Calorimeters searching for a signature typical of a Minimum Ionizing Particle (MIP).

Muon reconstruction algorithms use different combinations of ID and MS tracking information for different purposes.

The stand-alone tracks reconstruction starts with the identification of short straight-line local track segments reconstructed from hits in an individual MS station by means of a Hough transform [51]. These segments are then combined into preliminary track candidates and information from precision measurements in the bending plane is combined with measurements of the second coordinate from the trigger detectors to create three-dimensional track candidates. A global χ^2 fit of the muon trajectory through the magnetic field is then performed, taking into account the effects of possible interactions in the detector material along with possible misalignments between the different detector chambers.

The global muon reconstruction is performed using information from the ID, MS and Calorimeters, using five reconstruction strategy leading to the corresponding muon "types":

- Combined muons (CB), identified by matching MS tracks to ID tracks and performing a combined track fit based on the ID and MS hits, taking into account the energy loss in the calorimeters;
- Inside-out combined muons, reconstructed using a complementary inside-out algorithm, which extrapolates ID tracks to the MS and searches for at least three loosely-aligned MS hits. The ID track, the energy loss in the calorimeters and the MS hits are then used in a combined track fit;
- Muon spectrometer extrapolated (ME), used when an MS track cannot be matched to an ID track, thus its parameters are extrapolated to the beamline. This method allows for fully exploiting the MS coverage;
- Segment-tagged muons, by requiring that an ID track extrapolated to the MS satisfies tight angular matching requirements to at least one reconstructed MS segment. A successfully-matched ID track is identified as a muon candidate, and the muon parameters are taken directly from the ID track fit. This method is useful for low- p_T muon tracks, which do not reach all the layers of the muon spectrometer due to the bending in the magnetic field and also in regions with reduced geometrical acceptance of the detector;
- Calorimeter-tagged muons, identified by extrapolating ID tracks through the calorimeters to search for energy deposits consistent with a MIP. The deposits are then used to tag the ID track as a muon, and the muon parameters are again taken directly from the ID track fit. This algorithm allows for improving purity in the region of limited MS coverage ($\eta < 0.1$).

After the reconstruction, muon candidates are classified and identified by a set of requirements on the number of hits in the different ID sub-detectors and different MS stations, on the track fit properties, and on variables that test the compatibility of the individual measurements in the two detector systems.

Five "Working Points" (WP) are defined to cover the needs of the physics analyses: Loose, Medium, Tight, High- p_T and Low- p_T .

The Loose selection WP was optimised for the reconstruction of Higgs boson decays in the four-muon final state, which, due to the high muon multiplicity and large signal-to-background ratio, benefits from a higher efficiency at the cost of less purity and larger systematic uncertainties.

The Medium WP provides an efficiency and purity suitable for a wide range of analyses, while keeping the systematic uncertainties in the prompt muon efficiency and background rejection small.

The Tight WP provides the highest purity, with a substantially improved background rejection at the cost of a few percent efficiency loss for prompt muons with respect to Medium muons.

The Tight WP benefits analyses that are limited by background from non-prompt muons.

For analyses targeting extreme phase-space regions The High- p_T and the Low- p_T WP are provided. The former is optimized for W' and Z' searches, ensuring an optimal momentum measurement for muons with $p_T > 100$ GeV and providing the best momentum

resolution.

The latter targets the lowest p_T muon, where the background from non-prompt muons can be large and which are less likely to be reconstructed as full tracks in the MS.

The performance of the three WPs for muon $p_T > 100$ GeV are shown in Figure 7.1.

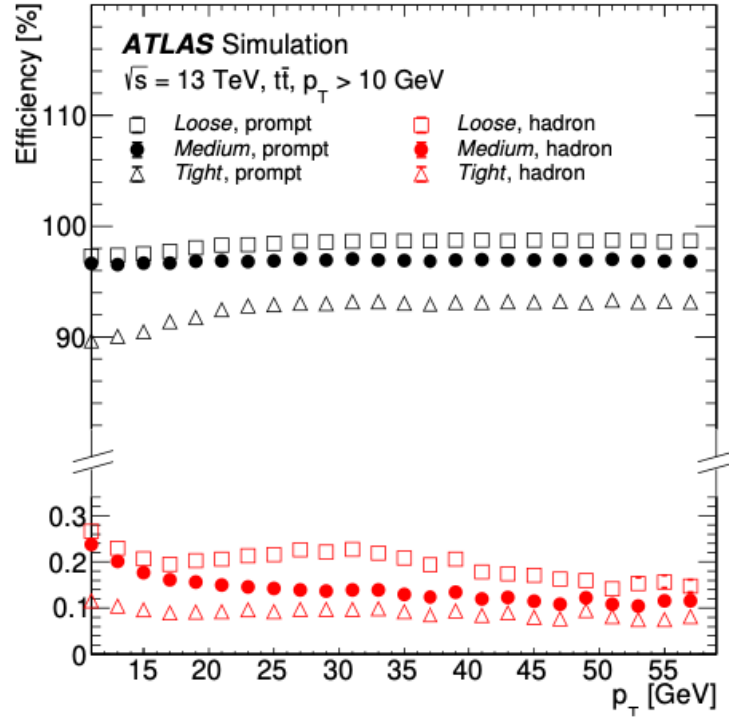


Figure 7.1: Efficiency as a function of the muon p_T for the Loose, Medium and Tight WPs. The performance are simulated using $t\bar{t}$ events.

7.2 Muon isolation in the ATLAS experiment

Muons originated from Standard Model (SM) prompt decays of weak bosons can be discriminated from those generated from hadron (non-prompt muons) decays, Figure 7.2, by measuring the activity in their neighbourhood [52].

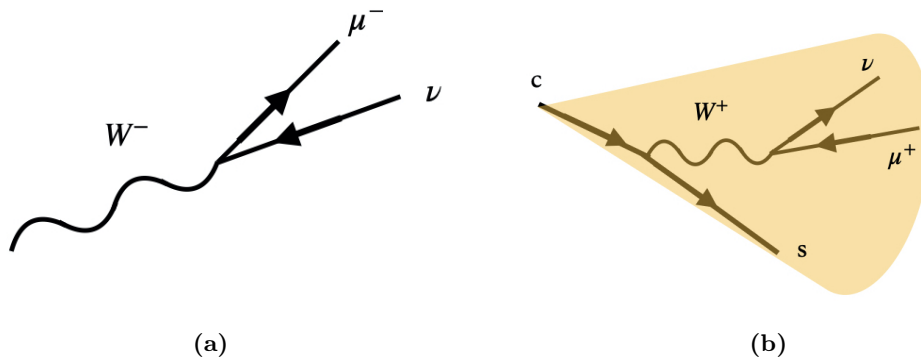


Figure 7.2: Example of (a) prompt and (b) non-prompt muons.

The isolation is defined as the transverse energy (or momentum of tracks) reconstructed in a cone around the muon track divided by the muon p_T . This technique allows for efficiently rejecting muons coming from hadron decays and is used in combination with identification and reconstruction selections which are efficient in the suppression of muon originated from light-hadron decays and hadrons misidentified as muons.

Three techniques are adopted to measure the muon isolation:

- Using only the information extracted from the Inner Detector(ID) [53];
- Using only the information extracted from the Calorimeters by means of topological cell clusters [54];
- Combining ID and Calorimeters information using a particle-flow algorithm [55];

These techniques allow to define several "Working Points" [52] characterized by different isolation cuts optimized for the different analyses requirements, and are based on the balance of prompt-muon acceptance, rejection of non-prompt muons, and performance in close proximity to other objects.

Track-based isolation criteria are calculated as the scalar sum of the transverse momenta of the reconstructed ID tracks associated with the primary vertex, which are measured in a $(\eta \times \Phi)$ cone of size ΔR around the muon track, excluding the muon track itself. The ΔR size can be chosen to be fixed or variable. In the former case, $\Delta R=0.2$ and the corresponding selection criterium is labeled as p_T^{cone20} . This selection is used by analyses which are not negatively affected by efficiency loss for high- p_T muons. Indeed, it ensures a good rejection of non-prompt-high- p_T muons and decreases the influence of the Overlap Removal, which is an isolation requirement where muons within an angular distance of 0.4 from a jet are removed from the analysis ($\Delta R < 0.4$). In the latter case, labeled as $p_T^{\text{varcone30}}$, ΔR decreases with p_T^μ as:

$$\Delta R = \min(10 \frac{\text{GeV}}{p_T^\mu}, R) \quad (7.1)$$

being $R = 0.3$ and is used for boosted signatures and for topologies where several objects, as jets or other leptons, can be very close to the energetic muon direction and when the contamination from non-prompt muons is not of major interest. Some isolation criteria uses $p_T^{\text{varcone30}}$ for $p_T < 50$ GeV and p_T^{cone20} for $p_T > 50$ GeV in order to increase the rejection of hadronic activity.

Track-based isolation variables are mostly independent of pile-up, due to the rejection of tracks originating from pile-up vertices or with large transverse impact parameters relative to the primary vertex.

All muon isolation WPs include a selection on one track-based isolation variable, with or without an additional criterion for calorimeter-based or particle-flow-based isolation, which are described in more detail in the following.

Calorimeter-based isolation are measured as topological cell clusters in a cone of size $\Delta R=0.2$ around the muon position extrapolated to the calorimeter, after subtracting the contribution of the muon itself and correcting for pile-up effects [56]. This technique has a poor energy resolution due to the large pile-up corrections, therefore it is always combined with a stringent requirement on the track isolation.

The ID and Calorimeters provide complementary information, therefore better performance are achievable when they are combined together. The track based isolation shows better resolution and lower pile-up dependence, while the calorimeters include also neutral particles and particle below the ID p_T threshold. On the other hand these two isolation redundantly measure the hadronic activity because charged particles are measured by both.

In order to remove the overlap between these two contributions, the particle-flow algorithm has been developed. The final isolation variable is measured as the sum of:

- Track-based isolation using $p_T^{\text{varcone30}}$ for $p_T < 50$ GeV and p_T^{cone20} for $p_T > 50$ GeV;
- Transverse energy of the neutral particle-flow object in a cone of size $\Delta R=0.2$ (E_T^{neflow20}), corrected for the contribution from the energy deposit of the muon itself and for pile-up effects.

This method allows for improving the resolution with respect to the Calorimeters-based isolation because the charged particle contribution is removed and the pile-up effect on neutral particles is better corrected, resulting in a decrease of the pile-up dependence. Figure 7.3 shows the isolation variables discussed above divided for the muon p_T , obtained using prompt and non-prompt muons extracted from $t\bar{t}$ simulated events. The plot shows that the prompt muons distribution is well peaked around zero, while for non-prompt muons the distribution is almost flat.

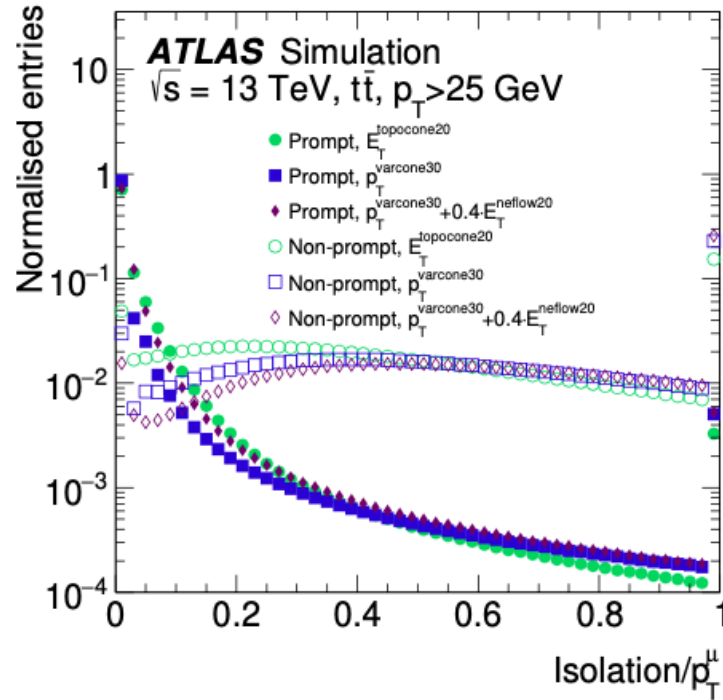


Figure 7.3: Isolation variables divided for the muon p_T normalized to unit area. Prompt and non-prompt muons are extracted from $t\bar{t}$ simulated events.

The muon isolation WPs built with the criteria discussed above are summarized in Table 7.1 along with two additional cut-based working points, the HighPtTrackOnly and TightTrackOnly, which use as discriminants the p_T^{cone20} and $p_T^{\text{varcone30}}$ respectively.

Table 7.1: Definition of the isolation working points. The PflowLoose, PflowTight, Loose, Tight and TightTrackOnly WPs exist in two variants: one with the ΔR cone decreasing with increasing p_T^μ as $\min(\text{Gev}/p_T^\mu, 0.3)$ and the other with $\Delta R = 0.2$ for $p_T^\mu > 50$ GeV.

WP	Definition	Track p_T requirement
PFlowLoose	$(p_T^{\text{varcone30}} + 0.4E_T^{\text{neflow20}}) < 0.16p_T^\mu$	$p_T > 500$ MeV
PFlowTight	$(p_T^{\text{varcone30}} + 0.4E_T^{\text{neflow20}}) < 0.045p_T^\mu$	$p_T > 1$ GeV
Loose	$p_T^{\text{varcone30}} < 0.15p_T^\mu, E_T^{\text{topocone20}} < 0.3p_T^\mu$	$p_T > 1$ GeV
Tight	$p_T^{\text{varcone30}} < 0.04p_T^\mu, E_T^{\text{topocone20}} < 0.15p_T^\mu$	$p_T > 1$ GeV
High p_T TrackOnly	$p_T^{\text{cone20}} < 1.25$ GeV	$p_T > 1$ GeV
TightTrackOnly	$p_T^{\text{varcone30}} < 0.06p_T^\mu$	$p_T > 1$ GeV
PLV	BDT score (PLV) > -1.1	-

An additional working point, called "PLV", is also used applying cuts on the Prompt Lepton Tagging algorithm, which matches electrons and muons to track jets, and then uses track jet properties to train a multi-variate algorithm [57]. The multivariate discriminant is based on a Boosted Decision Tree (BDT) and is built to maximise the rejection power of non-prompt muons from heavy-flavour hadrons.

7.3 Muon isolation efficiency and scale factors

The muon isolation efficiency is measured using the Tag&Probe method applied on $Z \rightarrow \mu\mu$ sample, which represents a clean sample of dimuon pairs. In this method one of the muon, the "tag", is required to satisfy stringent isolation and identification criteria and is used as trigger for the online event selection, while the second candidate muon, the "probe", is used to test the isolation algorithm. The isolation efficiency is thus defined as the ratio between probe muons which satisfy the isolation cuts according to the selection criteria adopted "X" and the number of total selected probes:

$$\epsilon_{\text{isolation}} = \frac{N_{\text{probe}}^{\text{X}}}{N_{\text{probe}}^{\text{tot}}} \quad (7.2)$$

Probes are counted in data events after the subtraction of the backgrounds which are estimated using simulations. In simulation, both the tag and probe muons are required to be a prompt muon at generator level in order to remove any background contamination.

The agreement between the efficiency measured in data, $\epsilon^{\text{Data}}(\text{X})$, and the corresponding efficiency in Monte Carlo sample, $\epsilon^{\text{MC}}(\text{X})$, is called "Scale Factor" and is defined as :

$$\text{SF} = \frac{\epsilon^{\text{Data}}(\text{X})}{\epsilon^{\text{MC}}(\text{X})} \quad (7.3)$$

The SF quantifies the deviation of the simulation from the real detector behaviour, and is therefore used in physics analysis to correct the simulation.

7.4 Muon isolation efficiency and scale factors in $t\bar{t}$ events

The scale factors are used to correct simulation in all physics analyses and are currently measured using $Z \rightarrow \mu\mu$ sample, which provides a clean sample of muons for the efficiency measurement and SF derivation.

However, these may be applied to event with topologies and environments very different with respect to those of $Z \rightarrow \mu\mu$ events. In order to demonstrate the independence of the SFs from the background activity, these quantities have been measured in $t\bar{t}$ events, which is characterized by a harsher background with respect to $Z \rightarrow \mu\mu$.

At the Large Hadron Collider the top quark is mainly produced via gluon-gluon fusion (Branching Ratio =87%) and $q\bar{q}$ annihilation (BR= 13%) as shown in Figure 7.4.

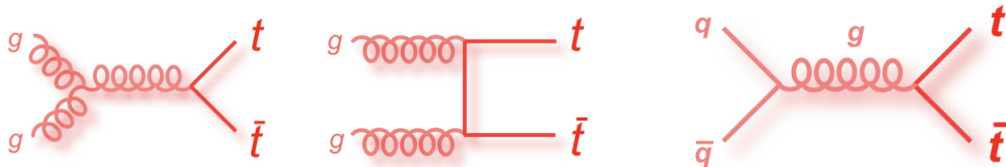


Figure 7.4: Feynman diagrams of the top quark production modes at the Large Hadron Collider: gluon-gluon fusion (left and center) and $q\bar{q}$ annihilation (right).

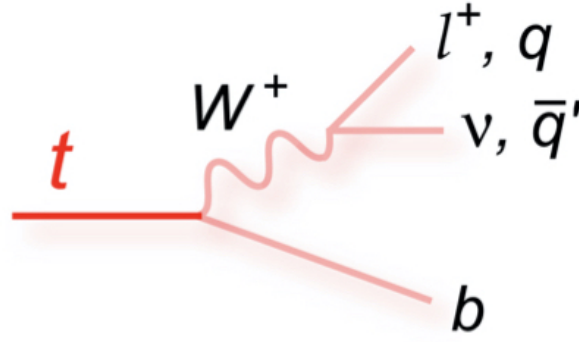


Figure 7.5: Feynman diagram of the top quark decay.

The top quark decays almost-exclusively in a W boson and a b -quark (BR = 99.8%) as shown in Figure 7.5.

There are three decay channels available:

- Hadronic channel: $t\bar{t} \rightarrow Wb + Wb \rightarrow (jj)b + (jj)b$, with BR = 46.2%;
- Semi-leptonic channel: $t\bar{t} \rightarrow Wb + Wb \rightarrow (l\nu)b + (jj)b$, with BR = 43.5%;
- Di-lepton channel: $t\bar{t} \rightarrow Wb + Wb \rightarrow (l\nu)b + (l\nu)b$, with BR = 10.3%

The hadronic channel signature consists in six jets, four of them are light and the other two come from the b -quark hadronisation. It shows the highest BR, but is affected by a large contamination of multiple jets due to strong interactions which do not involve top quark production (multijet QCD).

In the semi-leptonic decay one of the W bosons decay into two light jets, while the other decay in a lepton and a neutrino.

The presence of one isolated lepton in the decay products allows to reduce the background and events easily.

In the di-leptonic channel both W bosons decay leptonically. The presence of two neutrinos makes the kinematic reconstruction very difficult, but on the other hand the two high transverse energy leptons provide an efficient discrimination of the signal events with small background contamination, especially for leptons of different flavours.

For this reason, despite of the low branching ratio, the di-leptonic channel has been chosen to extract isolation efficiency and SF, because it offers the opportunity to build a clean sample of muons.

This work can be summarized in three steps:

- Development of the selection to isolate $t\bar{t}$ events with the highest purity in order to obtain a clean sample of muons for the efficiency measurement and SFs derivation;
- Check the Data and Monte Carlo agreement of the quantities under study;
- Measurements of efficiency and scale factors in $t\bar{t}$ events and comparison with those currently derived by the ATLAS Muon Combined Performance group, obtained using $Z \rightarrow \mu\mu$ sample with the Tag&Probe method

7.5 Data and Monte Carlo samples

The dataset used in this work comprises the data from LHC pp collisions at the center of mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS detector in 2015 and 2016, corresponding to the total integrated luminosity of 36 fb^{-1} . Only the data recorded during a period in which the ATLAS detectors were in good operating condition and the beam was stable have been taken into account.

The MC samples used in this analysis are summarized in Table 7.2.

Table 7.2: Monte Carlo samples used for the analysis.

Sample	Generator
$t\bar{t}$	Powheg + Pythia 8
single- t	Powheg + Pythia 8
WW/WZ/ZZ	Sherpa 221
Z + jets	Sherpa 221
W + jets	Sherpa 221

The $t\bar{t}$ dileptonic events and single top events are generated using Powheg [59] + Pythia 8 [60] and tuned using the A14 set of tuned parameters [61] and the NNPDF23LO set of parton distribution functions [62]-[63]. The WW / WZ / ZZ, Z/W + jets events are generated with Sherpa 2.2.1 [58], tuned with NNPDF3.0 NNLO, using NNPDF30NNLO PDFs [64].

7.6 Physics object

The physics objects used for this analysis are muons, electrons, jets and b -jets as expected from $t\bar{t}$ dileptonic events.

The analysis has been performed using AnalysisTop software with TOPQ1 derivation using the recommendation as implemented in AnalysisBase-21.2.173.

7.6.1 Muons

Muons must have a $p_T > 10$ GeV and have to satisfy the Medium quality identification requirement, which ensures high efficiency and purity while keeping the systematic uncertainties in the prompt-muon efficiency and background rejection small, as discussed in Section 7.1.

The Medium requirement comprises both combined (CB) and inside-out combined (IO) muon types.

These cuts correspond to a prompt muon efficiency of 97%, with a corresponding hadron misidentification rate of 0.17% in the region with $p_T > 20$ GeV and of 0.85% for $10 < p_T(\text{GeV}) < 20$ GeV.

The muon represent the tag particle for this analysis, therefore no isolation requirements have been applied except for the Overlap Removal, therefore muons within $\Delta R = \sqrt{(\Delta\eta)^2 + \Delta\Phi^2} < 0.4$ from a jet are removed from the analysis.

7.6.2 Electrons

Electrons in the final state must have $p_T > 10$ GeV and satisfy the Tight likelihood identification (TightLH) [65], which requires objects with at least two hits in the pixel

detector with one of them in the innermost layer and an overall number of seven hits in the pixel and silicon strips.

The electron represents the tag in this analysis, therefore it has to satisfy the PLVTight selection, based on BDT score, which is based on fixed requirements on the calorimeter and in the track isolation variables.

7.6.3 Jets and b-tagging

Jets are reconstructed using the anti- k_t algorithm [66]-[67] on electromagnetic (EM) topo-clusters jets with a radius value of $R = 0.4$ (small-R jets). The topo-clusters represent the inputs to jet reconstruction and are topologically-grouped noise-suppressed clusters of calorimeter cells.

Topo-clusters are formed from seed cell(s) with more than 4σ of energy, where σ is the average amount of noise expected in the cell in question, defined as the sum of the expected electronic and pile-up noise. Topo-clusters are calibrated at the EM scale, where the energy of an isolated topo-cluster is the sum of its constituent cell energies [68].

The b-jets [69] are tagged using MV2c10 algorithm, a multivariate discriminant based on the track impact parameters and displaced vertices [70], corresponding to an efficiency of 77 % per b-jet for the selected working point.

In this analysis two b-tagged jets with $p_T > 25$ GeV are required.

7.6.4 Event selection

Within $t\bar{t}$ dileptonic events only those with an associated primary vertex (measured with the vertex association criteria) and with one muon and one electron in the final state are studied, in order to avoid the contamination due to $Z \rightarrow \mu\mu$ events, thus obtaining a cleaner sample for the efficiency measurement and scale factor derivation. In the final state at least one electron, one muon and two b-tagged jets, satisfying the criteria discussed in Section 7.6 are required.

The two leptons must have opposite charge and the electron is required to pass the electron trigger [72] listed in Table 7.3.

Table 7.3: Electron trigger.

Data taking year	Electron trigger
2015	e24_lhmedium_L1EM20VH
	or e60_lhmedium
	or e120_lhloose
2016	e26_lhtight_nod0_ivarloose
	or e60_lhmedium_nod0
	or e140_lhloose_nod0

By requiring two b-tagged jets and the lepton opposite charge a significant part of the background have been reduced and a clean sample of $t\bar{t}$ events have been produced. The number of prompt and no-prompt muons after applying these selection is shown in Table 7.4, evaluated considering prompt and non prompt muons extracted from MC simulation at truth level.

Table 7.4: Signal and background events after applying the final selection, which comprises the request of 2 b-tagged jets and leptons with opposite charge.

Sample	N_{μ}^{prompt}	$N_{\mu}^{\text{no-prompt}}$
$t\bar{t}$	100×10^3	10^3
WW/WW/ZZ	25	7
single-t (s/t channels)	2	35
Wt	3500	50
W + jets	1	47
Z + jets	80	20

Simulated MC events are reconstructed and analysed with the same algorithms used for data. All simulated events are corrected so that the object identification, reconstruction and trigger efficiencies, energy scales and energy resolution match those determined from data control samples [73]-[52]-[56]-[74]. In this work only statistical uncertainties are taken into account.

7.6.5 Signal and background definition

In order to improve the efficiency and scale factor measurements and to have higher statistics, the signal region which comprises prompt muons originated from $t\bar{t}$ events has been extended also to prompt muons generated by Wt and WW/WZ/ZZ events. The study of the muon origin in MC samples shows that a very high fraction of muons in these events comes from W or Z and not from heavy flavour decays, as shown in Table 7.4. For this reason these samples have been considered as signal and the corresponding prompt muons have been included both in Data and MC efficiency measurements. The contribution to the background comes from Z/W+jets and single-t (s/t-channels), where muons mainly come from heavy flavour decays.

7.6.6 Data and Monte Carlo agreement

Figure 7.6 shows the data and MC distribution of the muon p_T , distance of the muon from the nearest jet and muon η for all the samples (signal and background) included in this analysis. The distributions of the other quantities are reported in Appendix 7.7.

The results can be summarized as follows:

- The Data and MC are in good agreement and no problematic trends have been observed. The observed difference between data and MC in the p_T distribution is a well-known effect observed in many measurements. These differences can be partially reduced by including the missing NNLO corrections to the top-quark p_T in the prediction, or by changing the hadronisation model [75]. However, this discrepancy does not affect the results shown in this analysis;
- The main source of background comes from non-prompt muons originated from $t\bar{t}$ and Wt events and the impact of the other processes is almost negligible;
- The fraction of non-prompt muons is higher for muon $p_T < 40$ GeV, therefore their main impact in the efficiency measurement is expected in this region;

7.6.7 Results: measurement of the muon isolation efficiency and SFs

The muon isolation efficiency and SFs have been measured for several working points, but here only PFlowTight_FixedRad and PFlowLoose_FixedRad will be reported. The

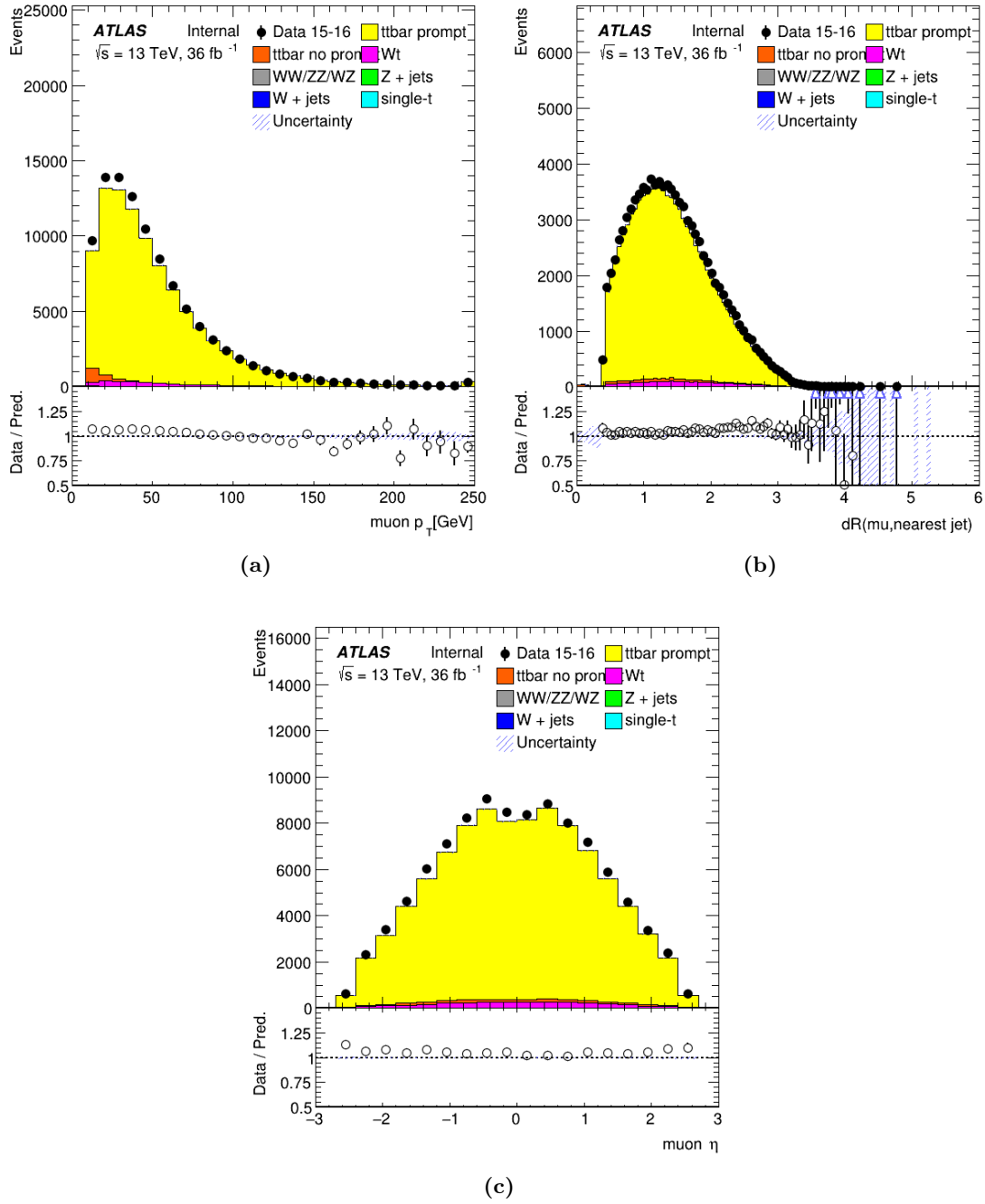


Figure 7.6: Data and MC agreement for (a) the muon p_T , (b) distance of the muon from the nearest jet and (c) η .

results can be extended to the other WPs, which are reported in Appendix 7.8. The results are given as a function of the muon p_T and dR , being dR the angular distance between the muon and the leading jet:

$$dR = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2} \quad (7.4)$$

The efficiencies in Data and MC for a given selection "X" are defined as:

$$\epsilon_{\text{Data}} = \frac{N_{\mu,\text{signal}}^X - N_{\mu,\text{background}}^X}{N_{\mu,\text{signal}}^{\text{tot}} - N_{\mu,\text{background}}^{\text{tot}}} \quad (7.5)$$

$$\epsilon_{\text{MC}} = \frac{N_{\mu,\text{signal}}^X}{N_{\mu,\text{signal}}^{\text{tot}}} \quad (7.6)$$

and the corresponding SFs are measured as in Equation 7.3.

The efficiency and scale factors are provided for both $t\bar{t}$ and $Z \rightarrow \mu\mu$ samples. In the latter case cuts have been applied in order to be consistent with the $t\bar{t}$, therefore the regions with muon $p_T < 10$ GeV and/or $dR(\mu, b - jet) < 0.4$ have been excluded from the analysis.

In the efficiency and SFs plots only statistical uncertainties are reported except for the $Z \rightarrow \mu\mu$ SF plots, where also the systematics uncertainties have been taken into account. Figure 7.7 shows the efficiency and scale factors comparison for the PFlowLoose_FixedRad working point, while Figure 7.8 shows the same quantities for the PFlowTight_FixedRad working point.

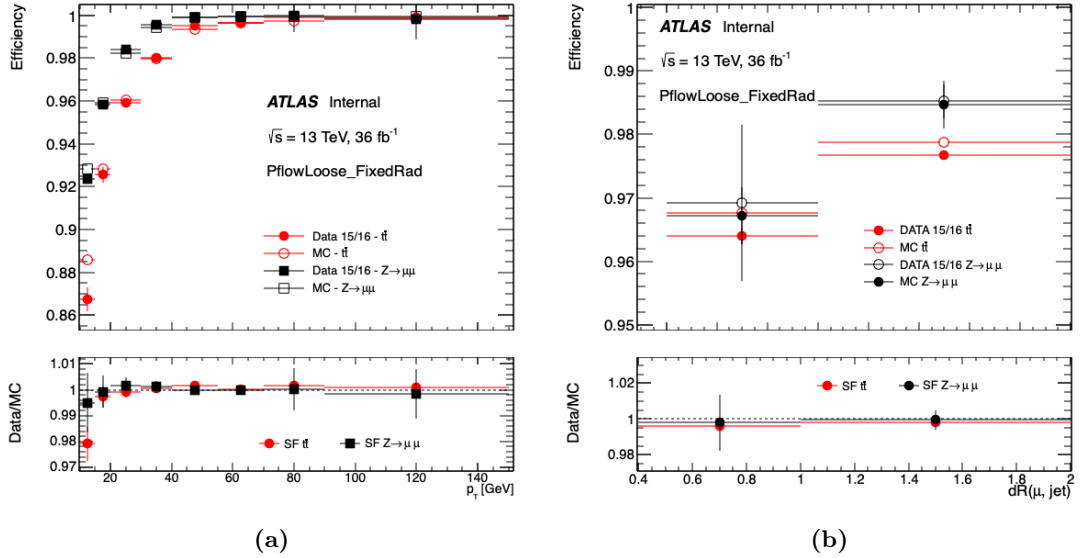


Figure 7.7: Efficiency and SFs as a function of (a) the muon p_T and (b) dR for $t\bar{t}$ and $Z \rightarrow \mu\mu$ samples measured for the PFlowLoose_FixedRad working point. The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

The results are the same for both working points and can be summarized in the following points:

- The Data and MC are in good agreement in both samples in the entire p_T spectrum ;
- In the region $p_T < 40$ GeV the efficiency in $t\bar{t}$ events is smaller than that obtained with $Z \rightarrow \mu\mu$ sample, due to the busier background environment which characterized the $t\bar{t}$ sample. In this region, as shown in Figure 7.6, the non-prompt contribution is higher and the number of fake events affects the efficiency calculation. In dR the efficiency are consistent within the error bars

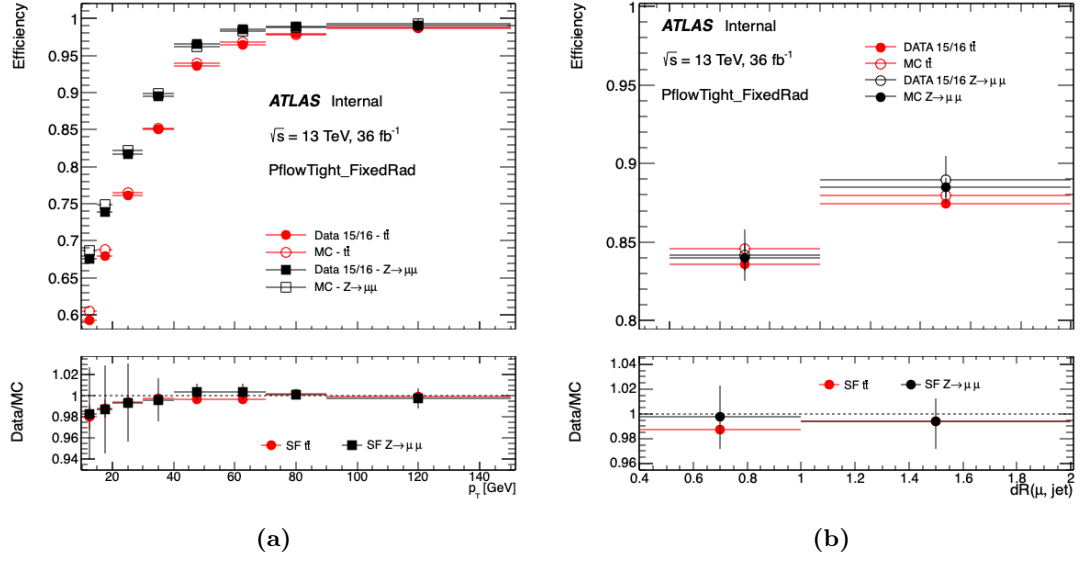


Figure 7.8: Efficiency and SFs as a function of (a) the muon p_T and (b) dR for $t\bar{t}$ and $Z \rightarrow \mu\mu$ samples measured for the PFlowTight_FixedRad working point. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

- The scale factors are consistent within the error bars in the entire p_T and dR spectra

These results suggest that the Scale Factors are independent from the background activity where they are extracted, therefore this measurement represent a good complementary measurement to $Z \rightarrow \mu\mu$ of efficiency and scale factors.

7.6.8 Conclusions

In this chapter the measurement of muon isolation efficiency and scale factors (SF) in a busy environment using $t\bar{t}$ events is presented. The muon isolation efficiency and scale factors have been compared with those currently used in ATLAS using $Z \rightarrow \mu\mu$ sample, in order to demonstrate the independence of these parameters from the background environment within which they are calculated. The scale factors extracted are consistent with each other, showing that this procedure can give a complementary measurement to the current technique used to extract these quantities.

Conclusions

In this thesis several environment-friendly gas mixtures for the Resistive Plate Chamber detectors have been tested, using both RPC in operation during Run-2 (called ATLAS-RPC legacy) and a new type of RPCs (thinner electrodes and gas gap) planned for the High-Luminosity phase of the LHC.

The standard gas mixture, composed of $\text{C}_2\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6$, currently used in the RPCs at the Large Hadron Collider experiments, has a high Global Warming Potential (GWP) ~ 1430 due to the presence of $\text{C}_2\text{H}_2\text{F}_4$ and SF_6 . In this thesis new gas mixtures for RPCs have been proposed and studied with the purpose to replace both the high-GWP molecules of the standard gas mixture.

The first study on new gas mixtures consisted in the substitution of $\text{C}_2\text{H}_2\text{F}_4$ with a proper mixture of CO_2 and Tetrafluoropropene ($\text{C}_3\text{H}_2\text{F}_4$), using the CO_2 as the main gas component.

In Chapter 4 studies on a 2 mm gas gap have been performed varying the CO_2 concentration, showing the result that the $\text{C}_3\text{H}_2\text{F}_4$ fraction can be lower up to 15% without worsening the RPC performance in terms of efficiency ($> 93\%$) and avalanche-streamer separation (~ 400 V). The possibility to work with a low- $\text{C}_3\text{H}_2\text{F}_4$ concentration is crucial in sight of the detector ageing, which is dominated by the copious fluorinated pollutants production inside the gas that can damage the electrodes surfaces.

Chapter 5 shows the results obtained testing an ATLAS legacy-type RPC in presence of a muon beam and under a strong photon irradiation, with the following new gas mixtures: ECO2 ($\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 60/35/4/1$) and ECO3 ($\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 70/25/4/1$). The test demonstrates that these new eco-gases could represent a good alternative to the standard gas mixture, offering a good detection efficiency ($> 93\%$) and a good avalanche-streamer separation (~ 400 V) also in presence of the high HL-LHC-like background (~ 200 Hz/cm²). The aging test of the RPC using ECO2 is currently ongoing at the GIF++ to certify this new gas mixture in sight of its possible future usage for the RPCs in ATLAS. Chapter 6 shows the performance test of a new ATLAS RPC (1 mm gas gap) in presence of a muon beam and under a strong photon irradiation, using ECO2, ECO3, ECO65 ($\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 30/65/4/1$) and ECO55 ($\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{SF}_6 = 40/55/4/1$) gas mixtures.

The new ATLAS RPC shows very good performance with ECO55 and ECO65 gas mixtures in terms of efficiency ($> 93\%$), current and timing properties. The possibility to work also with a high $\text{C}_3\text{H}_2\text{F}_4$ concentration (65%), without worsening the rate capability and accelerating the aging process, is possible thanks to the use of a new Front-end electronics with a low threshold of $1\div 4$ fC, which allows to operate with these new eco-gas mixtures under irradiation at the same current of the standard gas. Both ATLAS-RPC legacy and the new ATLAS RPCs, foreseen for the phase 2 HL-LHC upgrade, show an improvement of the time resolution when operated with the new eco-gases used in these tests.

One of the most important results obtained in the thesis is the possibility to operate

RPC with a totally environment-friendly gas mixture. A very good alternative to the SF_6 , the Chloro-Trifluoropropene ($\text{C}_3\text{H}_2\text{ClF}_3$), has been successfully tested. Gas mixtures composed of $\text{CO}_2/\text{C}_3\text{H}_2\text{F}_4/\text{i-C}_4\text{H}_{10}/\text{C}_3\text{H}_2\text{ClF}_3$ show high detection efficiency ($> 93\%$) and a good avalanche-streamer separation (~ 400 V) with a Global Warming Potential around 10, making them totally eco-friendly.

Once the aging tests on this gas will be completed with satisfactory results, it could represent a good alternative to the standard gas mixture for the RPCs in present and future experiments.

Appendix

7.7 Control plots

The Data and MC agreement of the objects studied in Chapter 7 are reported.

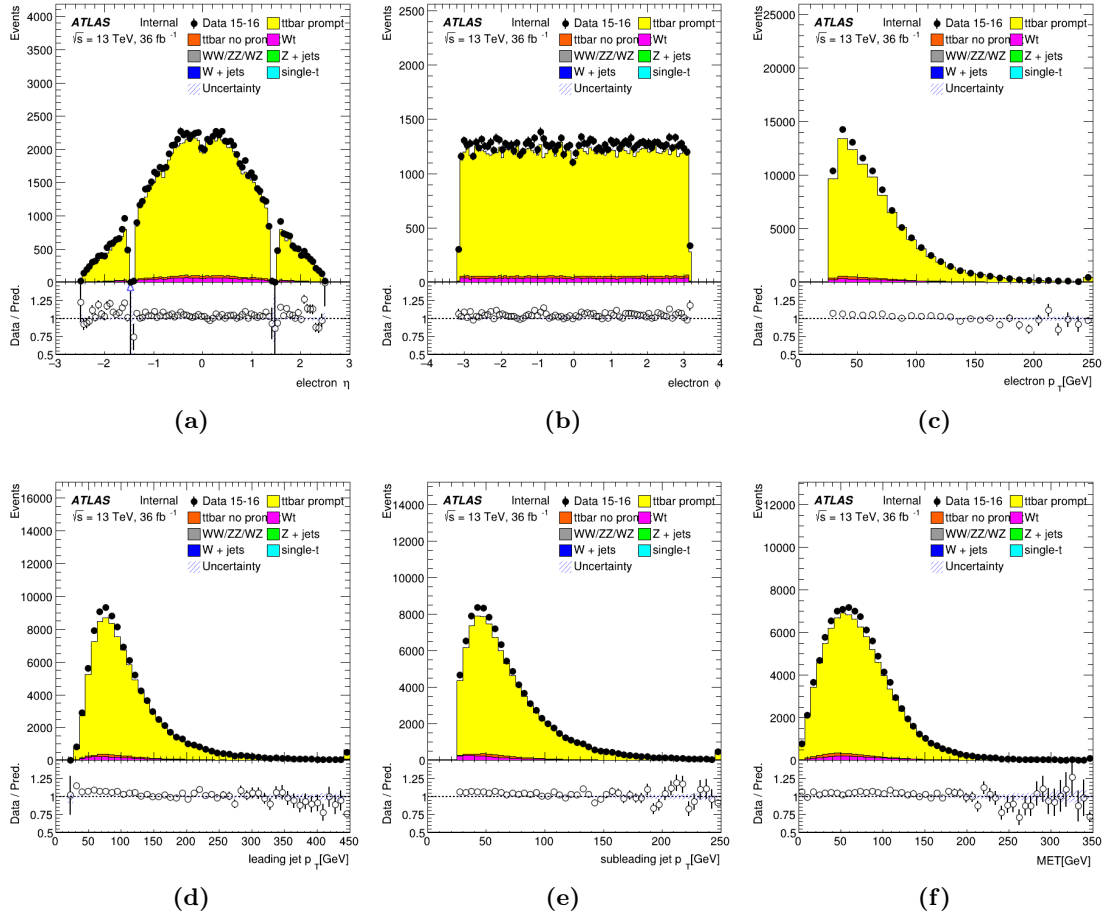


Figure 7.9: Data and MC agreement of (a) electron η , (b) electron ϕ , (c) electron p_T , (d) leading jet p_T , (e) subleading jet p_T and (f) missing transverse energy

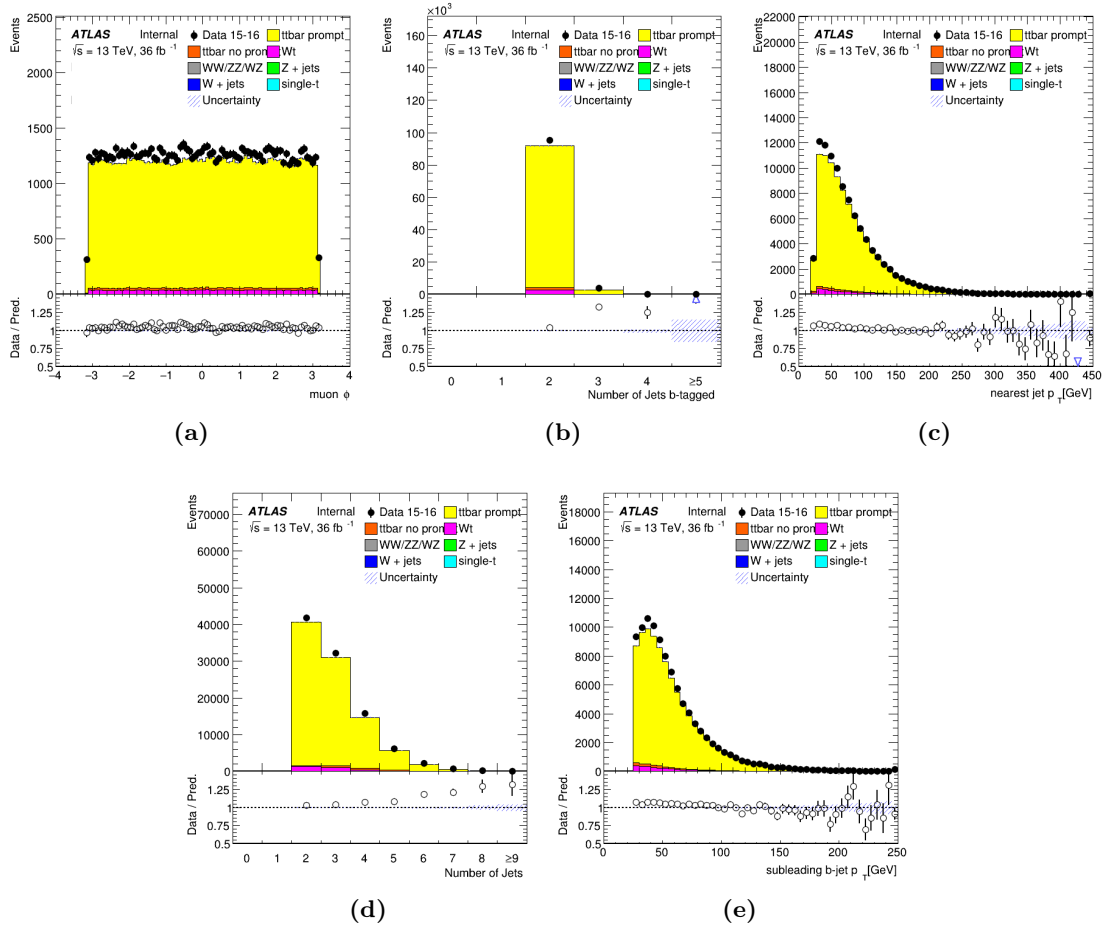


Figure 7.10: Data and MC agreement of (a) muon ϕ , (b) number of b-tagged jets, (c) nearest jet to muon, (d) number of jets and (e) subleading b-jet p_T

7.8 Efficiency and SFs measurement

The efficiency and SFs as a function of the muon p_T and $\Delta R(\mu, \text{jet})$ are reported.

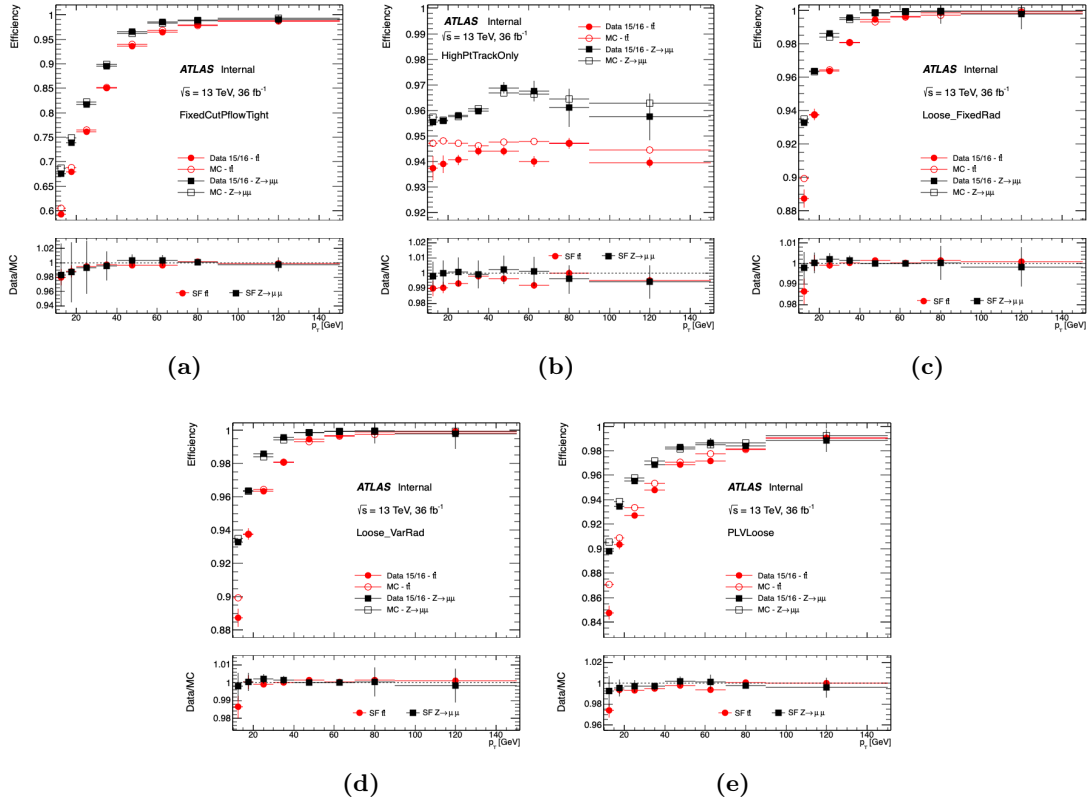


Figure 7.11: Muon isolation efficiency and scale factors measured in $Z \rightarrow \mu\mu$ (black squares) and $t\bar{t}$ (red points) events for the (a) FixedCutPflowTight, (b) HighPtTrackOnly, (c) Loose_FixedRad, (d) Loose_VarRad and (e) PLVLoose working points, as a function of the muon p_T . The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

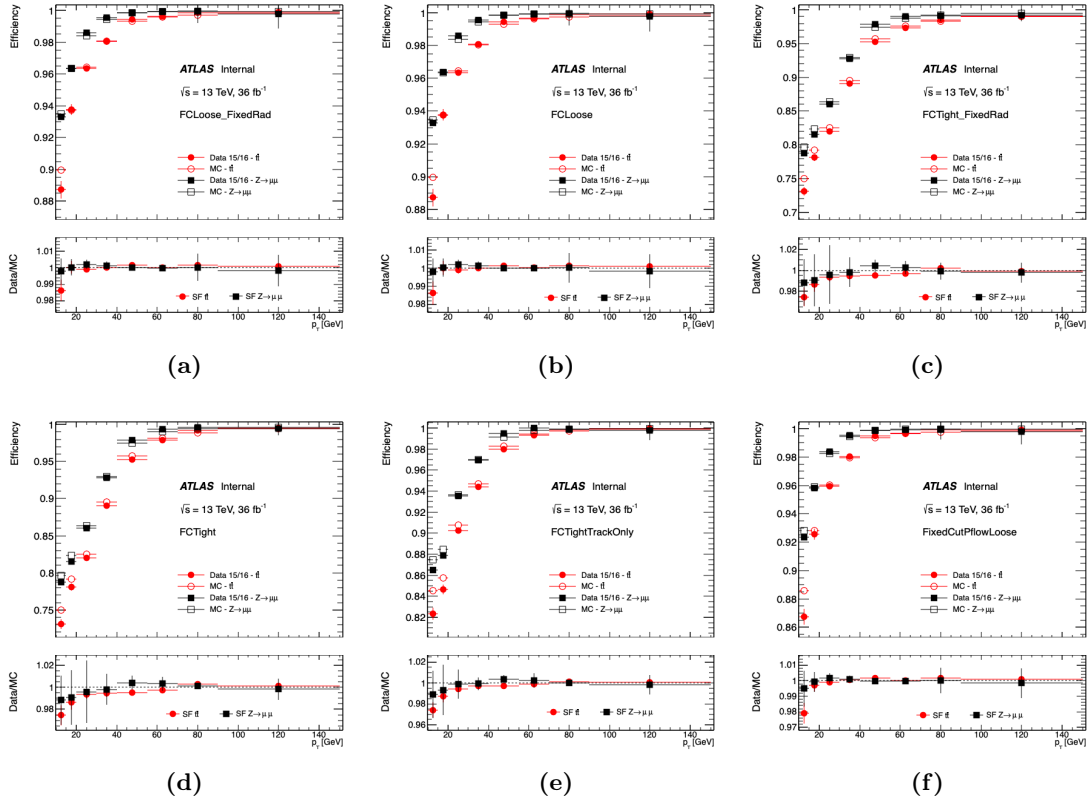


Figure 7.12: Muon isolation efficiency and scale factors measured in $Z \rightarrow \mu\mu$ (black squares) and $t\bar{t}$ (red points) events for the (a) FCLoose_FixedRad, (b) FCLoose, (c) FCTight_FixedRad, (d) FCTight, (e) FCTightTrackOnly and (f) FixedCutPflowLoose working points, as a function of the muon p_T . The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

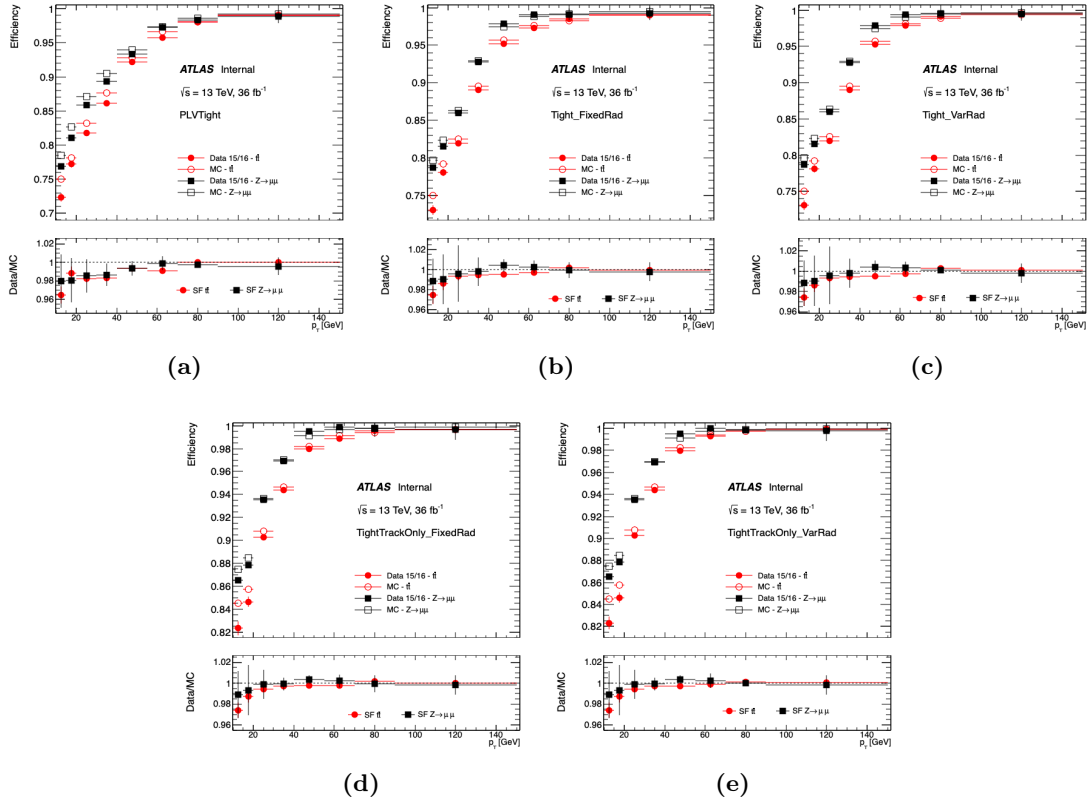


Figure 7.13: Muon isolation efficiency and scale factors measured in $Z \rightarrow \mu\mu$ (black squares) and $t\bar{t}$ (red points) events for the (a) PLVTight, (b) Tight_FixedRad, (c) Tight_VarRad, (d) TightTrackOnly_FixedRad and (e) TightTrackOnly_VarRad working points, as a function of the muon p_T . The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

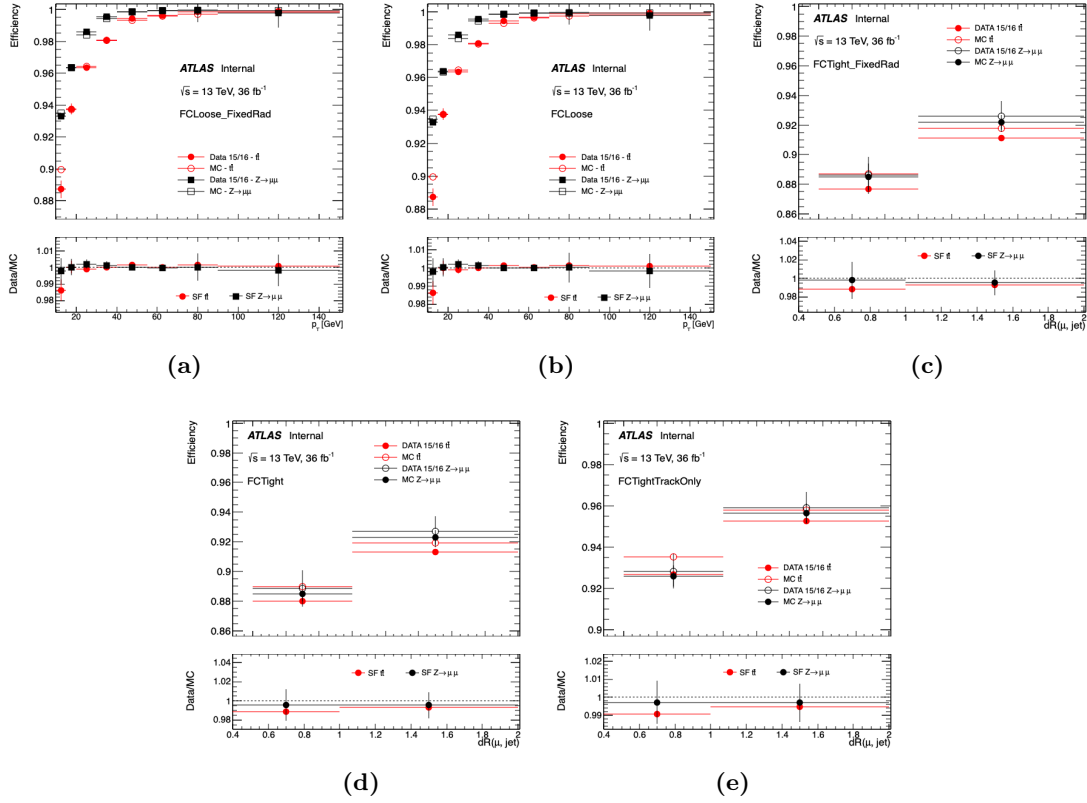


Figure 7.14: Muon isolation efficiency and scale factors measured in $Z \rightarrow \mu\mu$ (black squares) and $t\bar{t}$ (red points) events for the (a) FCLoose_FixedRad, (b) FCLoose, (c) FCTight_FixedRad, (d) FCTight and (e) FCTightTrackOnly working points, as a function of the $\Delta R(\mu, \text{jet})$. The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

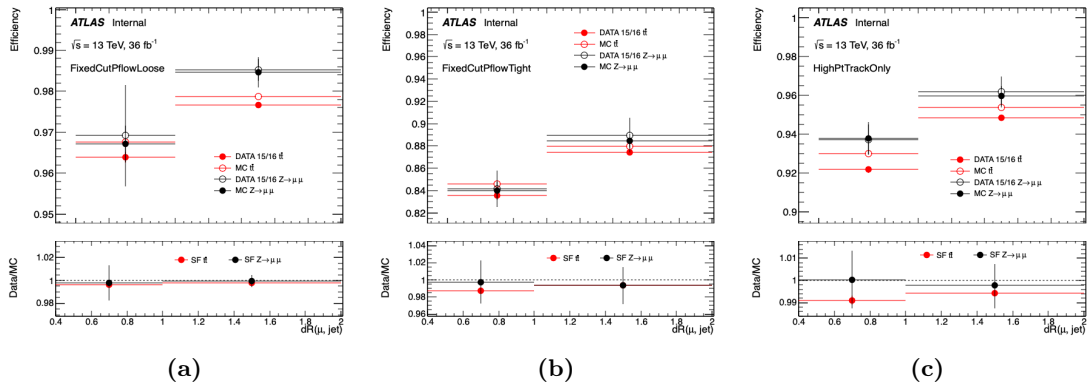


Figure 7.15: Muon isolation efficiency and scale factors measured in $Z \rightarrow \mu\mu$ (black squares) and $t\bar{t}$ (red points) events for the (a) FixedCutPflowLoose, (b) FixedCutPflowTight and (c) HighPtTrackOnly working points, as a function of the $\Delta R(\mu, \text{jet})$. The error bars in the efficiency plots are referred to the statistical uncertainties. The error bars in the scale factor plot are referred to the statistical uncertainties for $t\bar{t}$ events and to the sum square of statistical and systematics uncertainties for $Z \rightarrow \mu\mu$ events.

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