ATLAS EXPERIMENT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Environment-friendly gas mixtures for the ATLAS Phase-2 Resistive Plate Chambers

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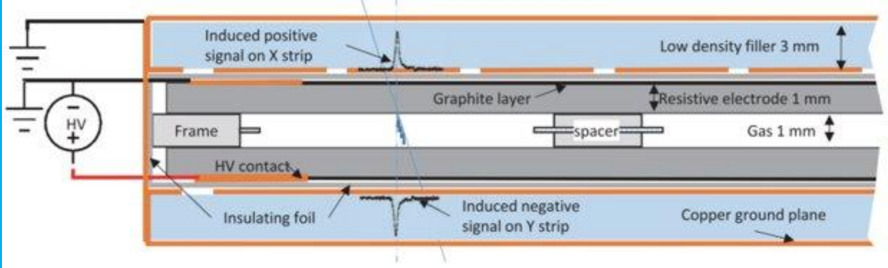
Sustainable HEP 2026

10/07/2026

The Resistive Plate Chambers(RPC) in the ATLAS experiment

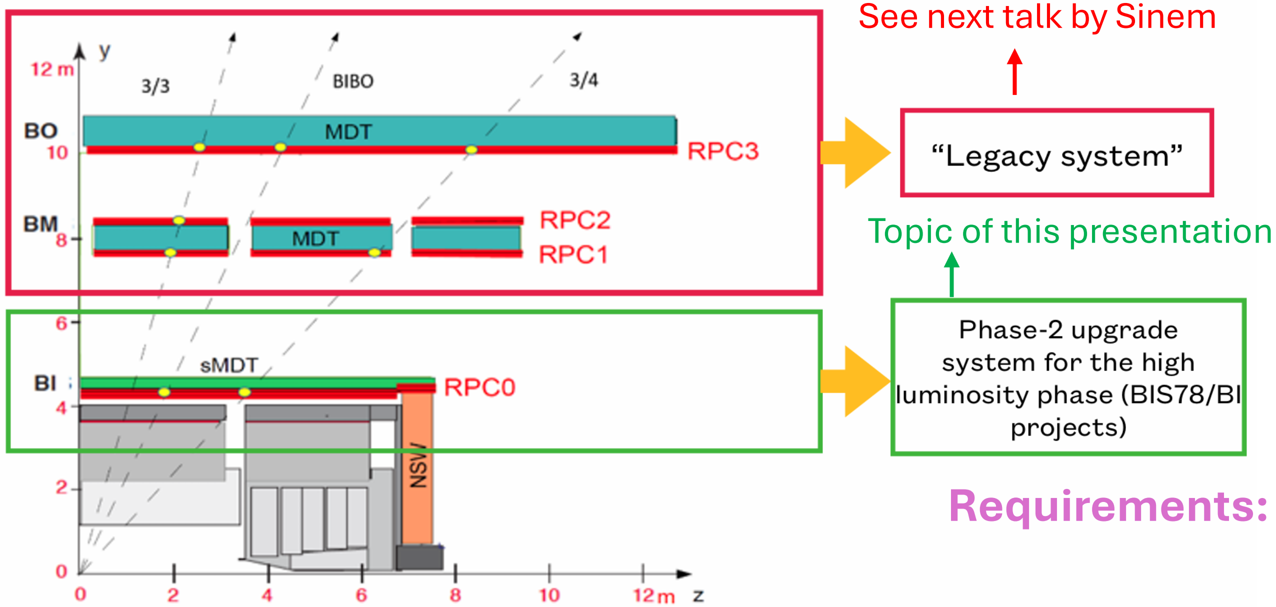
The RPC are planar gaseous detectors used for triggering on muons in the LHC experiments, due to their excellent timing performance

Sketch of an RPC



Uniform electric field generated by two parallel Resistive electrodes
Gas gap = region closed by the electrodes, filled with gas, in the mm range size
Excellent time resolution depending on the gas gap width (tens of ps to ns)

RPC in ATLAS



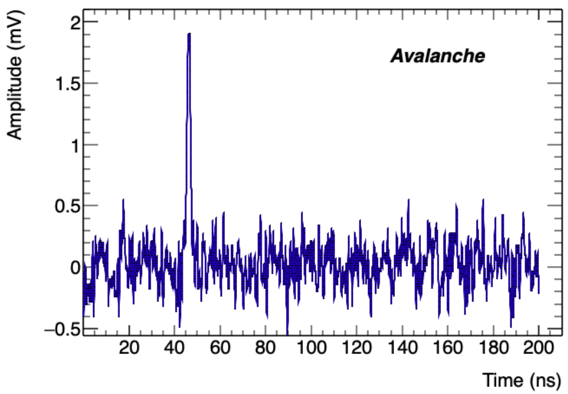
During HL-LHC a new generation of RPC will be installed in the ATLAS experiment :

1) Gas gap width = 1 mm (legacy gas gap =2 mm);
2) Time resolution ~ 300 ps (legacy time resolution=1 ns);
3) Newly Front-end electronics, threshold of few fC on the electronic signal (legacy threshold ~ 50 fC)

Requirements: good rate capability, performance and long term operation

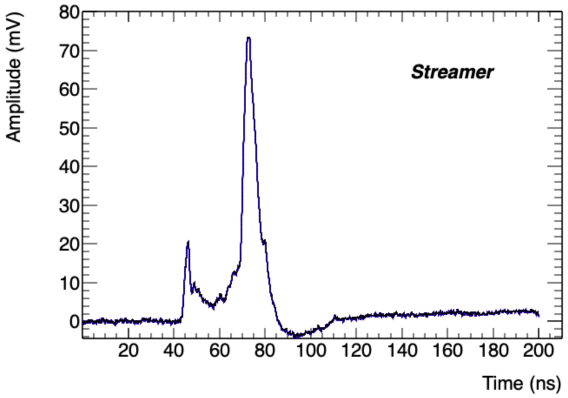
RPC in avalanche mode with the standard gas mixture

Avalanche signal



- Low current (good longevity)
- High rate capability
- RPC in high radiation environment (like ATLAS)

Streamer signal

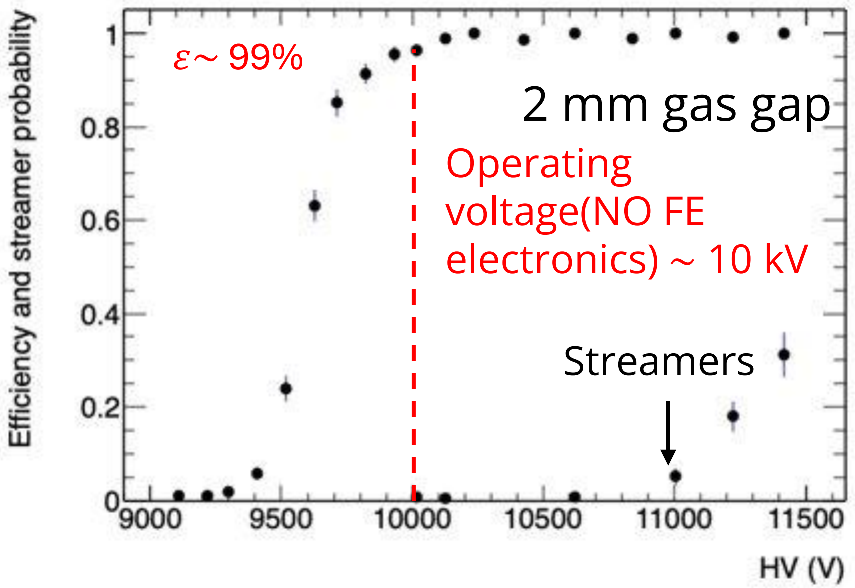


- High current→low rate capability and faster aging
- No sophisticated FE electronics needed
- Low rate experiment

The standard gas mixture is composed of 94.7% $C_2H_2F_4$ (TFE)/5%i-C_4H_{10}/0.3%SF_6

Primary target　Quencher　Streamer suppressor

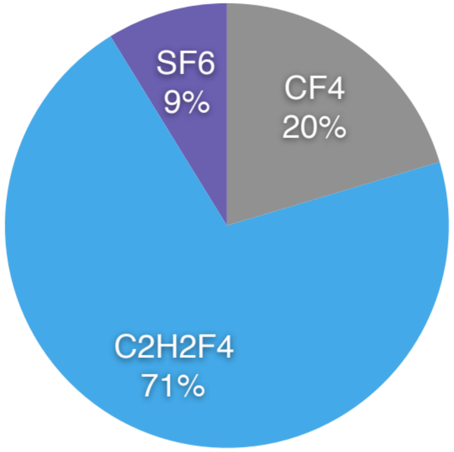
- High gas density ensuring high detection efficiency
- Modest working current and good rate capability
- Comfortable avalanche-streamer separation



[1]

Search for an eco friendly gas mixture

The standard gas mixture has a high Global Warming Potential (GWP)



Total GHG contribution

$C_2H_2F_4$ +i-C_4H_{10} + SF_6

GWP ~ 1430 GWP ~ 5 GWP ~ 23000 → **Total GWP ~ 1450**

GWP(CO_2) = 1

European union regulation have imposed a progressive phase down in the production and use of the F-gases, like $C_2H_2F_4$ and SF_6 in industry

Reduction of the availability

Increase of the cost

These gases represent the biggest contribution of the CERN particle detectors greenhouse gas emission

Search for an alternative gas mixture →

- Performance comparable to those of the standard gas (efficiency, current, rate capability, time resolution…)
- Low GWP
- Longevity of the detector for collider experiments

Search for an environment friendly gas mixture

Strategy

- Reduce the impact of the Tetrafluoroethane (TFE)→main gas component (94.7% for a total GWP ~ 1390) →largest contribution to the GWP

- Replacement of the SF_6 → highest GWP molecule (GWP~23000)

Goal : Low-GWP gas mixture with excellent performance (similar to the standard one) with no critical aging impact

Performance

- High efficiency (>90%) and excellent time resolution (400 ps)

- Rate capability: Excellent performance maintained at the high rate expected during HL-LHC in ATLAS (~150 $\mathrm{Hz/cm^2}$)

Aging

Good performance for the entire duration of the experiment:

- Gas flux and humidity
- Low current→operation in avalanche mode due to low charge signals
- Minimization of F^- radicals →reduced damaging on electrodes surfaces.

Long term and performance

Gas mixture parameters

- Density/cross section → High efficiency
- Capability to suppress streamer(electronegativity, affinity, electron capture cross section) → Low charge/ current
- Molecular structure to avoid an excess of fluorine radicals production → Reduce the probability to damage surfaces
- No flammable, no toxic → Fullfill experiments safety requirements

Detector parameters

- Gas gap width : the thinner the gap, the higher the gas density should be to achieve good efficiency (more critical for ATLAS upgrade RPCs)
- Front end electronics threshold:possibility to compensate fluorine production by working at lower field(current) by reducing the threshold
- Material and manifacturing

Strategy

1) **ATLAS intermediate** (since ~2 years) : Reduction of **TFE** emissions

$30\%CO_2/64.8\%C_2H_2F_4$ +4.7%i-C_4H_{10} + $0.5\%SF_6$

Pro: no large impact expected on detector longevity in terms of fluorine production

Cons: Small reduction of the **GWP ~ 1162**

Fully replace both high GWP gas components → Hydrofluoroolefins(HFOs)→ low-GWP molecules characterized by a double C-C bond widely used in refrigeration industry

2 steps strategy:

1) **Short term** : $CO_2/C_2H_2F_4$ +i-C_4H_{10} + $\underbrace{C_3H_2ClF_3}_{\text{GWP} \sim 1}$
[2]

Pro: can be used in short term in ATLAS (replacement of SF6 at per mille level)

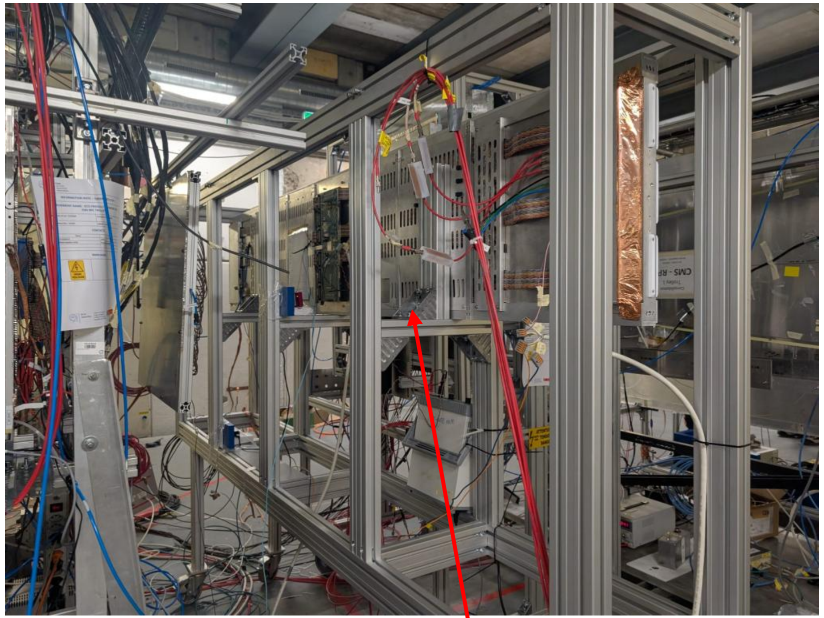
Cons: **GWP ~ 939** (still an improvement)

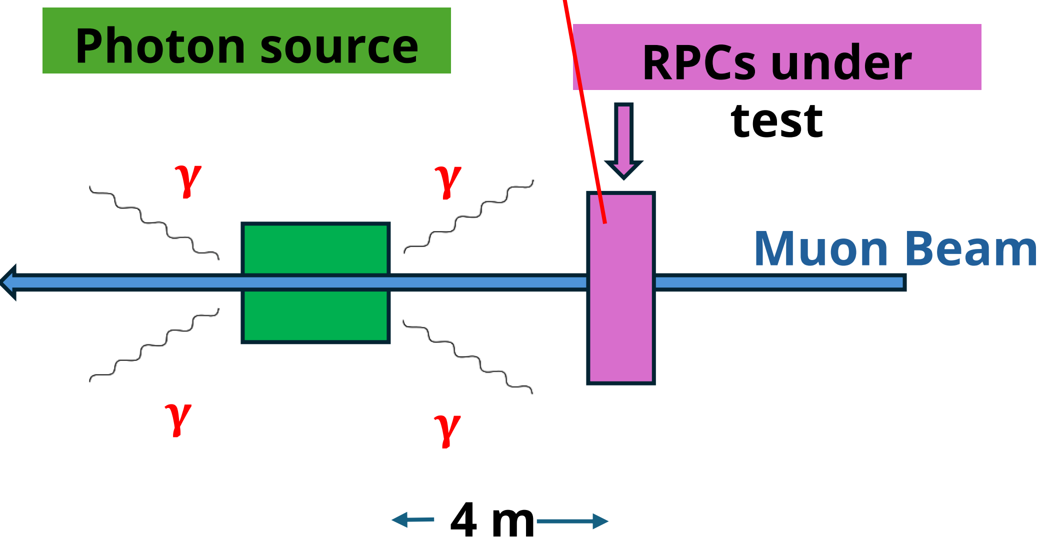
2) **Longer term** : $CO_2/\underbrace{C_3H_2F_4}_{\text{GWP} \sim 1}$ +i-C_4H_{10} + $\underbrace{C_3H_2ClF_3}_{\text{GWP} \sim 1}$
[1],[3]

Pro: **GWP ~ 10 (100 times less with respect to the standard gas)**

Cons: Extensively aging campaign needed→ more fluorine radicals production→possible faster aging

Measurement strategy





Performance and aging tested at the Gamma Irradiation Facility at CERN (GIF++) :

- Muon beam
- γ irradiation reproducing the background foreseen in the ATLAS experiment during HL-LHC

Module-0 ATLAS phase-2 upgrade: three RPCs 1 mm wide equipped with phase2 low-threshold FE electronics[4,5]

Very recent results from beam test on May 2026 presented here

2 scenarios explored:

1) Muon beam + no irradiation;
2) Muon beam + 170 Hz/cm2 γ background (ATLAS background rate)

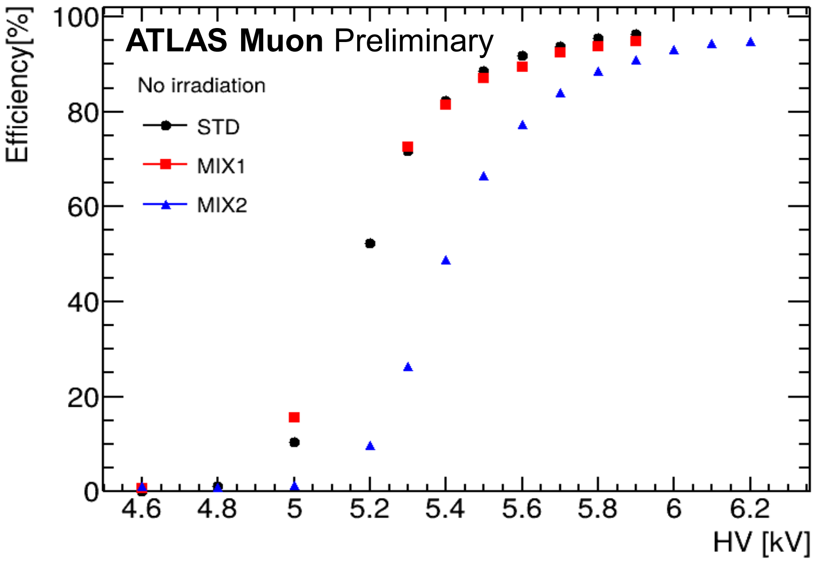
Results: short term solution

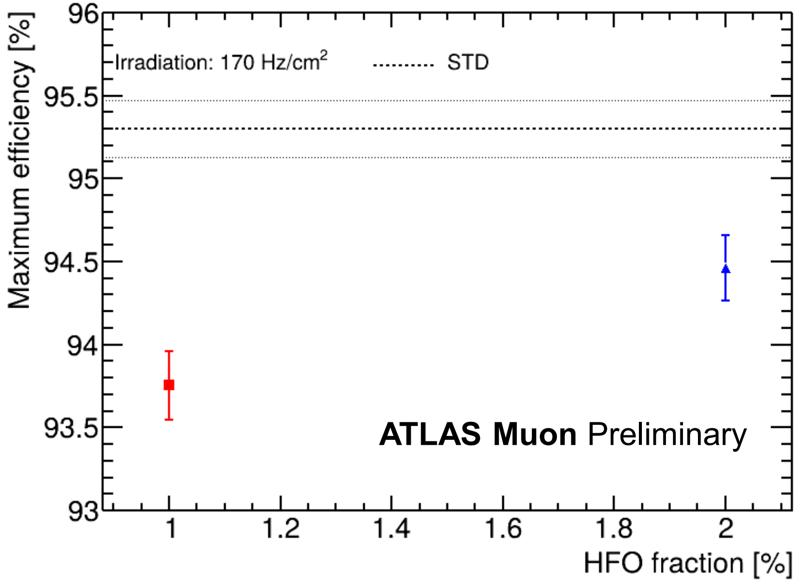
STD= 94.7%TFE/4.7%i-butane/0.3%SF_6 **GWP~1450**

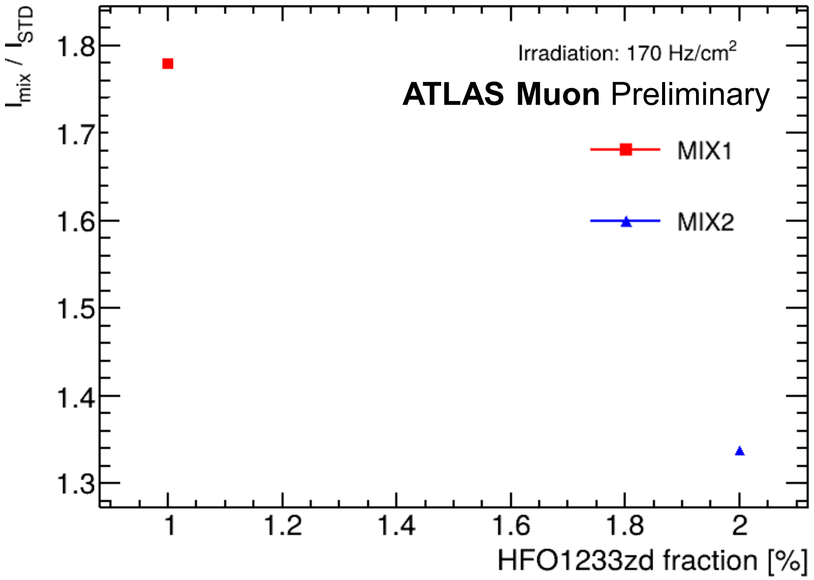
MIX1= 64.3%TFE/**30% CO_2** /4.7%i- C_4H_{10}/**1% $C_3H_2ClF_3$(HFO1233zd)**

MIX2= 63.3%TFE/**30% CO_2** /4.7%i- C_4H_{10} /**2% $C_3H_2ClF_3$ (HFO1233zd)**

GWP~939







1)Good plateau efficiency slightly below wrt the standard gas (94.8% vs 95.6%)

2)Efficiency above 90% under ATLAS γ -background

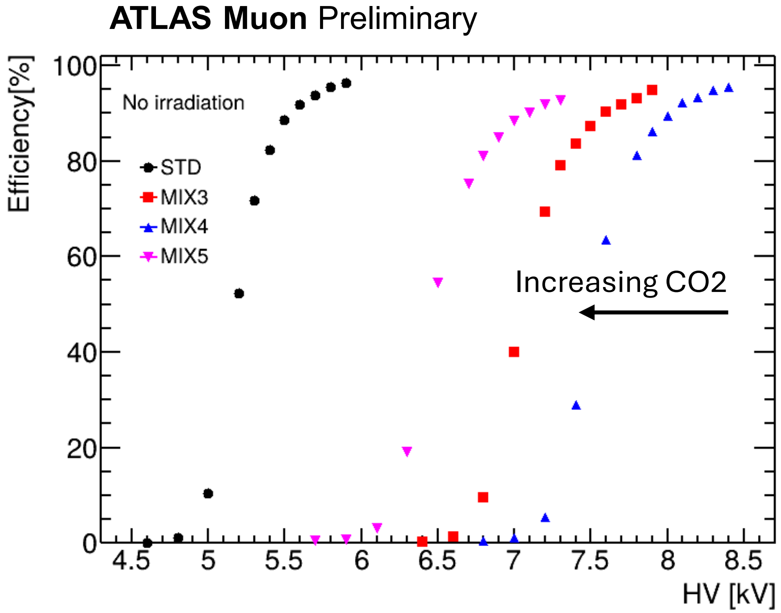
3)MIX2 current 1.3 times higher wrt the standard gas → in agreement with what is observed using SF6 instead of HFO1233zd[2]

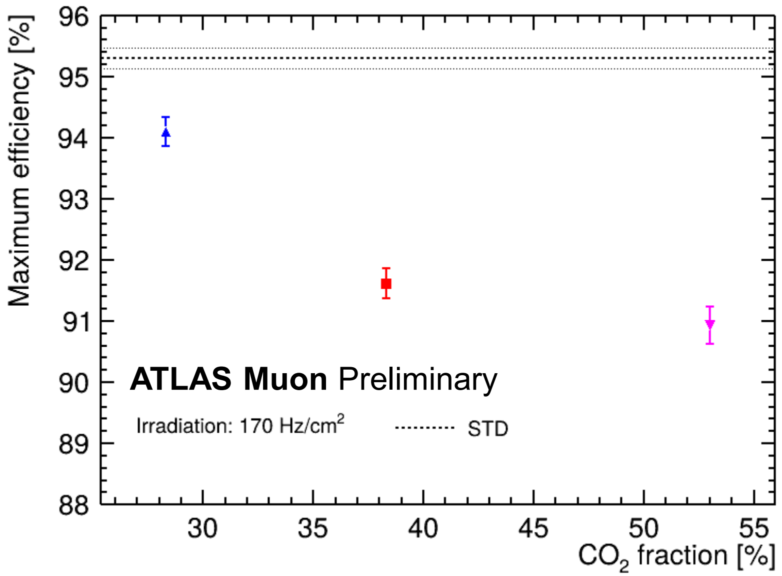
No worrying impact on the rate capability and current

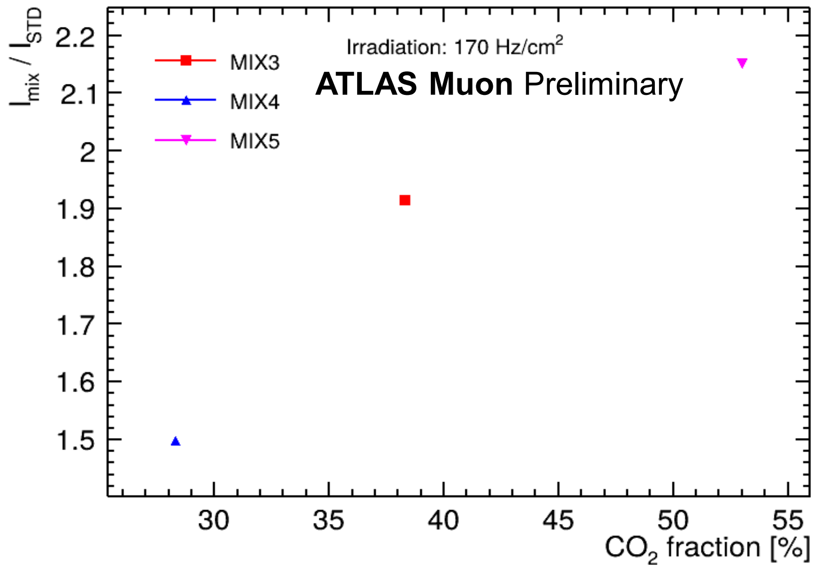
Results: long term solution

MIX3= 55% $C_3H_2F_4$ (HFO1234ze)/38.3%CO_2 /4.7% i-C_4H_{10} /2%HFO1233zd
MIX4= 65% $C_3H_2F_4$ (HFO1234ze) /28.3% CO_2 /4.7%i- C_4H_{10} /2%HFO1233zd
MIX5= 40% $C_3H_2F_4$ (HFO1234ze) /53% CO_2 /4.7%i- C_4H_{10}/2%HFO1233zd

$\Big\}$ **GWP~10**







1)Good plateau efficiency slightly below wrt the standard gas (94.8% vs 95.6%)

2)Efficiency above 90% under ATLAS γ -background

3)MIX4 (30%CO_2+2%HFO1233zd) shows the best performance in terms of efficiency and current under irradiation

No worrying impact on the rate capability and current

Summary

The replacement of high-GWP molecule $C_2H_2F_4$ and SF_6 in RPCs plays a crucial role for the usage of these key detectors in present and future experiments.

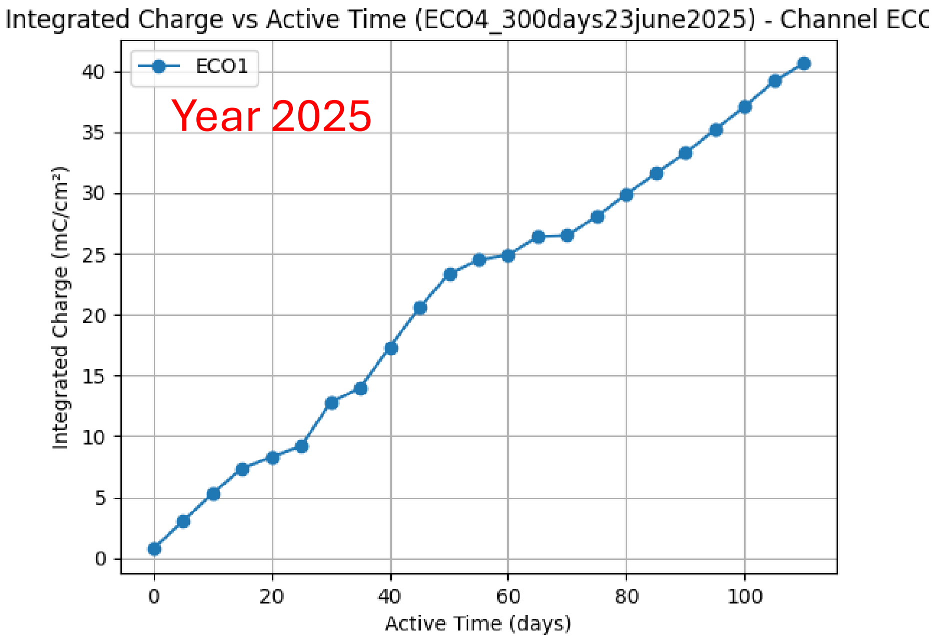
The ATLAS experiment is studying the possibility to replace them with eco-friendly gases like HFO1234ze and HFO1233zd

Recent results from test beam with ATLAS upgrade RPC (1 mm gas gap) confirms:

1) The HFO1233zd is an excellent candidate for SF6 replacement
2) HFO1234ze gives good performance in terms of rate capability at the expected γ-rate in ATLAS

Longevity test will be completed for the certification for the ATLAS experiment→Possibility to work with a GWP~10 gas mixture!!!

Aging progress



References

[1] G.Proto, 'Study of environment-friendly gas mixtures for Resistive Plate Chambers in view of future applications', PhD thesis, CERN-THESIS-2022-383, https://inspirehep.net/literature/2762484

[2] G.Proto et al, 'Replacing SF6 in resistive plate chamber detectors for HL-LHC experiments and beyond', 2025 JINST 20 P06031

[3] G. Proto *et al*,'On a new environment friendly gas mixture for Resistive Plate Chambers', 2022 *JINST* **17** P05005

[4]L. Pizzimento et al., 'On novel front-end electronics for the ATLAS BI RPC upgrade at HL-LHC developed in SiGe BiCMOS technology with a high-resolution rad-hard Time-To-Digital converter embedded', 2024 NIMA, 169892, ISSN 0168-9002

[5]M. Corradi et al, 'An FPGA Based Sub-Nanosecond Hit Time Measurement Board for the Muon Spectrometer of the ATLAS Experiment at HL-LHC', 2022 Proc. IEEE NSS/MIC

Thank you
Questions are welcome

Backup

Replacement of the $C_2H_2F_4$

See how it will become afyer the introduction. You can drop the figures → more clear

Largest contribution to the GWP of the standard gas due to the Tetrafluoroethane (TFE) because it is the main gas component (94.7% for a total GWP ~ 1390)

1) Substitute the $C_2H_2F_4$ with an environment friendly gas mixture:

$CO_2/C_3H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⟶ GWP ~ 200

1. Reduction of the GWP
2. Larger production of fluorine molecules (possible faster aging)
3. Concentration of $C_3H_2F_4$ strongly depends on the gas gap thickness

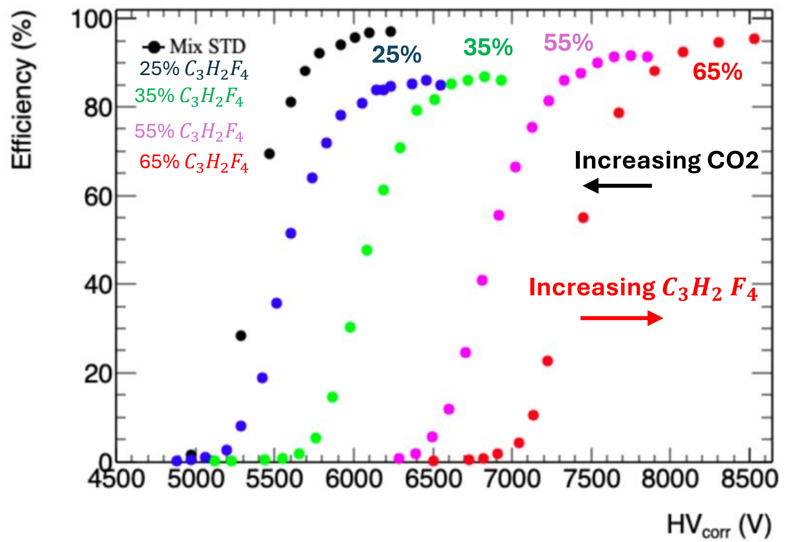
2) Reduction of the $C_2H_2F_4$ concentration introducing CO_2 (ATLAS intermediate):

$CO_2/C_2H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⟶ GWP ~ (1017-1162)

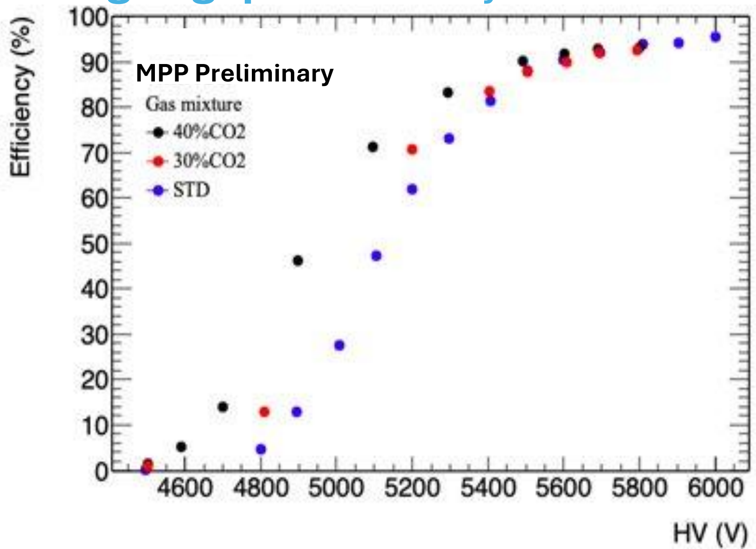
1. No large impact expected on detector longevity in terms of fluorine production
2. Small reduction of the GWP

Both cases → higher current wrt standard gas (1.5-1.7 times higher)

1 mm gas gap : efficiency vs HV vs %$C_3H_2F_4$



1 mm gas gap : efficiency vs HV vs %CO2

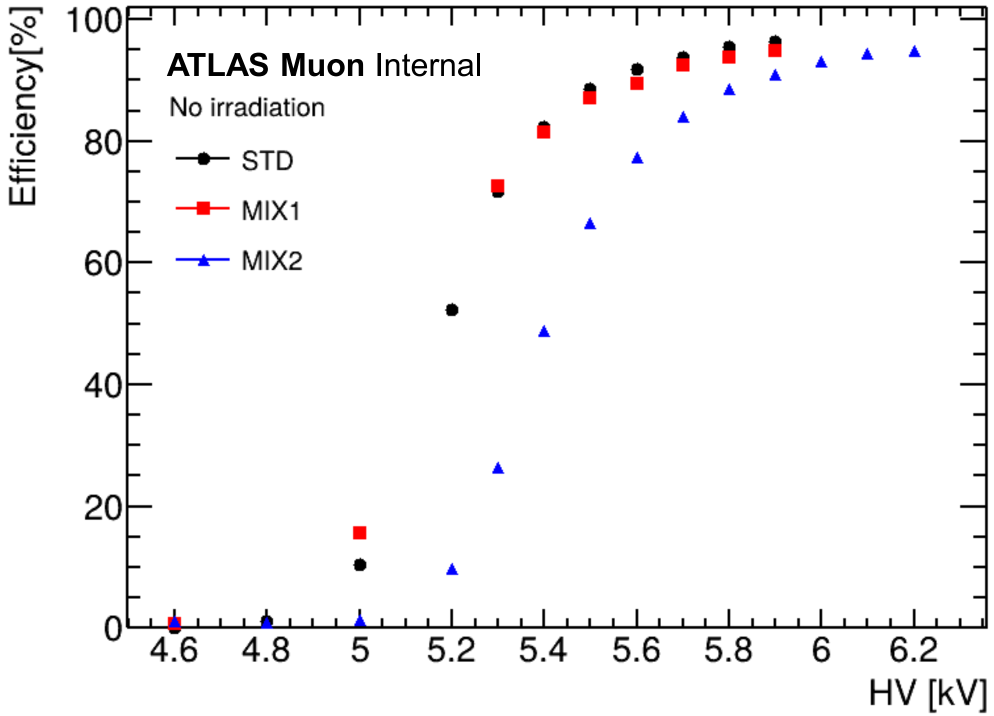


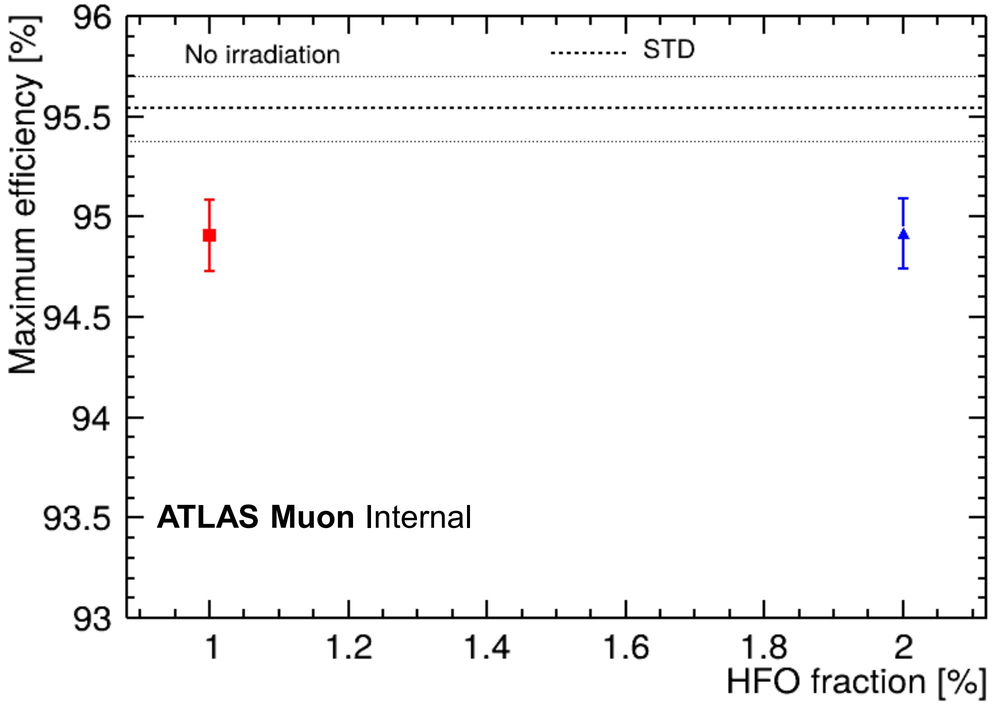
‘ATLAS’-like mixtures: no irradiation

GWP~939

MIX1= 64.3%TFE/30%CO2/4.7%i-butane/1%HFO1233zd

MIX2= 63.3%TFE/30%CO2/4.7%i-butane/2%HFO1233zd





Current ATLAS mixture with SF6 replaced by the HFO1233zd

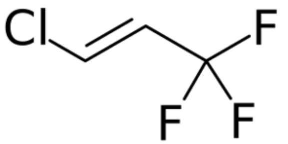
Same WP as the STD gas mixture for %HFO=1%, 200 V shift for HFO=2%

Good plateau efficiency slightly below wrt the standard gas (94.8% vs 95.6%)

Replacement of the SF_6

Same comment as previous slide → drop plots

Possibility to replace the highest GWP molecule, the SF_6, with an environment friendly gas: the Chlorotrifluoropropene ($C_3H_2ClF_3$, **GWP ~ 1**)



$CO_2/C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ → GWP ~ 939

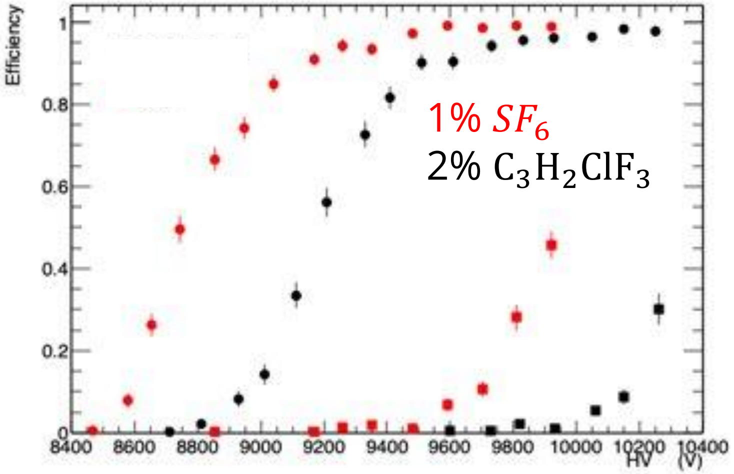
G. Proto *et al* 2025 *JINST* **20** P06031

$CO_2/C_3H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ → GWP ~ 10 (100 times less than the standard gas!!)

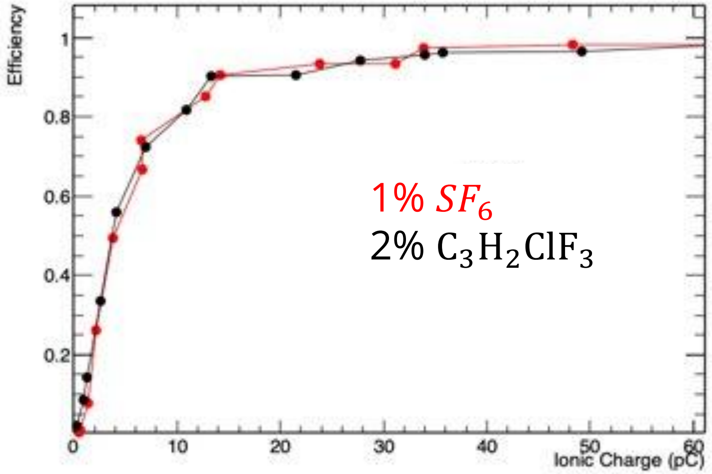
Possibility to operate the RPC with a totally environment-friendly gas mixture(G. Proto *et al* 2022 *JINST* **17** P05005)

Main results (2 mm gas gap)

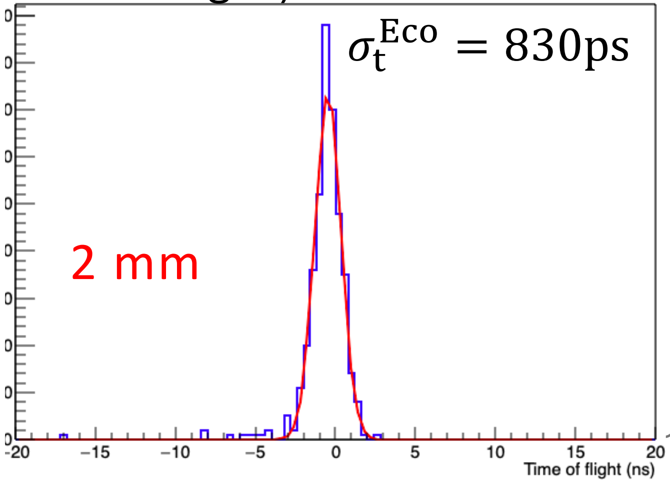
Same avalanche-streamer separation



Same current @ same efficiency



Good time resolution (24%better wrt standard gas)



Summary data taking

GWP Standard gas(STD) ~ 1450

GWP ATLAS current mixture (64.8%TFE/30%CO2/4.7%i-butane/0.5%SF6) ~ 1051

1 gas with one color → use the same color through the presentation

- Step 1 : replacing SF6 with HFO1233zd in the ATLAS mixture

Mixture studied:

MIX1= 64.3%TFE/30%CO2/4.7%i-butane/1%HFO1233zd

MIX2= 63.3%TFE/30%CO2/4.7%i-butane/2%HFO1233zd

GWP~939

- Step 2 : Replacing TFE with HFO1234ze and SF6 with HFO1233zd

Mixture studied composed of HFO1234ze/CO2/i-butane/HFO1233zd

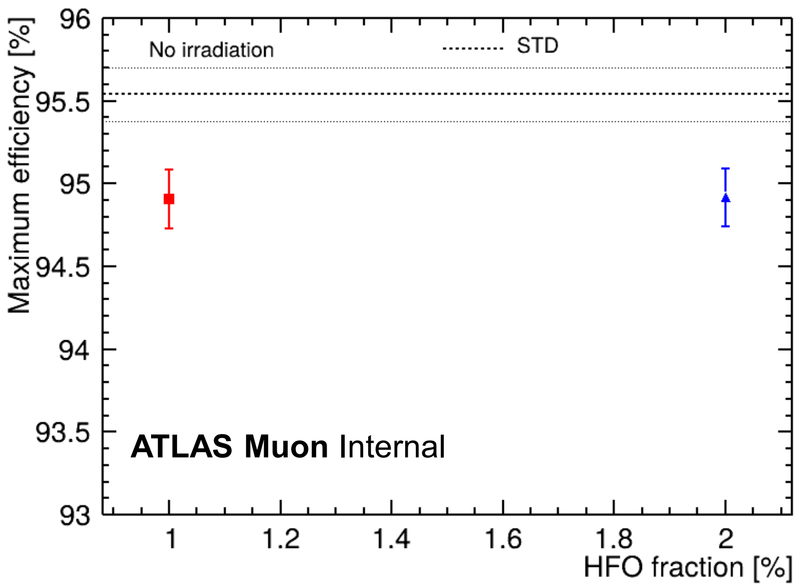
1) Study of the efficiency vs CO2 fraction (critical for 1 mm gap)
CO2 range explored (30-53)%, i-butane and HFO1233zd fixed at 4.7% and 2%

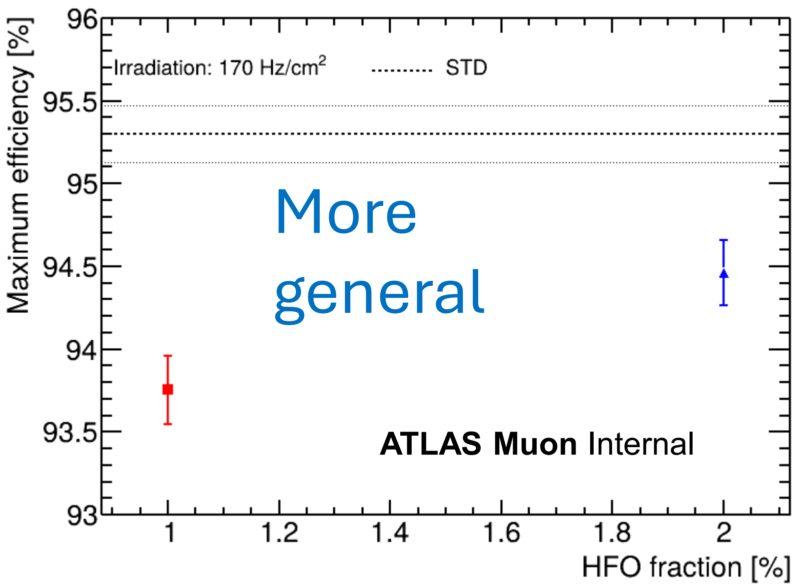
2) Study of the streamer rejection
HFO1233zd range explored (2-4)%, CO2 variation(30-53)%

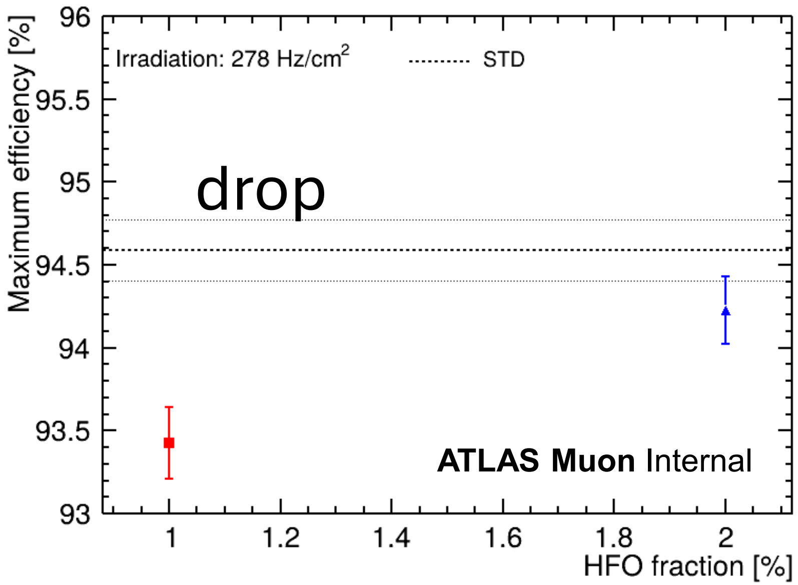
GWP~10

‘ATLAS’-like mixtures: irradiation results

GWP~939







Reduction of the efficiency plateau(wrt no irradiation case):

170 Hz/cm2 : 1% for (1%HFO1233zd+30%CO2), 0.5% for (2% HFO1234ze +30%CO2)

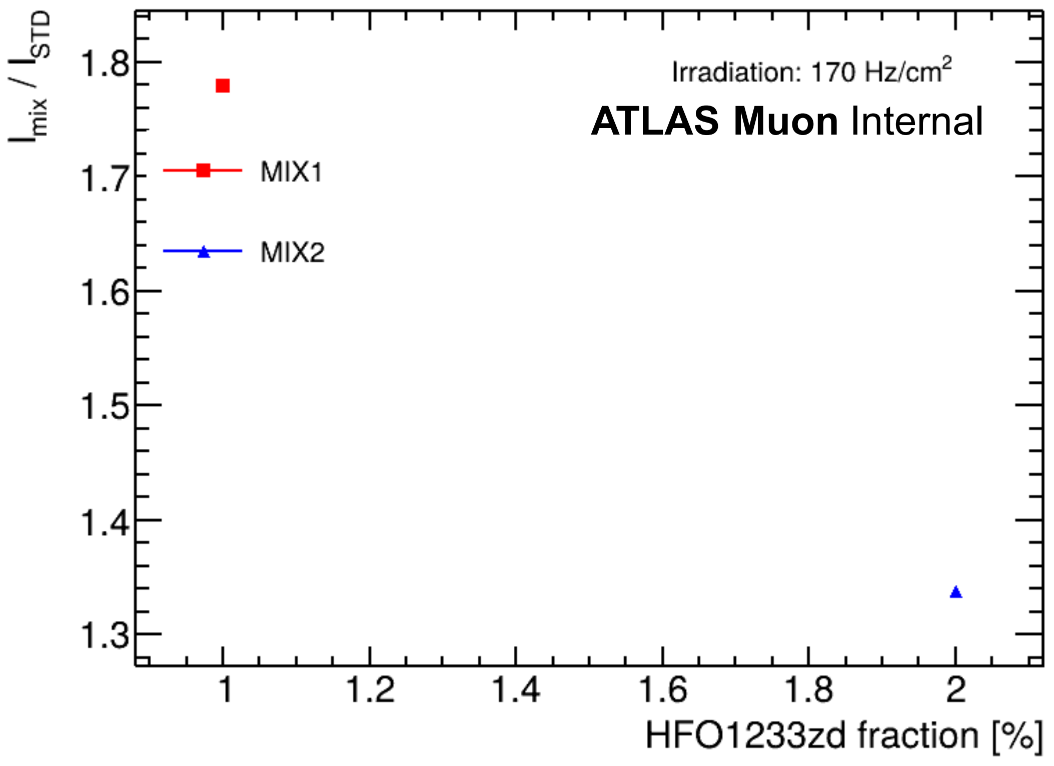
278 Hz/cm2 : 1.5% for (1%HFO1233zd+30%CO2), 0.7% for (2% HFO1234ze +30%CO2)

Good efficiency plateau up to 278 Hz/cm2

'ATLAS'-like mixtures: Currents

GWP~939

Message more clear!
(general comment)
Introduce better the current



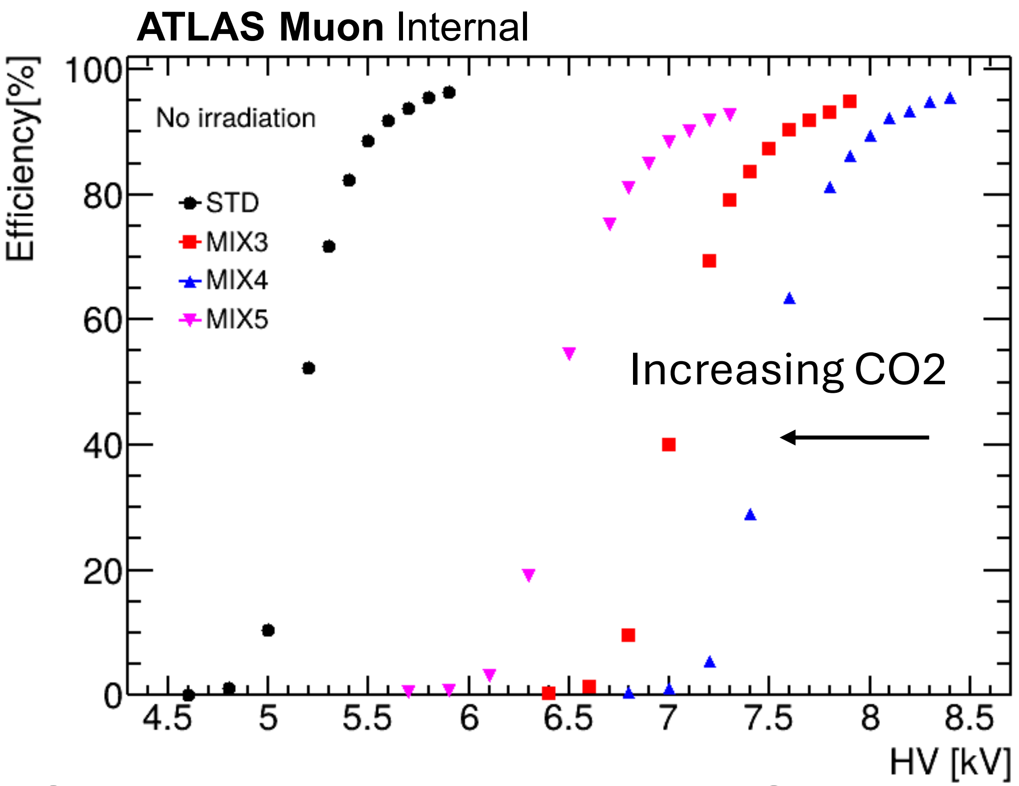
High current observed in MIX1 due to streamer contamination

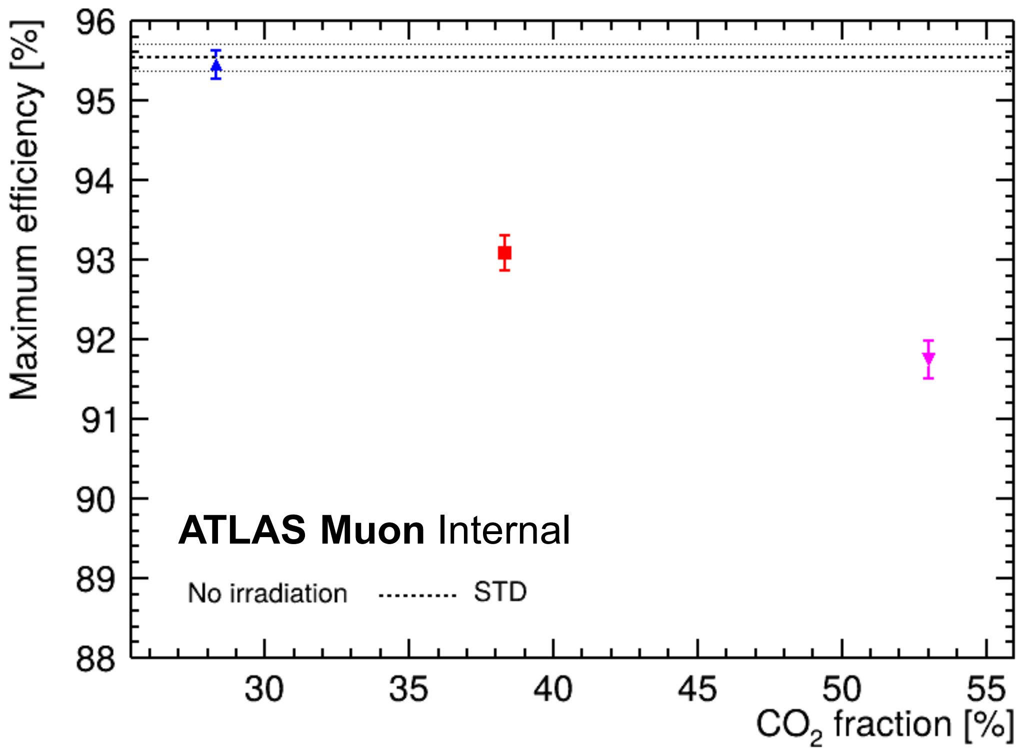
MIX2 current 1.3 times higher wrt the standard gas → in agreement with what is observed using SF6 instead of HFO1233zd (see here)

Ecogas : no irradiation results

MIX3= 55%HFO1234ze/38.3%CO_2/4.7%i-butane/2%HFO1233zd
MIX4= 65%HFO1234ze /28.3%CO_2/4.7%i-butane/2%HFO1233zd
MIX5= 40%HFO1234ze /53%CO_2/4.7%i-butane/2%HFO1233zd

GWP~10

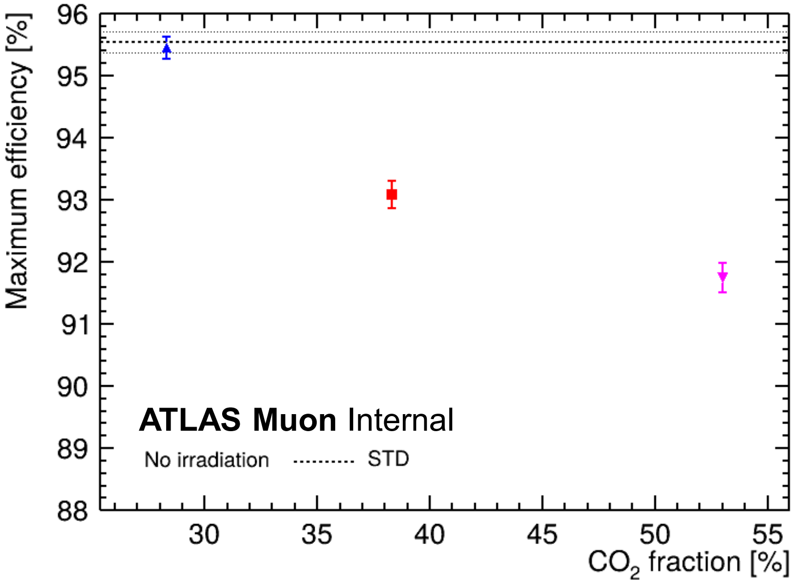


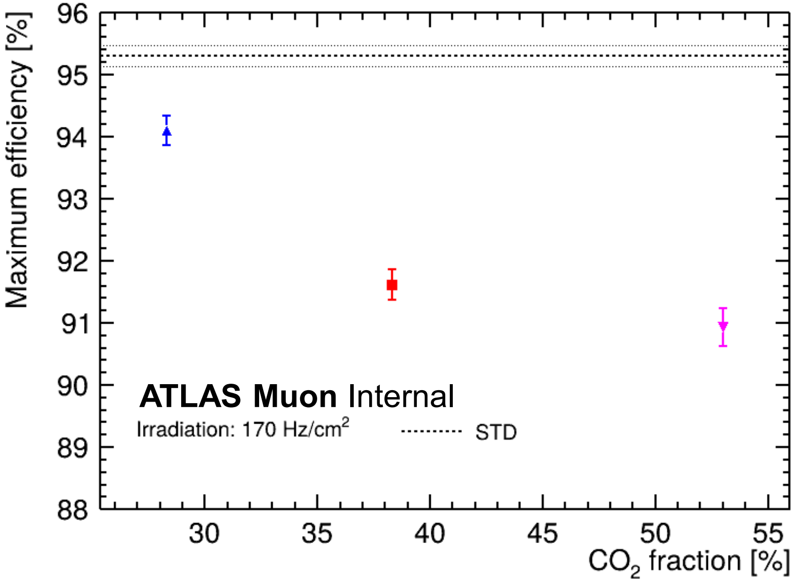


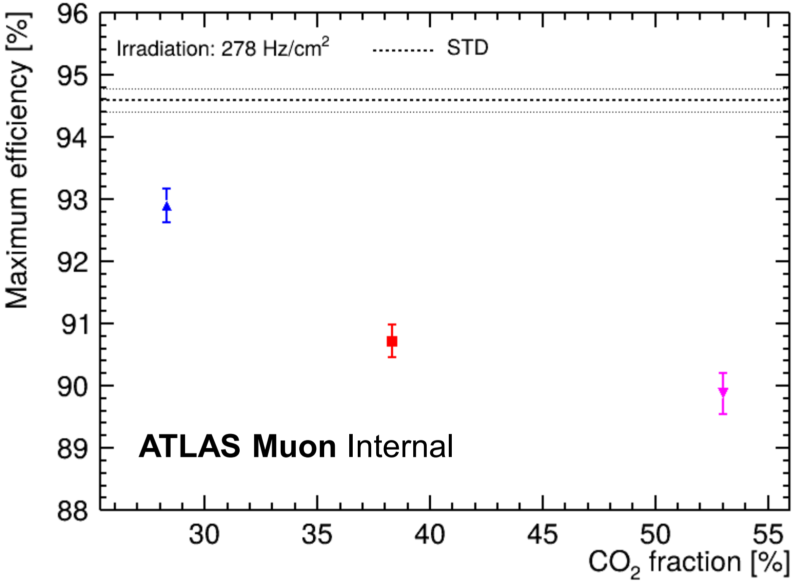
Shift WP of 500 V/10%HFO addiction
Efficiency above 92% up to 53%CO_2!
All mixtures good candidates from efficiency point of view

Ecogas: efficiency under irradiation

GWP~10







Reduction of the efficiency plateau(wrt no irradiation case):

170 Hz/cm2 : ~1.5% for all mixtures

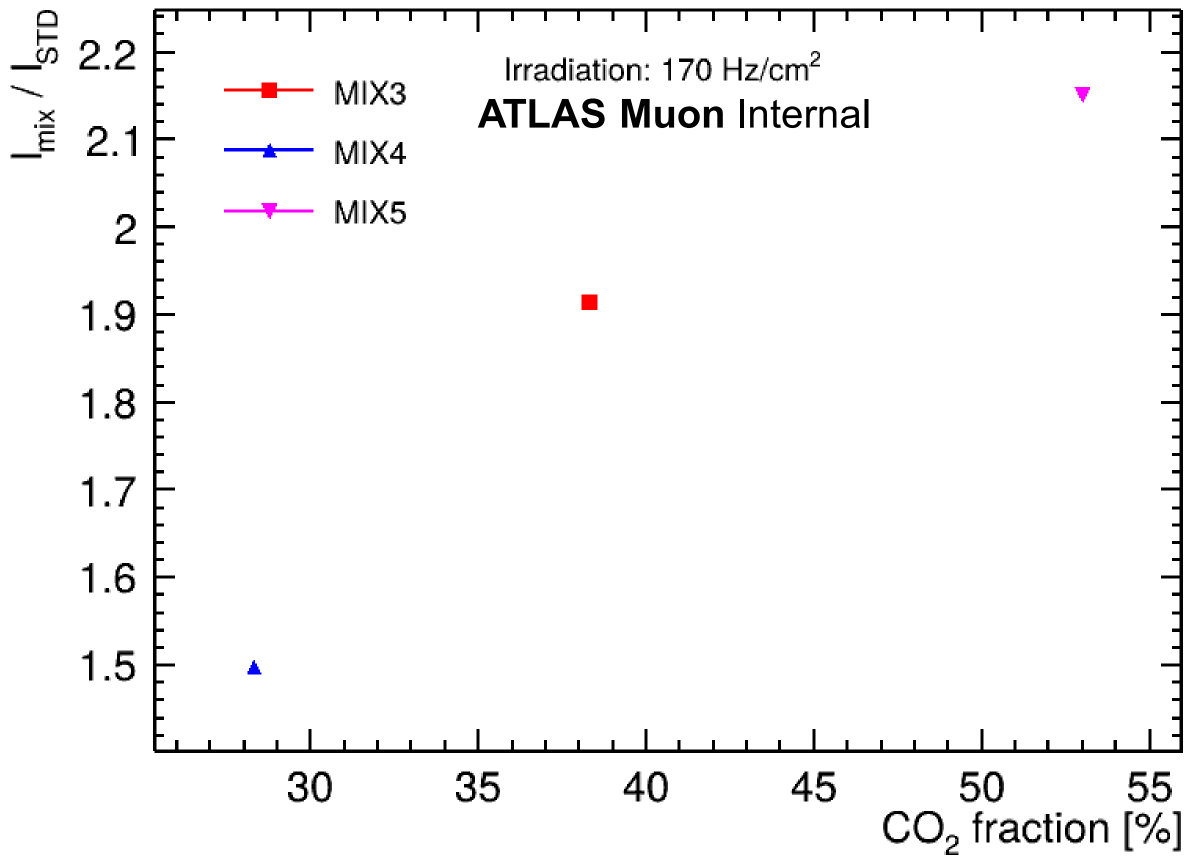
278 Hz/cm2 : ~2 for all mixtures

Efficiency above 90% up to 278 Hz/cm2

Ecogas: current under irradiation

GWP~10

(Iecogas/Istd) vs CO2 fraction @ 91%efficiency



Current at the same efficiency increases by increasing CO2 fraction

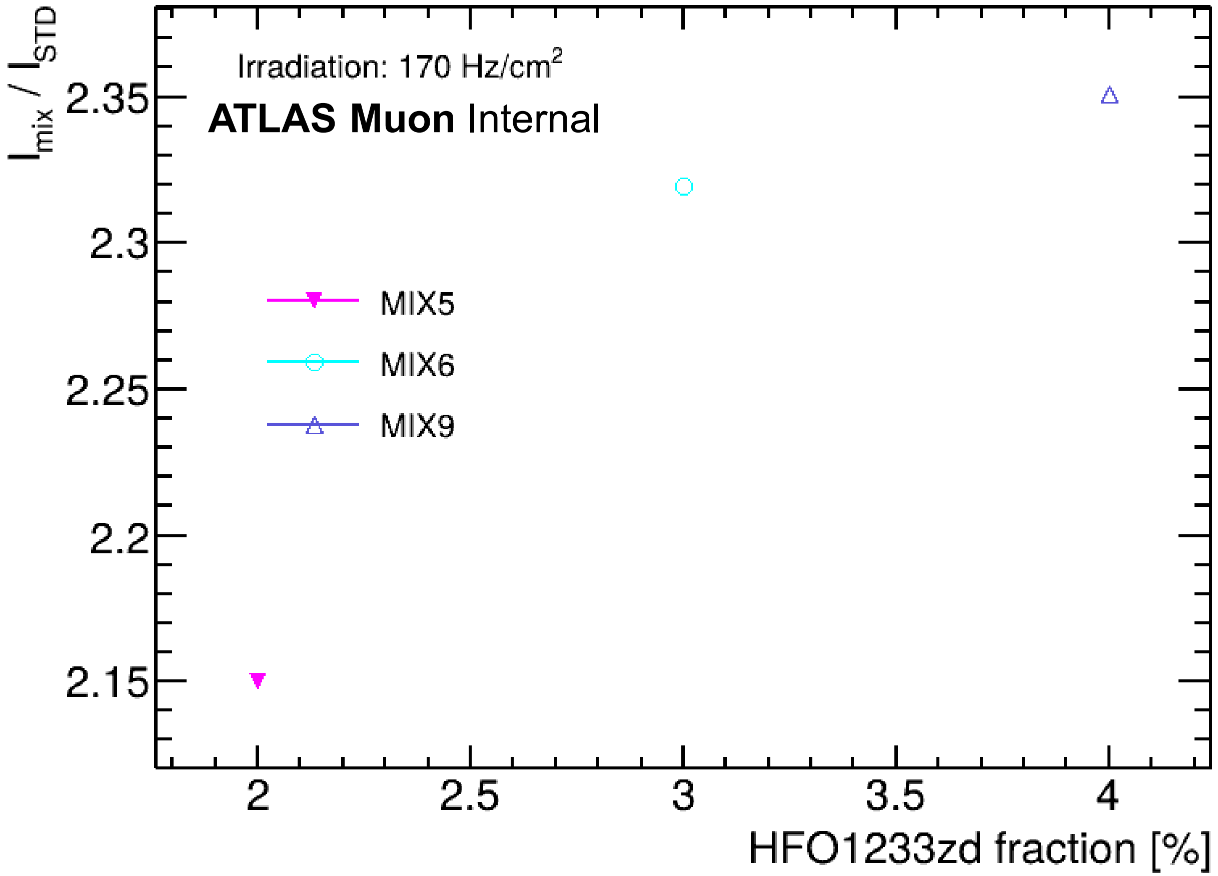
I(MIX3)~ 1.5I(STD)
I(MIX4)~ 1.9I(STD)
I(MIX5)~ 2.1I(STD)

No worrying trend observed

Increasing HFO1233zd in ecogases

GWP~10

First attempt to decrease the current → test increasing the streamer suppressor (HFO1233zd)



Mixture with maximum amount of **CO2 studied(53%)**→ increase of HFO1233zd (decreasing HFO1233ze)

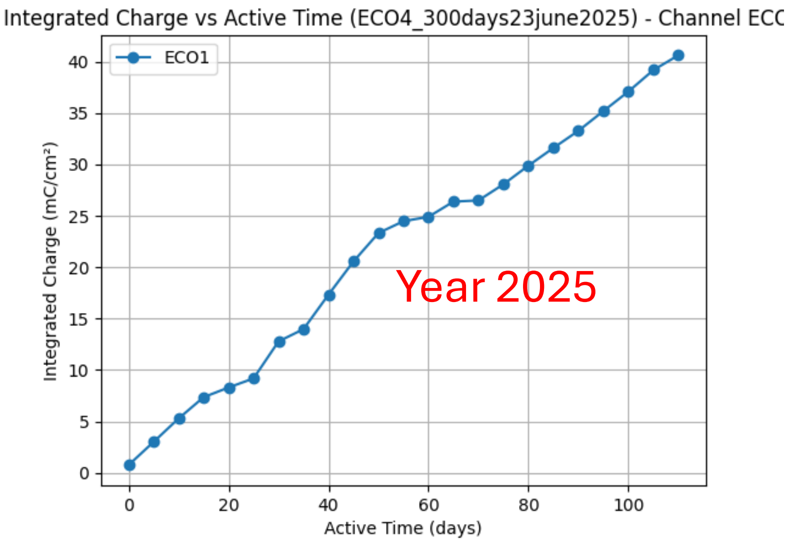
Maximum efficiency stable

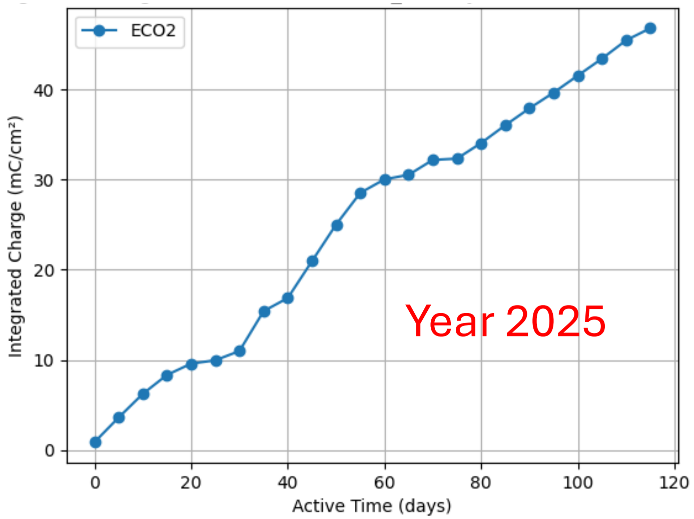
No gain in increasing the HFO1233zd fraction → minimum at 2%

Backup

Aging status and plan

2 prototypes in aging with the gas mixture : **94.7%$C_2H_2F_4$/4.7%i-C_4H_{10}/0.6% $C_3H_2ClF_3$**





The detectors are at 90% efficiency and the current over time is monitored under γ-irradiation

Integrated charge during **2024** (20 effective days) ~ 8.5 $\mathrm{mC/cm^2}$ (ECO1) and 9.5 $\mathrm{mC/cm^2}$ (ECO2)

Integrated charge (2024+2025) in ~100 effective days ~ 60 $\mathrm{mC/cm^2}$

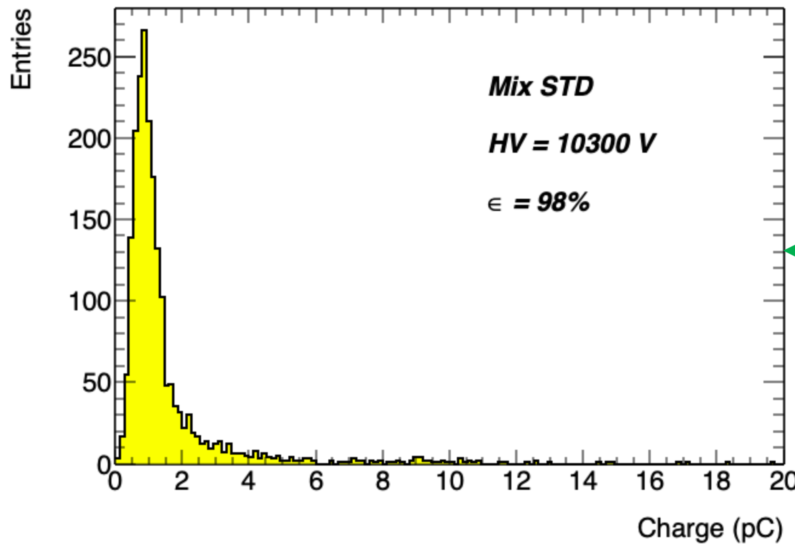
Target ~ 178 $\mathrm{mC/cm^2}$ (Safety Factor 3, Duty Cycle 33%)

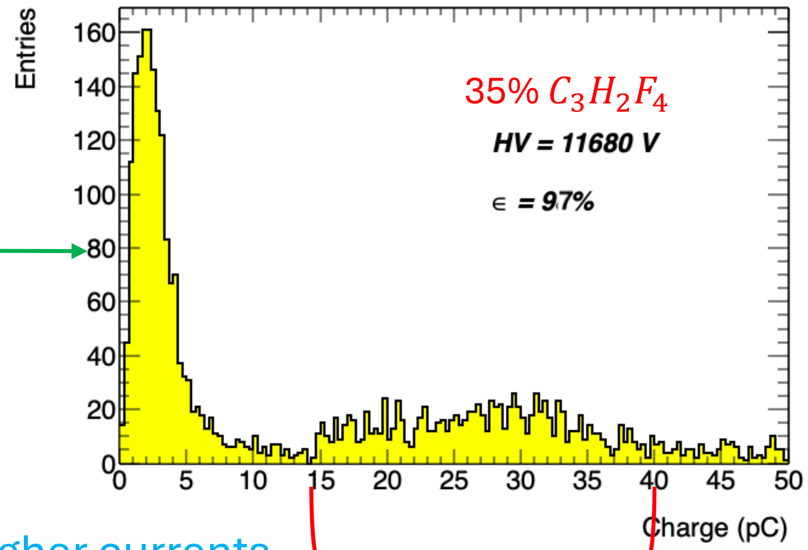
No increase in the current over time observed

Currents stable in both prototypes → plan to accelerate aging

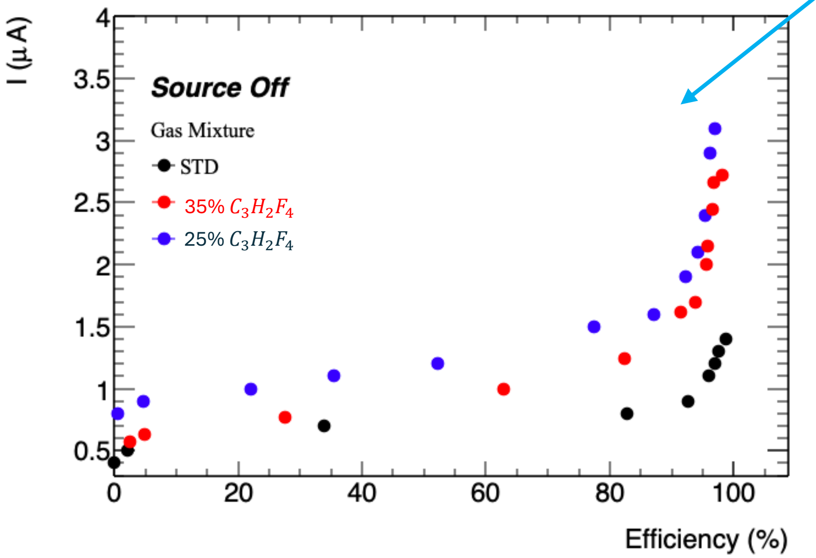
Current and charge distribution

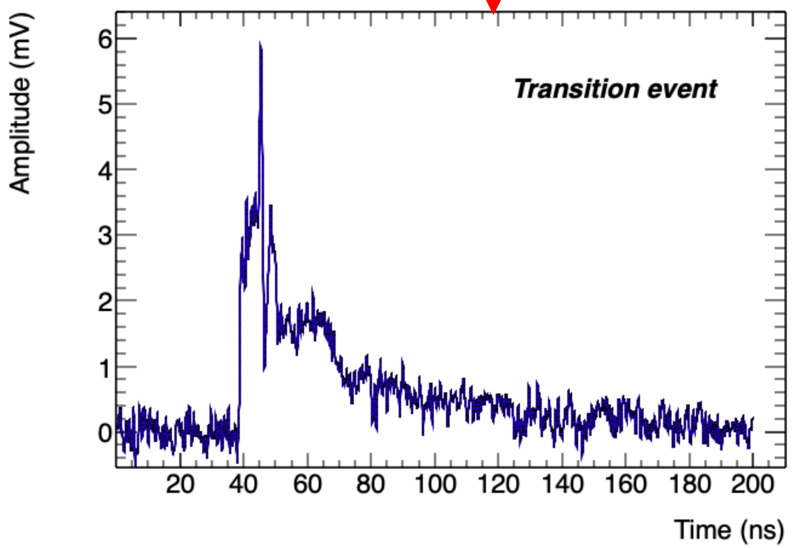
Different charge distribution @ same efficiency





Higher currents



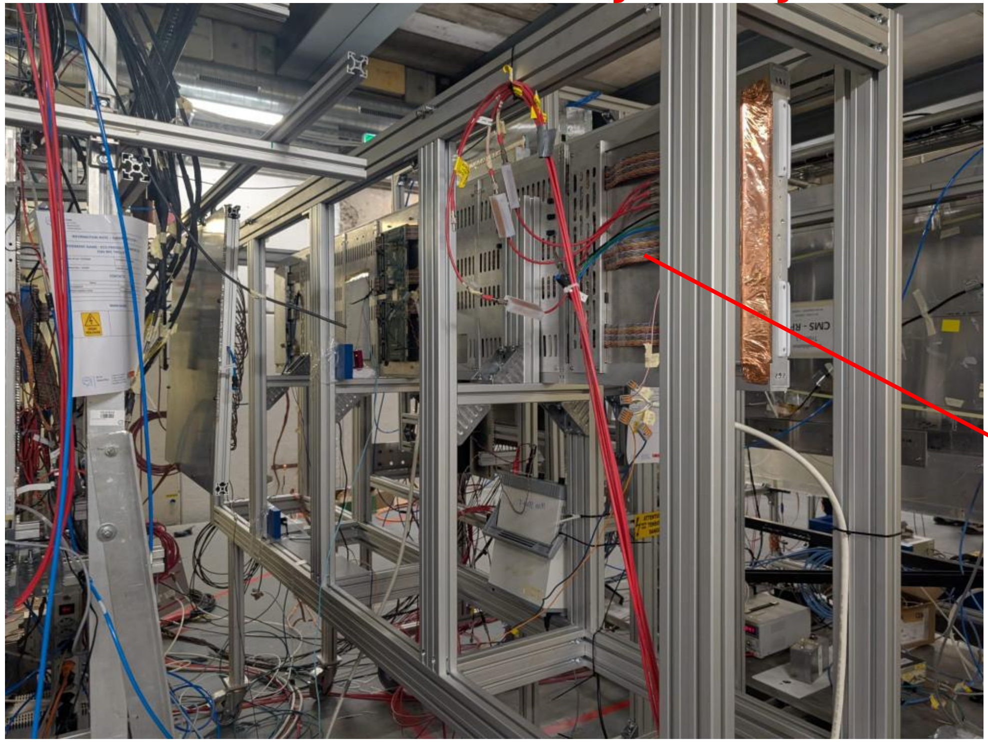


Presence of transition events at WP →Higher current →Impact on the detector aging to be defined in $CO_2/C_3H_2F_4$

Larger amount of fluorine production →impact on aging tbd

Test beam: Setup at the GIF++

Recent test beam May this year



Detector tested under γ irradiation and in presence of a muon beam at the Gamma Irradiation Facility at CERN (GIF++)

- Module-0 ATLAS phase-2 upgrade: three RPCs 1 mm wide within the same mechanical structure
- 3 FE boards per side (total number of boards =18, total number of channels =144) . (L. Pizzimento et al. 2024 NIMA, 169892, ISSN 0168-9002)
- Read-out :phase-2 DCT : TDC+FPGA(M. Corradi et al. 2022 Proc. IEEE NSS/MIC) drop

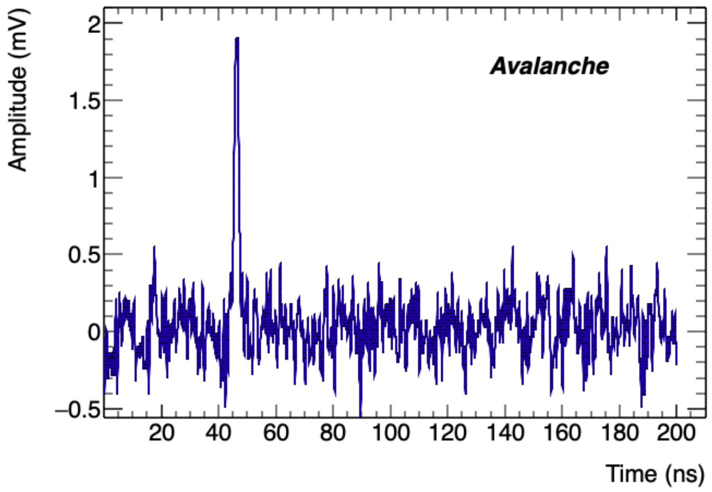
3 scenarios explored:

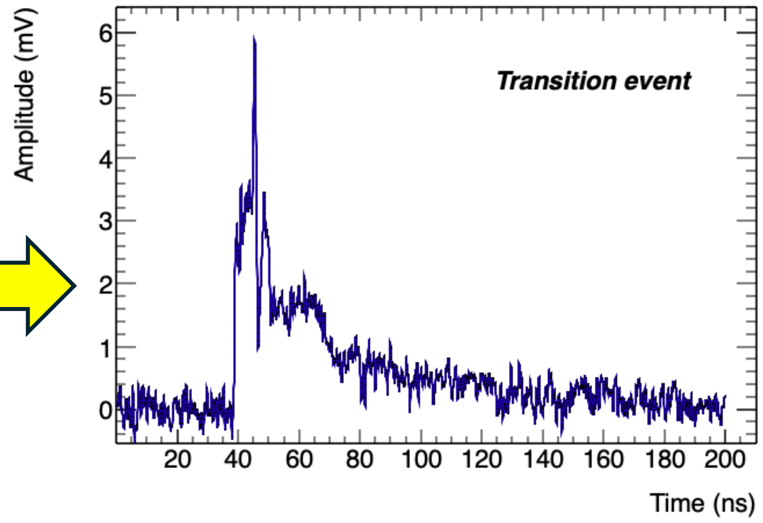
1) Muon beam + no irradiation;
2) Muon beam + 170 Hz/cm2 γ background
3) Muon beam + 278 Hz/cm2 γ background→drop

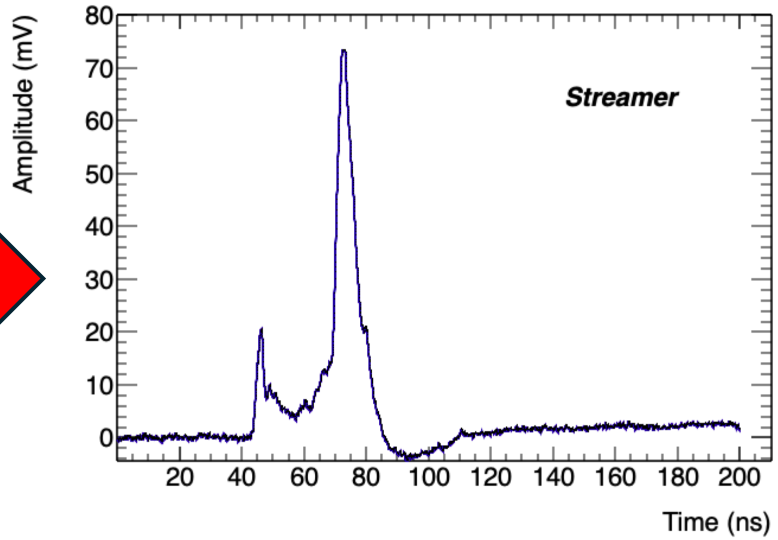
Maximum ATLAS background : 150 Hz/cm2

Measured ATLAS background + higher irradiation (2x)

Transition events







Avalanche : very short single signal (4-5 ns), low amplitude (~ mV) and low charge content (~ 1 pC)

Transition signal: multiple avalanche signal and/or a large tail following the precursor

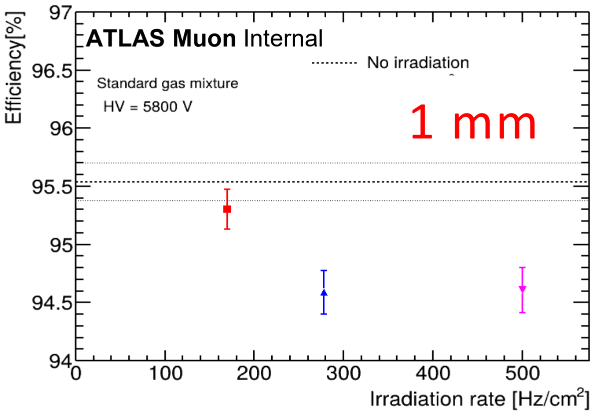
Streamer: avalanche signal precursor followed by a wide signal (~100 mV) lasting tens of ns and with a high charge content (~ 100 pC).

Interpretation: streamers precursor, representing those events in which the delayed avalanches don't merge together to form the streamer but they ionize the gas: the CO_2 produces many photons which produce secondary electrons that ionize the gas but are not able to trigger the streamer because they are restrained by the HFO.

Eco-gases in ATLAS during HL-LHC

During HL-LHC there will be two types of ATLAS RPC : 2 mm (legacy) and 1 mm (upgrade) gas volume thickness

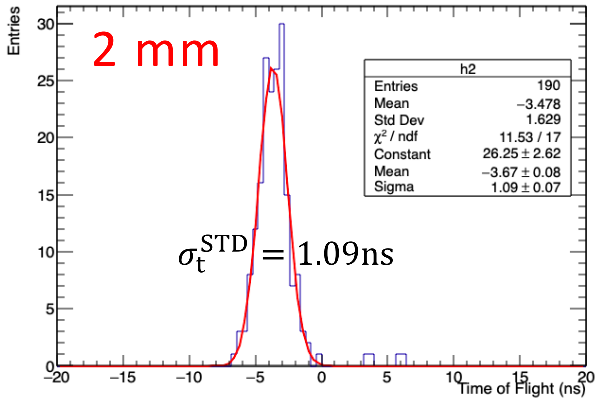
Topic of this presentation



1) Performance

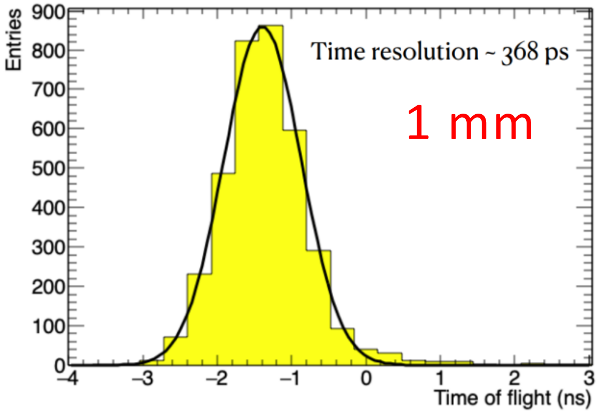
High efficiency (>90%) for both options (more critical for 1 mm)

Time resolution (~ 1 ns for 2 mm gas gap and ~ 400 ps for 1 mm gas gap)



2) Rate capability :

Average rate expected during HL-LHC in ATLAS RPC : 150 Hz/cm^2



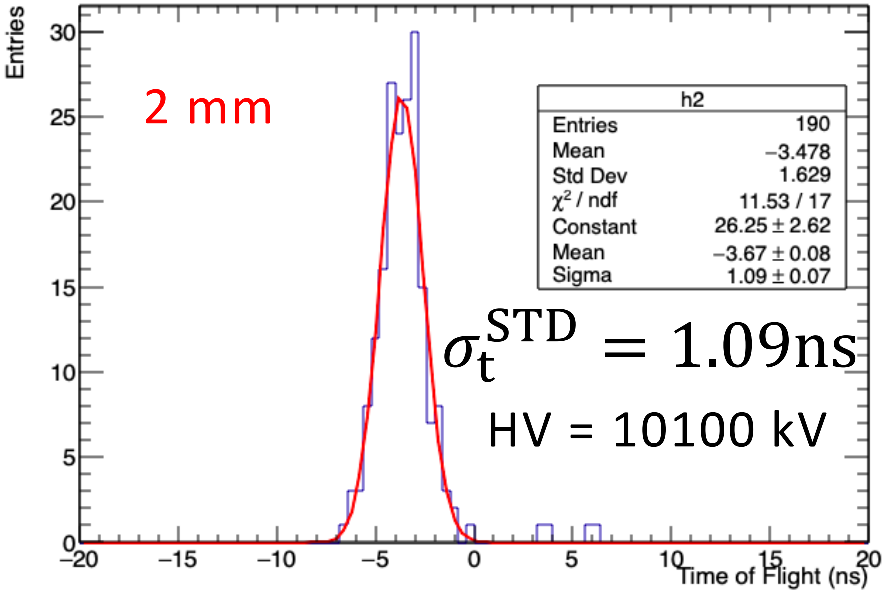
3) Aging

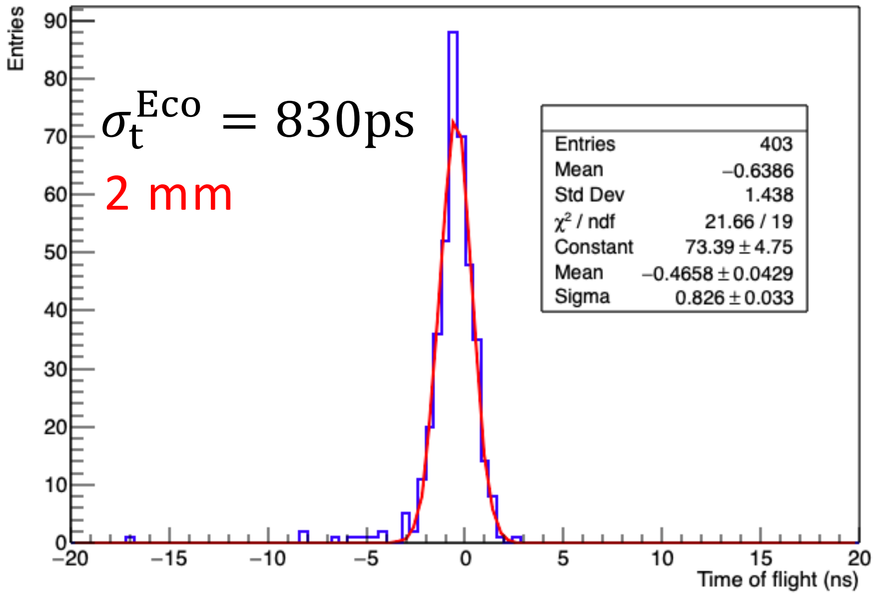
Low total charge delivered within the gas →low current

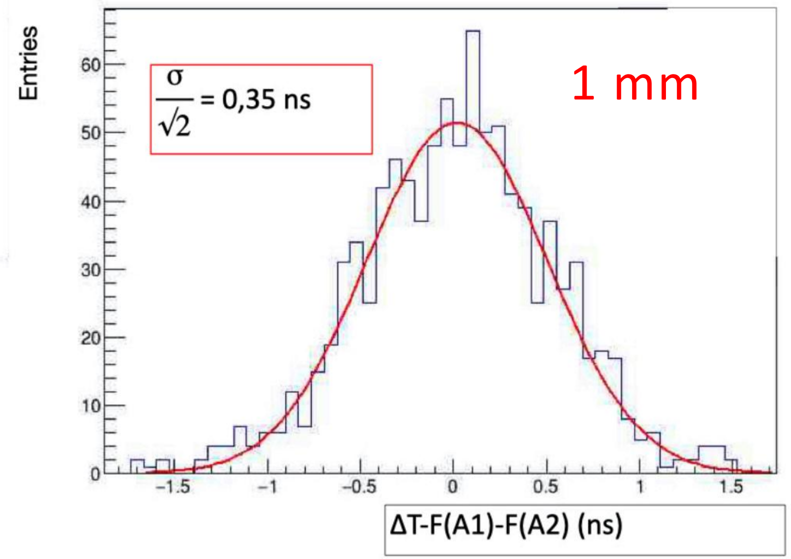
Low Fluorine radicals production

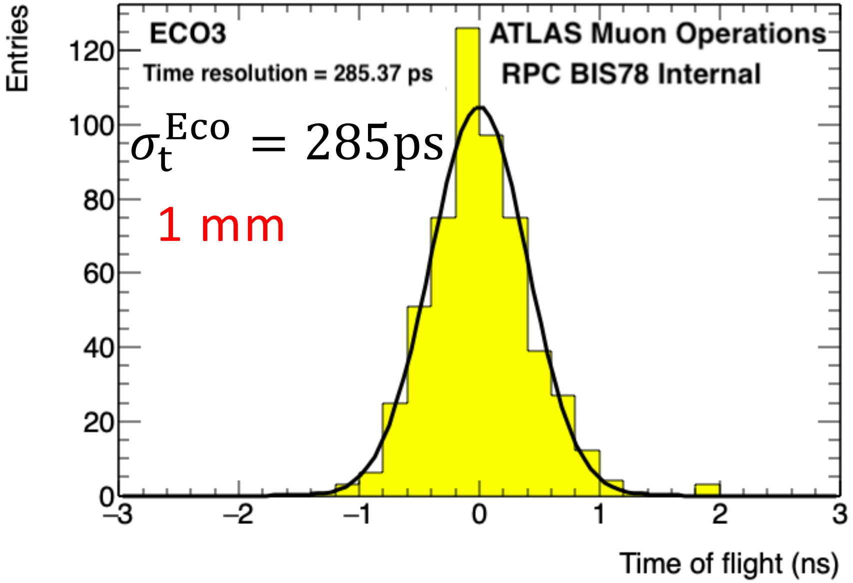
Reference on sinem talk
Don’t highlight 2 mm vs 1 mm
Consider to put in Backup

Time resolution



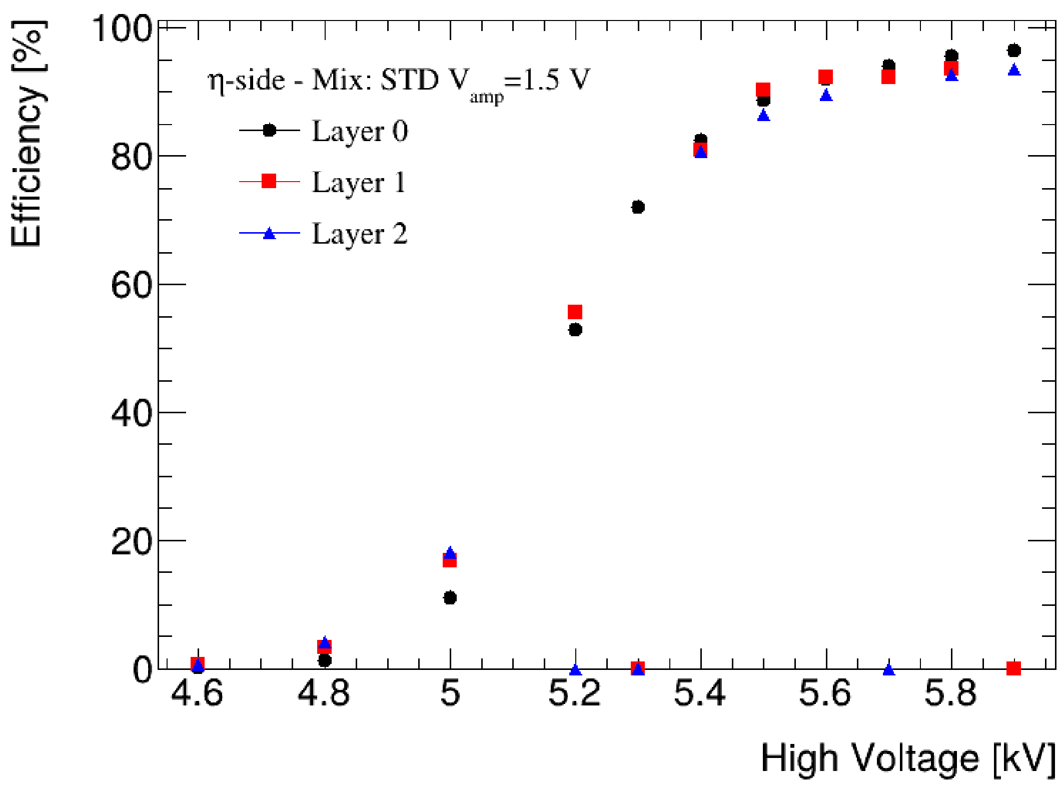


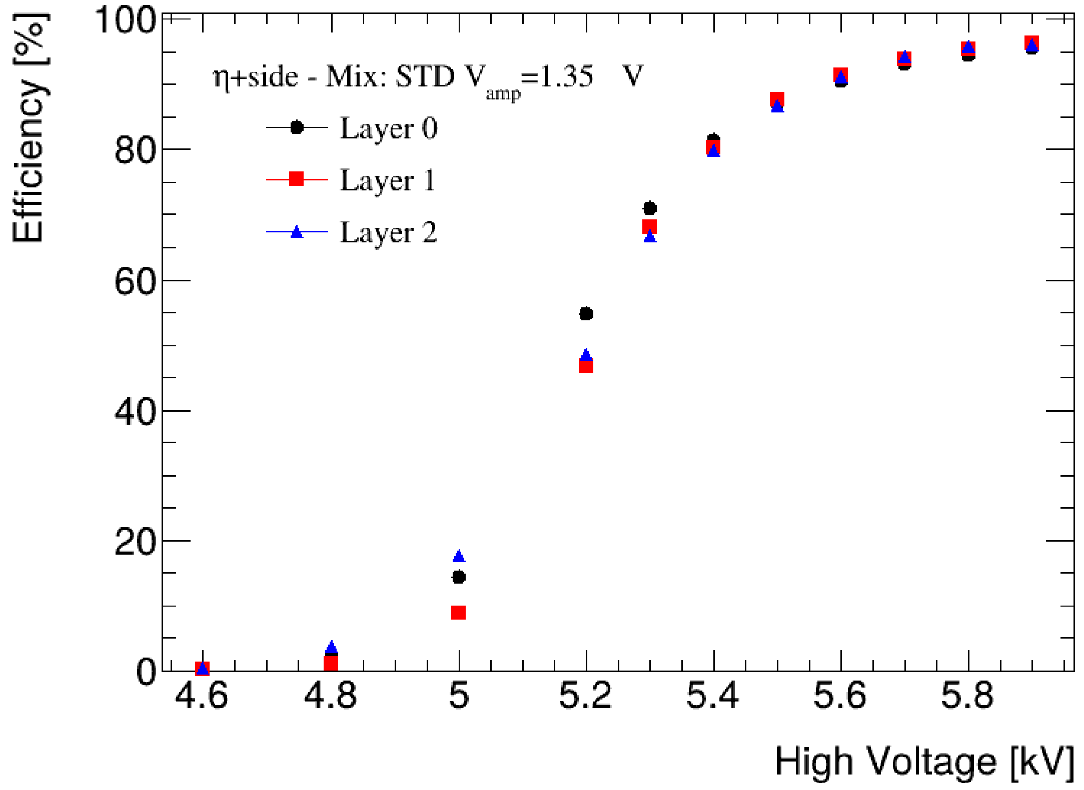




Better time resolution in CO_2-based mixtures due to the larger drift speed

Results with no irradiation : Efficiency vs HV



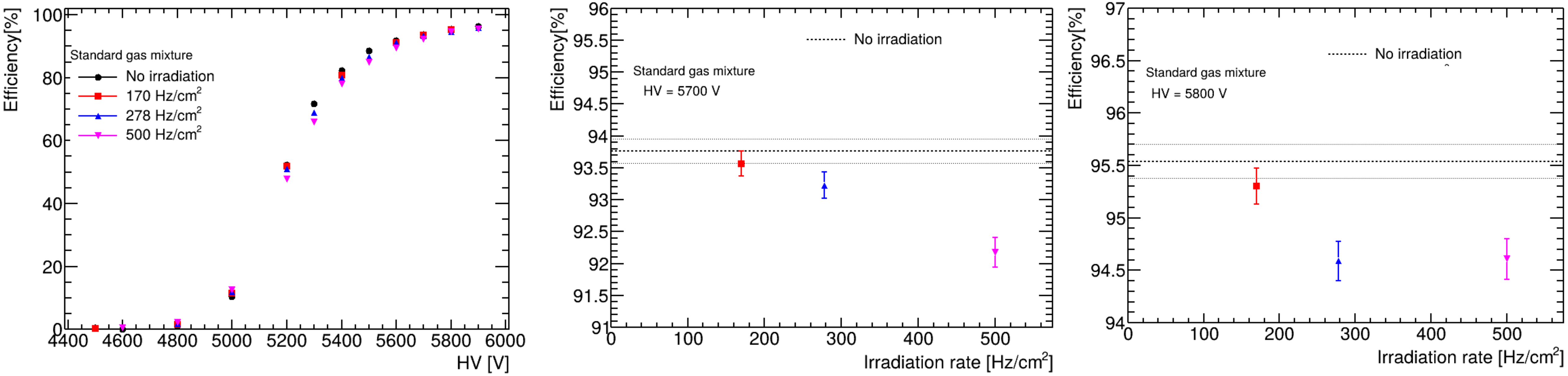


- Efficiency measured considering 2/3 layers as trigger and applying a spatial cut of 1 strip
- Efficiency plateau of 95% reached at 5.7 kV

- Efficiency in agreement among layers and among sides

Results irradiation: Efficiency vs HV

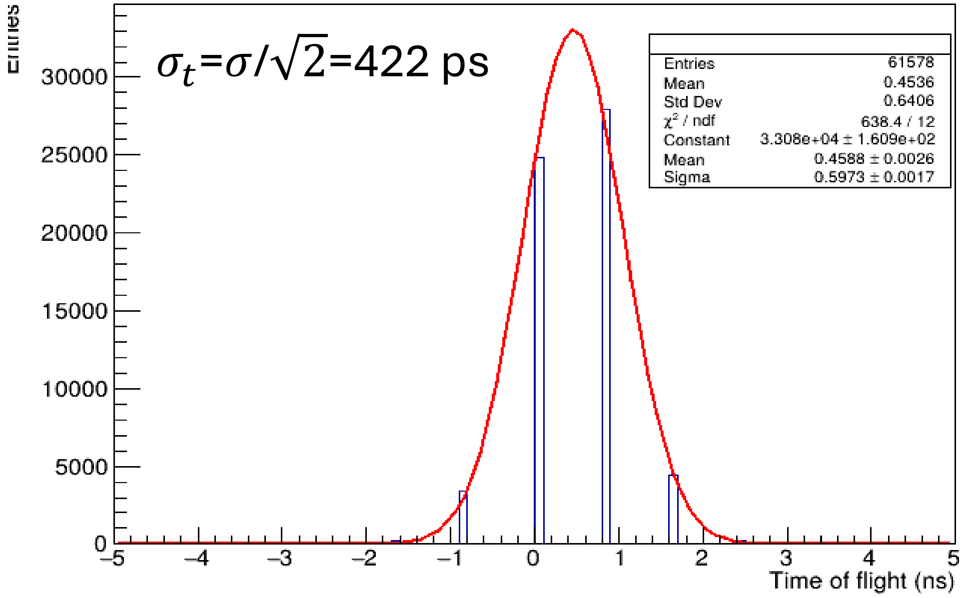
Scan vs irradiation for all layers. Just layer 1 shown but the results can be extended to all layers



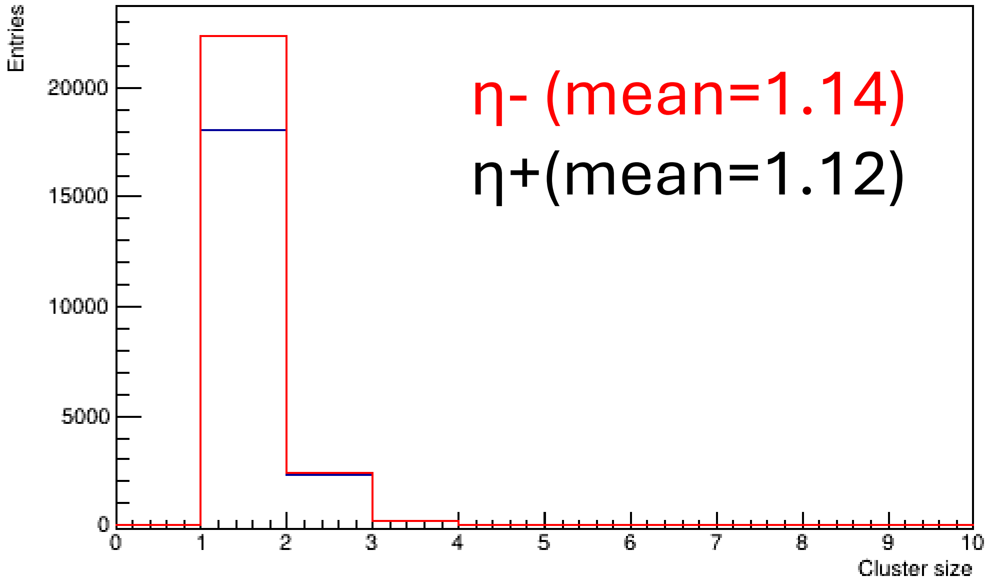
- Good efficiency plateau up to 500 Hz/cm2
- Maximum efficiency @500 Hz/cm2 =94.5% reached at 5.8 kV→1%less wrt the no irradiation case

Results with no irradiation : Performance at the working point (5.7 kV)

Time resolution (RAW)



Cluster size



RAW time resolution(no quality cuts applied) of ~422 ps, in agreement with what expected for 1 mm gas gap RPC

Cluster size near the physical value for both sides