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

Towards Eco-friendly gas solutions for Resistive Plate Chambers: a sustainable alternative to SF_6

Giorgia Proto

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Vienna

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The Resistive Plate Chambers (RPC)

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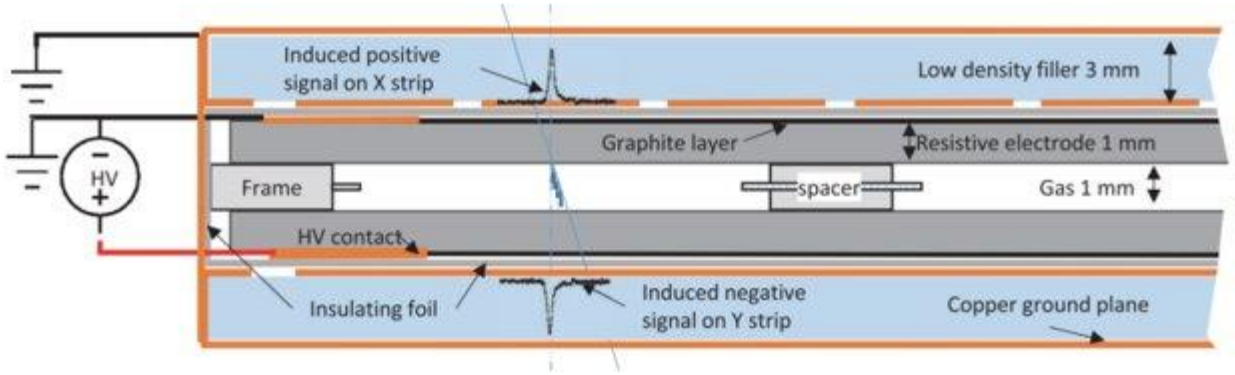
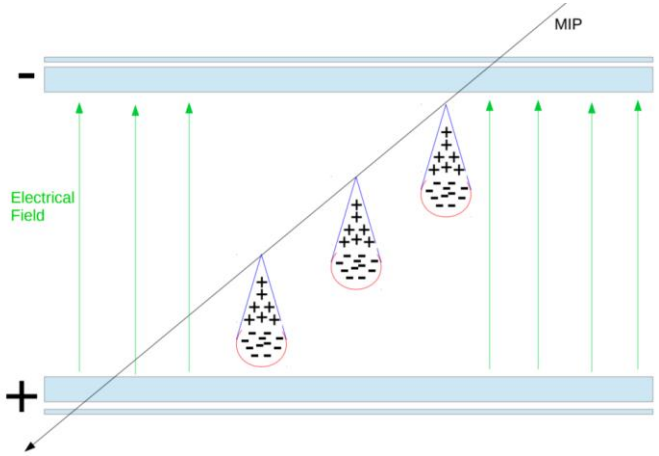
Very fast gaseous detectors with excellent time resolution



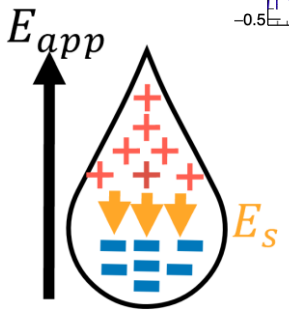
- Gas gap in the range of mm size
- Parallel resistive electrodes
  - Internal surface : linseed oil
  - External surface : graphite

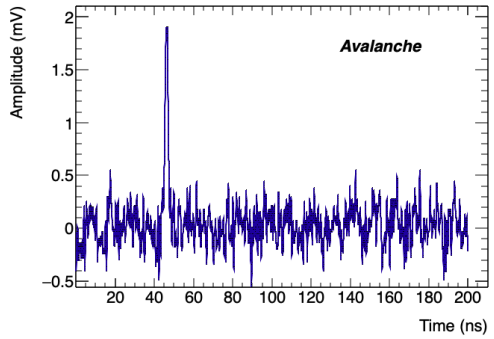
- Insulating layer
- Read-out strips
- Uniform electric field

Primary ionization
Avalanche formation



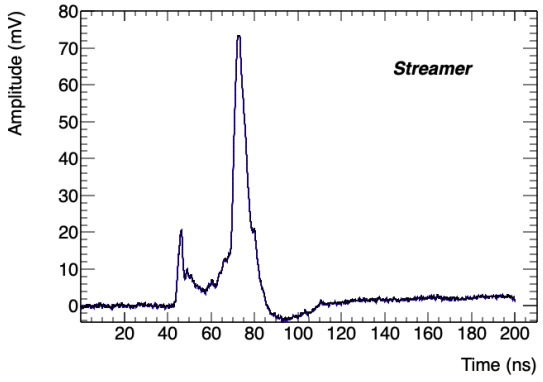
~mV
~ns
~pC





Saturated avalanche mode

Electron-ion recombination with UV photon emission
Streamer formation



~tens mV
~tens ns
~100 pC

RPC in avalanche mode with the standard gas mixture

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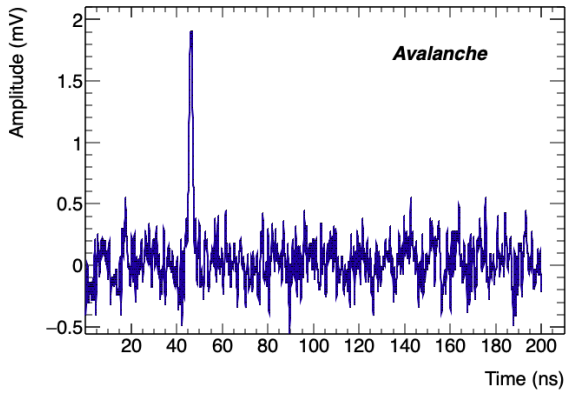
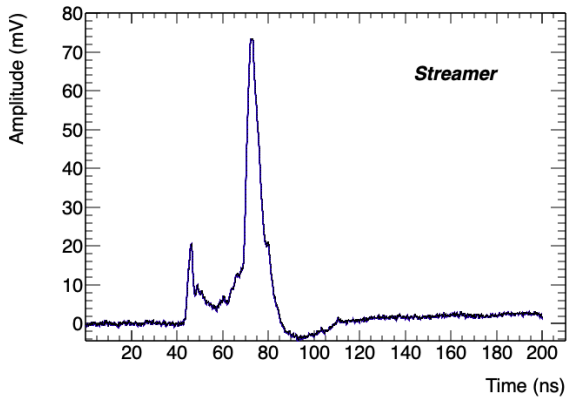
Avalanche signal



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

Streamer signal

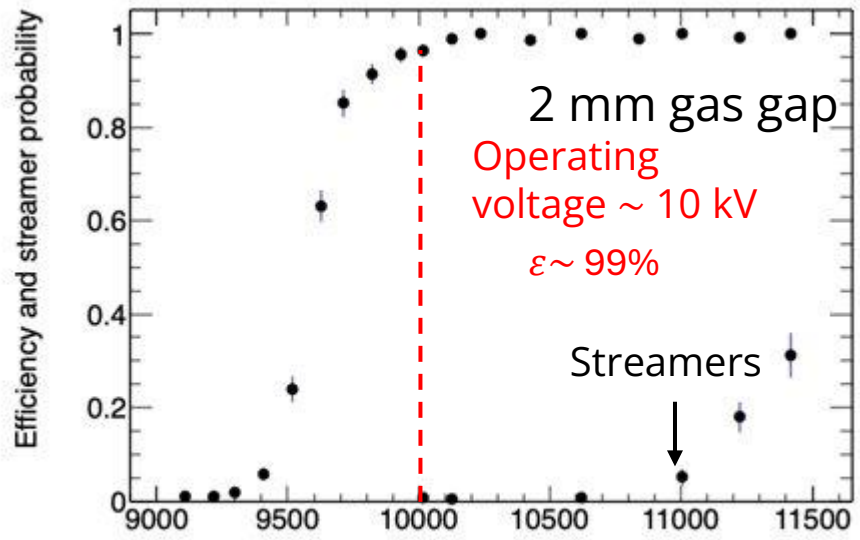


- High current→low rate capability and faster aging
- No sophisticated FE electronics needed
- Low rate experiment

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



Search of an eco friendly gas mixture

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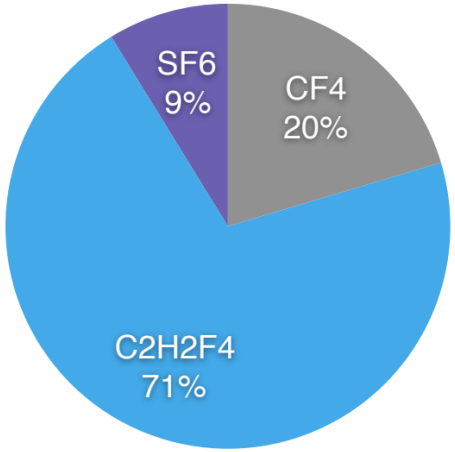
The standard gas mixture has a high Global Warming Potential (GWP)



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

Eco-gases in ATLAS during HL-LHC

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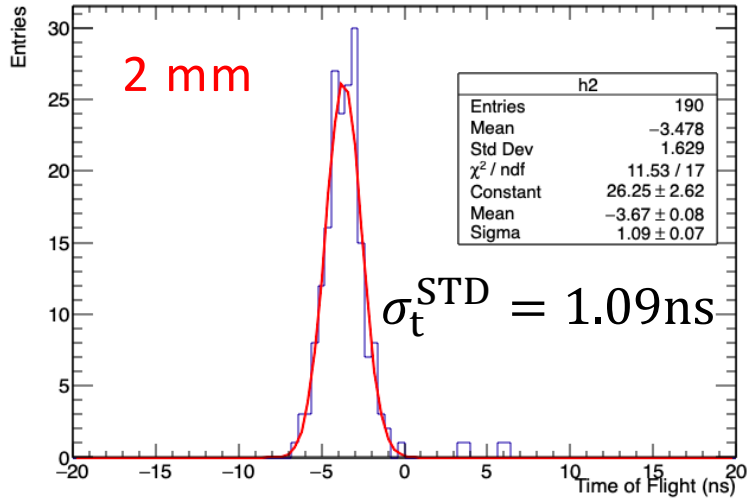
During HL-LHC there will be two types of ATLAS RPC : 2 mm (legacy) and 1 mm (upgrade) thick

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 :

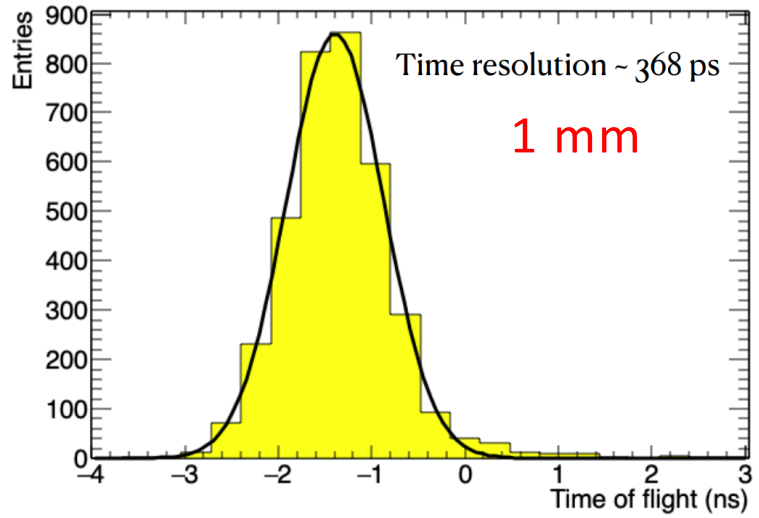
Average rate expected during HL-LHC in ATLAS RPC : 200 Hz/cm^2

Hottest spot during HL-LHC in ATLAS RPC : 500 Hz/cm^2

3) Aging

Low total charge delivered within the gas →low current

Low Fluorine radicals production



Substitution of the $C_2H_2F_4$

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

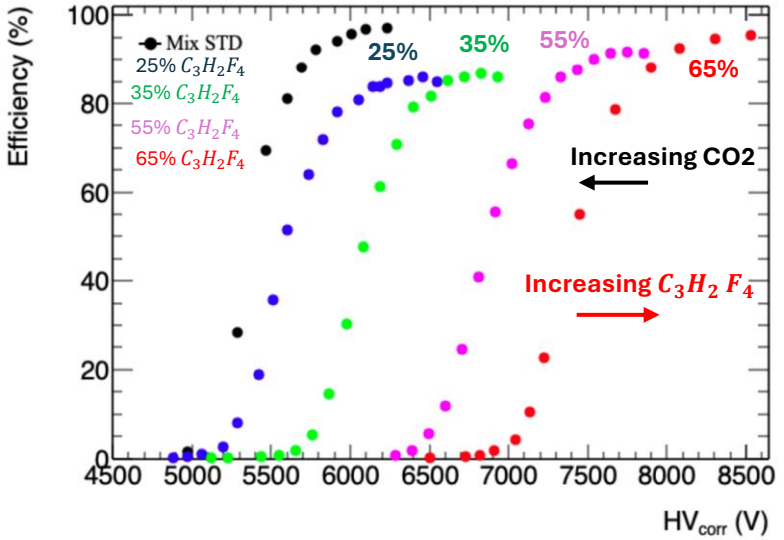
2) Reduction of the $C_2H_2F_4$ concentration introducing CO_2 (ATLAS intermediate):

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

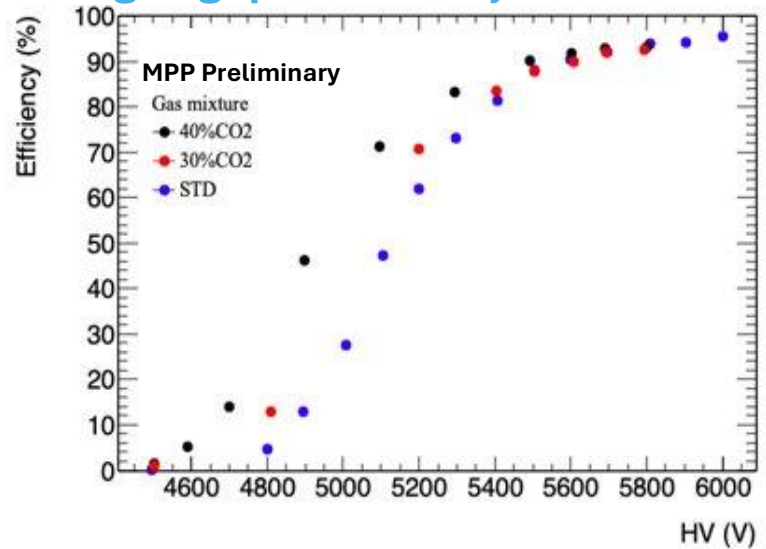
1. No large impact expected on detector longevity in terms of fluorine production
2. Small reduction of the GWP

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



The impact of SF_6

The SF_6 is the molecule with the largest GWP in the standard gas (22900)

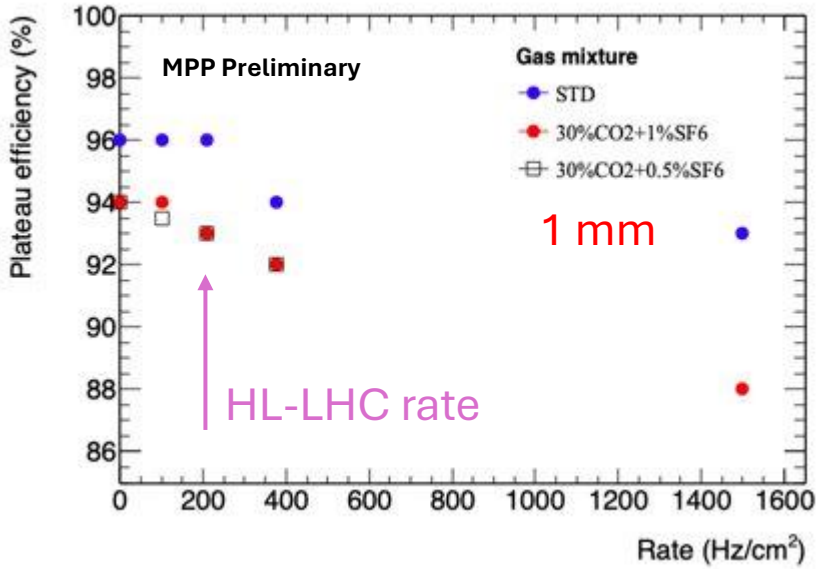
All the alternatives to the $C_2H_2F_4$ require an increase in the SF_6 concentration in order to avoid streamers→ higher GWP

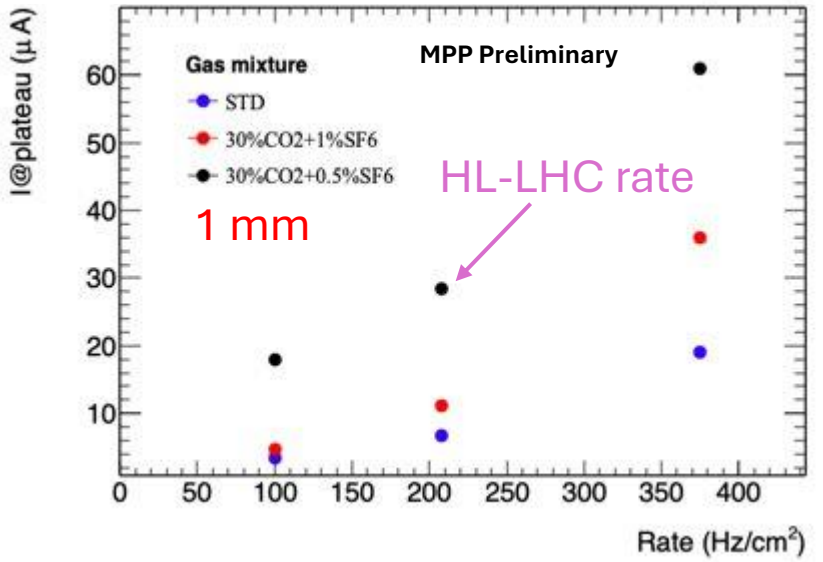
What happen if we reduce the SF_6 concentration in the ATLAS intermediate solution?

$CO_2/C_2H_2F_4$ +i-C_4H_{10} + 0.5% SF_6

✓ Reduction of the GWP (**1041** vs **1164**)

✗ Large increase of the currents due to transition (high-charge) events and/or streamers





Substitution of the SF_6

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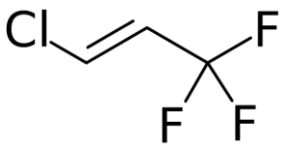
Possibility to replace the highest GWP molecule, the SF_6, with an environment friendly gas: the Chlorotrifluoropropene ($C_3H_2ClF_3$, **GWP ~ 1**)

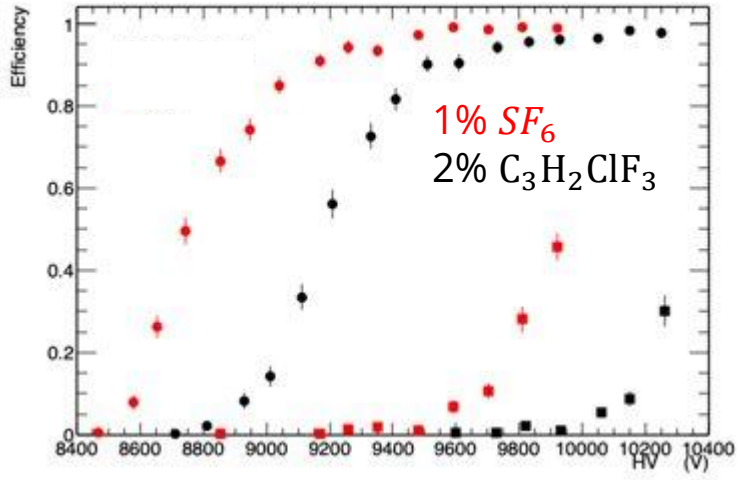


$CO_2/C_3H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ ⟶ GWP ~ 10 (100 times less than the standard gas!!)

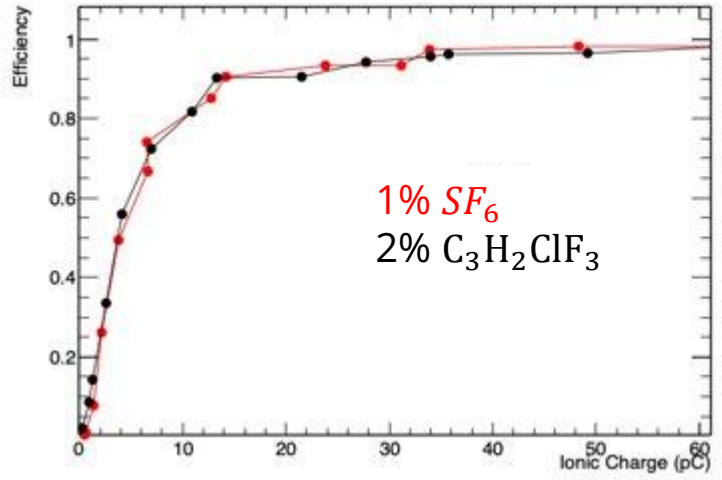
Possibility to operate the RPC with a <u>totally</u> environment-friendly gas mixture
(G. Proto *et al* 2022 *JINST* **17** P05005)

Main results (2 mm gas gap)

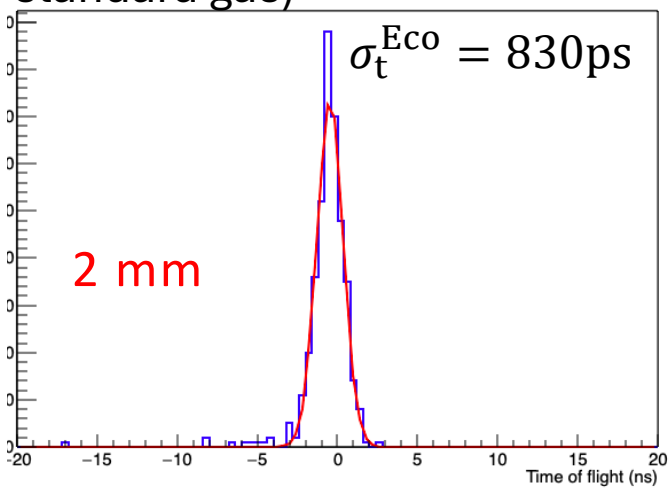
Same avalanche-streamer separation



Same current @ same efficiency



Good time resolution (24%better wrt standard gas)



Certification of $C_3H_2ClF_3$ for short-term applications

1.Early appearance of streamers/transition events → high current and low rate capability

2. High current under irradiation → aging and low rate capability

3. Long term effects → Study of the behaviour of the gas after integrating the corresponding HL-LHC charge

1. Decouple the contribution of the $C_3H_2ClF_3$ from the other gases

$C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ → The behaviour of $C_2H_2F_4$ and i- C_4H_{10} is well known → Any of the effect cited above due to $C_3H_2ClF_3$

2. Application to ATLAS intermediate gas mixture

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

- Opportunity to start to replace the SF_6
- Possibility to reduce the $C_2H_2F_4$ by increasing the $C_3H_2ClF_3$ with an improvement of the GWP

Set-up at the Gamma Irradiation Facility (GIF++)

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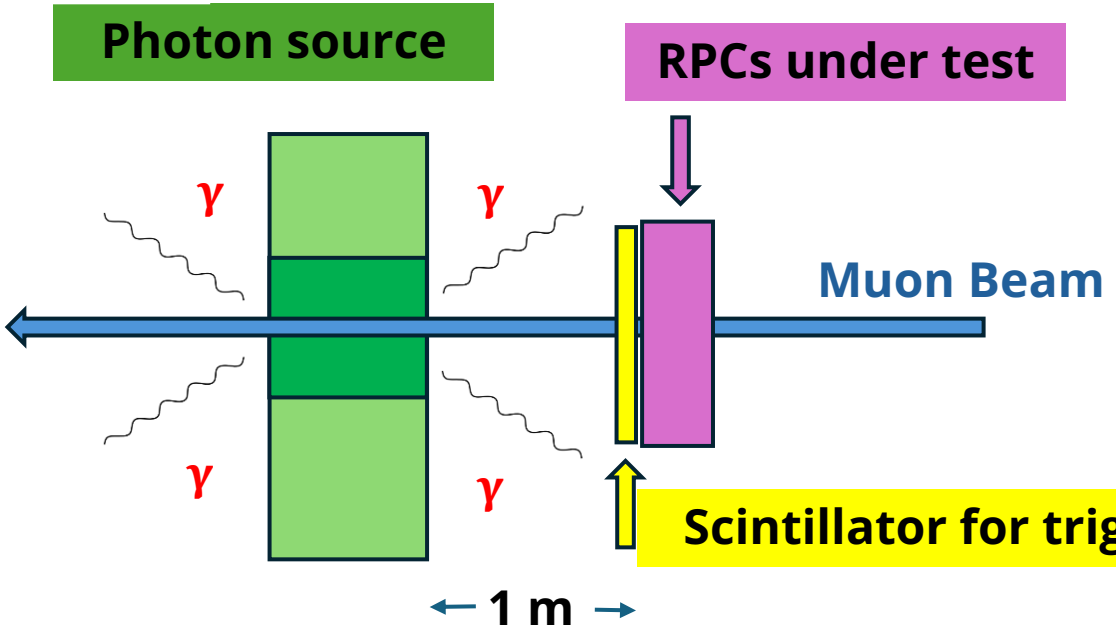
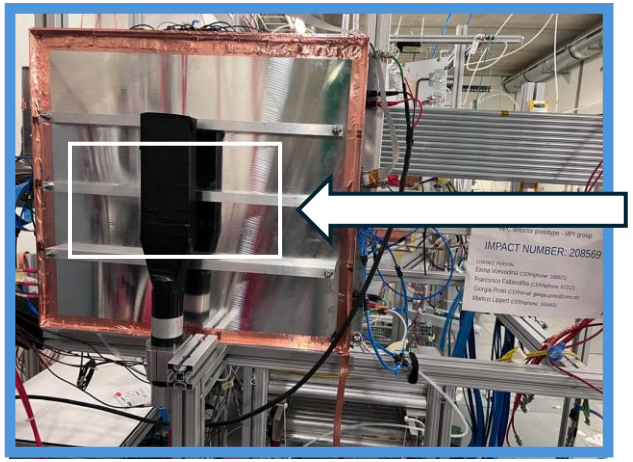
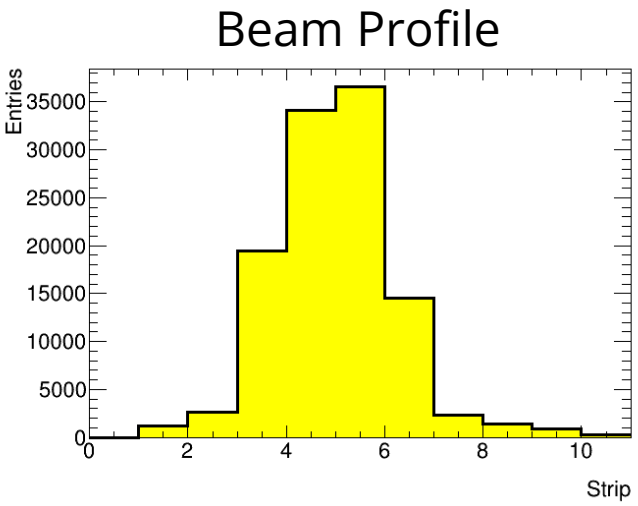




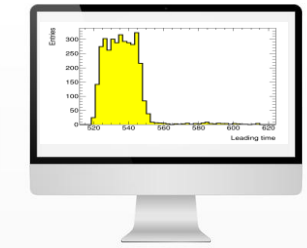


Three 1 mm gas gap RPCs
1.4 mm electrode thickness
Amplified signal with
Cardarelli FE electronics
(transimpedence amplifier)

Discriminator
(4 mV thr)

TDC CAEN
100 ps (LSB)-
400 ps effective
resolution

Laptop for DAQ and offline analysis



Results (I)

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Mixtures

$94.7\%C_2H_2F_4 + 4.7\%\text{i-}C_4H_{10} + 0.6\%C_3H_2ClF_3$

$94.3\%C_2H_2F_4 + 4.7\%\text{i-}C_4H_{10} + 1\%C_3H_2ClF_3$

Efficiency and currents in presence of γ-irradiation in comparison with the standard gas

Study of the efficiency

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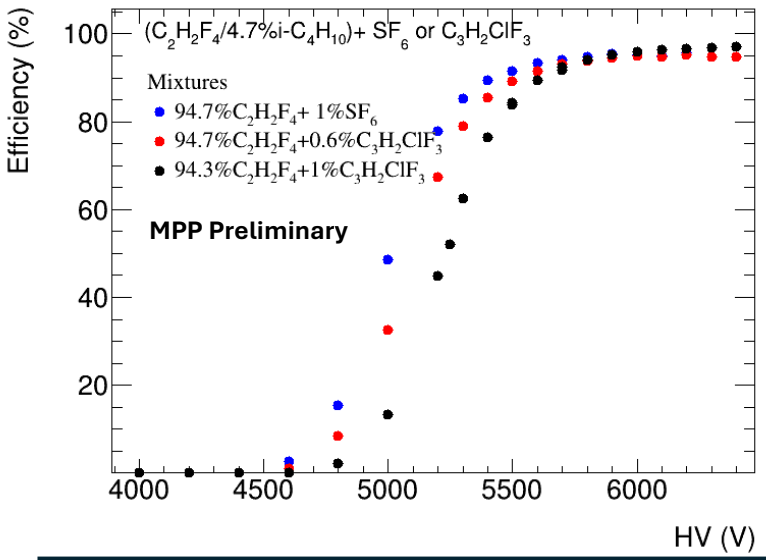
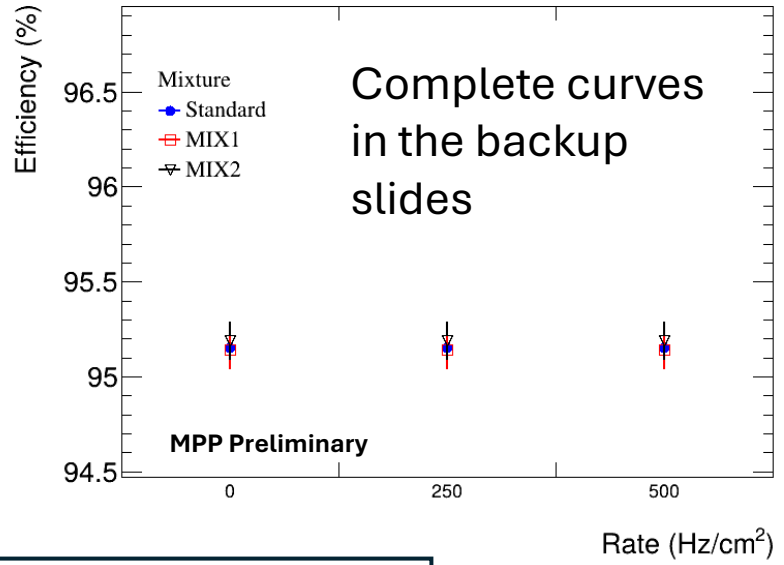
Efficiency vs HV:NO irradiation

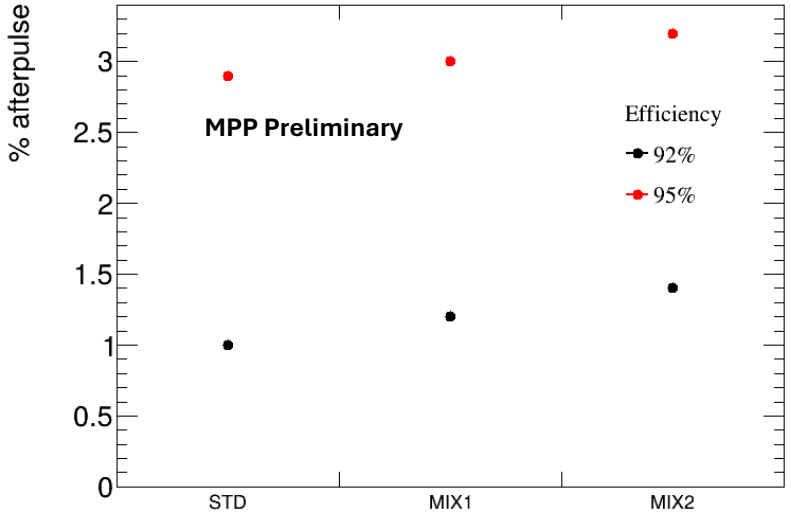


Plateau vs γ-rate



Complete curves in the backup slides

% after pulse vs mixture @ WP



1. MIX1 : 94.7%$C_2H_2F_4$/4.7%i-C_4H_{10}/**0.6%** $C_3H_2ClF_3$

2. MIX2 :94.3%$C_2H_2F_4$/4.7%i-C_4H_{10}/**1%** $C_3H_2ClF_3$

1. Same efficiency around 95%
2. Working point shifted by 100 V (0.6% $C_3H_2ClF_3$) and 200 V (1% $C_3H_2ClF_3$) wrt the standard gas
3. No efficiency loss under irradiation→Same rate capability up to 448 Hz /cm^2

After pulse = number of multiple hits on the same strip

1. Number of after pulses of MIX1 (0.6% $C_3H_2ClF_3$) and MIX2 (1% $C_3H_2ClF_3$) consistent with the standard gas (at the same efficiency)

Study of the efficiency

Max-Planck-Institut für Physik
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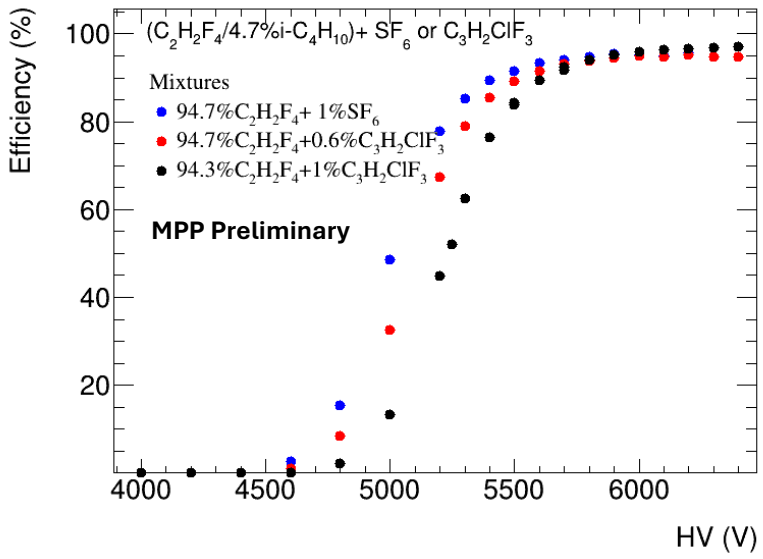
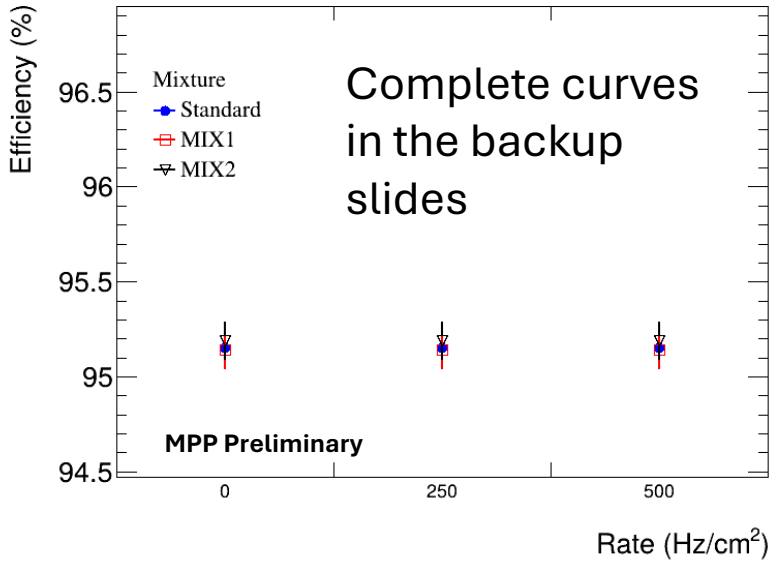
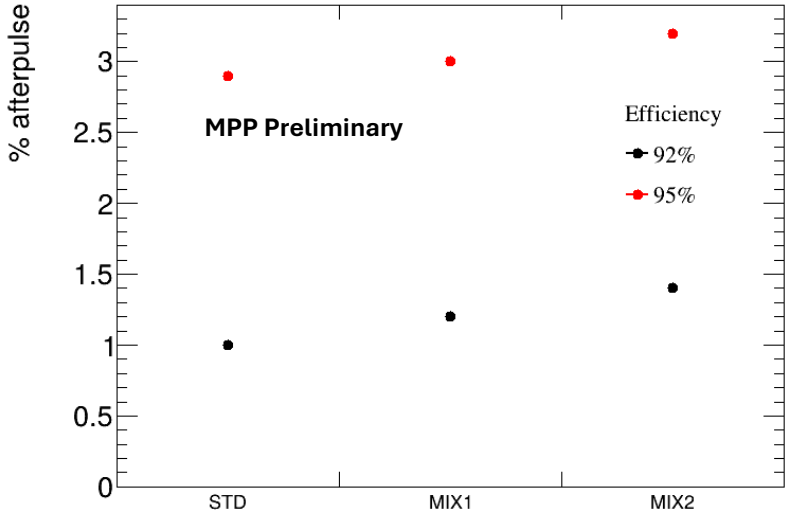
Efficiency vs HV:NO irradiation



Plateau vs γ-rate



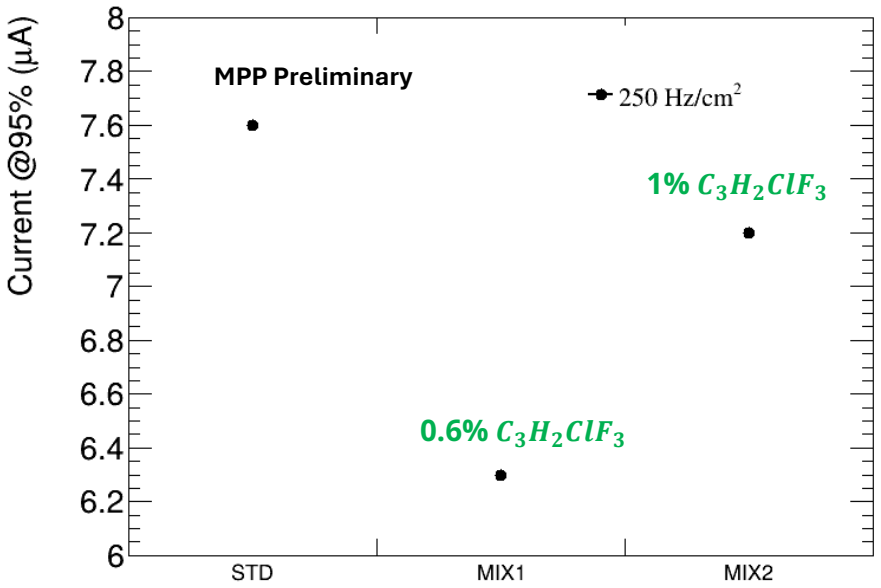
% after pulse vs mixture @ WP

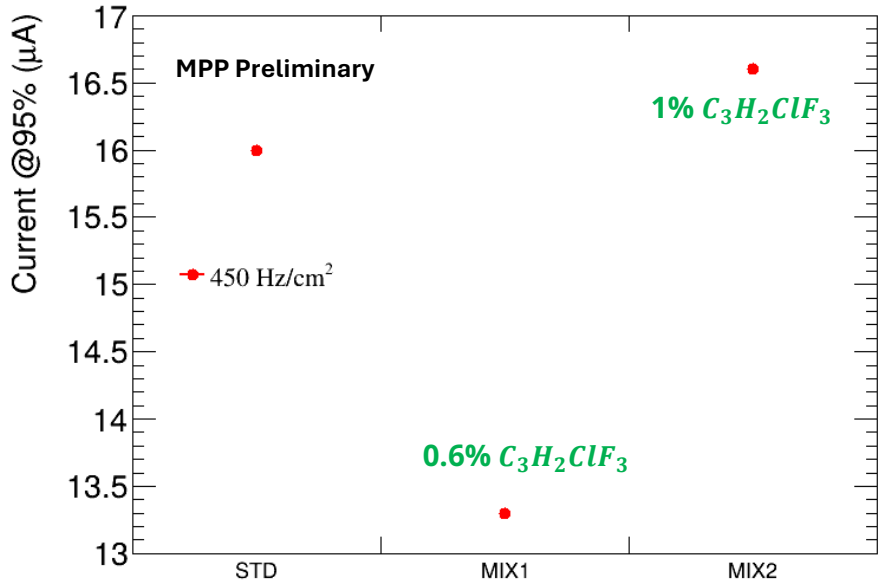


The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact on the rate capability

Results : Comparison at 95% efficiency

Currents at 95% efficiency at different irradiation : no irradiation, 235 Hz/cm^2 and 448 Hz/cm^2





The currents at the WP are at the same order of magnitude up to 448 Hz/cm^2 (slightly better in MIX1)

The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact in the detector performance

Results (II)

Mixtures :
(**30%** CO_2/4.7% i-C_4H_{10}) +

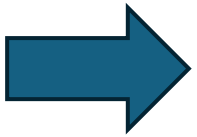
$64.3\%C_2H_2F_4 + 1\%C_3H_2ClF_3$
$63.3\%C_2H_2F_4 + 2\%C_3H_2ClF_3$
$62.3\%C_2H_2F_4 + 3\%C_3H_2ClF_3$
$61.3\%C_2H_2F_4 + 4\%C_3H_2ClF_3$

Mixtures :
(**40%** CO_2/4.7% i-C_4H_{10}) +

$53.3\%C_2H_2F_4 + 2\%C_3H_2ClF_3$
$52.3\%C_2H_2F_4 + 3\%C_3H_2ClF_3$
$51.3\%C_2H_2F_4 + 4\%C_3H_2ClF_3$

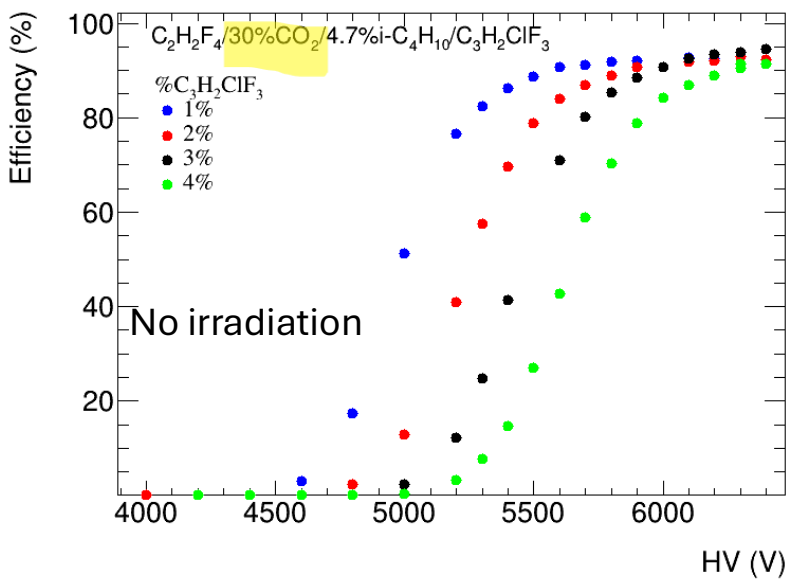
Efficiency and currents in presence of γ-irradiation in comparison with:

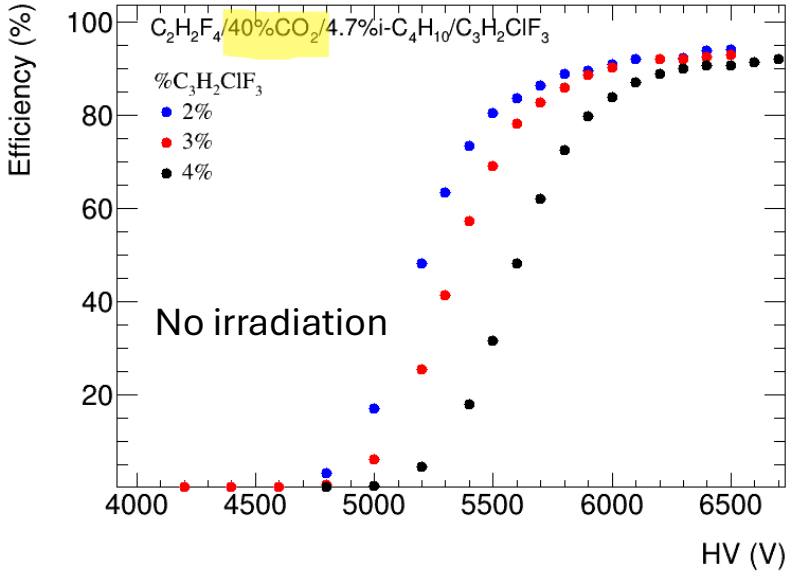
- standard gas
- $C_2H_2F_4/CO_2/i\text{-}C_4H_{10}/\mathbf{1\%SF_6}$
- $C_2H_2F_4/CO_2/i\text{-}C_4H_{10}/\mathbf{0.5\%SF_6}$

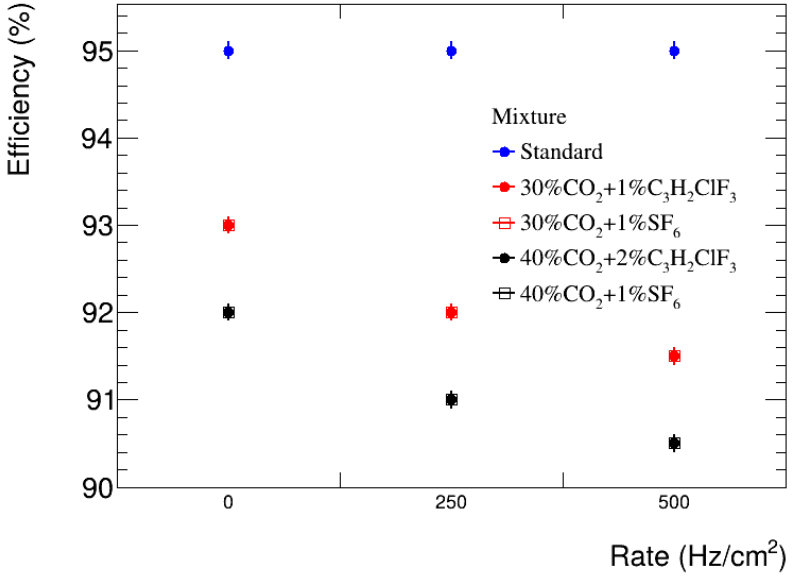


Direct comparison with SF_6

$C_2H_2F_2$ / CO_2 / i-C_4H_{10}/ $C_3H_2ClF_3$: Efficiency







plateau efficiency of the standard gas ~3% higher wrt the mixtures containing CO_2

Efficiency drop under irradiation:

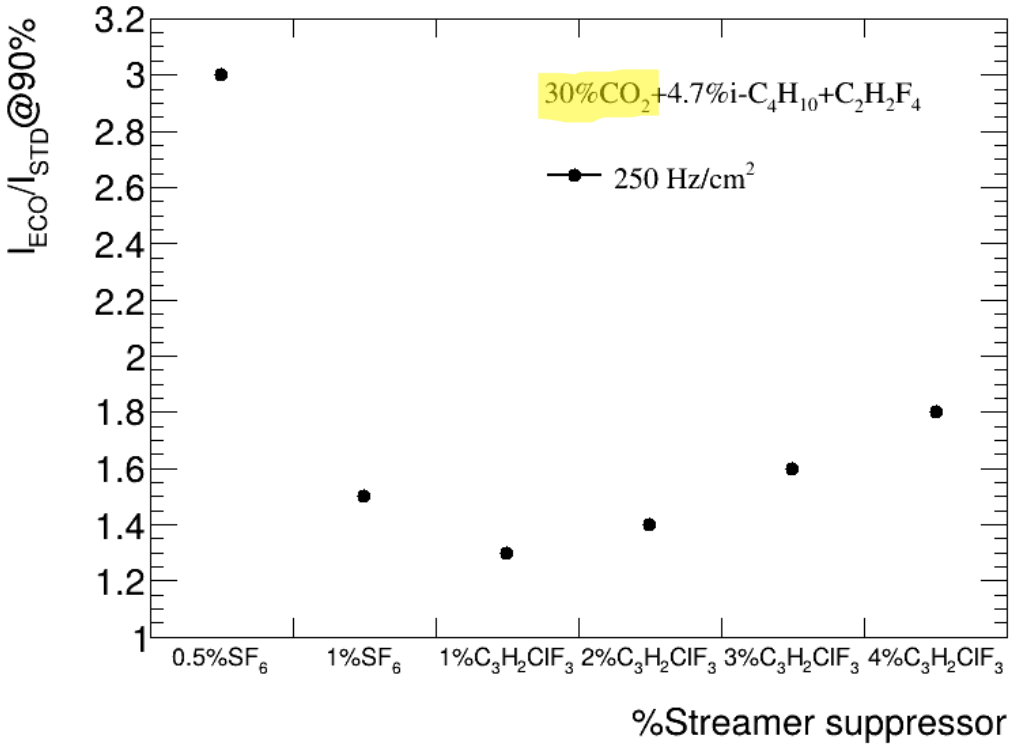
1) 253 Hz/ cm^2 : 0% for the standard gas, 1% for the other mixtures

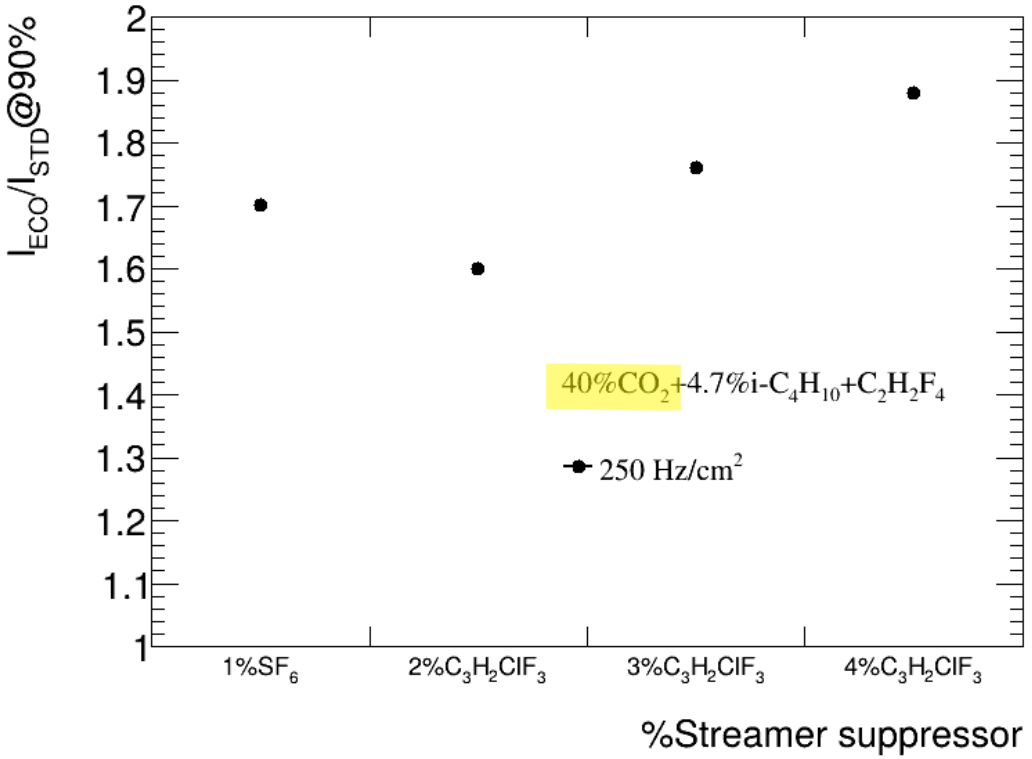
2) 448 Hz/ cm^2 : 0% for the standard gas, 2% for the other mixtures

Same results with $C_2H_2F_4/CO_2$/i-C_4H_{10}/$\underline{SF_6}$ gas mixtures (*Nucl.Instrum.Meth.A* 1066 (2024) 169580)

The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact in the efficiency

SF_6 vs $C_3H_2ClF_3$: Currents



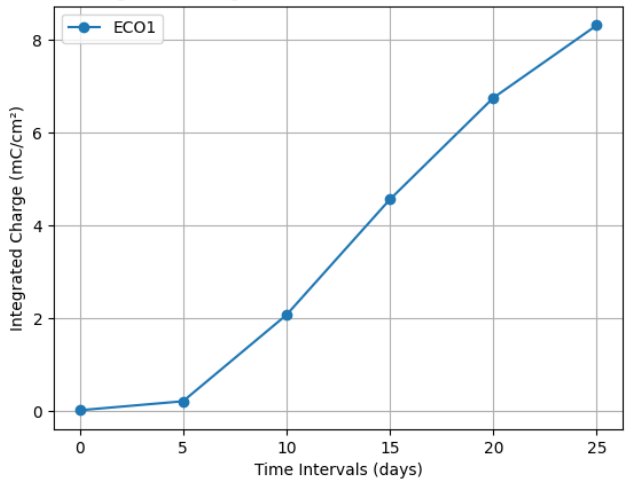


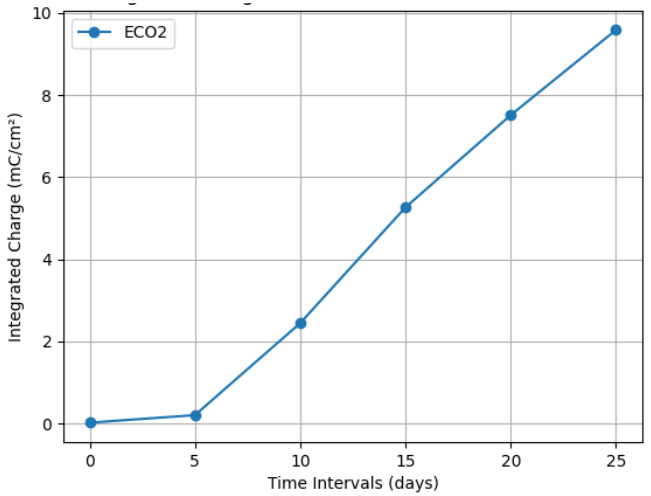
The currents are at the same order of magnitude and significantly lower wrt the 0.5% SF_6 case

The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact in the current

Aging status

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 (~ 1.2 kHz/ cm^2)

Integrated charge in 25 effective days ~ 9 mC/cm^2

Target ~ 280 mC/cm^2 (Safety Factor 3)

No increase in the current and resistivity over time observed

Currents stable in both prototypes → plan to accelerate aging and finish in ~ 6 months

Conclusions

The operation with environment friendly gas mixtures will be essential for the usage of RPC in future experiments

$C_3H_2\ ClF_3$ has been found as a replacement for SF_6

Aging studies are carried out as the final certification step for this new gas component

Operation of the RPC with a eco-friendly gas mixtures will be possible in the near future

Thank you
Questions are welcome

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

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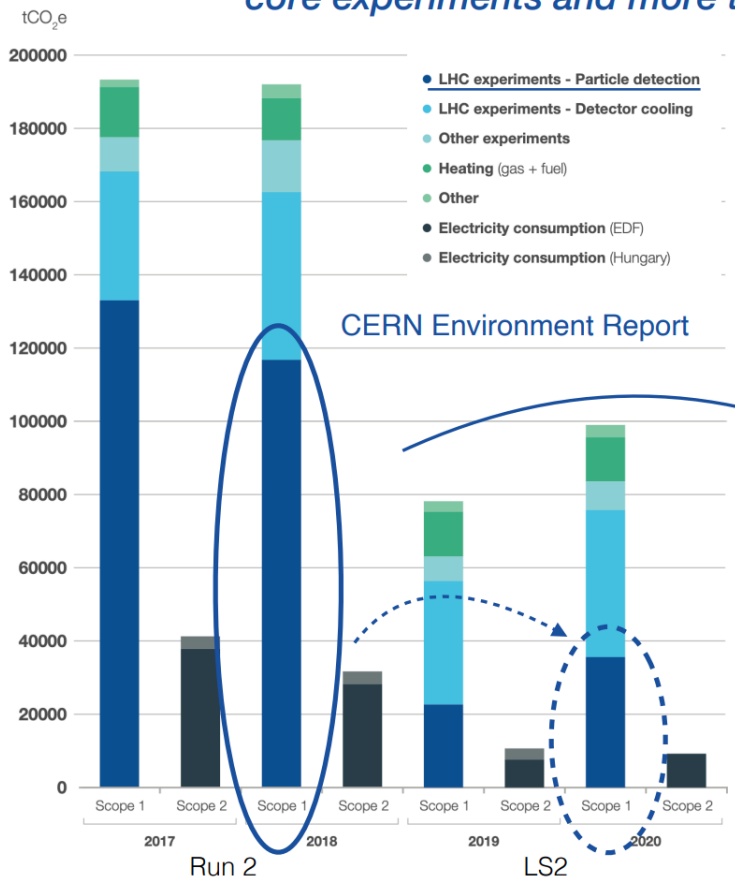
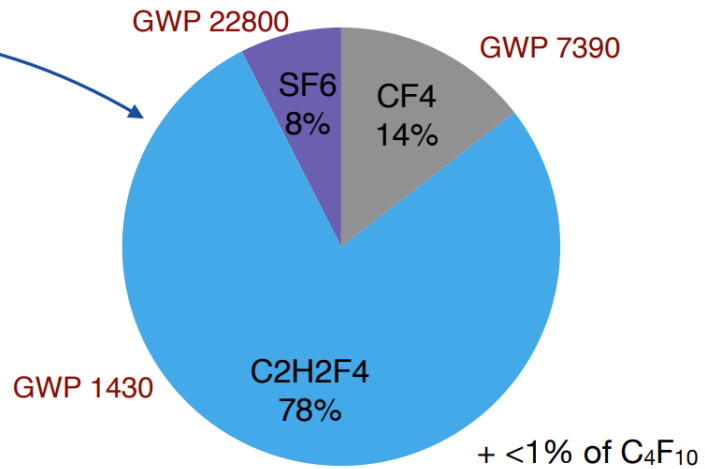
Backup

GHG emissions at CERN

Greenhouse gas emissions at CERN arise from the operation of the Laboratory's research facilities. The majority of emissions come from CERN's core experiments and more than 78% are fluorinated gases



- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection
- Drastic reduction of GHG emissions from particle detection during LS2



The CERN's objective is to reduce its scope emissions by 28% by the end of 2024

Slide taken from talk by **Beatrice Mandelli** at the 16° Pisa meeting on advanced detectors

TFE/SF6 impatc

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C2H2F4 tCO2e (2020) ~ 30.000

SF6 tCO2e (2020) ~ 3.040

Source	1 car	1 flight Vienna-Roma	Vienna underground trains	Coal power plant	Cruise
tCO2e	2	16.2	60k	3.500.000	287k

TFE impact ~ 15k cars, 2 k flights Vienna Roma, ½ Vienna underground trains etc...

SF6 impact ~ 1.5k cars, 190 flights Vienna Roma, 0.05 Vienna underground trains etc...

Results : Study of the efficiency under irradiation

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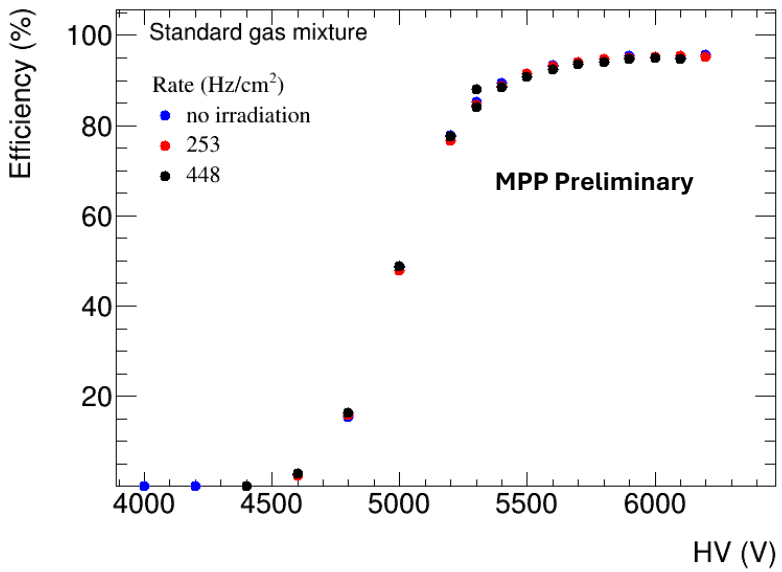
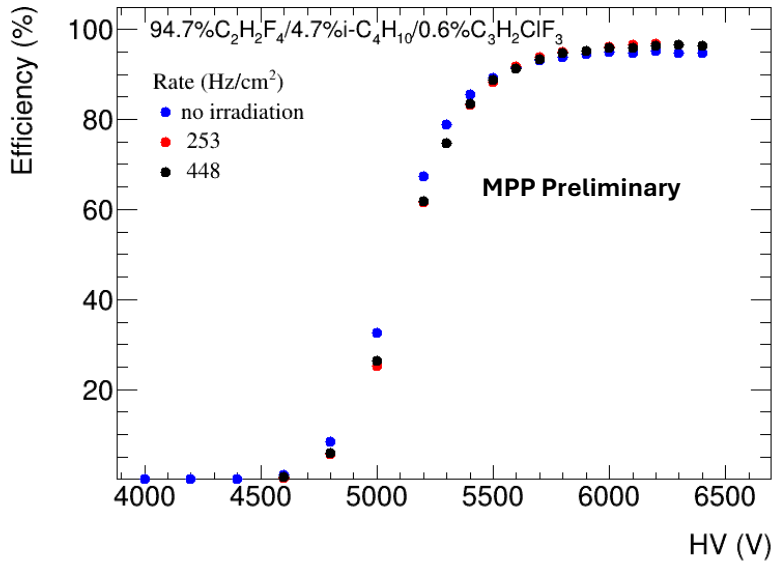
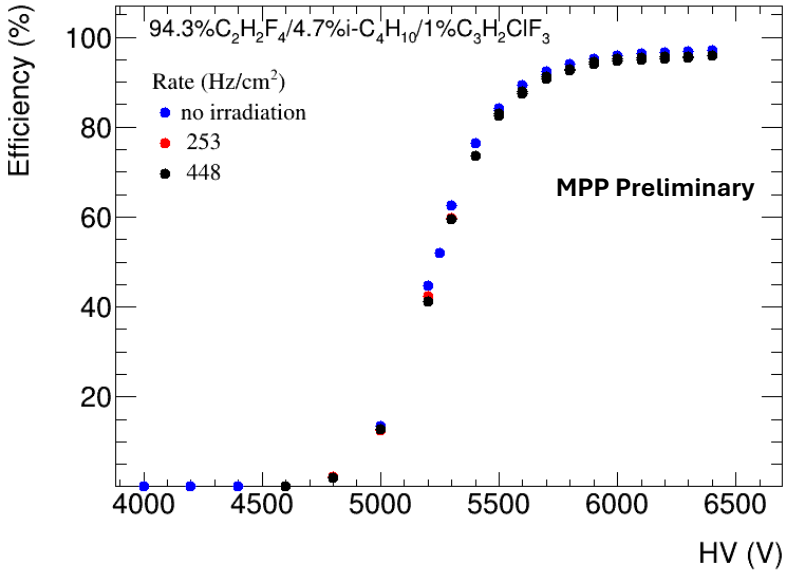
Standard gas



MIX1



MIX2



Maximum rate in ATLAS RPC during HL-LHC ~ 500 Hz/cm^2

All the curves show the same plateau efficiency at different γ-irradiation

NO efficiency loss up to 448 Hz /cm^2 →same rate capability

Current and charge distribution

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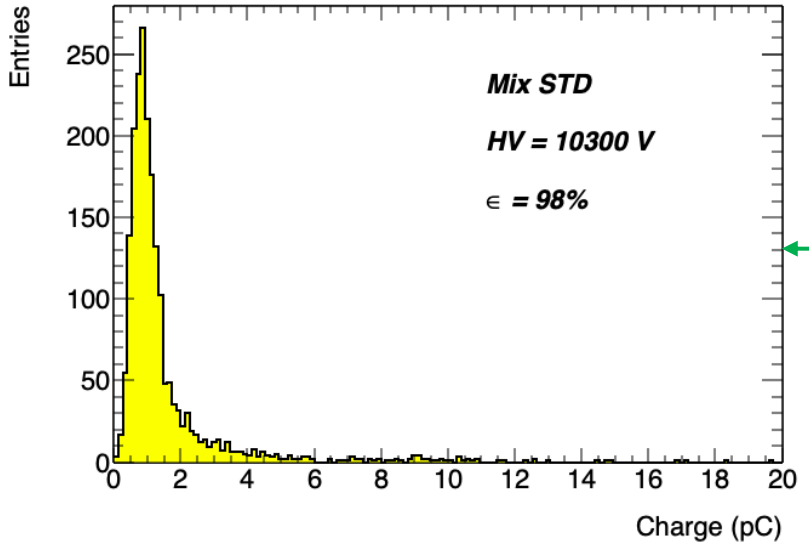
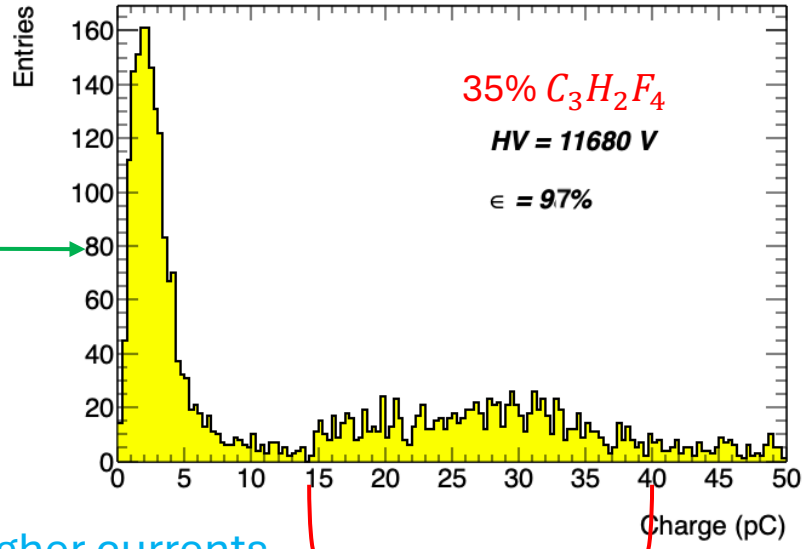
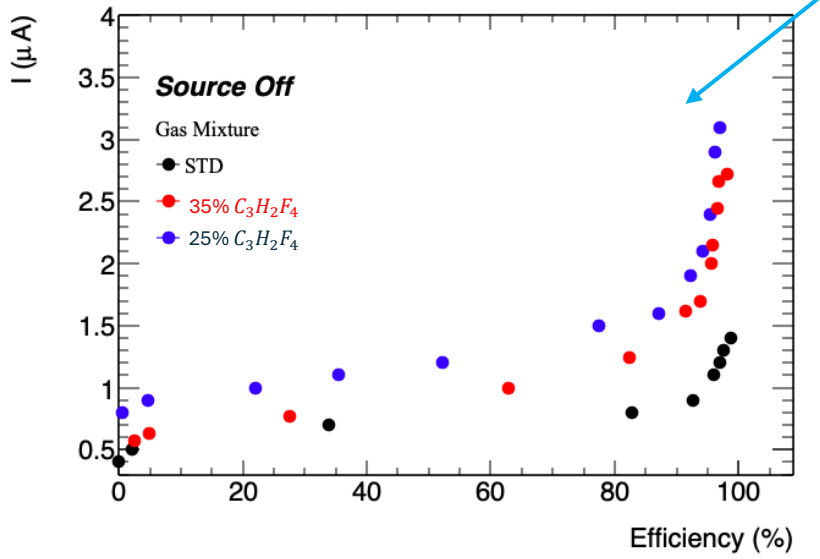
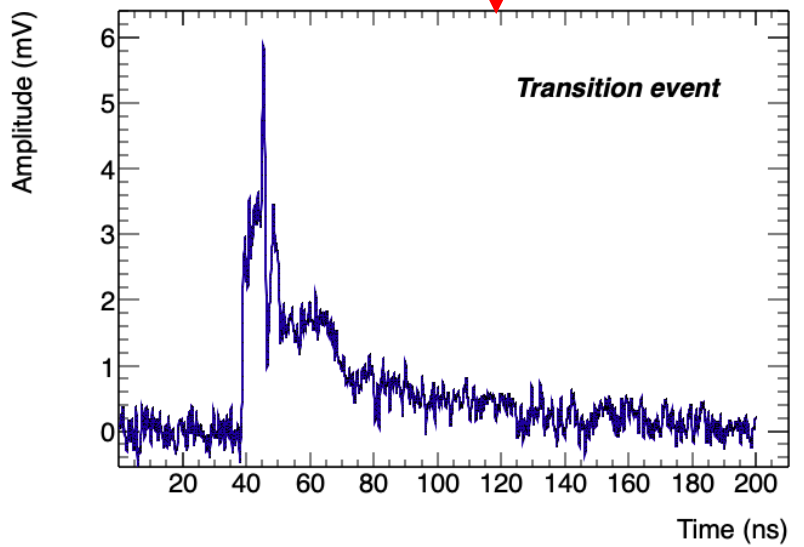
Different charge distribution @ same efficiency





Higher currents

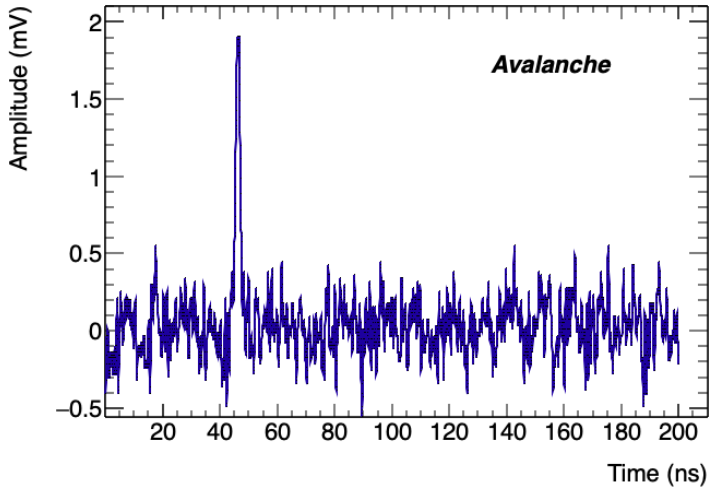


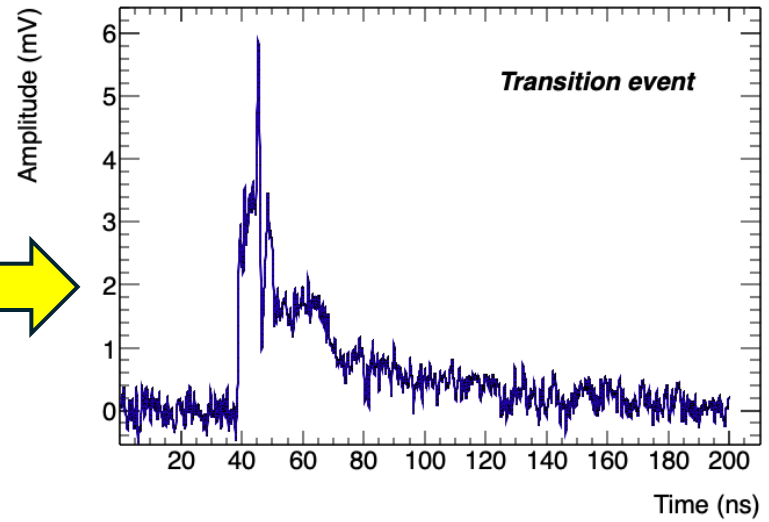


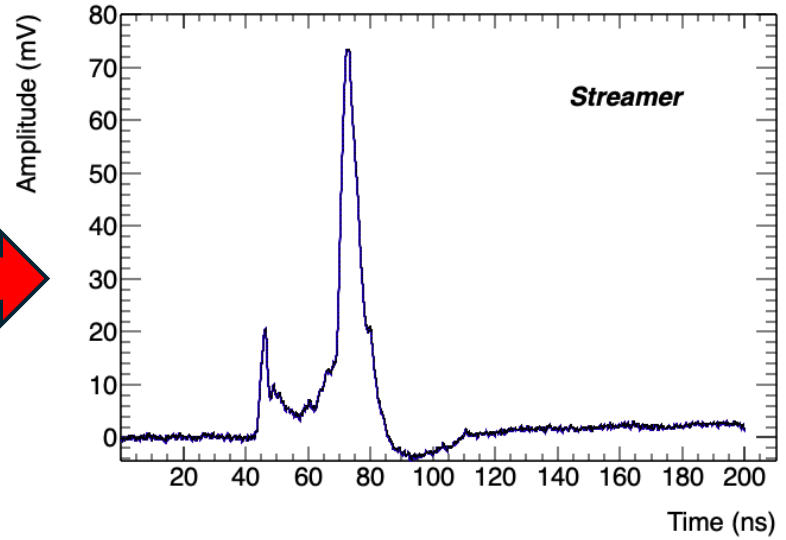
Presence of transition events at WP →Higher current →Impact on the detector aging to be defined in $CO_2/C_3H_2F_4$

Larger amount of fluorine production →impact on aging tbd

Transition events







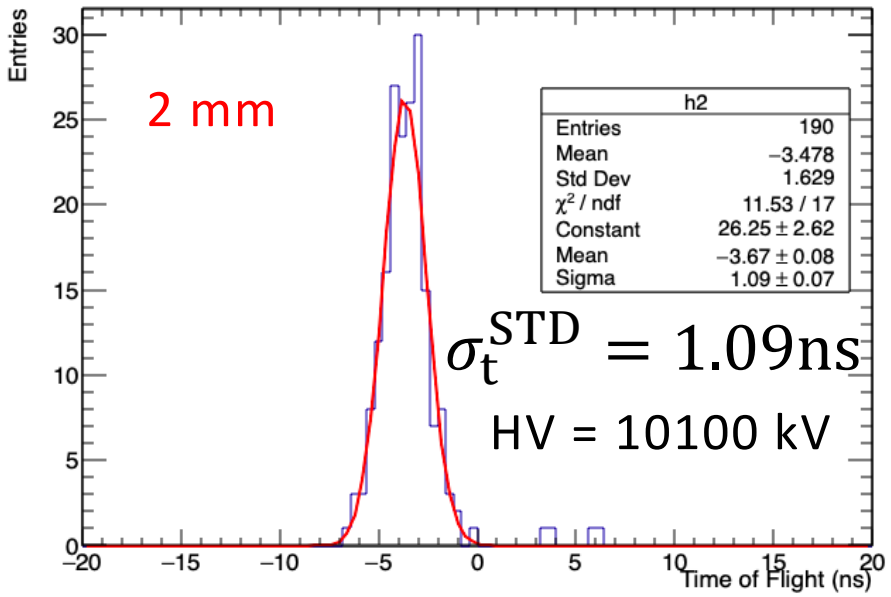
Avalanche : very short single signal (4-5 ns), low amplitude (~ mV) and low charge content (~ 1 pC)

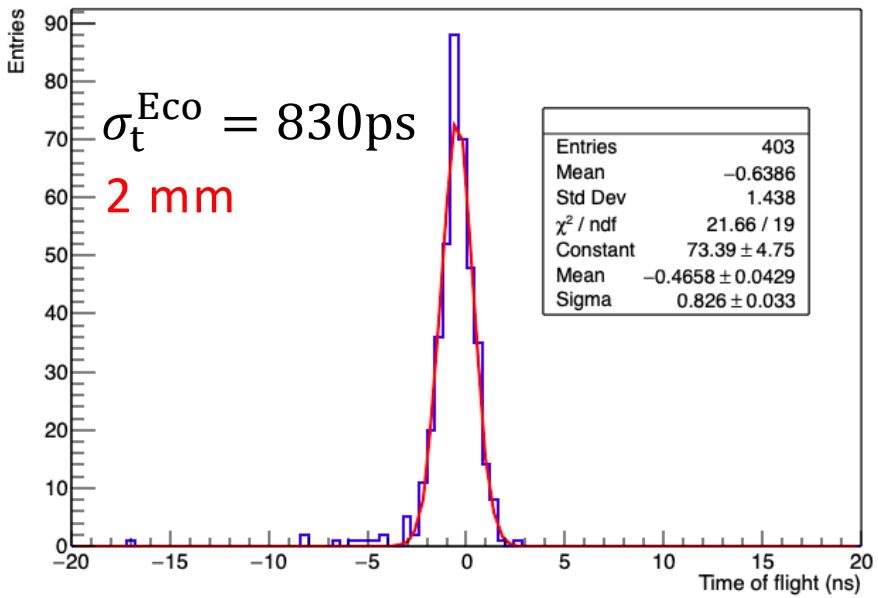
Transition signal: multiple avalanche signal and/or a large tail following the precursor

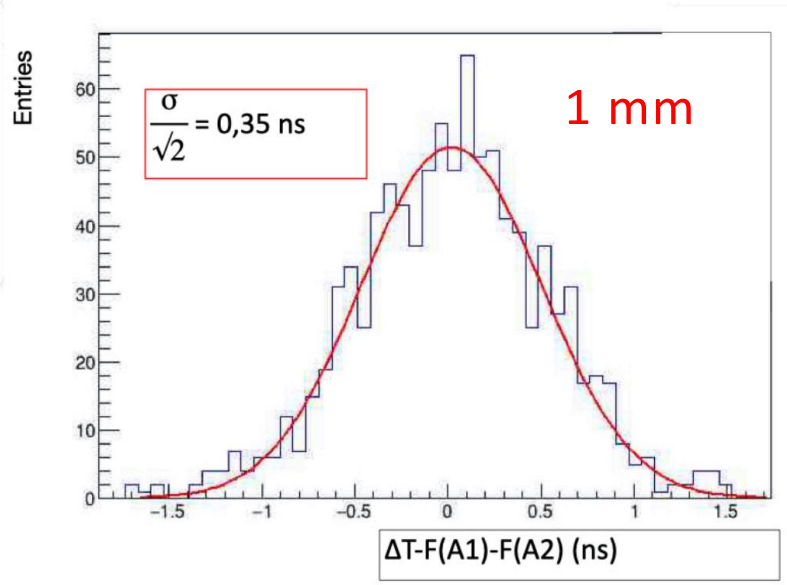
Streamer: avalanche signal precursor followed by a wide signal (~100 mV) lasting tens of ns and with a high charge content (~ 100 pC).

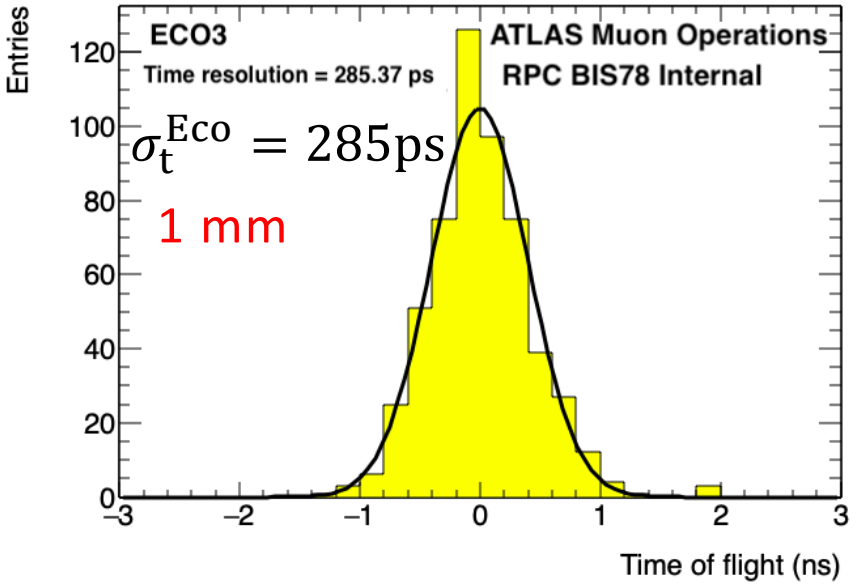
Interpretation: streamers precursor, representing those events in which the delayed avalanches don't merge together to form the streamer but they ionize the gas: the CO_2 produces many photons which produce secondary electrons that ionize the gas but are not able to trigger the streamer because they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

Time resolution









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

Option 2 : $CO_2/C_2H_2F_4$/i-C_4H_{10}/ 1% SF_6

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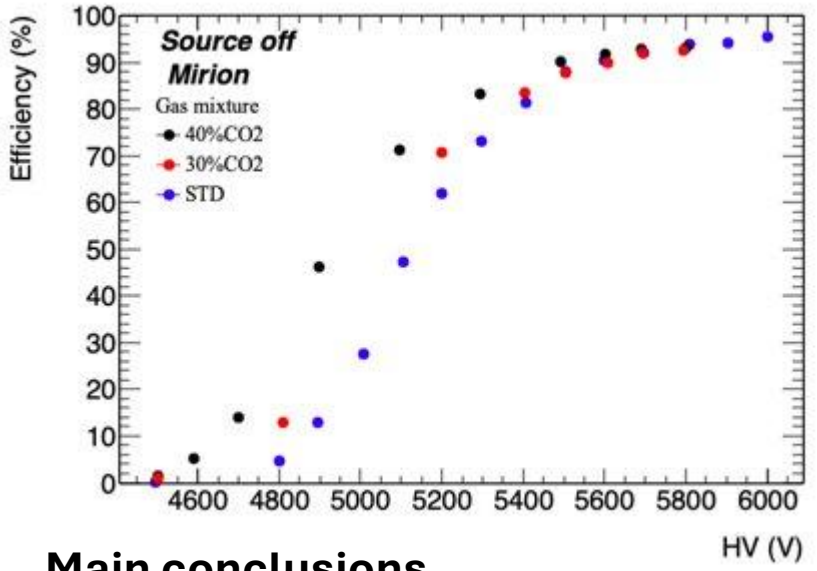
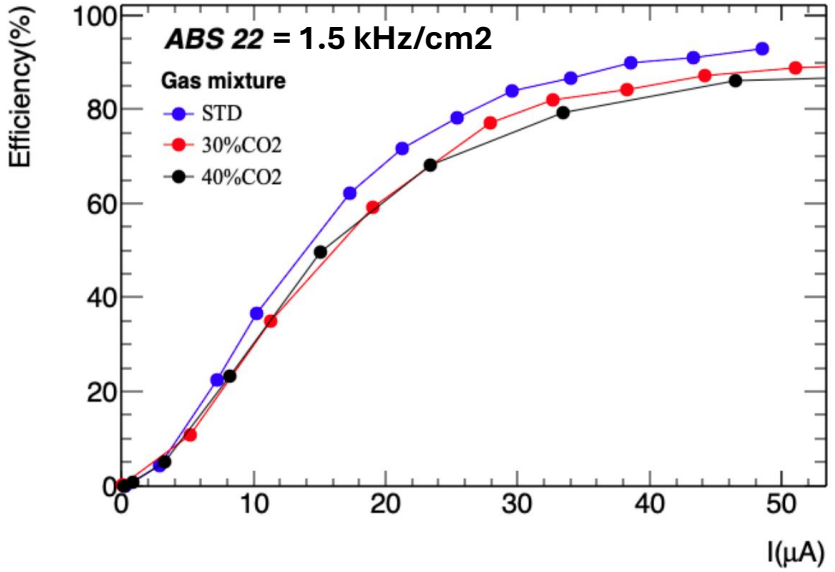
Attractive option for short term operation because →most of the mixture composition is the same → no worrying aging effect expected

Efficiency vs high-voltage



Efficiency vs current



Gas mixture studied

Standard gas mixture (No CO2)

30% CO_2 /65% $C_2H_2F_4$/4% i-C_4H_{10}/1% SF_6

40% CO_2 /55% $C_2H_2F_4$/4% i-C_4H_{10}/1% SF_6

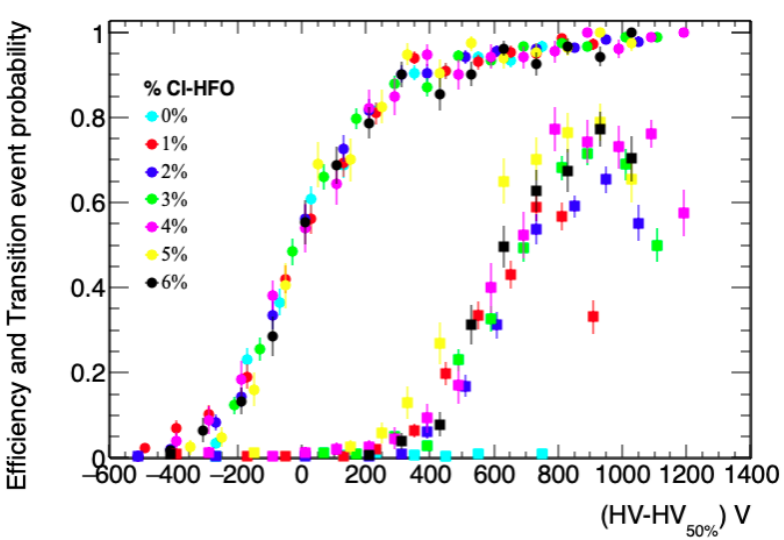
Main conclusions

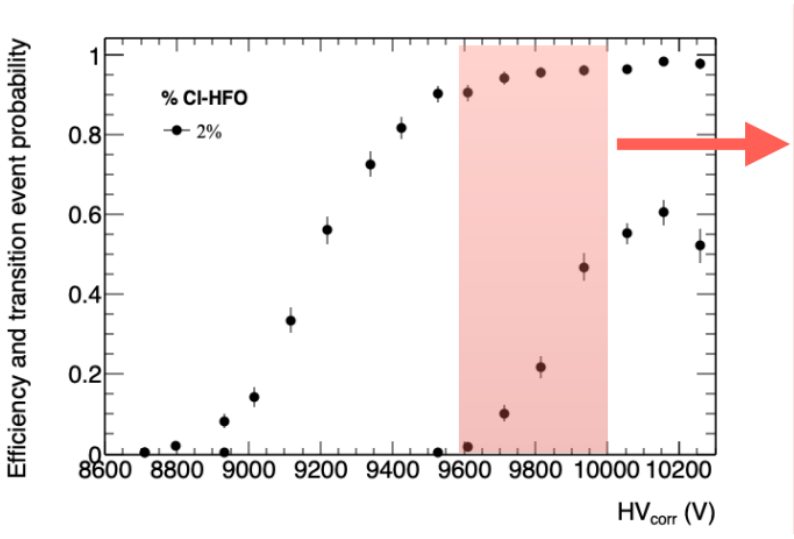
1. Current increases with the increase of CO2 :
   I(40%CO2) ~ 1.7 I(NO CO2)
   I(30%CO2)~1.5 I(NO CO2)

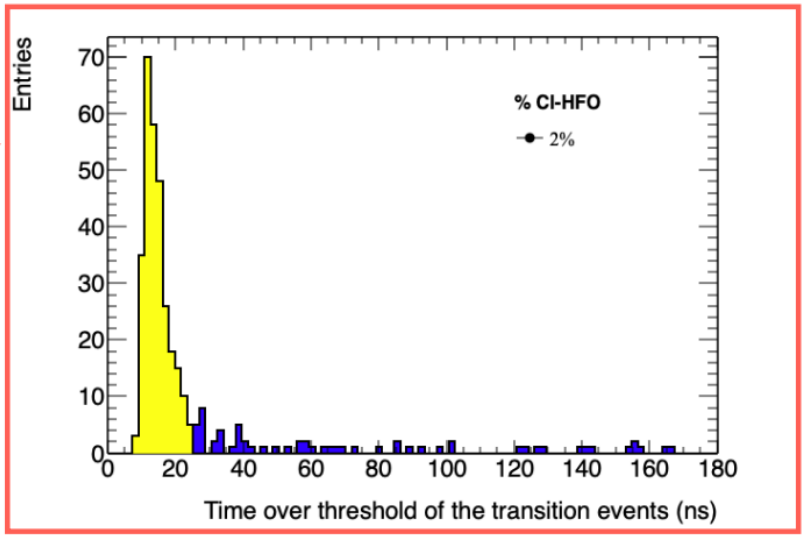
2. The maximum efficiency measured with the standard gas with no irradiation is 2% and 3% higher with respect to the mixtures containing 30%CO_2 and 40%CO_2 respectively

Best option : gas mixture with 30% CO_2
ATLAS legacy RPC are running with this gas mixture from 1 year

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : impact on the performance of the transition events

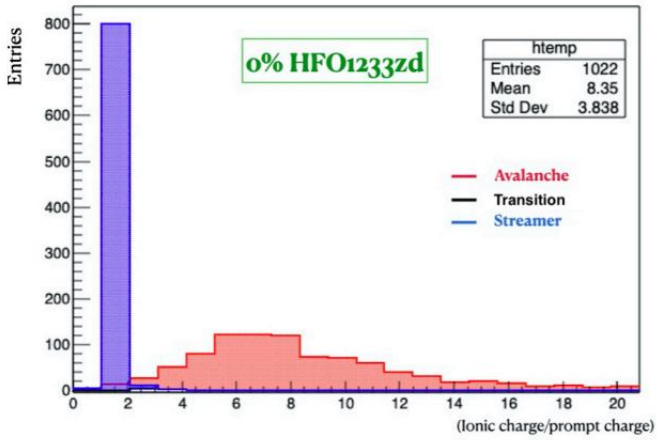


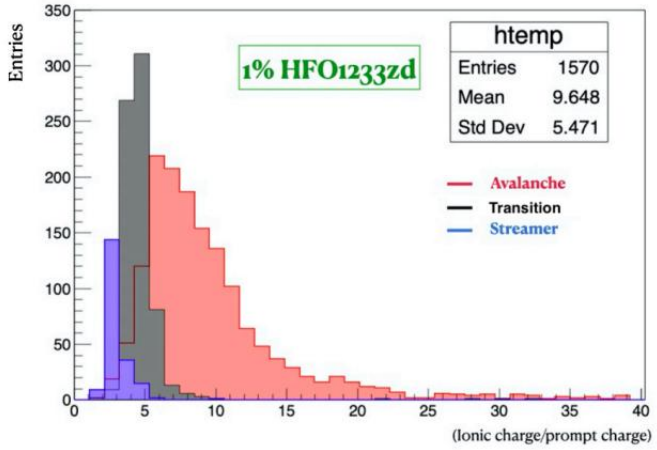


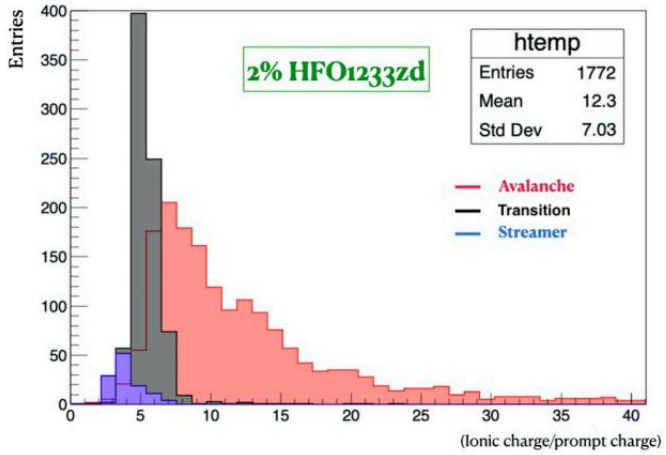


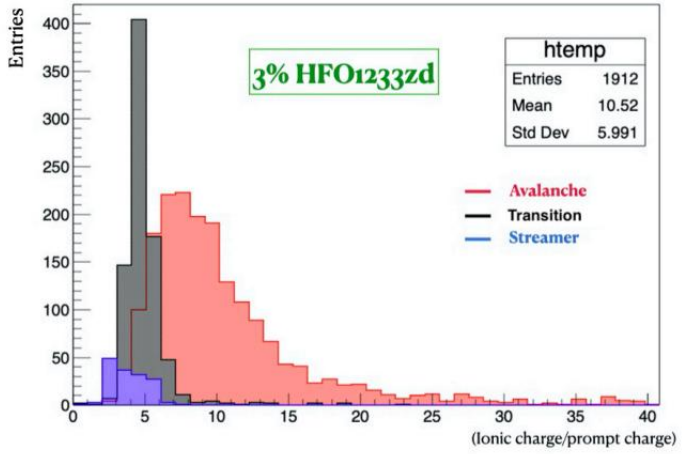
- The transition event probability decreases when streamers start to appear;
- The transition event are less than 20% at the operating voltage for all gas mixtures;
- The time over threshold of transition events is less than 25 ns.

Ionic to prompt charge ratio









Avalanche (Q/q) ~ 8-12

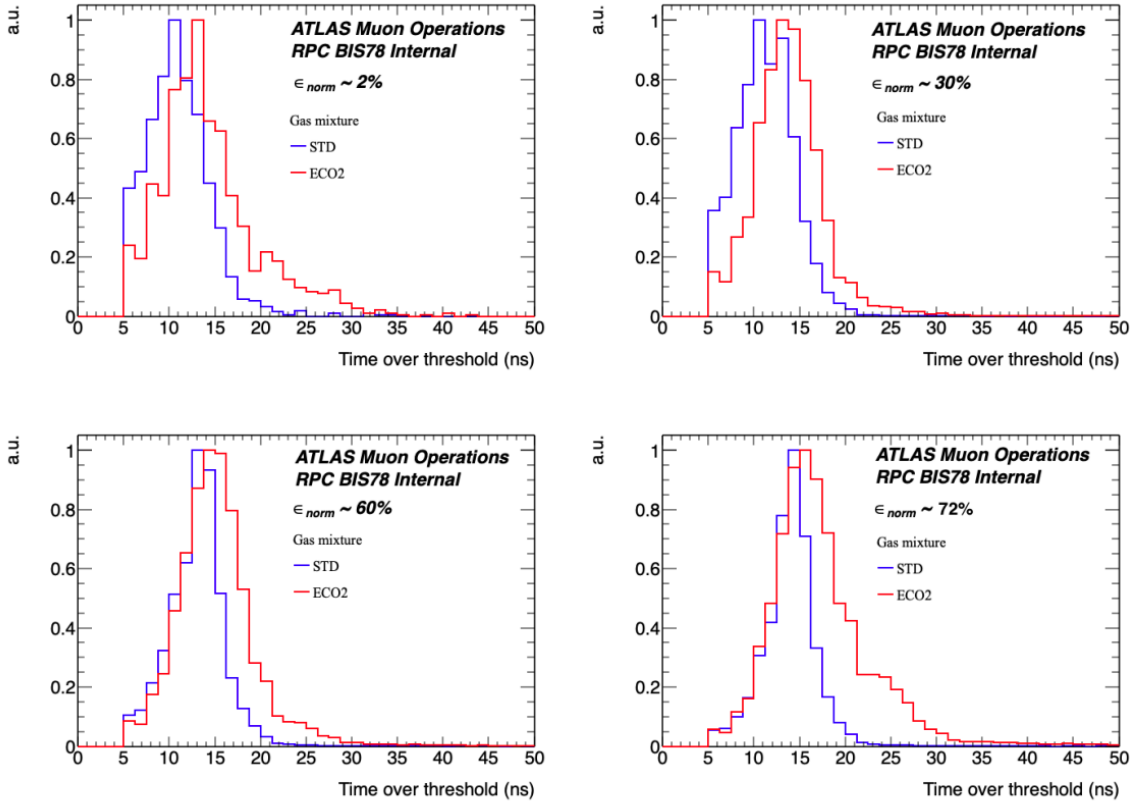
Streamer (Q/q) ~ 1.5

Transition (Q/q) ~ 5

Avalanche, transition events and streamers belong to different categories of signals

Prompt charge study

Evolution of the avalanche as a function of the efficiency

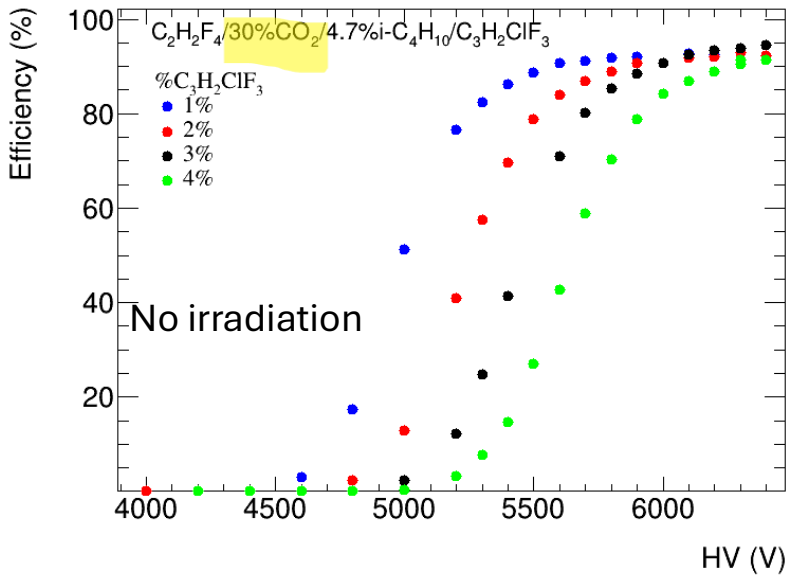


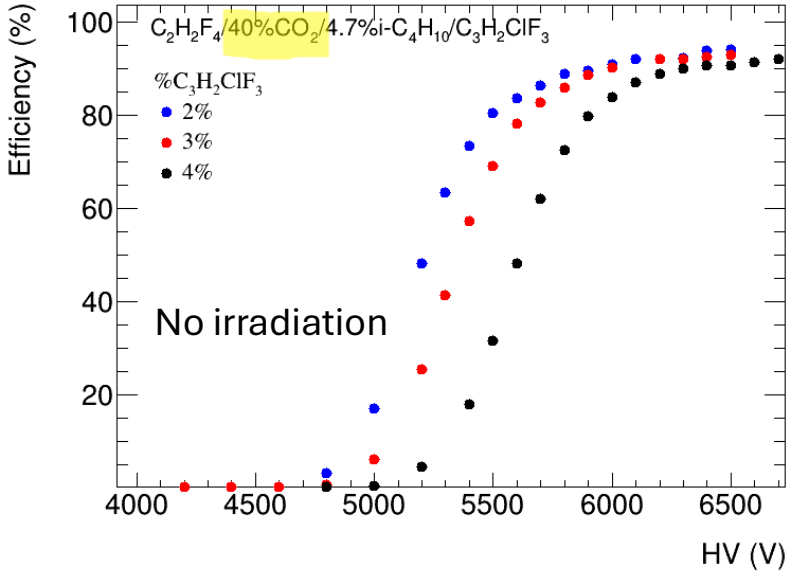
The time over threshold is proportional to the injected charge

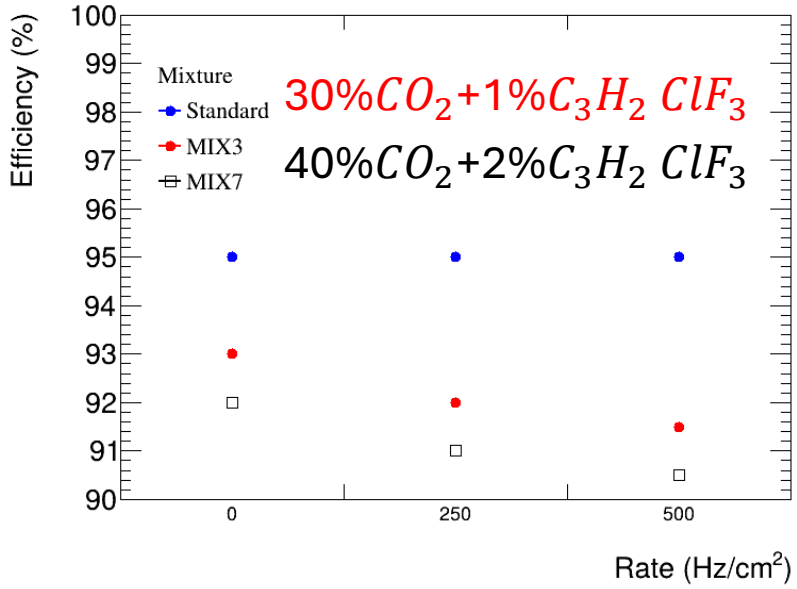
The charge distributions of ECO2 and STD gas mixtures have been compared at the same normalized efficiency in order to study the saturated avalanche model

- The STD gas mixture shows a higher shoulder at the lowest distribution end of low efficiency distributions, disappearing at higher field.
- Earlier saturation with the CO2, creating higher density avalanches
- The tail of the distribution observed with ECO2 is due to higher charge events (transition events)

$C_2H_2F_2$ / CO_2 / i-C_4H_{10} / $C_3H_2ClF_3$: Efficiency







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