Performance of new generation of Resistive Plate Chambers operating with alternative gas mixtures

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3rd International Conference on Detector Stability and Aging Phenomena

Outline

- The RPC in the ATLAS experiment (LHC and HL-LHC)
- Search of an environment friendly gas mixture : performance and aging
- TFE and SF6 substitute
  - Results with cosmic rays on a 2 mm gas gap
  - Results under photon irradiation on a 2 mm and 1 mm gas gap RPCs

The Resistive Plate Chambers (RPC) in the ATLAS experiment

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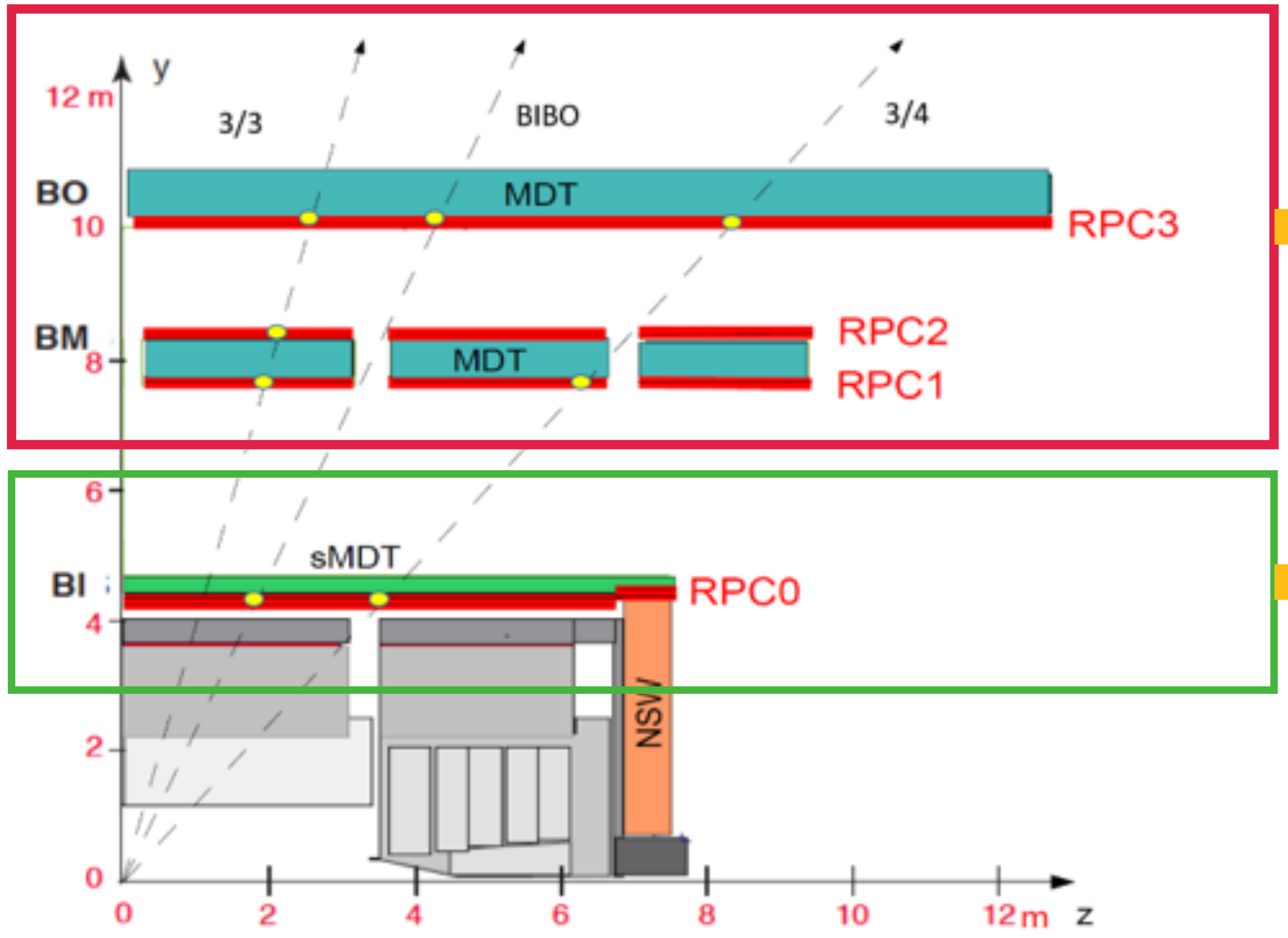
In the ATLAS experiment the RPCs are used for triggering on muons, due to their excellent timing performance and low-cost material



"Legacy system"

Phase-2 upgrade system for the high luminosity phase (BIS78/BI projects)

ATLAS BIS78/BI vs ATLAS legacy

- Triplet structure vs doublet configuration allows to use these detectors as a stand-alone trigger
- Thinner gas gap (1 mm vs 2 mm) and electrodes (1.3 mm vs 1.8 mm)
- Improved time resolution (0.4 ns vs 1 ns)
- Improved FE electronics with lower threshold (1-6 fC) leading to a better rate capability
- Same readout (2D orthogonal) for legacy and BIS78 type, while a (η-η) readout has been chosen for the BI RPC leading to the possibility to measure the second coordinate

Requirements: good performance, rate capability and long term operation → Saturated avalanche working mode

Operating RPC in avalanche mode with the "standard" gas mixture

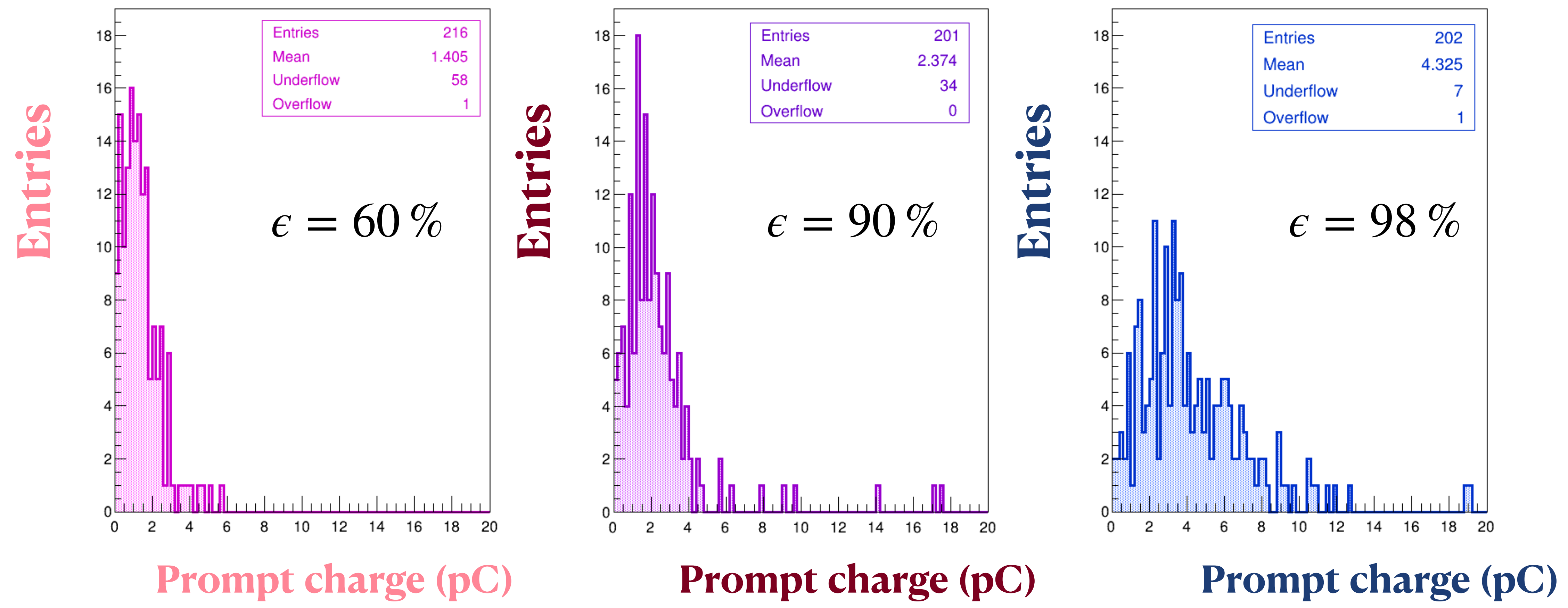
The standard gas mixture is composed of
94.7%$C_2H_2F_4$(TFE)/5%I-C_4H_{10}/0.3%SF_6

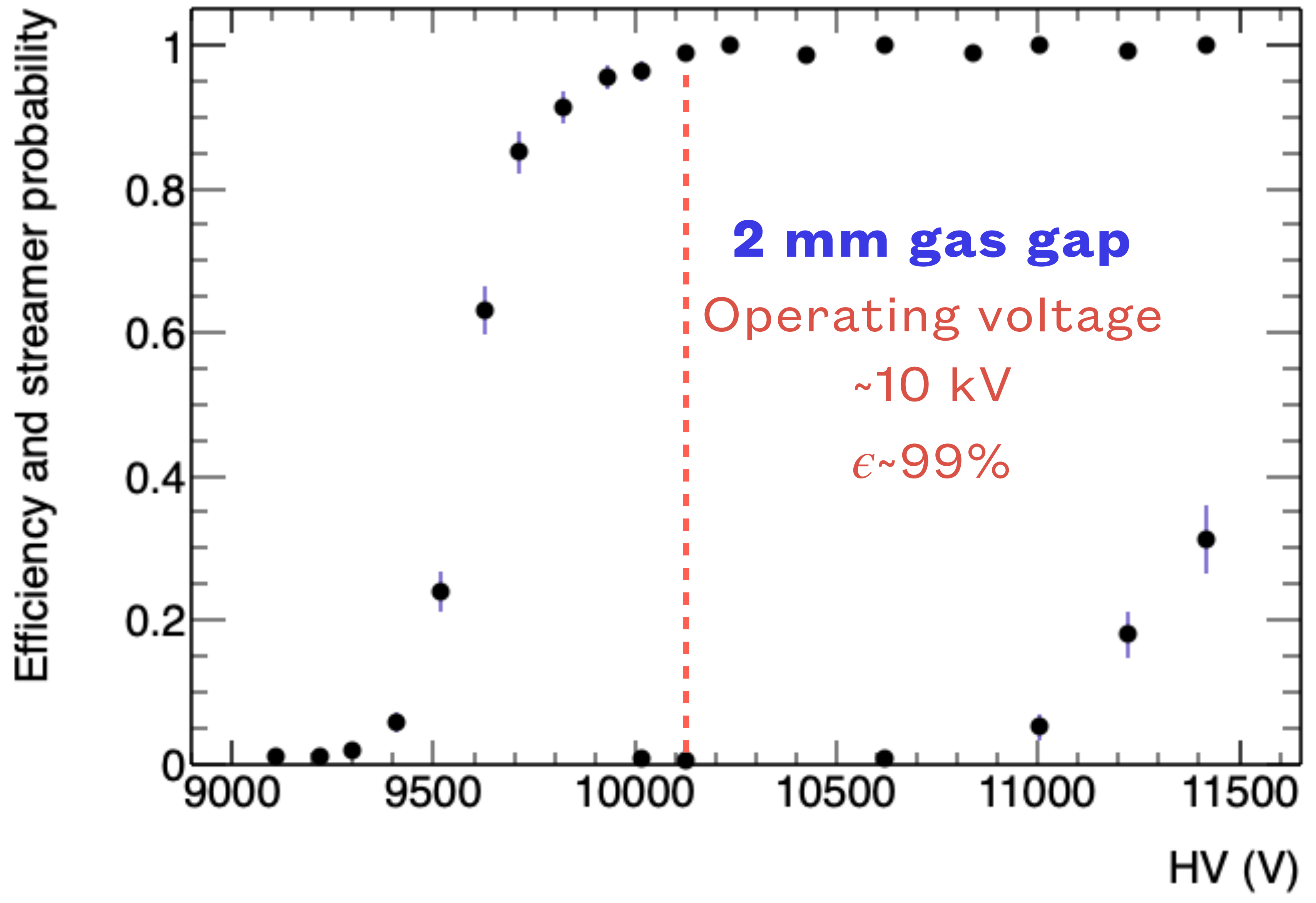
Primary target — $C_2H_2F_4$

"Quencher" — I-C_4H_{10}

Streamer suppressor — SF_6

- High gas density ensuring sufficient primary ionization even for gas gaps in the millimeter range size;
- Prompt charge slowly increasing with the applied voltage and high enough to overcome the FE threshold;
- Total delivered charge, dominated by the ionic charge, low enough to ensure modest working current and good rate capability;
- Comfortable avalanche-streamer separation
- Non-flammable and made of industrial components





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Search of an environment-friendly gas mixture

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

- $C_2H_2F_4$ + i-C_4H_{10} + SF_6 → **GWP ~ 1450**

The European Union regulations 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 most of the CERN particle detectors greenhouse gas emission

↓

CERN is pursuing a campaign toward the reduction of the greenhouse gas emission of ~ 30% with the aim of substitute these gas components in RPC detectors

Search of an environment-friendly gas mixture

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Strategy

- Substitution/reduction of the TFE (**more critical**)
- Substitution/reduction of the SF6

Goal : Low GWP gas mixture with high performance (similar to the STD one) with no critical aging impact

Long term and performance

ATLAS experience taught us that the RPC didn't show aging effect

- Gas flux and humidity
- Low current —> operating RPC in avalanche mode (low charge signals)
- Minimize the production of F^{-} radicals

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Long term and performance

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Gas 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 F^{-} production → Reduce the probability to damage surfaces
- non flammable, no toxic → Fullfill experiments safety requirements

Detector parameters

- Gas gap width : the thinner the gas gap , the higher the density of the gas to achieve good plateau efficiency
- FE electronics threshold: possibility to compensate the F^{-} production by working at lower field, thus current, thanks to low-threshold FE electronics
- Materials and manufacturing

Substitution of the Tetrafluoroethane

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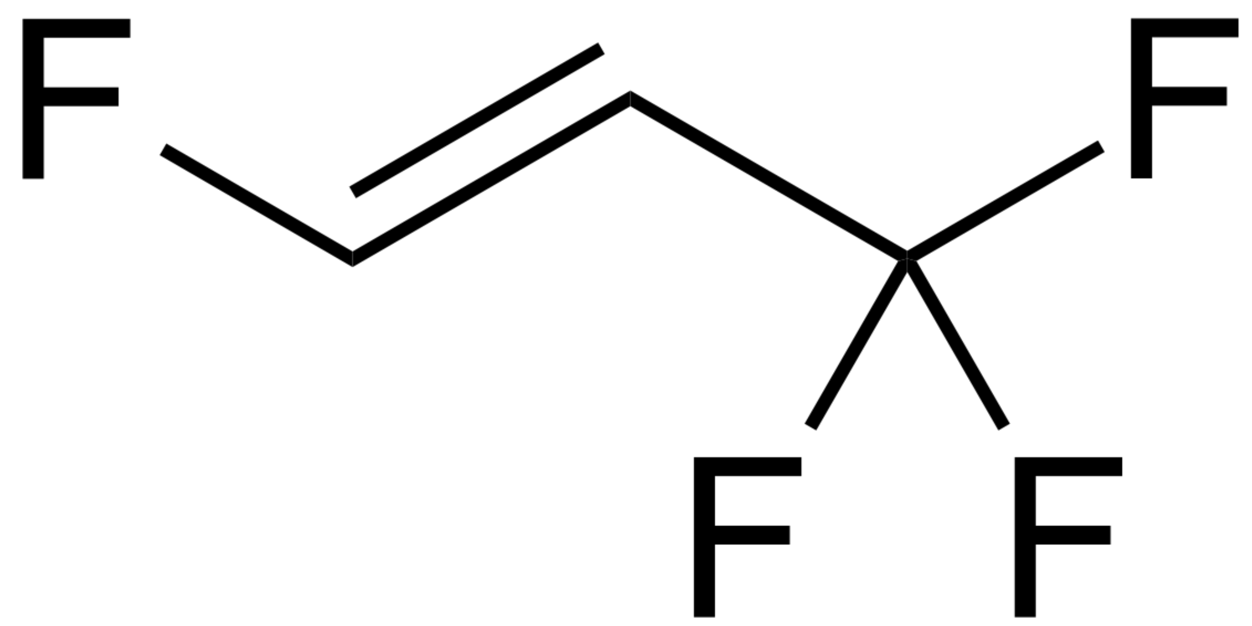
1) Substitute $C_2H_2F_4$ with an environment-friendly gas mixture

- CO_2 / $C_3H_2F_4$ **(HFO1234ze)** + i-C_4H_{10} + SF_6 → **GWP ~ 200**



1. A high-density gas is needed to ensure high particle detection efficiency → HFO concentration as high as possible

2. Low currents and low fluorine molecules are required to ensure long term operation → HFO concentration as low as possible

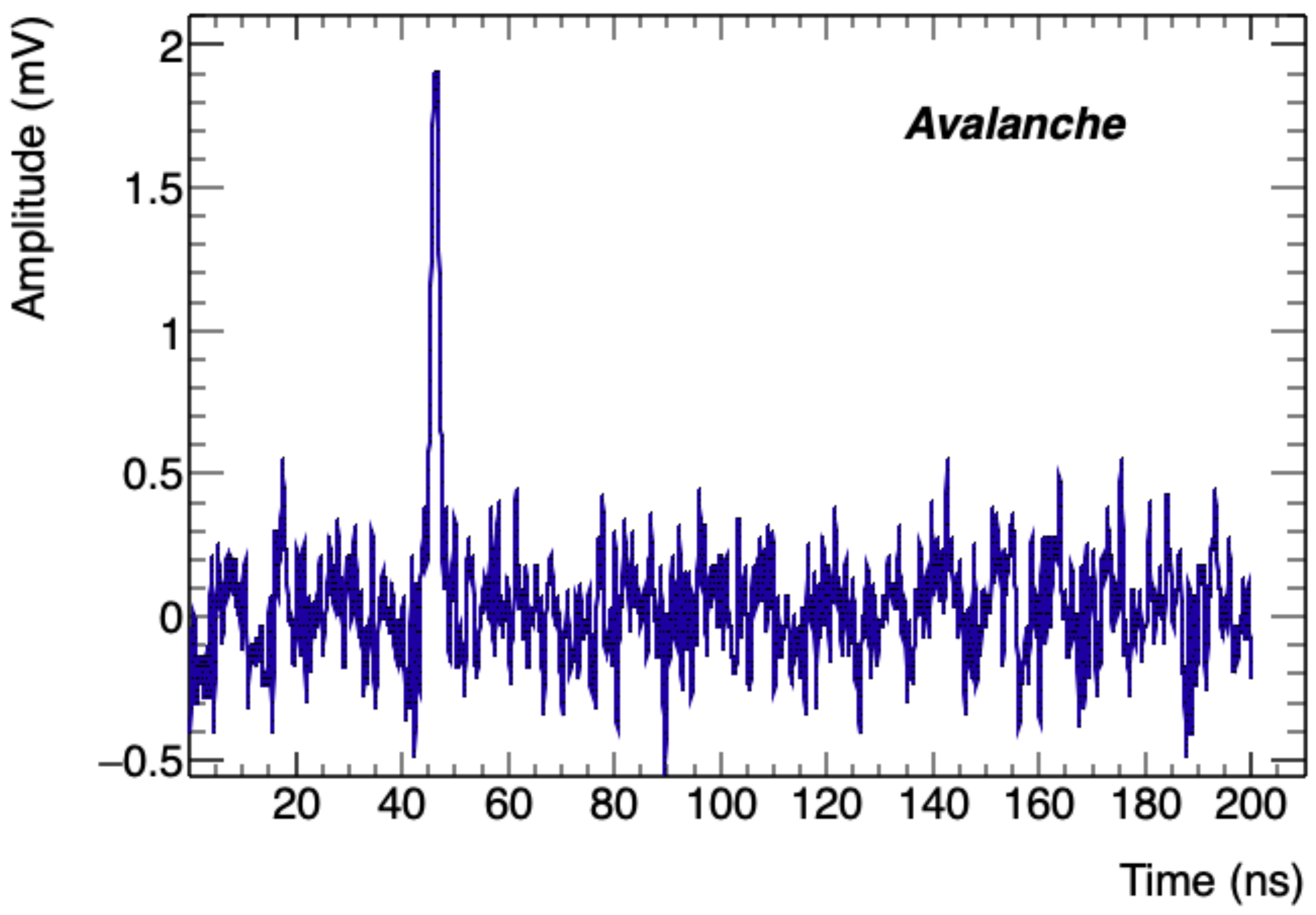
2) Reduction of the $C_2H_2F_4$ concentration introducing the CO_2:

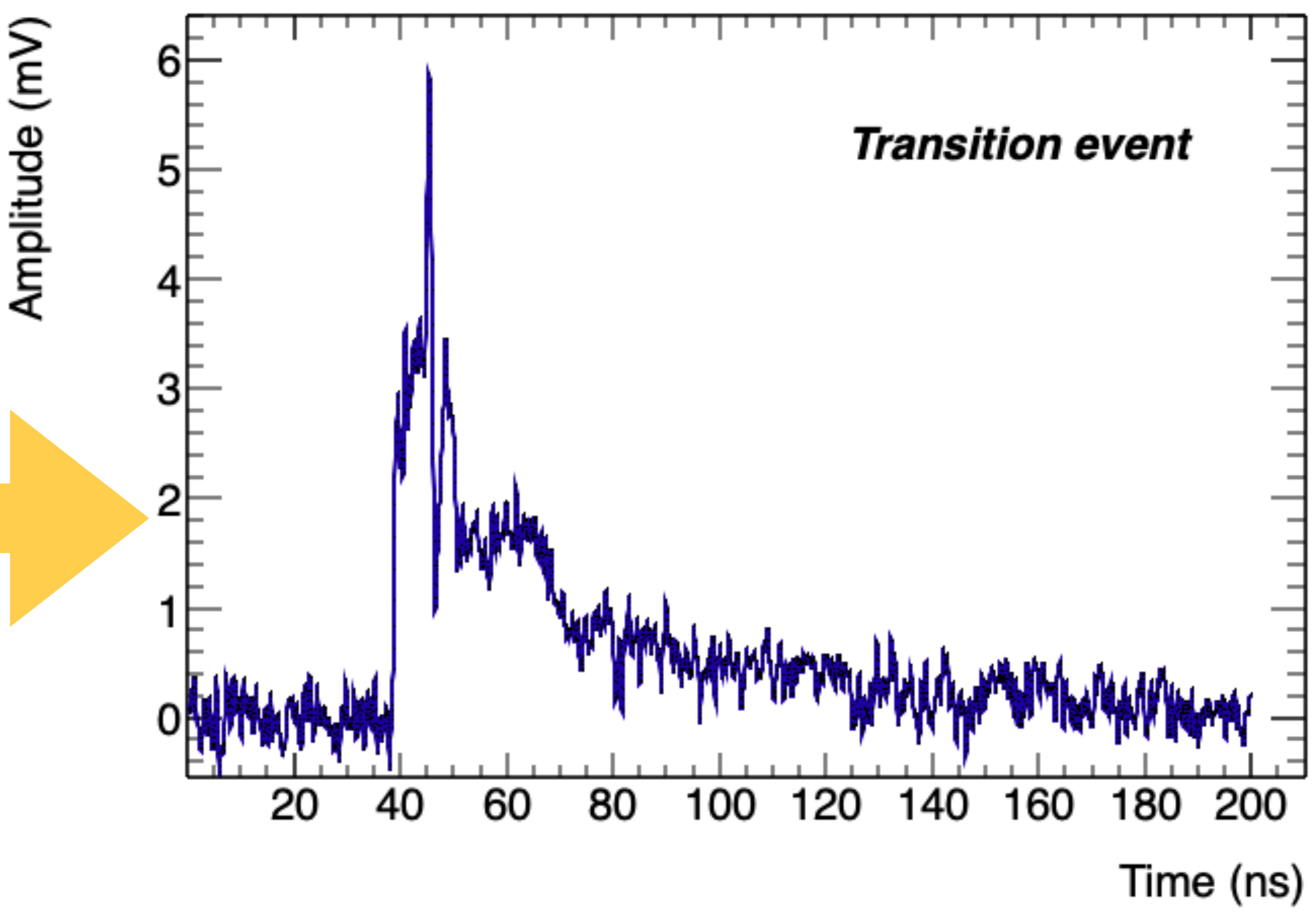
- CO_2 / $C_2H_2F_4$ + i-C_4H_{10} + SF_6 → **GWP ~ (1017 -1162) for the CO2 concentrations under study**

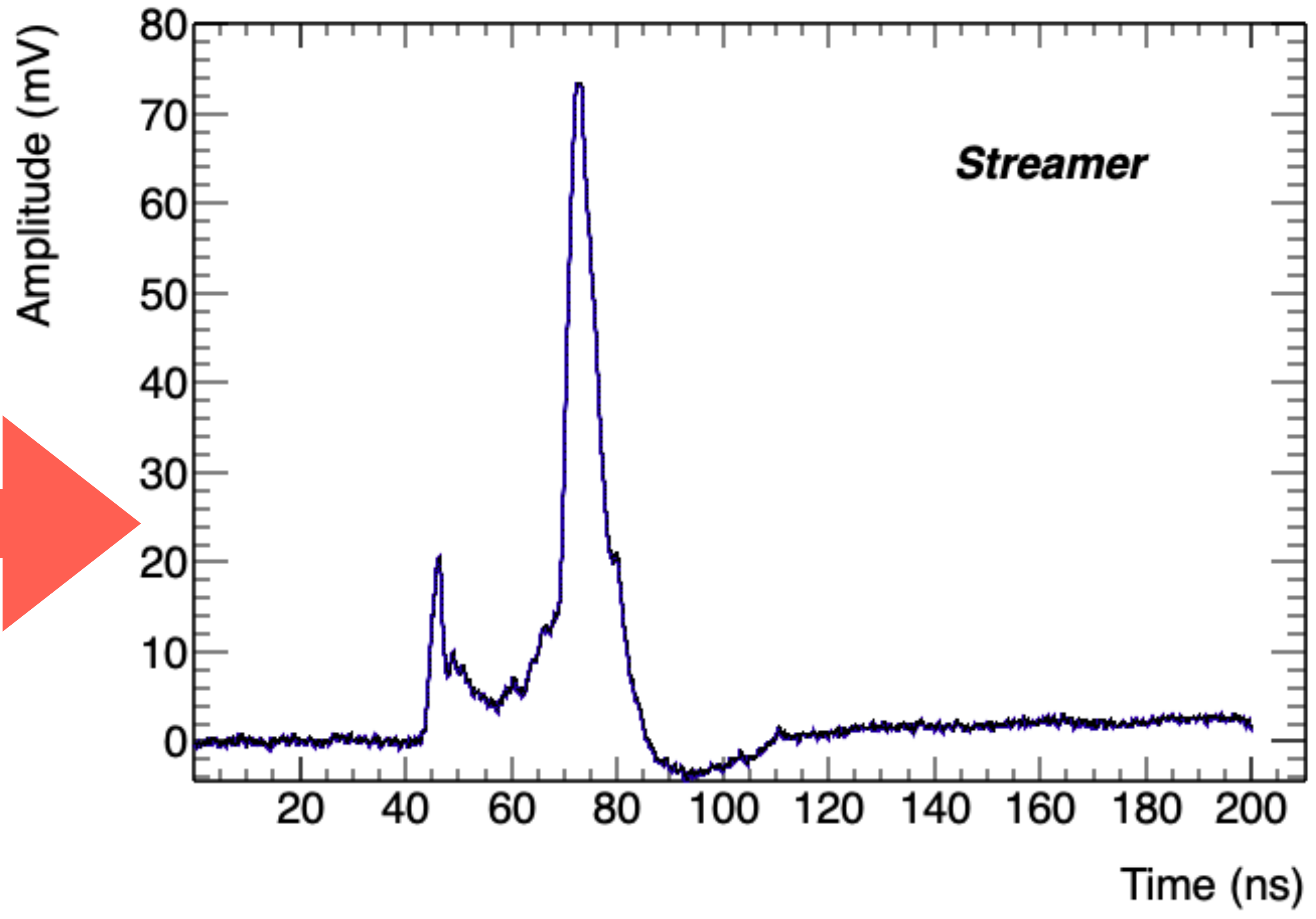
1. No large impact expected on aging in terms of fluorine production

2. Higher GWP

Working with CO2 : the transition events







- Avalanche : very short single signal
- Transition signal: multiple avalanche signal and/or a large tail following the precursor
- Streamer: avalanche signal precursor followed by a signal lasting tens of ns.

The transition events are negligible with the standard gas mixture but relevant in the new HFO/CO_2 gas mixtures.

Interpreted as streamers precursor: the delayed avalanche don't merge together and don't trigger the streamer

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Substitution of the Tetrafluoroethane with HFO1234ze/CO2 :results

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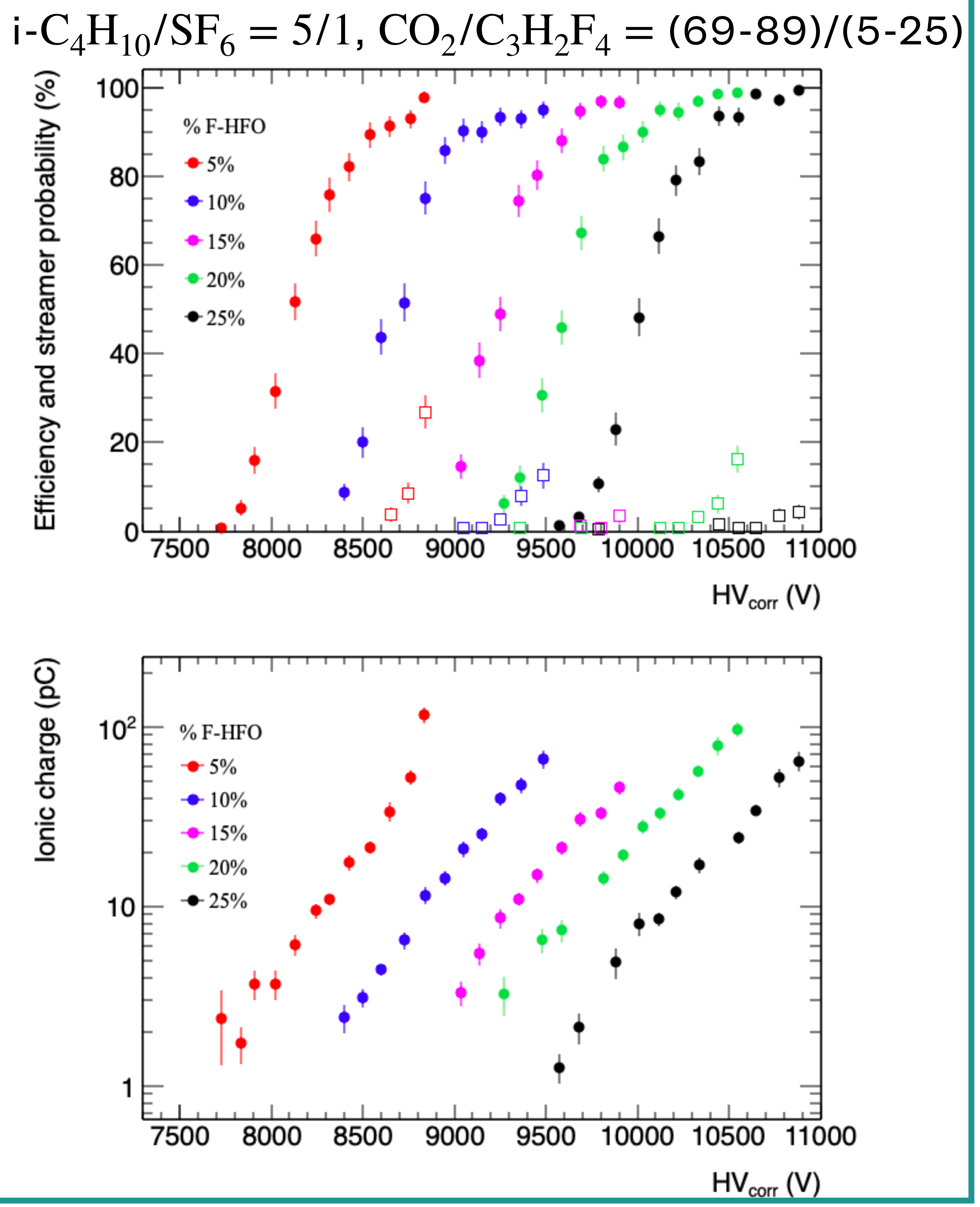

Test with cosmic rays (Rome2 laboratory) on a 2 mm gas gap + 1.8 mm electrodes thick ("ATLAS legacy"-like) with small dimensions. 1 read-out strip and no FE electronics

Goal : RPC performance as a function of the HFO1234ze (F-HFO)/CO_2 fraction

Main conclusions

- The detection efficiency is at least 93% for %F-HFO>10;
- The performances are degraded in terms of charge and avalanche streamer separation for %F-HFO <15%;
- The separation between avalanche and streamer mode is ~ 400 V for all gas mixtures with %F-HFO>15.
- Same trend of the ionic charge for %F-HFO>15%

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Test under irradiation at the Gamma Irradiation Facility

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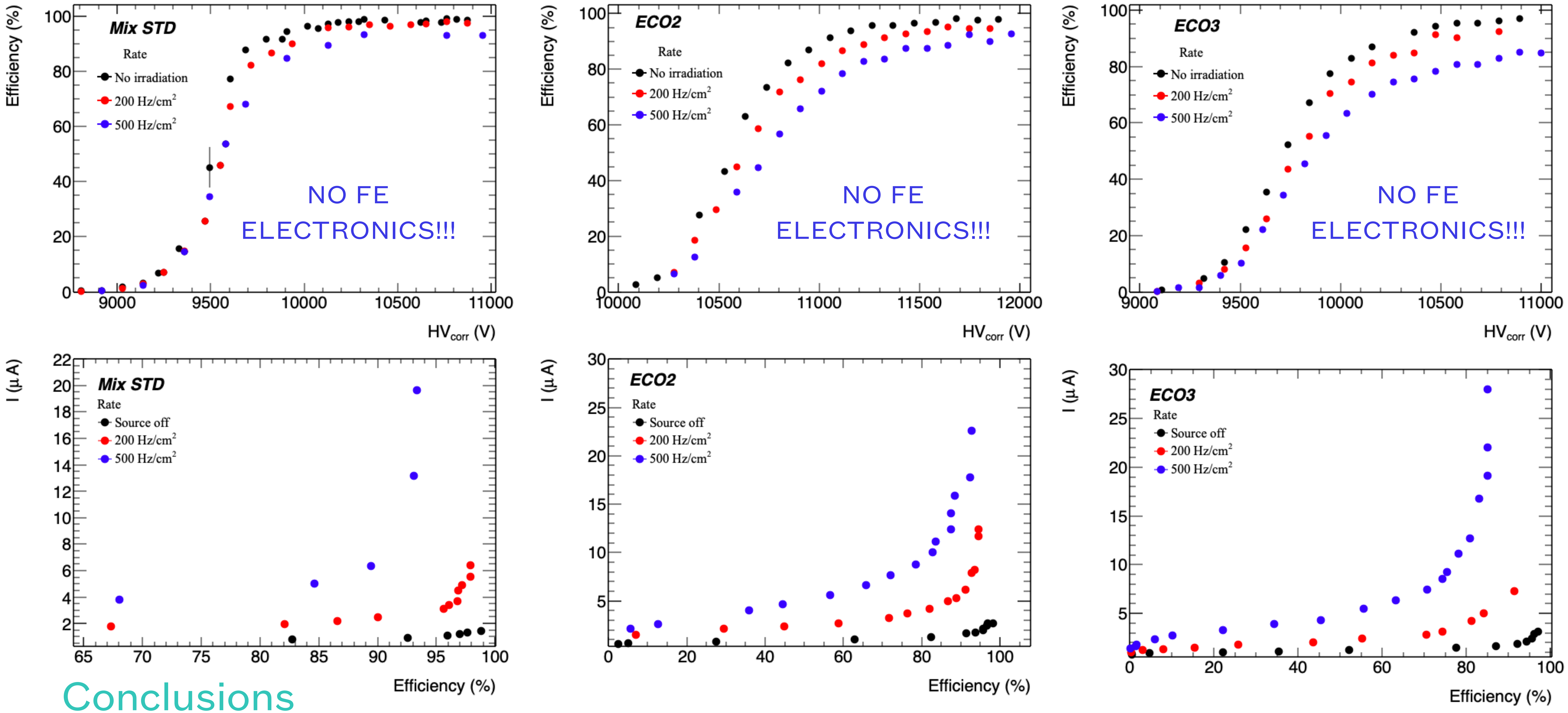
ECO2 = 35%HFO/60%CO2/4%ISO/1%SF6

ECO3 = 25%HFO/70%CO2/4%ISO/1%SF6



No irradiation

$I_{90\%}^{ECO3}$~1.2 $I_{90\%}^{ECO2}$~2 $I_{90\%}^{STD}$

200 Hz/cm^2

$I_{90\%}^{ECO3}$~1.2 $I_{90\%}^{ECO2}$~3 $I_{90\%}^{STD}$

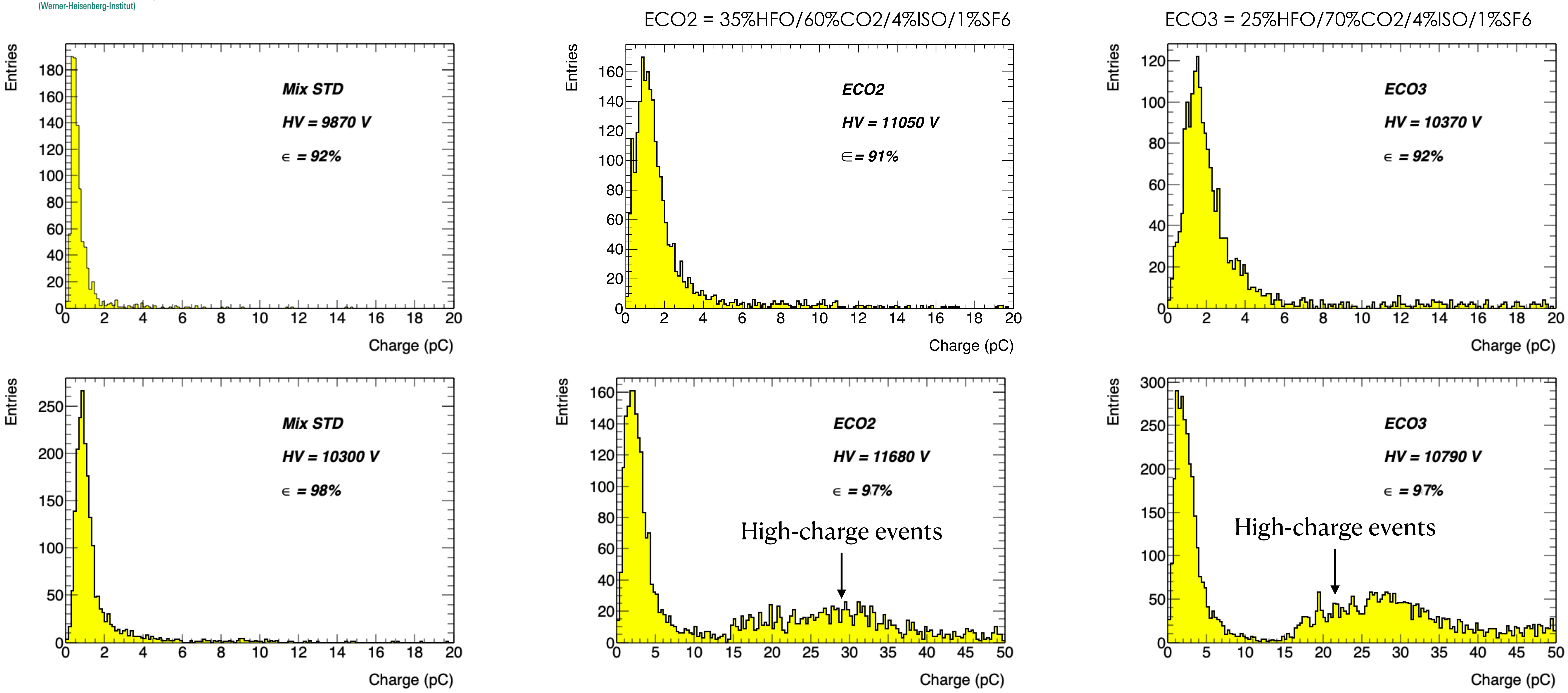
Conclusions

Good performance for eco gas mixtures up to 200 Hz/cm^2 (HL-LHC background)

The aging campaign is now ongoing using ECO2 gas mixture

* Thanks to the ECOGAS@GIF++ collaboration!

Prompt charge distribution



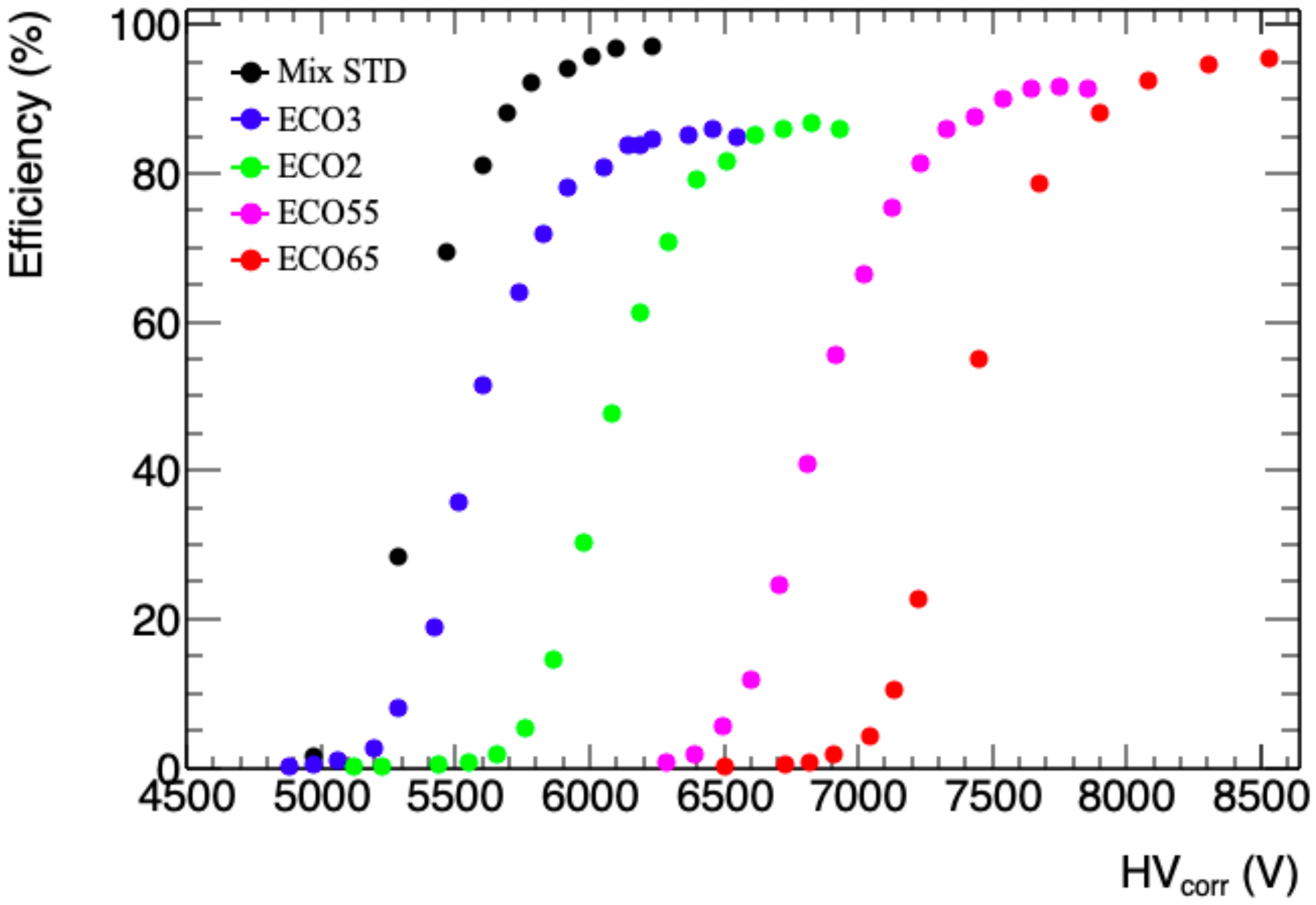
The charge distributions are comparable and well peaked until 90% efficiency

At higher efficiency high-charge events start to occur in the eco gas mixtures (second peak in the charge distribution)

ECOGAS for the ATLAS Phase-2 upgrade

Gas mixture studied

ECO3 = 25%HFO/70%CO2/4%ISO/1%SF6
ECO2 = 35%HFO/60%CO2/4%ISO/1%SF6
ECO55 = 55%HFO/40%CO2/4%ISO/1%SF6
ECO65 = 65%HFO/30%CO2/4%ISO/1%SF6



Test with gamma irradiation on a 1 mm gas gap + 1.3 mm electrodes thick on BIS78 RPC production chamber (ATLAS upgrade) equipped with the new low-threshold FE electronics

Main conclusions

- Concentration below 35% is not sufficient to achieve an efficiency > 90%
- Need to increase the HFO concentration

more fluorine radicals?

ECOGAS for the ATLAS Phase-2 upgrade : the FE threshold

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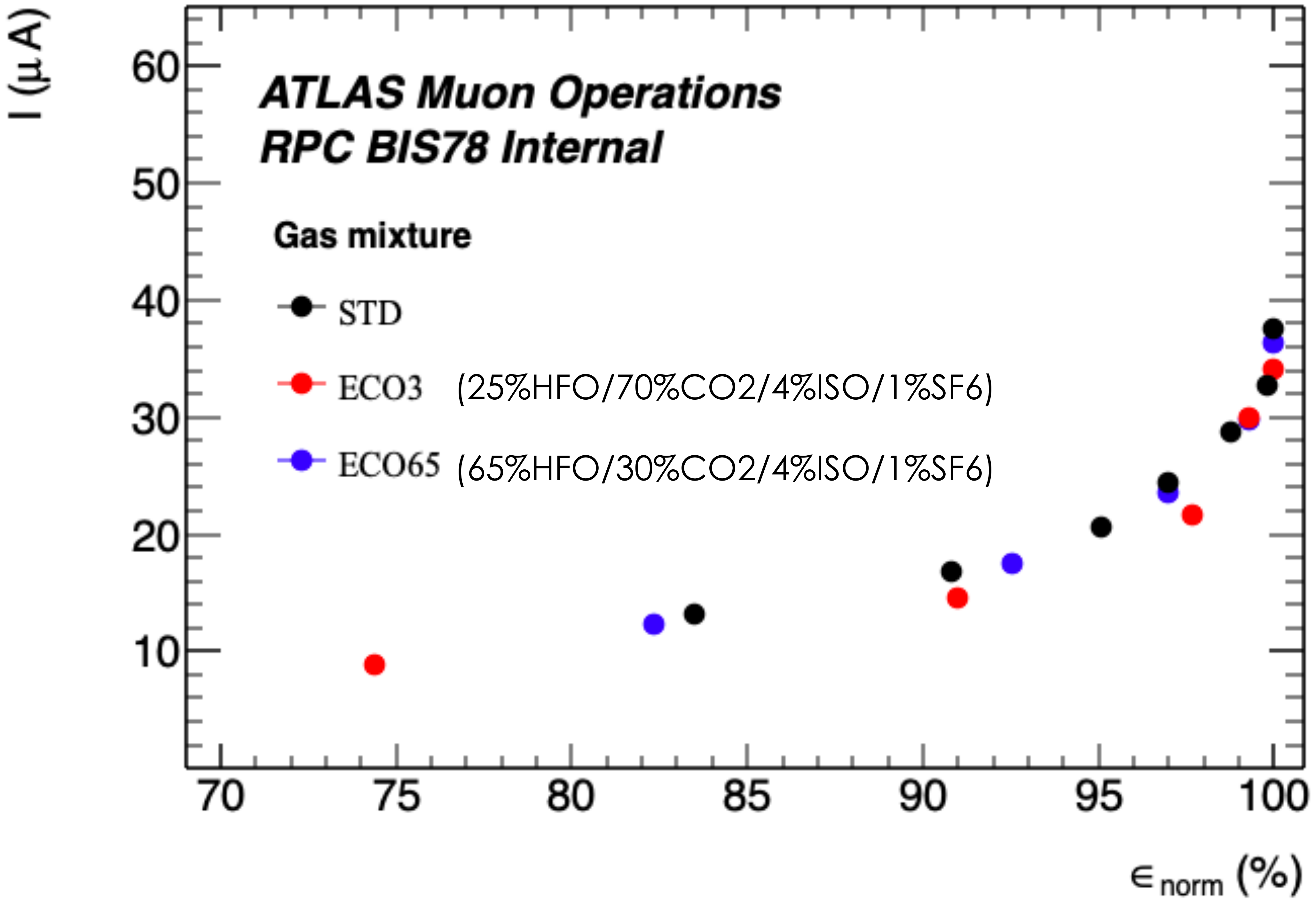
Possibility to balance the larger amount of F^- radicals by lowering the operating electric field, thus current → Work with low FE threshold (1-4 fC) → Same plateau efficiency reached at lower electric field, thus lower current.

γ current vs MIP normalized efficiency



The current due to photons vs MIPs efficiency very similar for different gas mixture, suggesting that the photon contribution to the detector current is independent from the gas mixture at the same normalized efficiency.

ϵ_{STD}~ 97.5%, ϵ_{ECO3}~ 88% , ϵ_{ECO65}~ 96.5%

ECOGAS might guarantees same aging and same rate capability as the standard gas mixture working with 1 fC threshold → under study

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Reduction of the Tetrafluoroethane introducing CO2 :results

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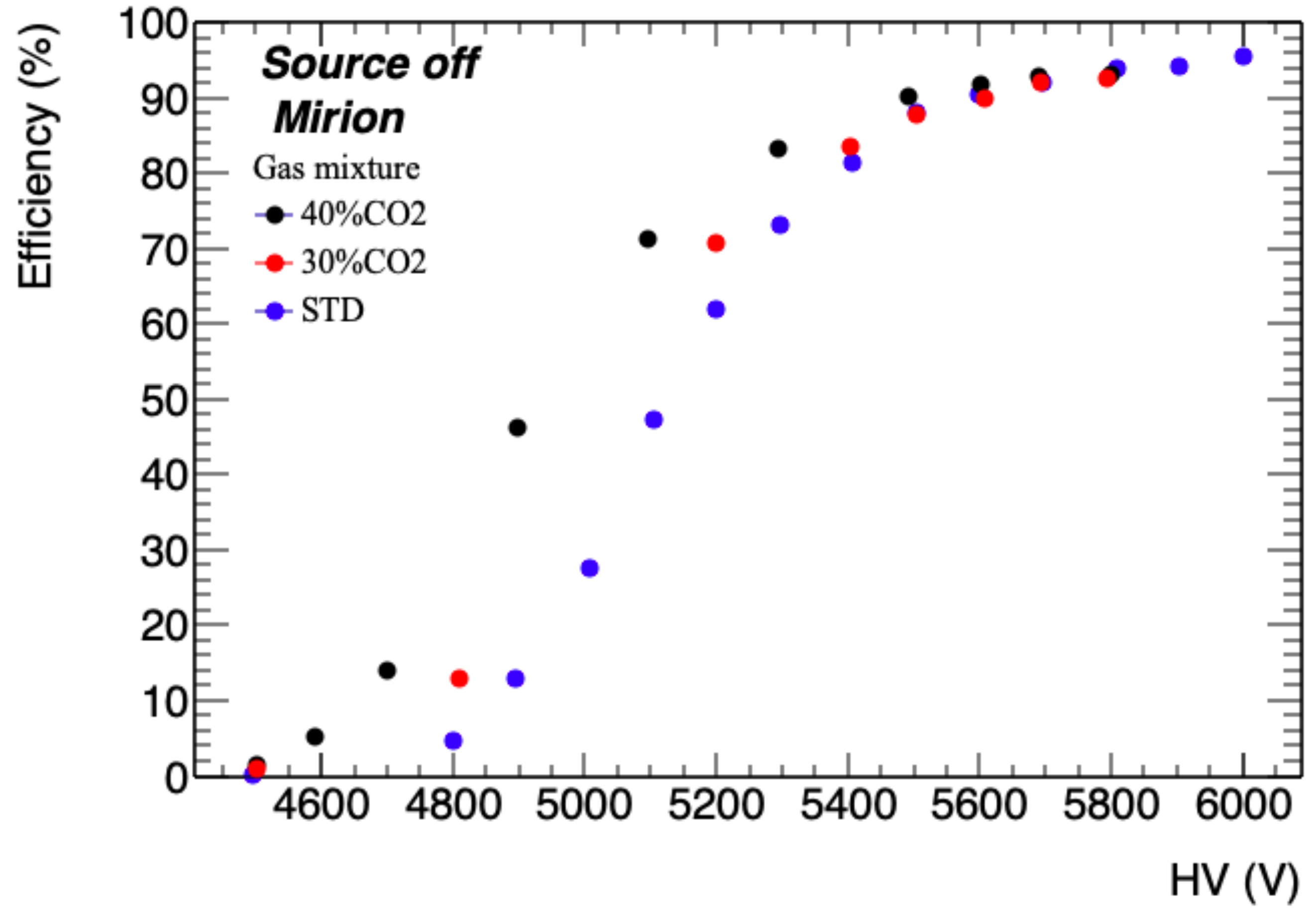
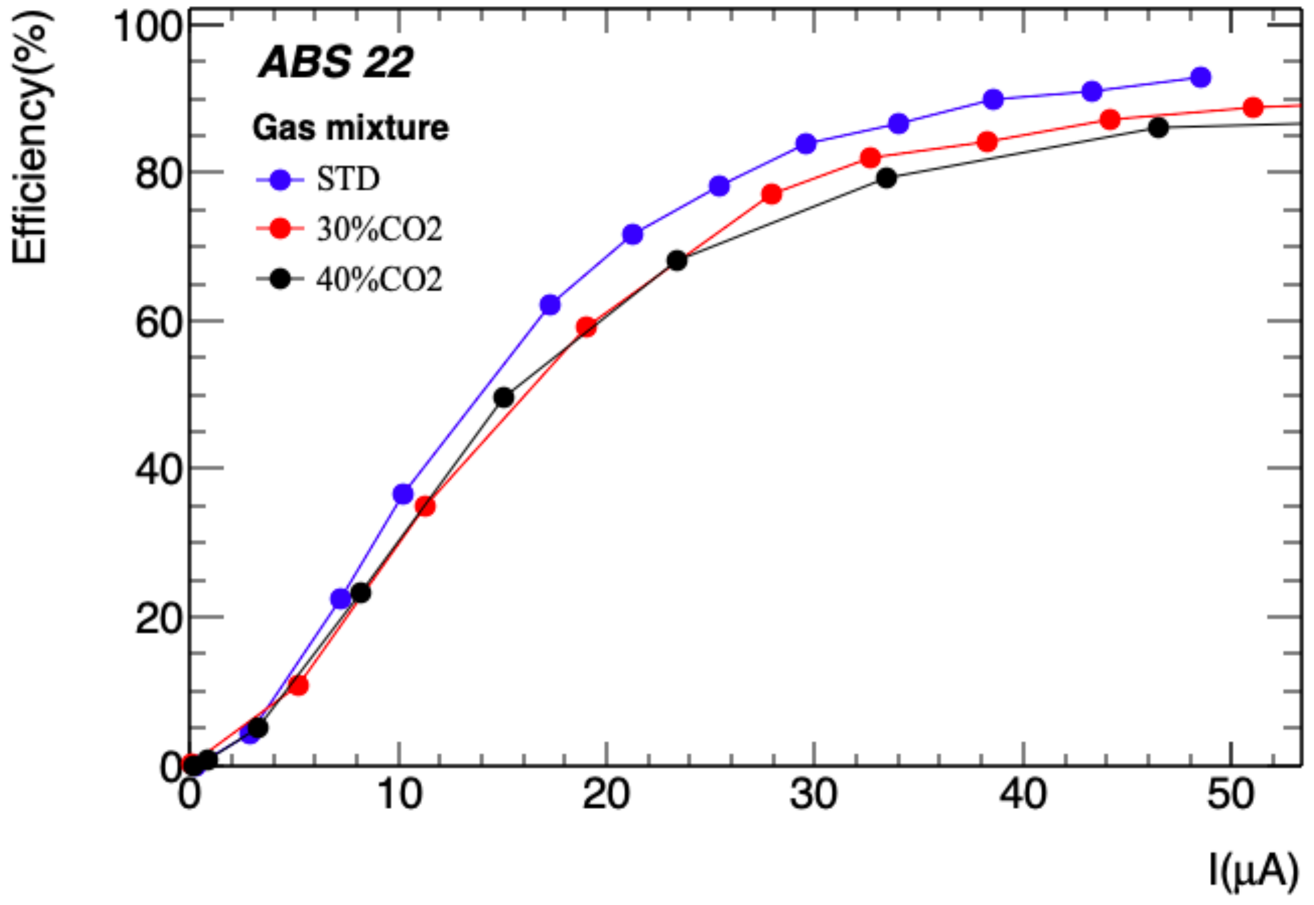
Efficiency vs high voltage



Efficiency vs current



Test with muon beam and γ irradiation on 1 mm gas gap + 1.3 electrode thick with dimensions (50x50) cm^2 built at MPI. 10 read-out strips + Transimpedance amplifier as FE electronics

Gas mixture studied

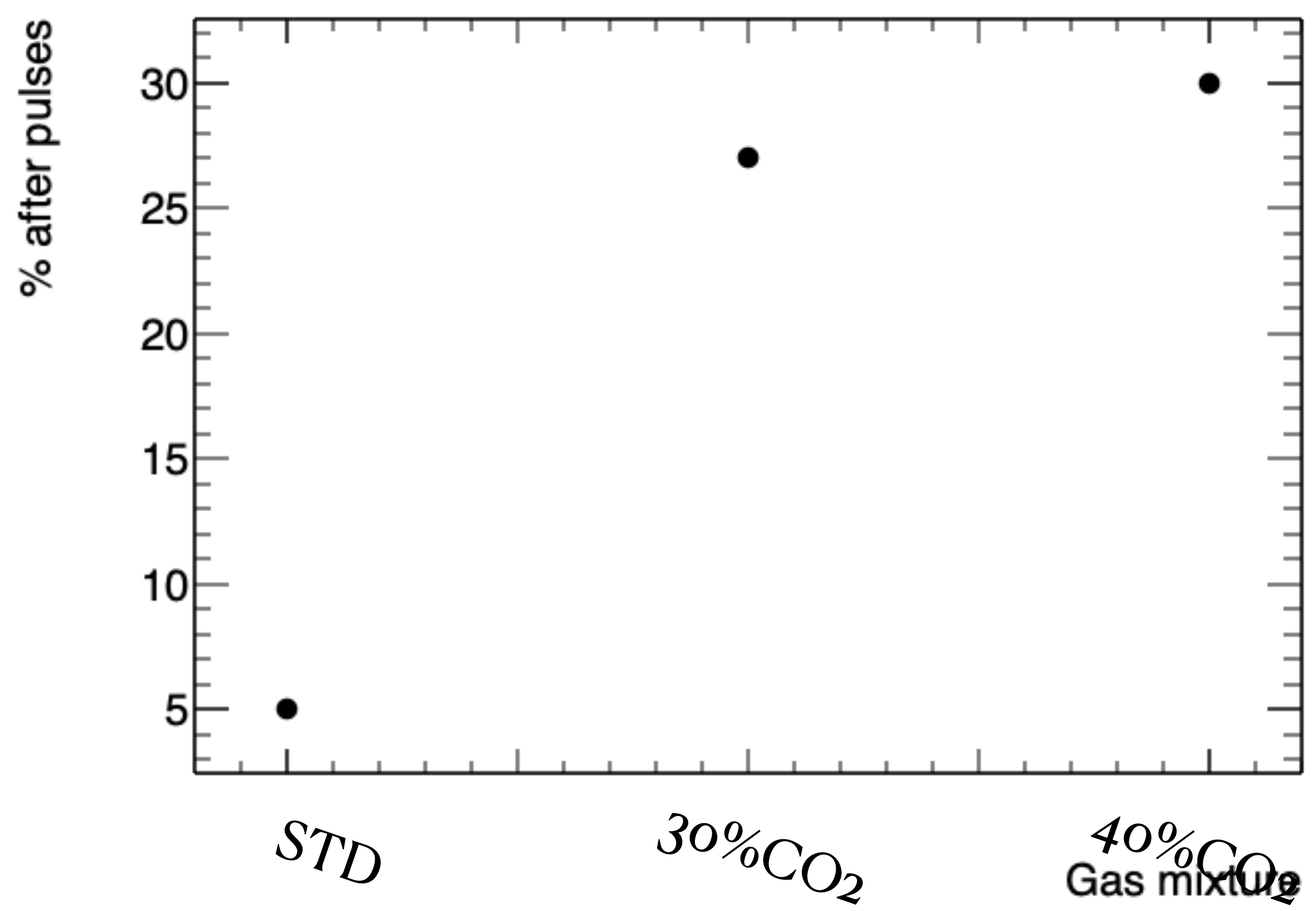
STD gas mixture

30%CO2/65%TFE/4%ISO/1%SF6

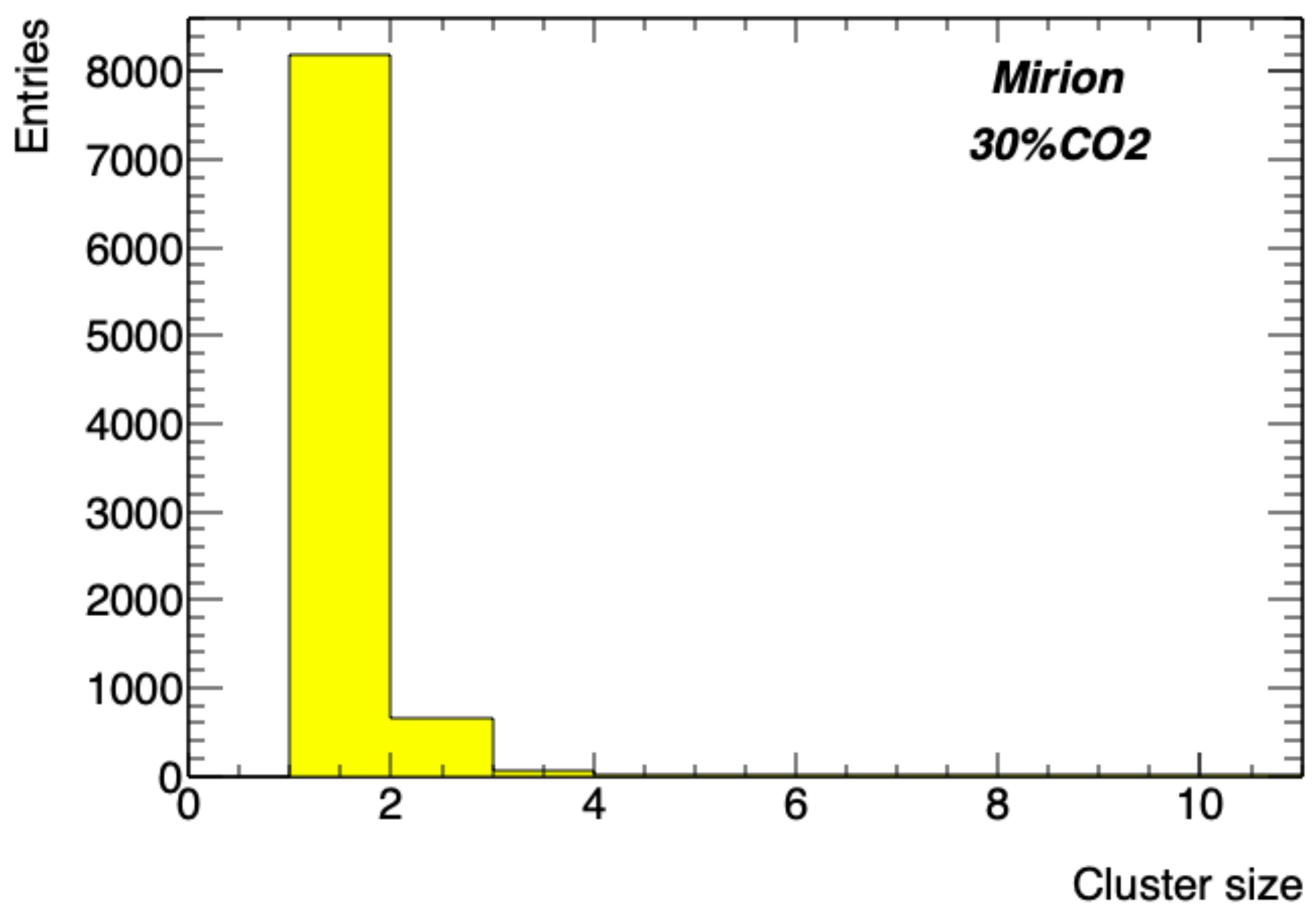
40%CO2/55%TFE/4%ISO/1%SF6

Main conclusions

%After-pulses vs gas mixture



Cluster size @ plateau



- Efficiency @ plateau: ~ 93% for Co2 gas mixtures, ~96% for the STD gas
- Cluster size ~ 1.1 for all gas mixtures
- Efficiency drop at the same irradiation (1.5 kHz) : 2% for the STD, 3% for 30%CO2, 4%for 40%CO2
- I(40%CO2) ~ 1.7 I(STD), I(30%CO2)~1.5 I(STD)
- "Contamination" at plateau from after-pulses: 5% for the STD, 27% for the 30%CO2 and 30% for the 40%CO2 gas mixtures

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The SF_6 substitute

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The highest GWP molecule in the standard and eco-gas mixtures is the SF6 (GWP ~ 23900).

Reduction of the SF6 fraction in TFE/CO2 gas mixtures from 1% to 0.5%

- **30%**CO_2 **/65.5%**$C_2H_2F_4$ + 4%i-C_4H_{10} + 0.5%SF_6 → **GWP ~ 1041**

- Reduction of the GWP

Possibility to replace this crucial component with a different environment-friendly gas : the **Chloro-trifluoropropene** , $C_3H_2ClF_3$ (HFO1233zd)

- CO_2 / $C_3H_2F_4$ **(F-HFO)** + i-C_4H_{10} + $C_3H_2ClF_3$**(Cl-HFO)** → **GWP ~ 10**

- Possibility to work with a <u>totally</u> environment-friendly gas mixture (JINST : https://arxiv.org/abs/2112.02659)

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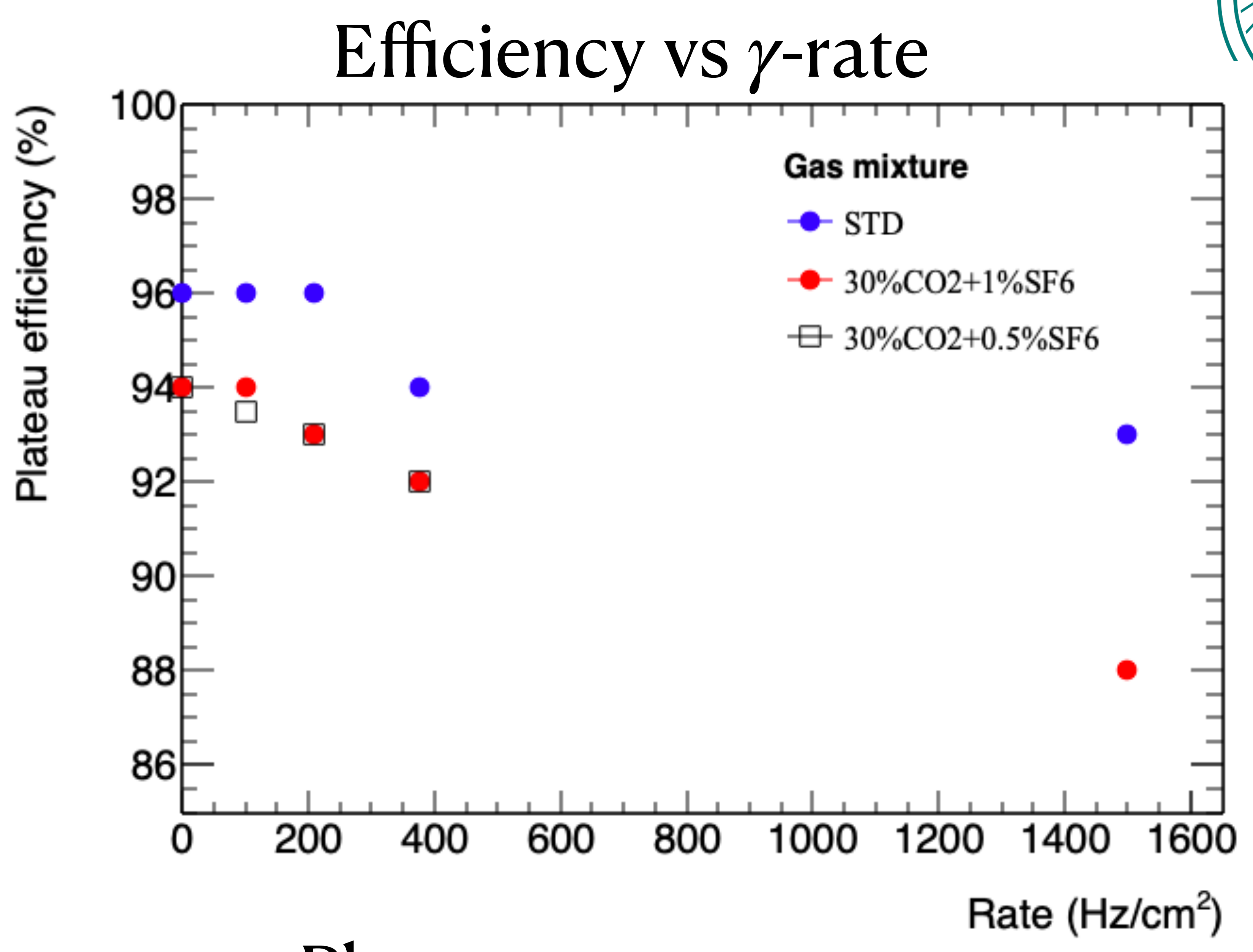
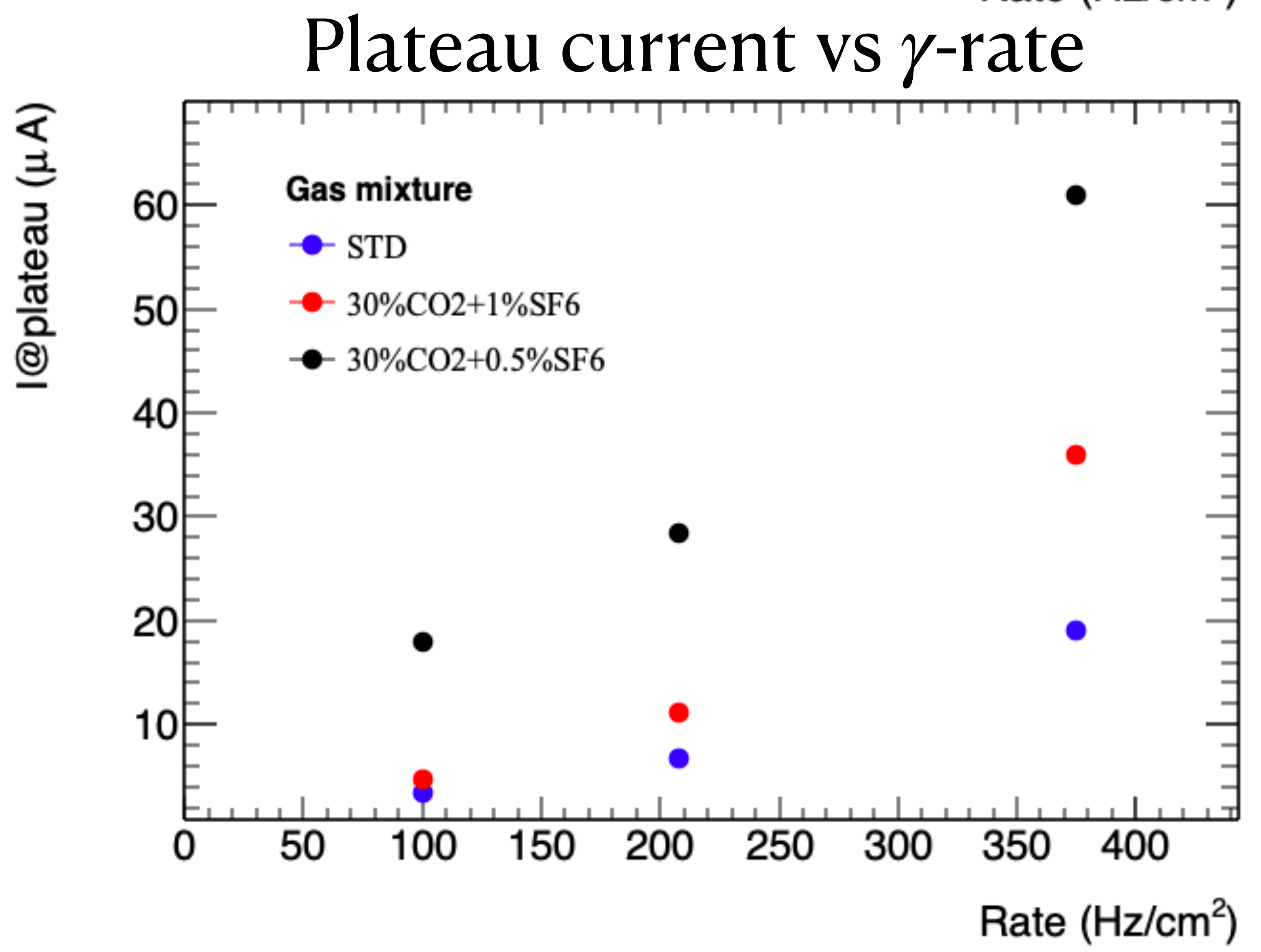
Results

Test with muon beam and γ irradiation on 1 mm gas gap + 1.3 electrode thick with dimensions (50x50) cm^2 built at MPI. 10 read-out strips + Transimpedance amplifier as FE electronics

Main conclusions

- The efficiency plateau of the gas mixtures studied does not change until a γ -rate of ~100 Hz/cm2
- The plateau efficiency until the γ-rate of 100 Hz/cm2 is 96% for the STD gas and 94% for the CO2 gas mixtures
- At γ-rate~ 200 Hz/cm2 the plateau efficiency of the STD gas does not change, while the other two gas mixtures show a drop of ~ 1%
- At γ-rate~ 400 Hz/cm2 the efficiency drop is ~ 2% for all gases
- Current ratio:
  - I(1%SF6) ~ 1.5 I(STD)
  - I(0.5%SF6)~3I(STD)

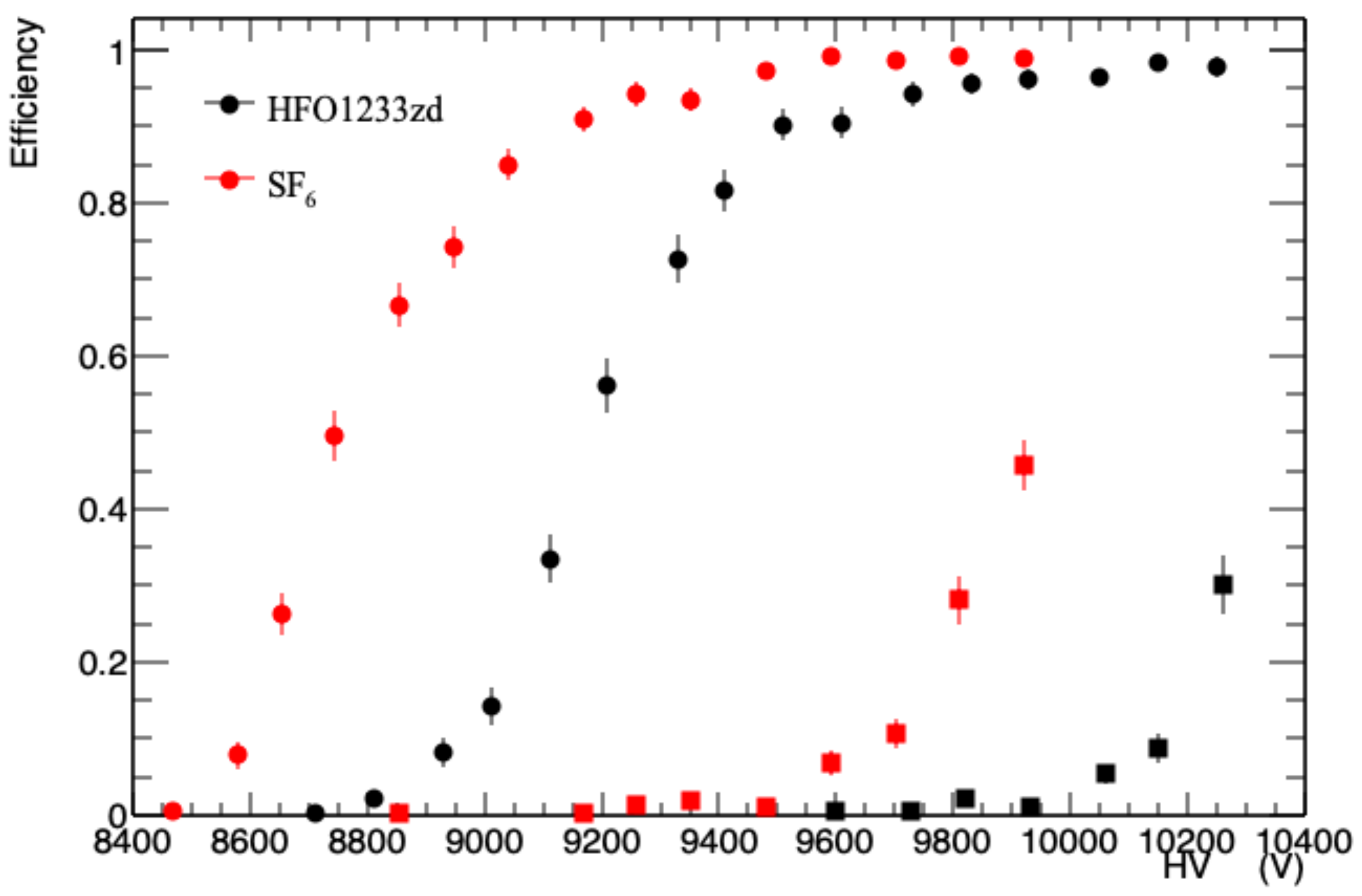


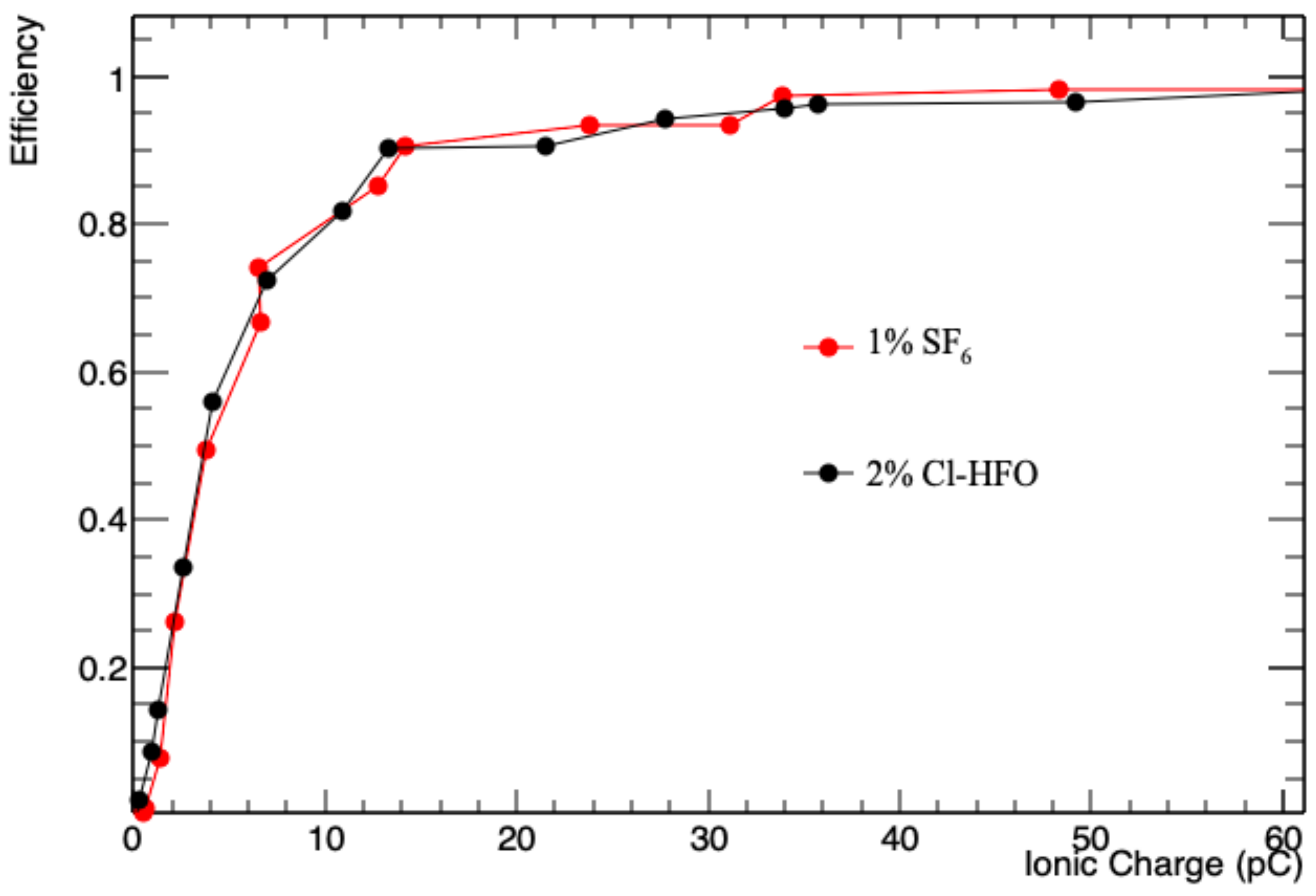


Comparison between HFO1233zd and SF6

Test with cosmic rays (Rome2 laboratory) on a 2 mm gas gap + 1.8 mm electrodes thick ("ATLAS legacy"-like) with small dimensions. No FE electronics

Mixture under study : HFO1234ze(FHFO)/CO_2/i-C_4H_{10}/SF_6 and HFO1234ze/CO_2/I-C_4H_{10}/HFO1233zd(Cl-HFO)





The Cl-HFO can substitute SF_6 in these gas mixtures

- Plateau knee at 90% efficiency for both gas mixtures, full efficiency plateau at 96%
- Avalanche-streamer separation ~400 V for both mixtures
- Same ionic charge at the same efficiency value

Conclusions and next steps

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In this presentation the results on alternative gas mixtures for Resistive Plate Chambers detectors have been presented

- Substitution of the Tetrafluoroethane:
  - HFO1234ze/CO_2/i-C_4H_{10}/SF_6 gas mixtures
  - R134a/CO_2/i-C_4H_{10}/SF_6 gas mixtures
- Substitution of the SF_6:
  - HFO1233zd
  - Reduce the amount of SF_6 from 1% to 0.5%

Next steps

Aging tests are planned, testing all these possible candidates to the standard gas.

The goal is to study the impact of the single gas component on RPC longevity and performance during time

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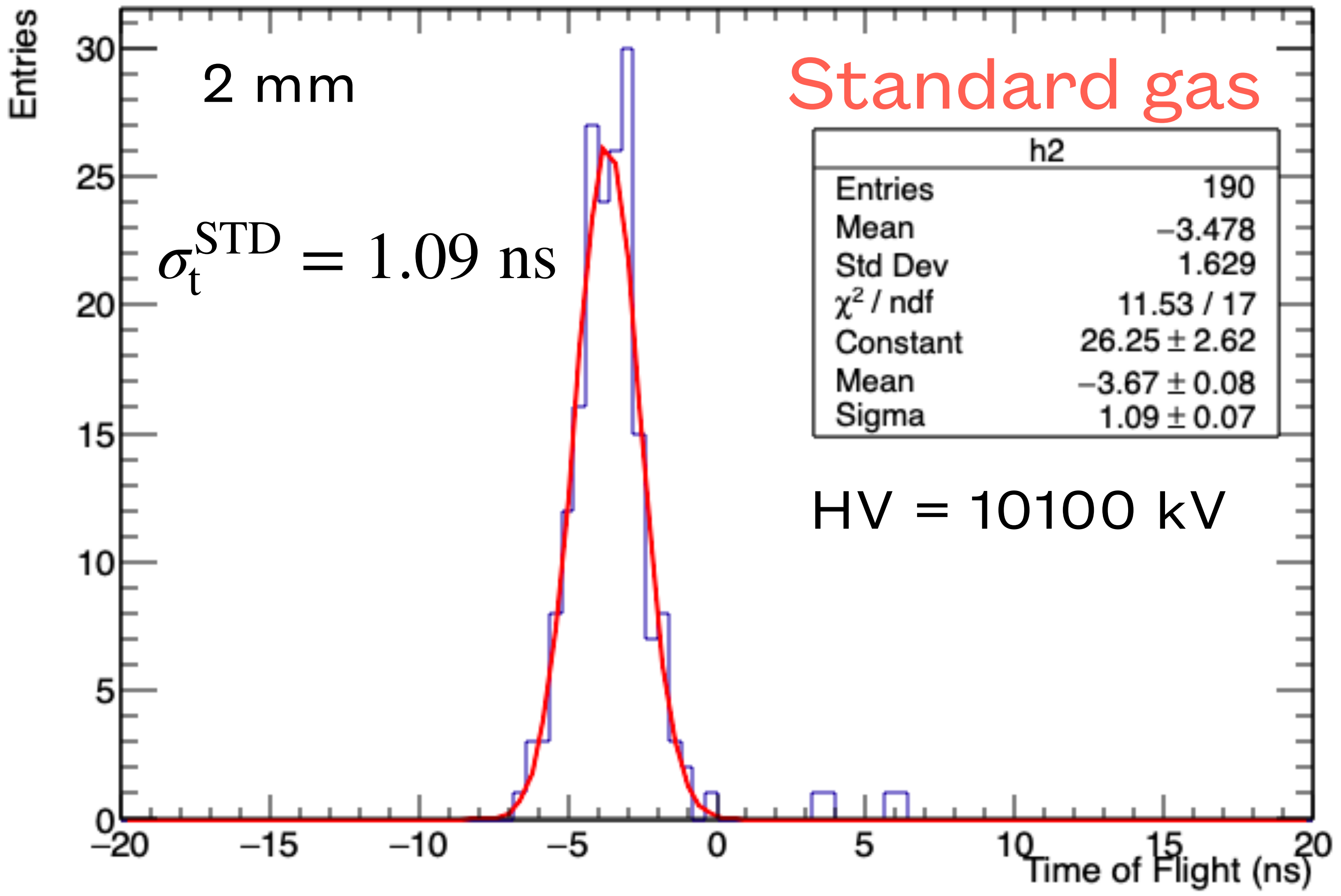
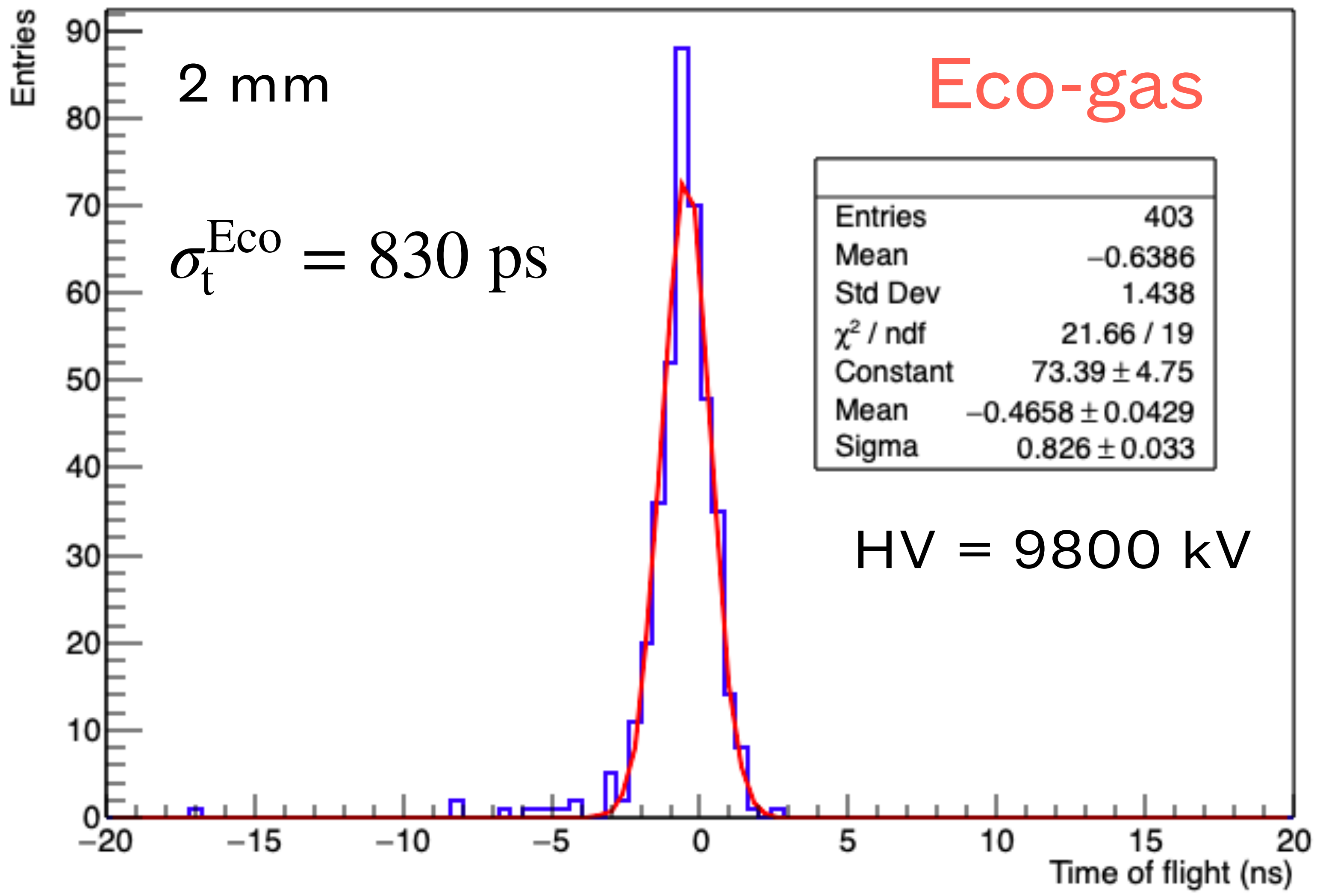
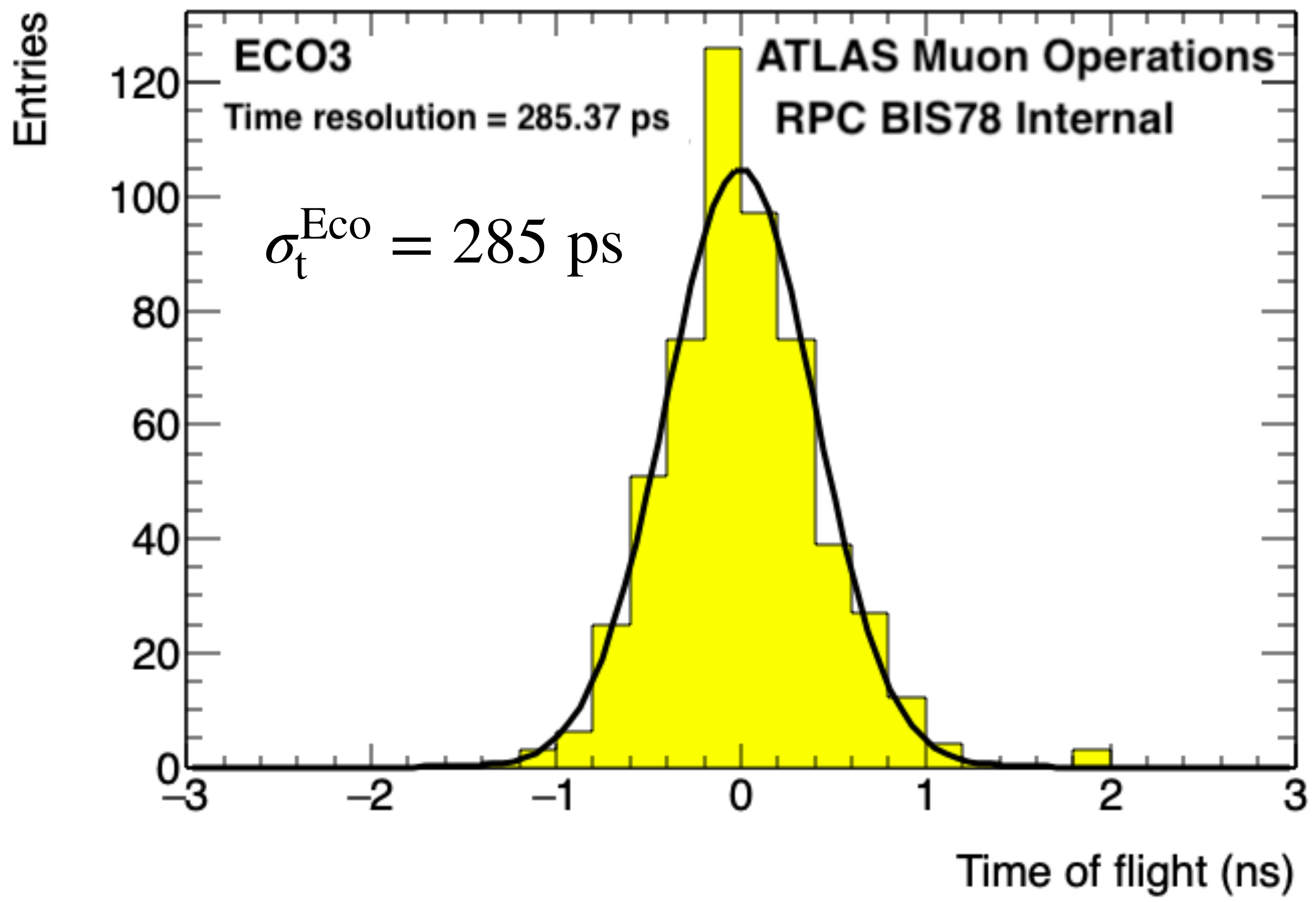
Thank You

Study of the time resolution



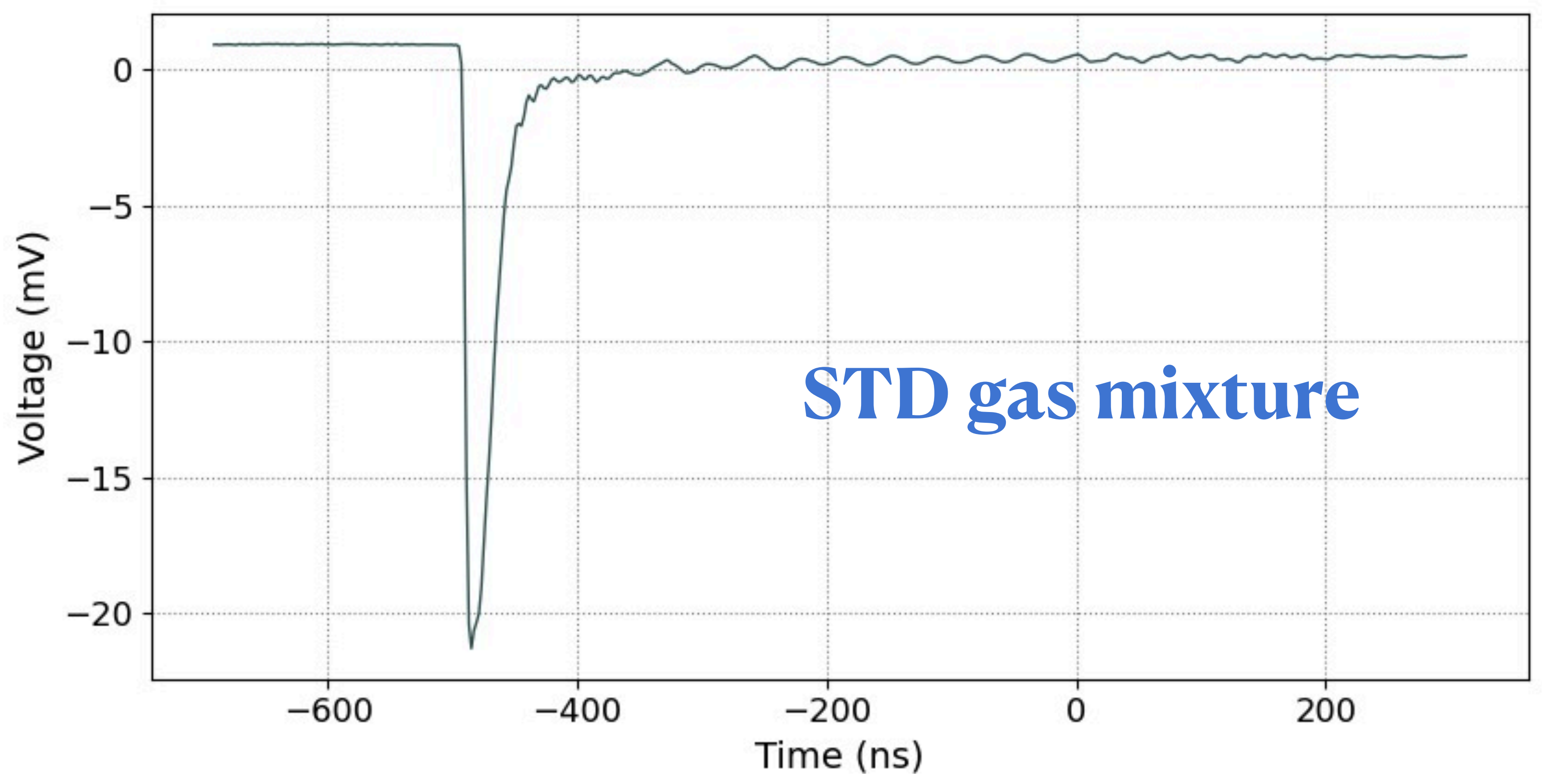


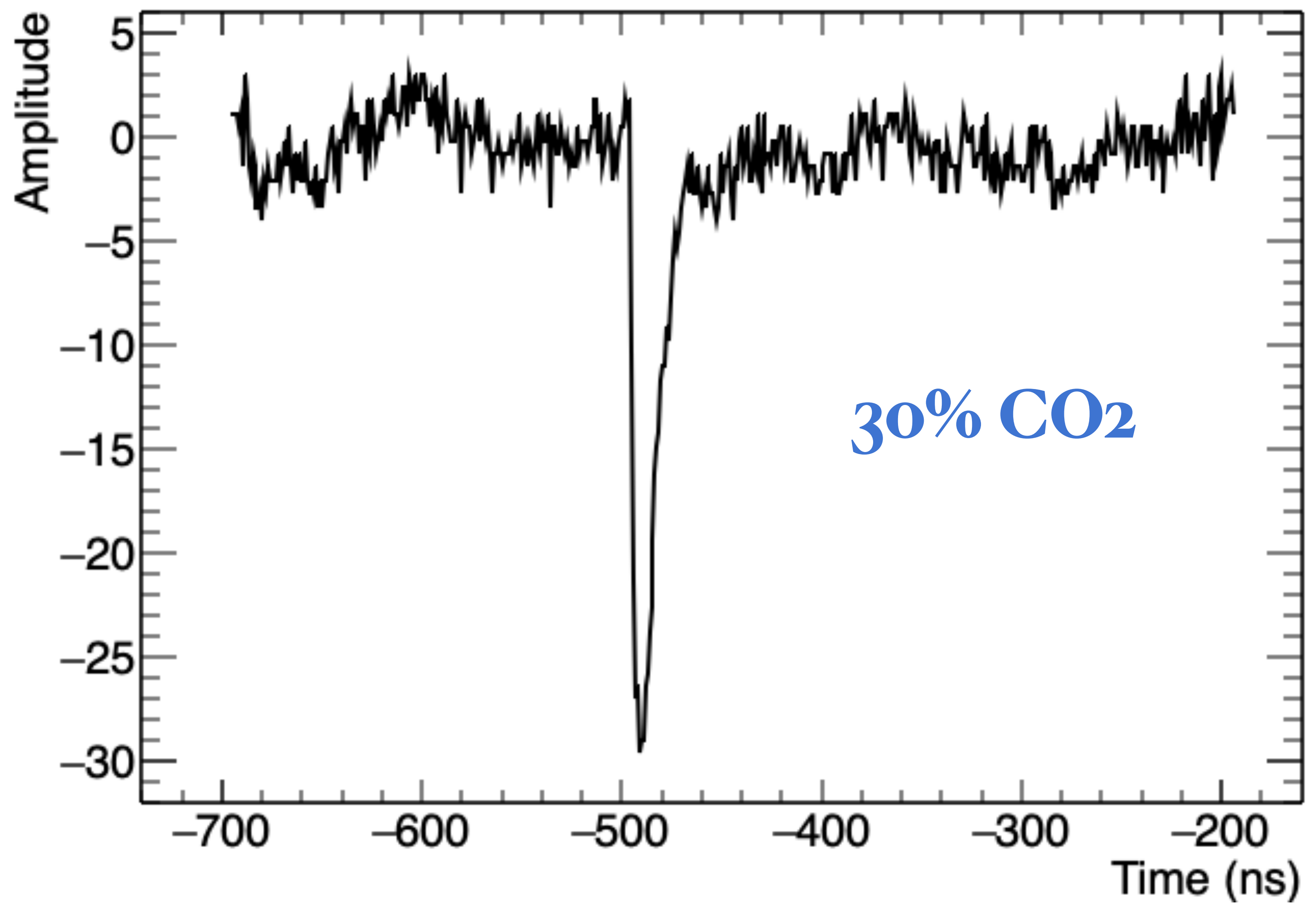


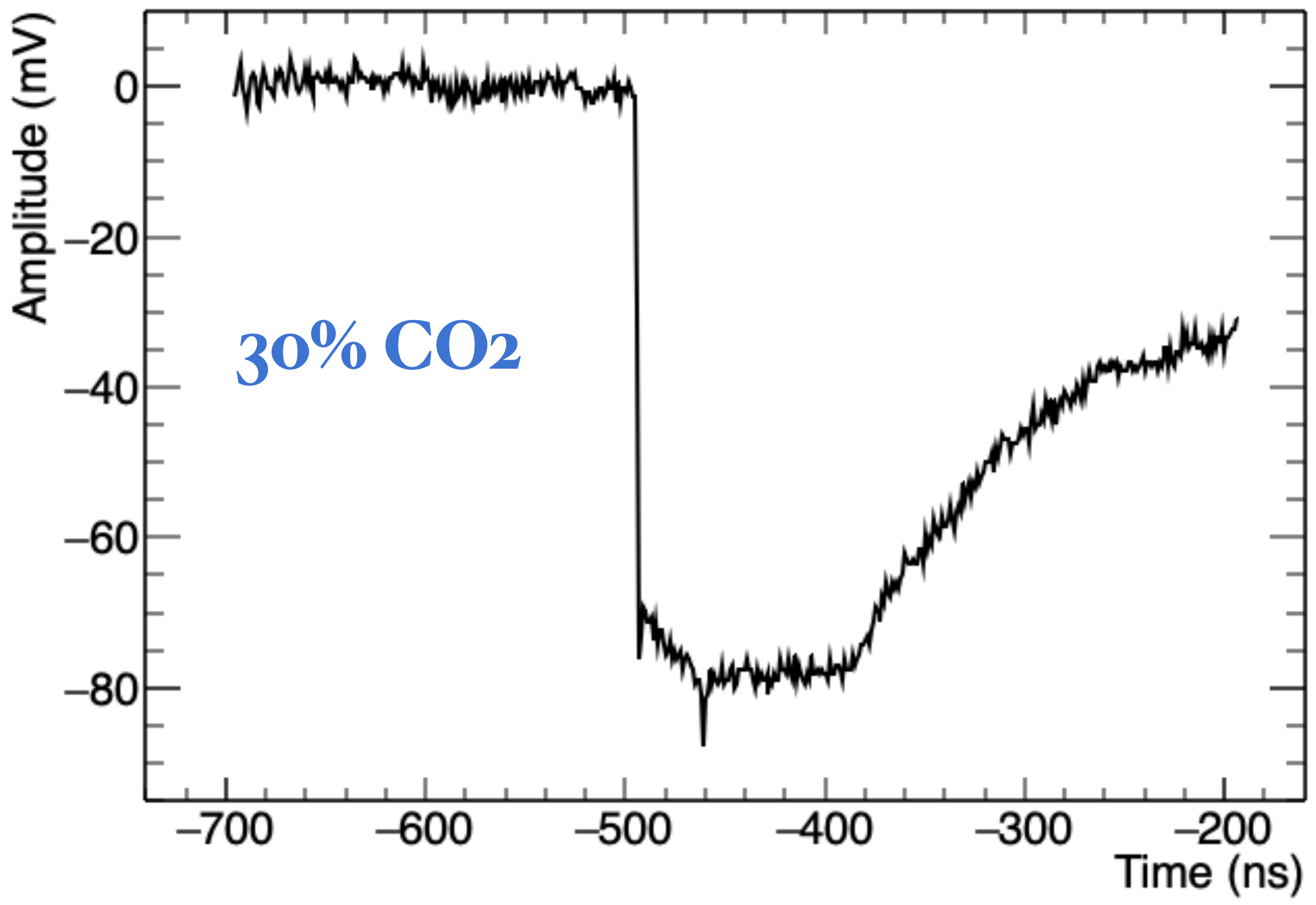
- The time resolution depends on the gas drift speed
- Time resolution measured with the time of flight (TOF) method using:
- a 0.5 mm gas gap as time reference for the measurement of the time resolution of the 2 mm gas gap. In this case the TOF distributions do not contain any kind of corrections for systematic effects
- two singlets operated with the same gas mixture for the measurement of the time resolution with the 1 mm gas gap. All the systematics have been studied and taken into account (electronic skew, cabling, time-walk)

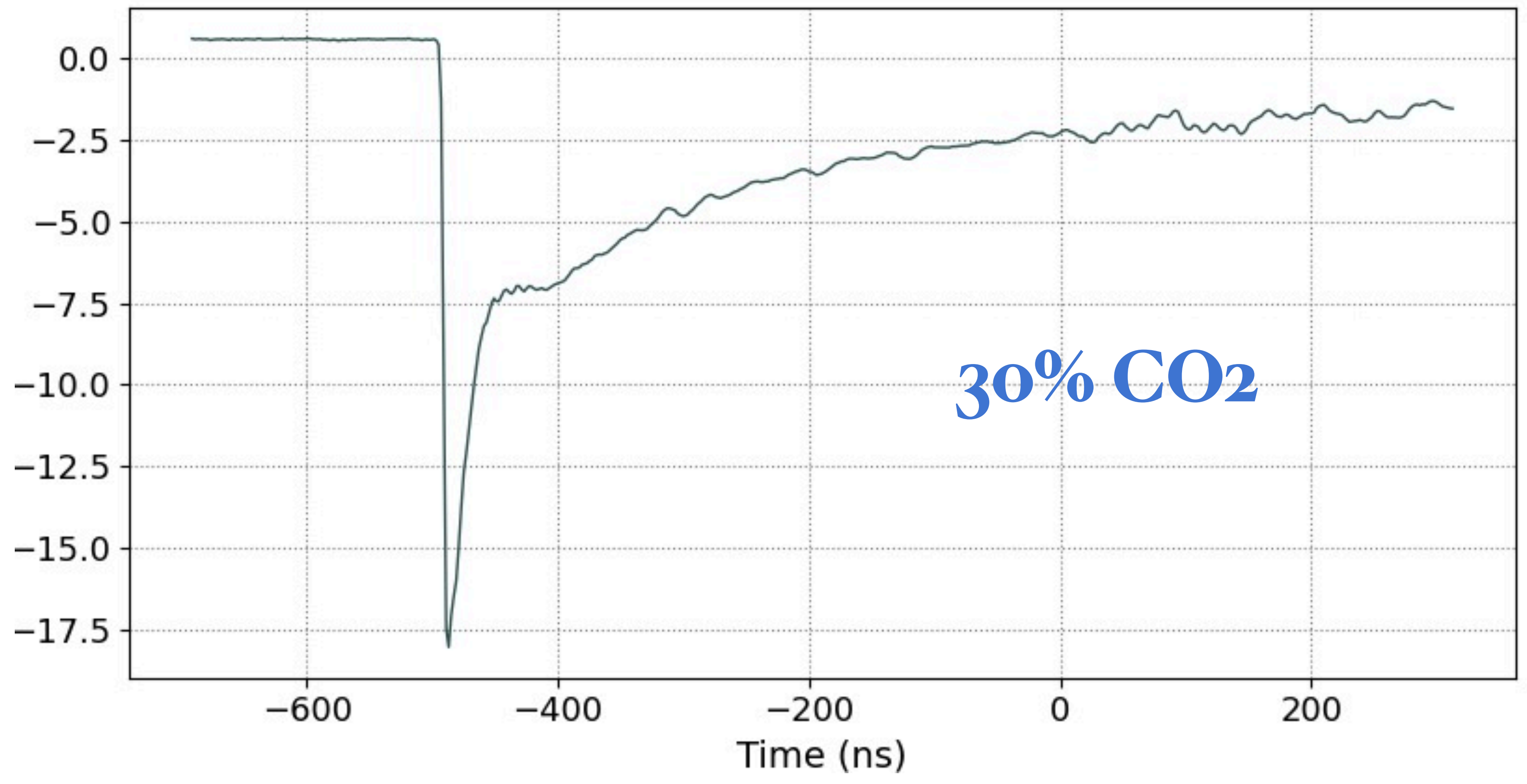
Better time resolution with ecogases

Signals shape



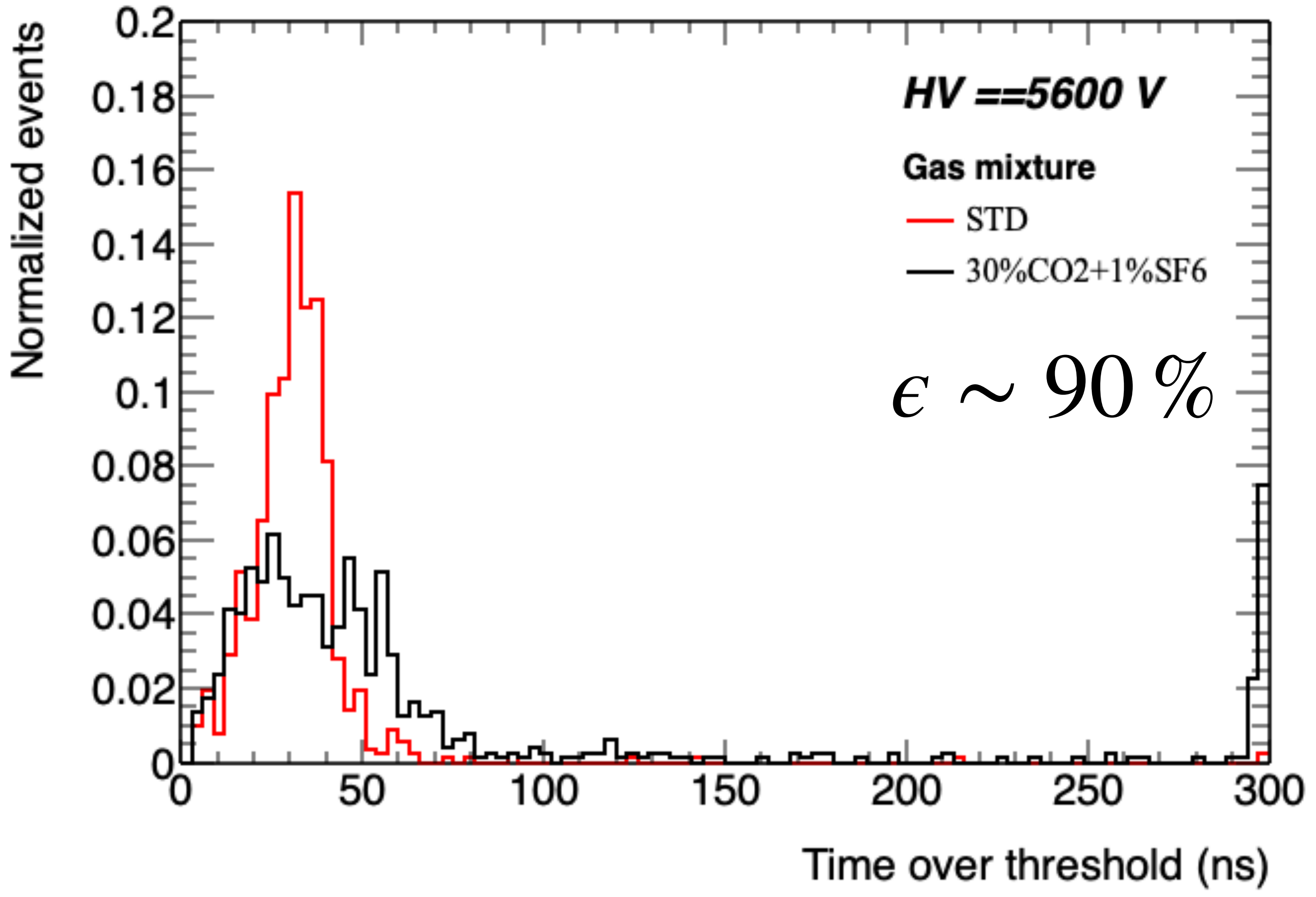


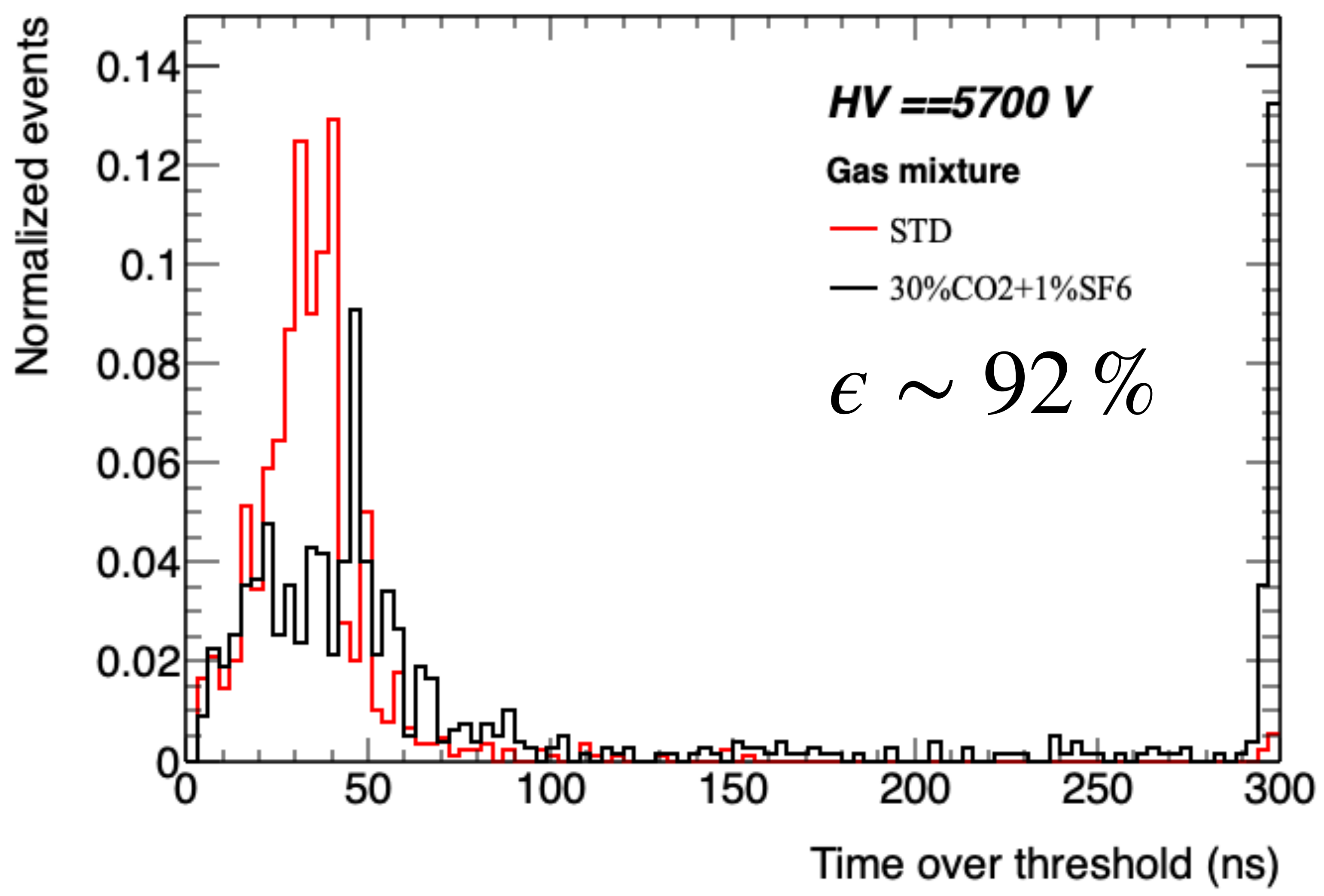


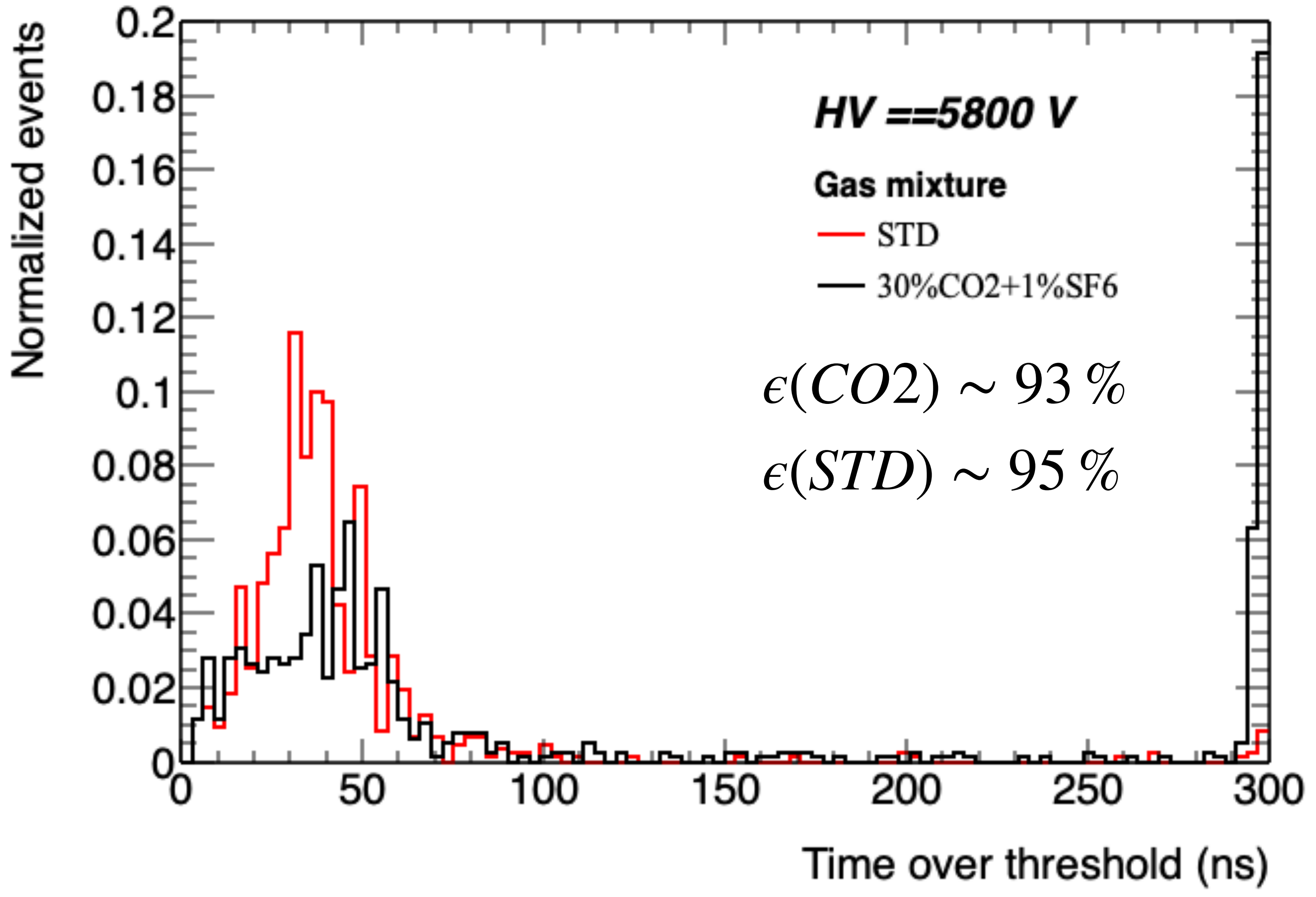


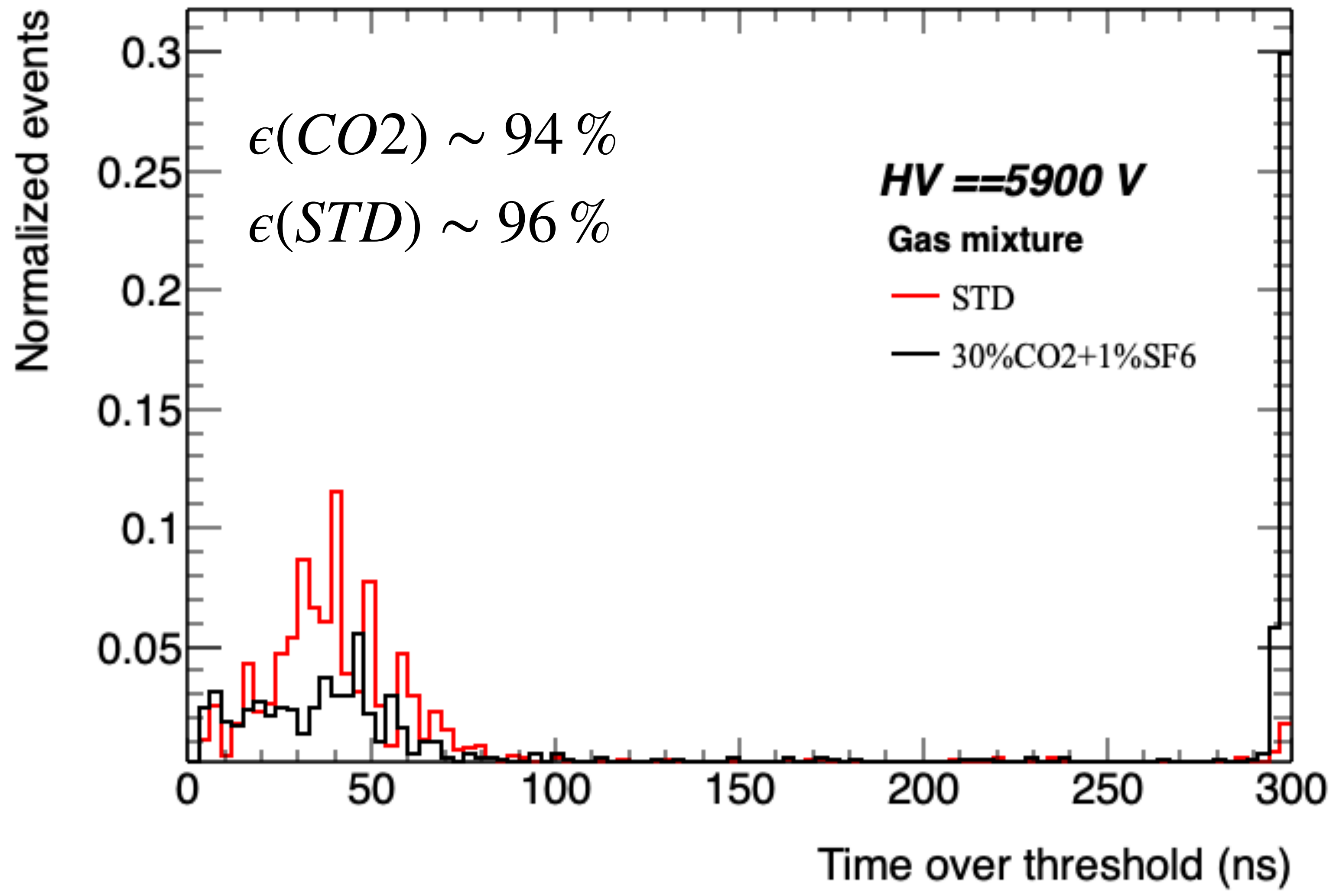
- Most of the event in the standard gas have the shape shown in figure.
- The CO2-based gas mixtures shows signals with a tail or very wide signals
- These signals could explain the higher amount of current measured in these alternative gases

Time over threshold distribution









- No charge estimation, just Time over threshold (Threshold = 10 mV)
- The distribution of the STD gas is within 50 ns until ~95% efficiency
- The CO2 distributions are wider and show a contamination from high-amplitude events that increases a lot with the increase of the HV

Search of an environment-friendly gas mixture

Strategy

- Substitution/reduction of the TFE (**more critical**)
- Substitution/reduction of the SF6

Goal : Low GWP gas mixture with high performance (similar to the STD one) with no critical aging impact

Gas parameters

- Density/cross section
- Capability to suppress streamer (electronegativity, affinity, electron capture cross section)
- Molecular structure to avoid an excess of F^- production
- non flammable, no toxic

Detector parameters

- Gas gap width : the thinner the gas gap , the higher the density of the gas to achieve good plateau efficiency
- FE electronics threshold: possibility to compensate the F^- production by working at lower field thanks to low-threshold FE electronics
- Materials and manufacturing