R&D studies on $C_3H_2F_4$-based mixtures with low environmental impact for Resistive Plate Chambers

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Outline

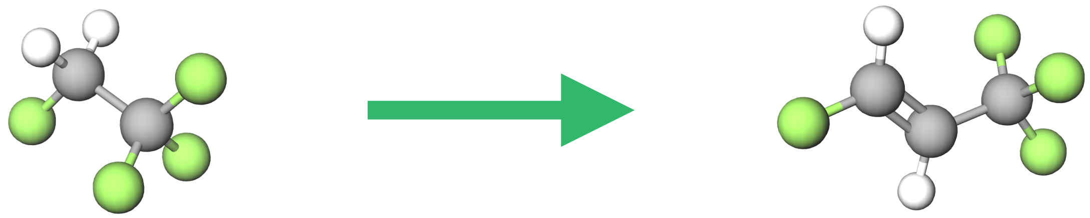
- **Motivation for R&D studies:**

  → goal: eco-friendly gas mixture for the ALICE muon RPCs

- **Characterization of mixtures with $C_3H_2F_4$:**

  → $C_3H_2F_4$ is tested as a replacement for $C_2H_2F_4$

  → $C_3H_2F_4$-based mixtures are tested with addition of Ar, N_2, O_2, CO_2

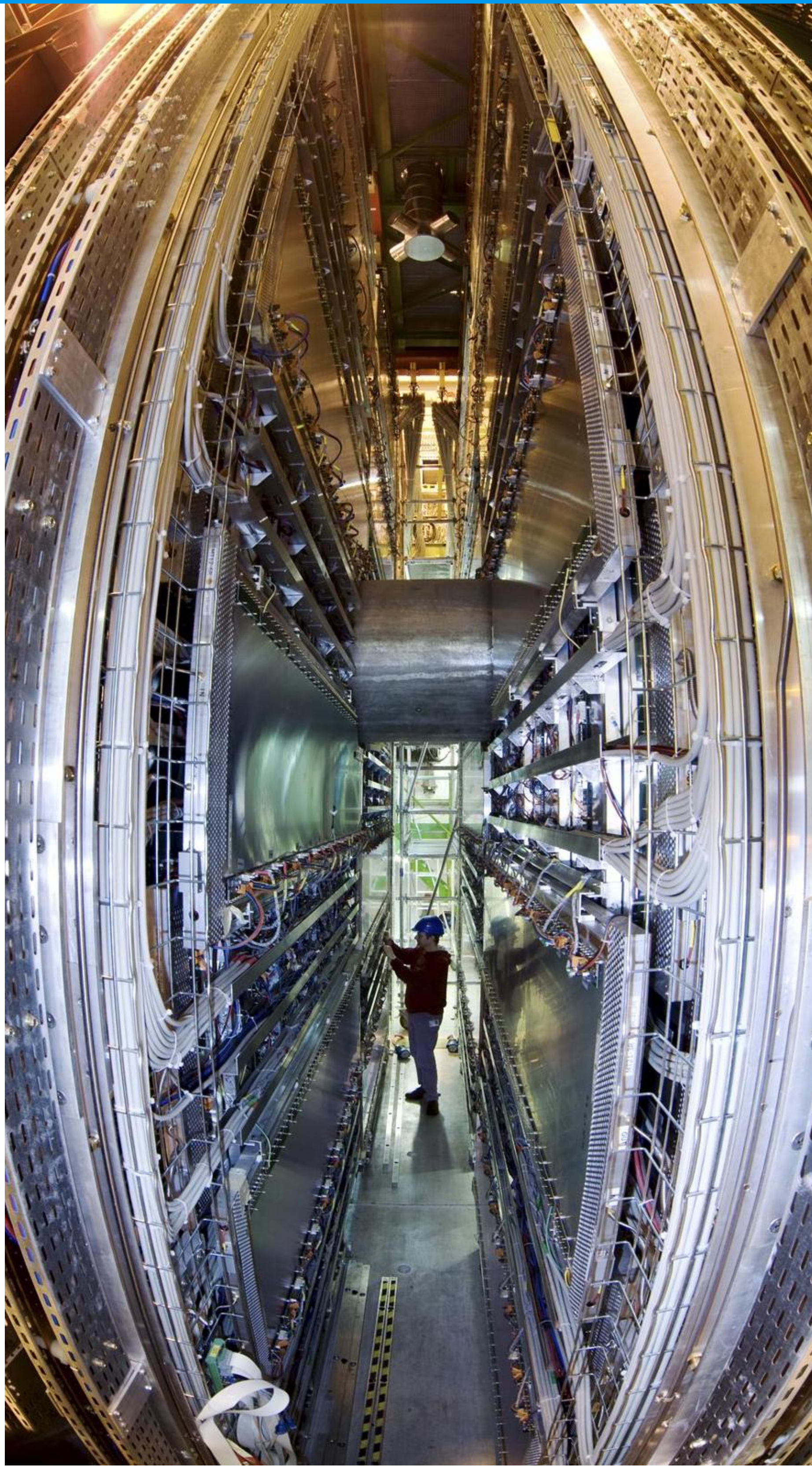


$C_2H_2F_4$ $C_3H_2F_4$

- **Identification of promising $C_3H_2F_4$-based mixtures and CO_2:**

  ➡ A. Bianchi et al, "*Characterization of tetrafluoropropene-based gas mixtures for the Resistive Plate Chambers of the ALICE muon spectrometer*", arXiv: 1907.03268 (submitted to JINST)

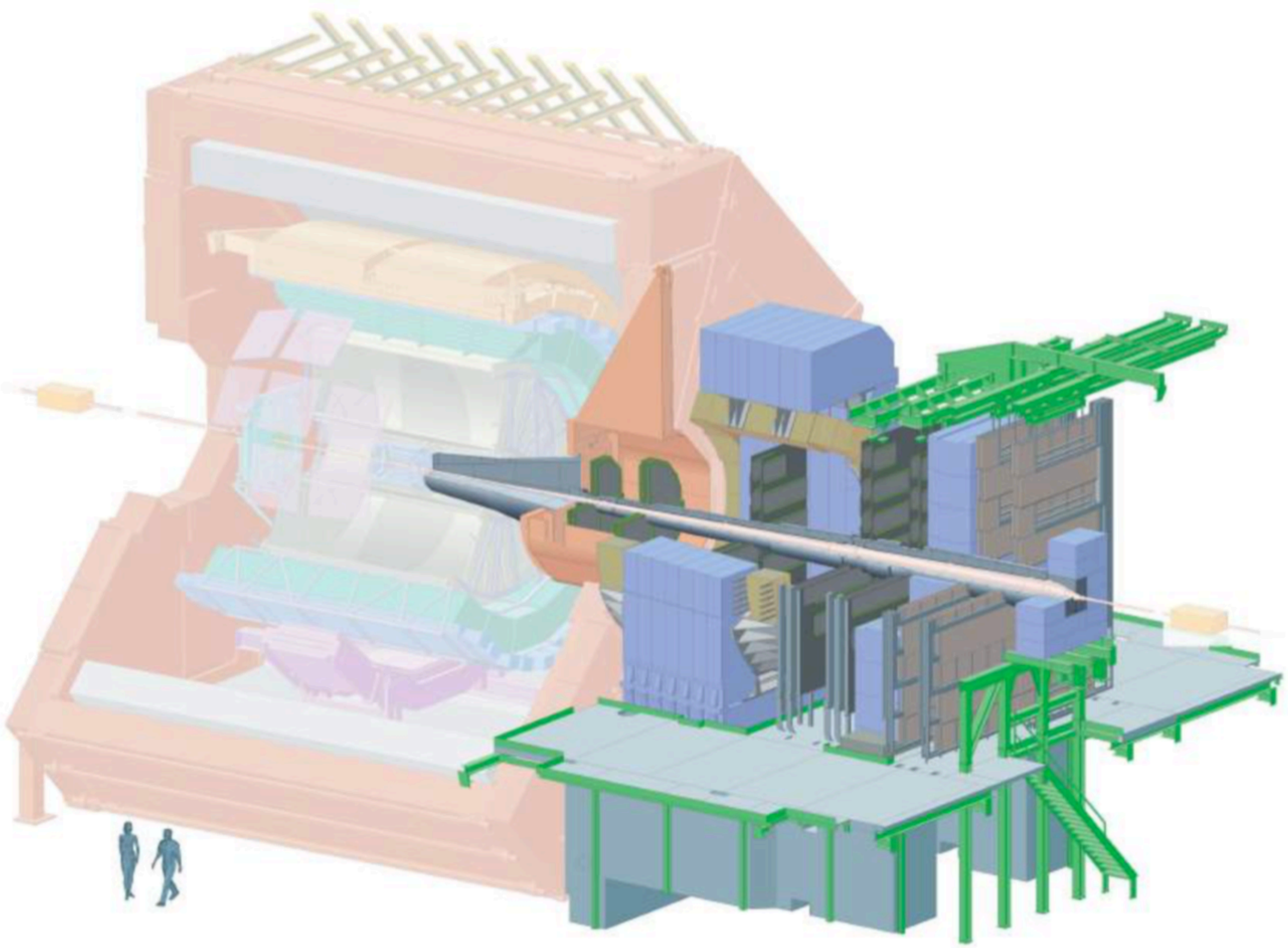
- **Outlook: long-term stability tests under irradiation**



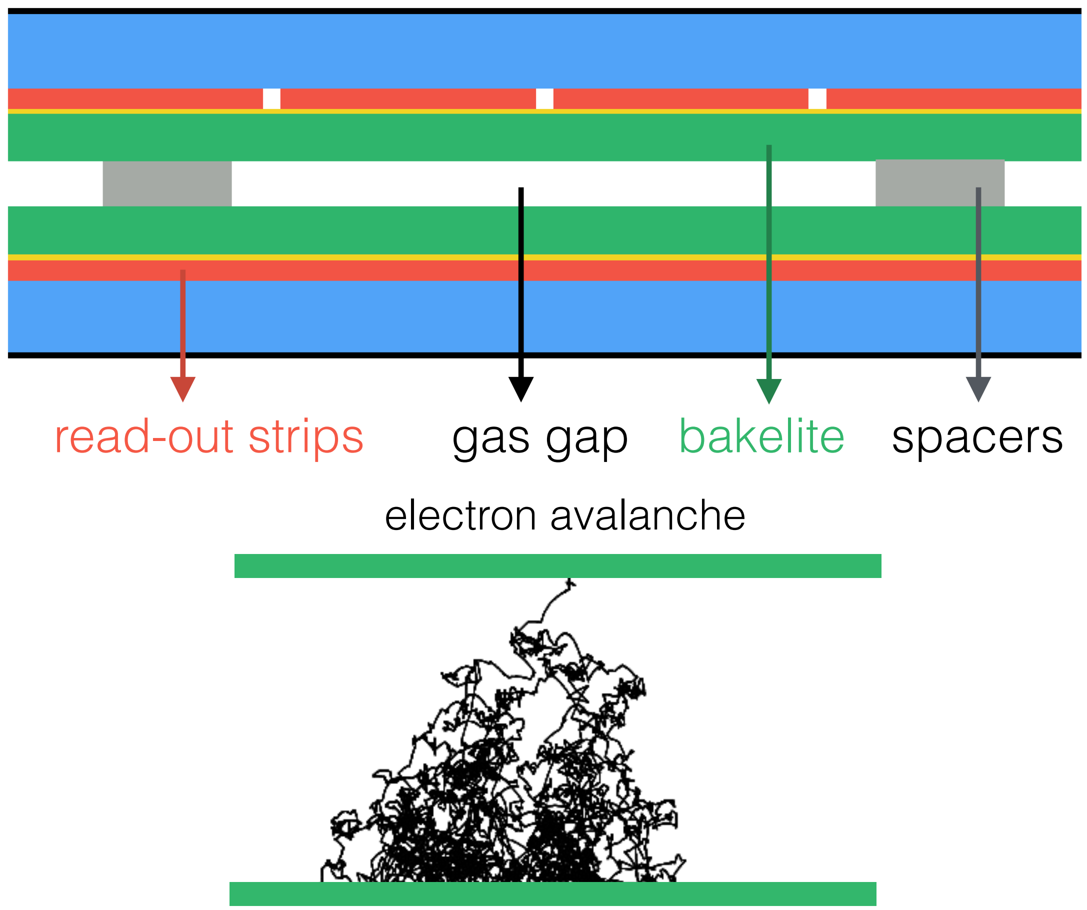
ALICE Muon Spectrometer Trigger Chambers

The ALICE Muon Identifier

ALICE is a general-purpose heavy-ion experiment at CERN-LHC, studying the **Quark-Gluon Plasma**. **Heavy-flavors and quarkonia** are studied via **their muonic decay channels with the ALICE muon spectrometer** at forward rapidity ($2.5 < y < 4$).



RPC sketch:



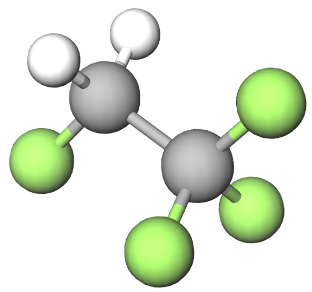
ALICE-muon RPCs have shown stable operation and an efficiency greater than 98% from the beginning of Run1 up to now (integrated charge of ~10 mC/cm^2). They are operating in maxi-avalanche mode at ~10.3 kV (ADULT FE) with **89.7% $C_2H_2F_4$, 10% *i*-C_4H_{10} and 0.3% SF_6. The present gas mixture has a GWP of 1351**.

Global Warming Potential (GWP): is the relative measure of how much heat a greenhouse gas traps in the atmosphere.
GWP_{CO2} = 1 by definition

Motivation

The main component of the ALICE gas mixture is:

$C_2H_2F_4$



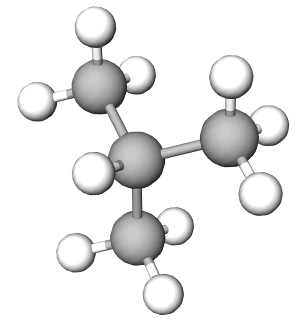
cluster density = 70/cm

ionization energy = 10.1 eV

GWP = 1430

with addition of

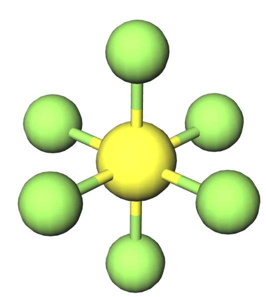
10.0% *i*-C_4H_{10}



GWP = 3

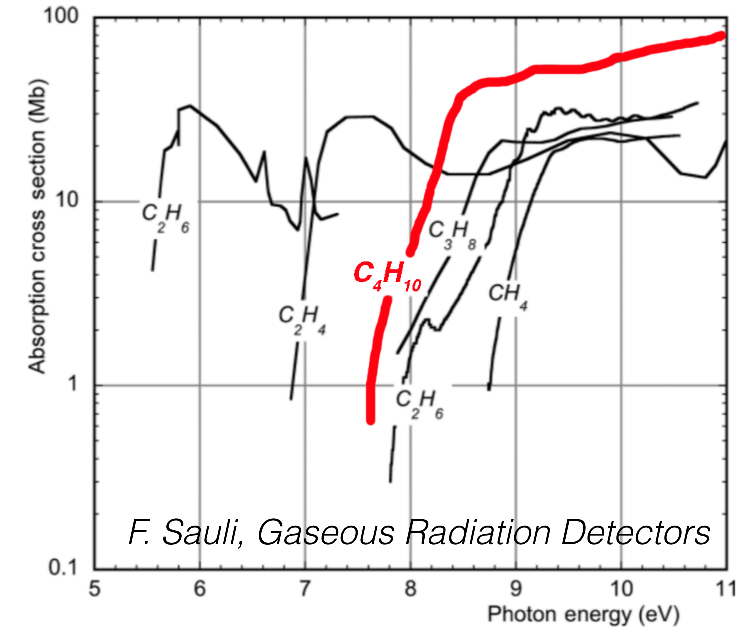
with addition of

0.3% SF_6

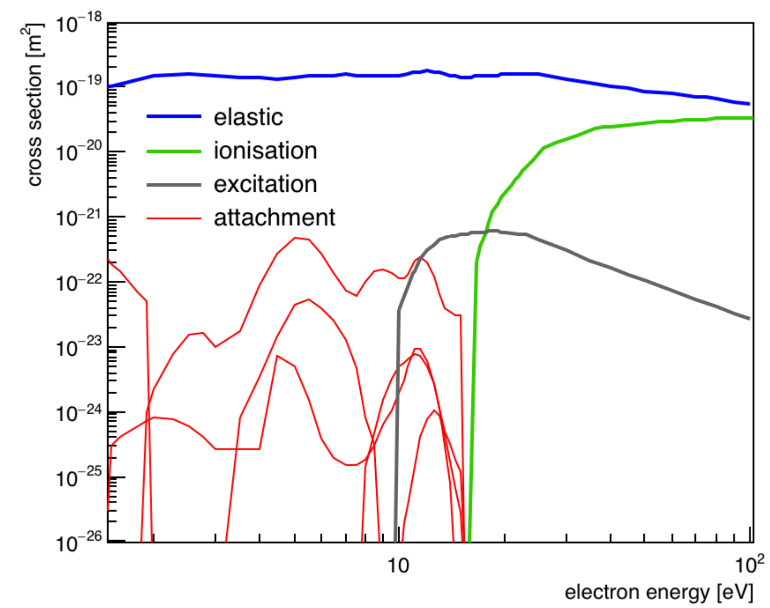


GWP = 22800

photoabsorption cross section for C_4H_{10}



cross sections between electrons and SF_6

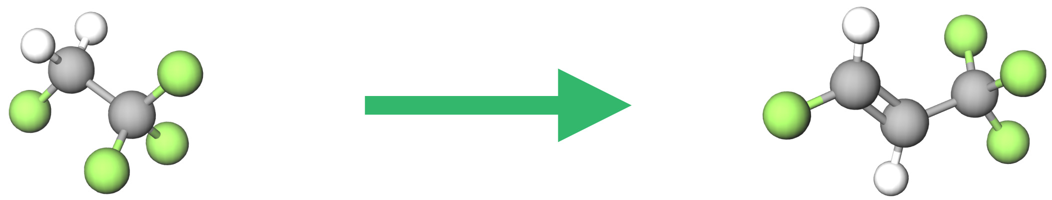


Motivation for R&D studies on new gas mixtures for the forthcoming Muon Identifier at ALICE:

- **reduce greenhouse gas emissions** in the atmosphere
- **cost saving**: $C_2H_2F_4$ is being phased out by EU regulations → **possible rise of prices and limited future availability**

Properties of $C_3H_2F_4$

95% of the total GWP of the ALICE mixture is due to the presence of $C_2H_2F_4$, therefore:

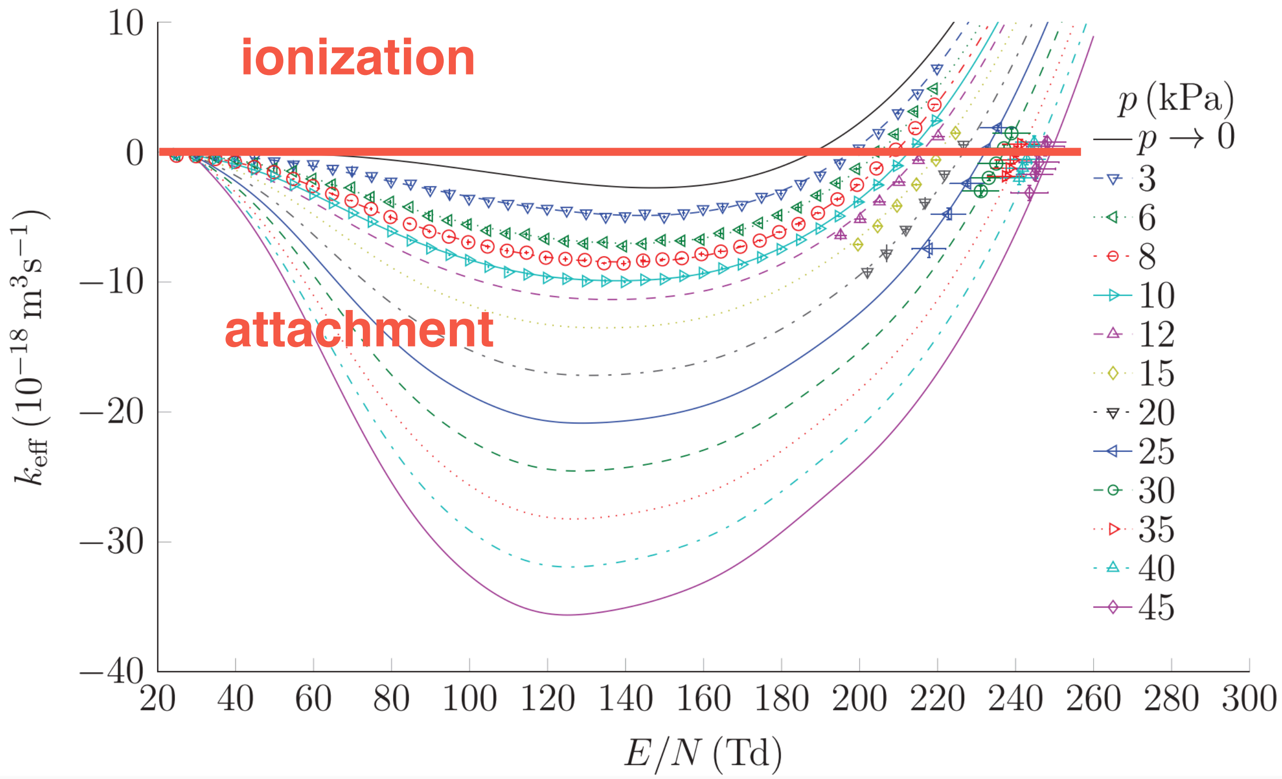


$C_2H_2F_4$ $C_3H_2F_4$

Tetrafluoropropene $C_3H_2F_4$ (HFO1234ze(E)):

- HFO1234ze(E) is **not flammable** at room temperature and its **GWP = 7***
- Products of the atmospheric oxidation of HFO1234ze(E) have negligible environmental impact
  → Javadi, M. S., et al., Atmospheric Chemistry and Physics, 2008
- N_p = ~90/cm and E_{ion} = ~9 eV
  → simulation by Saviano, G., et al., *JINST* 13.03, 2018
- **the strong electron attachment makes $C_3H_2F_4$ a promising gas for electric insulation**
  → Rabie M., et al., *Environmental science & technology* 52.2, 2018
- **since several parameters are unknown** (electron collision cross sections, the photon absorption spectrum, etc), **no possibility to implement reliable simulations (for now)**

Effective ionization rate coefficient as a function of the reduce electric field:



Chachereau A., et al, *Plasma Sources Science and Technology* 25.4, 2016.

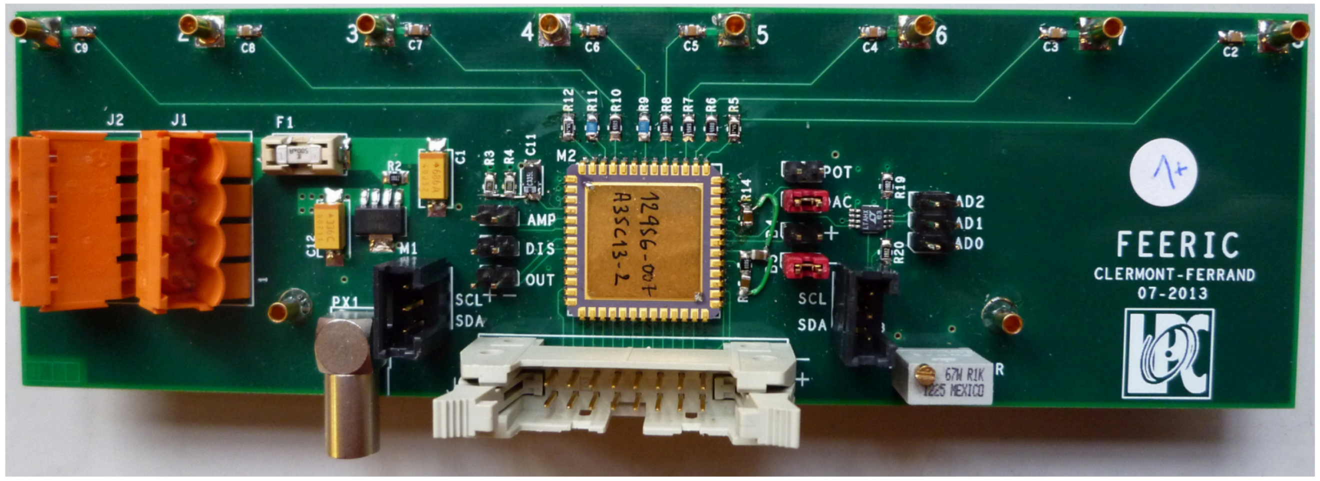
Pressure dependence of k_{eff} is a typical indication of **three-body attachment**

*5th IPCC has revised this value: GWP < 1

Experimental set-up

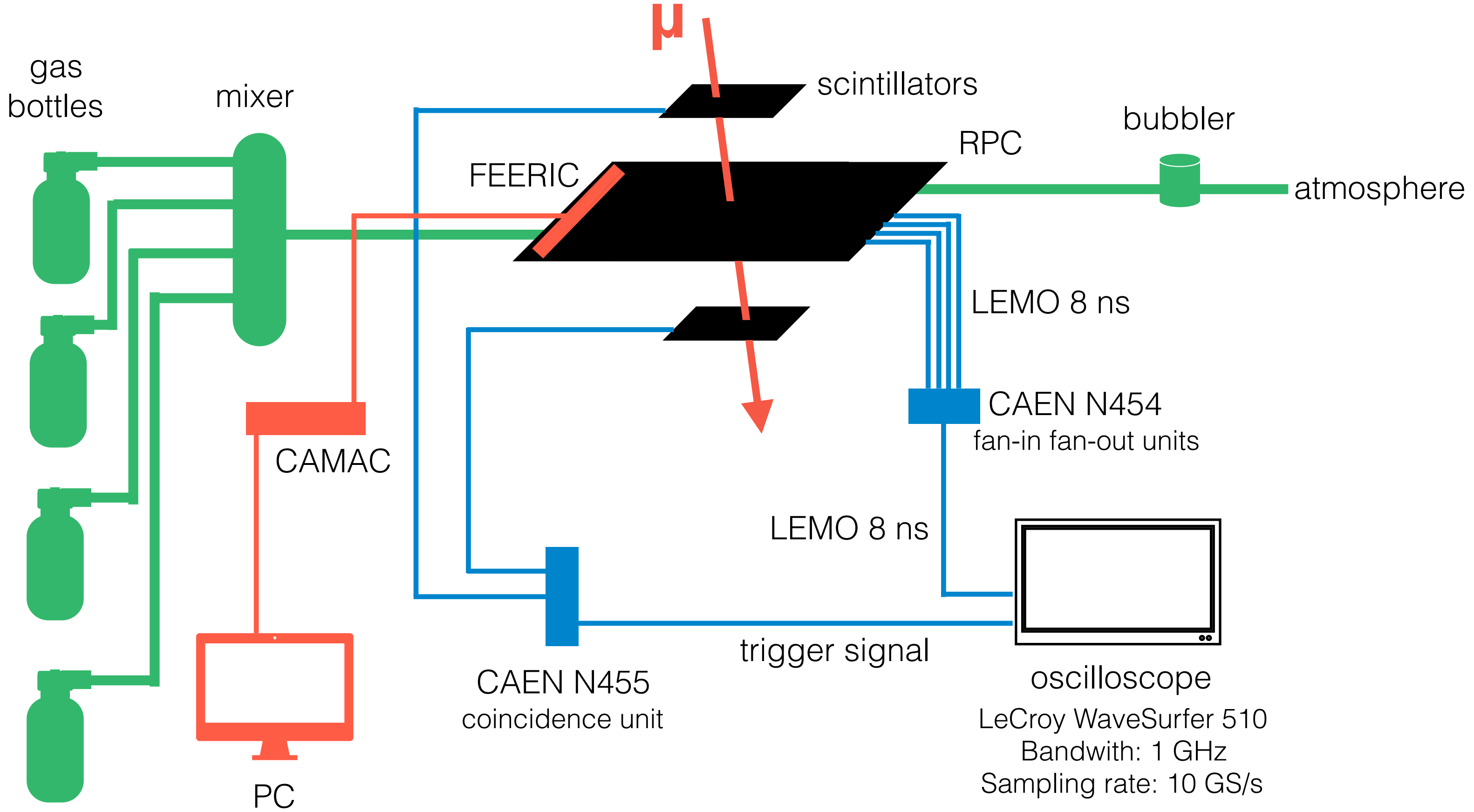
R&D studies on eco-friendly gas mixtures:

- small-size (50 x 50 x 0.2 cm^3) RPC inside a Faraday cage
- trigger: three scintillators coupled with photomultipliers
- HV is applied with temperature and pressure correction (p_0 = 1000 mbar and T_0 = 20 °C)
- possibility to mix at maximum 4 different gases with H_2O vapor
- signals in read-out strips (2 x 50 cm^2) **discriminated by FEERIC front-end electronics and acquired by oscilloscope**



Dupieux P. et al., *Upgrade of the ALICE muon trigger electronics*, JINST 9.09 (2014)

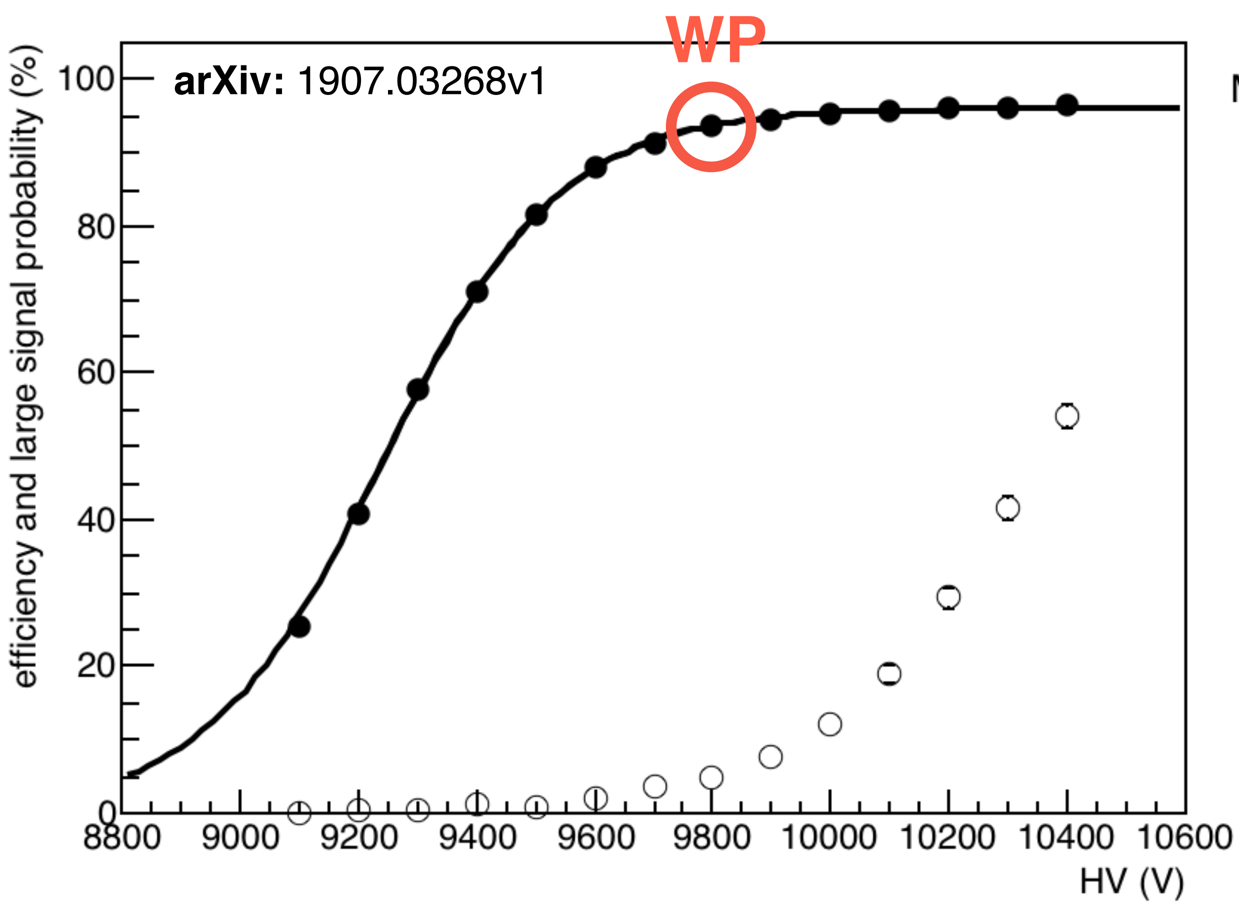
- FEERIC amplifies signals (input charge range = 0.1÷1 pC): this allows one to operate in pure avalanche mode with a lower charge per hit (by a factor 3÷5)

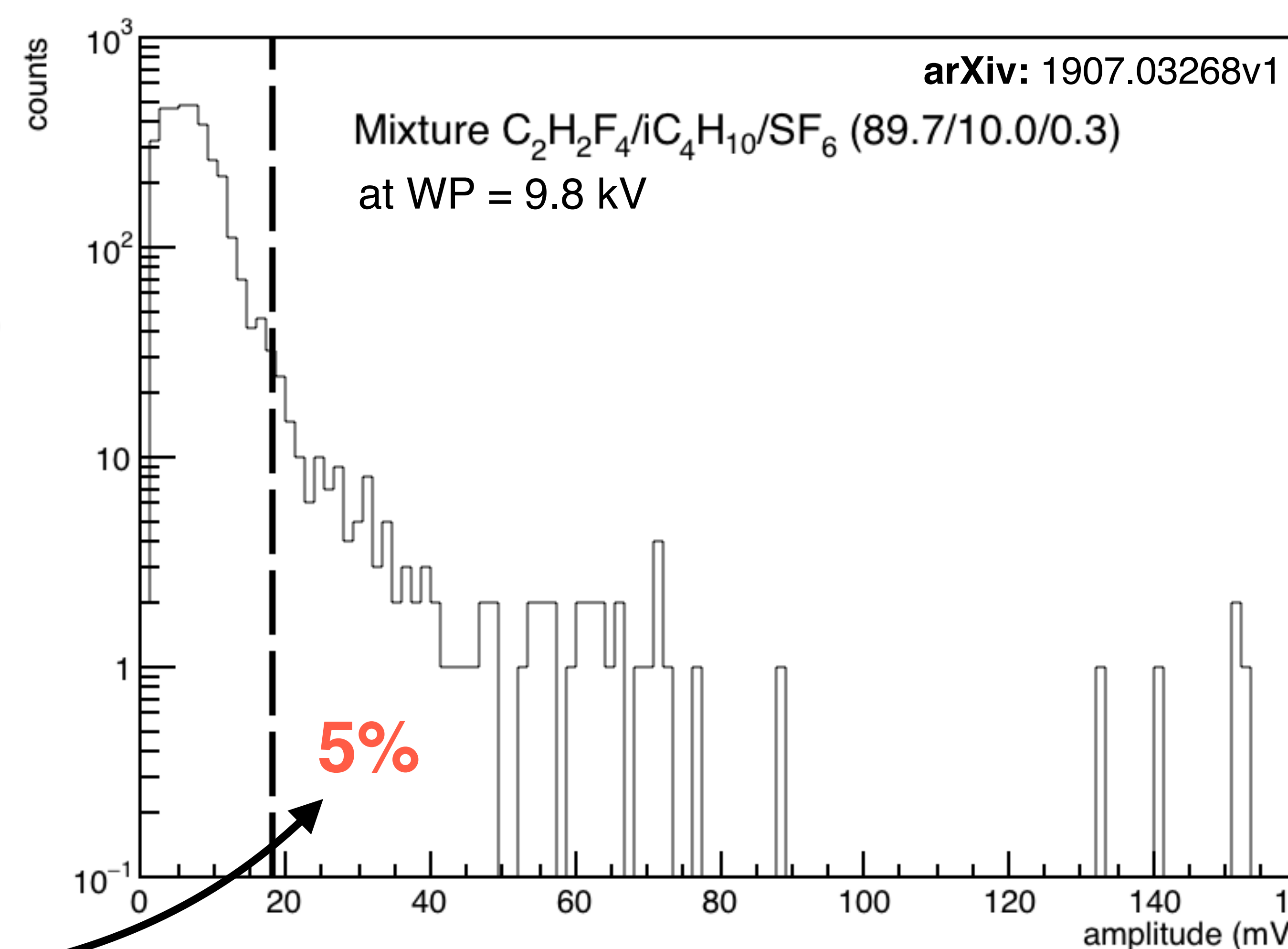


total trigger area: ~6 x 6 cm^2

Characterization with ALICE mixture

Efficiency and large signal probability with ALICE mixture:

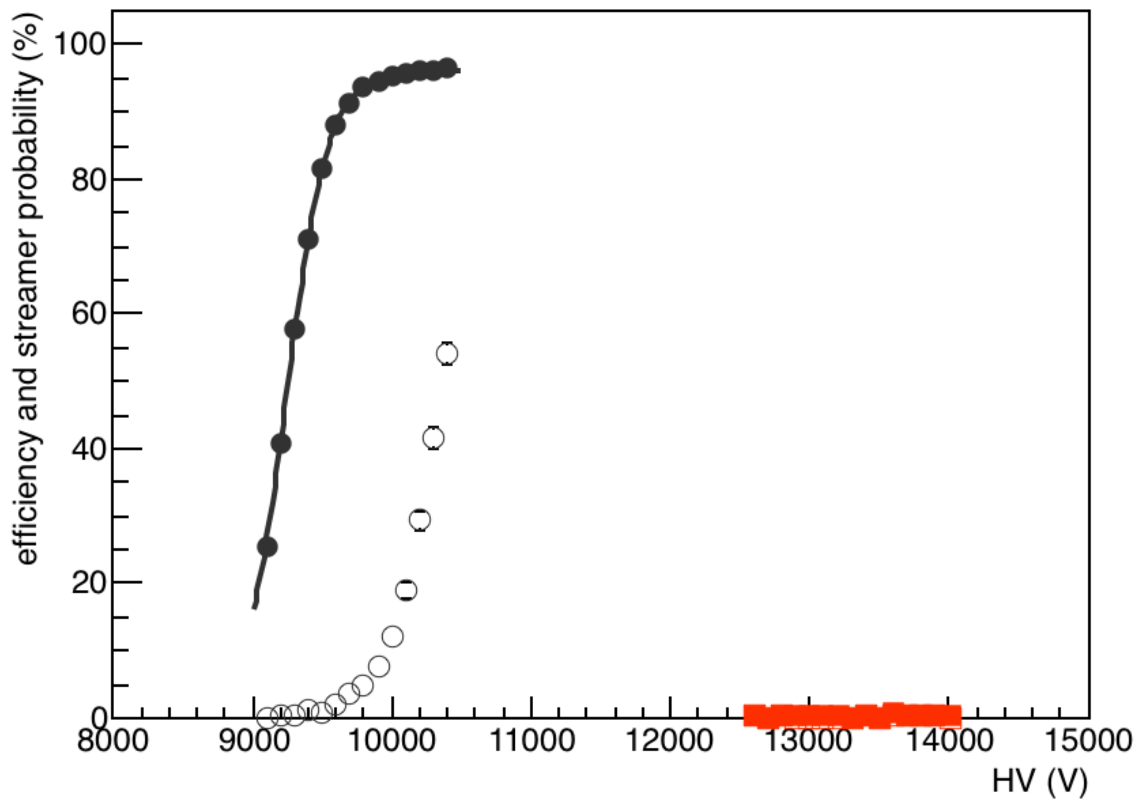




Thresholds used for the analysis:

- efficiency (FEERIC response):
  $Q_{induced}$ = ~130 fC (70 mV after amplification)
- large signal:
  amplitude (by the oscilloscope) > 18 mV
  (threshold used to tag 5% largest signals)

$C_3H_2F_4$-based mixtures

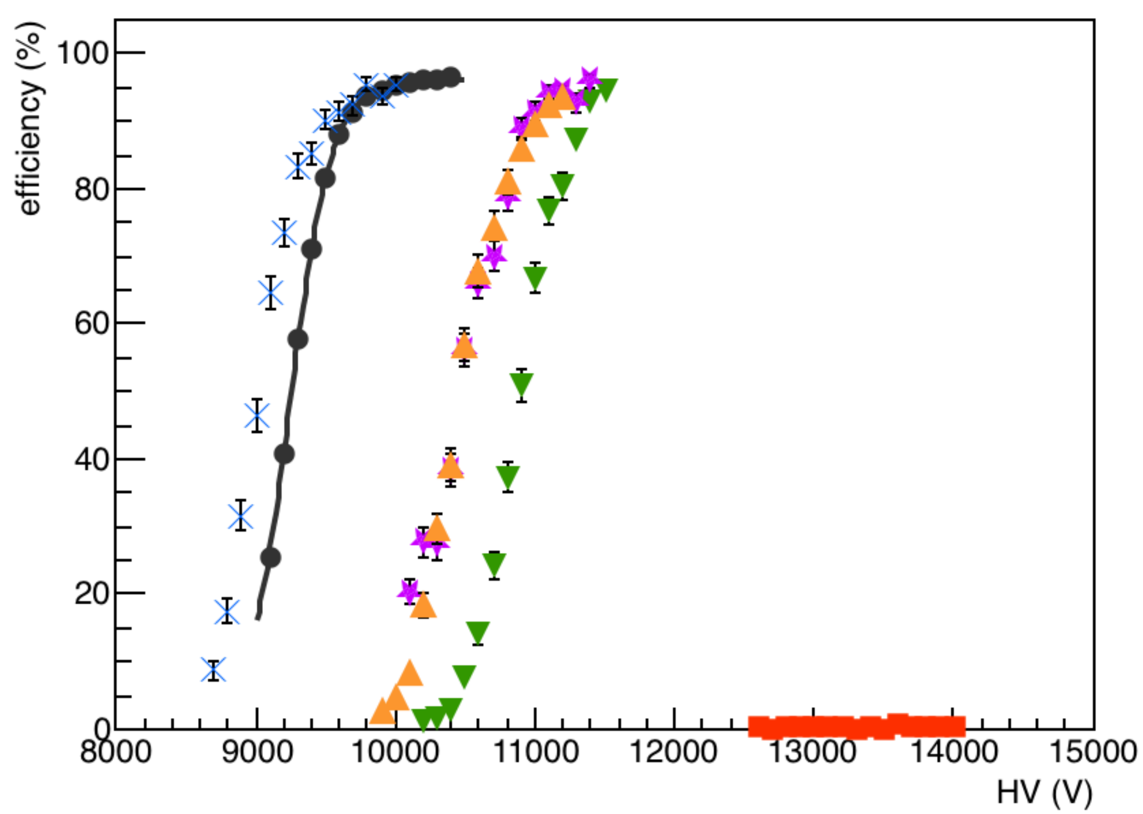


100% $C_3H_2F_4$: efficiency is ~0% at HV < 14 kV

→ maximum HV value of power supply is **15 kV** as well as HV cables and connectors are compatible with voltages up to 15 kV

→ would very likely result in current instabilities and **high detector noise**

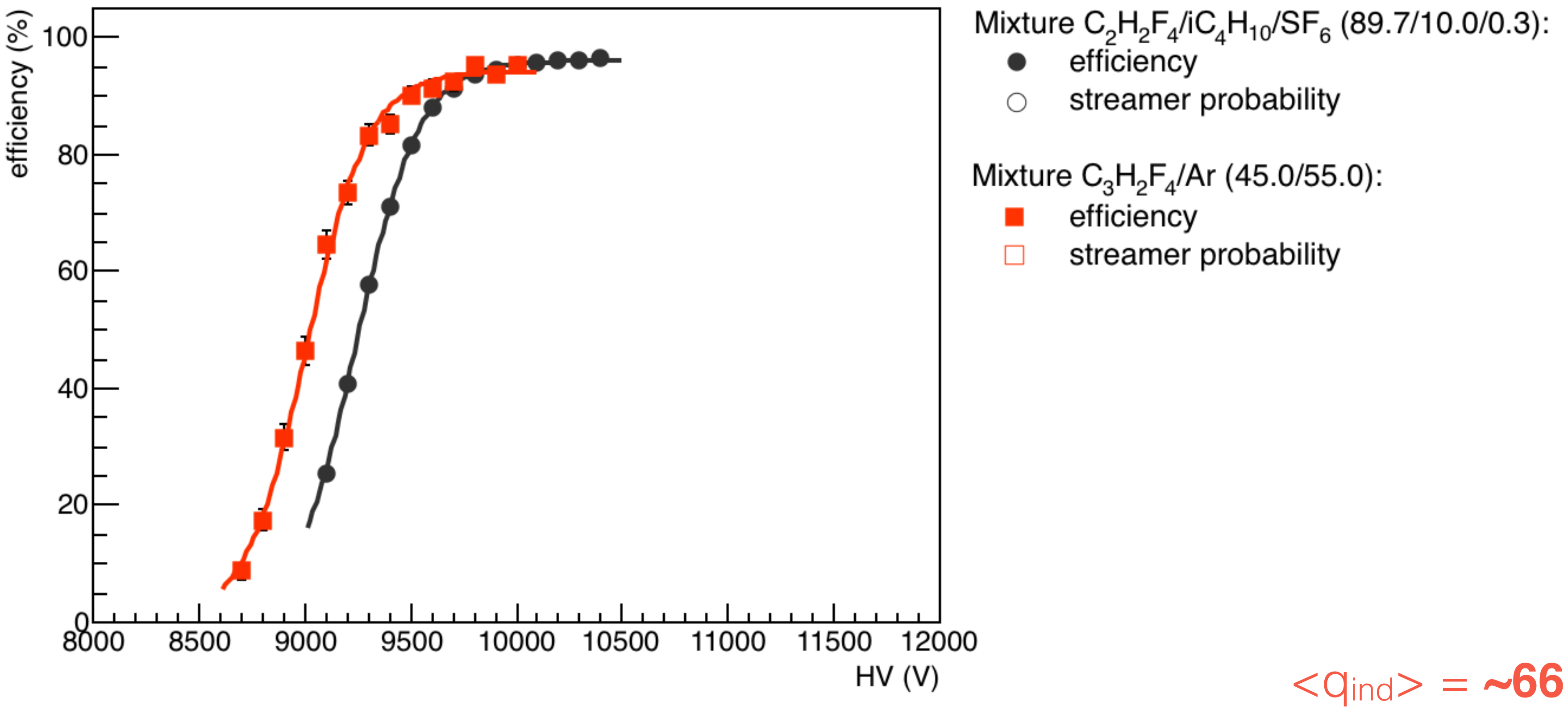
If $C_3H_2F_4$ is diluted, efficiency curves are shifted to lower HV values → **tests with Ar, N_2, O_2, CO_2**



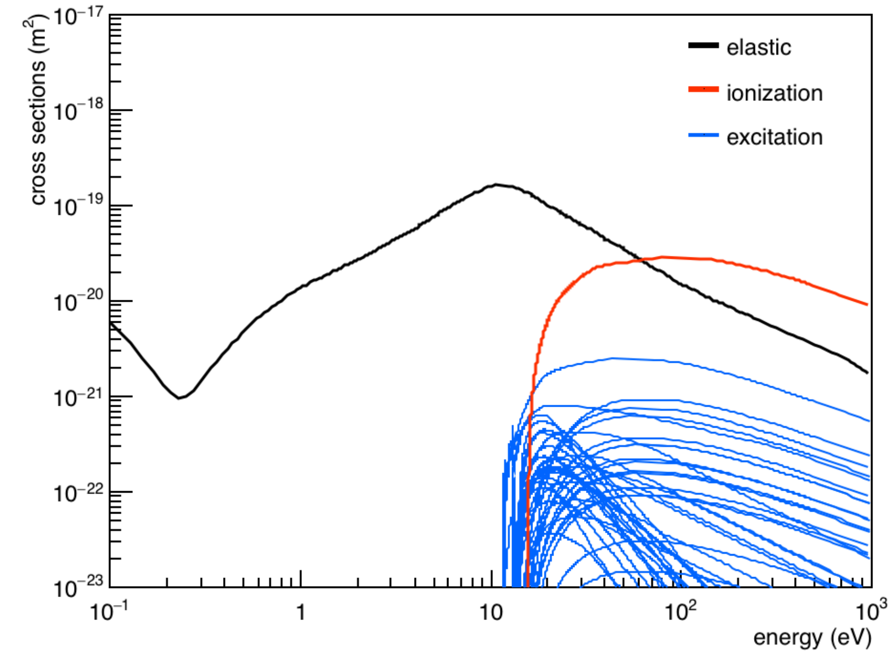
Gas mixtures are selected taking into account:

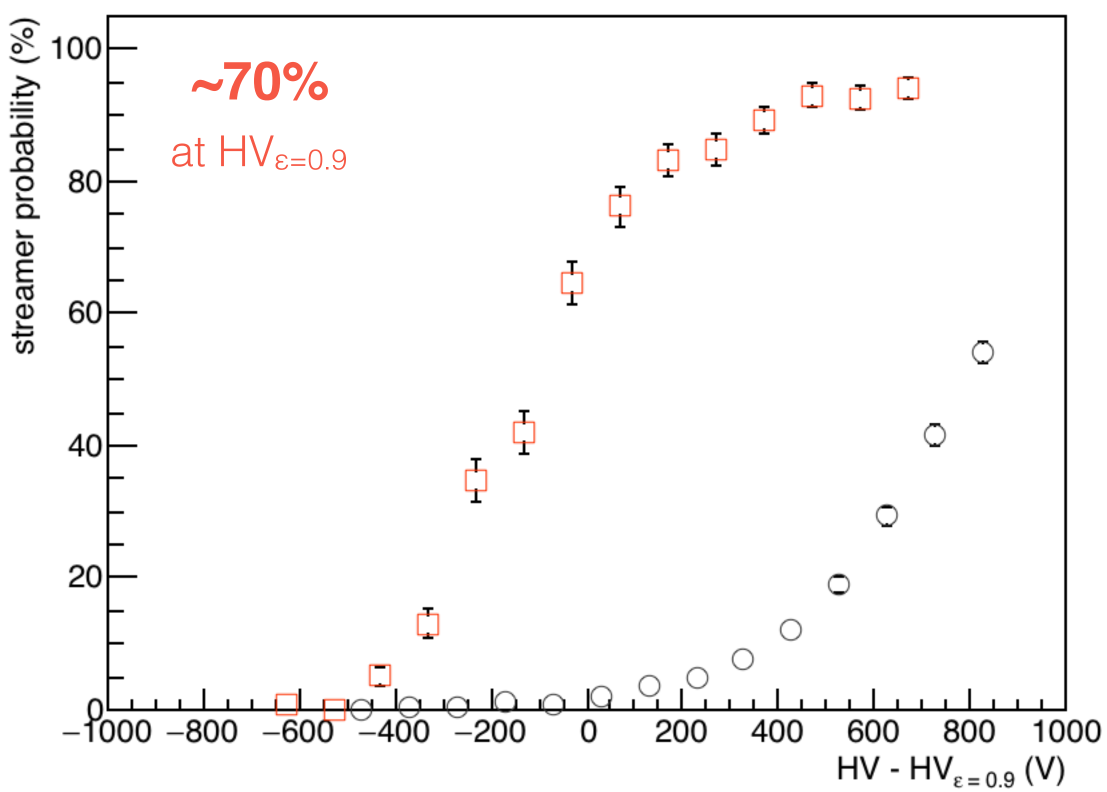
- streamer probability
- average induced charge
- current stability

45% $C_3H_2F_4$ + 55% Ar



Ar: N_p = 25/cm, E_{ion} = 15.7 eV, GWP = 0

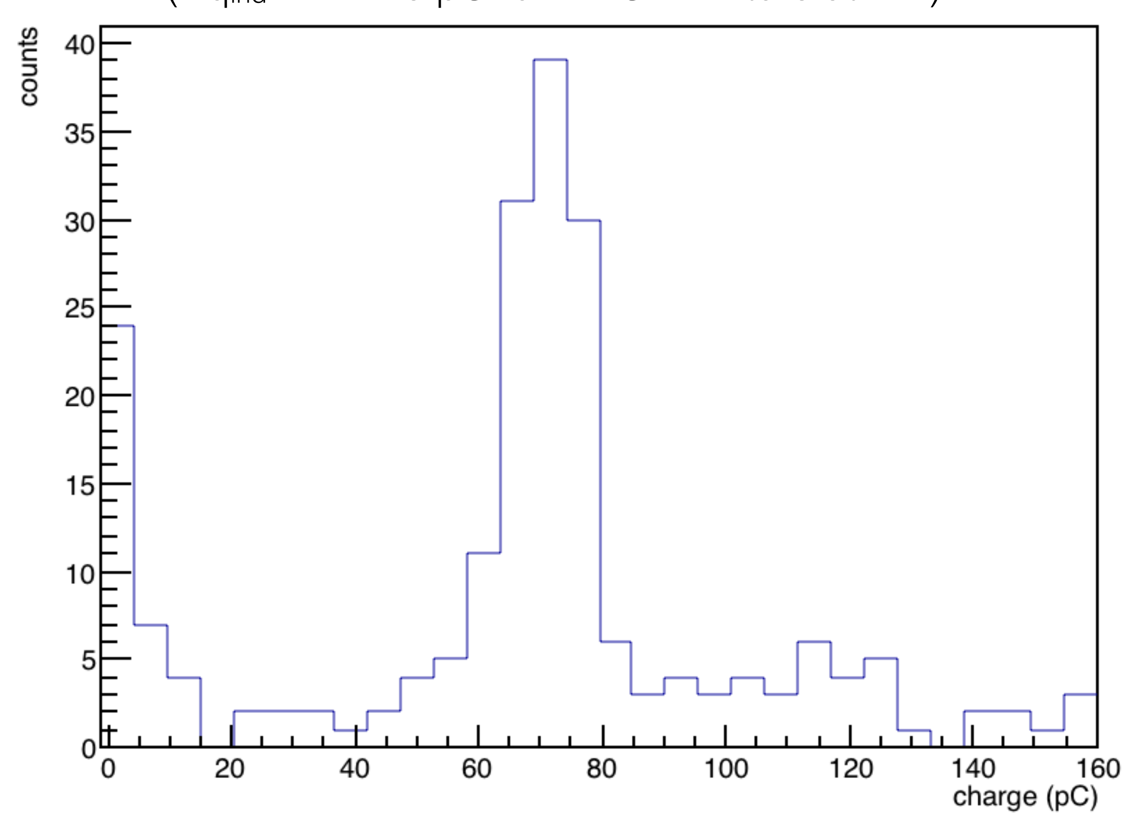




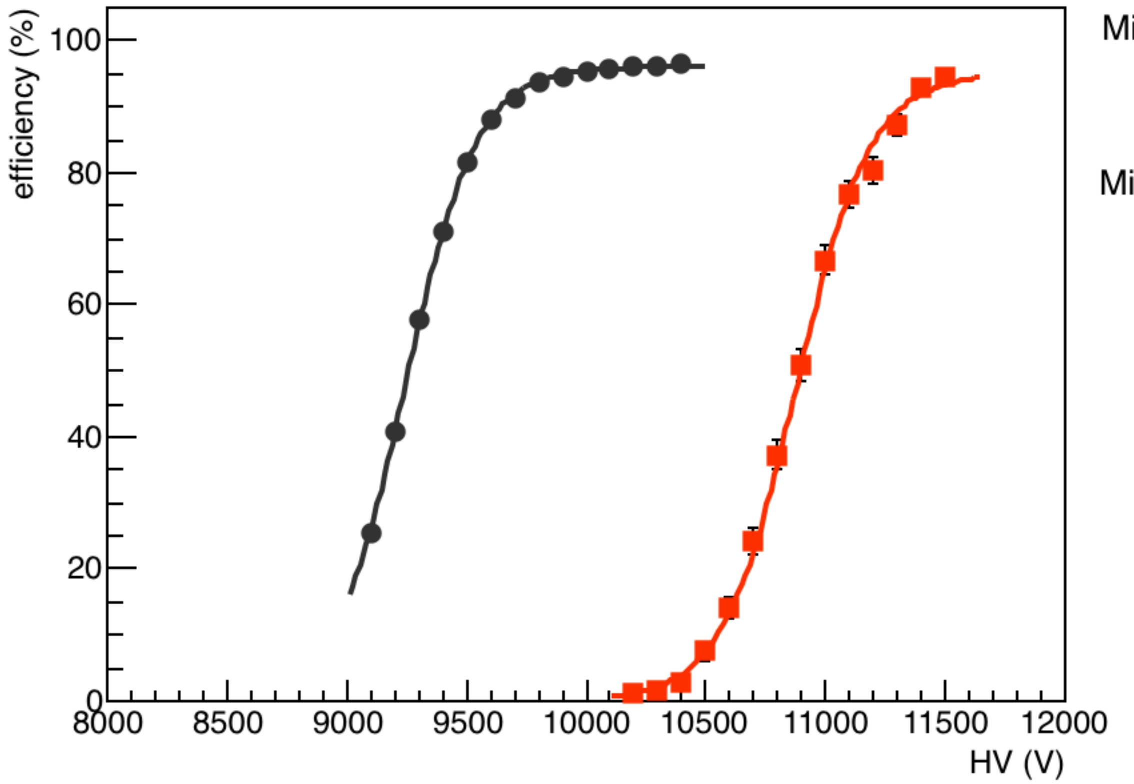
<q_{ind}> = **~66 pC** at WP of 9.8 kV

(<q_{ind}> = ~2.6 pC for ALICE mixture at WP)

x25



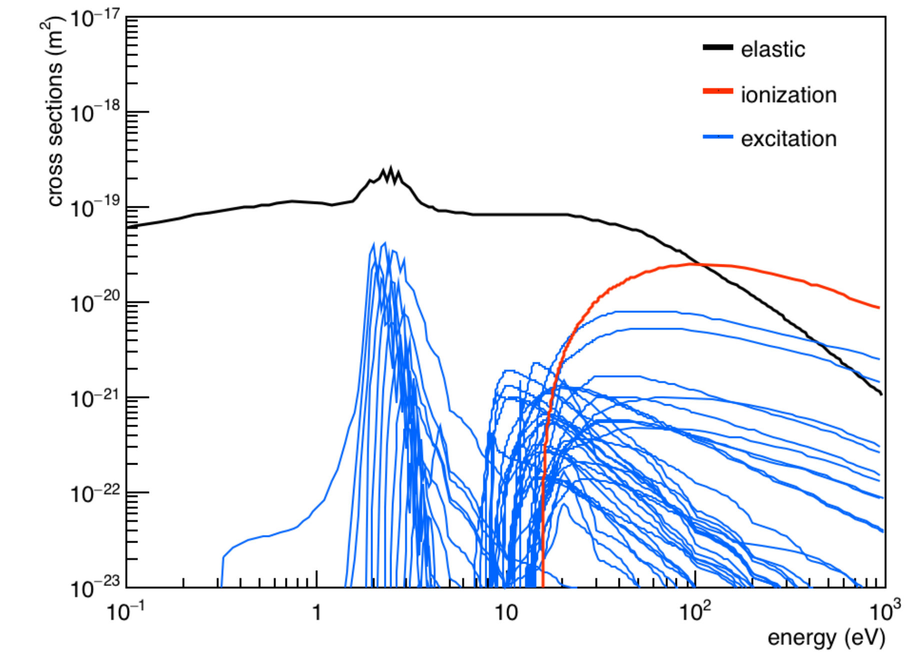
45% $C_3H_2F_4$ + 55% N_2

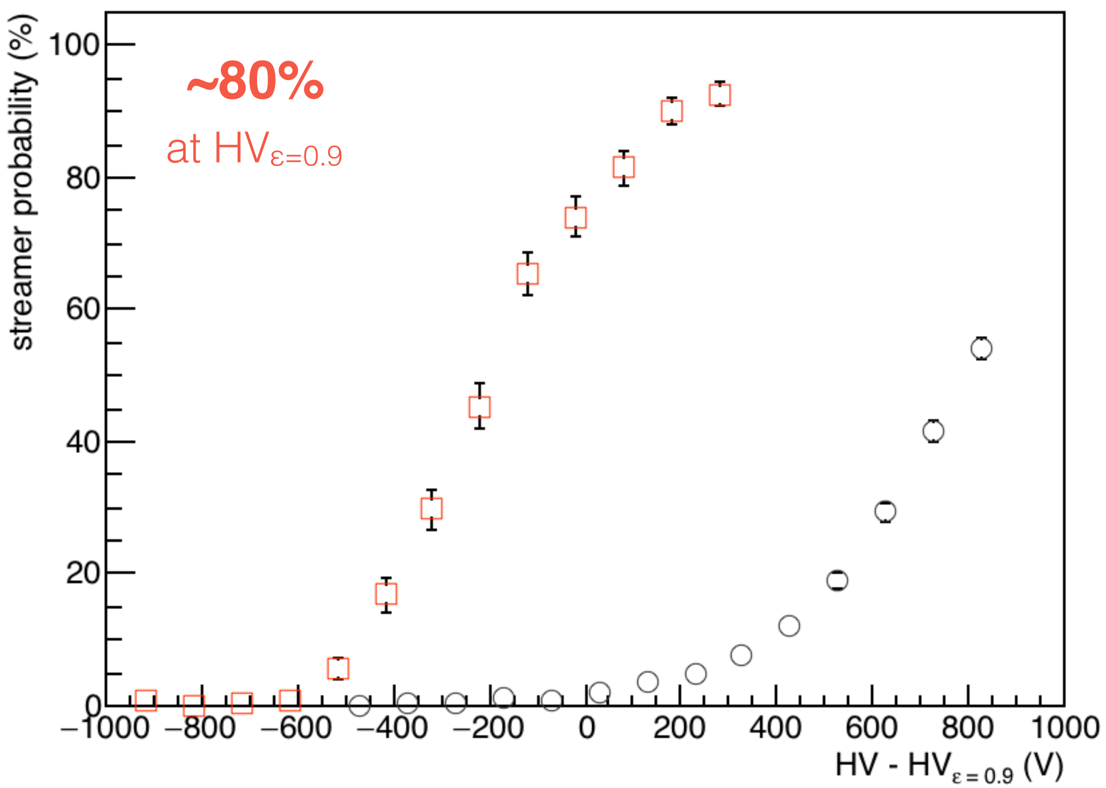


Mixture $C_2H_2F_4/iC_4H_{10}/SF_6$ (89.7/10.0/0.3):
- ● efficiency
- ○ streamer probability

Mixture $C_3H_2F_4/N_2$ (45.0/55.0):
- ■ efficiency
- □ streamer probability

N_2: N_p = ~24/cm, E_{ion} = 15.6 eV, GWP = 0

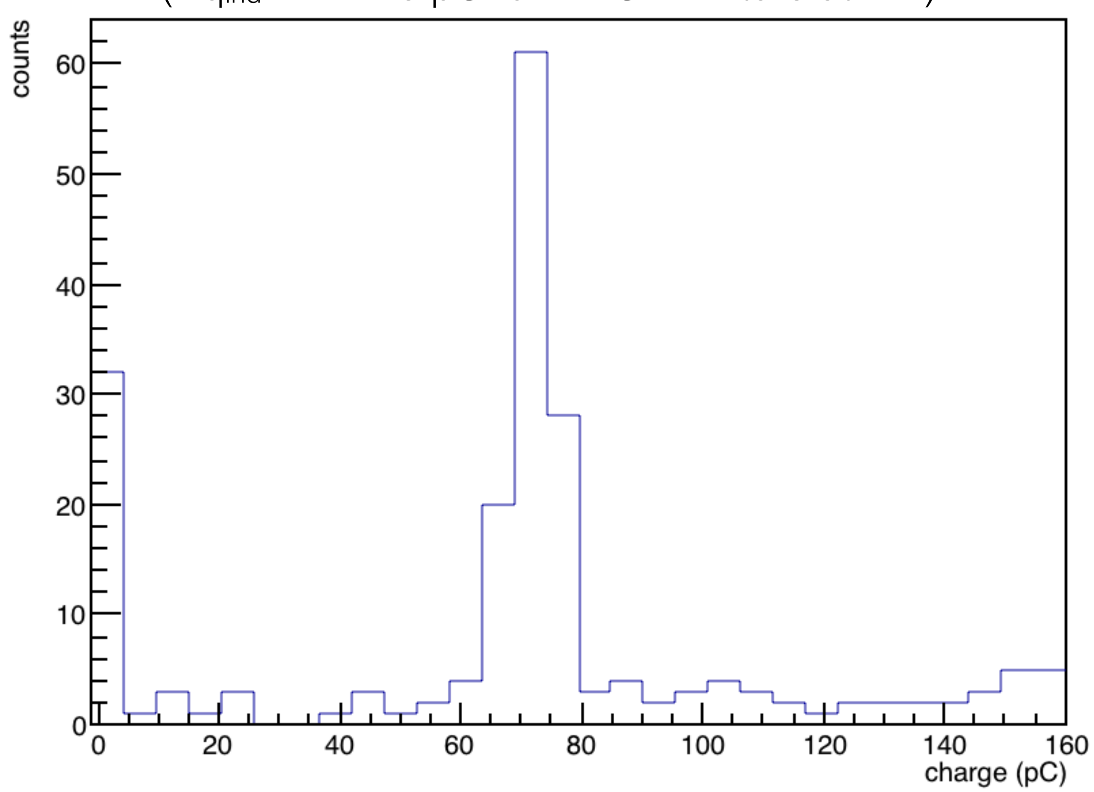




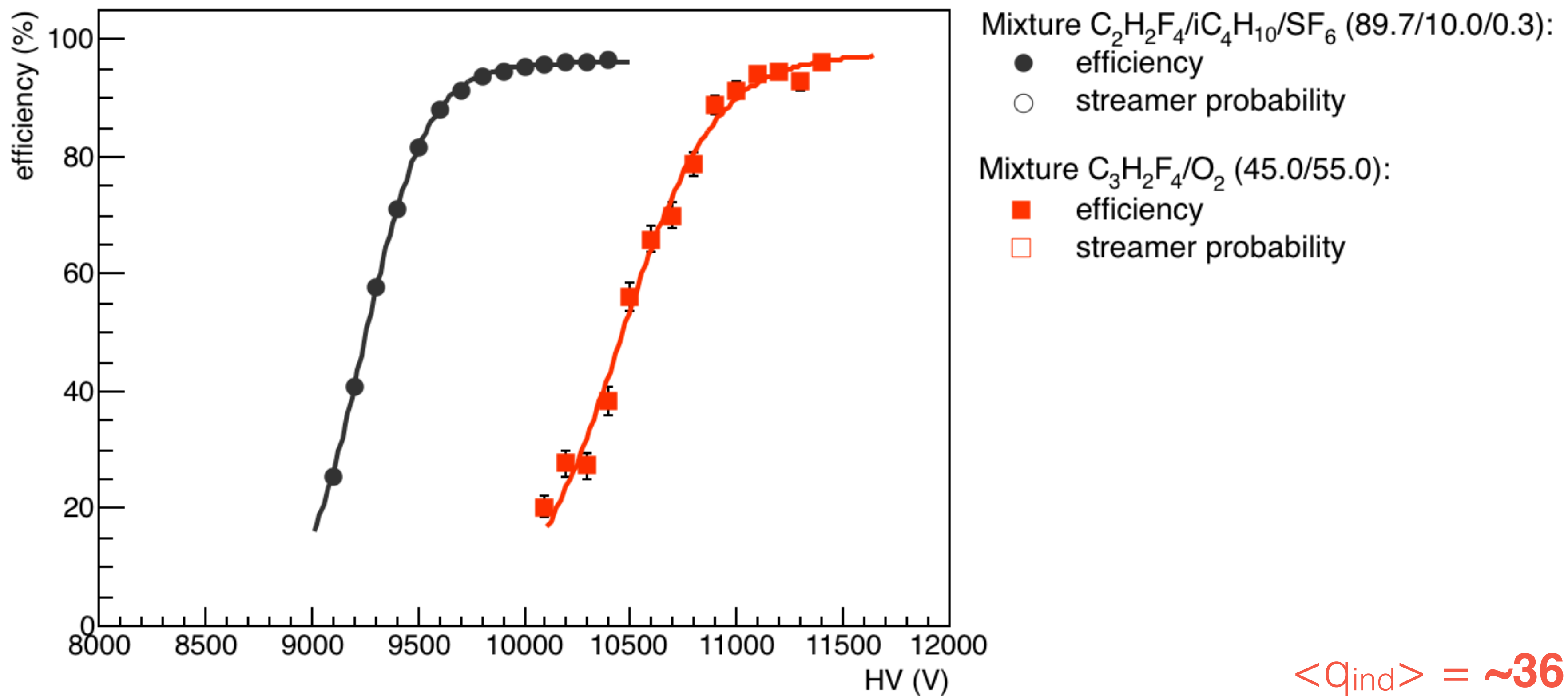
<q_{ind}> = **~68 pC** at WP of 11.5 kV

(<q_{ind}> = ~2.6 pC for ALICE mixture at WP)

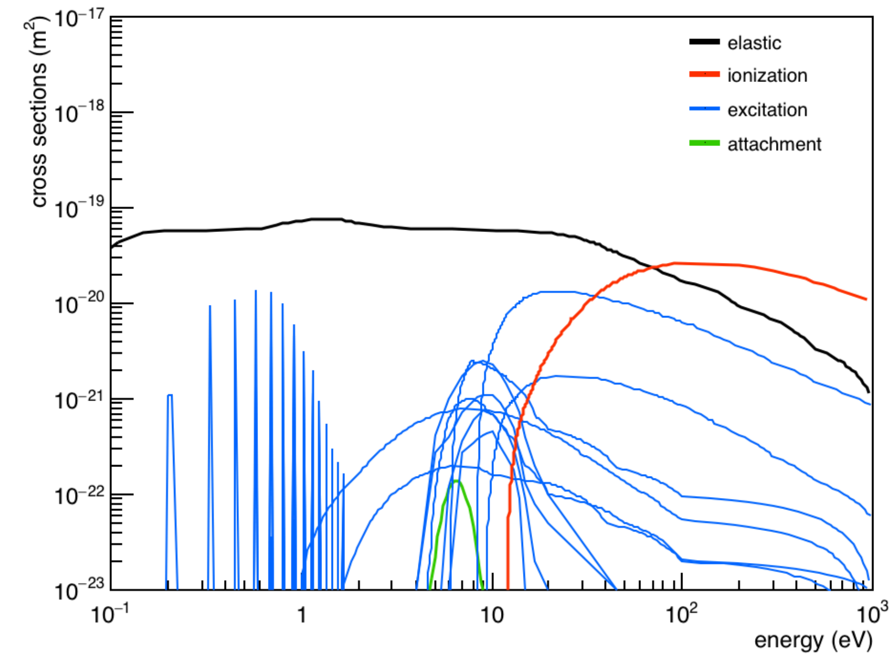
x26



45% $C_3H_2F_4$ + 55% O_2



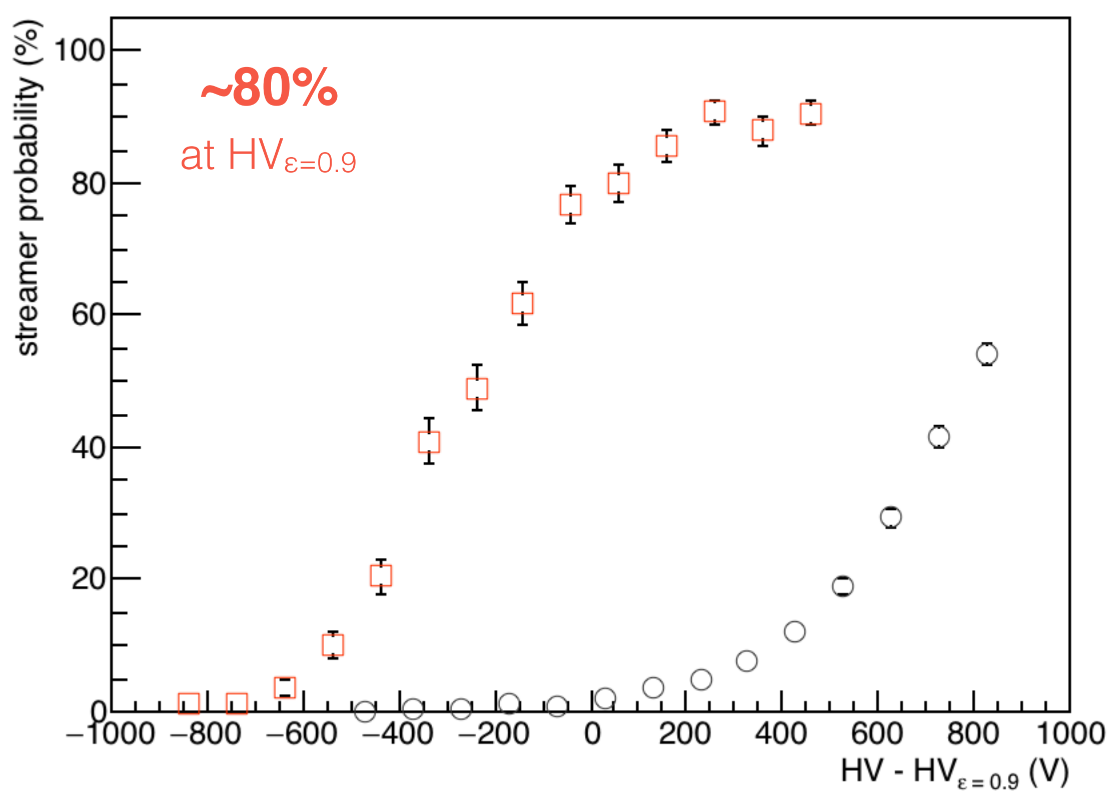
O_2: N_p = ~25/cm, E_{ion} = 12.1 eV, GWP = 0



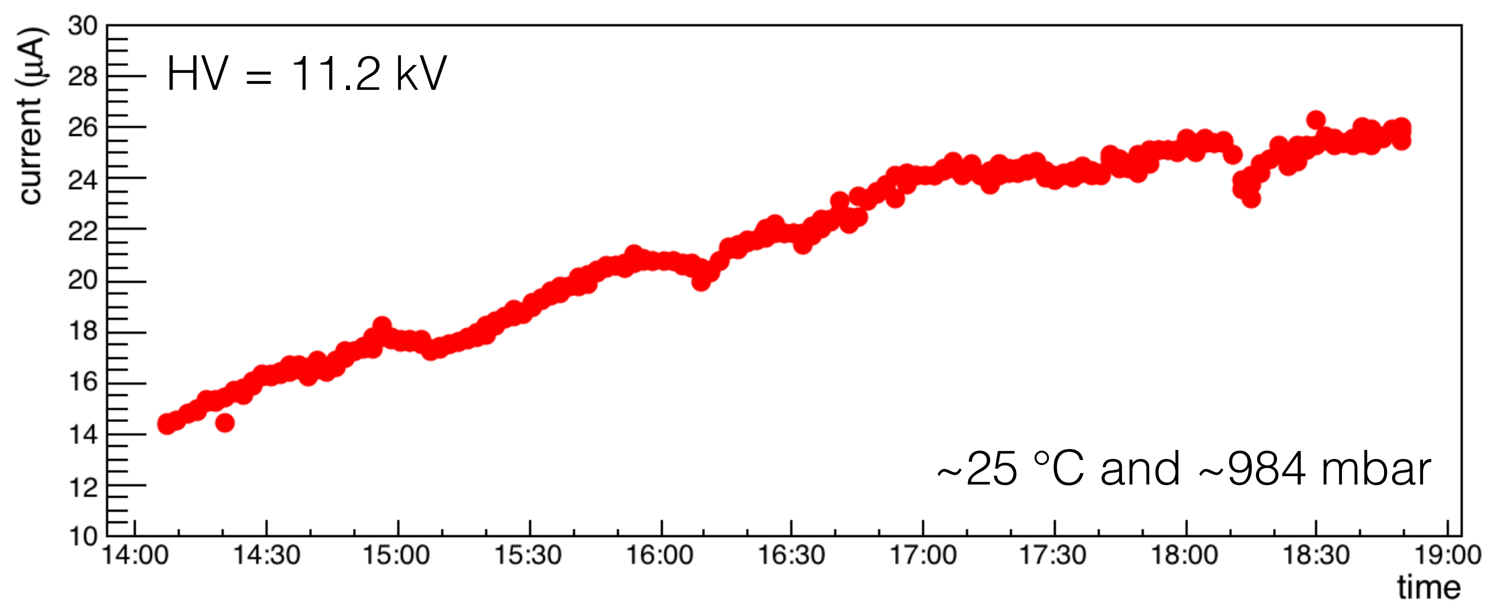
<q_{ind}> = **~36 pC** at WP of 11.2 kV

(<q_{ind}> = ~2.6 pC for ALICE mixture at WP)

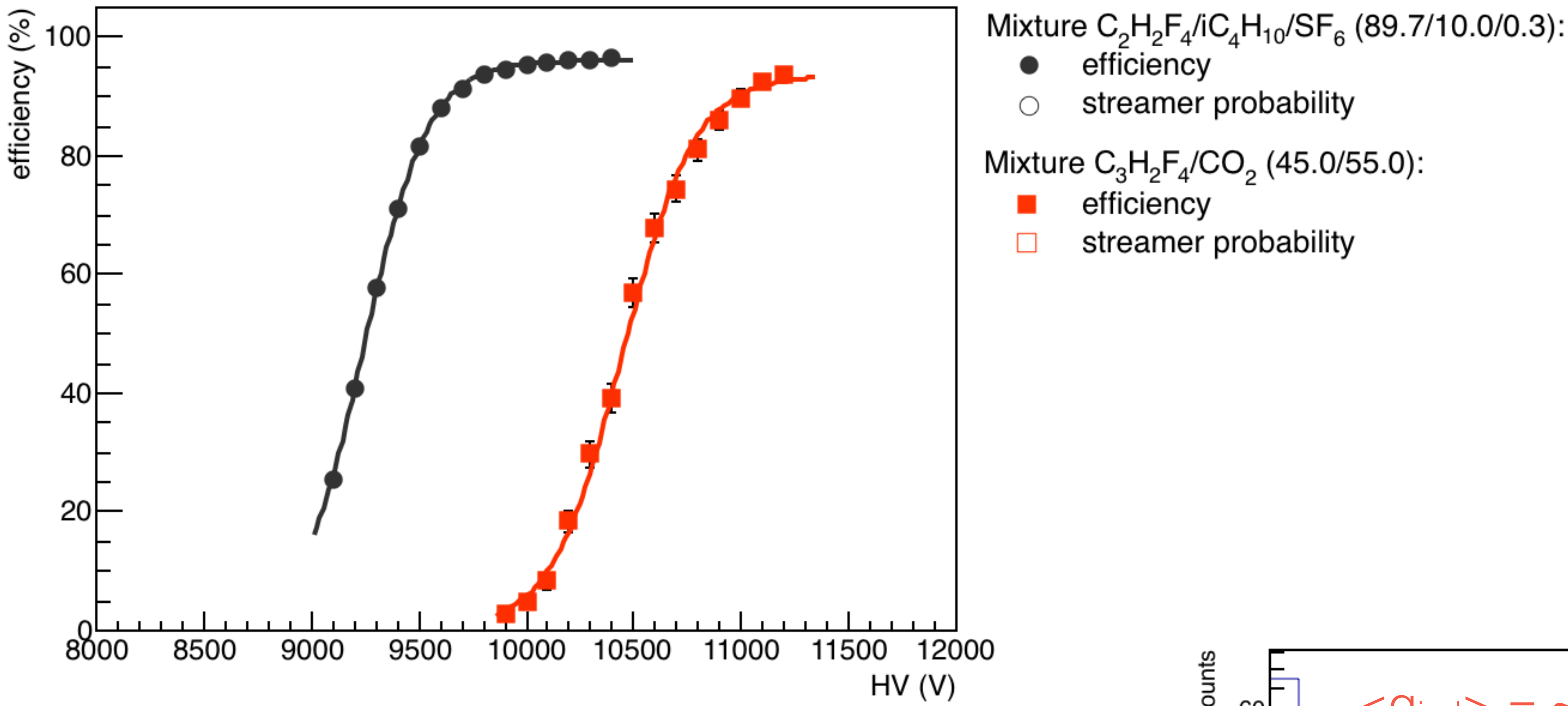
x14



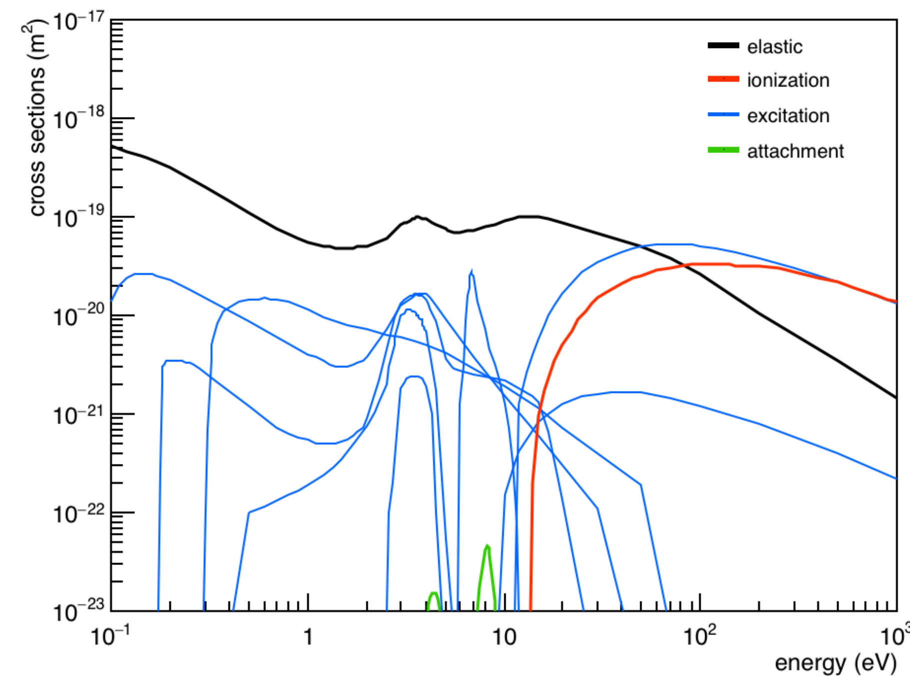
Current instability in $C_3H_2F_4$-based mixtures with O_2:

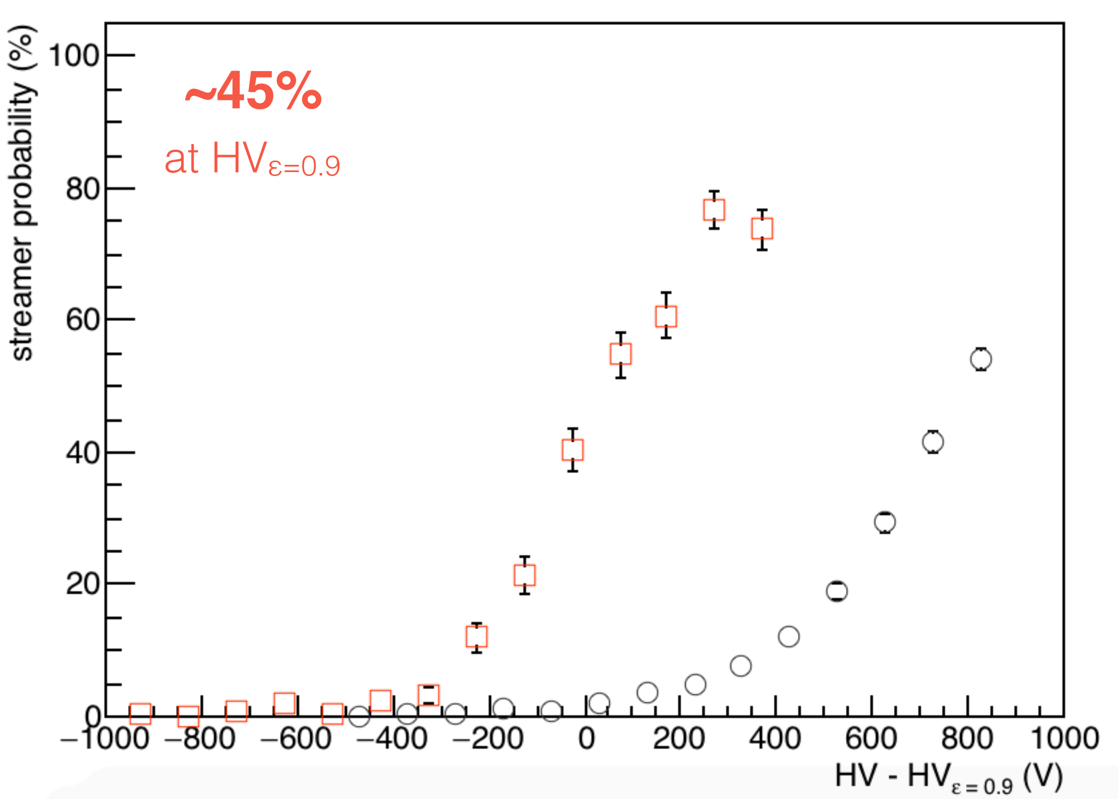


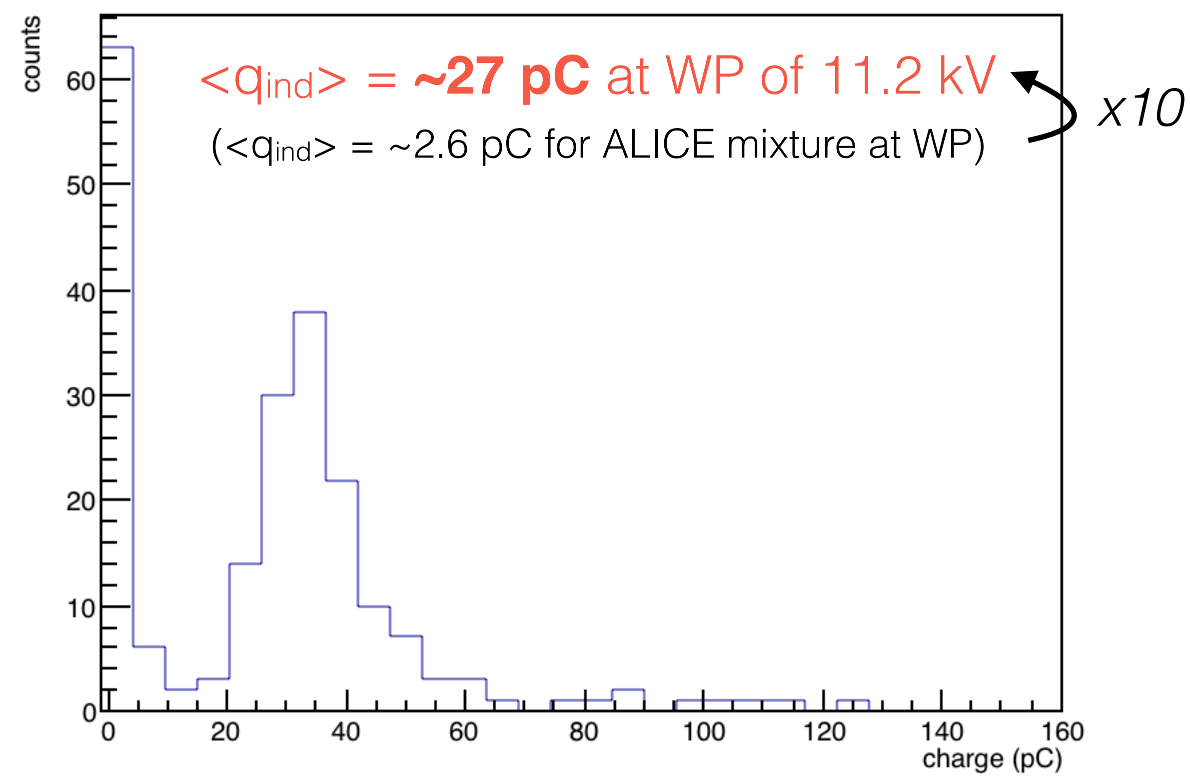
45% $C_3H_2F_4$ + 55% CO_2



CO_2: N_p = 34/cm, E_{ion} = 13.8 eV, GWP = 1

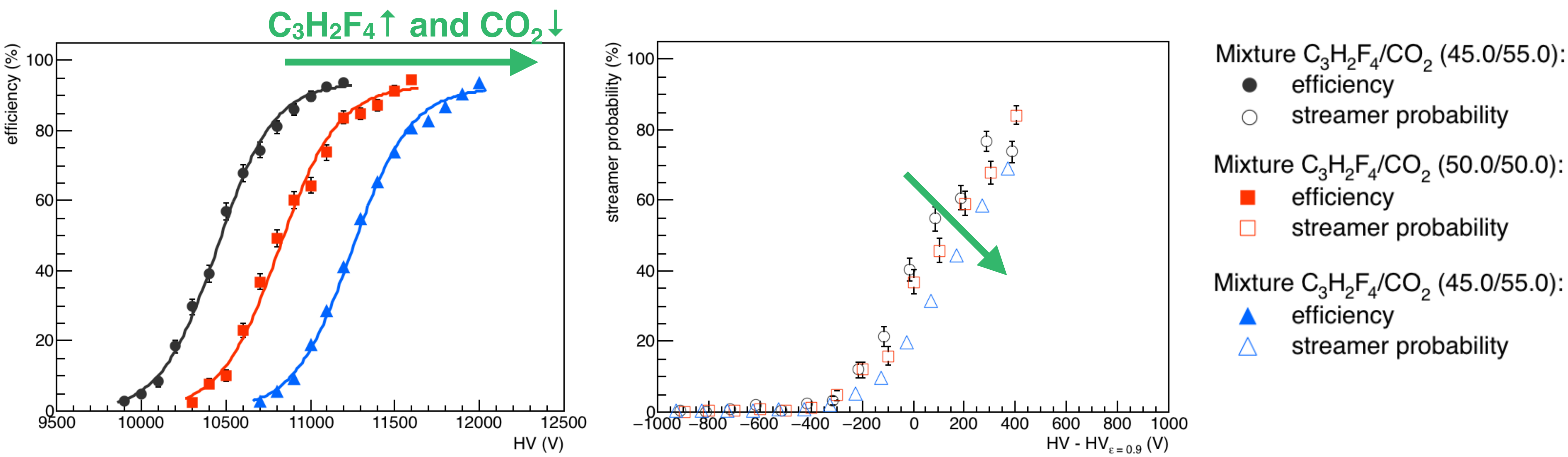




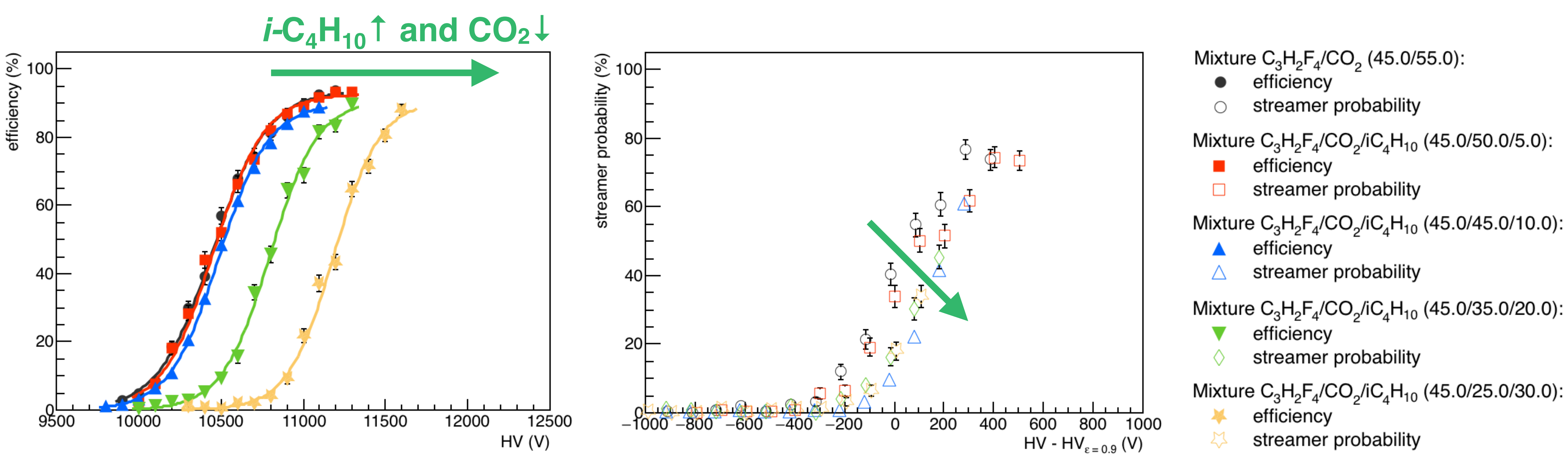


Values of streamer probability and average induced charge in $C_3H_2F_4$-based mixtures with CO_2 are the lowest ones in comparison to those with Ar, N_2 and O_2.

Variation of $C_3H_2F_4/CO_2$ and *i*-C_4H_{10}/CO_2

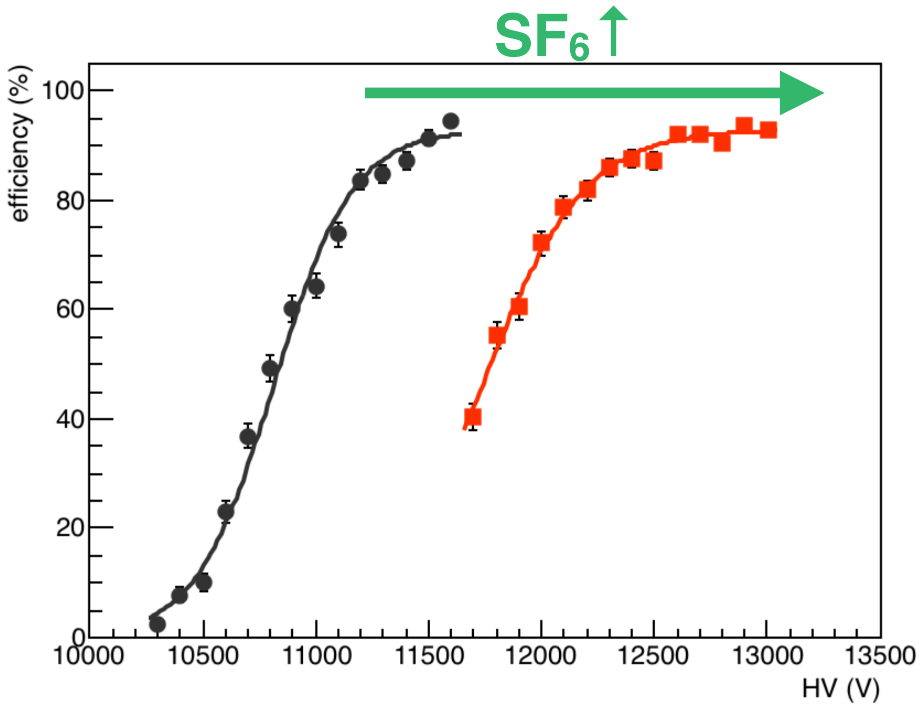


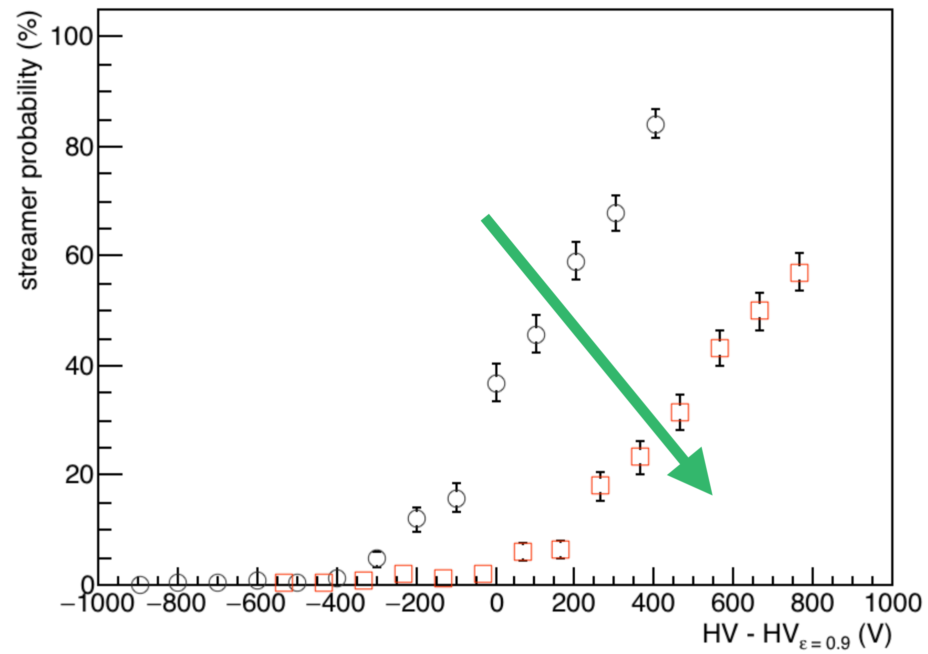
The addition of $C_3H_2F_4$ against CO_2 shifts the WP to higher HV values but decreases the streamer probability



The addition of more than 10% *i*-C_4H_{10} against CO_2 shifts the WP to higher HV values but reduces streamers

Addition of SF_6

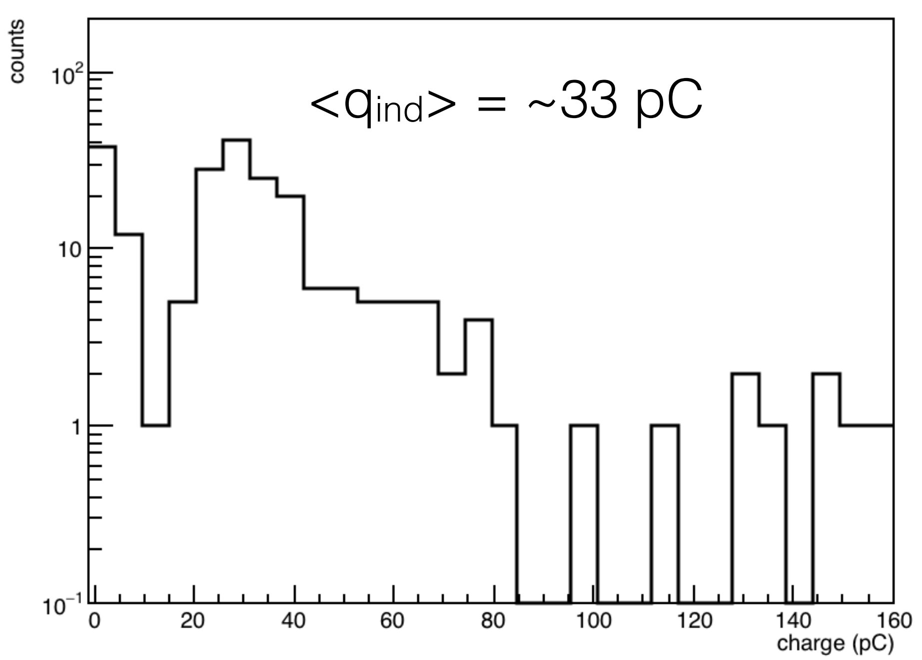




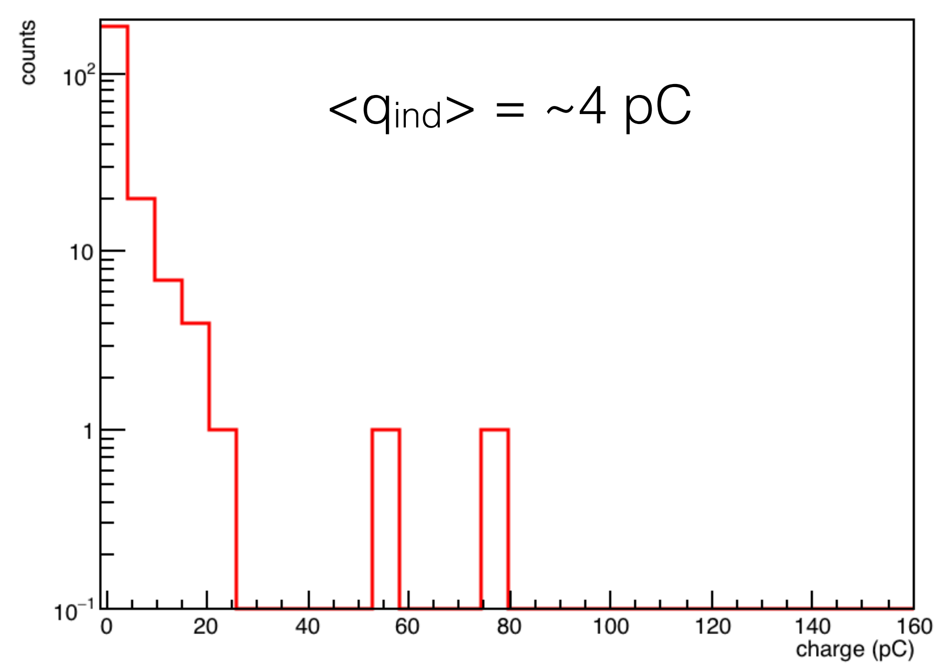
Mixture $C_3H_2F_4/CO_2$ (50.0/50.0):
- ● efficiency
- ○ streamer probability

Mixture $C_3H_2F_4/CO_2/SF_6$ (50.0/49.0/1.0):
- ■ efficiency
- □ streamer probability

$C_3H_2F_4/CO_2$ (50.0/50.0) at 11.6 kV



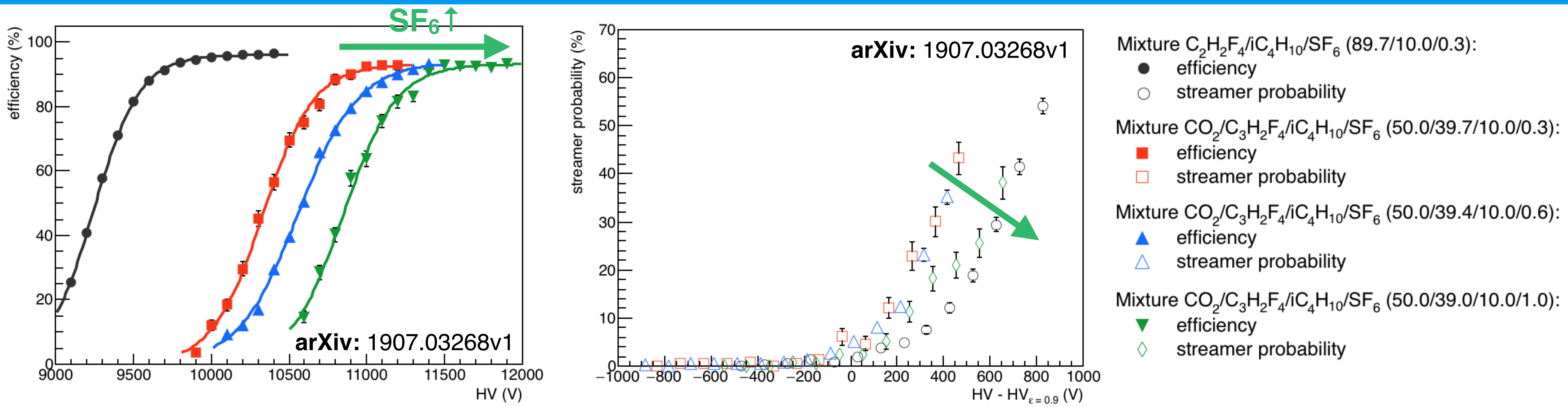
$C_3H_2F_4/CO_2/SF_6$ (50.0/49.0/1.0) at 12.7 kV



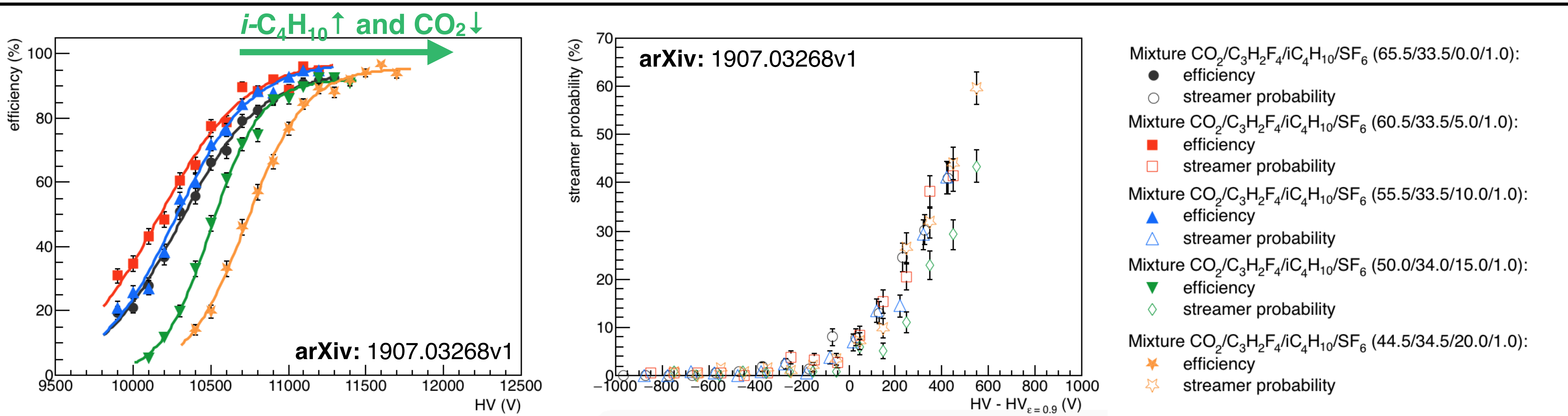
The addition of SF_6 reduces the streamer probability

→ Streamer suppression due to the use of SF_6 is already well known in $C_2H_2F_4$-based mixtures

Studies of gas mixtures with $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/SF_6$



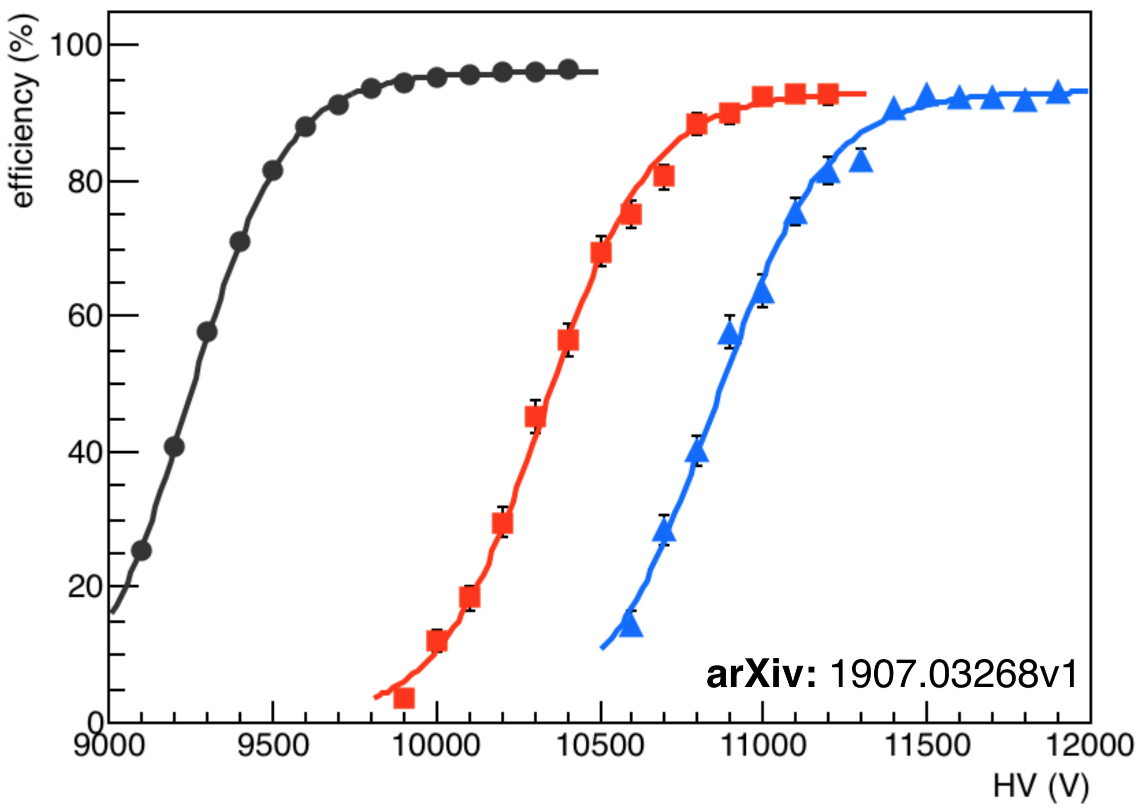
The addition of SF_6 shifts the WP to higher HV values but decreases the streamer probability

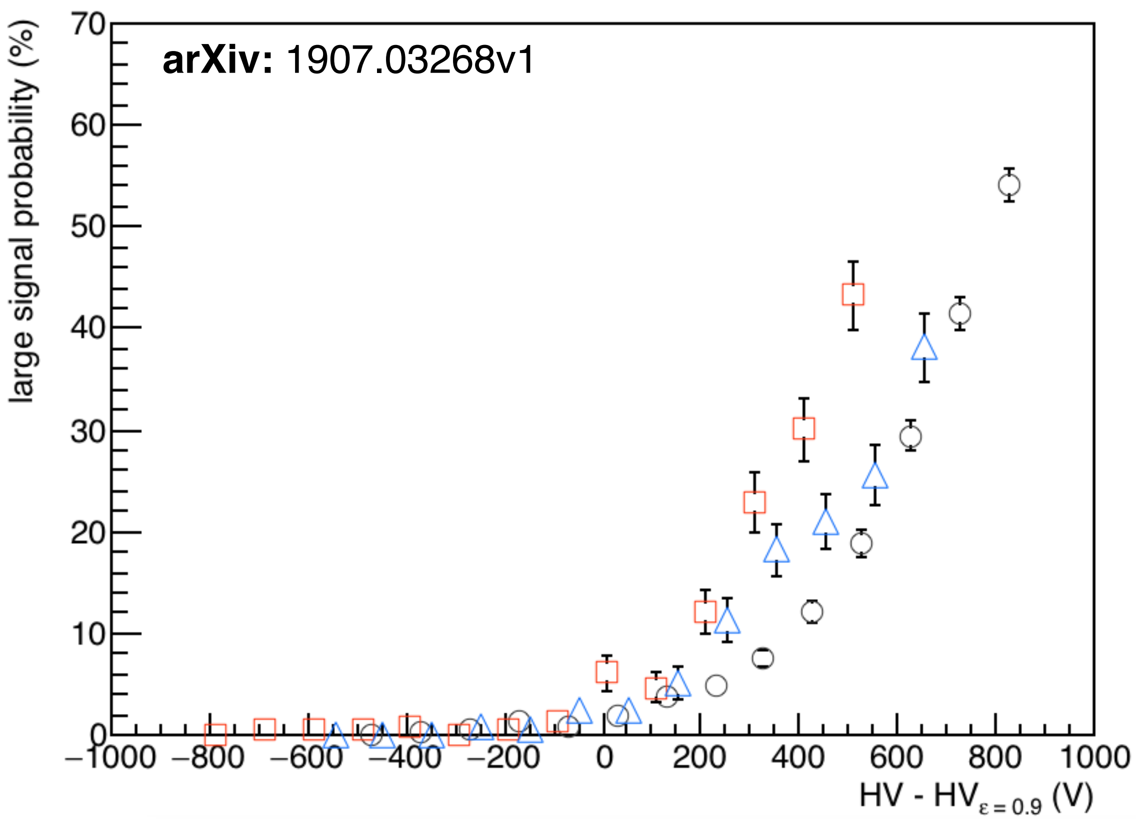


The shift of the working points is not monotonic versus the ratio $CO_2/i\text{-}C_4H_{10}$

The addition of $i\text{-}C_4H_{10}$ against CO_2 does not seem to decrease the streamer probability

Promising gas mixtures with low GWP





Mixture $C_2H_2F_4/iC_4H_{10}/SF_6$ (89.7/10.0/0.3):
- ● efficiency
- ○ large signal probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.7/10.0/0.3):
- ■ efficiency
- □ large signal probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.0/10.0/1.0):
- ▲ efficiency
- △ large signal probability

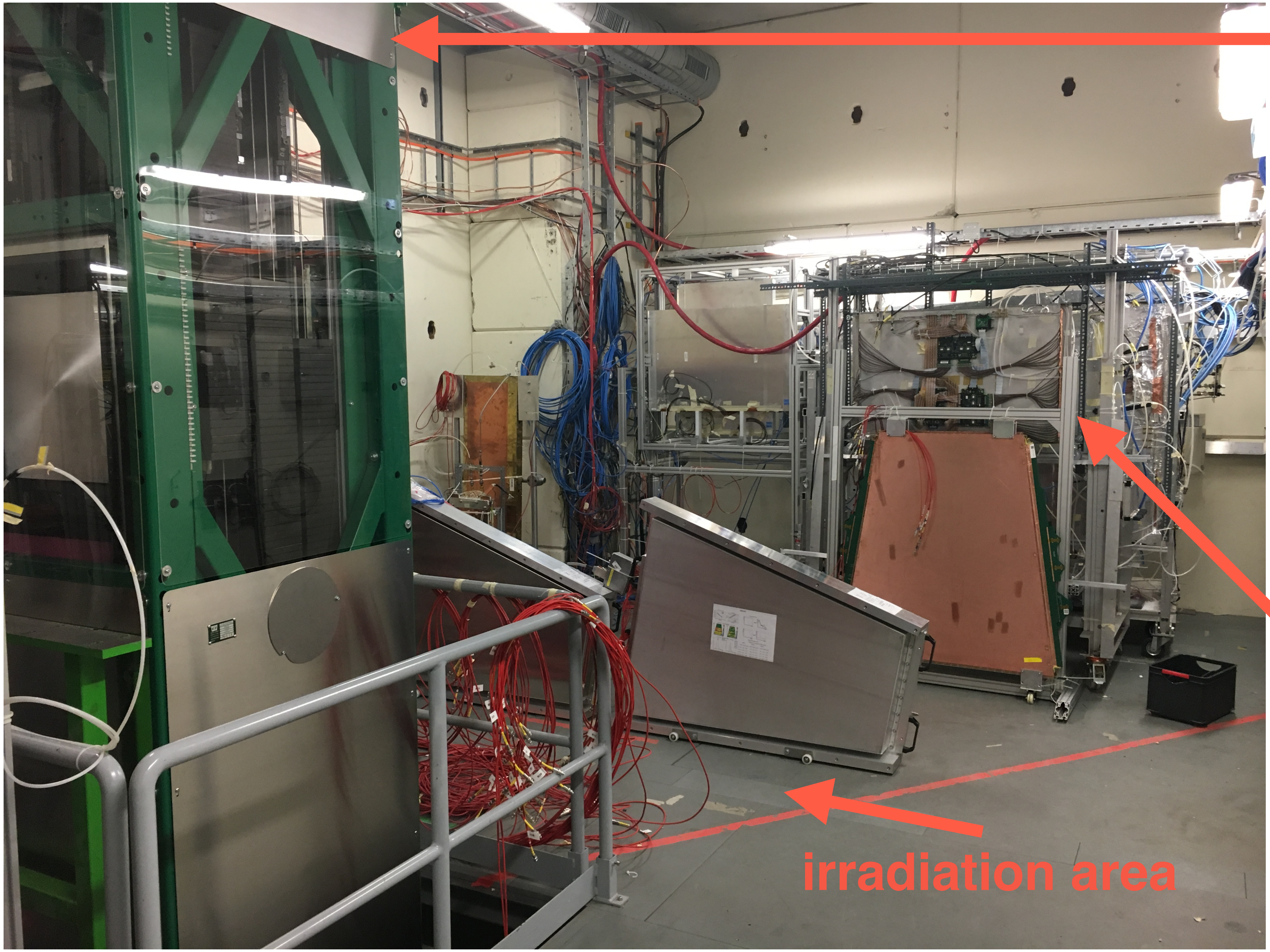
50% CO_2, 39.7% $C_3H_2F_4$, 10% *i*-C_4H_{10}, 0.3% SF_6:

- GWP: 72 (~20 times lower than the GWP of ALICE mixture)
- working point is quite close to the working point of the ALICE RPCs during LHC Run 1 and Run 2
- the large signal probability is not as low as in the current ALICE mixture

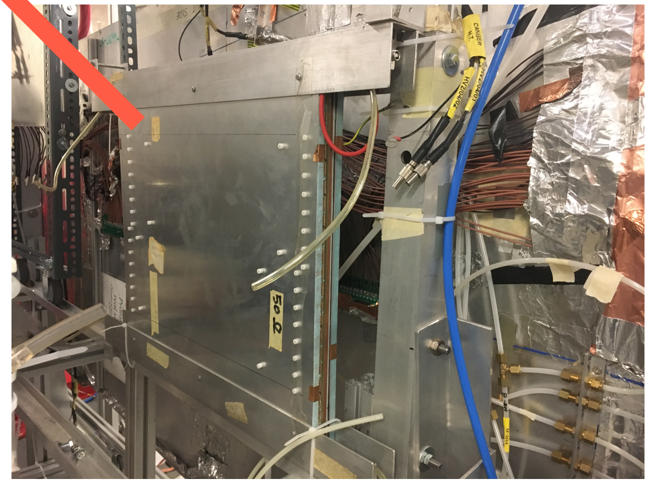
50% CO_2, 39% $C_3H_2F_4$, 10% *i*-C_4H_{10}, 1% SF_6:

- GWP: 232 (~5 times lower than the GWP of ALICE mixture)
- working point is higher (~1.5 kV)
- large signal probability is similar to the ALICE mixture, although slightly higher

Long-time stability tests at CERN-GIF++



^{137}Cs source (~13 TBq)



ALICE RPC

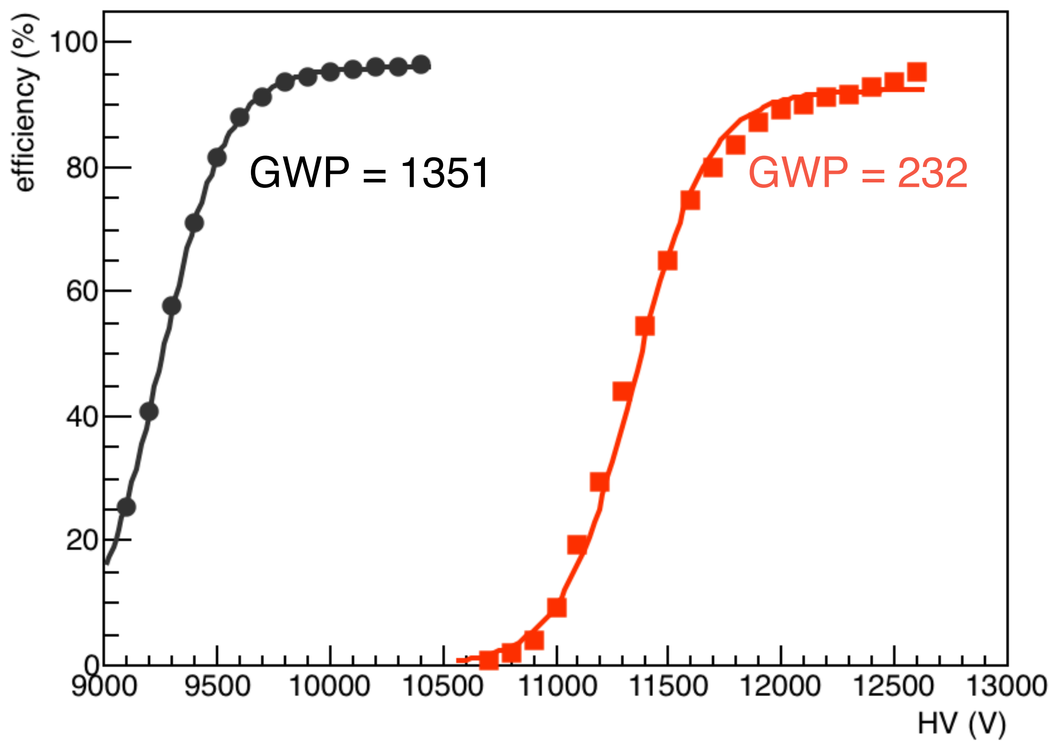
ECOGAS collaboration: ALICE, ATLAS, CMS and CERN/EP-DT

➡ long-time stability tests on several promising $C_3H_2F_4$-based mixtures are already ongoing

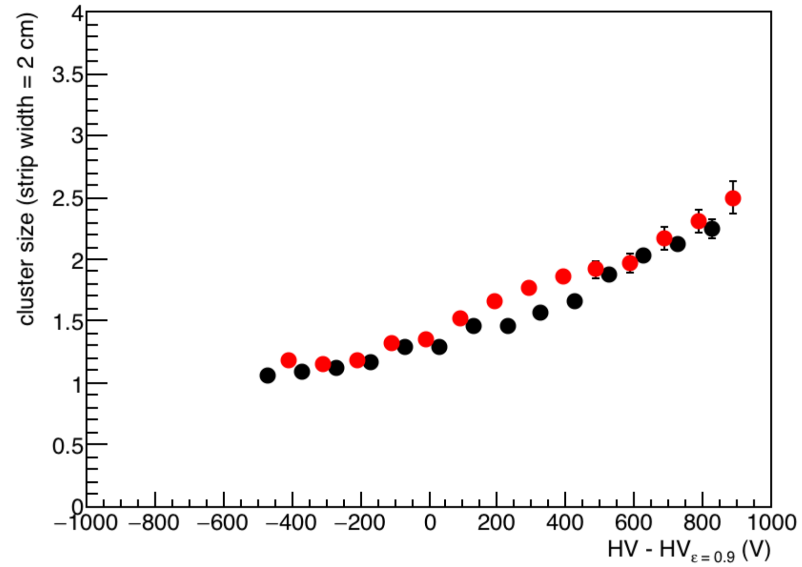
Preparation of test at CERN-GIF++

Since concentrations of *i*-C4H10 (flammable) higher than 5% are not allowed at GIF++, we carry out the aging test with the gas mixture 50% CO_2, 45% $C_3H_2F_4$, 4% *i*-C_4H_{10}, 1% SF_6:

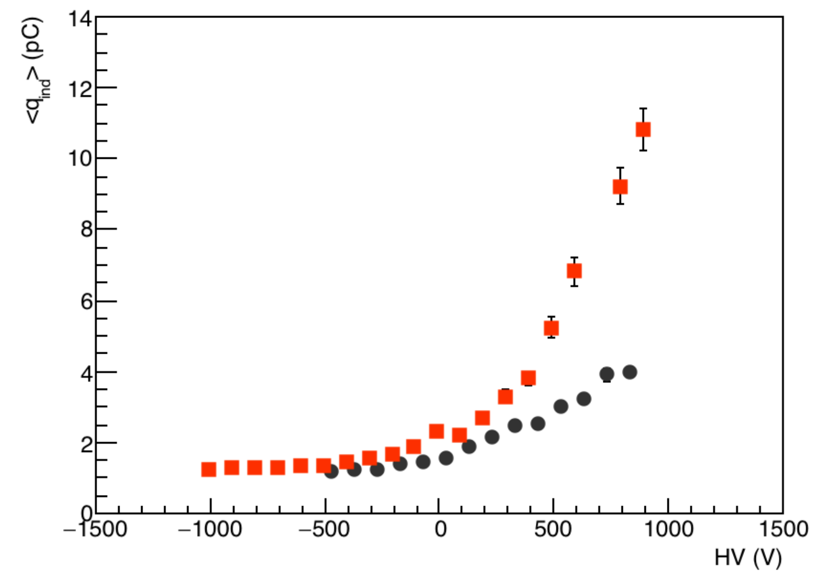
- 89.7% $C_2H_2F_4$, 10.0% *i*-C_4H_{10}, 0.3% SF_6
- 50% CO_2, 45% $C_3H_2F_4$, 4% *i*-C_4H_{10}, 1% SF_6

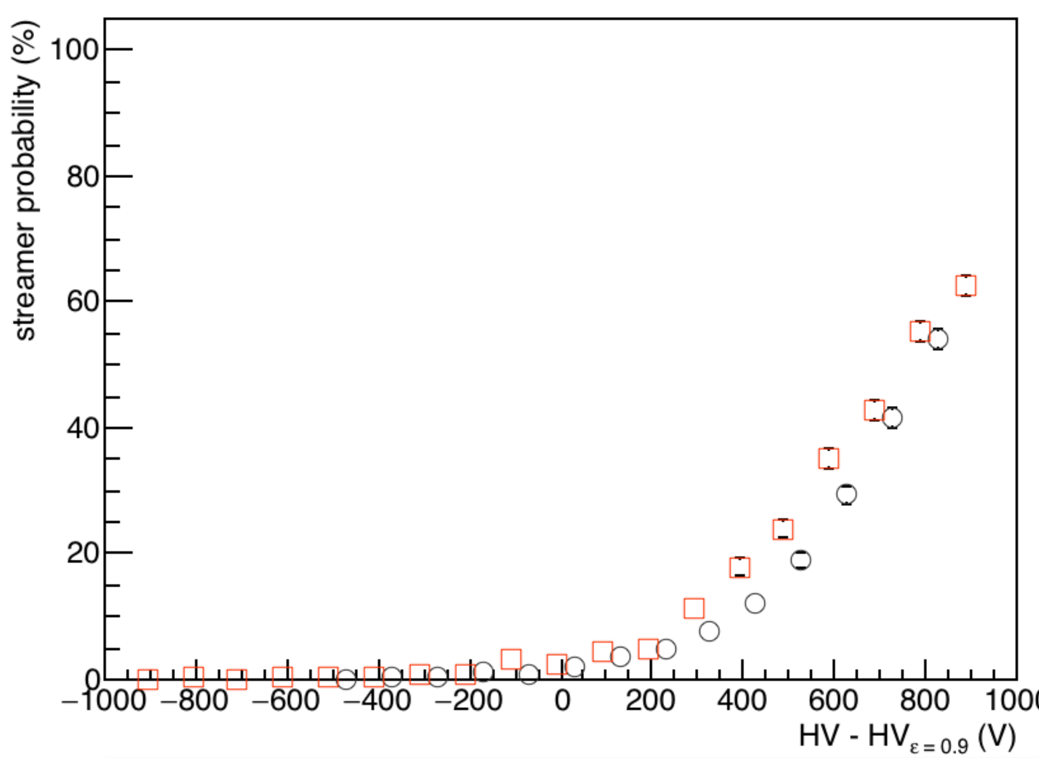


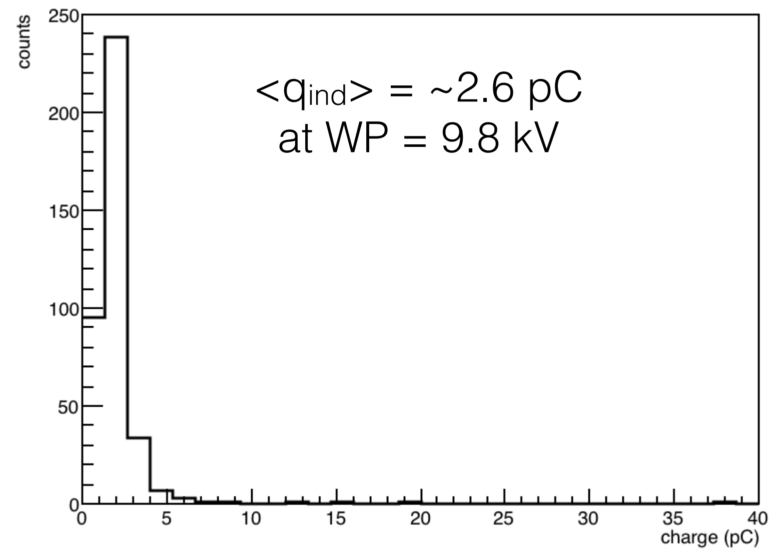
Cluster size:

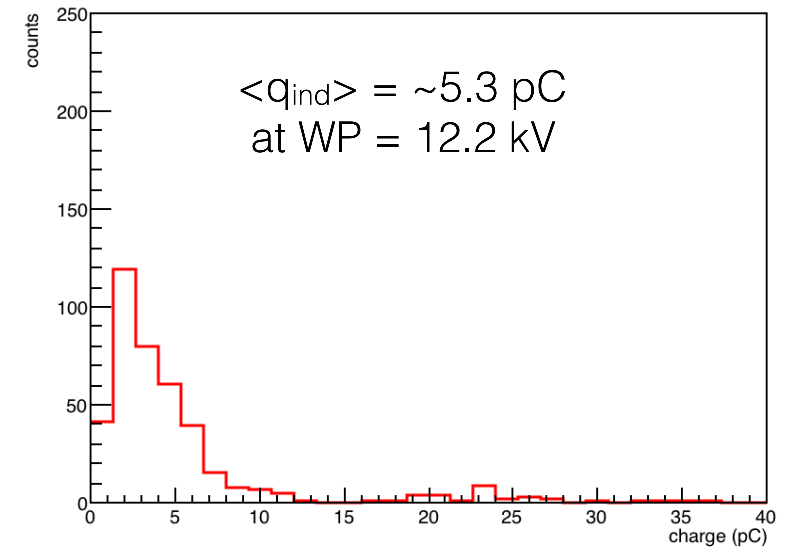


Average induced charge:





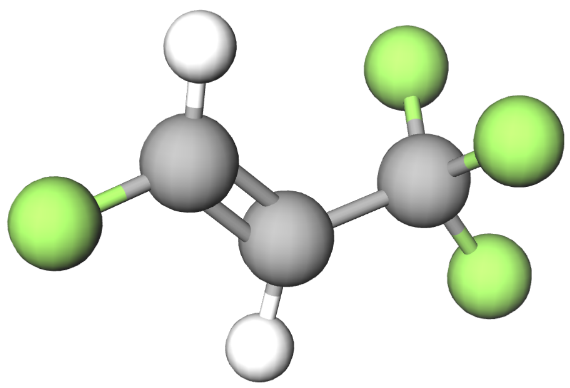




Aging test is ongoing…

Conclusions and outlook

- **R&D on eco-friendly gas mixtures:**
  → goal: to have a eco-friendly gas mixture (at least with a low GWP)
  → **$C_3H_2F_4$ is a possible candidate** to substitute $C_2H_2F_4$, thanks to its low GWP



- **Characterization of mixtures with $C_3H_2F_4$:**
  - direct replacement of $C_2H_2F_4$ with $C_3H_2F_4$ is not possible (working point > 14 kV)
  - strong dependence between the working point of the detector and the concentration of $C_3H_2F_4$
  - the **addition of Ar, N_2, O_2** is not suitable for ALICE-muon RPCs
  - the **addition of CO_2** to $C_3H_2F_4$-based mixtures is required to operate at lower voltages
  - in $C_3H_2F_4$-based mixtures with CO_2, i-C_4H_{10} and SF_6:
    - the increase of ***i*-C_4H_{10}** against CO_2 does not seem to reduce the streamer probability with 1% SF_6
    - **SF_6** turns out to play a crucial role in suppressing streamers in $C_3H_2F_4$ (as well as in $C_2H_2F_4$)
    - **promising $C_3H_2F_4$/CO_2-based mixtures, found so far, with a GWP reduced by a factor 5÷20**
    - details in arXiv: 1907.03268 (submitted to JINST)

- **As next step, long-time stability tests are required to check:**
  - $C_3H_2F_4$ tolerance to high particle flux
  - rate capability
  - long term performance (ageing issue)