Operating the Resistive Plate Chambers with new eco-gas mixtures

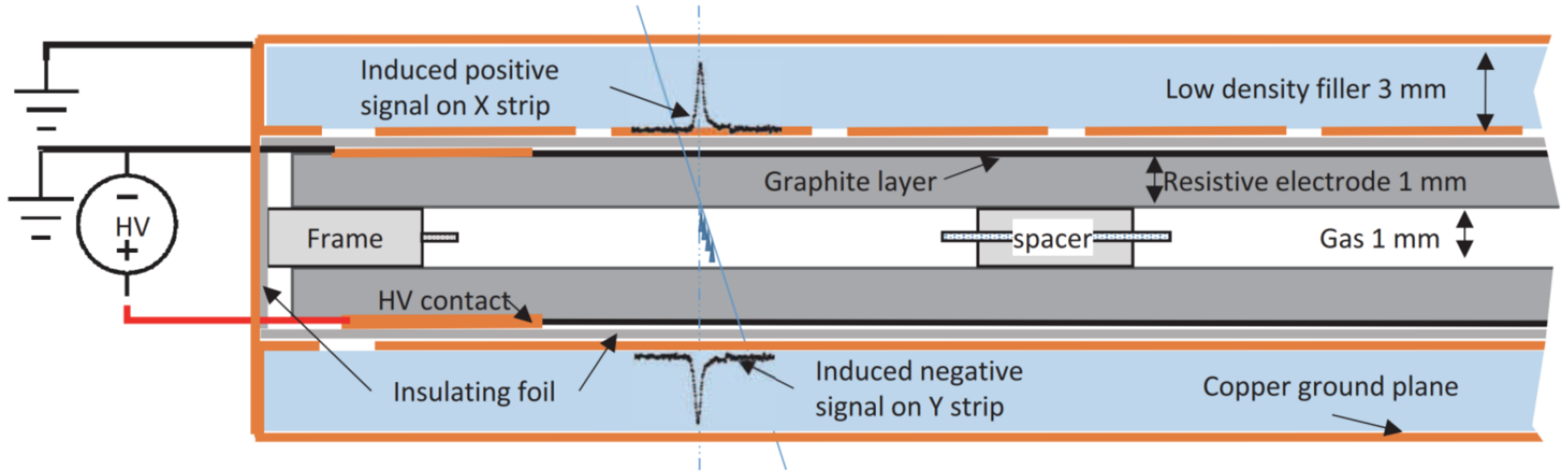
GIORGIA PROTO (UNIVERSITY OF ROMA TOR VERGATA AND INFN) ON BEHALF OF THE ROMA TOR VERGATA GROUP

VIENNA CONFERENCE ON INSTRUMENTATION

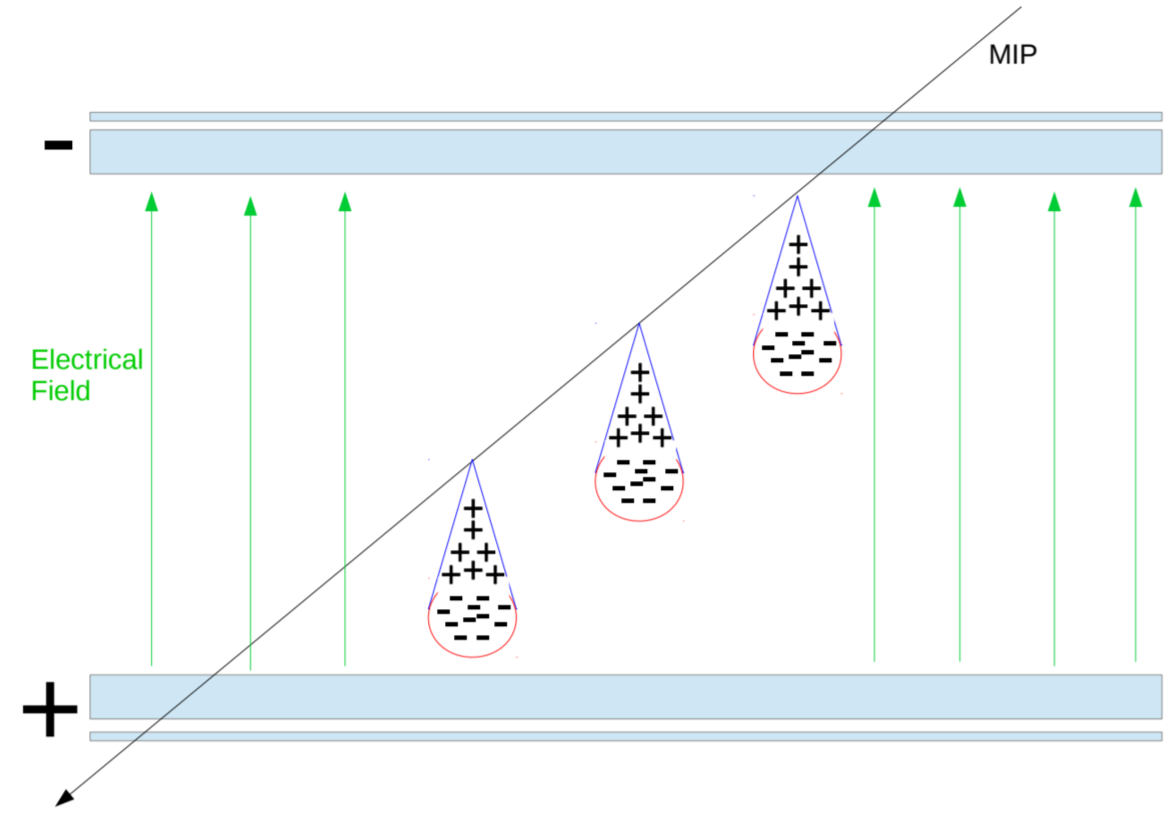
Outline

- Performance of the Resistive Plate Chambers with the standard gas mixture
- Decreasing the Global Warming Potential and Ozone Depletion Potential: the $C_2H_2F_4$ and SF_6 substitutes
- Experimental set-up
- Analysis criteria
- Results

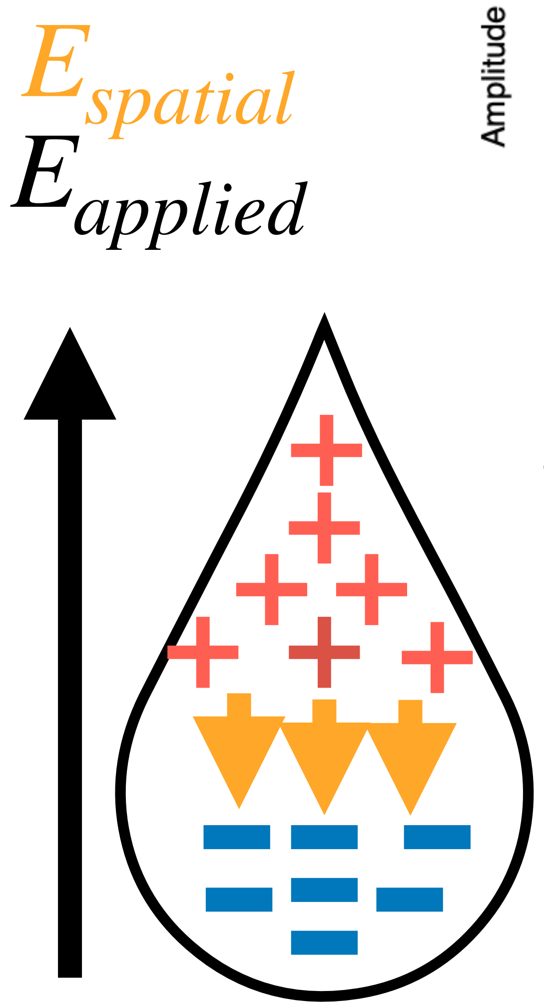
The Resistive Plate Chambers (RPC)

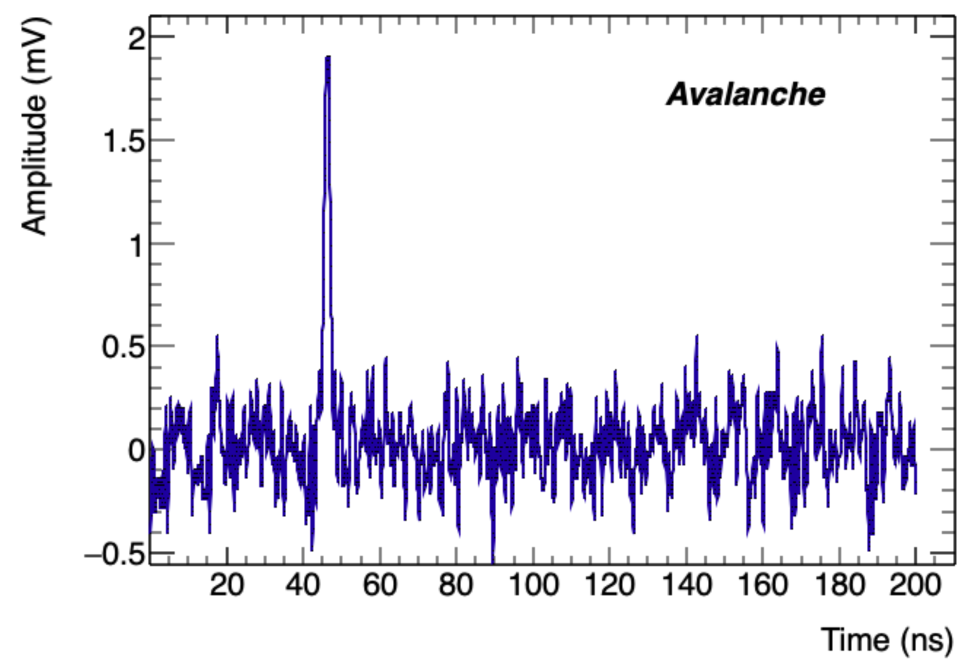


- Gas gap
- Parallel resistive electrodes
  - Internal surface: linseed oil
  - External surface: graphite
- Insulating layer
- Read-out strips

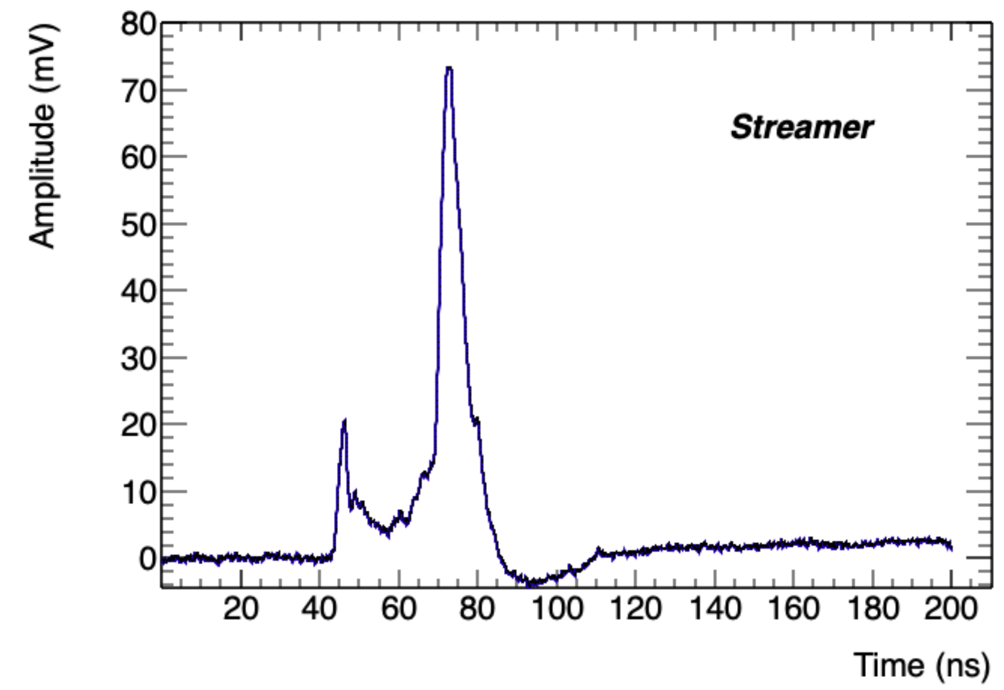


- Primary ionization
- Electron acceleration and avalanche charge formation





- Saturated avalanche mode

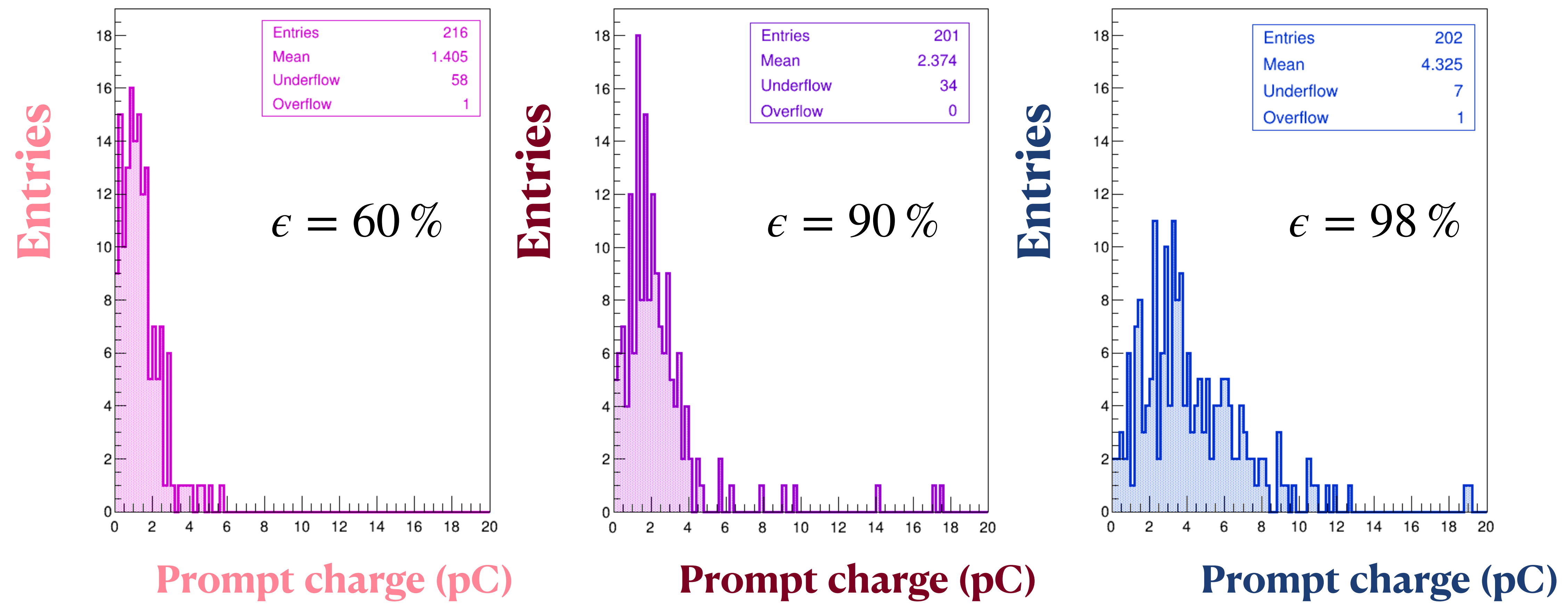


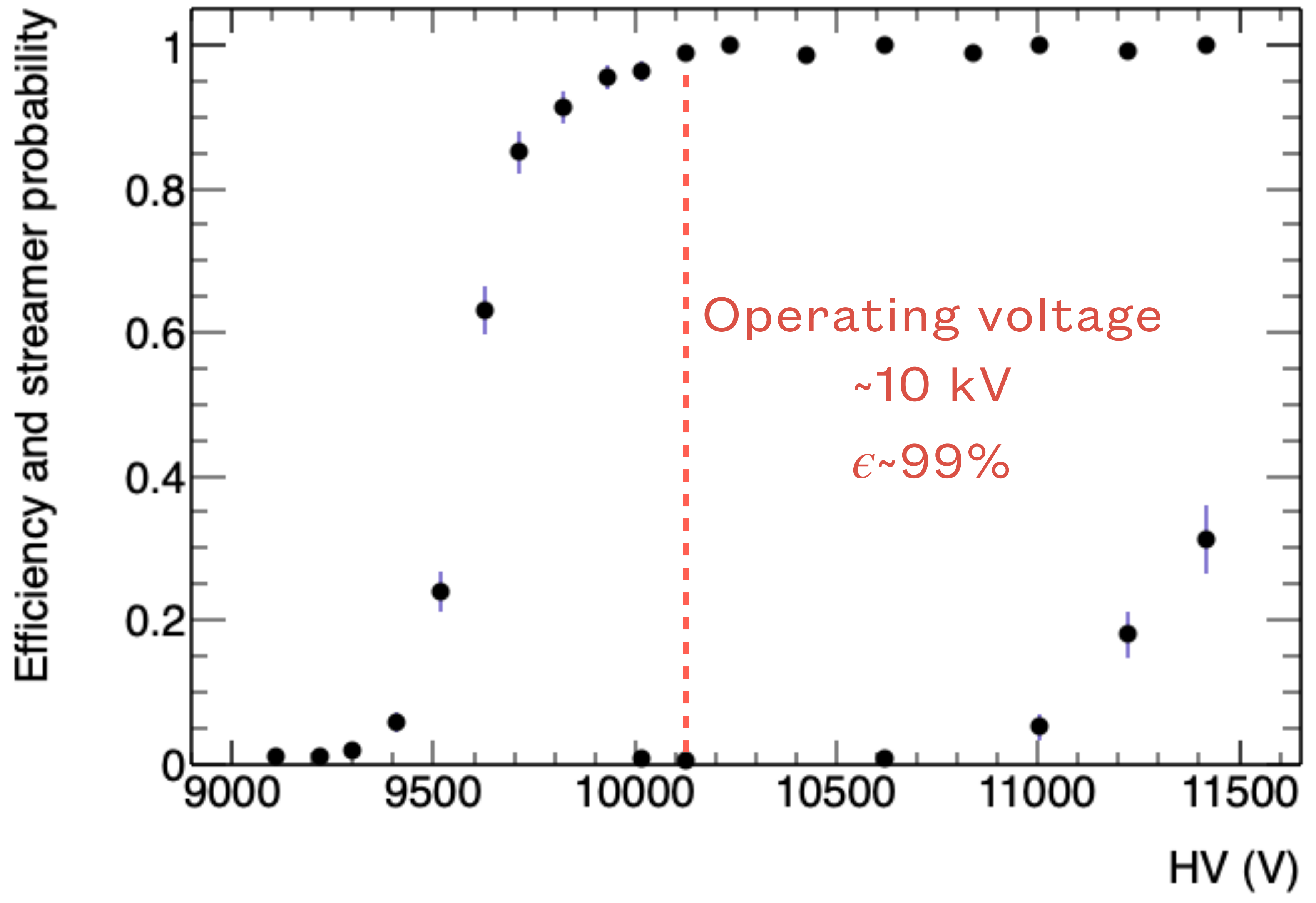
- Electron-ion recombination processes with UV photon emission
- Streamer formation

Operating RPC in avalanche mode with the “standard” gas mixture

The standard gas mixture is composed of $C_2H_2F_4$(TFE)/i-C_4H_{10}/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

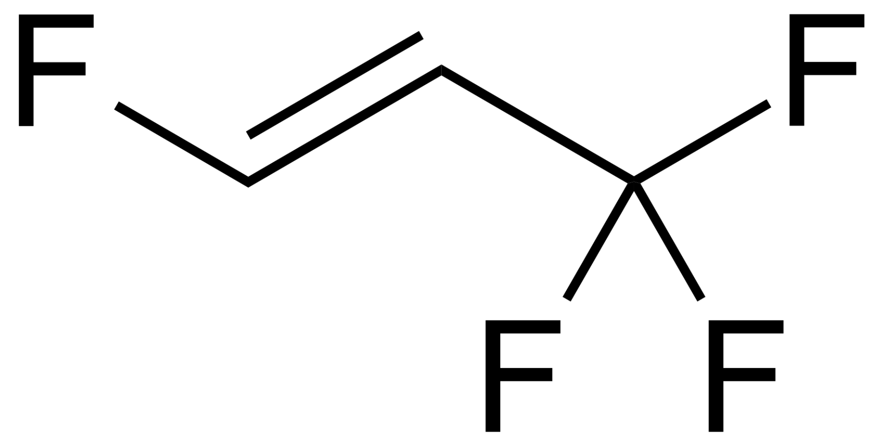




New eco-gas mixtures for RPC

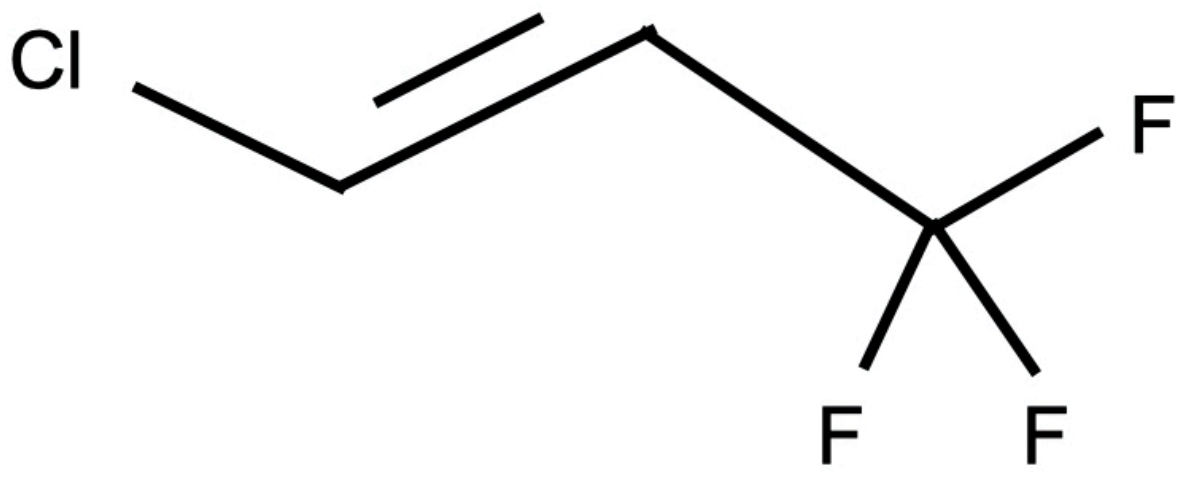
The standard gas mixture has a high Global Warming Potential (GWP)

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



Substitute $C_2H_2F_4$ with an environment-friendly gas mixture

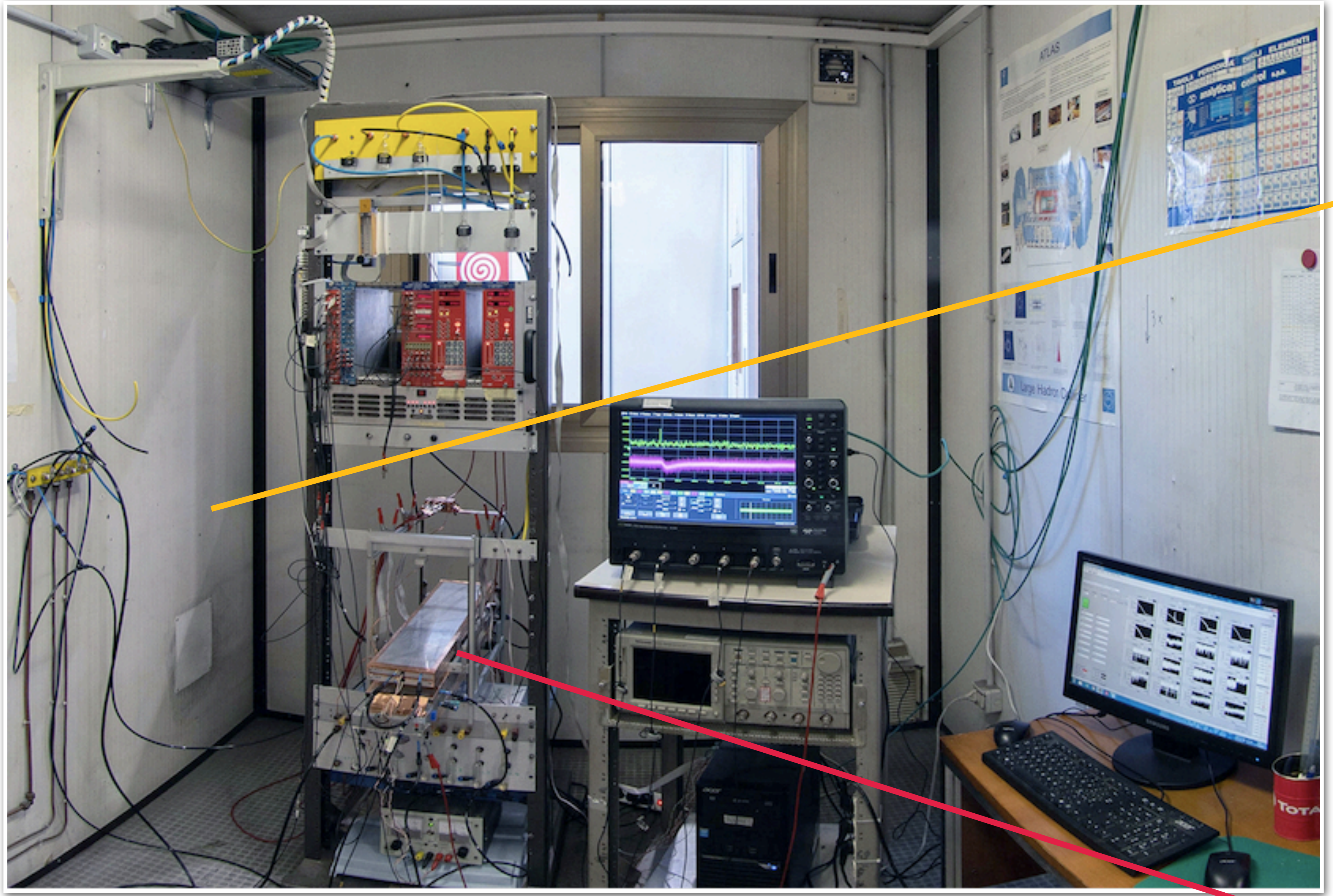
- CO_2 **/** $C_3H_2F_4$ **(HFO1234ze)** + i-C_4H_{10} + SF_6 → **GWP ~ 200**



Substitute the SF_6 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**

Experimental apparatus (I)

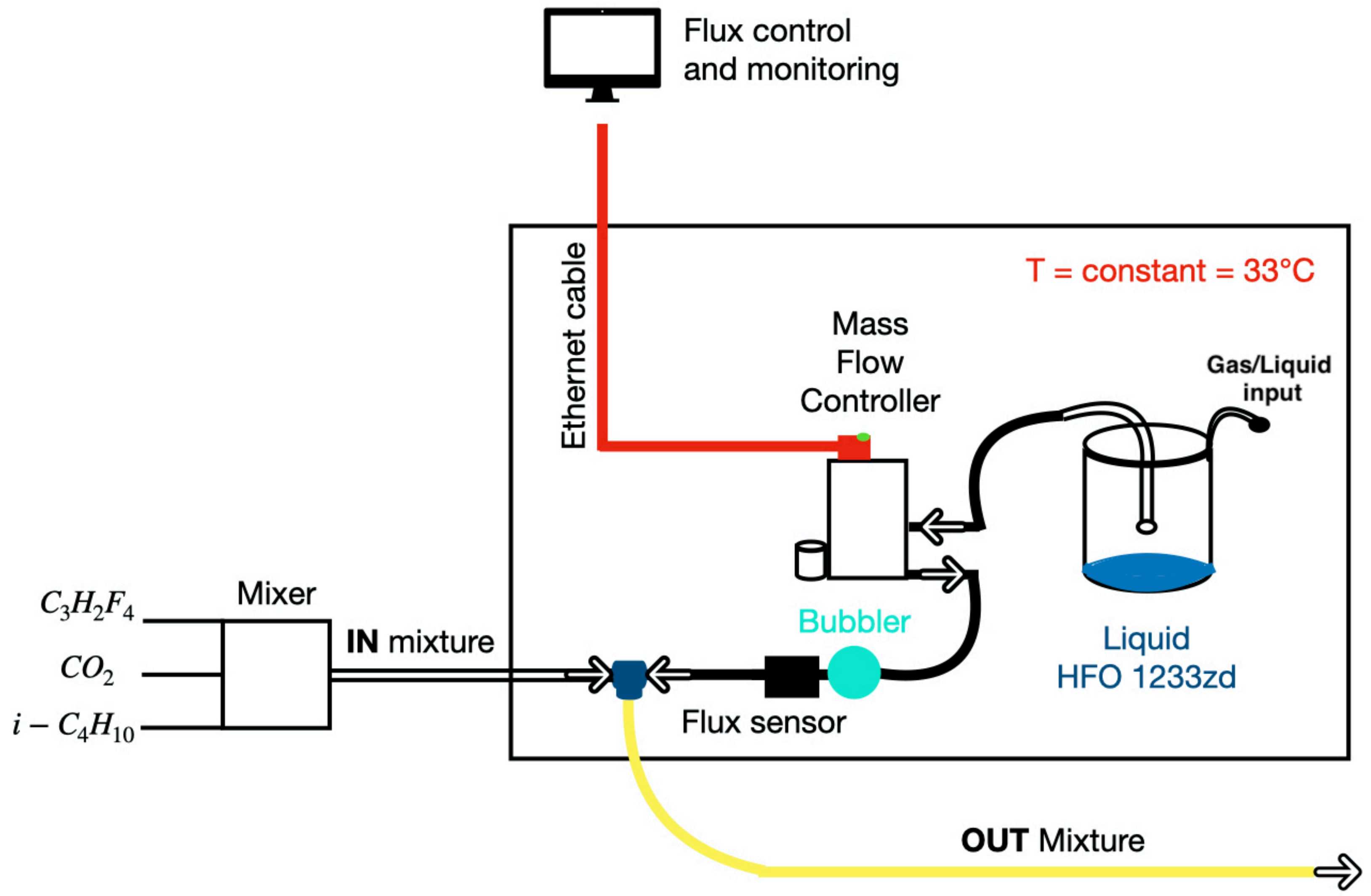


- Three 2 mm gas gap RPCs in coincidence, forming the ***trigger***
- One 0.5 mm RPC (confirm chamber)
- Detector under test : 2 mm gas gap RPC
- Oscilloscope (Bandwidth : 3 GHz; Sampling velocity : 20 Gs/s)

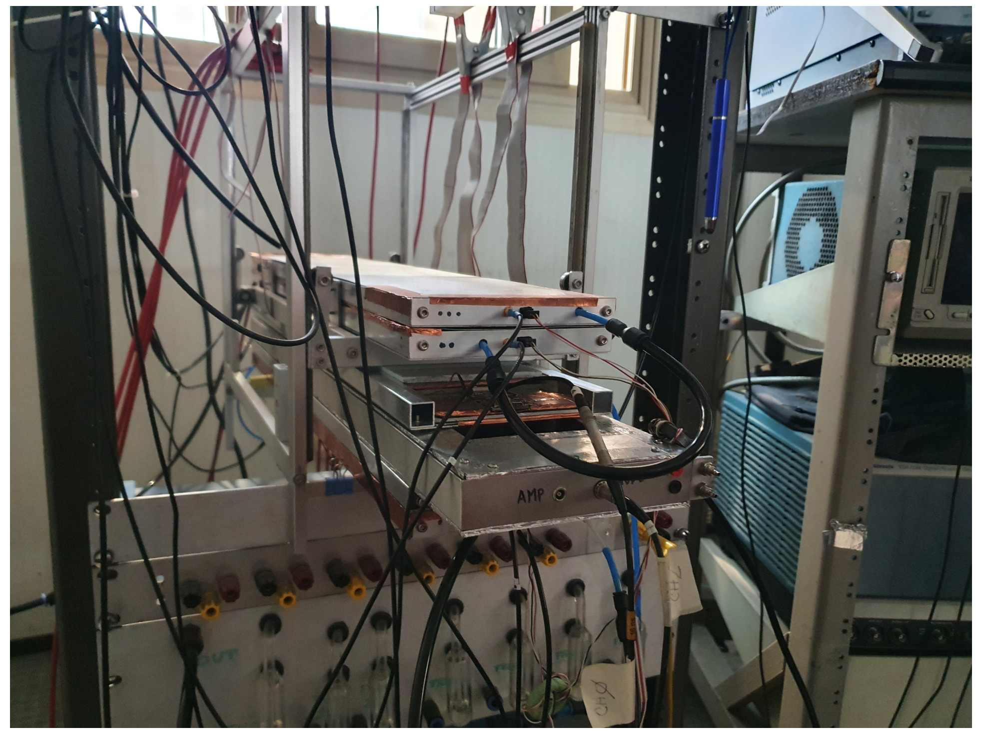
Gas system

System to avoid the Cl-HFO liquefaction (20 °C)

The mixture is prepared inside a climate chamber with T = constant = 33 °C



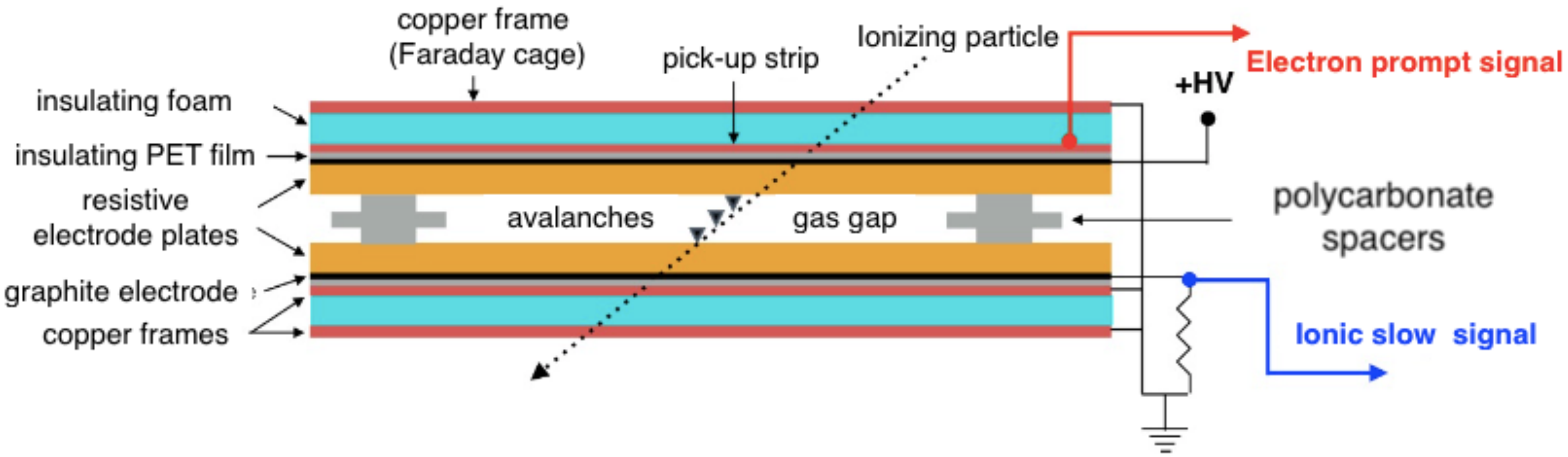
Trigger

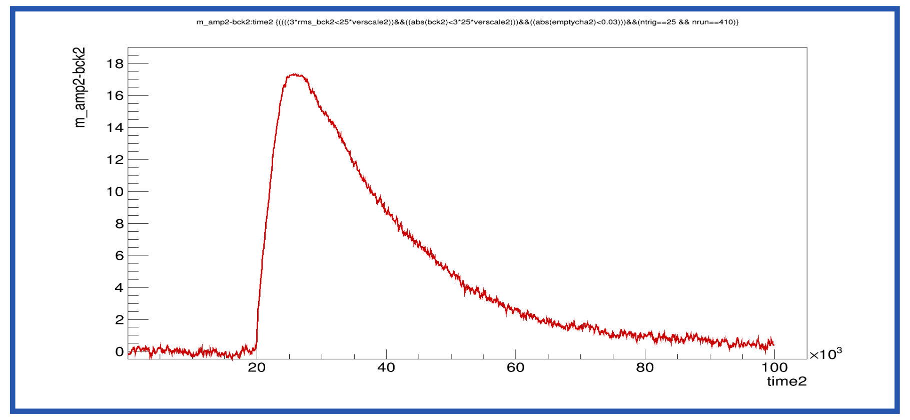


The 0.5 mm RPC is used as :

- Fourth trigger chamber for the efficiency measurement;
- Time reference

RPC under test



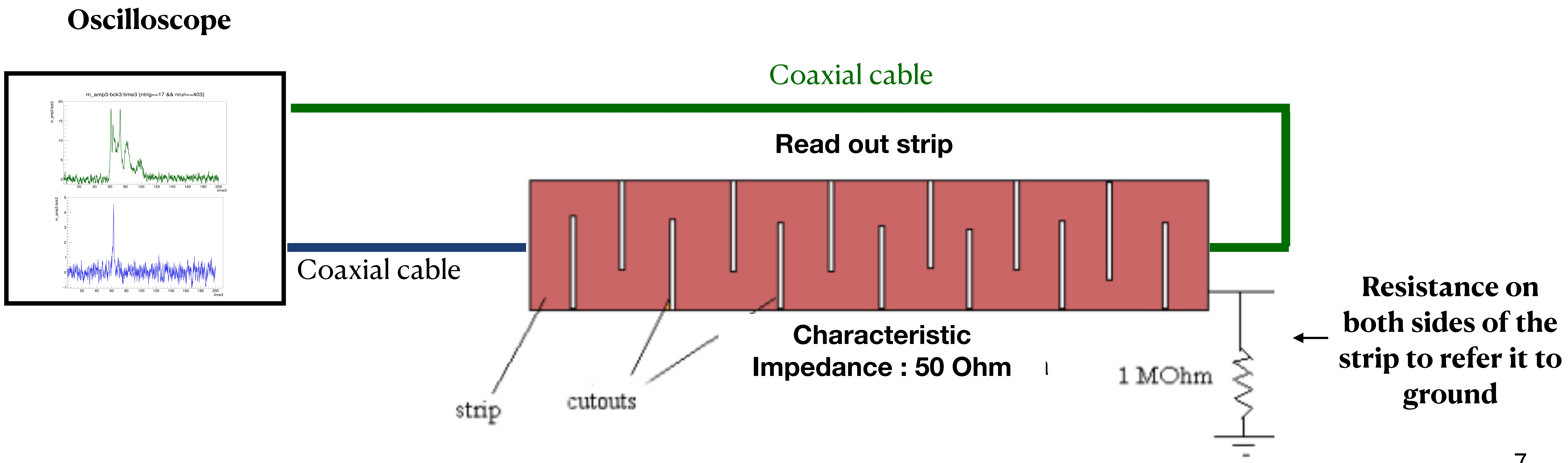


Ionic signal :read out on a resistance on the ground graphite electrode equal to 10 kOhm

- Dimensions : (57 x 10) cm^2
- Gas gap width : 2 mm
- Electrode thickness : 1.8 mm

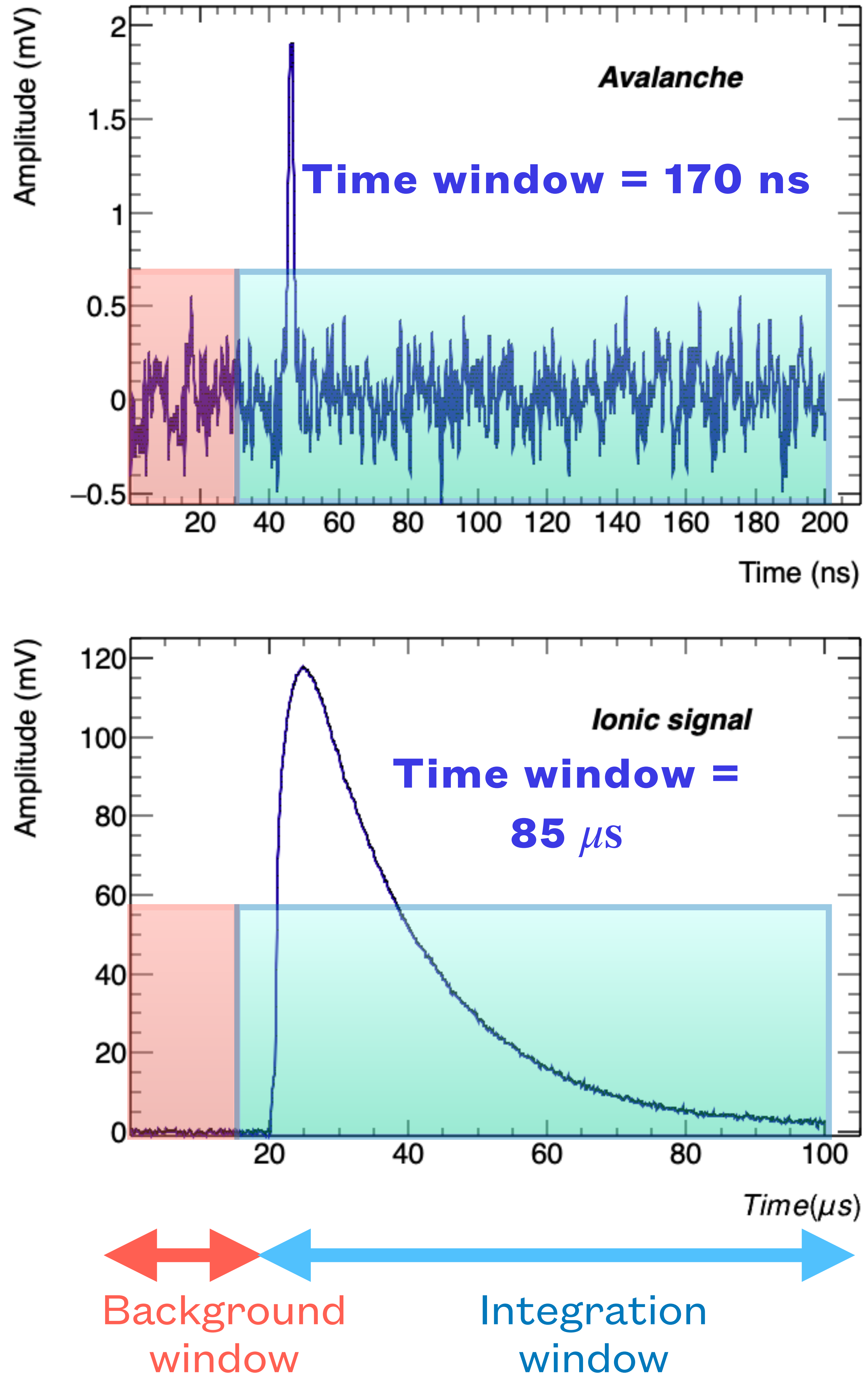
Read-out strip

- Prompt signal without amplification
- Efficiency measurement: maximum oscilloscope sensitivity
- Streamer analysis: oscilloscope variable scale

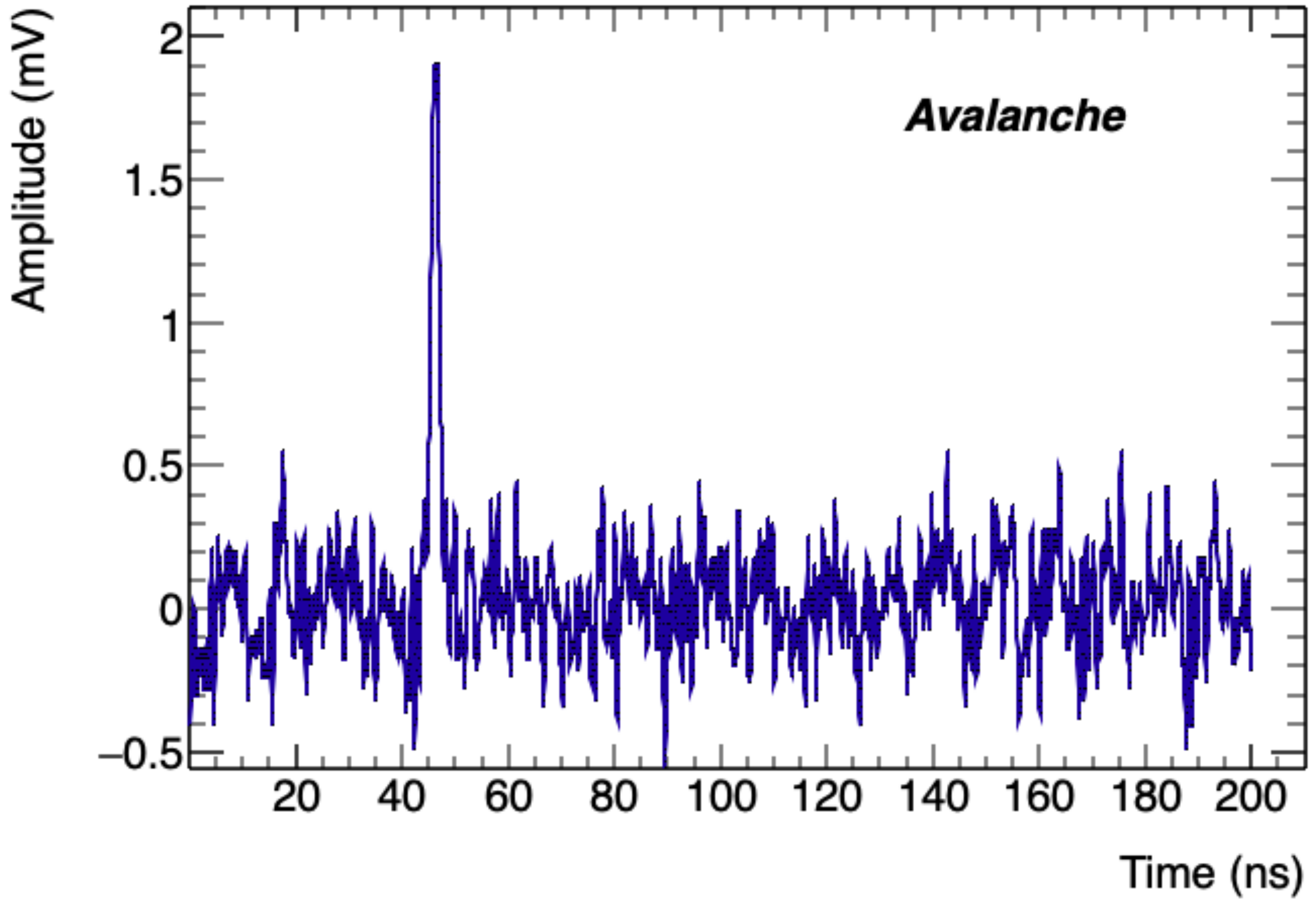


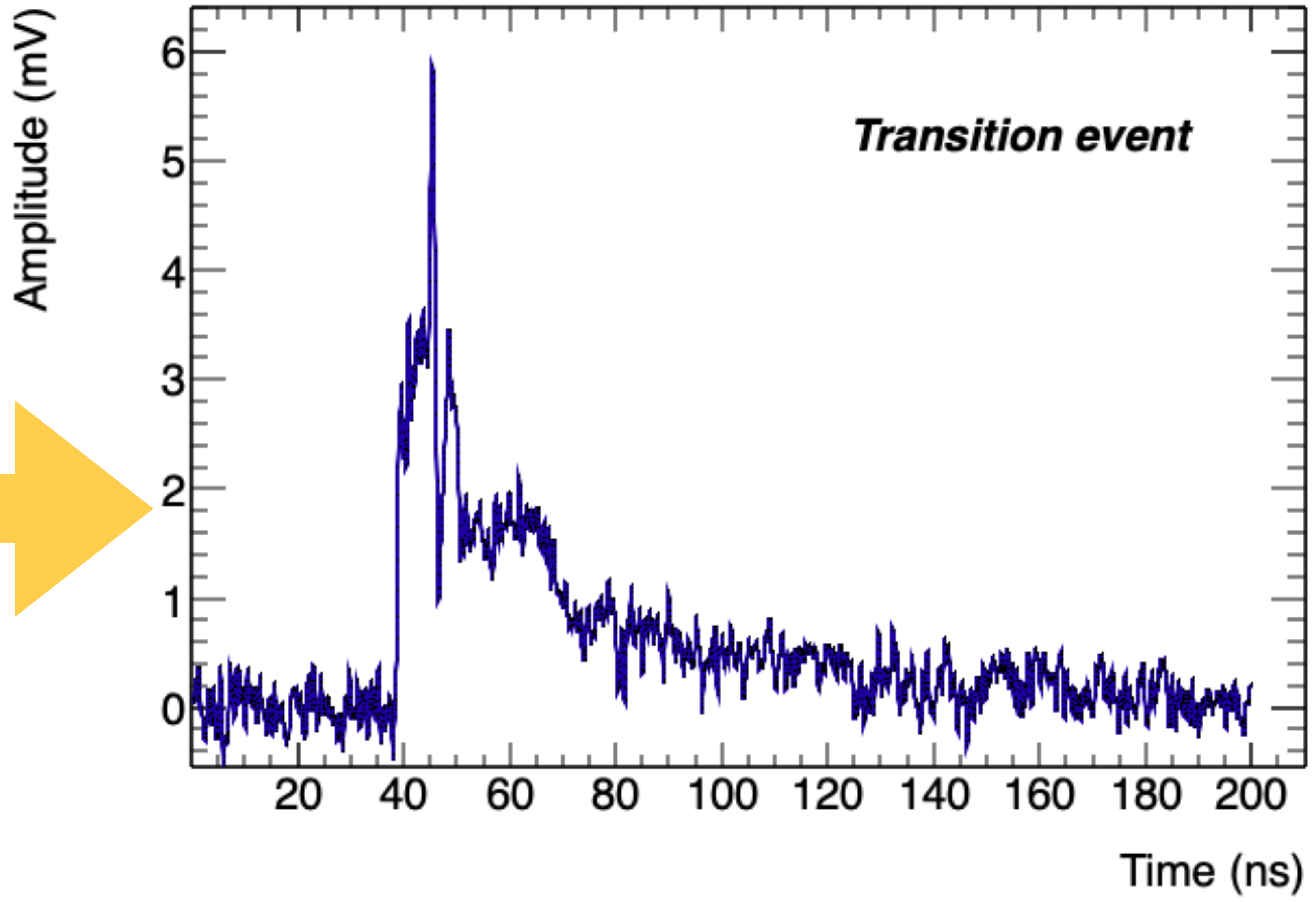
Analysis criteria

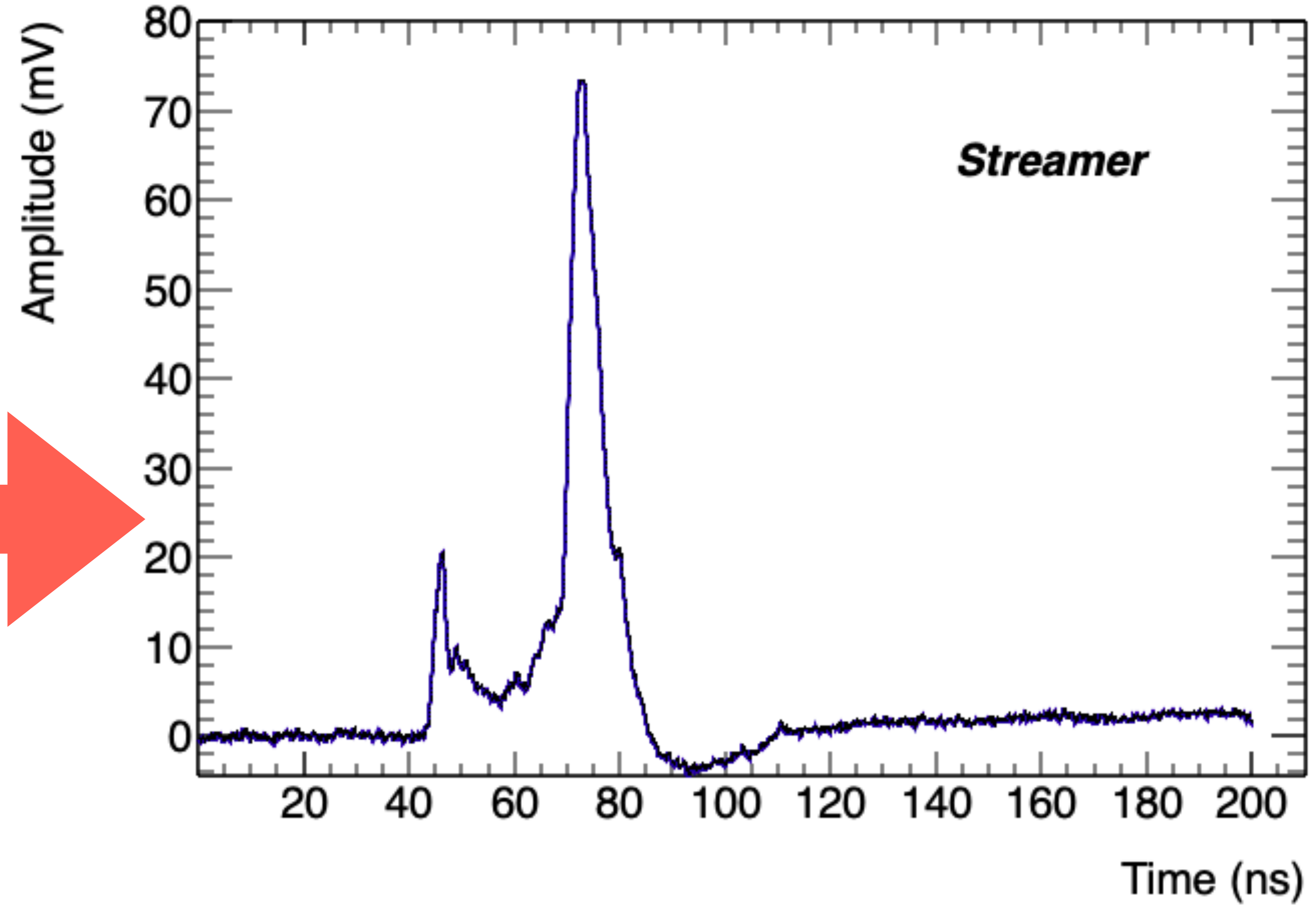
- Detection efficiency : signals which cross an amplitude threshold equal to 5 times the Root Mean Square (RMS) of the background amplitude.
    - The background amplitude is calculated in a time window of 30 ns which anticipates the avalanche signal
        - 5*$\overline{\mathrm{RMS}}$ in the whole data taking is ~ 0.85 mV
    - Only the events in which the confirm chamber is efficient have been considered in the analysis
- Charge study: charge integrated in a time window of:
    - **170 ns** for the prompt signal
    - **85** μs for the ionic signal



Signals classification: 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 gas mixtures.

Algorithms, based on duration and charge, have been developed to distinguish and classify these three event categories

Data analysis overview (I)

Gas mixtures tested: F-HFO/CO_2/i-C_4H_{10}/Cl-HFO

- F-HFO/i-C_4H_{10} at a fixed ratio of (15/7) %+ variable ratio of CO_2 /Cl-HFO in the range (78/72) %/(0-6) %

Quantities studied:

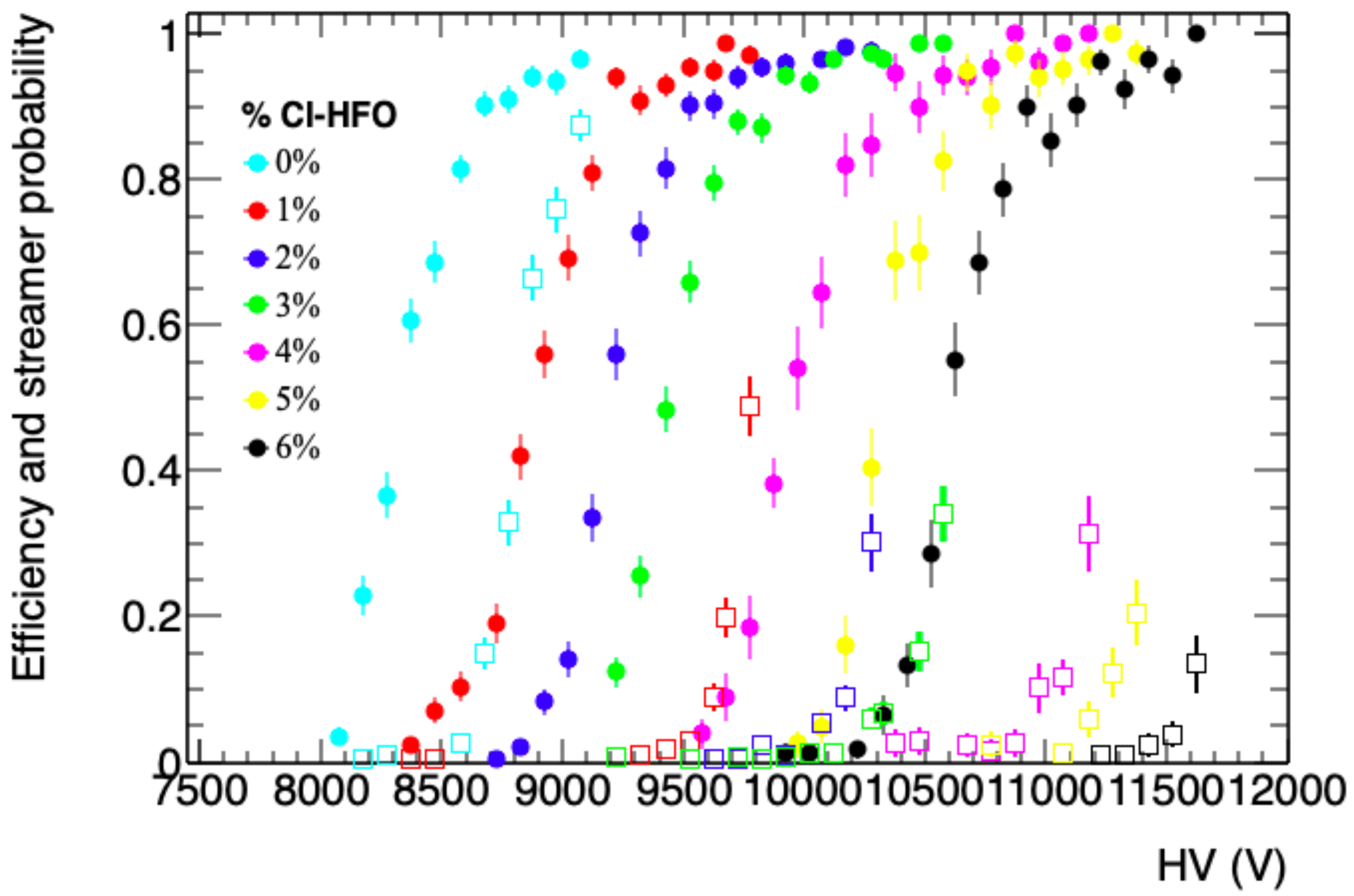
- Detection efficiency
- Streamer and transition event probability
- Total charge delivered inside the gas
- Time resolution

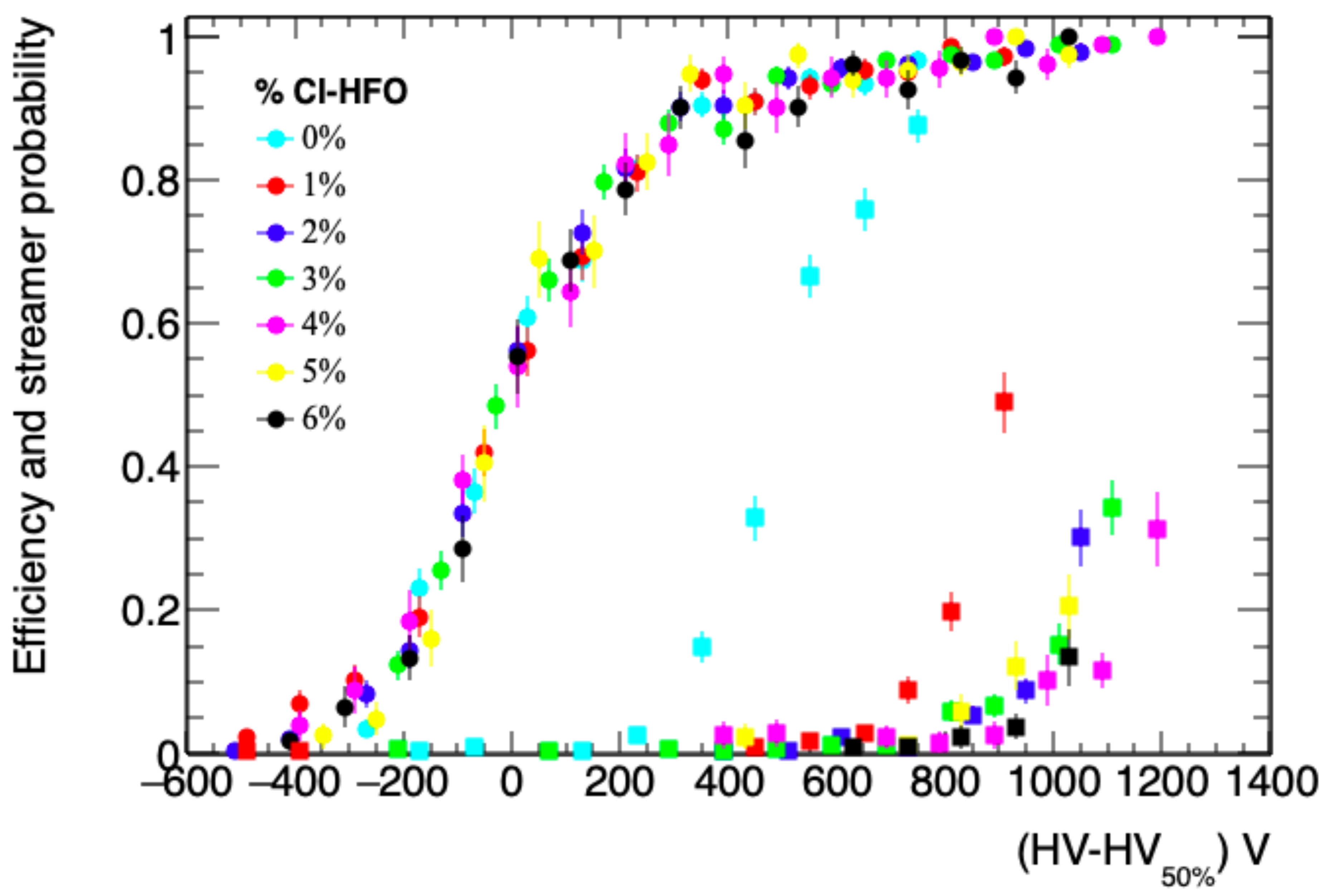
Signals classification

Signal type	Prompt charge (pC)	Time over threshold (ns)	Exceeding charge (*)
Avalanche	≤ 5	< 12	-
Transition	$5 < q < 30$	> 12	> 0.21
Streamer	≥ 30	≥ 30	-

(*) Exceeding charge = integrated charge over the tail of the signal, excluding the avalanche contribution

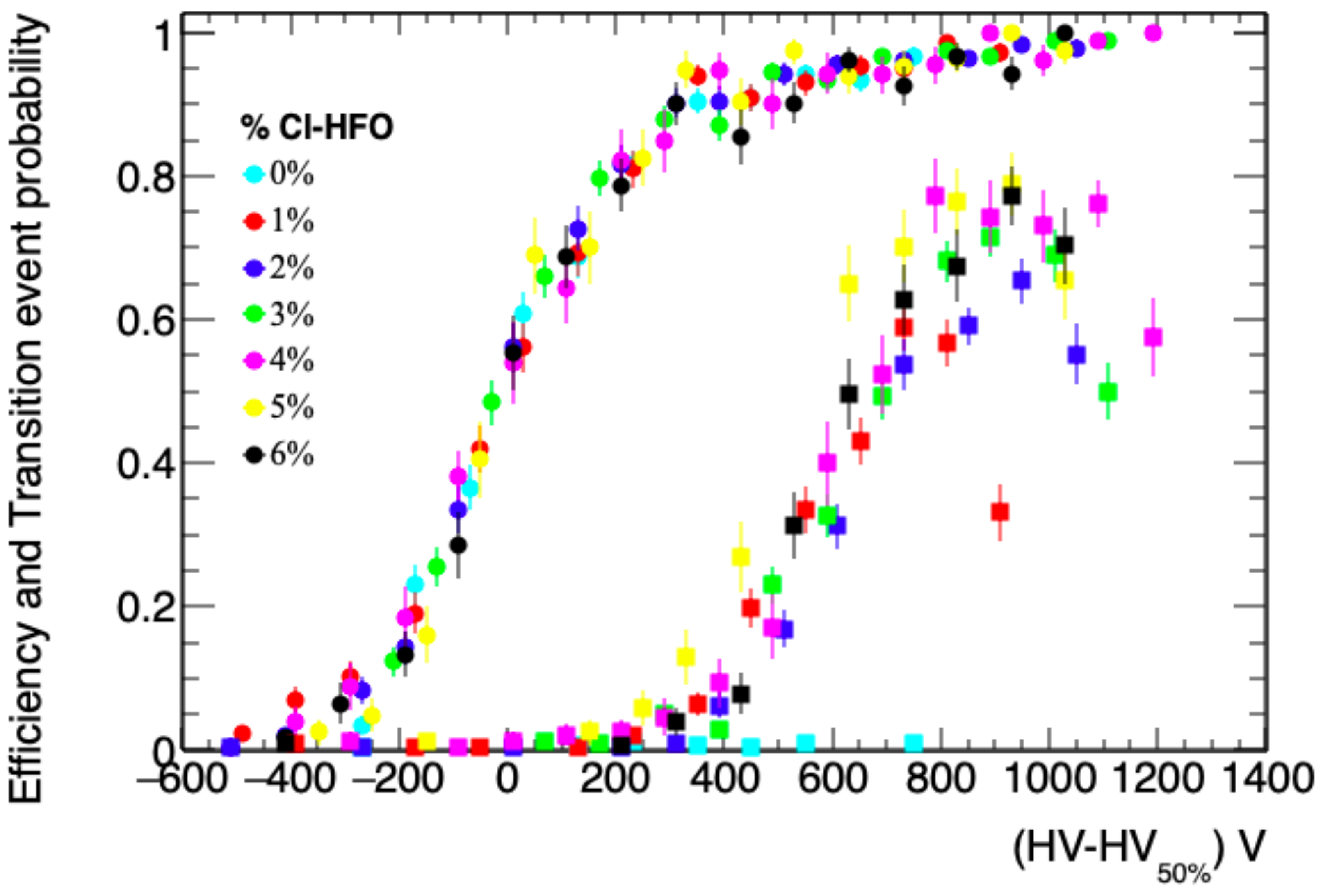
RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Efficiency

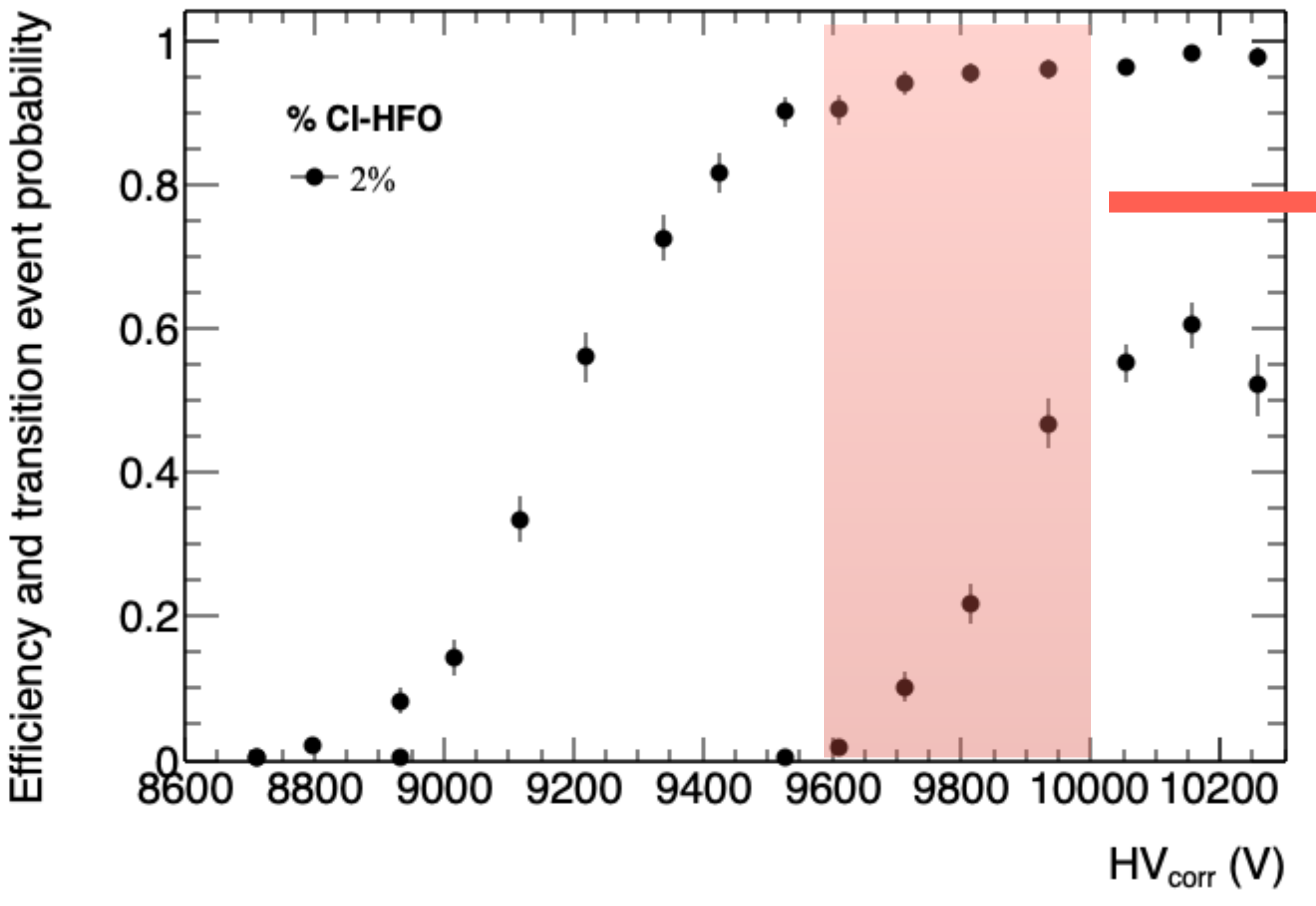


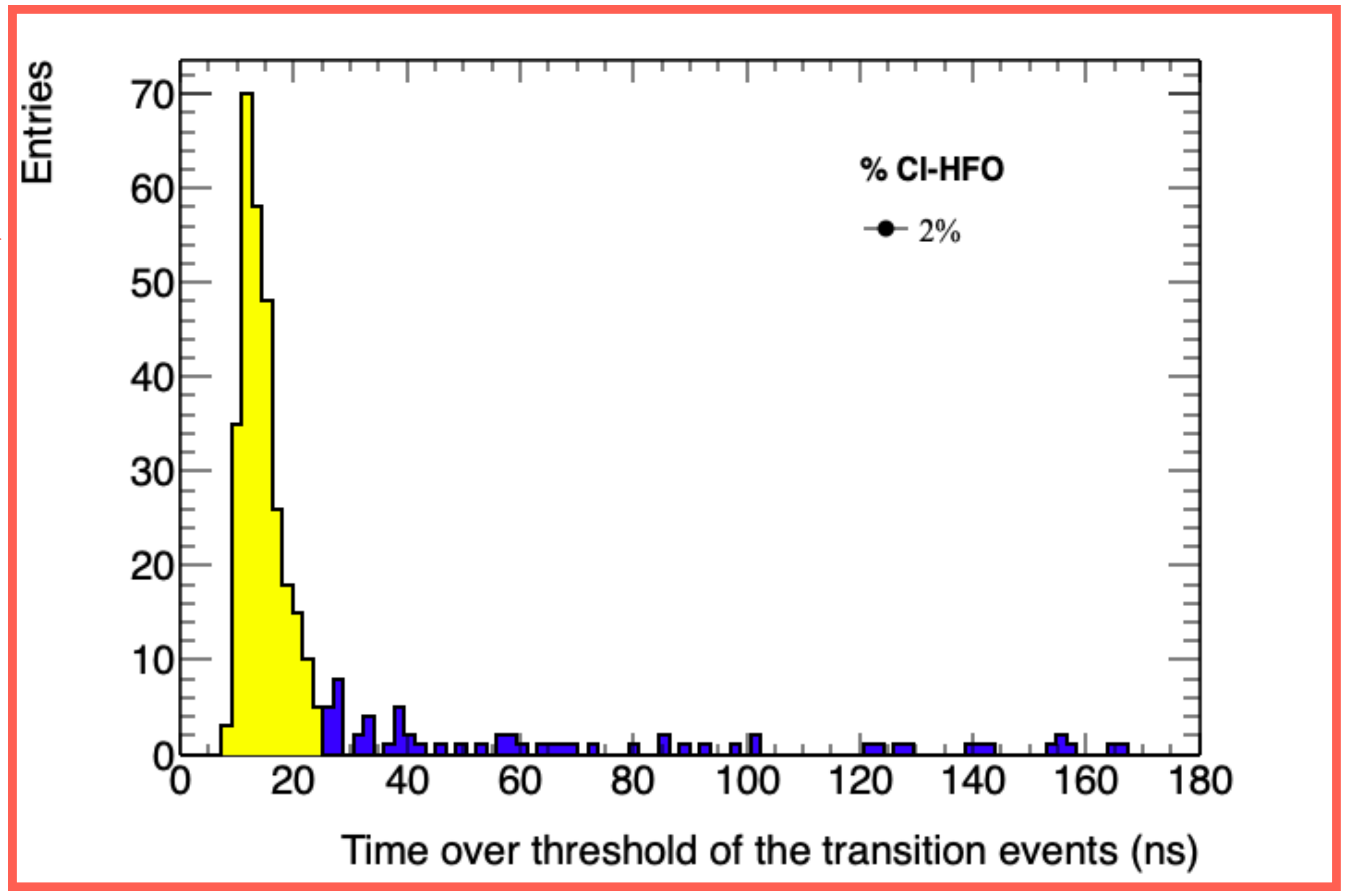


- The operating voltage increases at the rate ~ 400 V/1% Cl-HFO;
- The detection efficiency is at least 93% for all the gas mixtures;
- The mixture not containing Cl-HFO shows an overlapping between avalanche and streamer mode (35% streamer contamination at the plateau knee);
- The separation between avalanche and streamer mode is ~ 400 V for all gas mixtures.

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

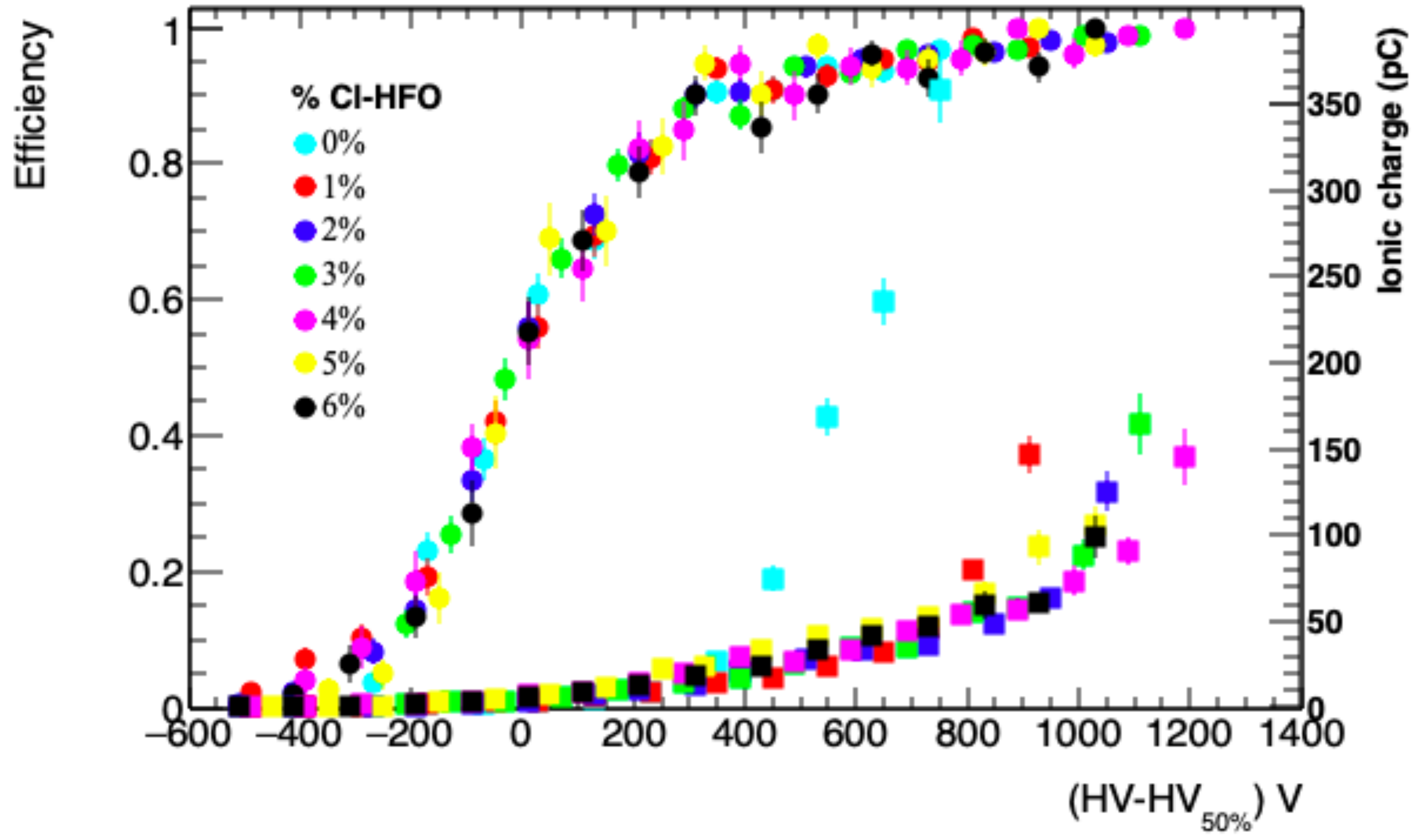


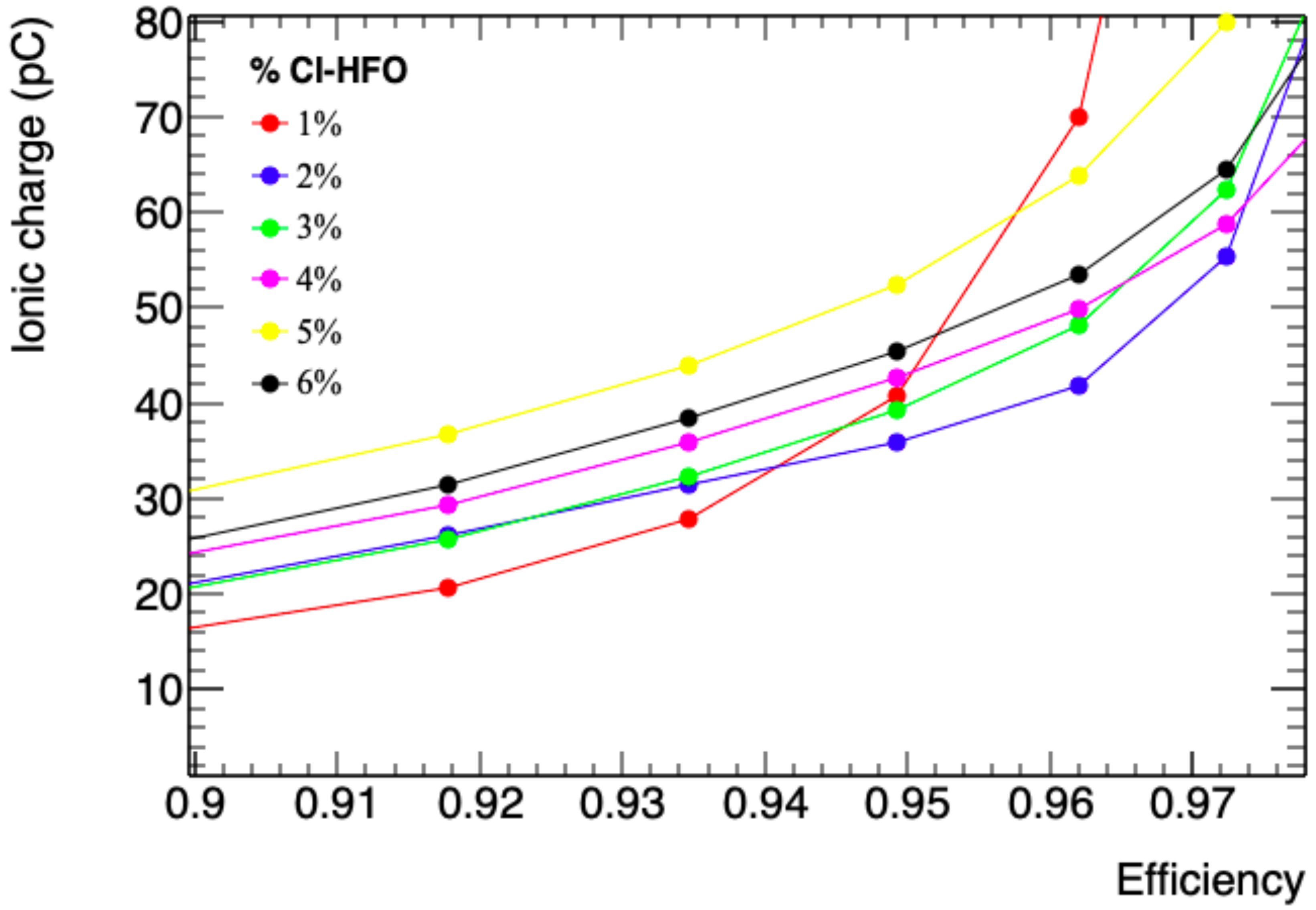




- The transition event probability decreases when streamers start to appear;
- The transition event are less than 20% at the operating voltage for all gas mixtures;
- The time over threshold of transition events is less than 25 ns.

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Ionic charge





- The ionic charge of the mixture without Cl-HFO reaches very high values (~ 75 pC) at low efficiency
- The mixture with 5% and 6% Cl-HFO have an ionic charge more than 30 pC at the first plateau value
- The mixture with 1% Cl-HFO shows the lowest ionic charge for $\epsilon < 94\,\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge for $\epsilon > 94\,\%$

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Considerations and choice of the best mixture

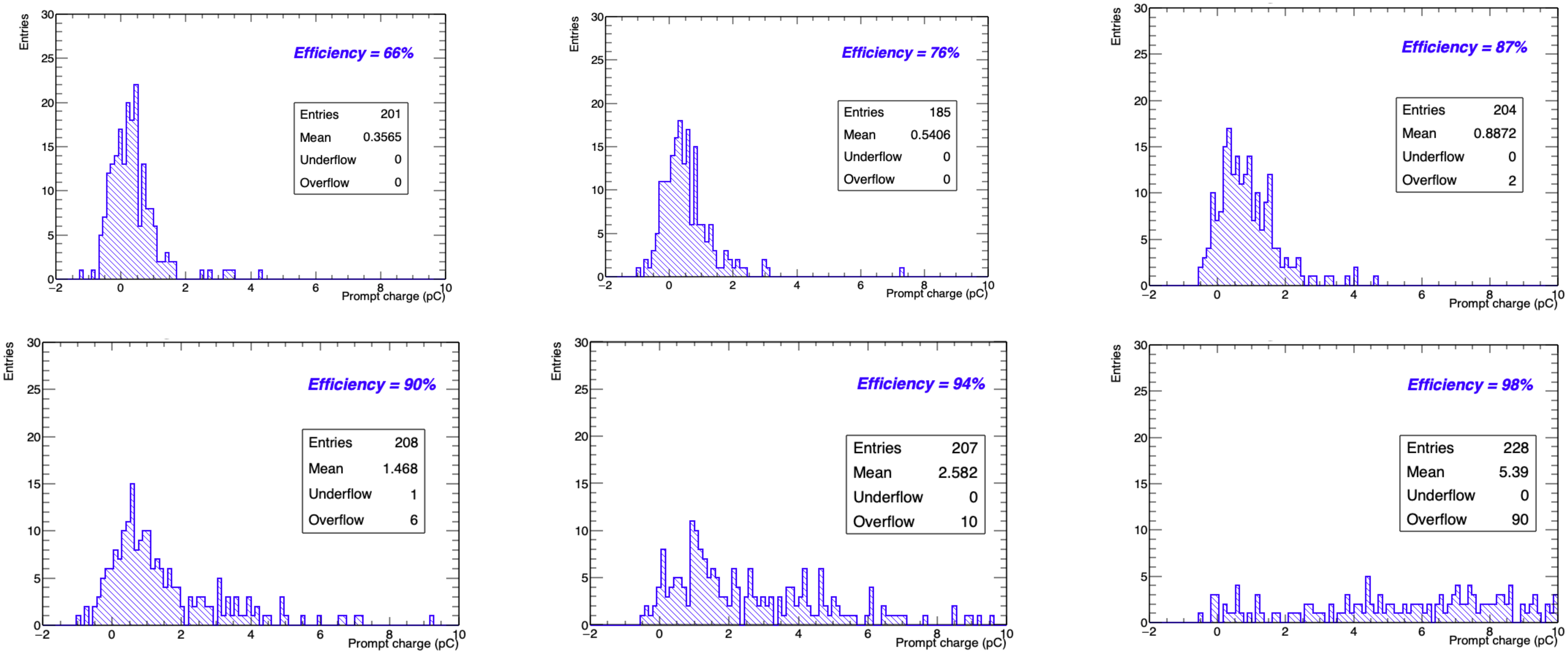
		% Cl-HFO	0	1	2	3	4	5	6
Efficiency	90%	streamer(%)	20	0	0	0	0	0	0
		transition event (%)	0	11	5	5	7	25	9
Efficiency	95%	%streamer	86	5	0	2	1	2	0
		%transition event	0	50	45	54	57	74	60
Efficiency	96%	%streamer	92	20	2	4	2	4	1
		%transition event	0	51	57	65	70	77	70

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

- The gas mixtures studied show a comfortable avalanche-streamer separation range and have a detection efficiency $\epsilon > 90\,\%$
- The transition event probability is less than 20% for $\epsilon < 95\,\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge.

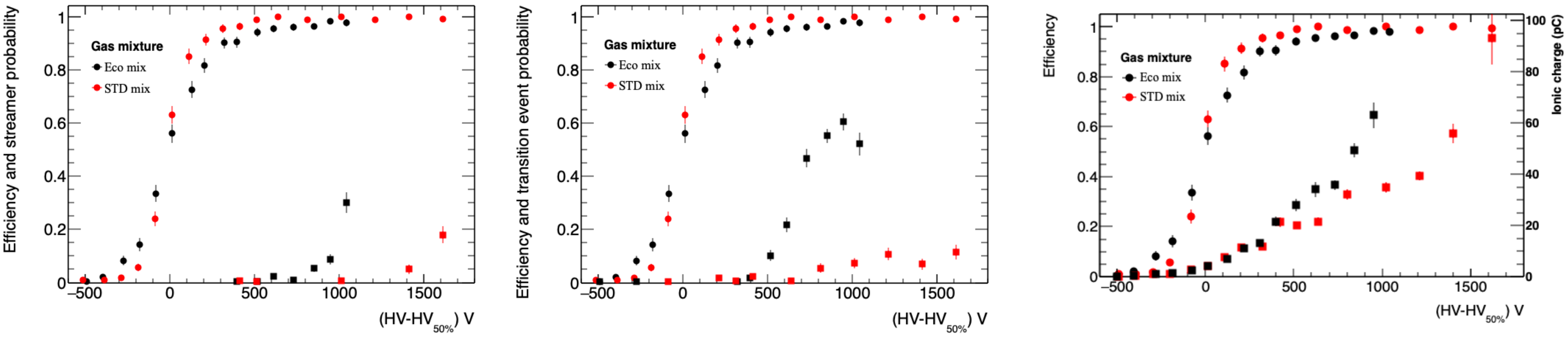
Best operating performance mixture :
CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO = (76/15/7/2)%

Best gas mixture: Prompt charge distribution



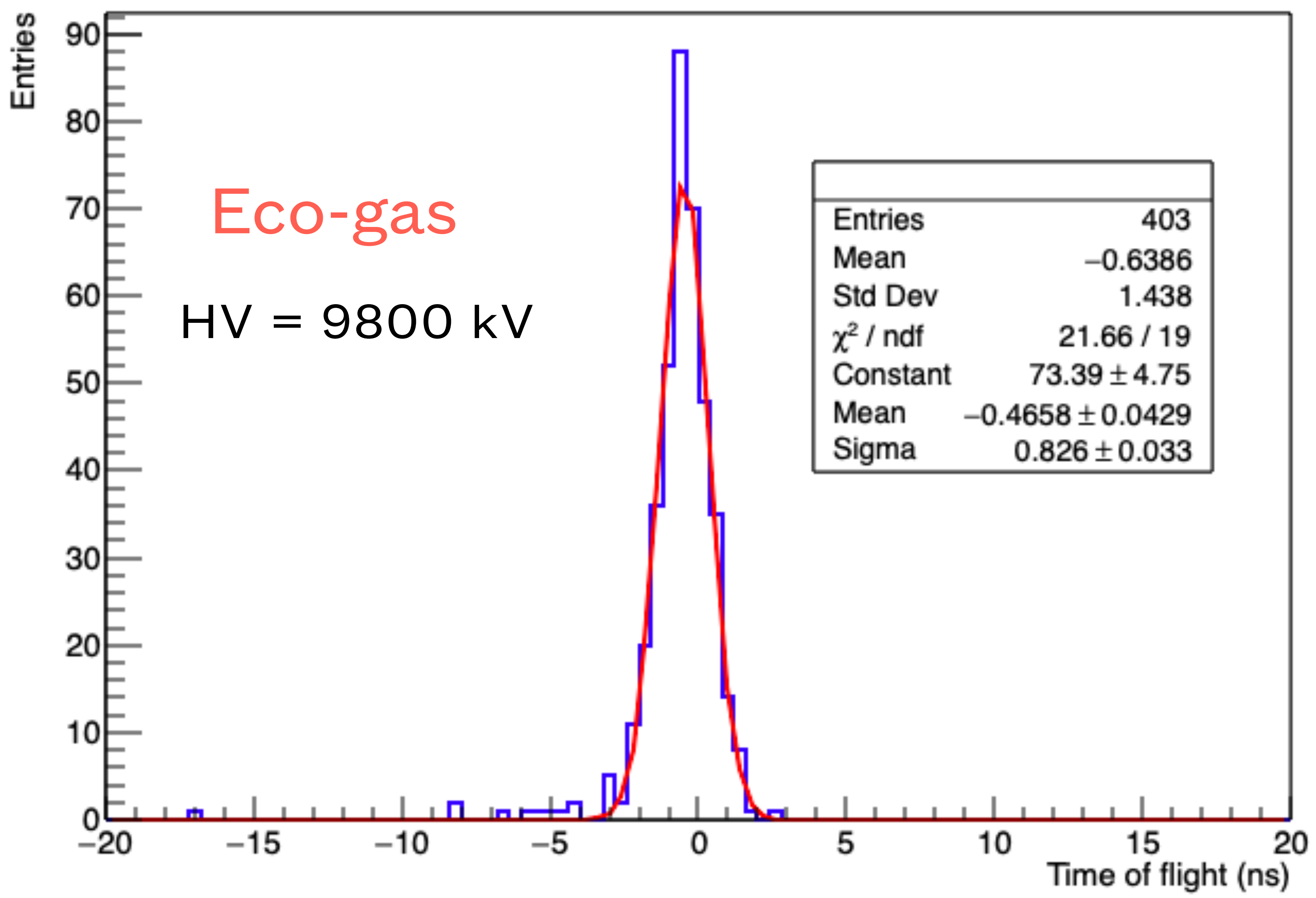
- Charge saturation for $\epsilon \leq 90\,\%$

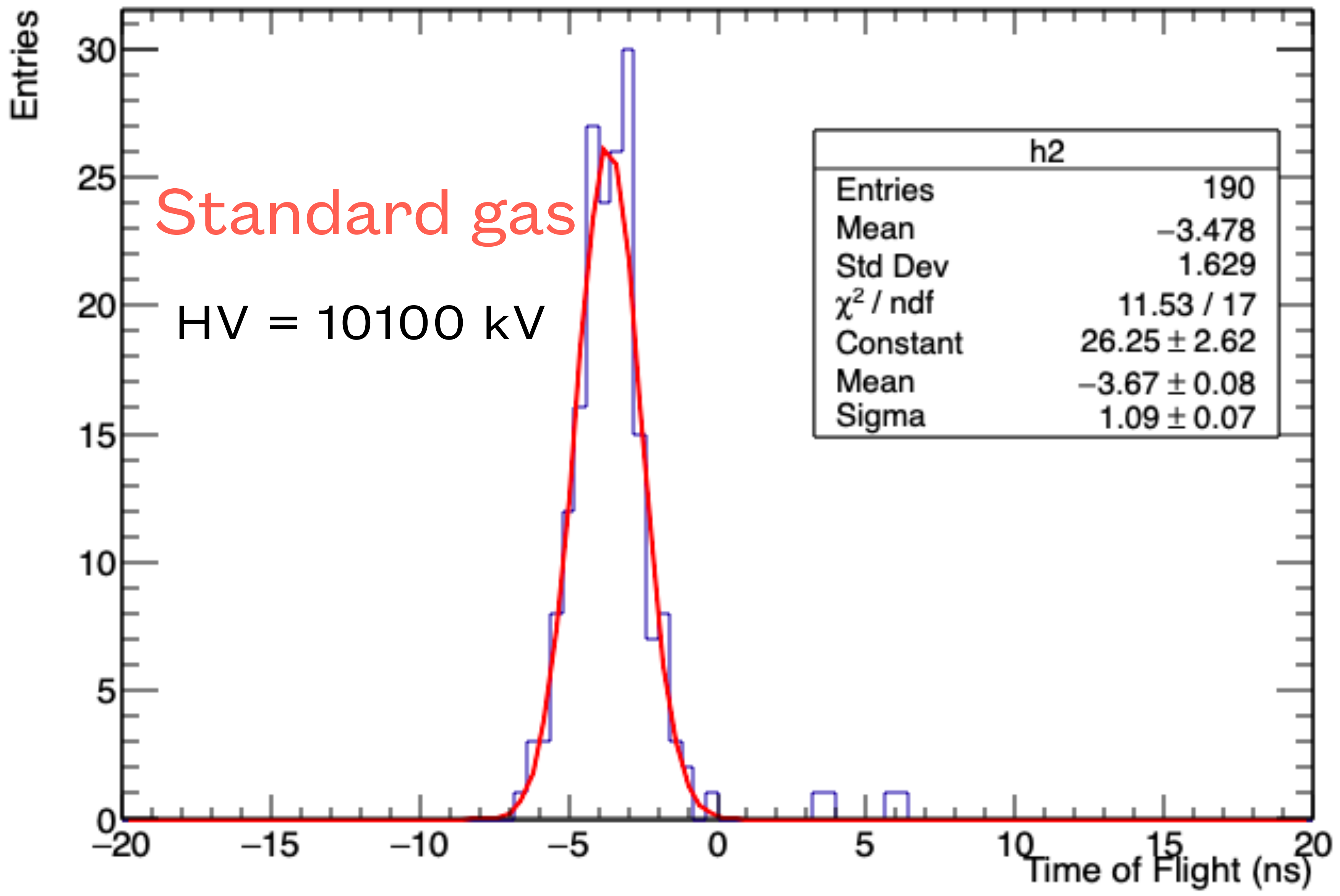
Comparison between eco and standard gas mixtures



- $HV_{ECO} \sim HV_{STD}$
- The efficiency curve has a faster rise with the standard mixture
- The avalanche-streamer separation with the standard gas is significantly larger than in the eco-mixture
- The fraction of transition events is much smaller with the standard gas
- The growth of the ionic charge is faster with the eco mixture

Comparison between eco and standard gas mixtures: Time resolution





- Time resolution measured with the time of flight (TOF) method, using the 0.5 mm gas gap as time reference

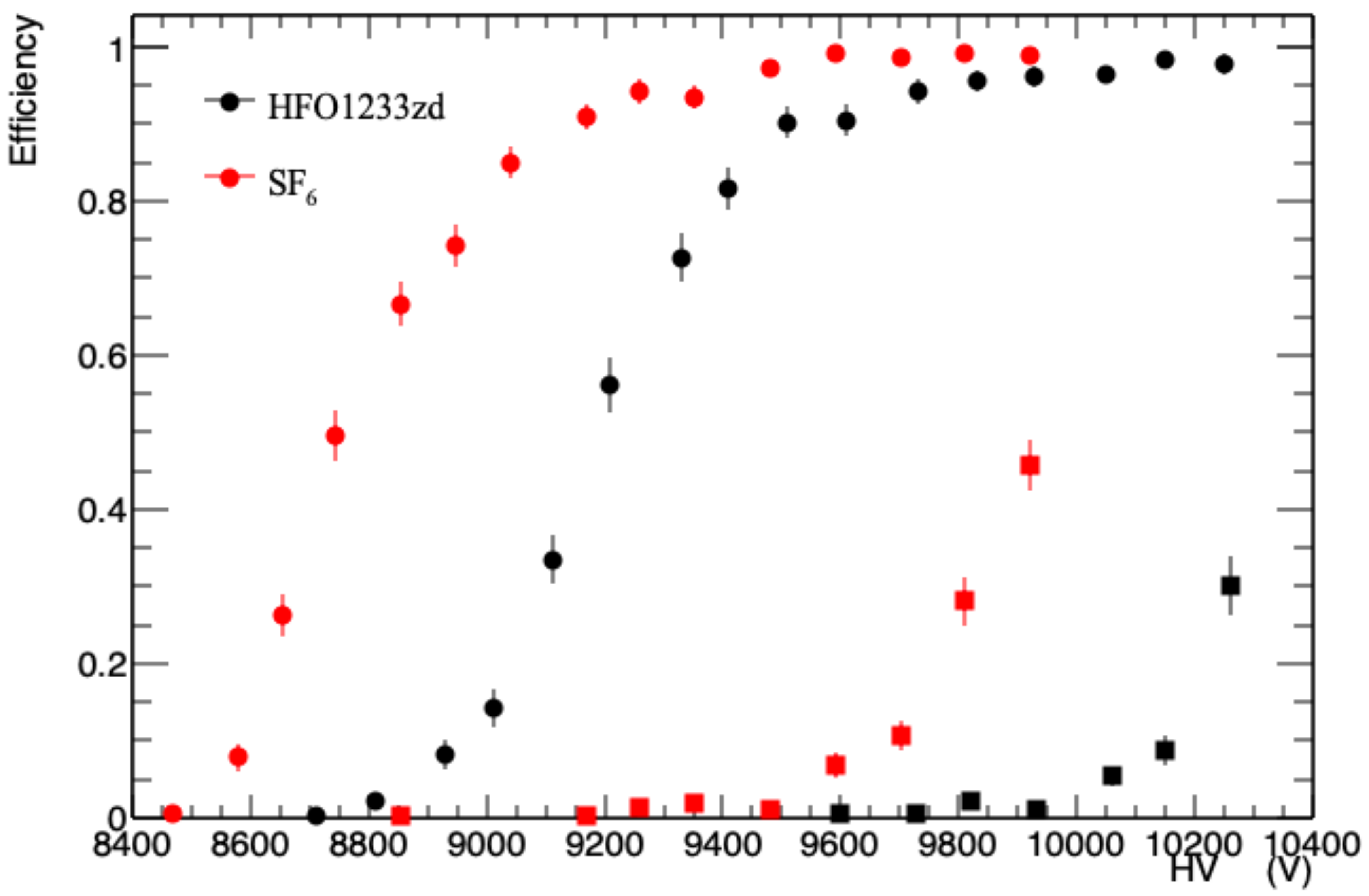
$$\sigma_t^{Eco} = (0.83 \pm 0.03)\text{ns}$$

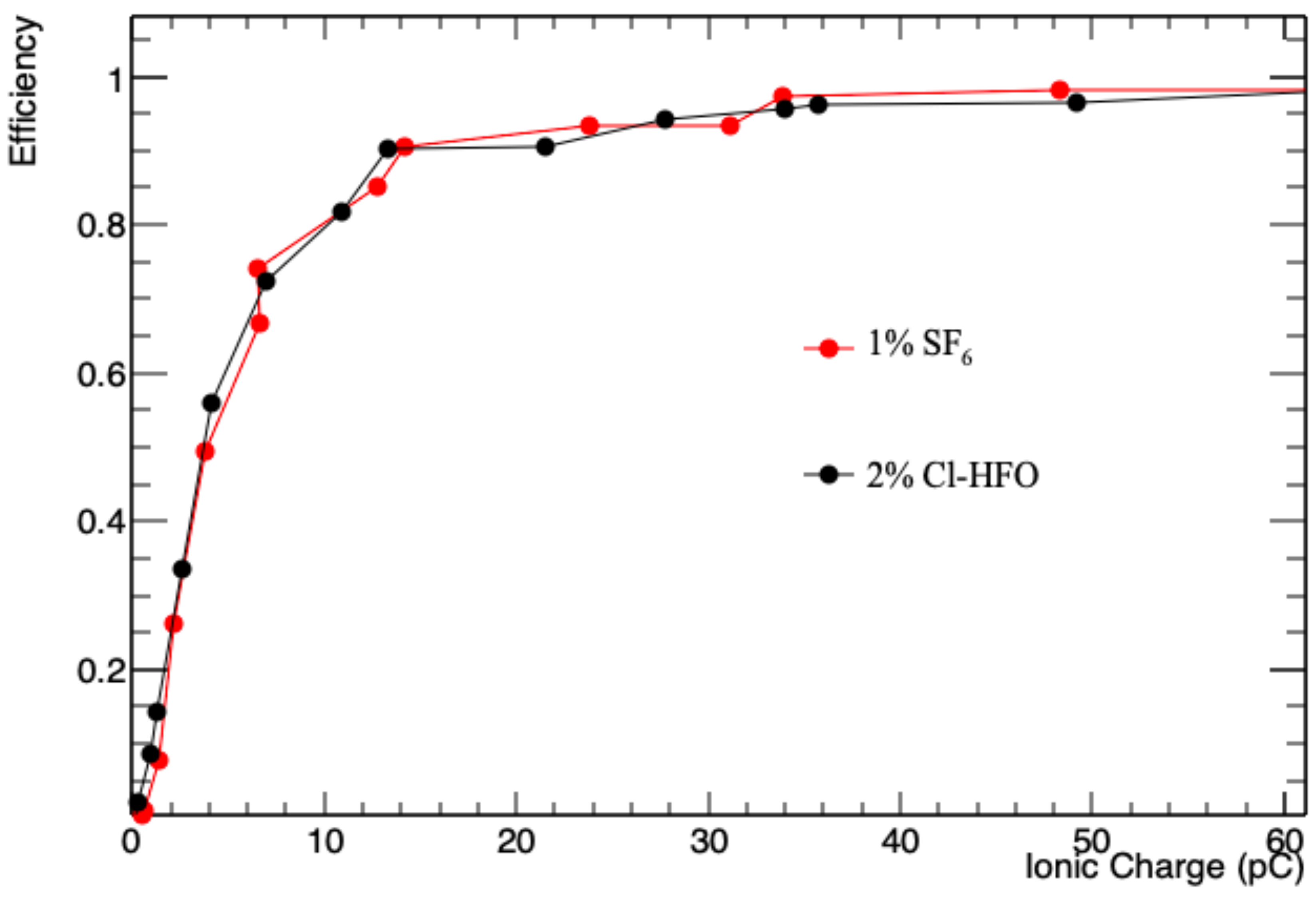
$$\sigma_t^{STD} = (1.09 \pm 0.07)\text{ns}$$

- These TOF distributions do not contain any kind of corrections for systematic effects
- The eco-mixture has a better time resolution

Comparison between Cl-HFO and SF6

Mixture under study : F-HFO/CO_2/i-C_4H_{10}/SF_6 and F-HFO/CO_2/i-C_4H_{10}/Cl-HFO





The Cl-HFO can substitute SF_6 in these gas mixtures

- $HV_{Cl-HFO} = (450 + HV_{SF_6})V$
- Plateau knee at 90% efficiency for both gas mixtures, followed by a slow increase up to 96%
- Avalanche-streamer separation ~350 V for both mixtures
- Same ionic charge at the same efficiency value

Conclusions

New eco friendly gas mixtures composed of $CO_2/C_3H_2F_4/i-C_4H_{10}/C_3H_2ClF_3$ have been tested. These mixtures have an Ozone Depletion Potential = 0 and a Global Warming Potential ~ 10.

- The voltage separation between avalanche and streamer mode is smaller compared with that of the standard gas (~350 V vs ~ 1 kV), but sufficient to insure a streamerless operation in avalanche mode
- The SF_6 can be replaced by the Cl-HFO molecule with no effect on the performance;
- The new gas shows a better time resolution with respect to the standard gas ($\sigma_t^{Eco} = (0.83 \pm 0.03)$ns, $\sigma_t^{STD} = (1.09 \pm 0.07)$ns)

https://arxiv.org/abs/2112.02659

Thank You

Backup

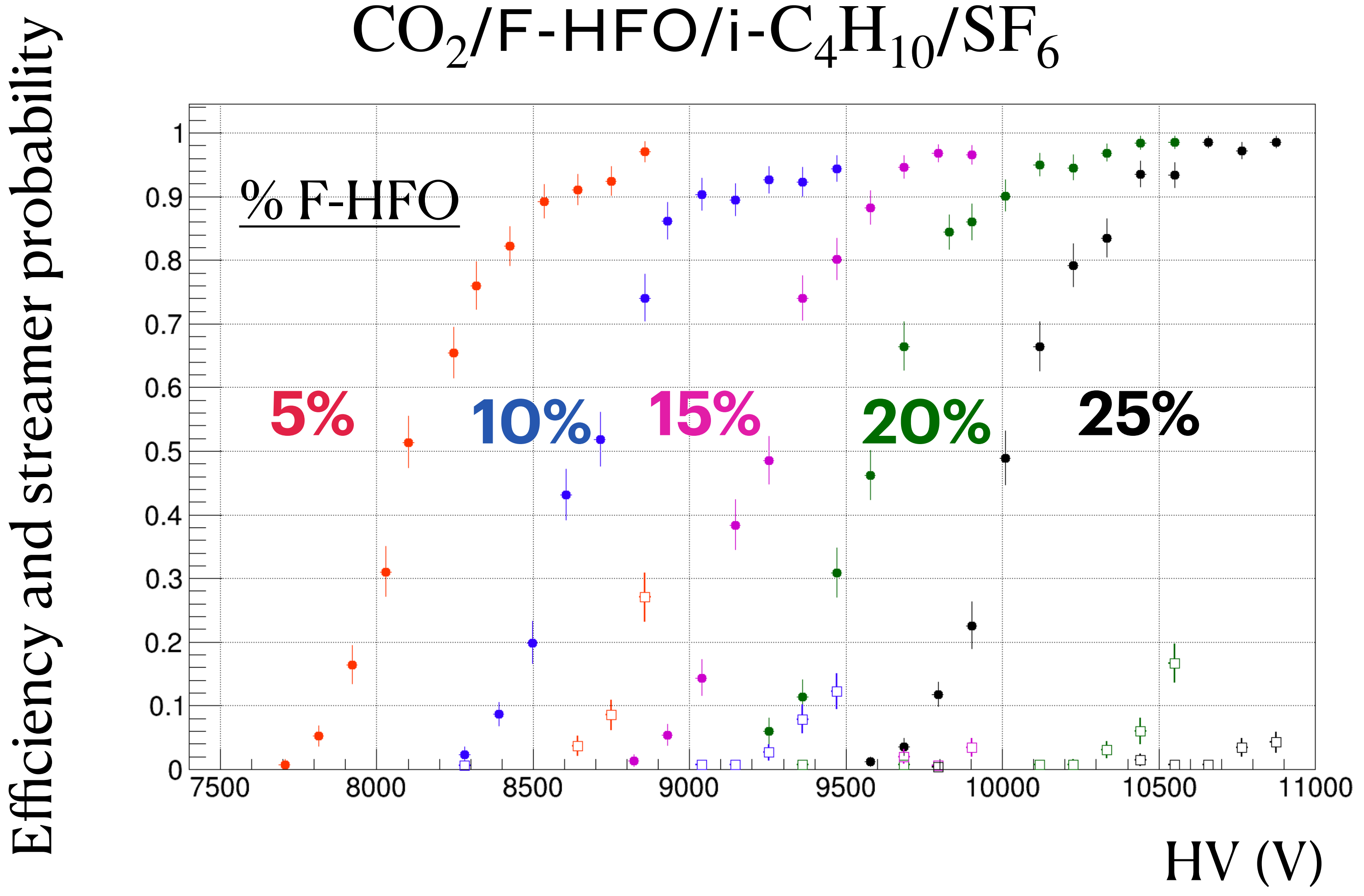
Comparison between eco and standard gas mixtures: Conclusions

- The efficiency curve is sharper with the standard mixture ;
- The avalanche to streamer separation in the eco gas is significantly smaller than in the standard mixture ;
- The fraction of the transition events is much smaller in the standard gas ;
- The mixture with 2% Cl-HFO shows a charge saturation for $\epsilon \leq 90\,\%$;
- We observed a better time resolution with the eco-mixture

Optimize the eco gas mixture for the RPC

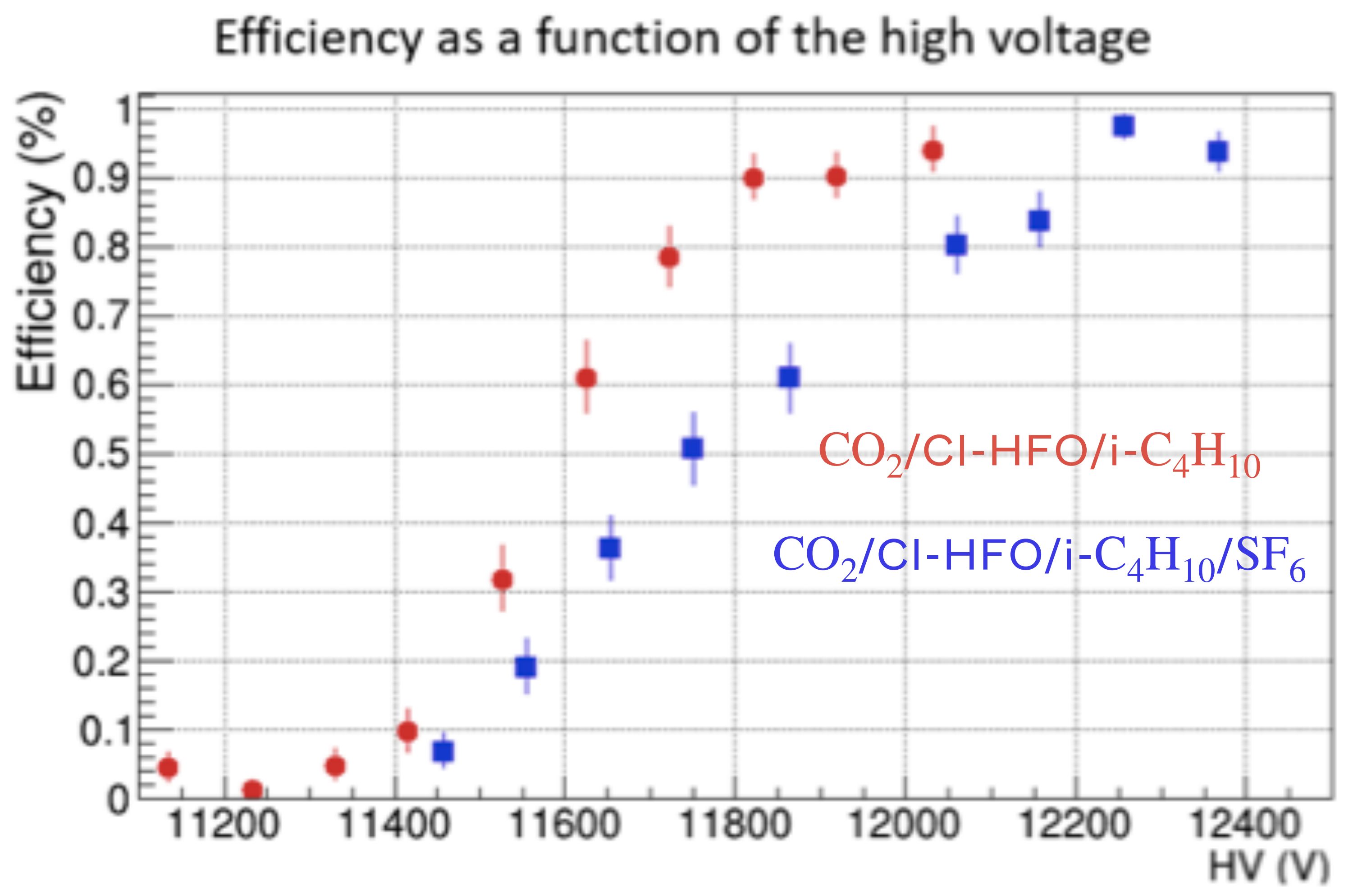
1. Test on a 2 mm gas gap RPC operating with CO_2/HFO1234ze/I-C_4H_{10}/SF_6 with a low concentration of HFO1234ze (F-HFO) to minimize aging effects:
   - No significant change in performance with a F-HFO concentration F-HFO in the range (15-25) %

CO_2/F-HFO/i-C_4H_{10}/SF_6



https://www.sif.it/riviste/sif/ncc/econtents/2021/044/02-03/article/42

2. [Test on a 2 mm gas gap RPC operating with](https://arxiv.org/pdf/2006.00331.pdf) CO_2/I-C_4H_{10}/HFO1233zd(Cl-HFO):
   - Cl-HFO concentration must be < 10%



https://arxiv.org/pdf/2006.00331.pdf

Mixtures under test

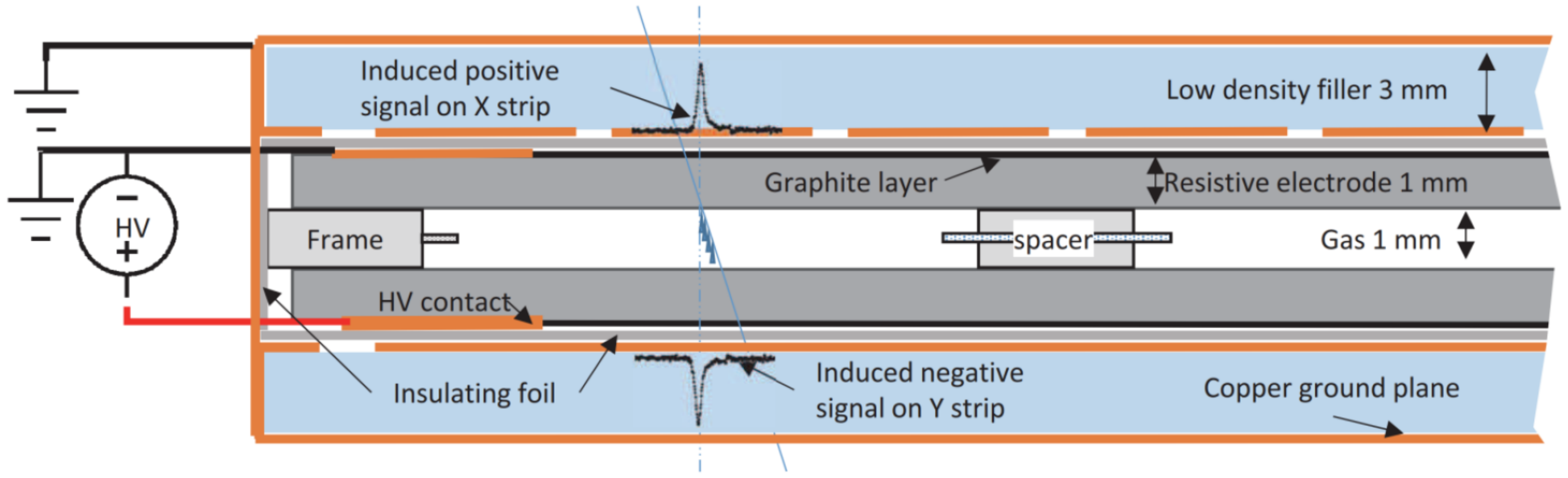
CO_2/F-HFO/i-C_4H_{10}/Cl-HFO

- F-HFO/i-C_4H_{10} fixed at 15/7
- Cl-HFO/CO_2 concentrations varying in the range (0-6)%/(78/72)%

Data analysis overview (II)

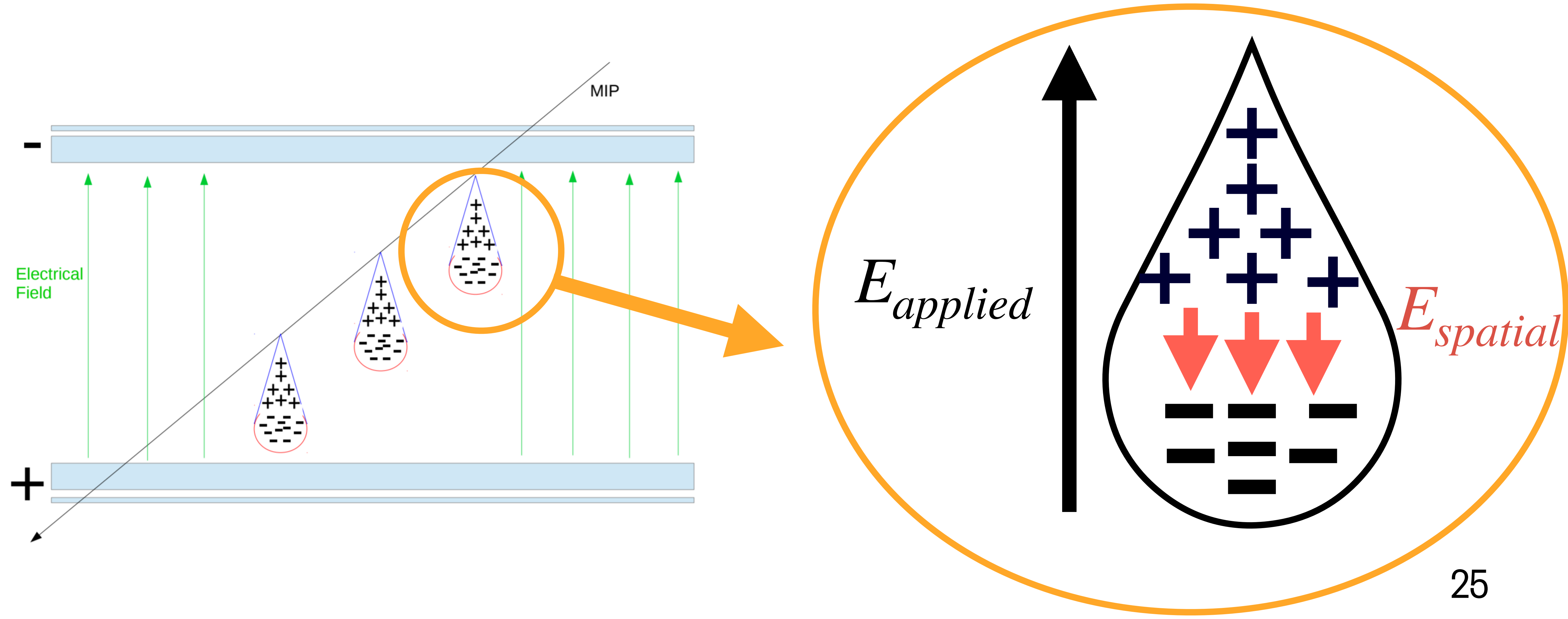
- Performance of the RPC operating with gas mixtures composed of CO_2/F-HFO/i-C_4H_{10}/Cl-HFO
- Comparison between the eco-mixture with the best performance and the standard gas mixture
- Direct comparison of the performance with SF_6 and Cl-HFO

The Resistive Plate Chambers (RPC)



- Gas gap
- Parallel resistive electrodes
  - Internal surface: linseed oil
  - External surface: graphite
- Insulating layer
- Read-out strips

- Primary ionization
- Electron acceleration and avalanche charge formation:
  - Saturated avalanche mode
  - Electron-ion recombination processes with UV photons emission
  - Streamer formation

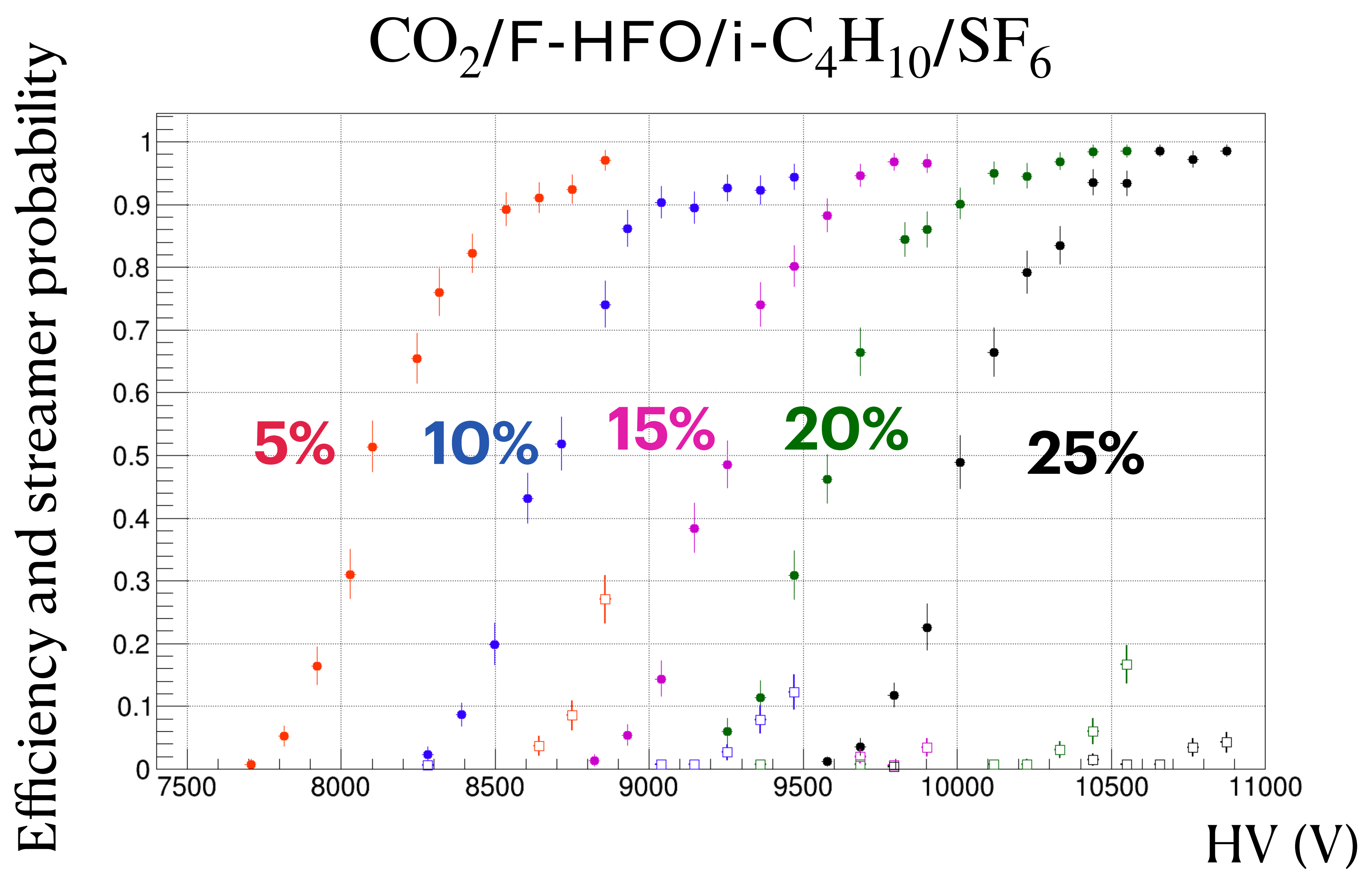


Optimize the eco gas mixture for the RPC

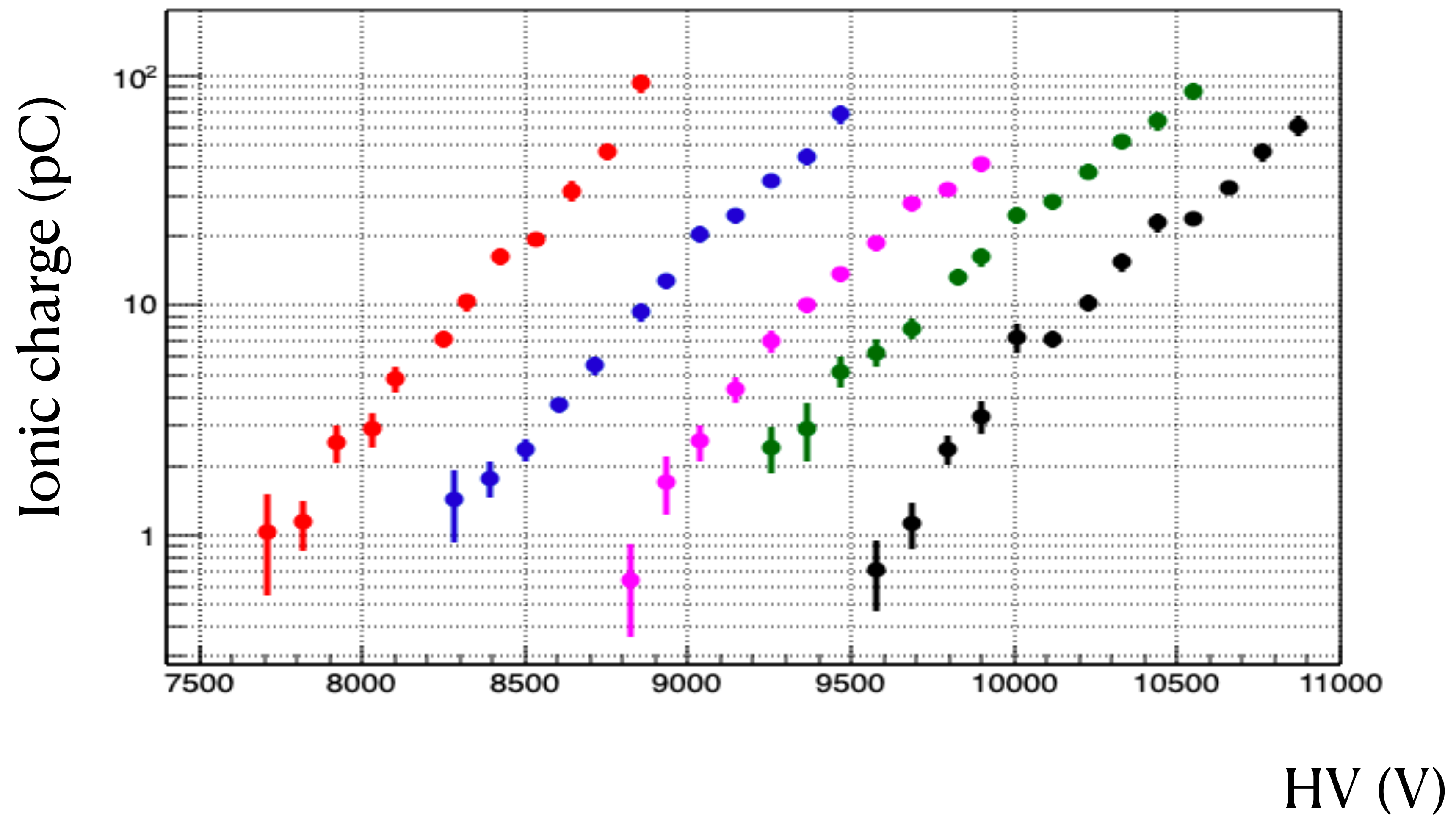
- 1)first step :Test RPC with a low concentration [low HFO1234ze] (F-HFO) to minimize aging effects:
    - No significant change in performance with a concentration F-HFO in the range (15-25) F-HFO %->higher hv 25% plateau at 10.5kv 8.6 kv freccia e titolo plot
    - 2)second step increasing I-C_4H_{10} includi sopra sots:
        - Both streamer fraction and total charge drastically reduced
- 2) Very preliminary test on HFO1233zd (Cl-HFO): metti plot specifica miscela
- The Cl-HFO concentration must be < 10%

...to the choice for this test

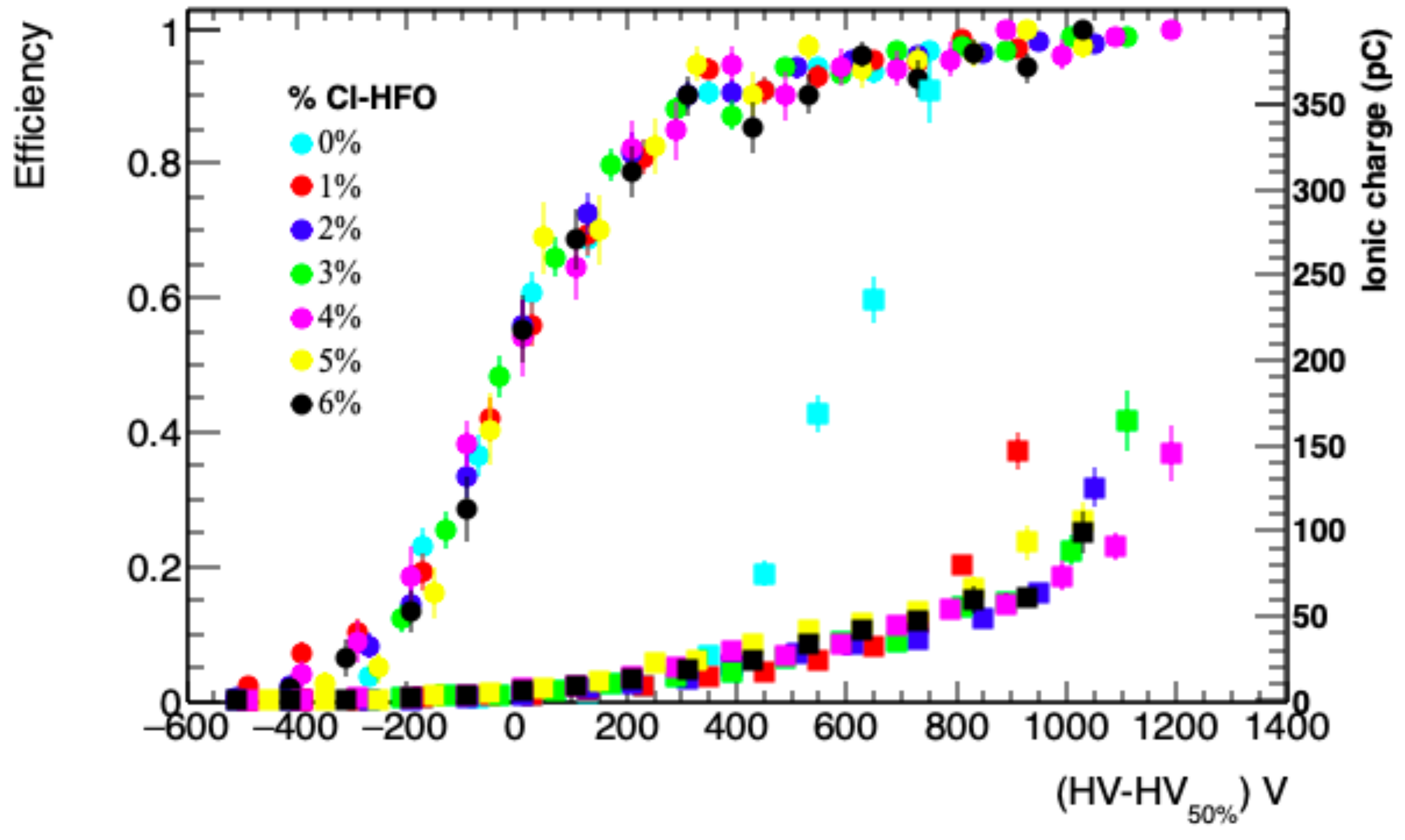
- F-HFO and i-C_4H_{10} concentrations fixed at 15/7
- Cl-HFO concentration within the range (0-6)%

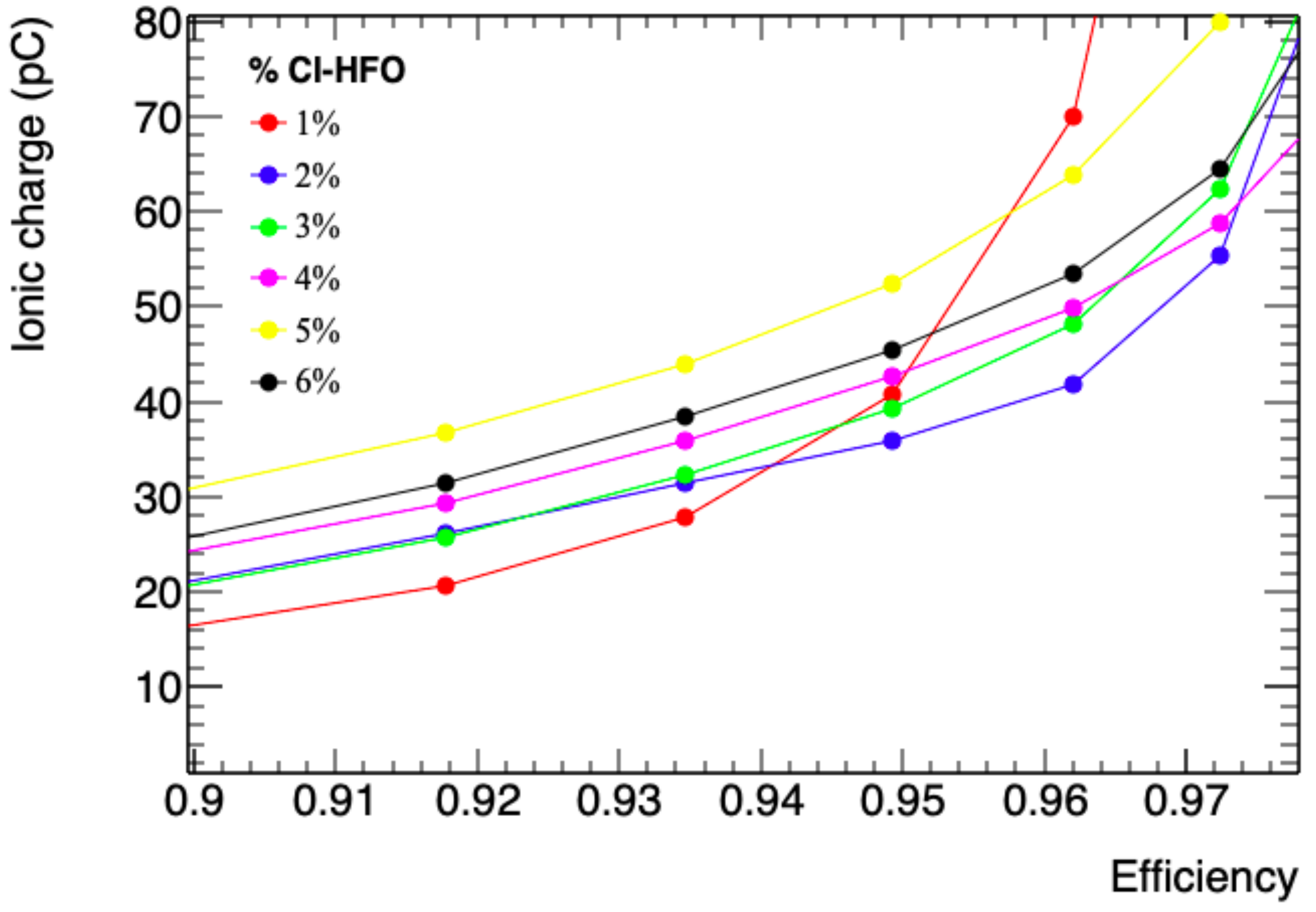


% F-HFO



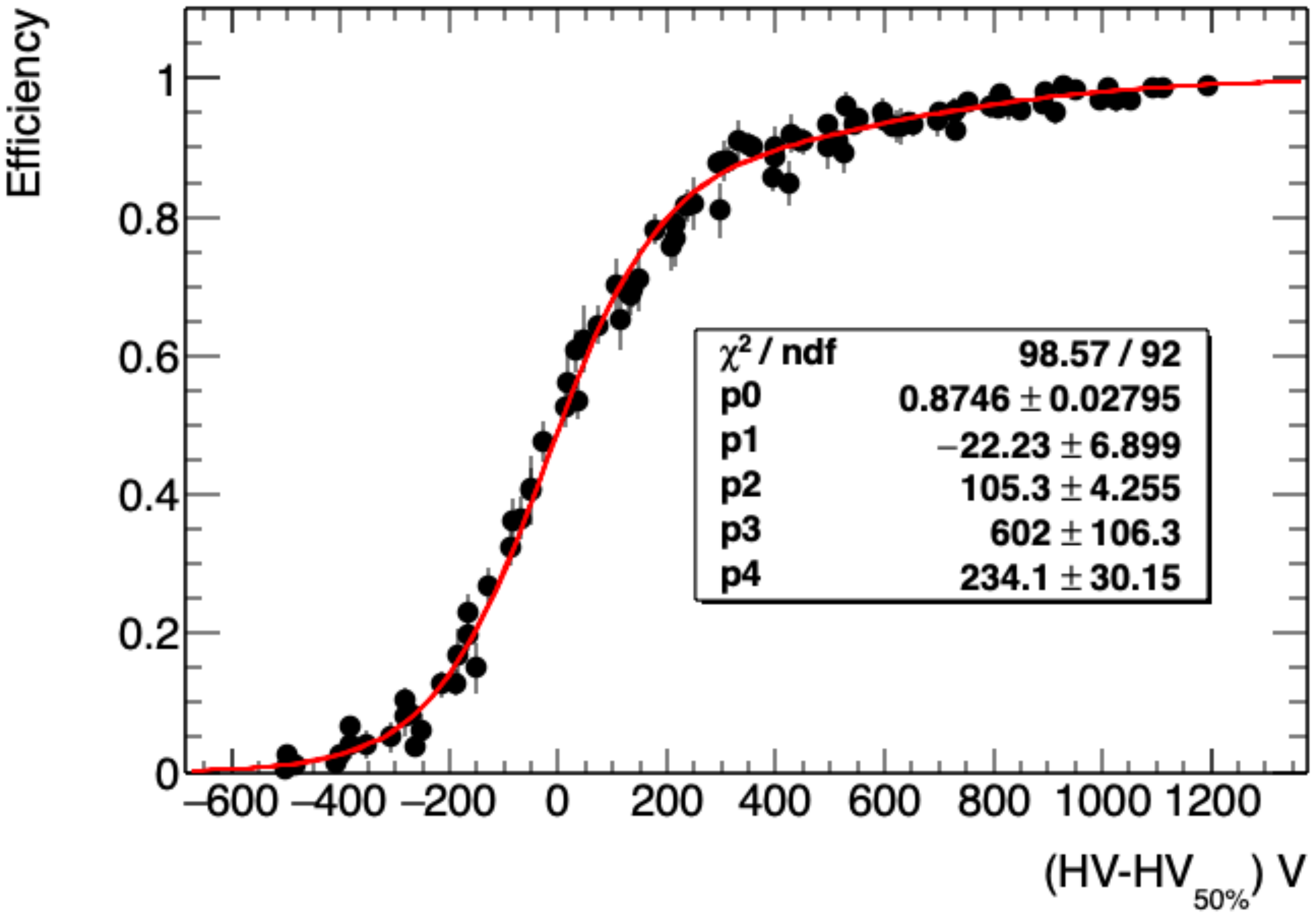
RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Ionic charge





- The ionic charge of the mixture without Cl-HFO reaches very high values (~ 75 pC) at low efficiency
- The mixture with 5% and 6% Cl-HFO have an ionic charge more than 30 pC at the first plateau value
- The mixture with 1% Cl-HFO shows the lowest ionic charge in the first three points but a faster rise
- The other mixtures shows an ionic charge between 20 and 30 pC up to 300 V above the operating voltage

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Fit analysis (I)



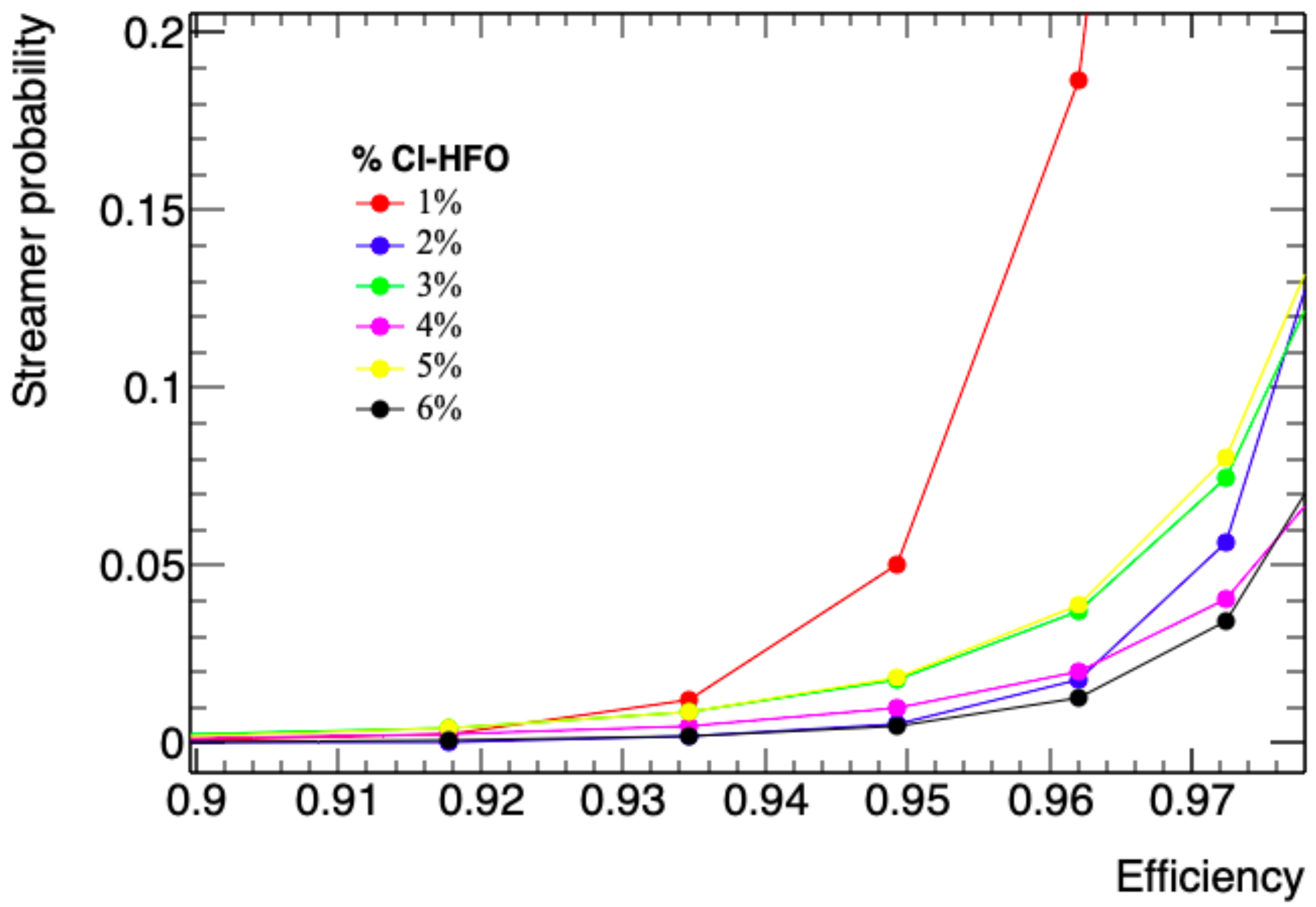
- The efficiency curves after the alignment have the same profile

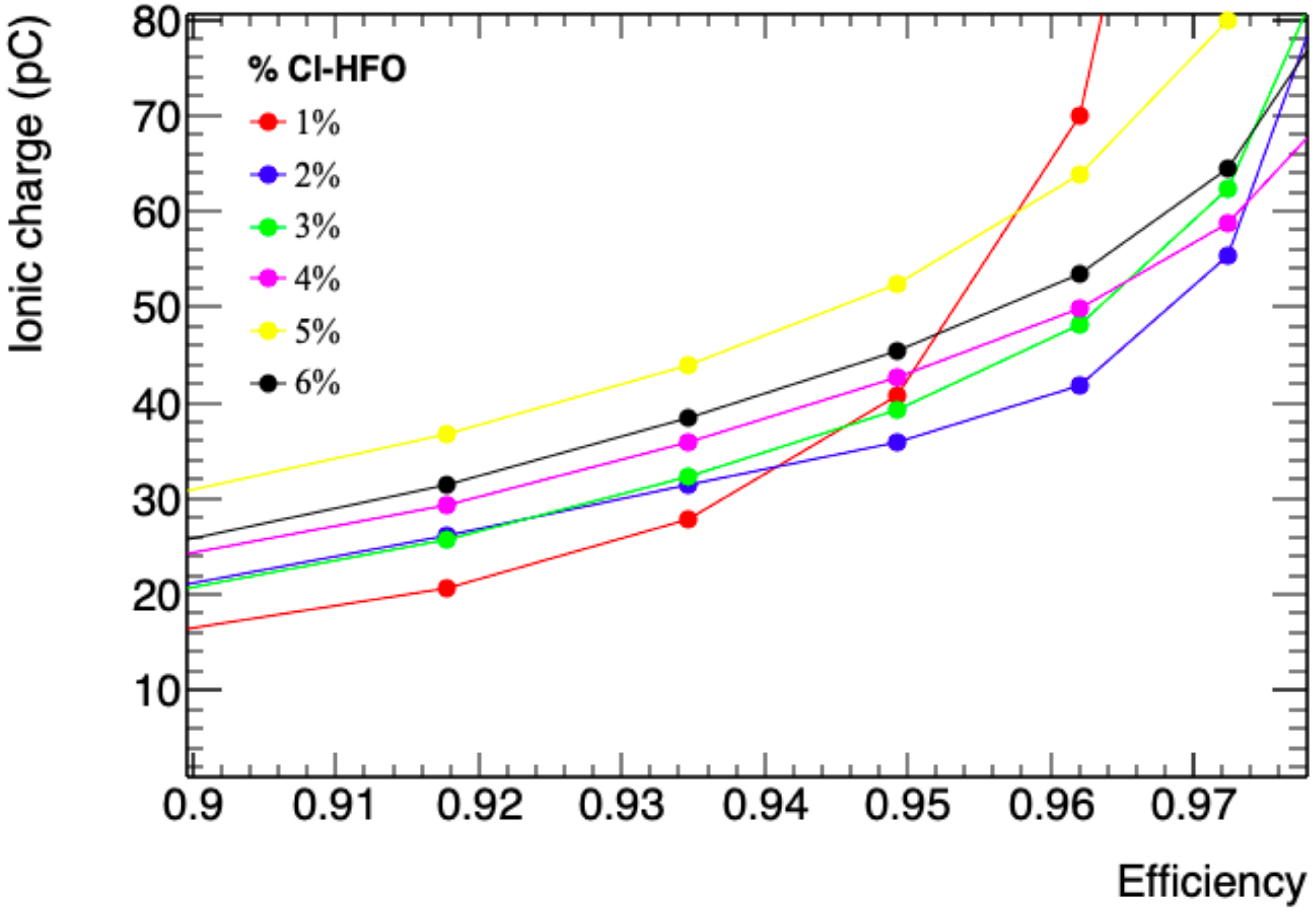
Fit function

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

- Streamer probability vs HV → Fermi function
- Transition event probability vs HV → Landau
- Prompt and ionic charges vs HV → Multi-degree polynomial fit

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Fit analysis (II)





- The streamer curve is faster in the mixture containing 1% Cl-HFO
- The mixture with 1% Cl-HFO shows the lowest ionic charge for $\epsilon < 94\,\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge for $\epsilon > 94\,\%$

Ionic to prompt ratio