Università di Roma Tor Vergata

INFN Istituto Nazionale di Fisica Nucleare

RPC 2022

On a new environment-friendly gas mixture for Resistive Plate Chambers

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

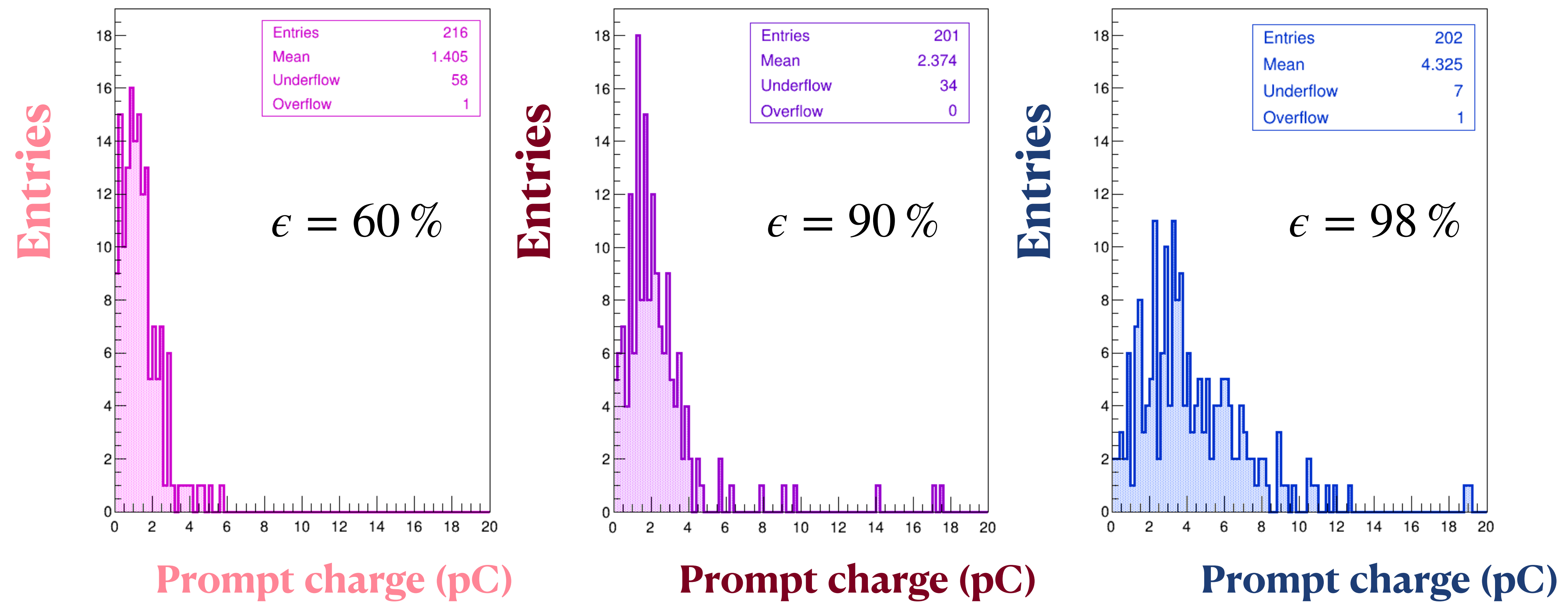
Outline

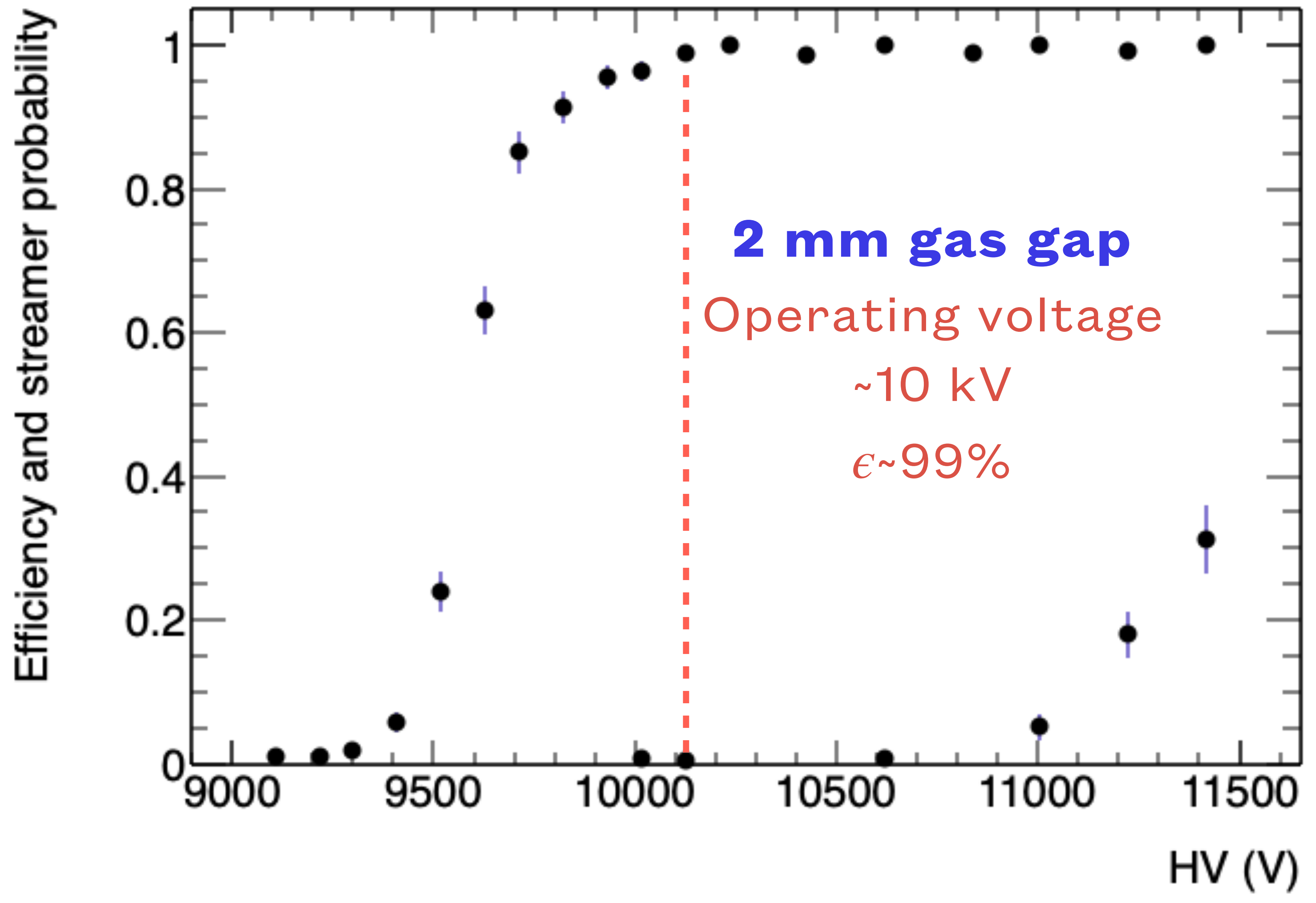
- Performance of the Resistive Plate Chambers with the standard gas mixture
- Decreasing the Global Warming Potential and Ozone Depletion Potential: the $C_2H_2F_4$ and SF_6 substitutes
- Experimental set-up
- Analysis criteria
- Results

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

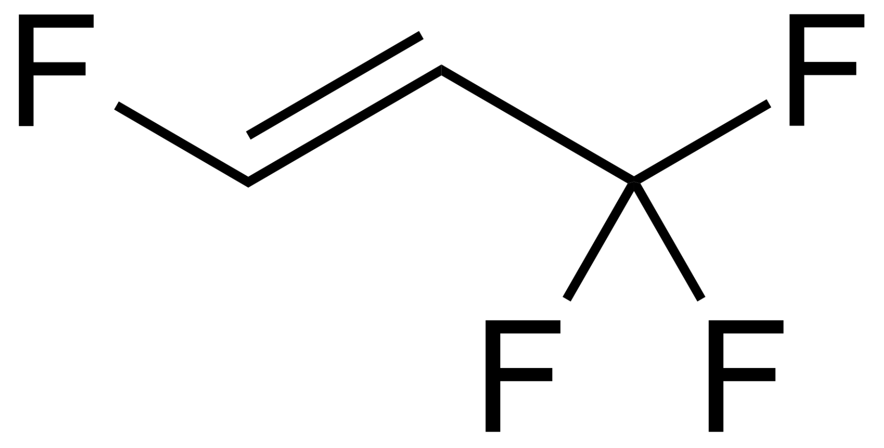




New eco-gas mixtures for RPC

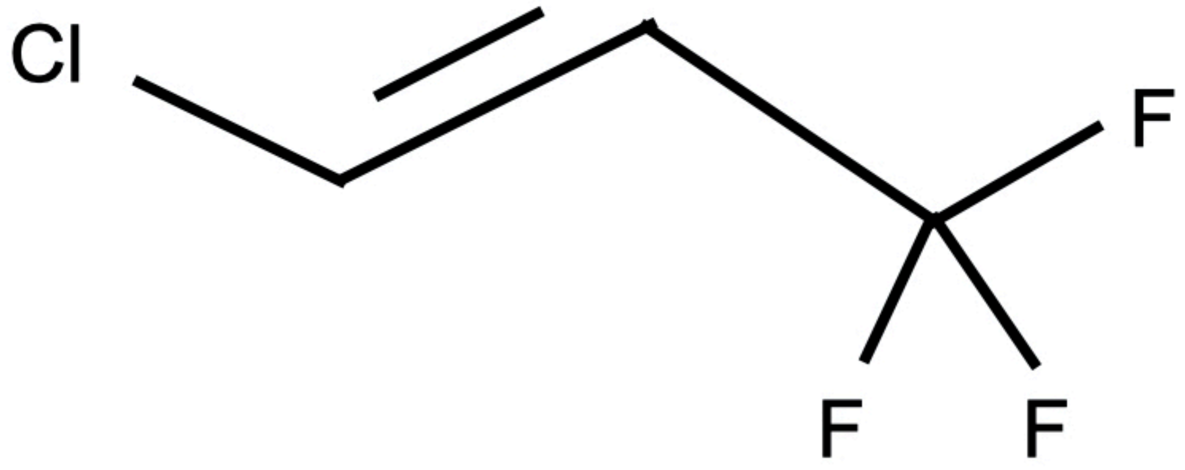
The standard gas mixture has a high Global Warming Potential (GWP)

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



Substitute $C_2H_2F_4$ with an environment-friendly gas mixture

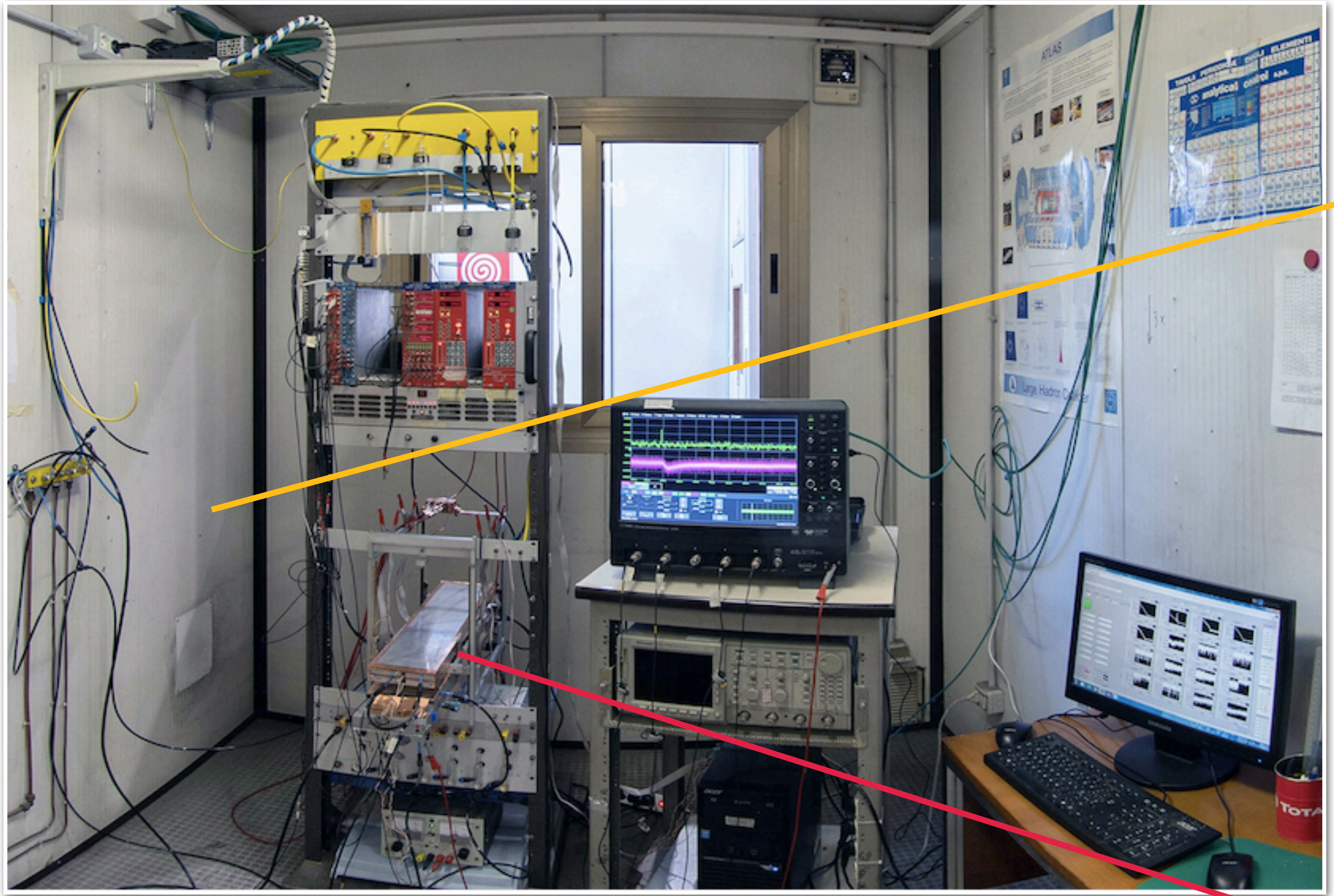
- CO_2 / $C_3H_2F_4$ **(HFO1234ze)** + i-C_4H_{10} + SF_6 → **GWP ~ 200**



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 set-up (I)

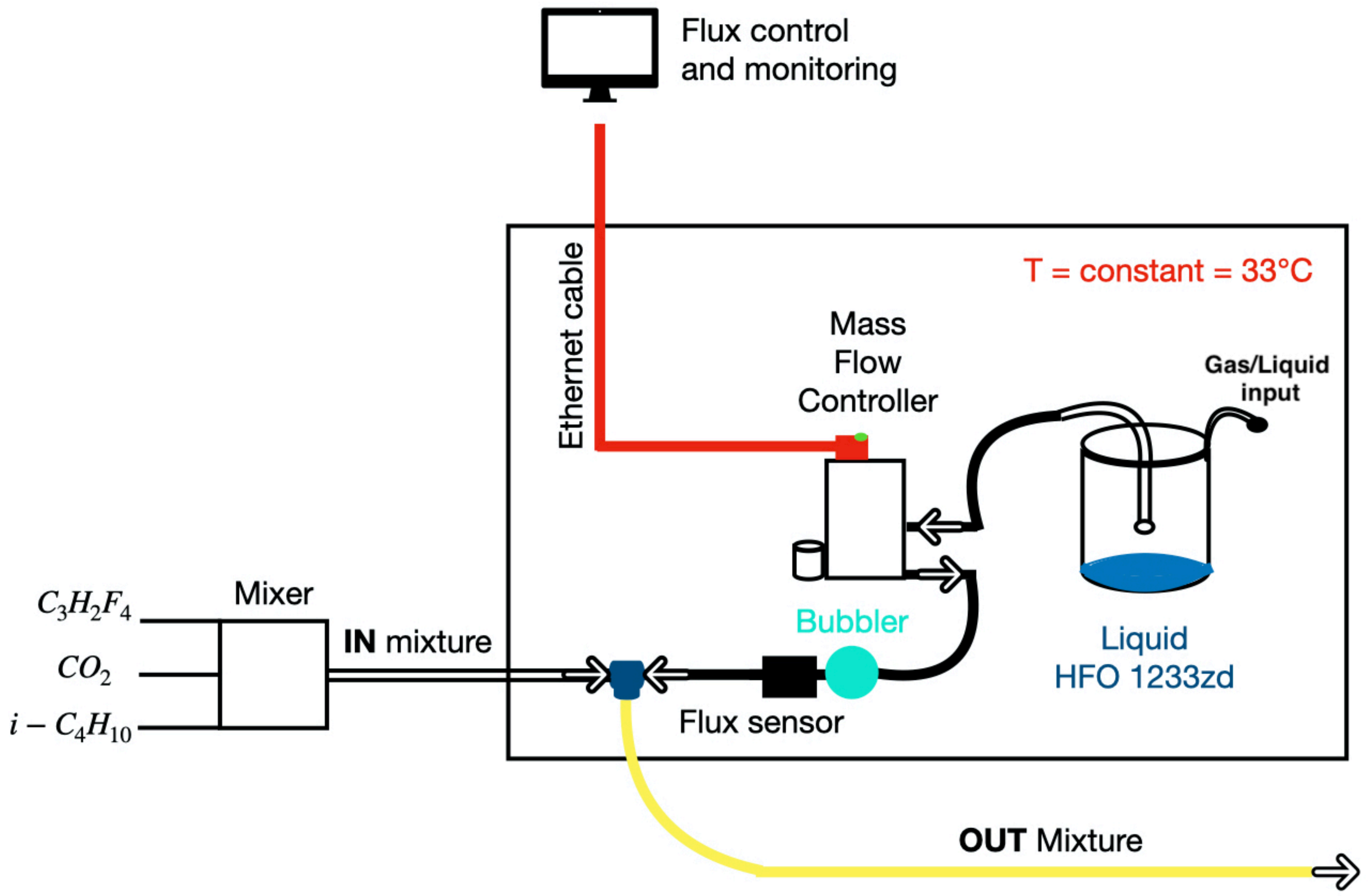


- Three 2 mm gas gap RPCs in coincidence, forming the ***trigger***
- One 0.5 mm RPC (confirm chamber)
- Detector under test : 2 mm gas gap RPC
- Oscilloscope (Bandwidth : 3 GHz; Sampling velocity : 20 Gs/s)

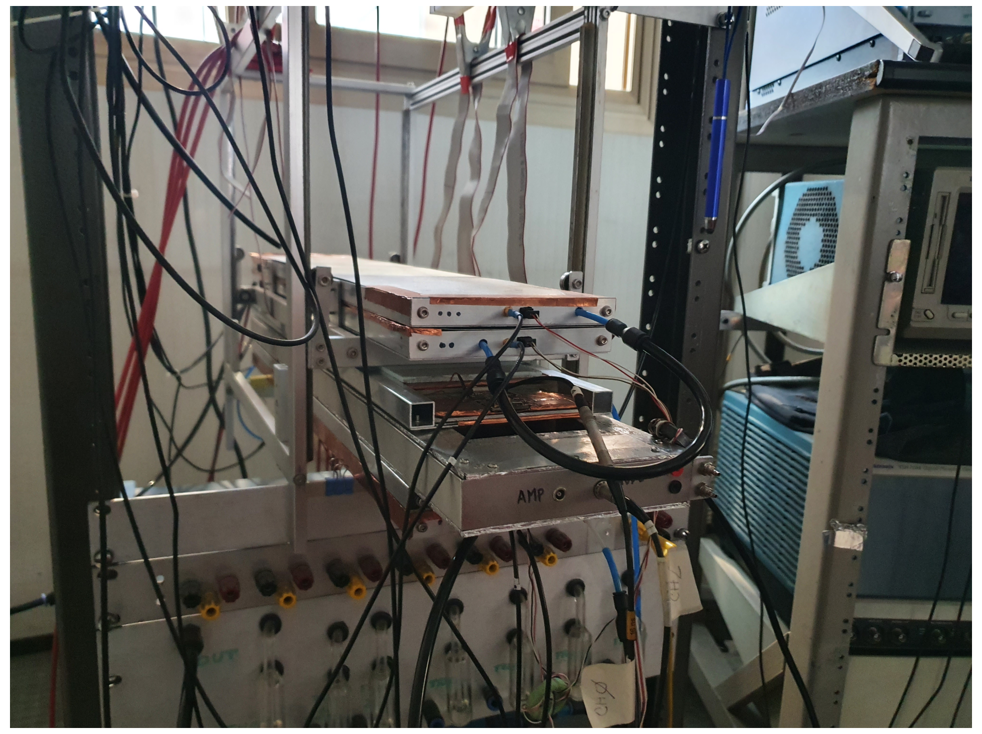
Gas system

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

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



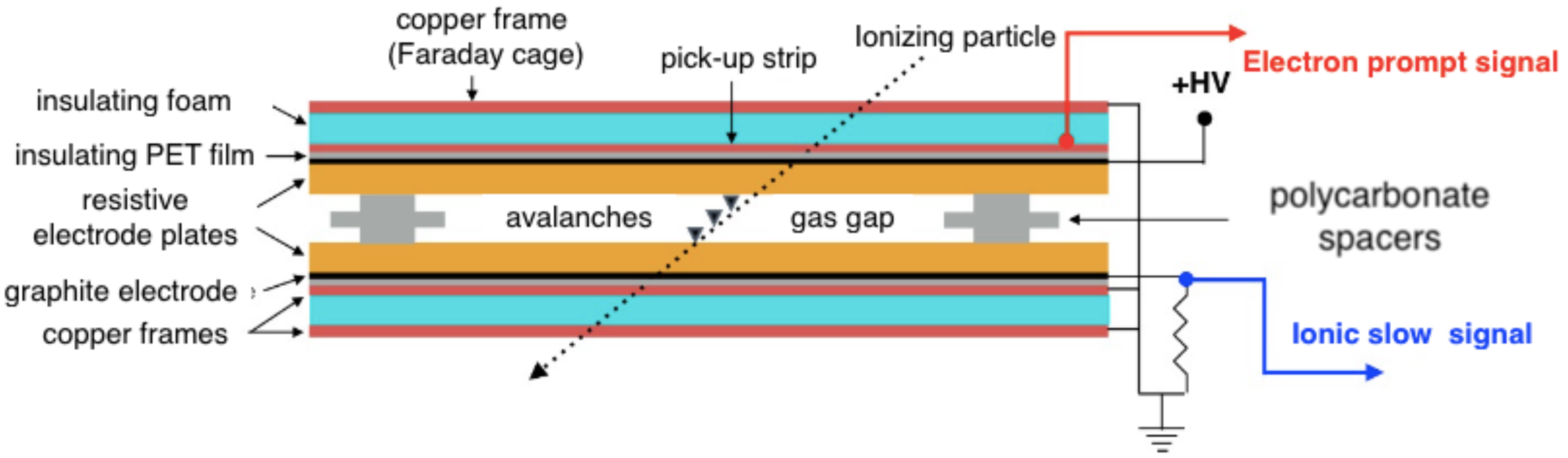
Trigger

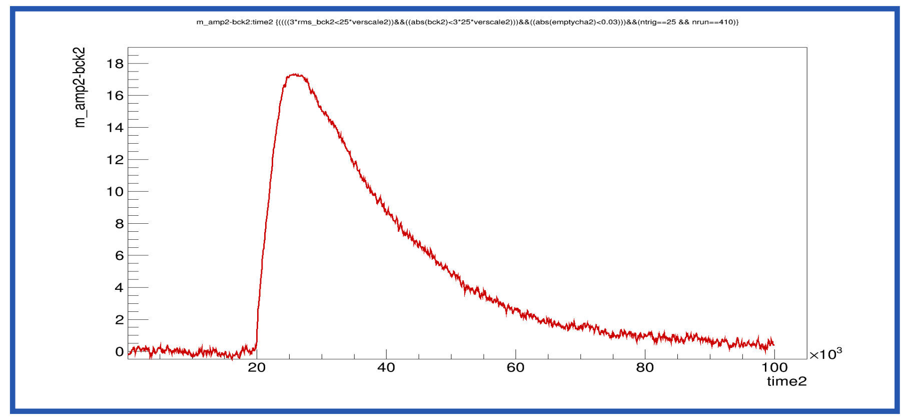


The 0.5 mm RPC is used as :

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

RPC under test





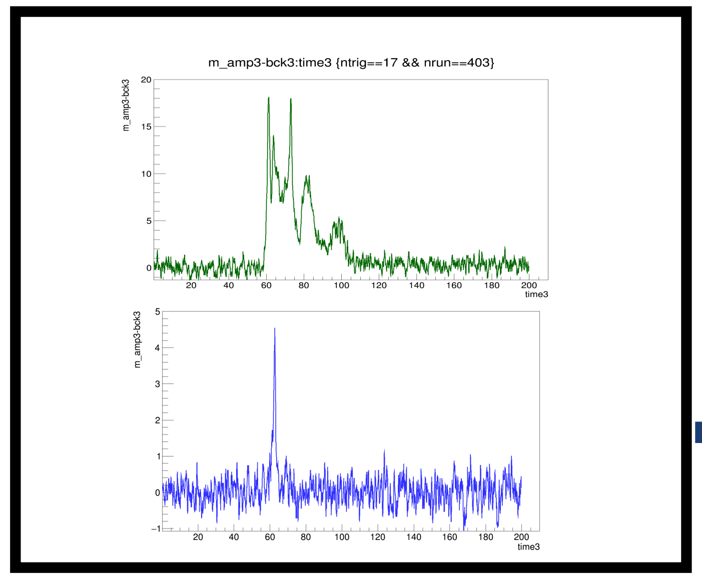
Ionic signal :read out on a resistance on the ground graphite electrode equal to 10 kOhm

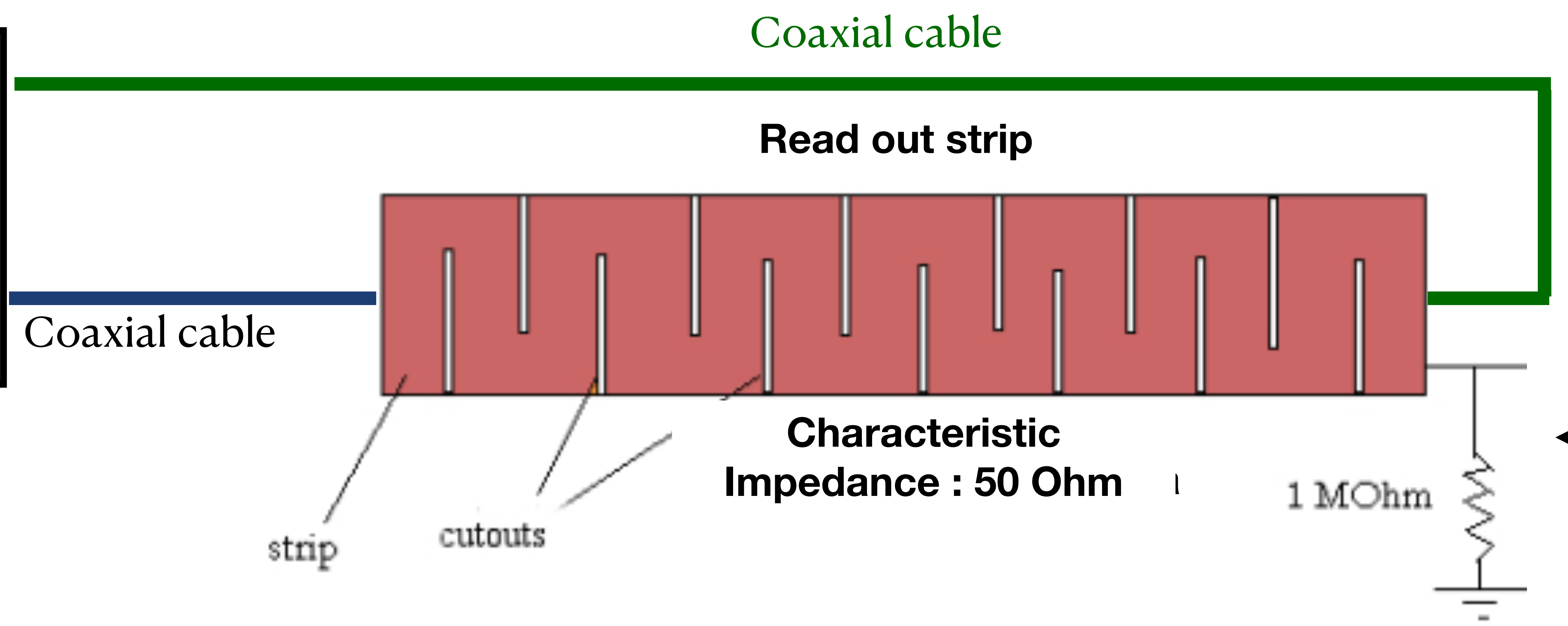
- Dimensions : (57 x 10) cm^2
- Gas gap width : 2 mm
- Electrode thickness : 1.8 mm

Read-out strip

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

Oscilloscope

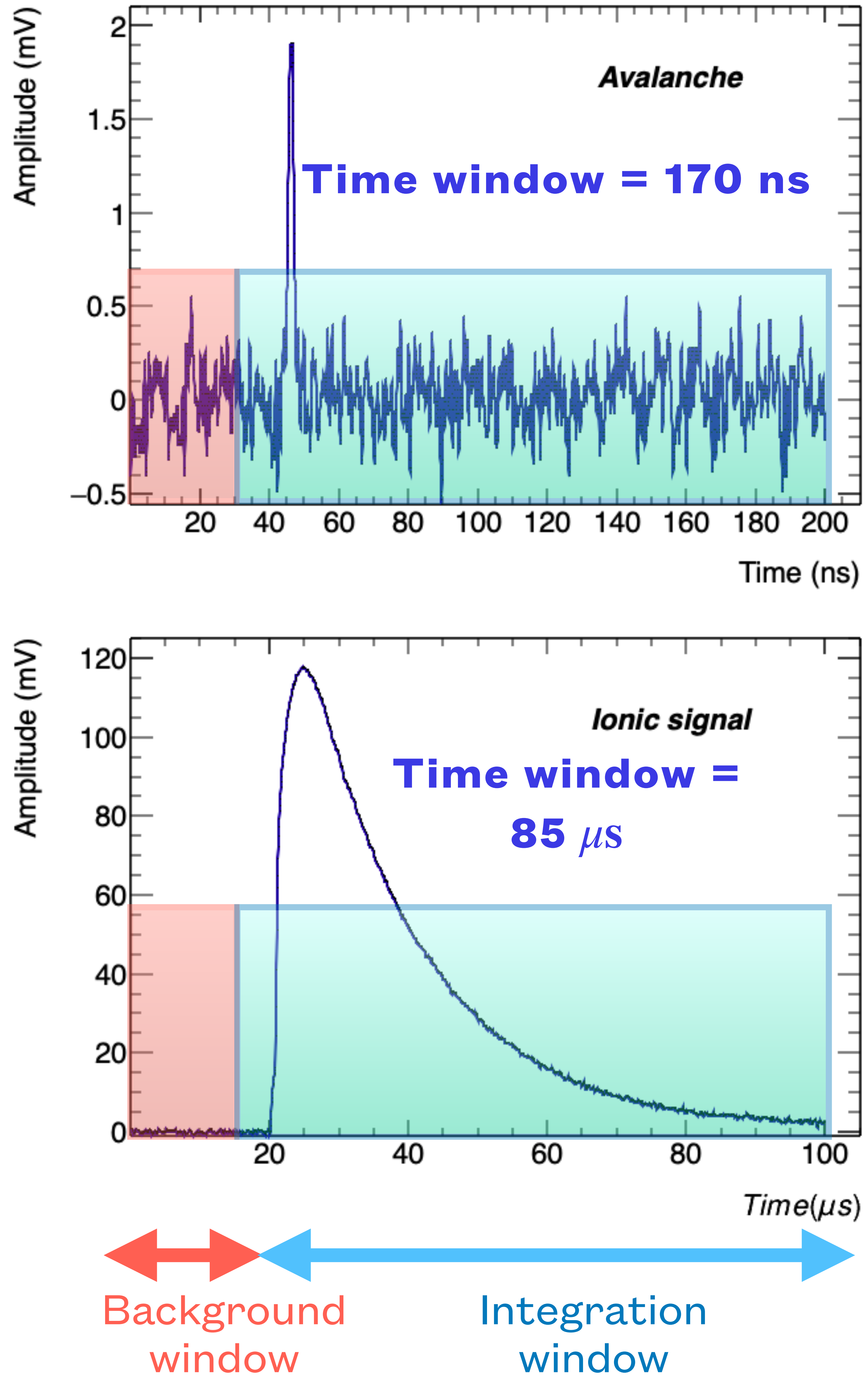




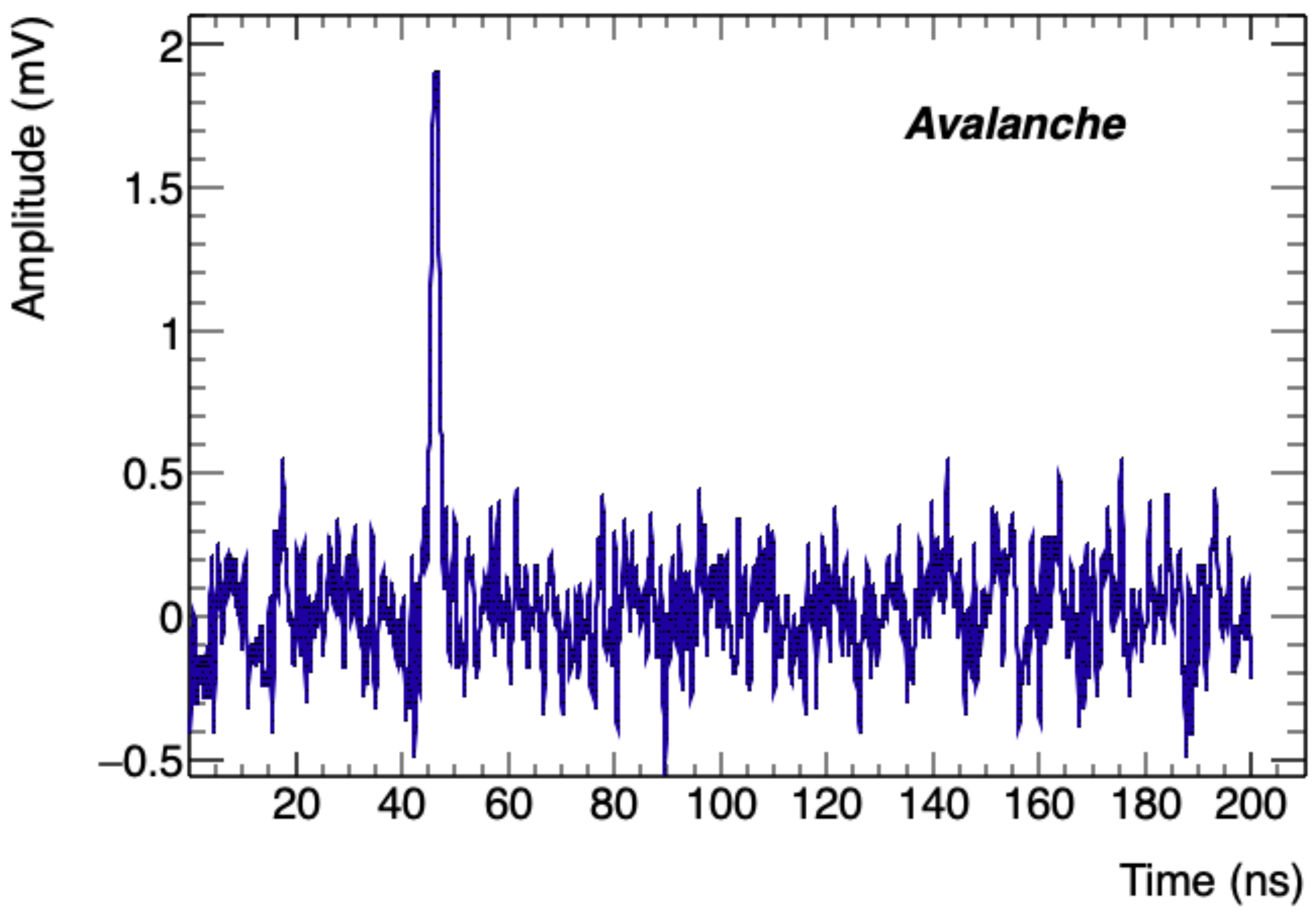
Resistance on both sides of the strip to refer it to ground

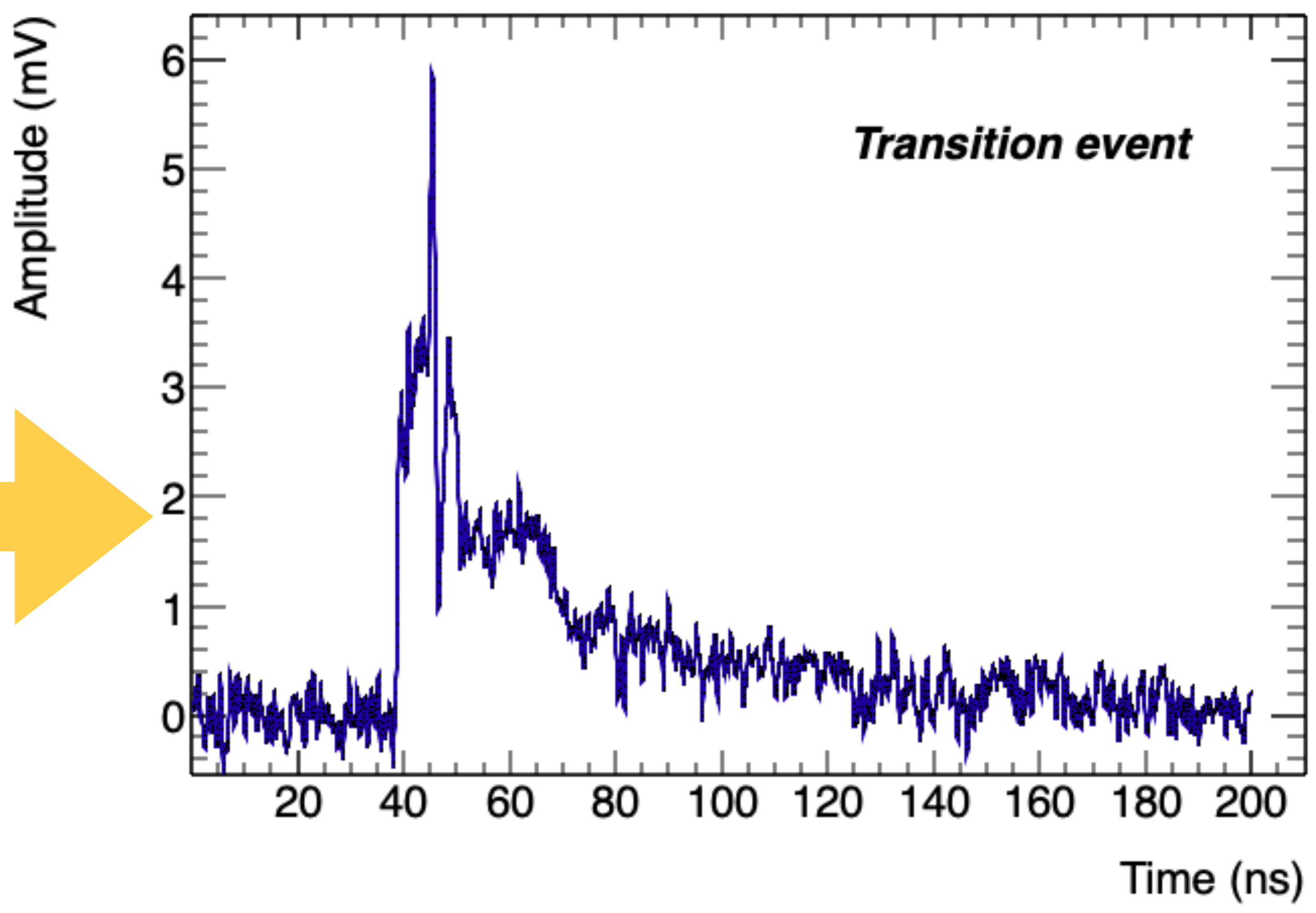
Analysis criteria

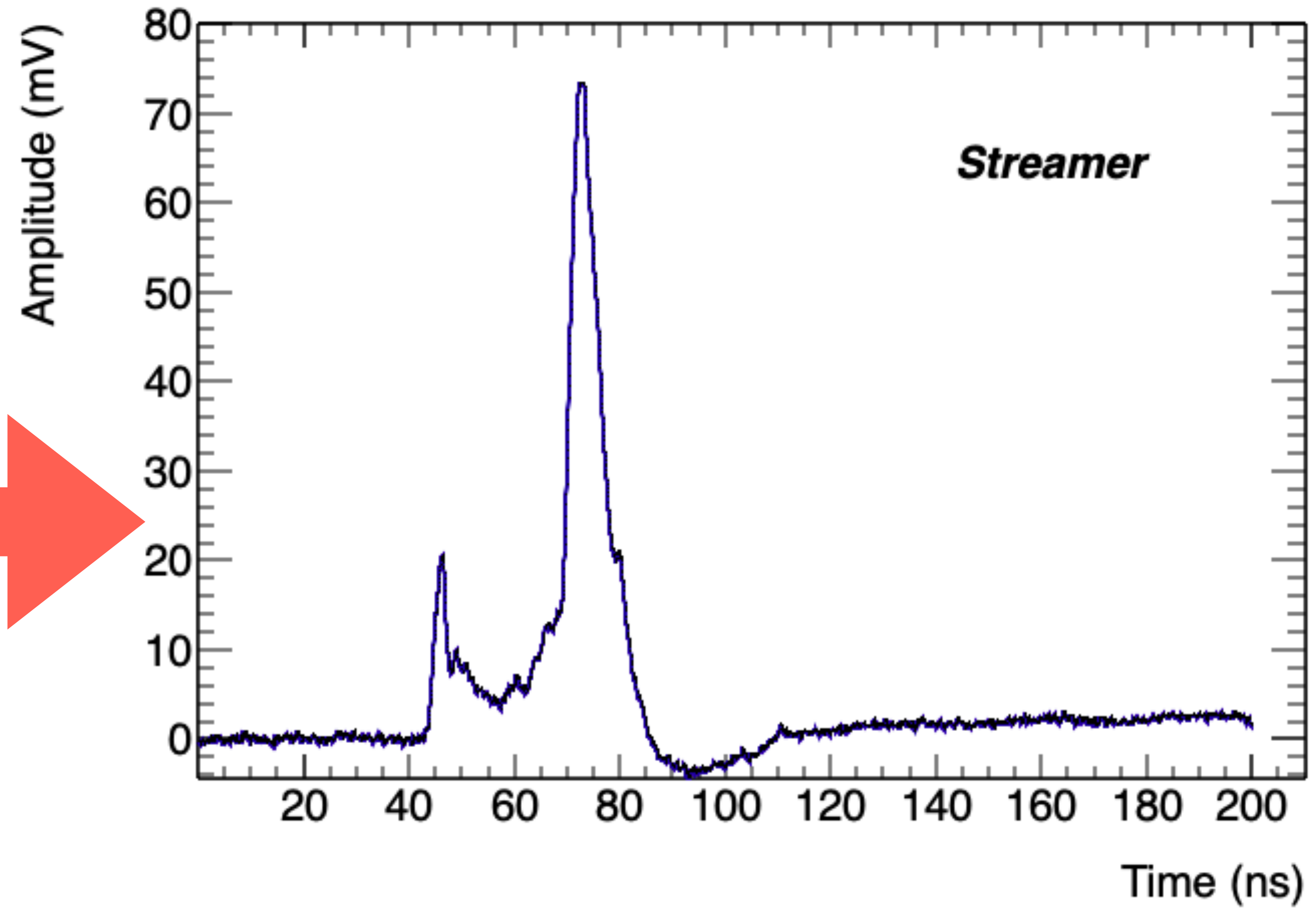
- Detection efficiency : signals which cross an amplitude threshold equal to 5 times the Root Mean Square (RMS) of the background amplitude.
    - The background amplitude is calculated in a time window of 30 ns which anticipates the avalanche signal
        - 5*$\overline{\mathrm{RMS}}$ in the whole 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







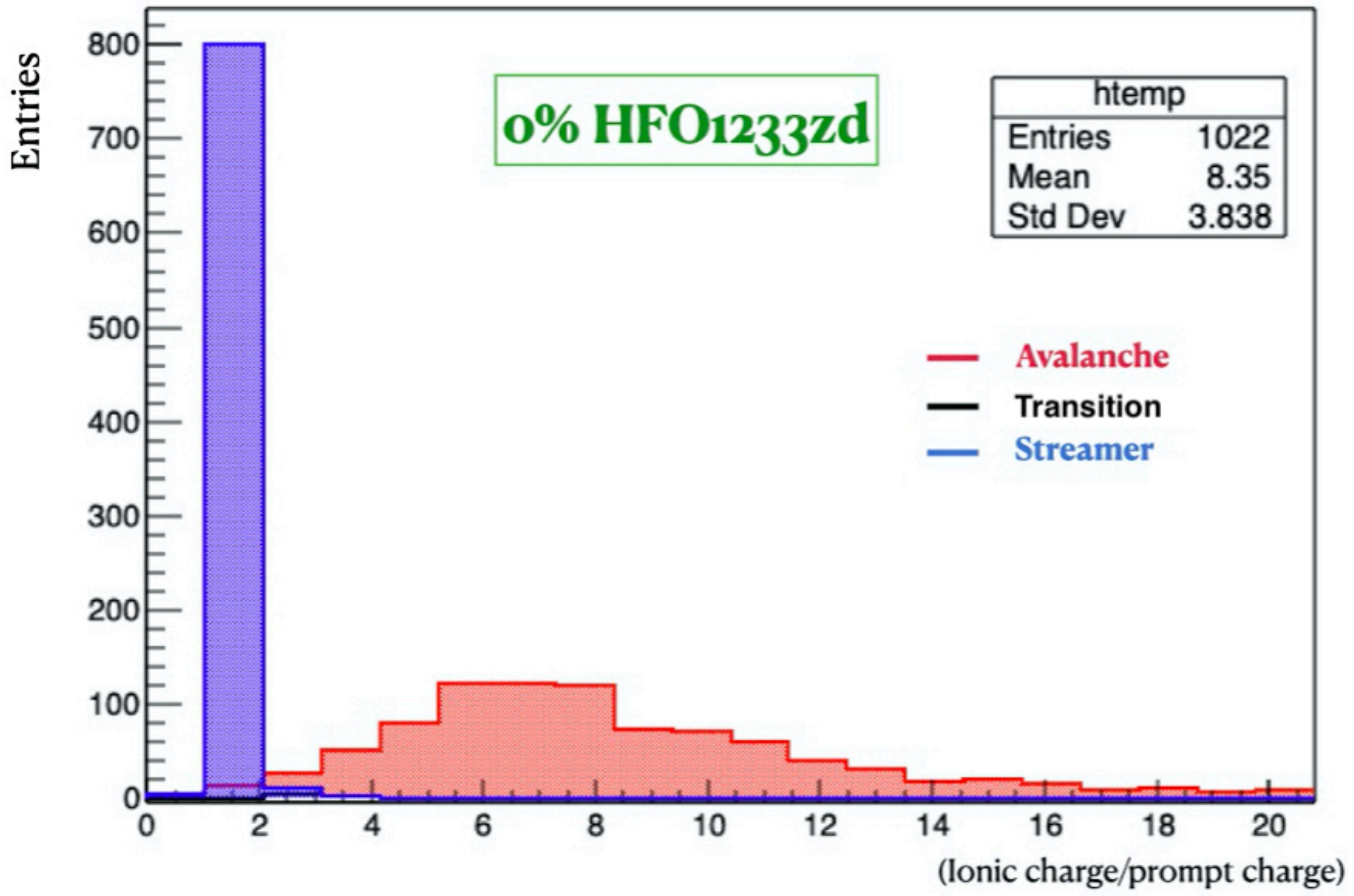
- Avalanche : very short single signal
- Transition signal: multiple avalanche signal and/or a large tail following the precursor
- Streamer: avalanche signal precursor followed by a signal lasting tens of ns.

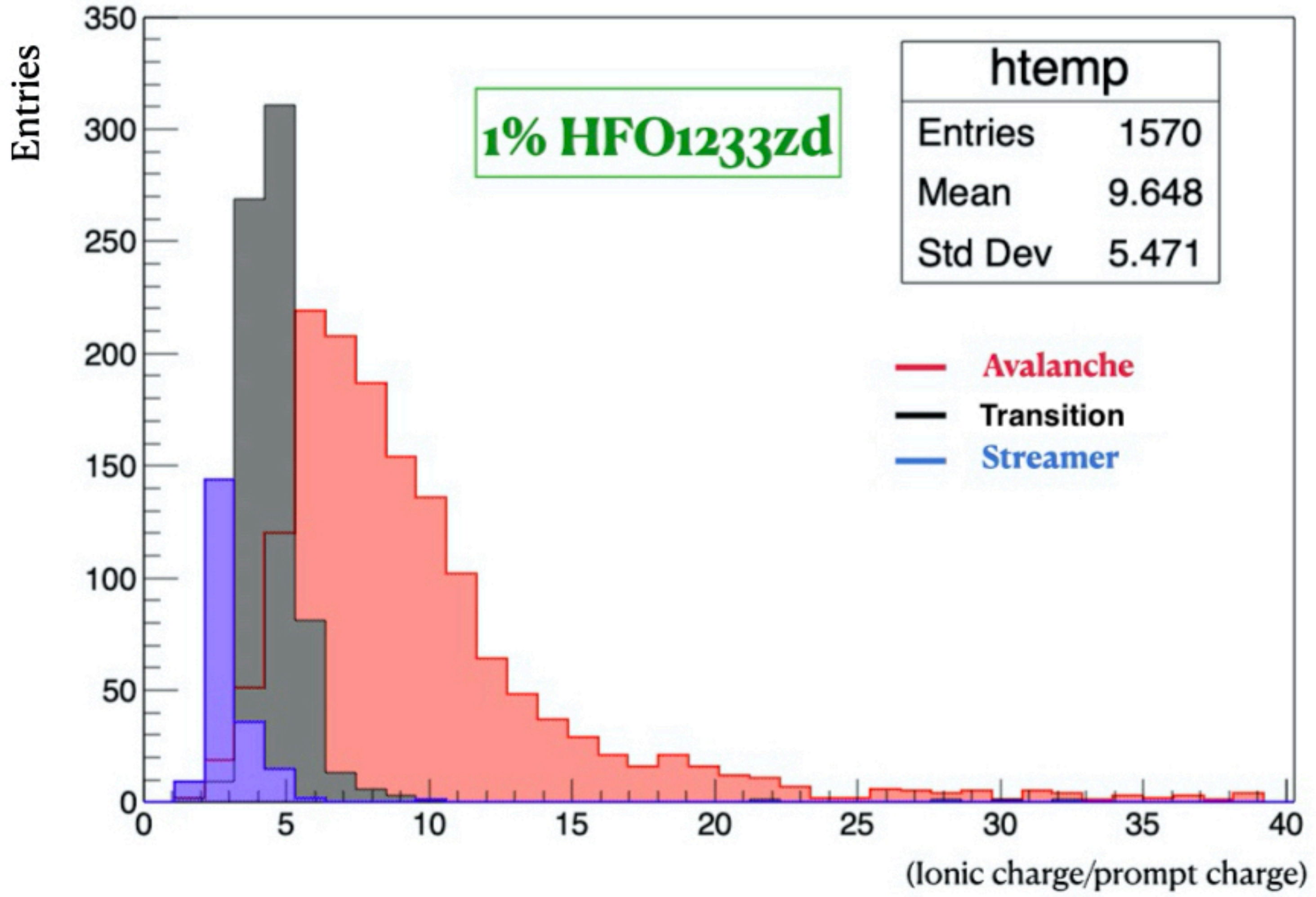
The transition events are negligible with the standard gas mixture but relevant in the new HFO/CO_2 gas mixtures.

⇨

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

Ionic to prompt ratio

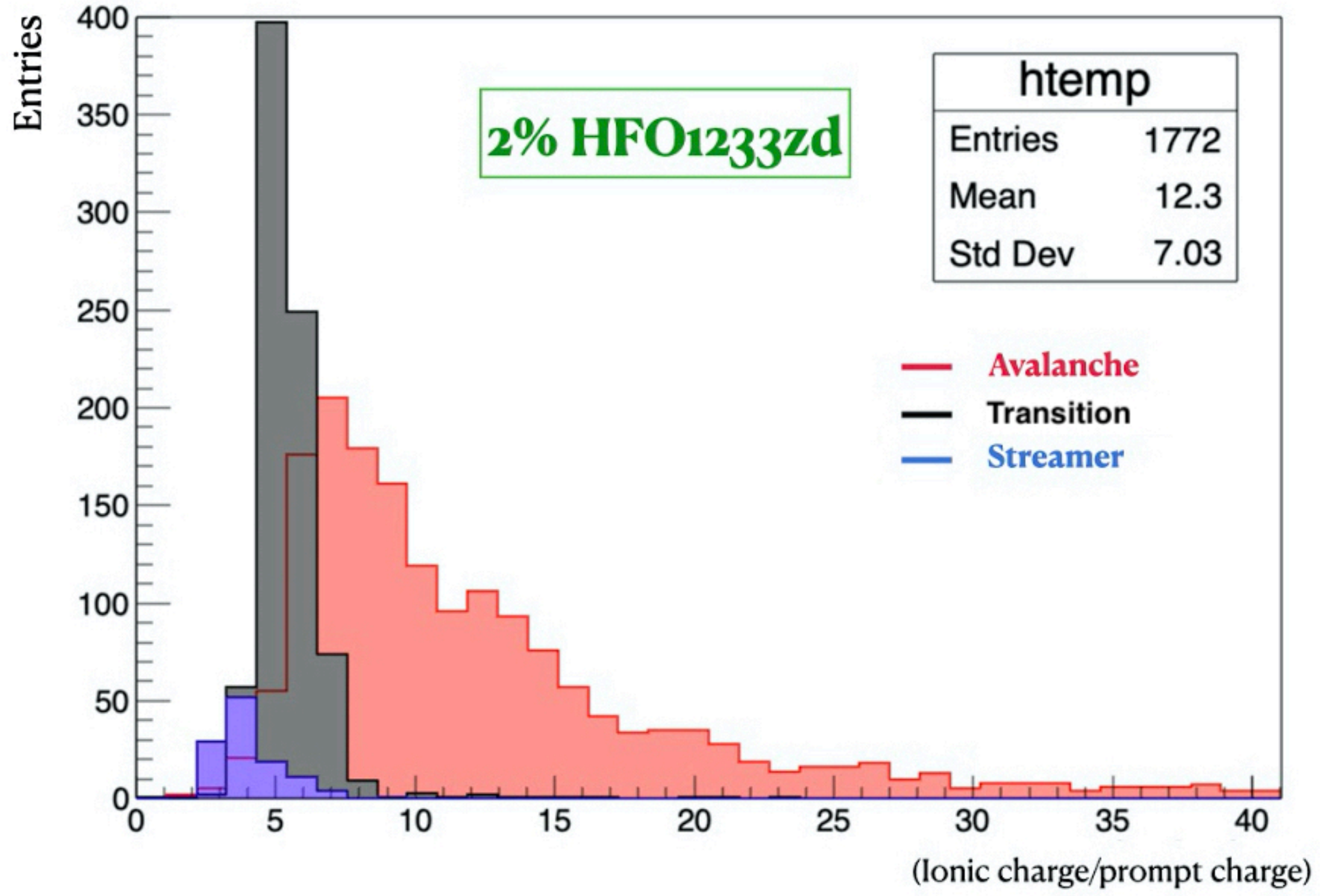


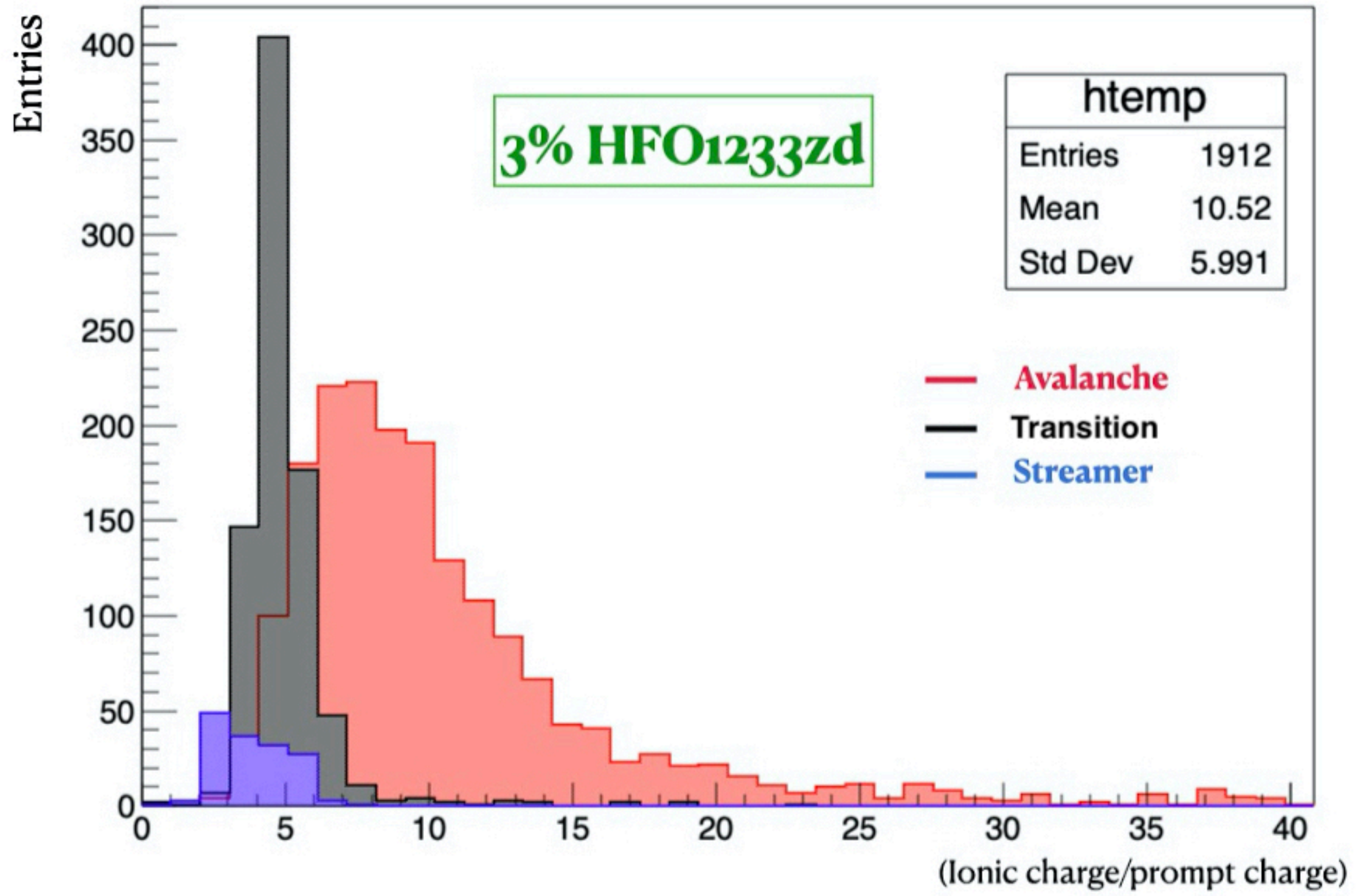


Avalanche (Q/q) ~ 8-12

Streamer (Q/q) ~ 1.5

Transition (Q/q) ~ 5





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

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:

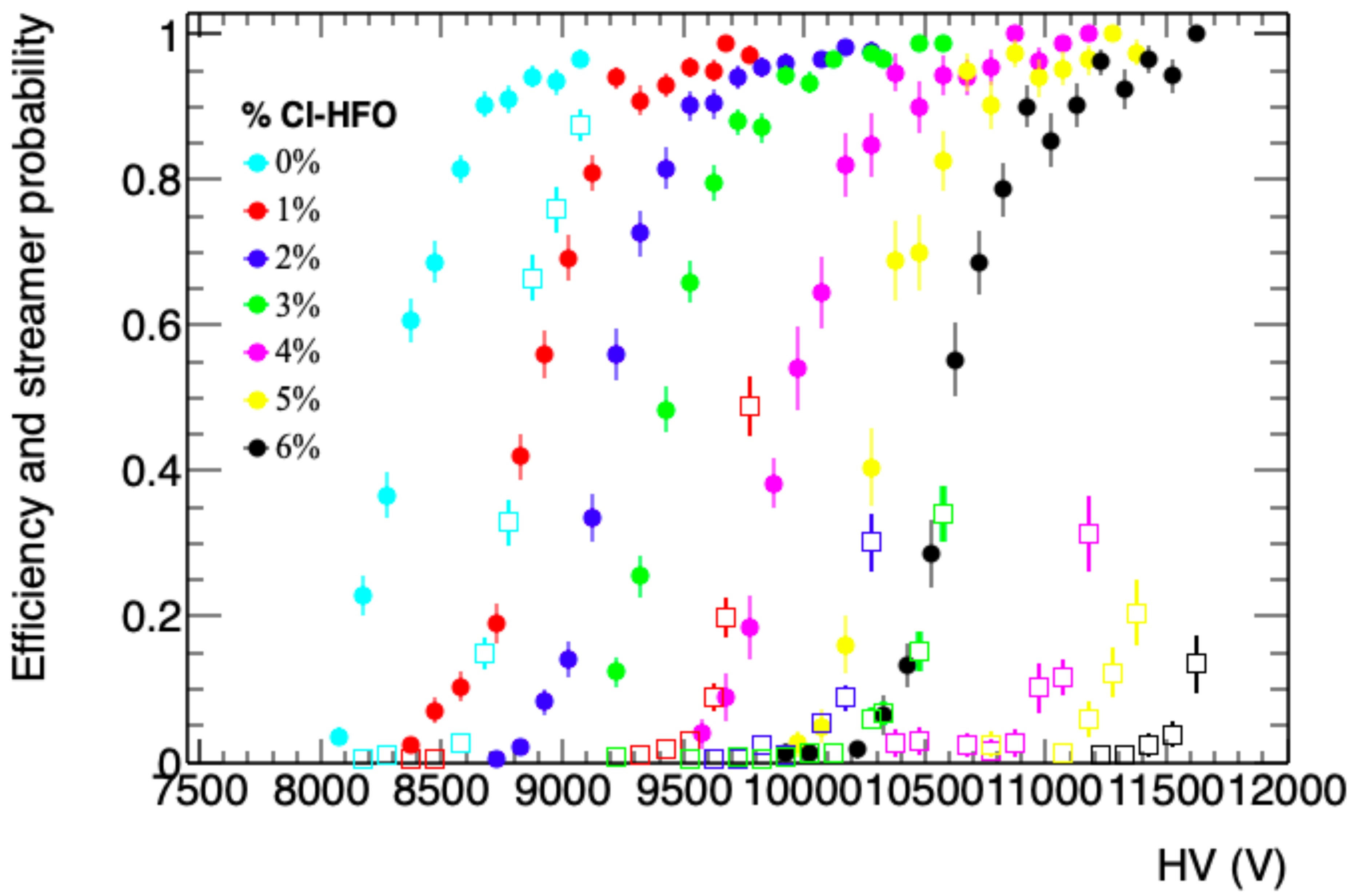
- Detection efficiency
- Streamer and transition event probability
- Total charge delivered inside the gas
- Time resolution

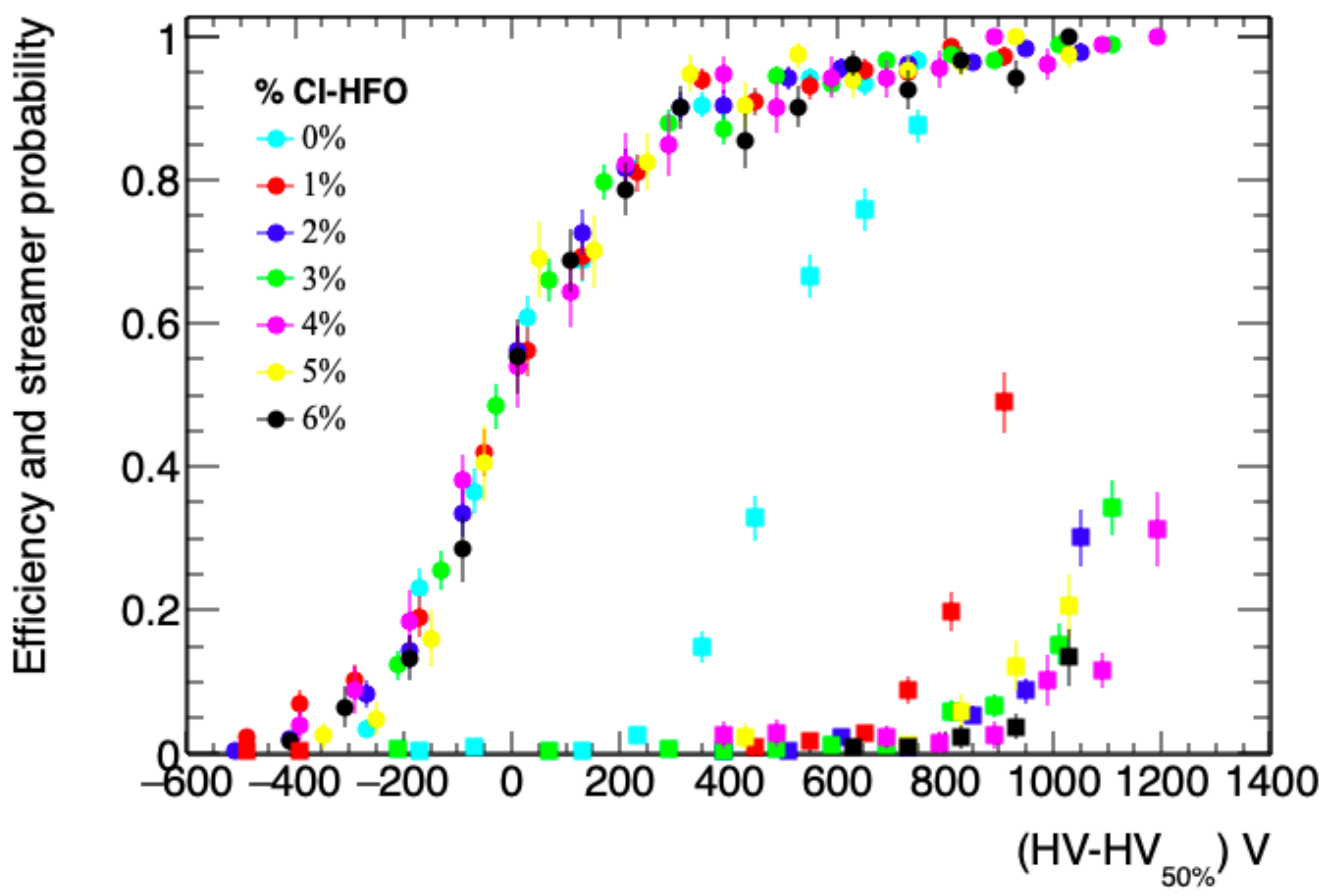
Signals classification

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

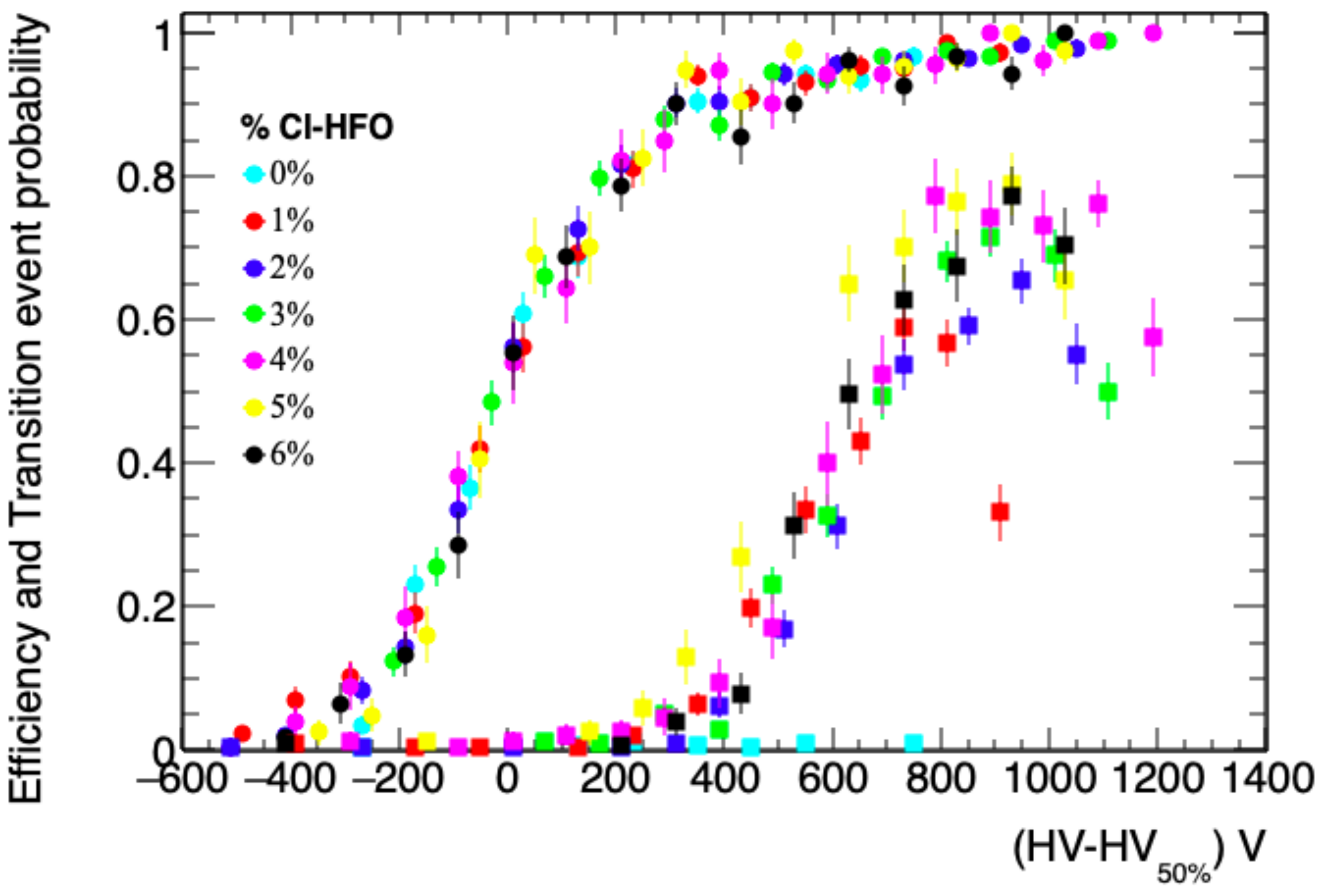
Efficiency vs high voltage for different Cl-HFO concentrations

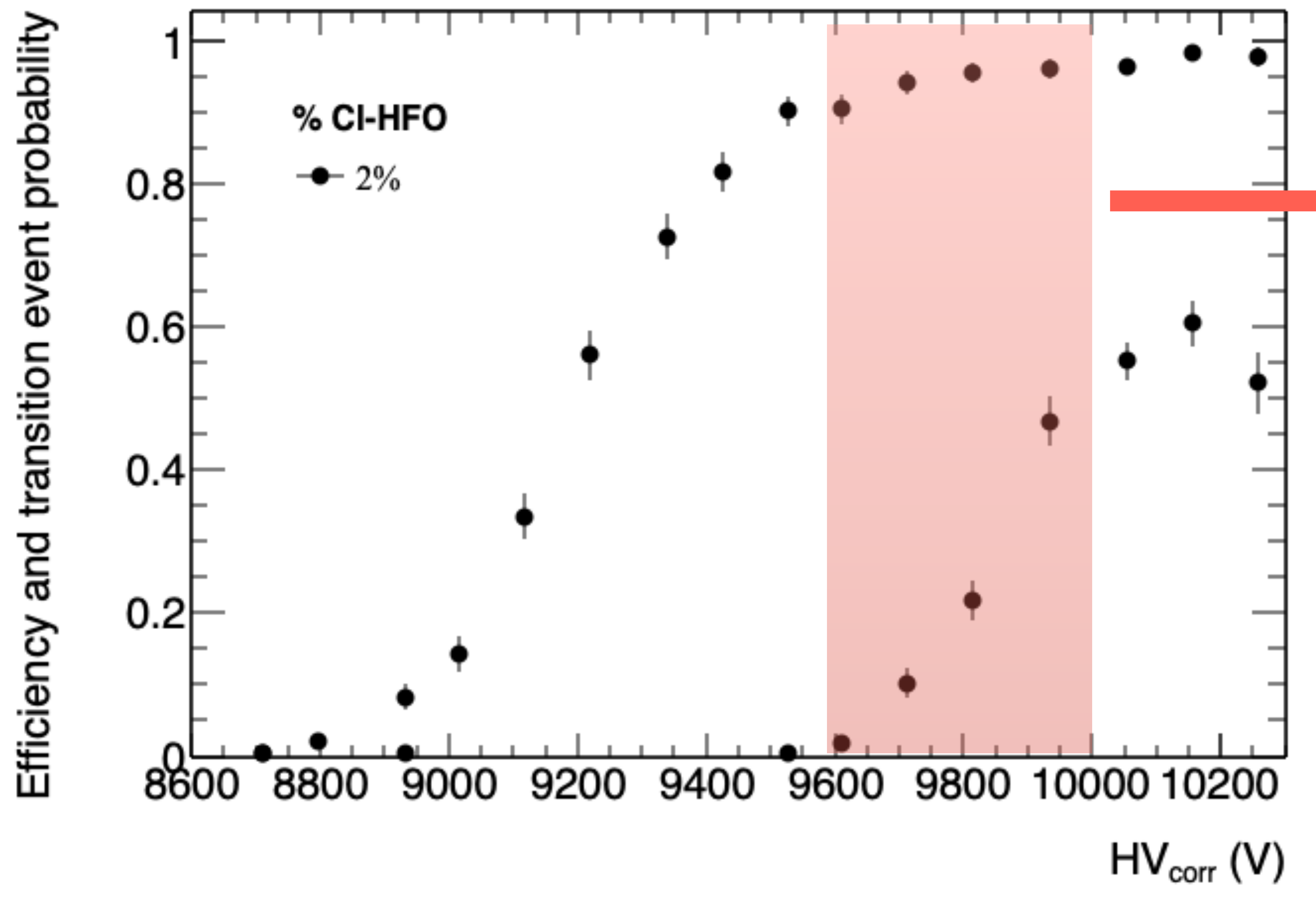


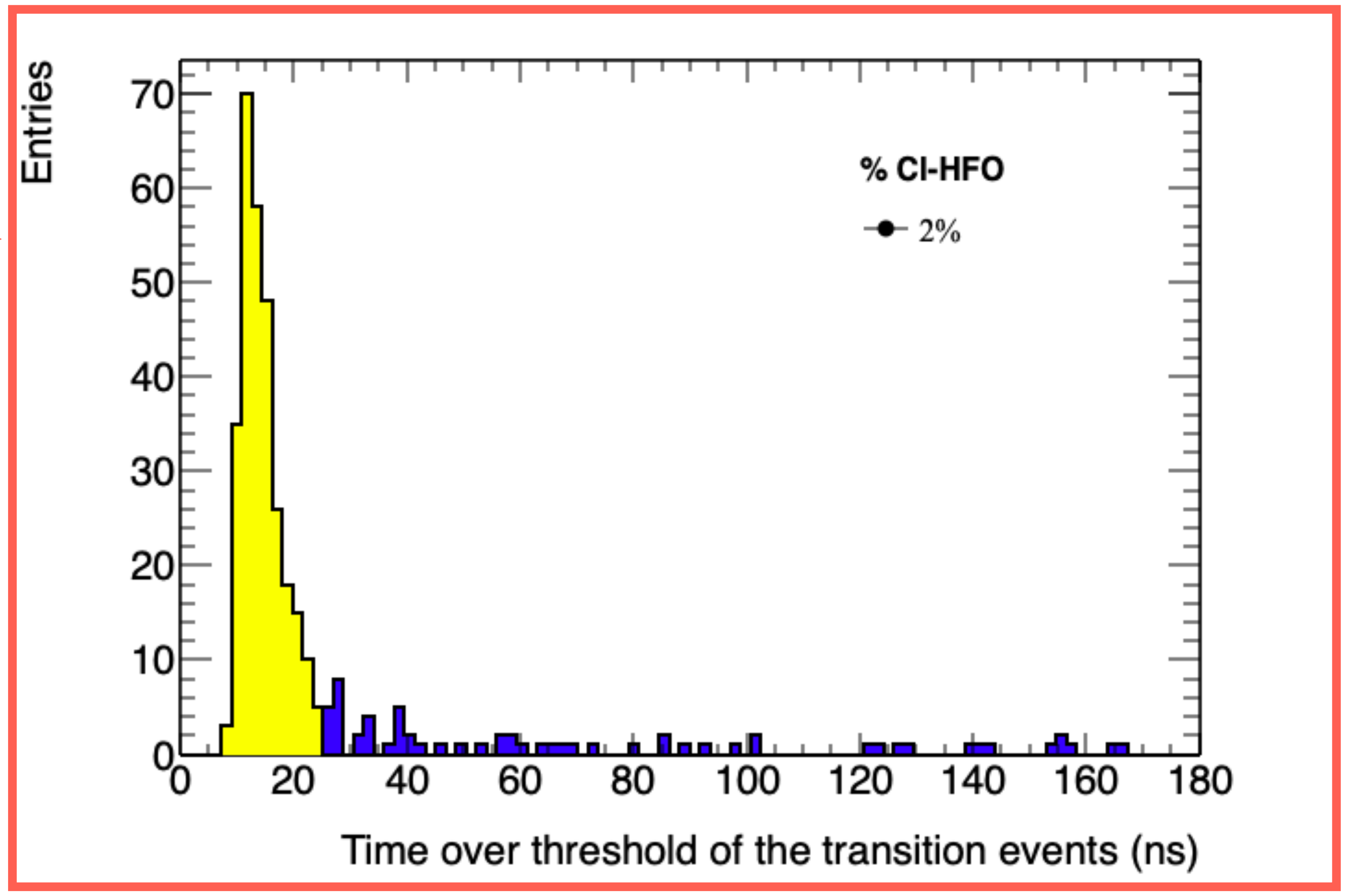


- The operating voltage increases at the rate ~ 400 V/1% Cl-HFO;
- The detection efficiency is at least 93% for all the gas mixtures;
- The mixture not containing Cl-HFO shows an overlapping between avalanche and streamer mode (35% streamer contamination at the plateau knee);
- The separation between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

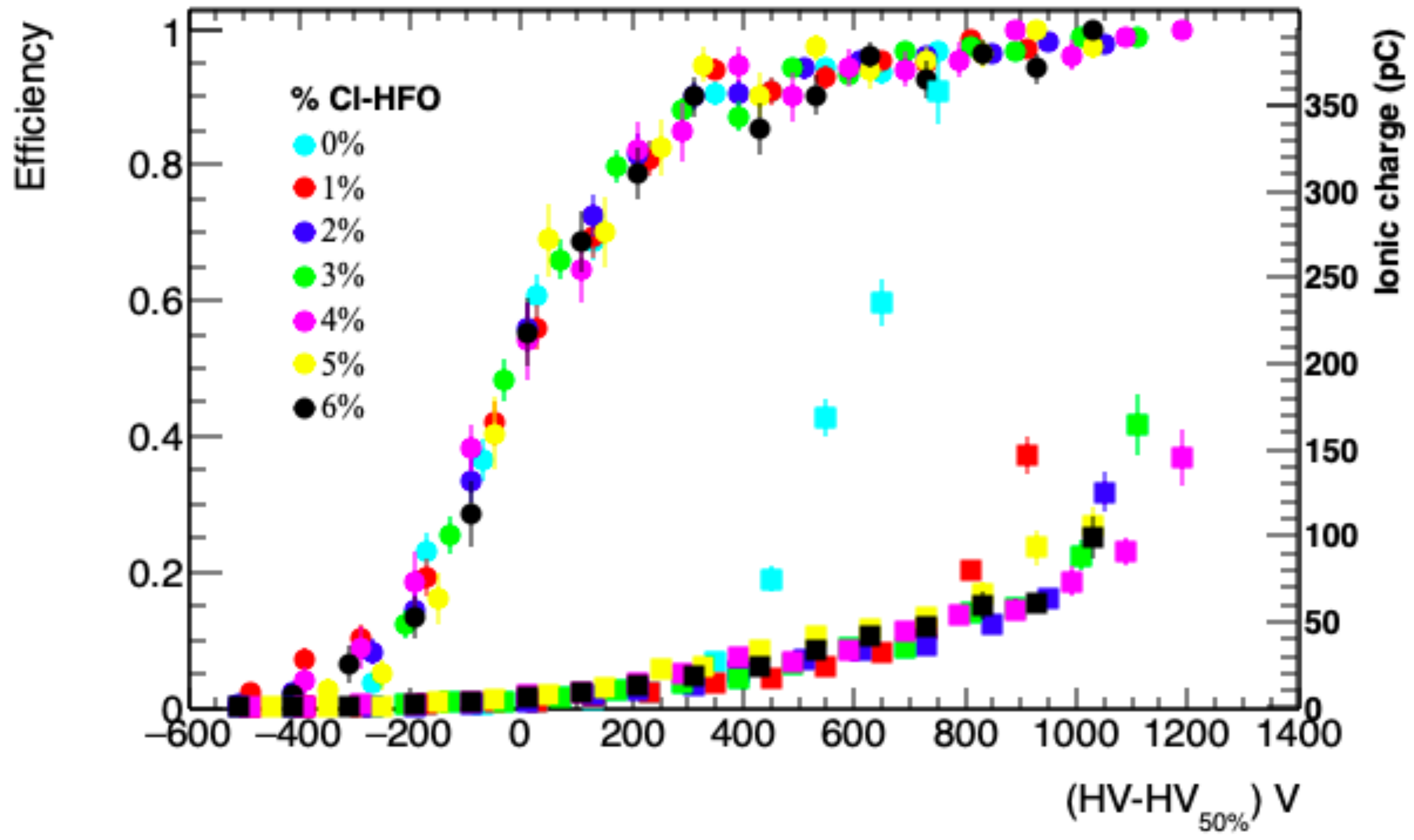


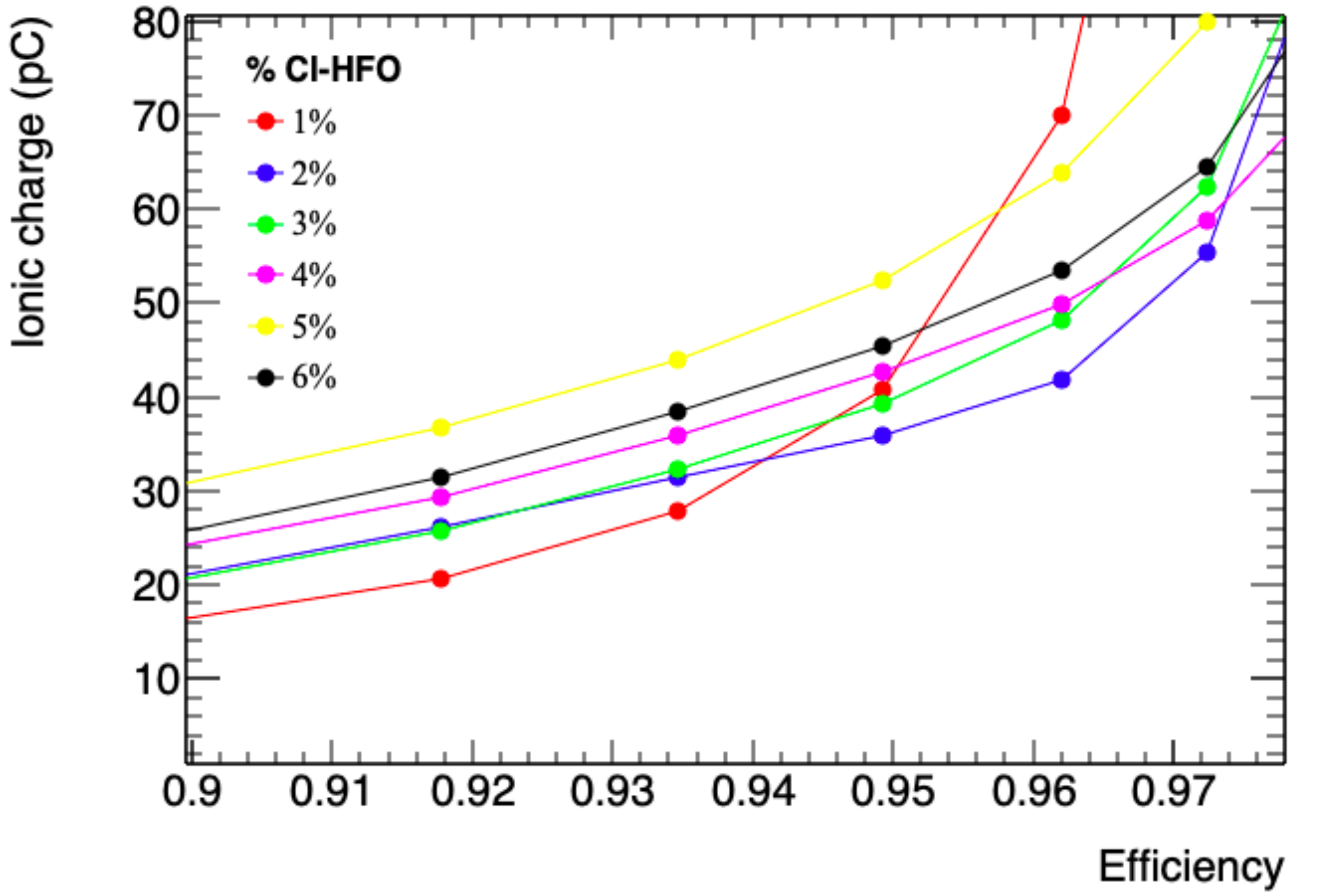




- The transition event probability decreases when streamers start to appear;
- The transition event are less than 20% at the operating voltage for all gas mixtures;
- The time over threshold of transition events is less than 25 ns.

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 : Selection of the best mixture

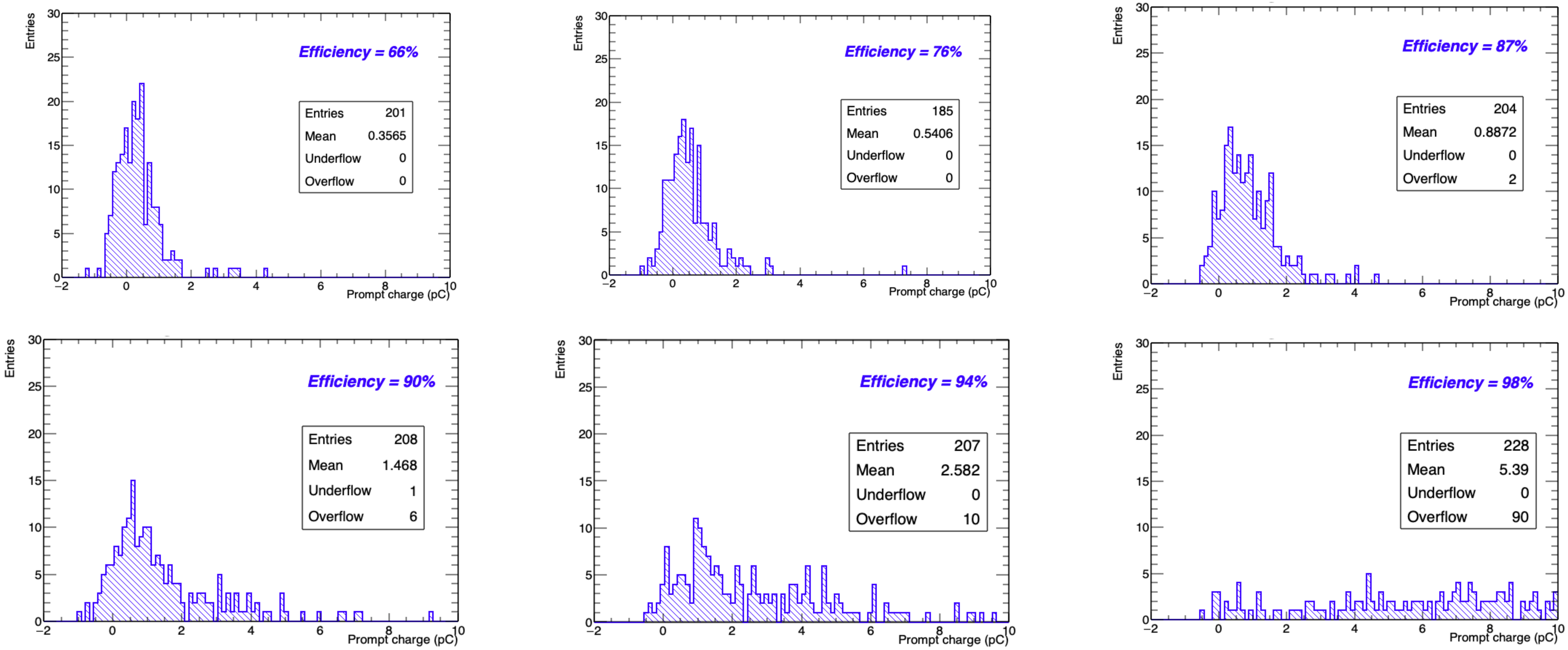
- The gas mixtures studied show a comfortable avalanche-streamer separation range and have a detection efficiency $\epsilon > 90\,\%$
- The transition event probability is less than 20% for $\epsilon < 95\,\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge.

	% 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

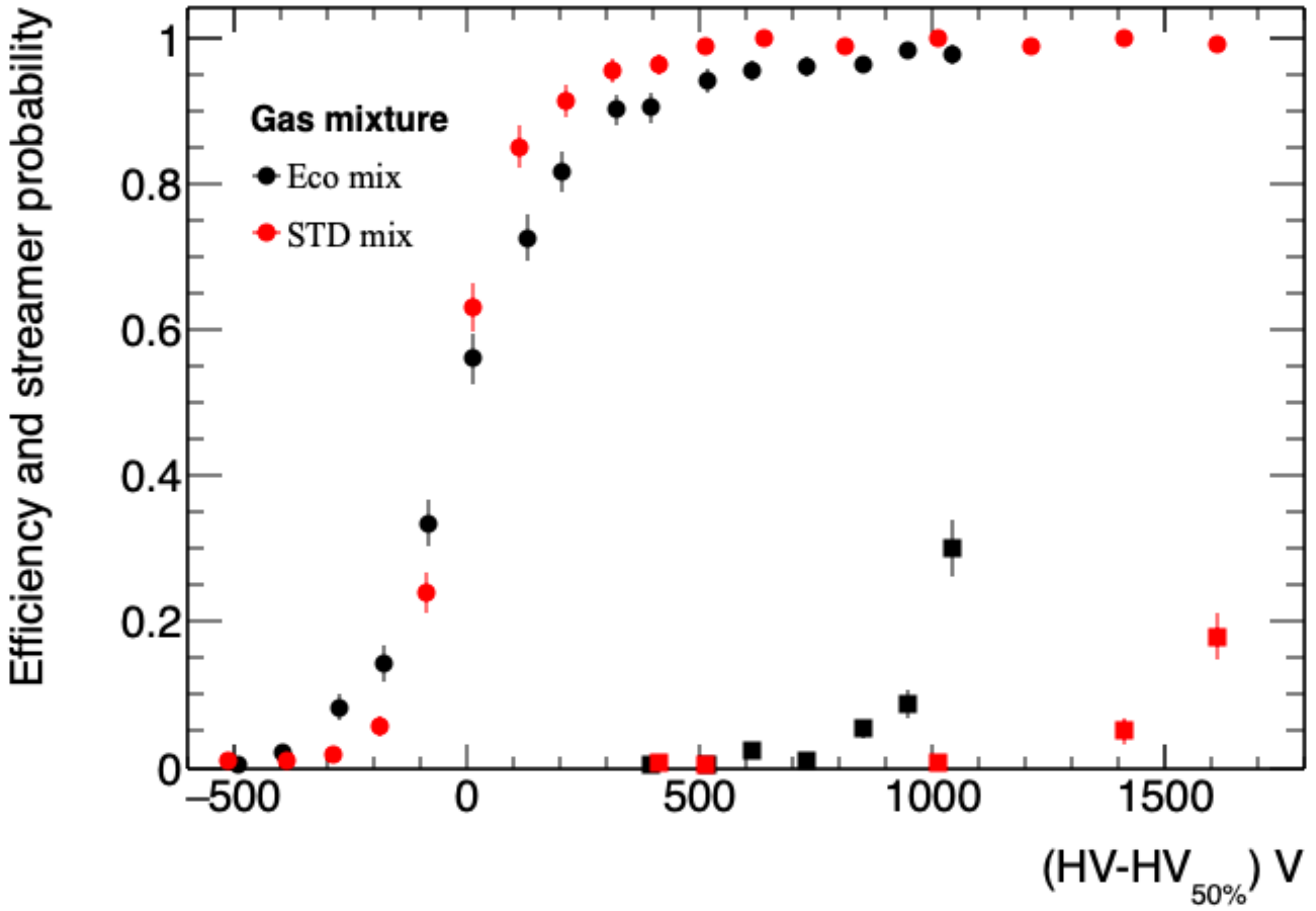
Best operating performance mixture :
CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO = (76/15/7/2)%

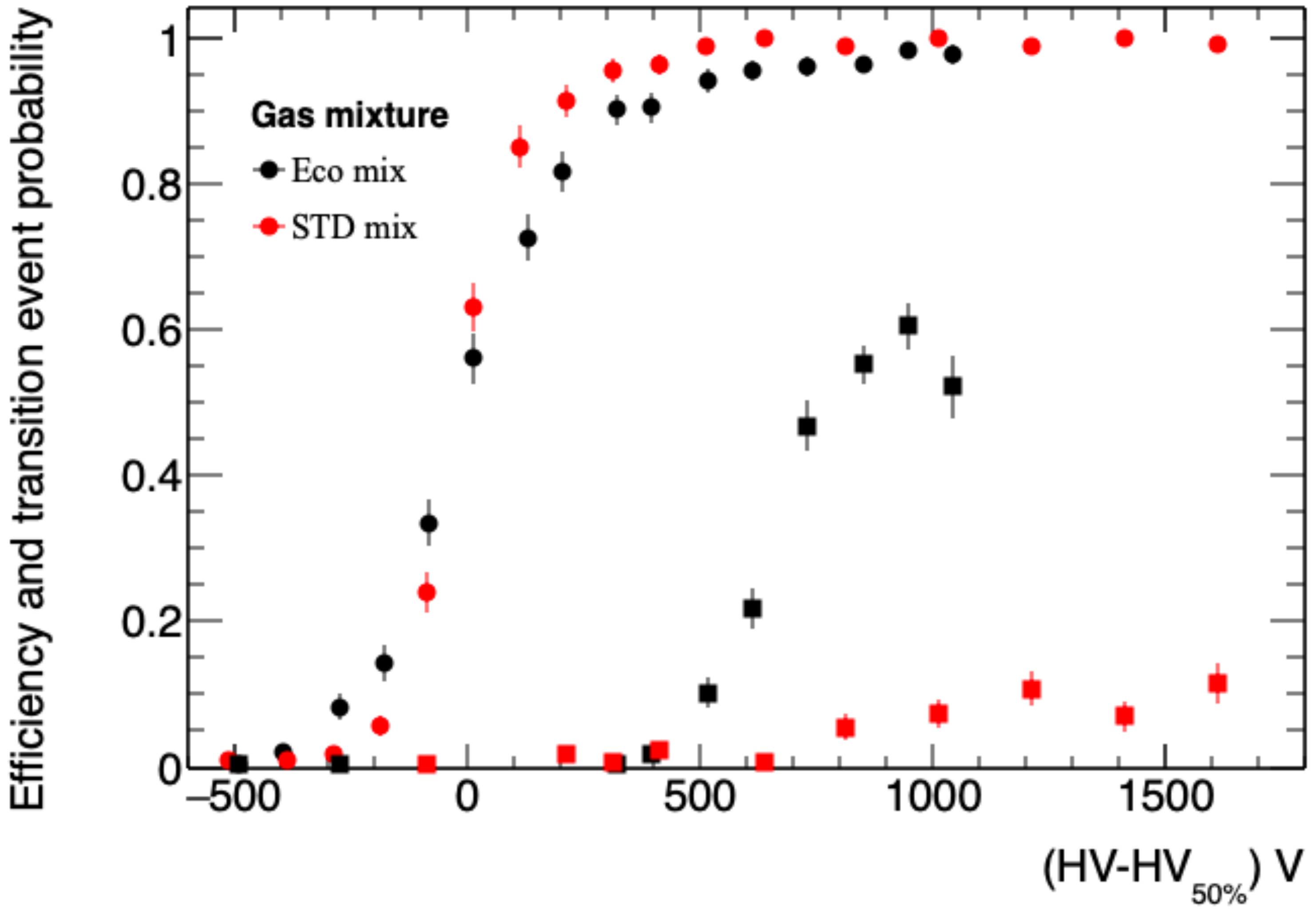
Best gas mixture: Prompt charge distribution

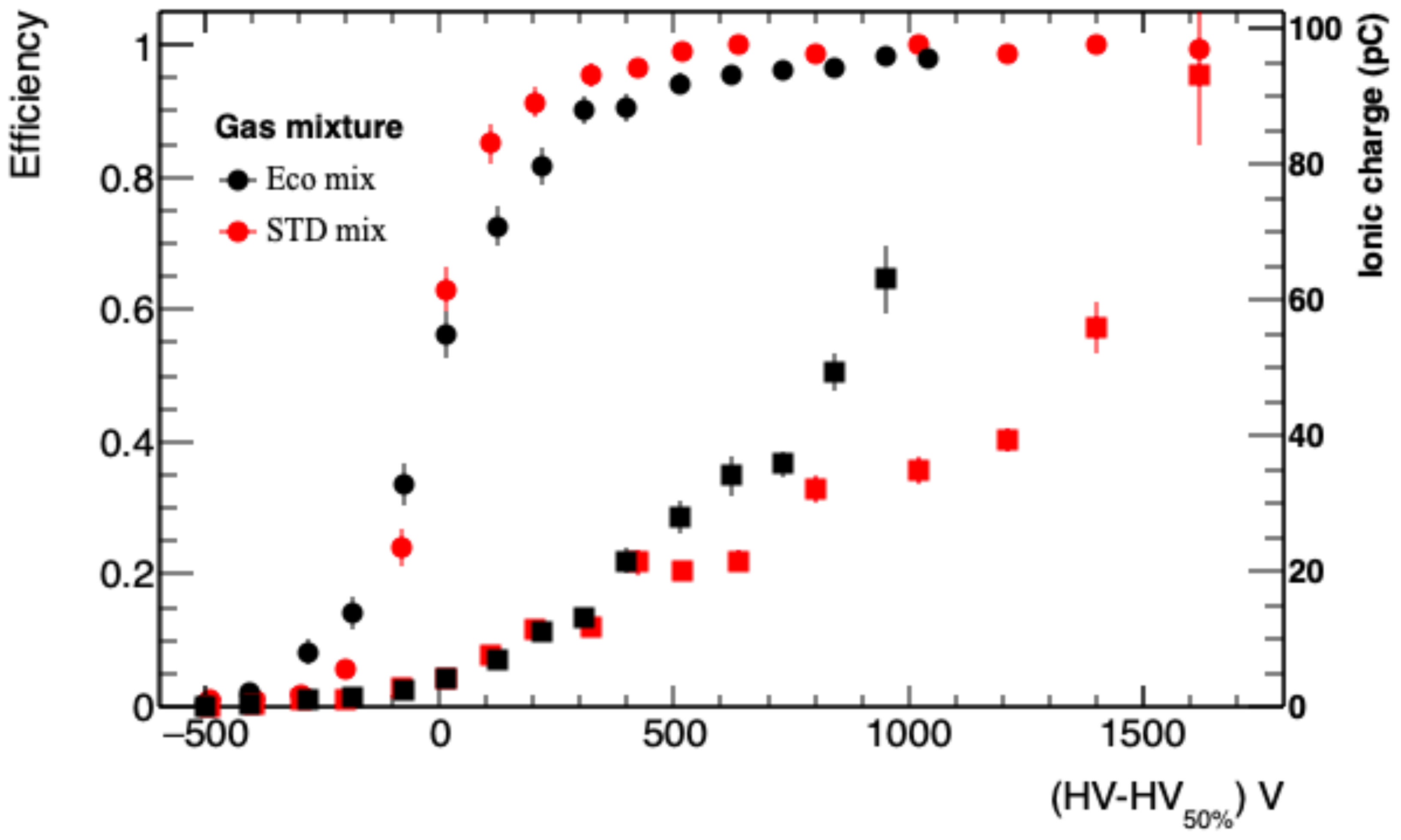


- Very wide distributions for $\epsilon \geq 90\,\%$

Comparison between eco and standard gas mixtures

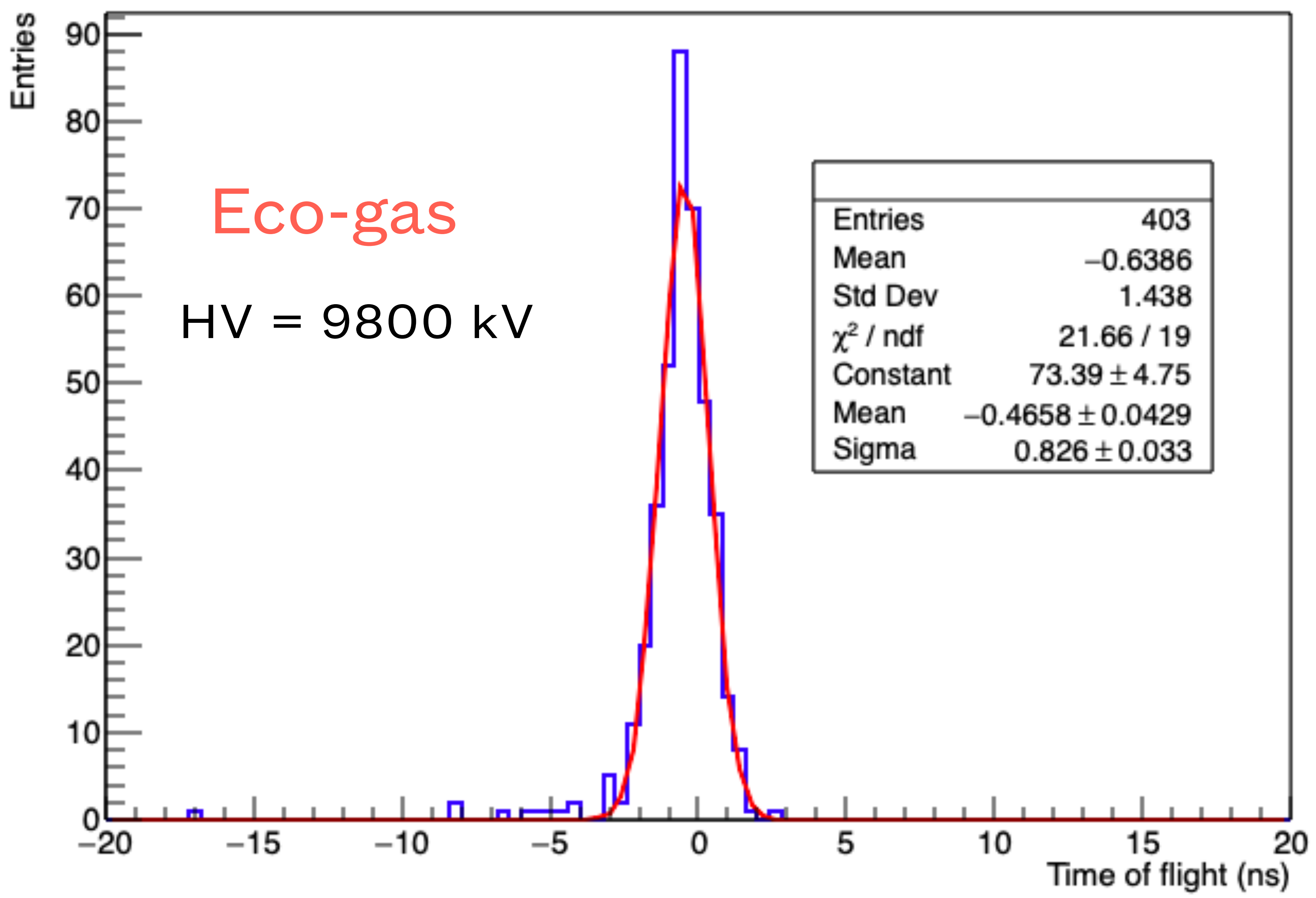


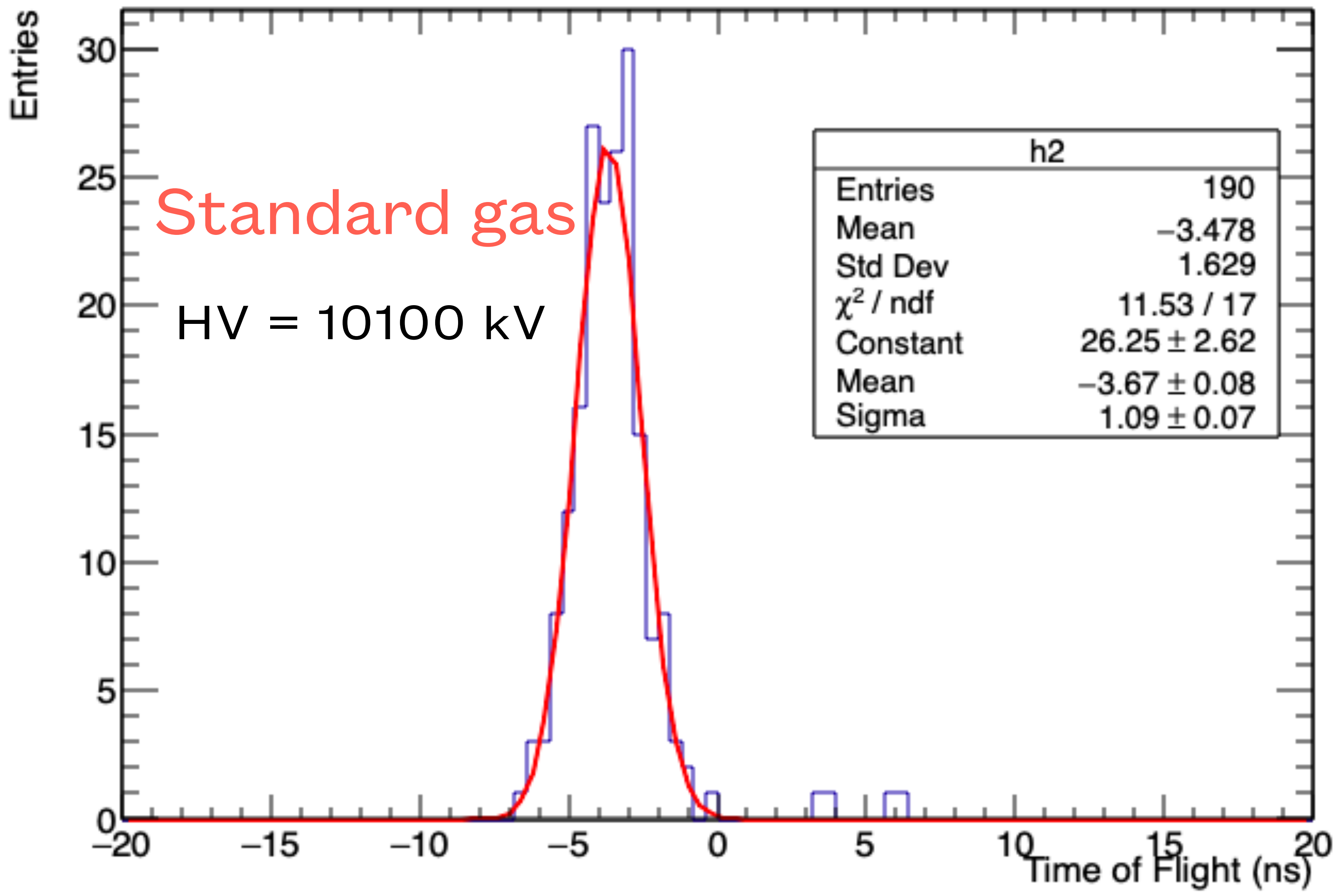




- $HV_{ECO} \sim HV_{STD}$
- The efficiency curve has a faster rise with the standard mixture
- The avalanche-streamer separation with the standard gas is significantly larger than in the eco-mixture
- The fraction of transition events is much smaller with the standard gas
- The growth of the ionic charge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

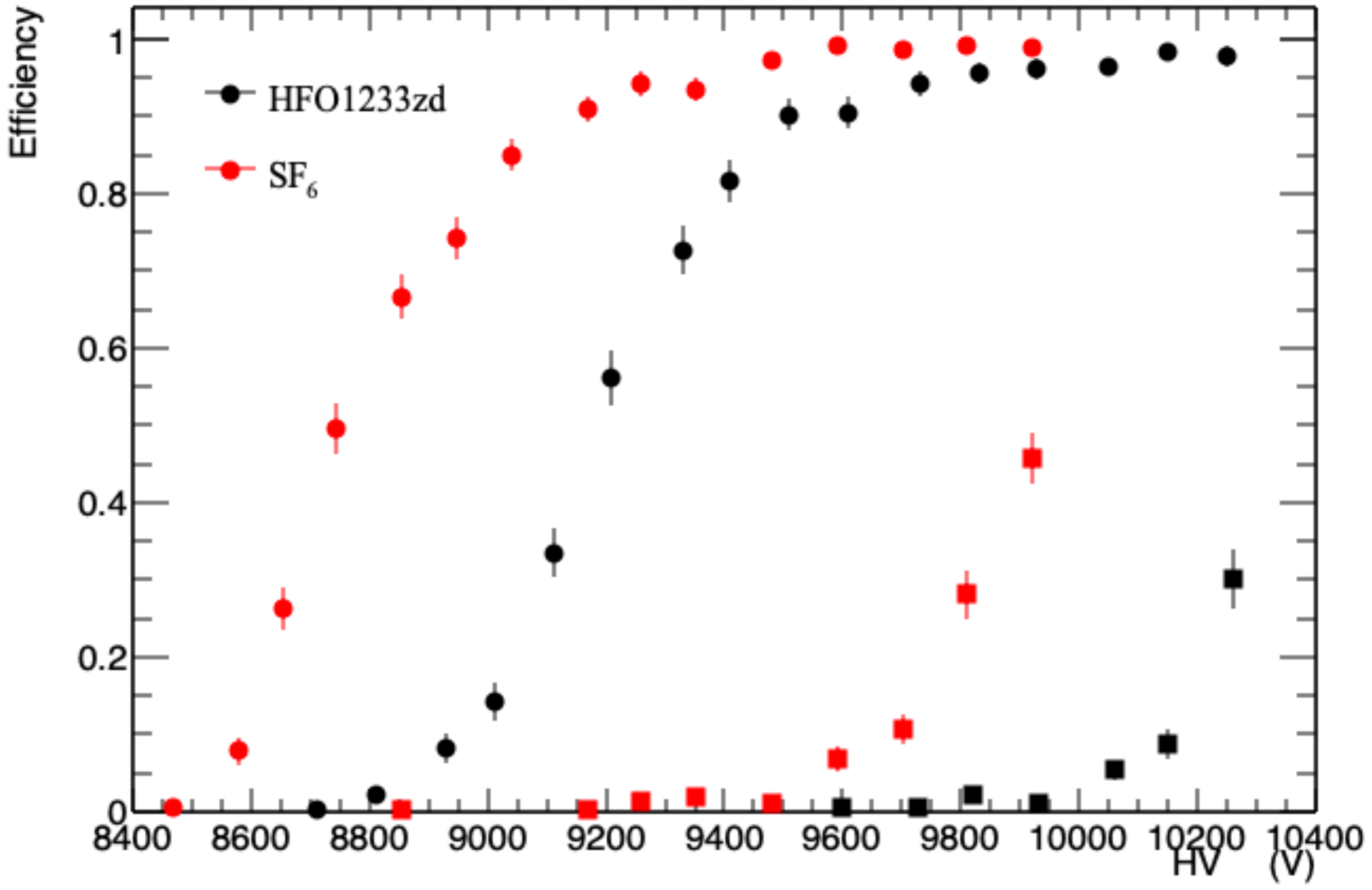
$$\sigma_t^{Eco} = (0.83 \pm 0.03)\text{ns}$$

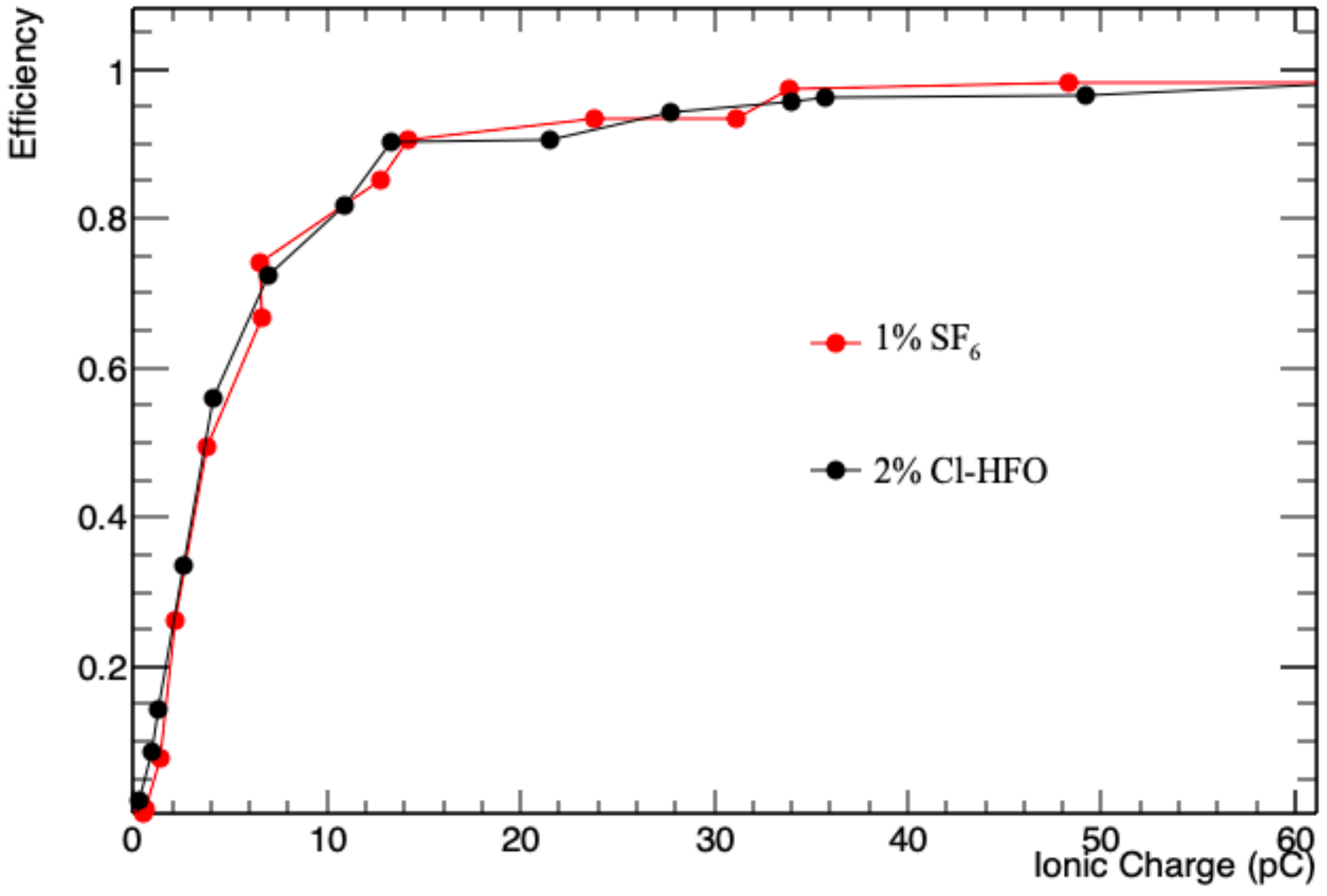
$$\sigma_t^{STD} = (1.09 \pm 0.07)\text{ns}$$

- 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 $CO_2/C_3H_2F_4/iC_4H_{10}/C_3H_2ClF_3$ 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 eco 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)

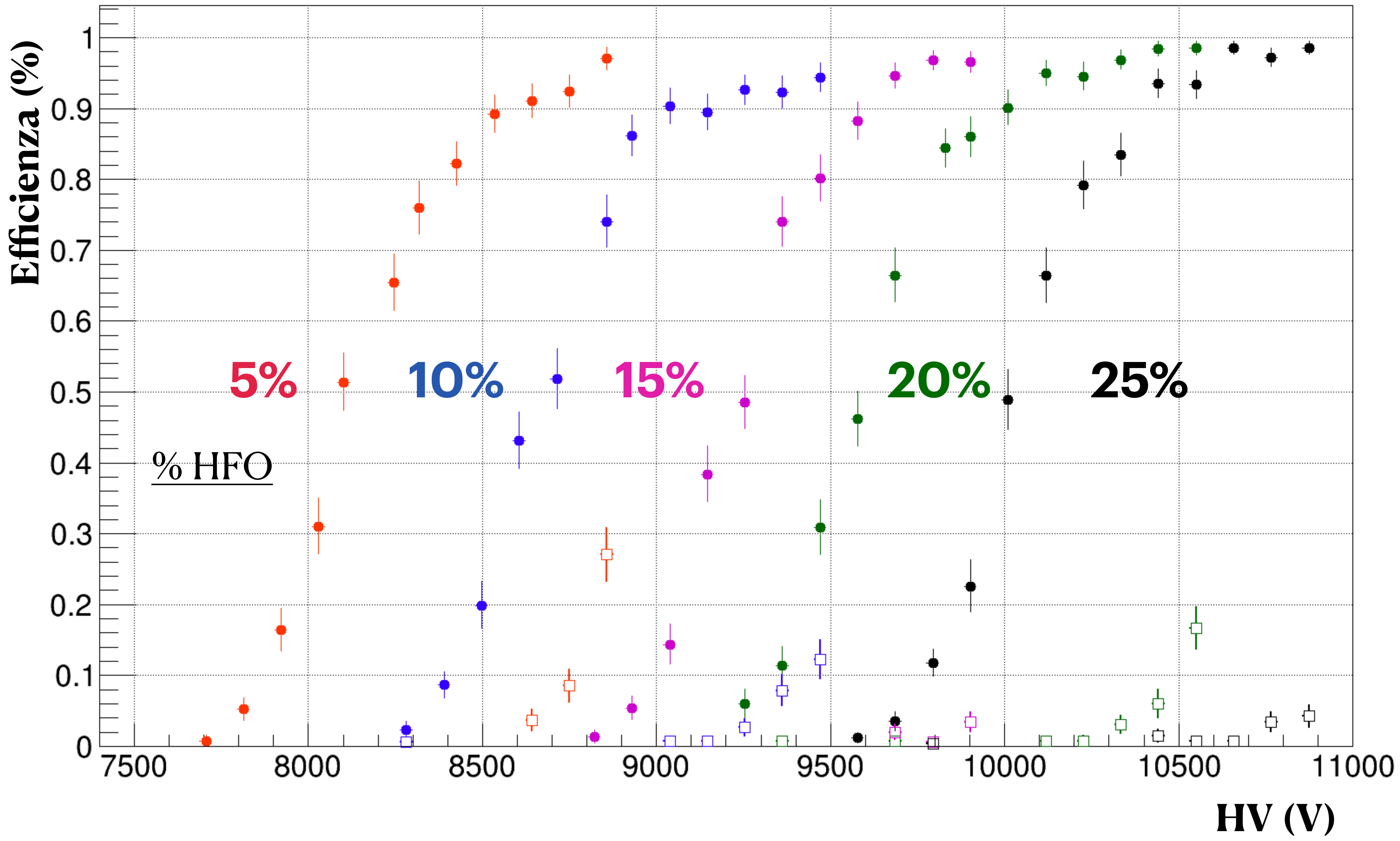
https://arxiv.org/abs/2112.02659

Thank You

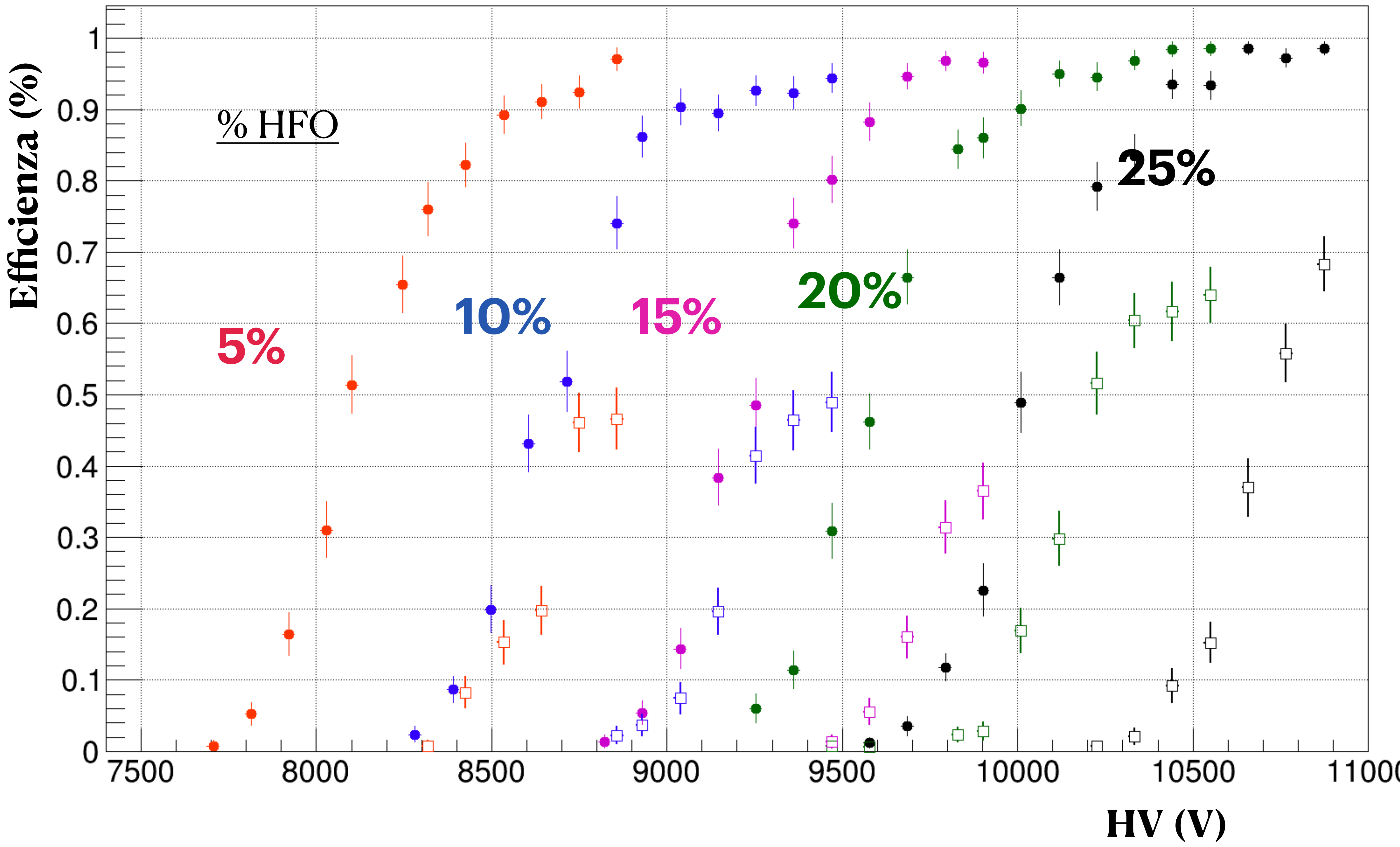
Backup

Serie i-Butano/SF_6=costante=5/1 - CO_2=89/84/79/74/69 : Studio dell'efficienza

Efficienza e probabilità di streamer



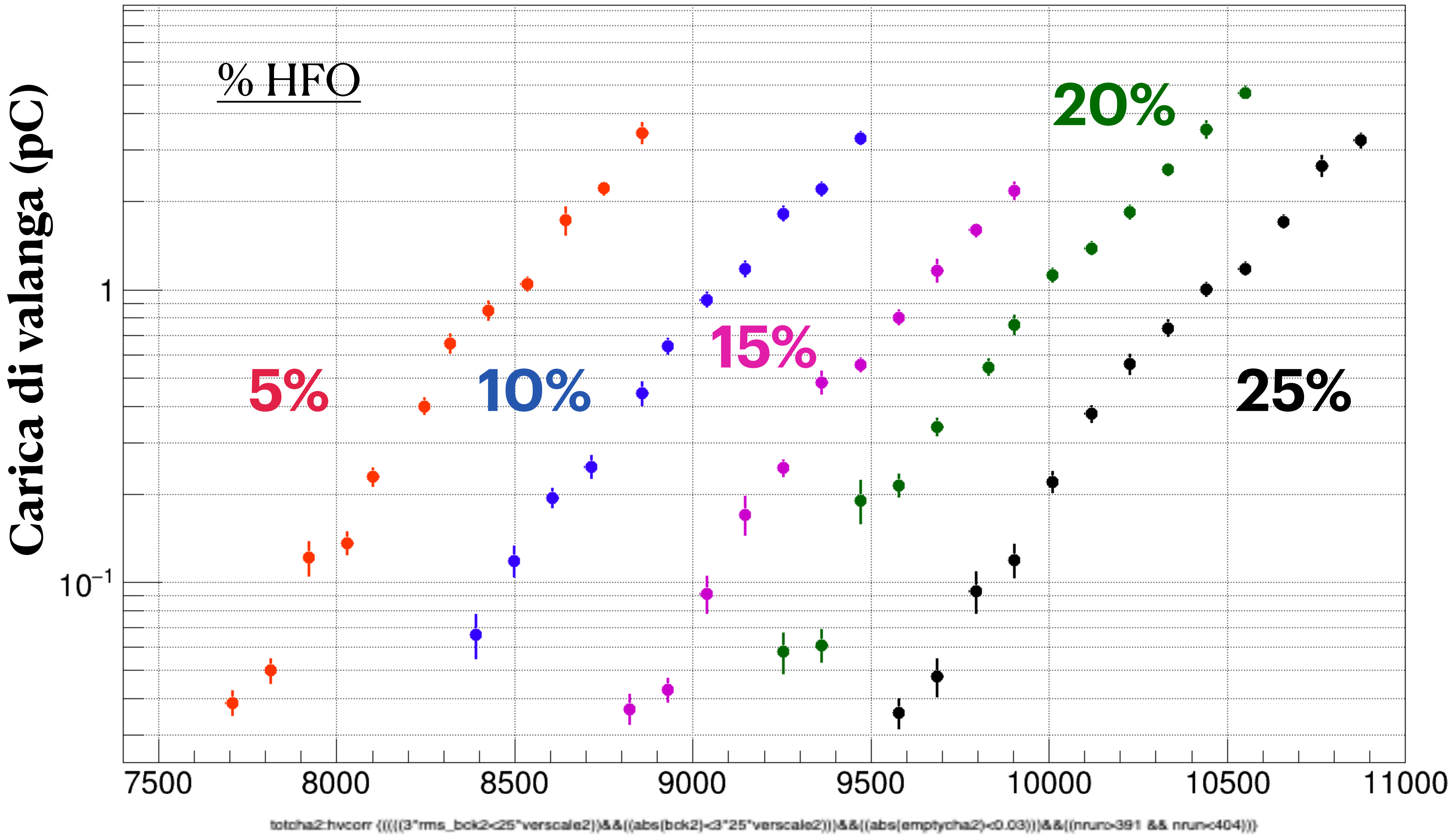
Efficienza e probabilità di extra carica

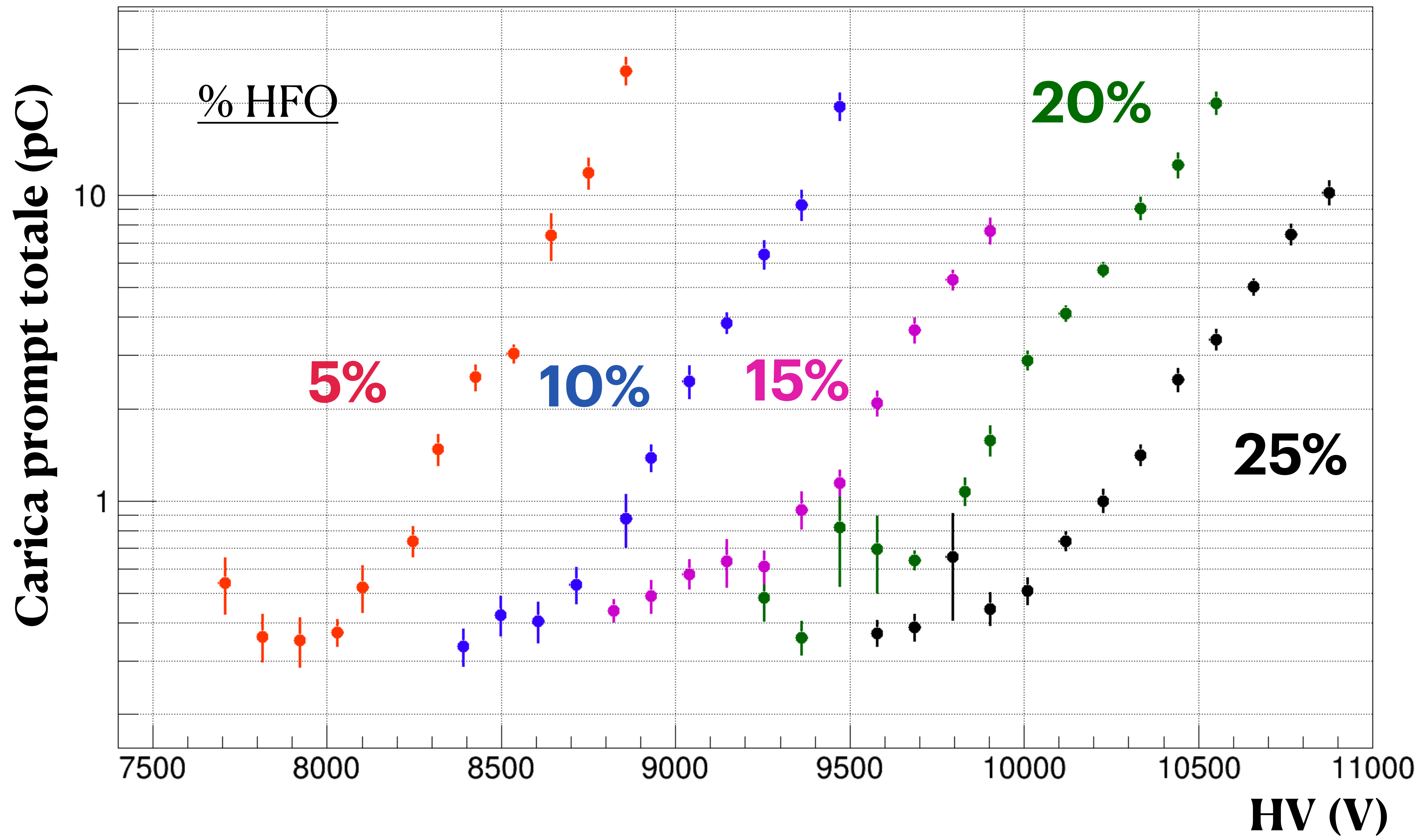


% HFO1234ze	V_{knee}	Efficienza @plateau	%streamer @ V_{knee} + 200 V	%extra carica@ V_{knee} + 200 V
5%	8.5 kV	93%	8.5%	46%
10%	9 kV	93.5%	3%	41%
15%	9.5 kV	96.5%	0.6%	31%
20%	9.9 kV	98%	0.8%	30%
25%	10.4 kV	98%	0.7%	37%

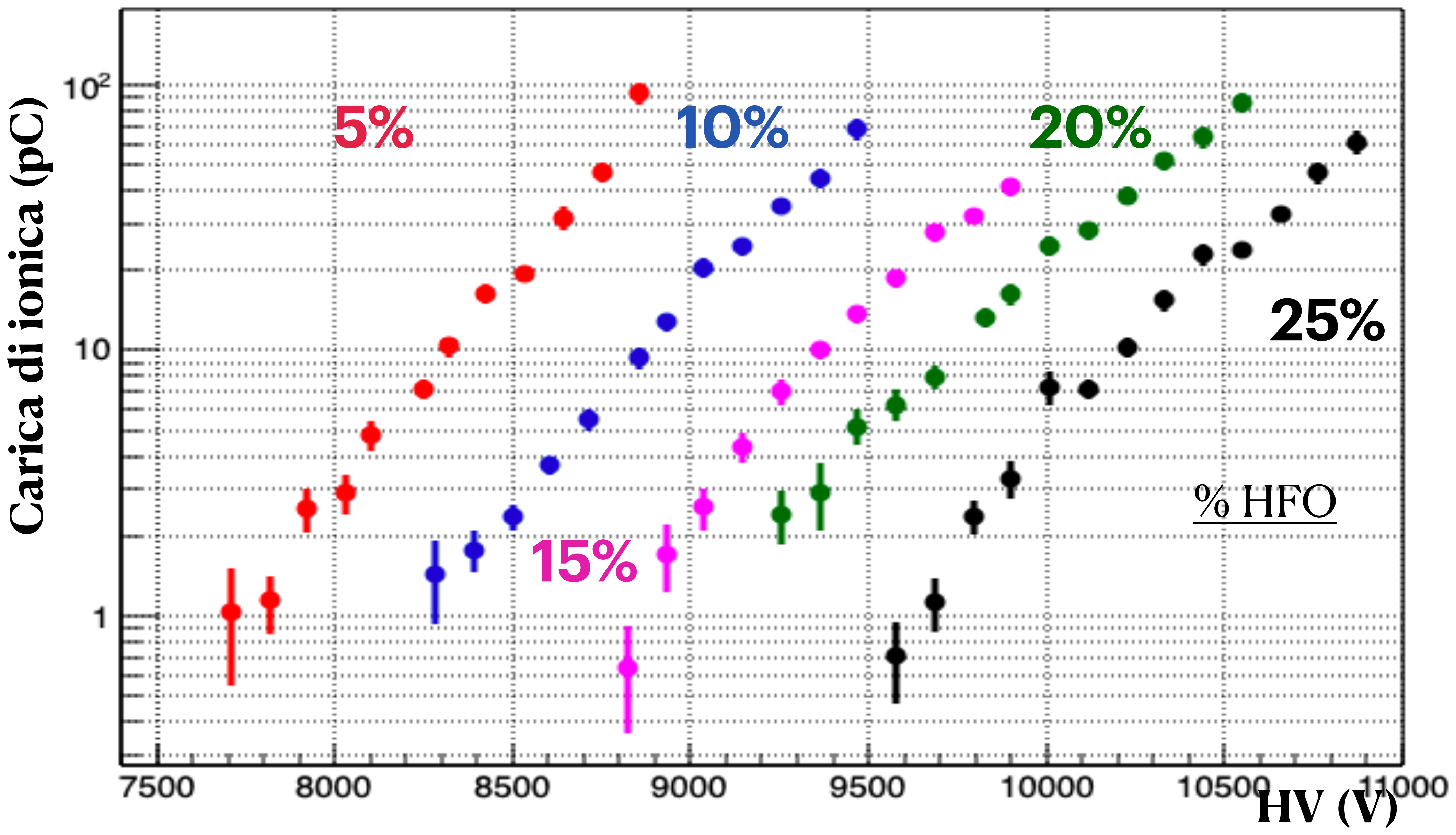
Vknee= Tensione @90% di efficienza

Serie i-Butano/SF_6=costante=5/1 - CO_2=89/84/79/74/69 : Studio delle cariche



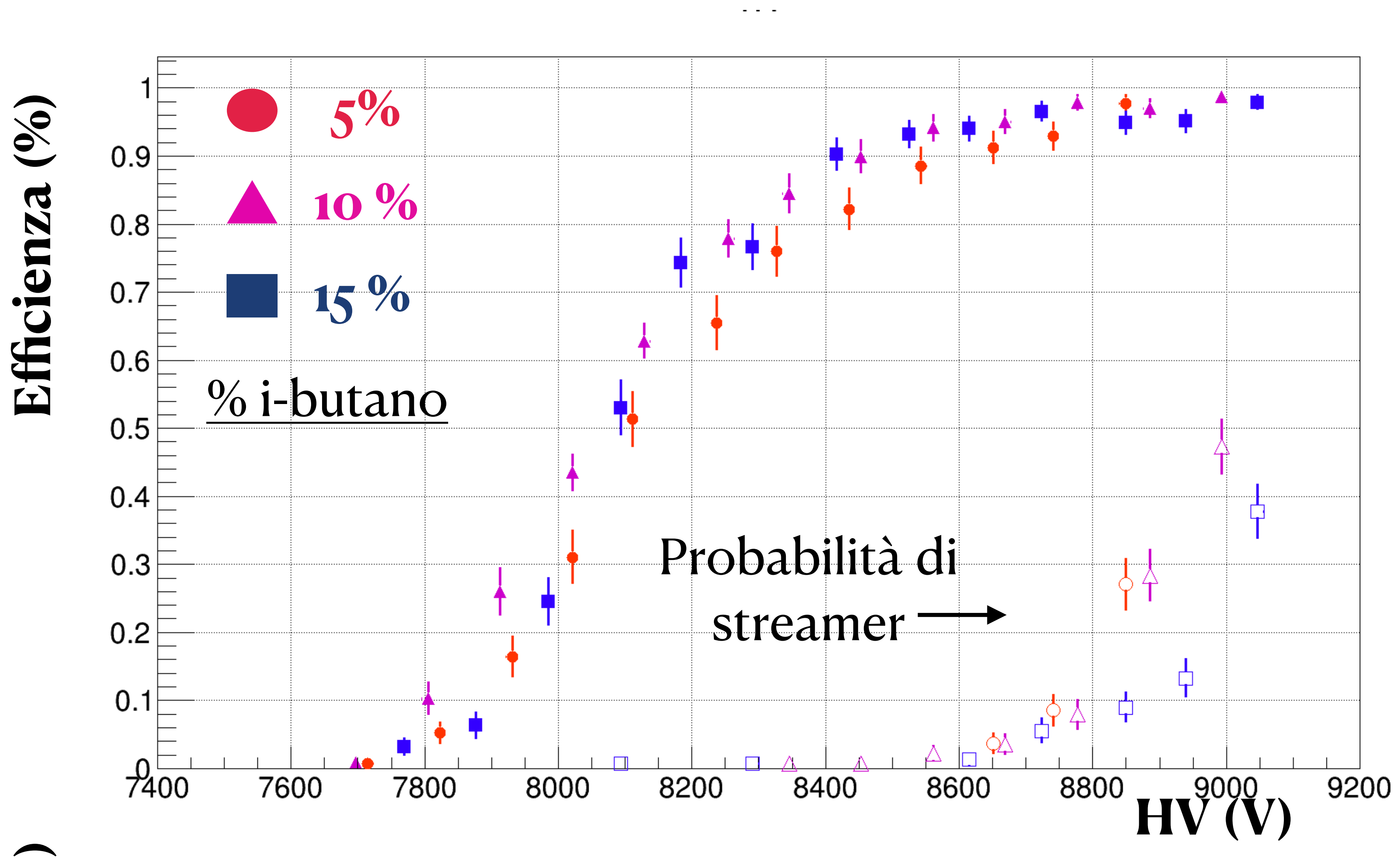


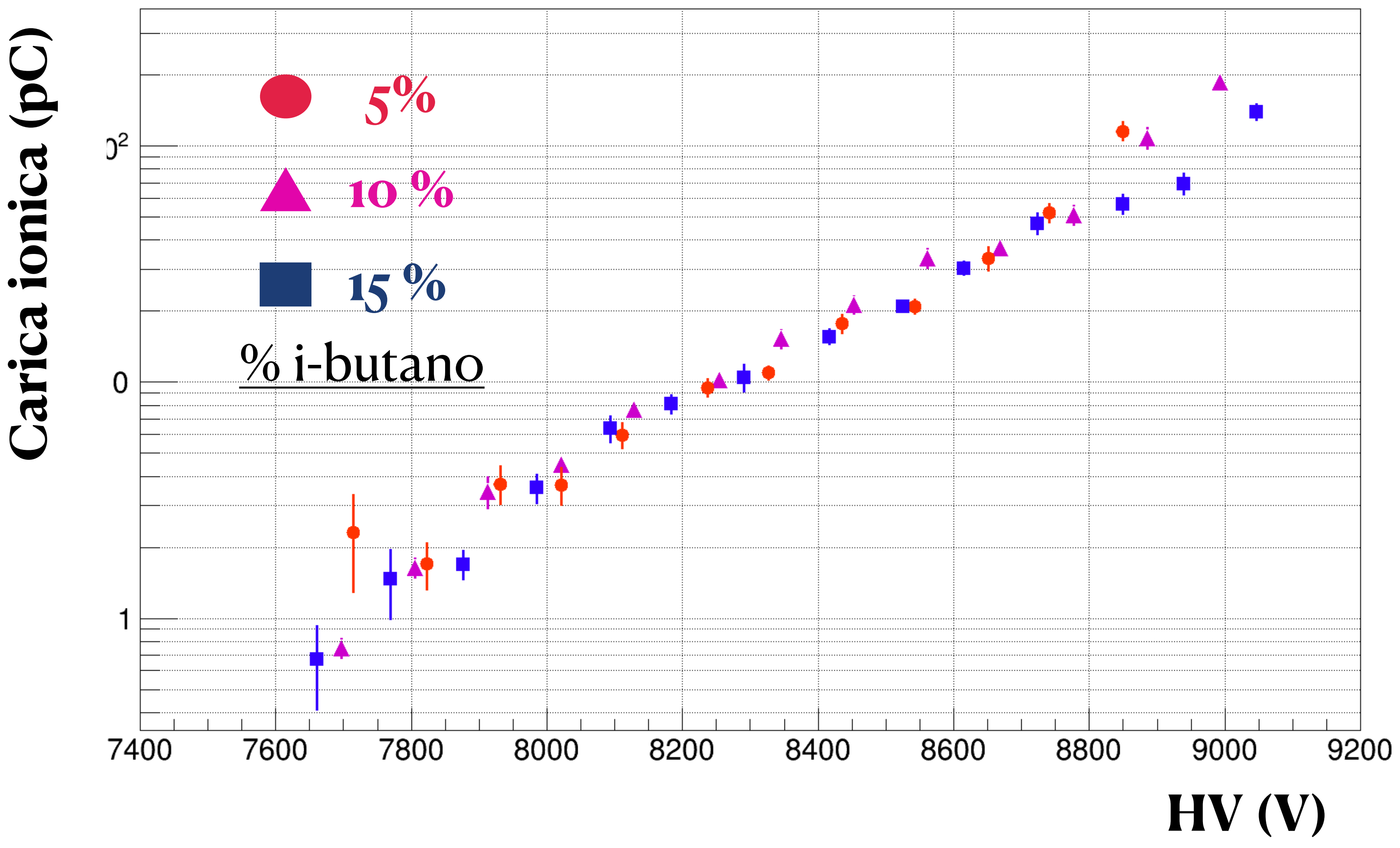
Vknee= Tensione @90% di efficienza



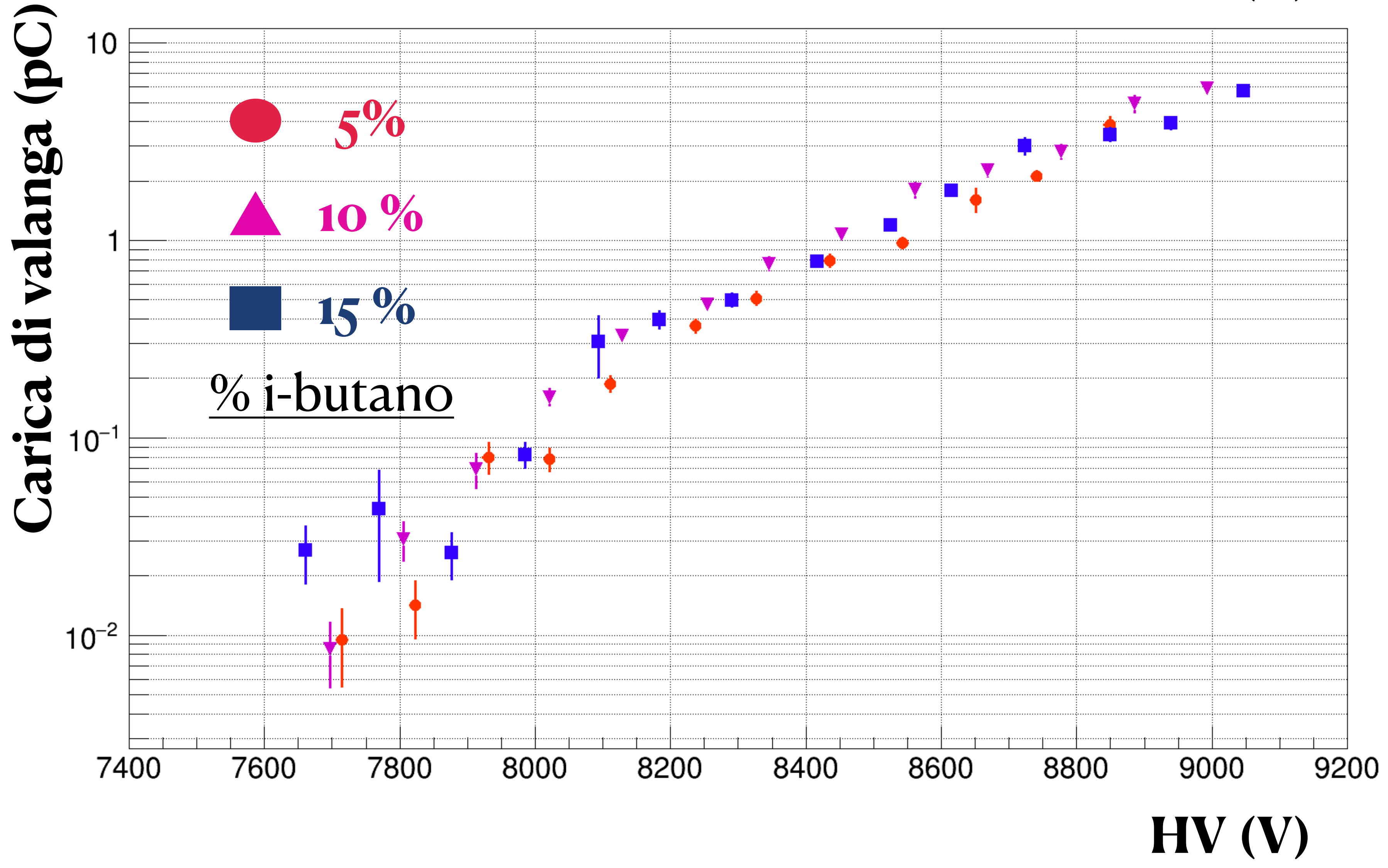
% HFO	V_{knee}	Carica valanga@ V_{knee} + 200 V	Carica prompt totale @ V_{knee} + 200 V	Carica ionica @ V_{knee} + 200 V
5%	8.5 kV	2.1 pC	11.5 p C	50 pC
10%	9 kV	1.9 pC	7 pC	38 pC
15%	9.5 kV	1.6 pC	4.3 pC	32 pC
20%	9.9 kV	1.5 pC	4 pC	31 pC
25%	10.4 kV	1.7 pC	5 pC	34 pC

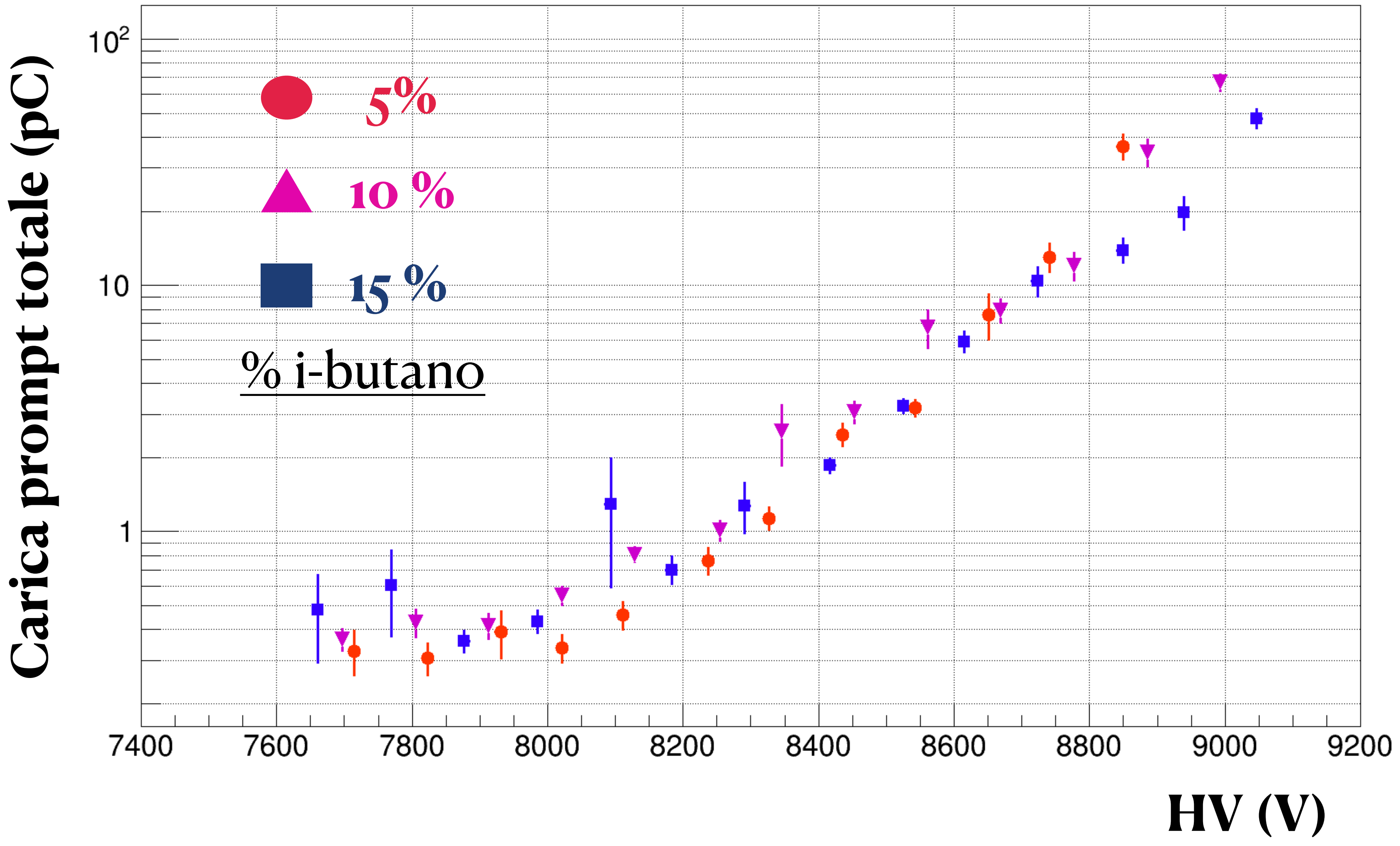
Serie HFO1234ze/SF_6= costante=5/1 - CO_2=89/84/79





% i-butano	V_{knee}	%streamer @ V_{knee} + 200 V	%extra carica@ V_{knee} + 200
5%	8.5 kV	8.5%	46%
10%	8.45 kV	3.5%	46%
15%	8.4 kV	1%	35%





% I-butano	Carica valanga@ V_{knee} + 200 V	Carica prompt totale @ V_{knee} + 200 V	Carica ionica @ V_{knee} + 200 V
5%	2.1 pC	11.5 pC	50 pC
10%	2.2 pC	7.3 pC	37 pC
15%	1.8 pC	5.3 pC	30 pC

Vknee= Tensione @90% di efficienza

Comparison between eco and standard gas mixtures: Conclusions

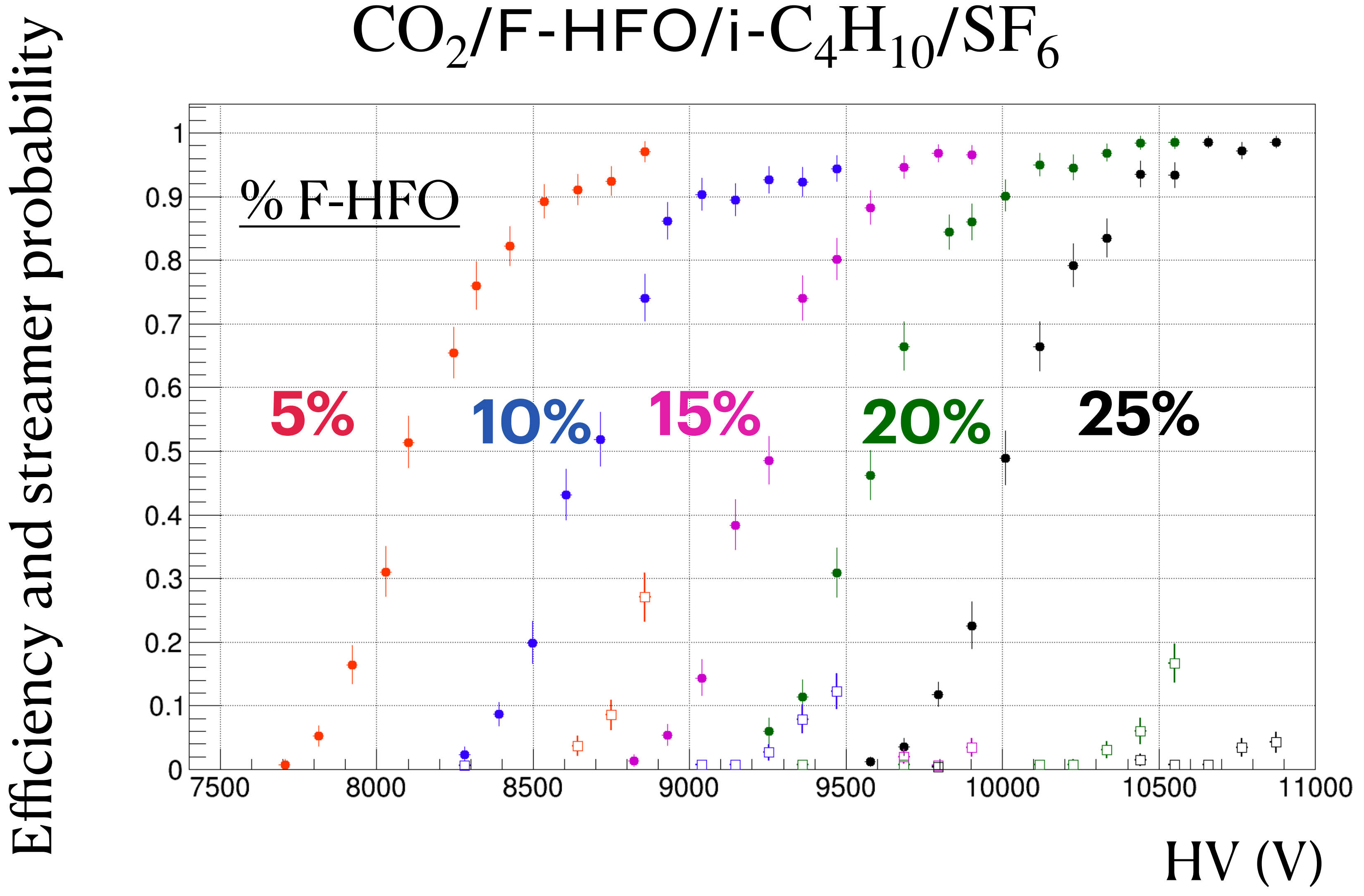
- The efficiency curve is sharper with the standard mixture ;
- The avalanche to streamer separation in the eco gas is significantly smaller than in the standard mixture ;
- The fraction of the transition events is much smaller in the standard gas ;
- The mixture with 2% Cl-HFO shows a charge saturation 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) %

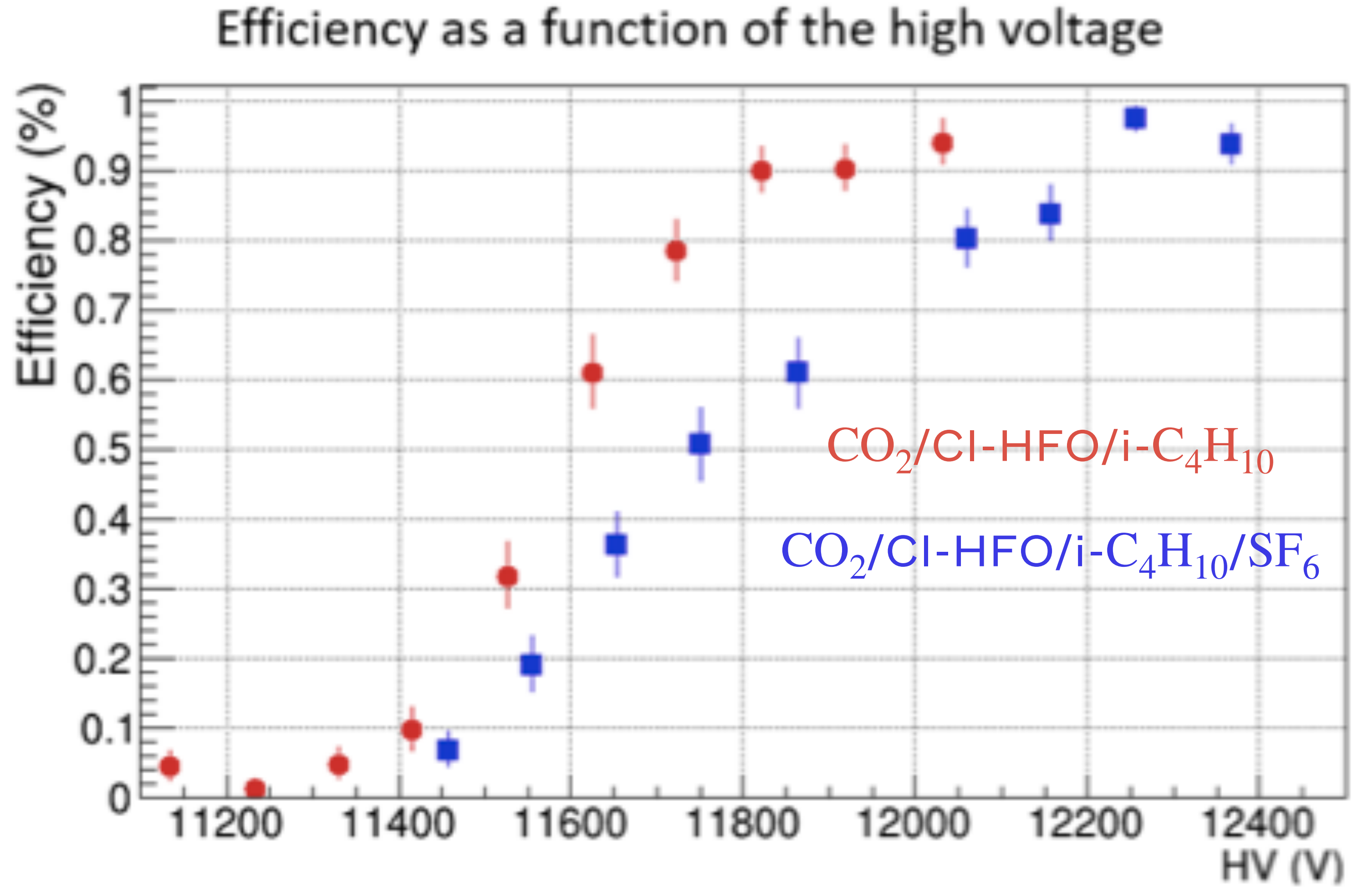
CO_2/F-HFO/i-C_4H_{10}/SF_6



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 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

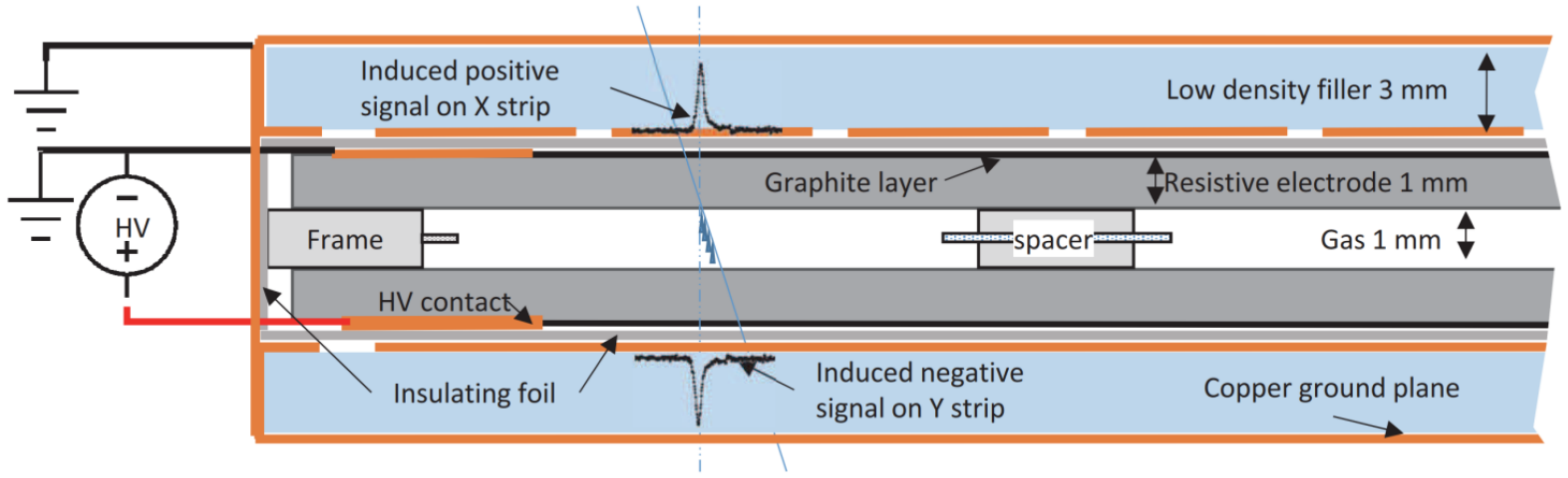
CO_2/F-HFO/i-C_4H_{10}/Cl-HFO

- 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)

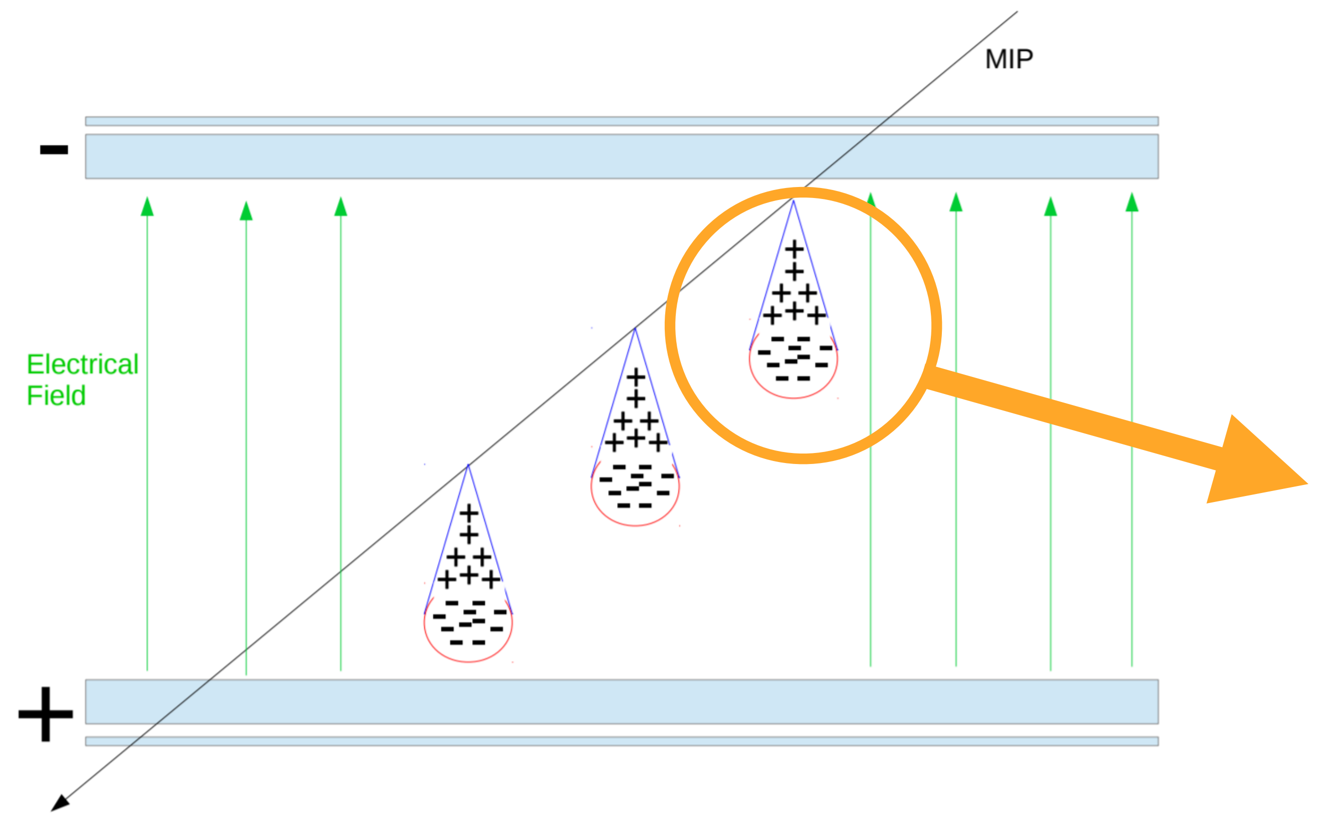
- Performance of the RPC operating with gas mixtures composed of CO_2/F-HFO/i-C_4H_{10}/Cl-HFO
- Comparison between the eco-mixture with the best performance and the standard gas mixture
- Direct comparison of the performance with SF_6 and Cl-HFO

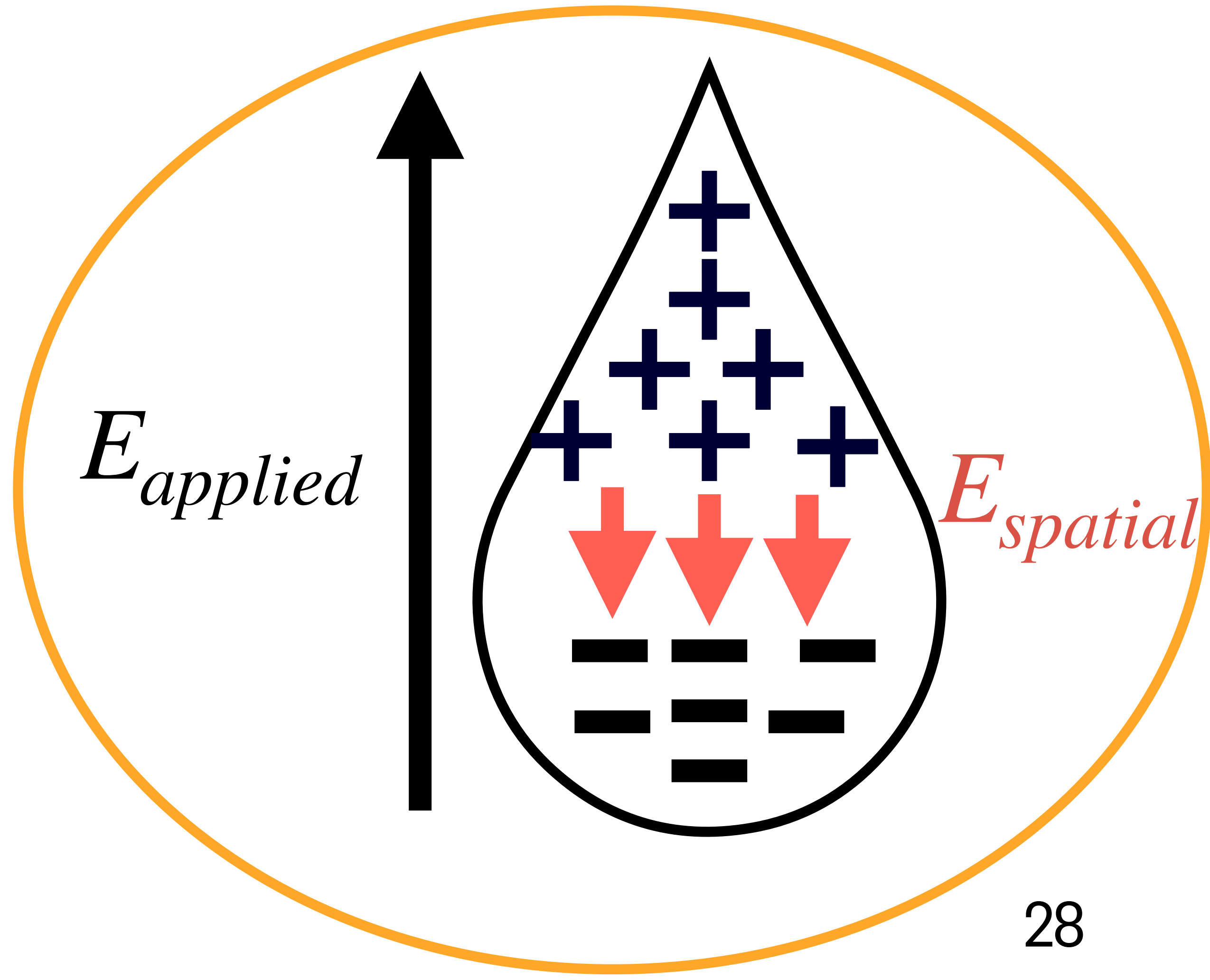
The Resistive Plate Chambers (RPC)



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

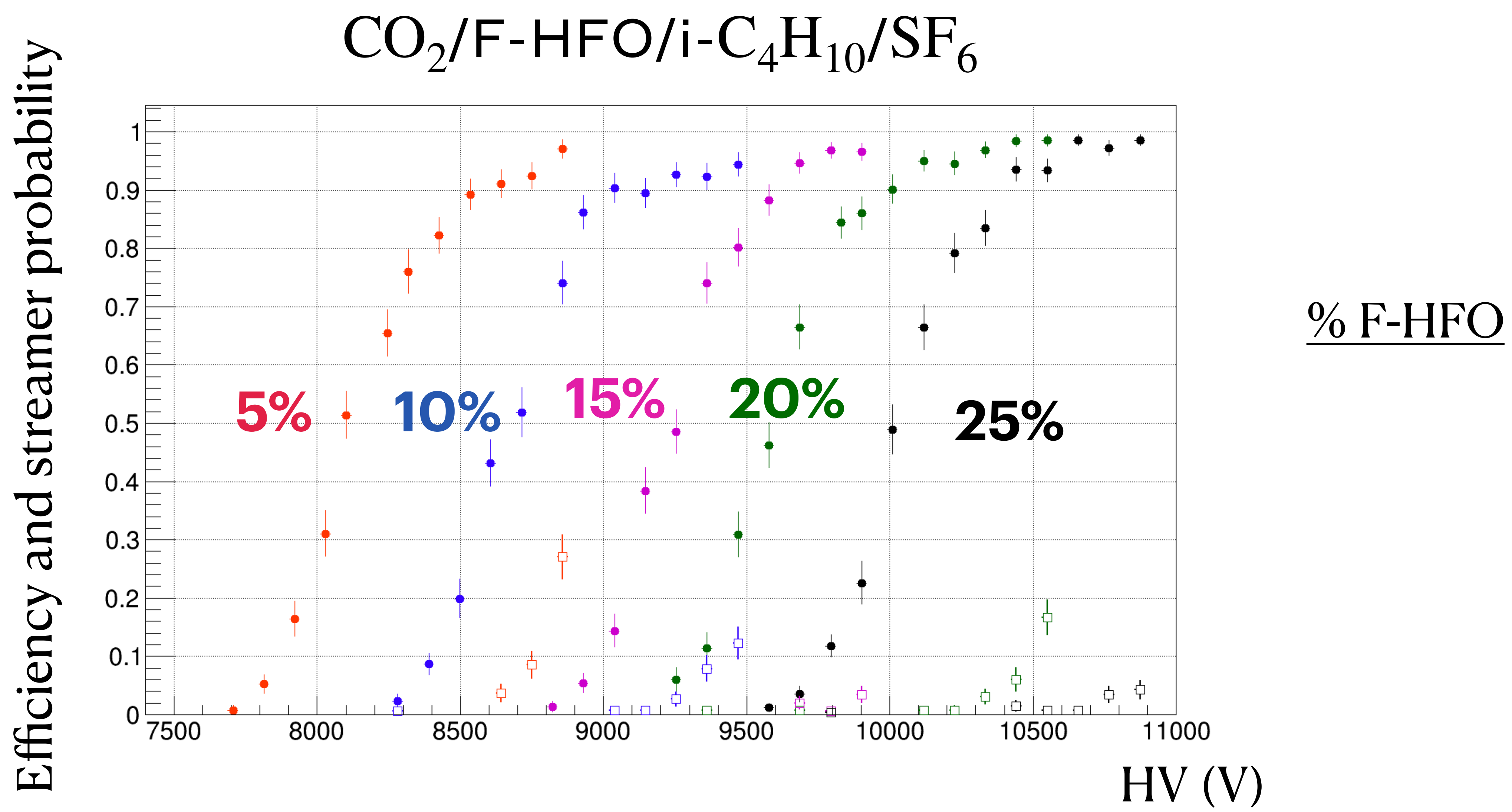
- Primary ionization
- Electron acceleration and avalanche charge formation:
    - Saturated avalanche mode
    - Electron-ion recombination processes with UV photons emission
    - Streamer formation

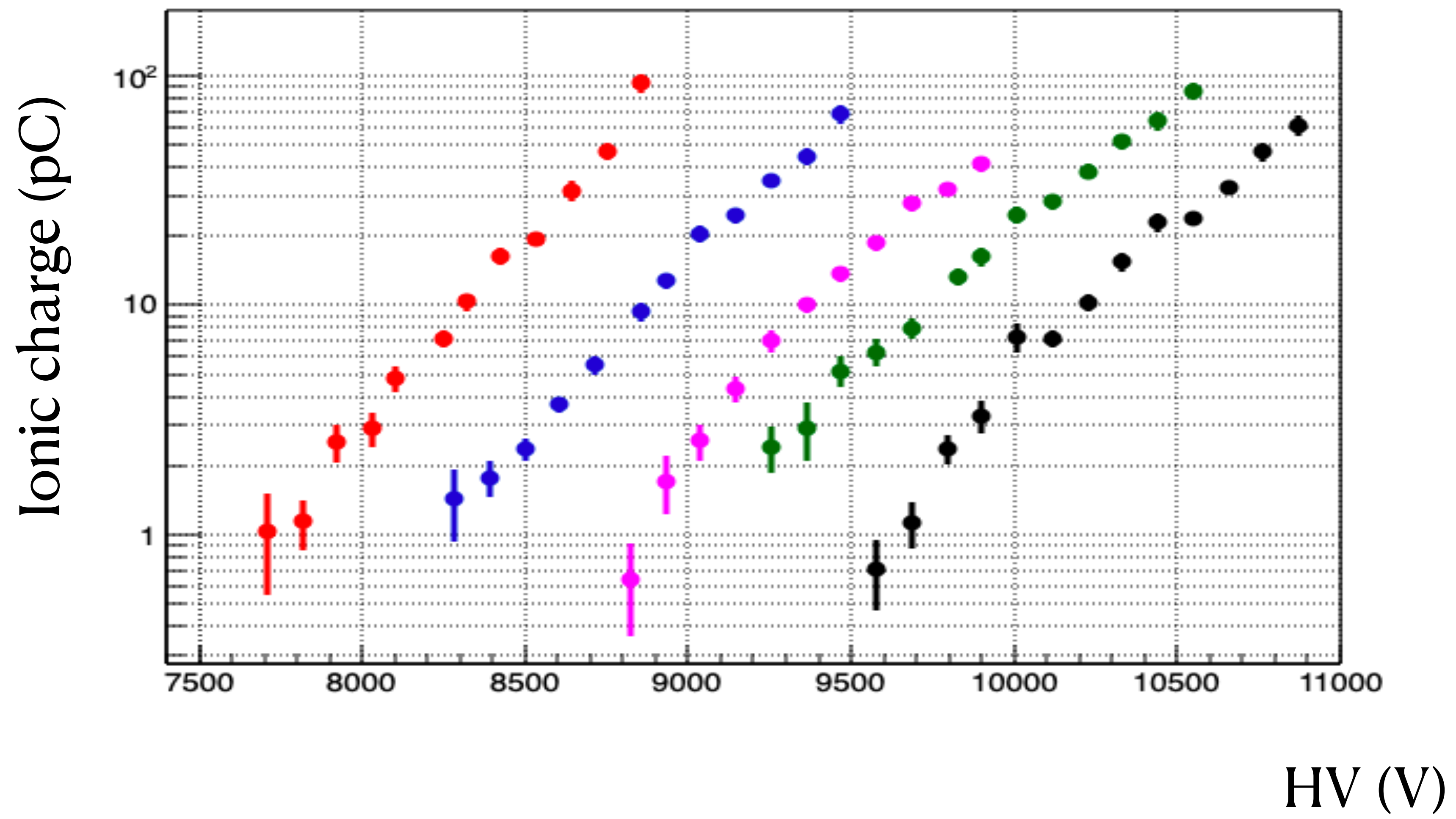




Optimize the eco gas mixture for the RPC

- 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%

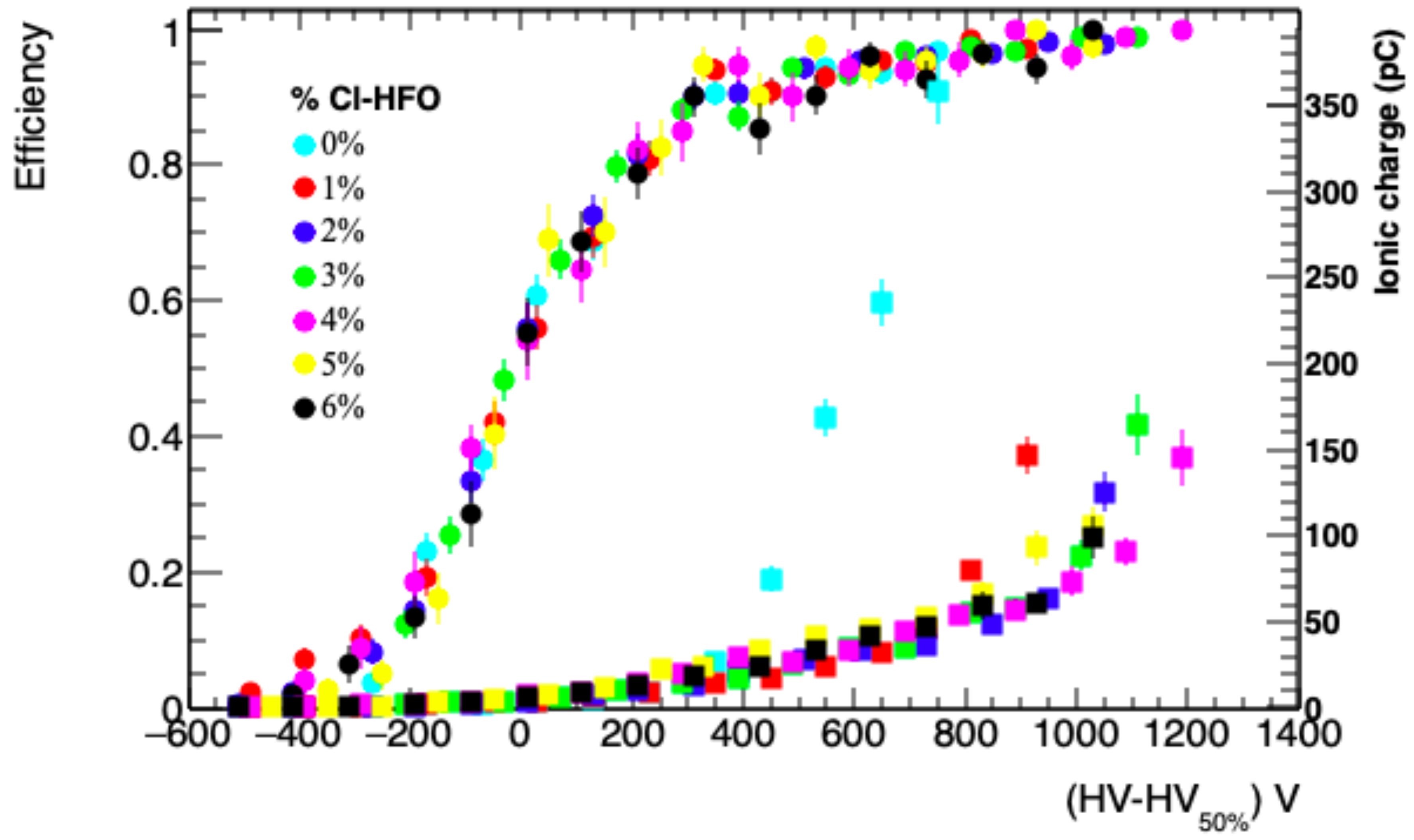


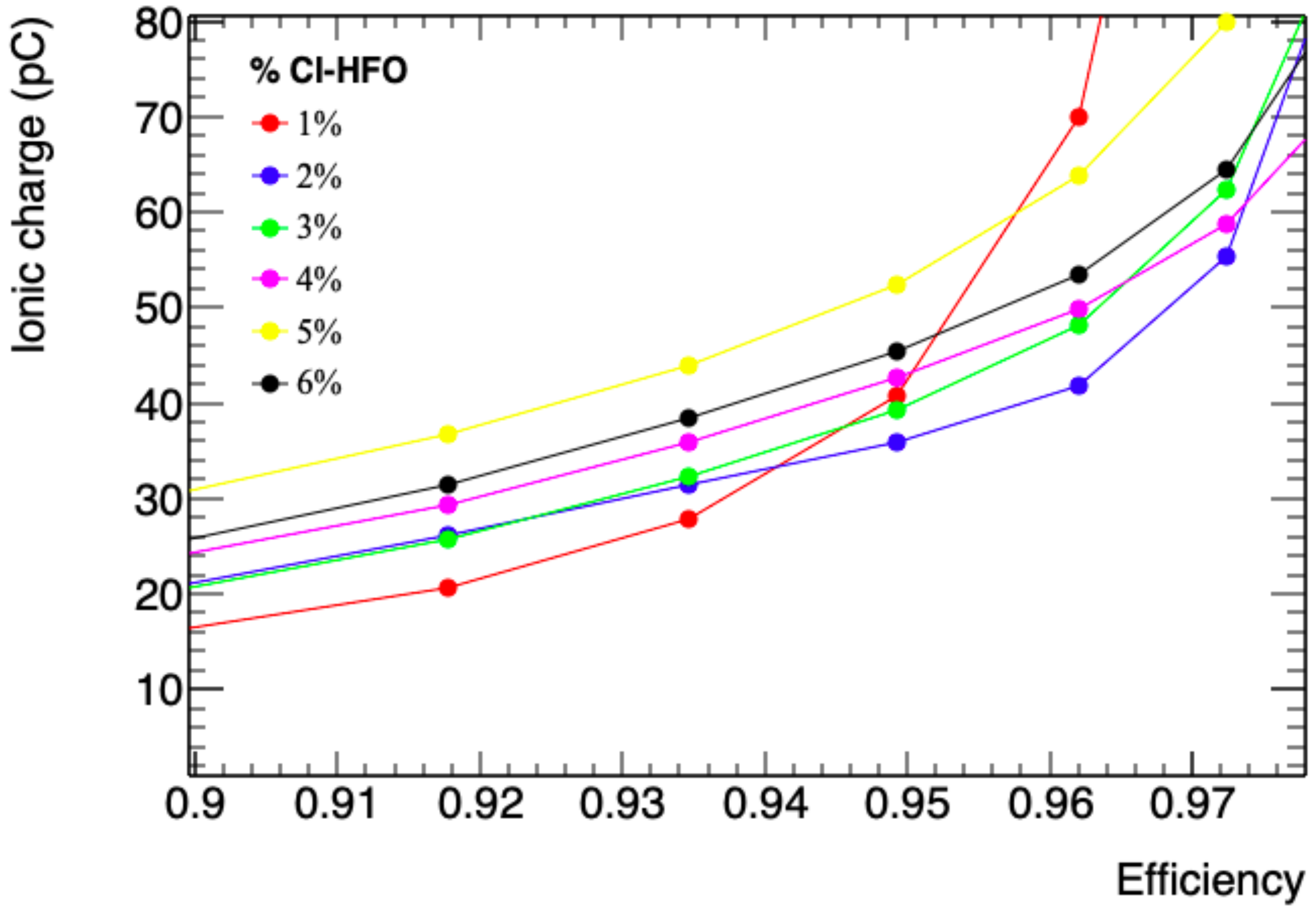


...to the choice for this test

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

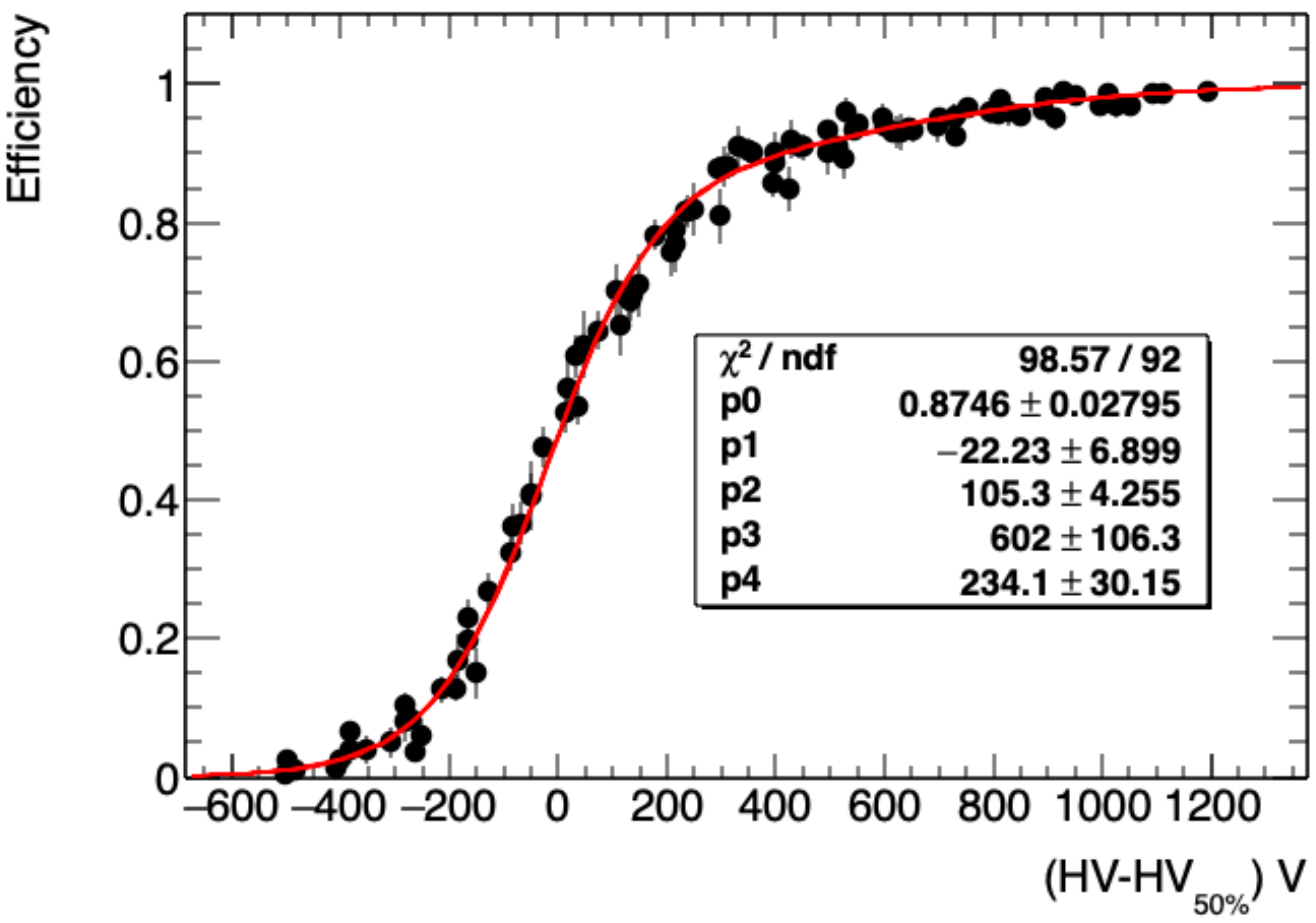
RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Ionic charge





- 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)



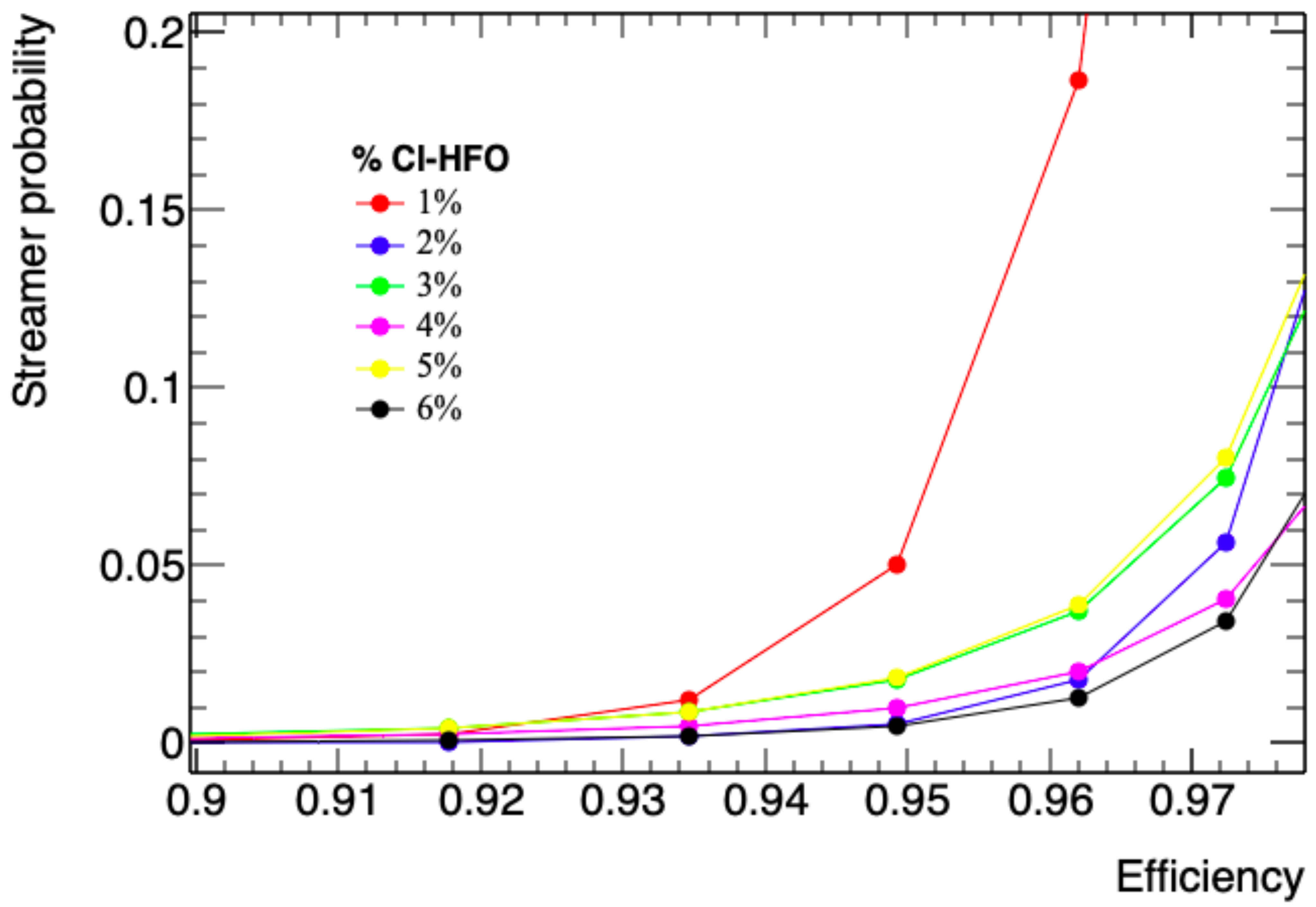
- The efficiency curves after the alignment have the same profile

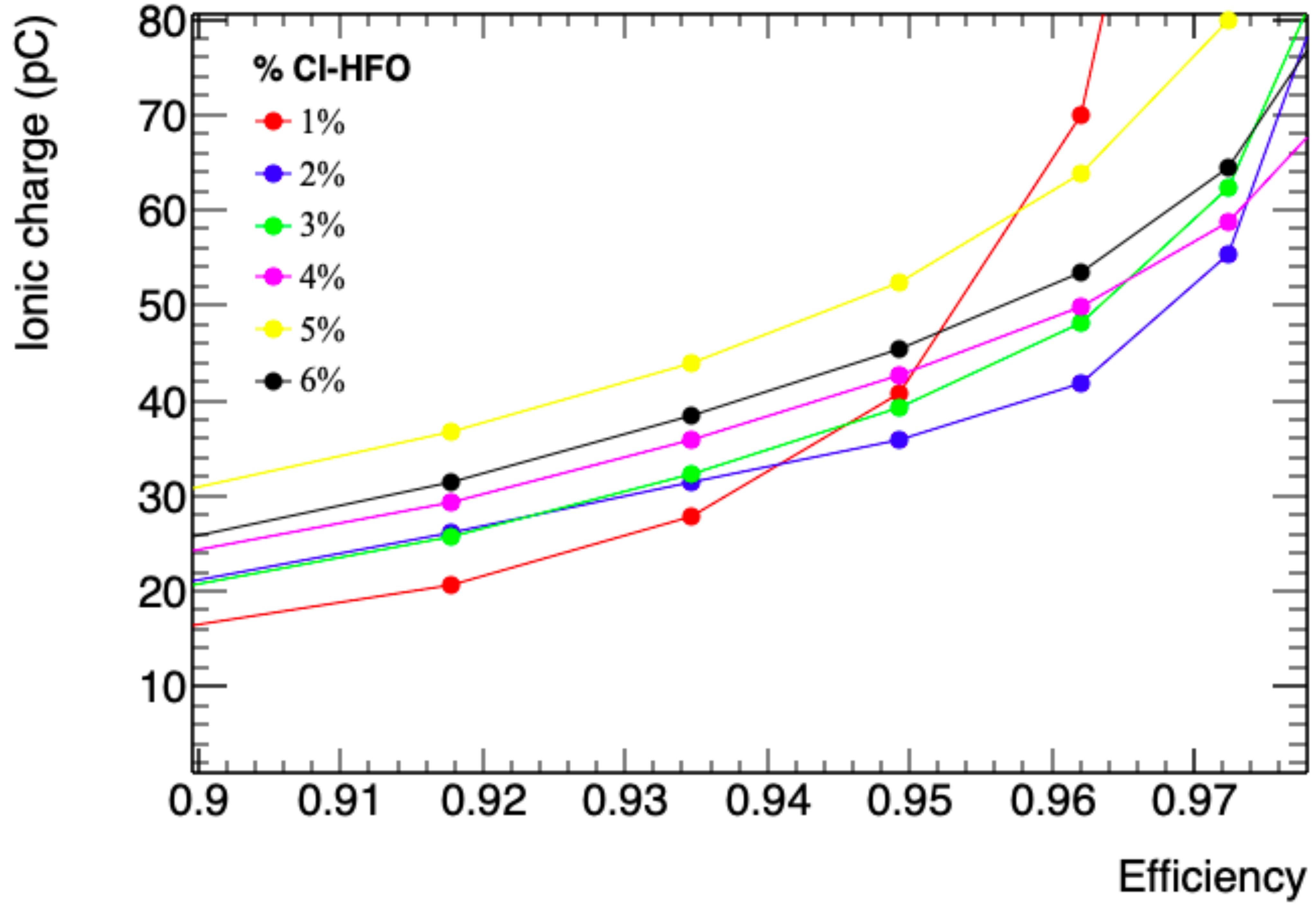
Fit function

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

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

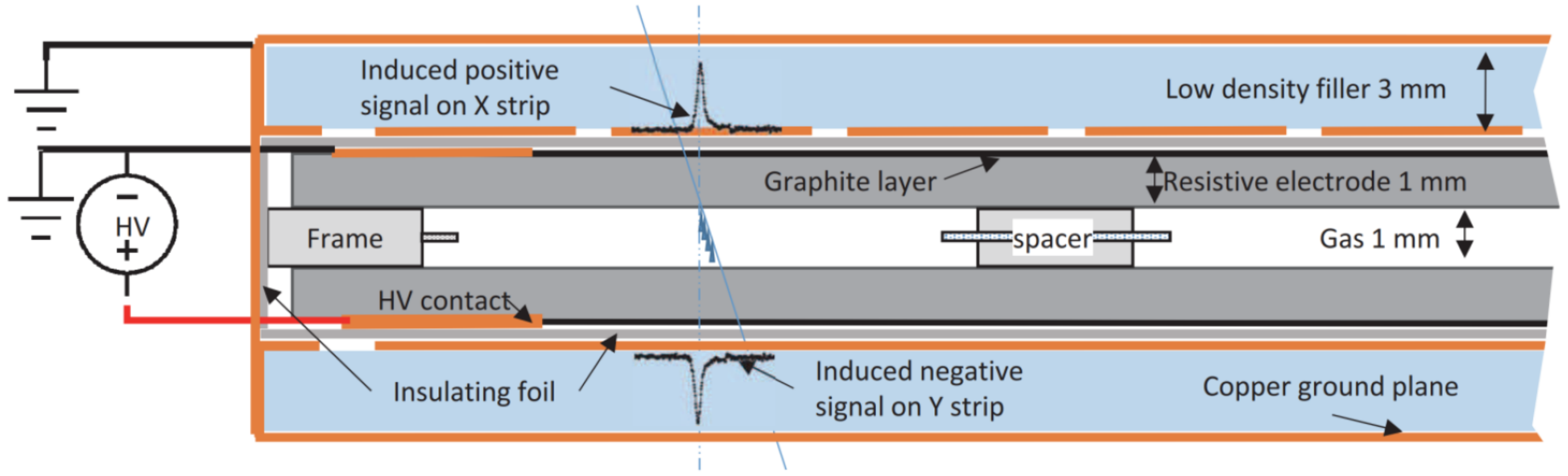
RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Fit analysis (II)



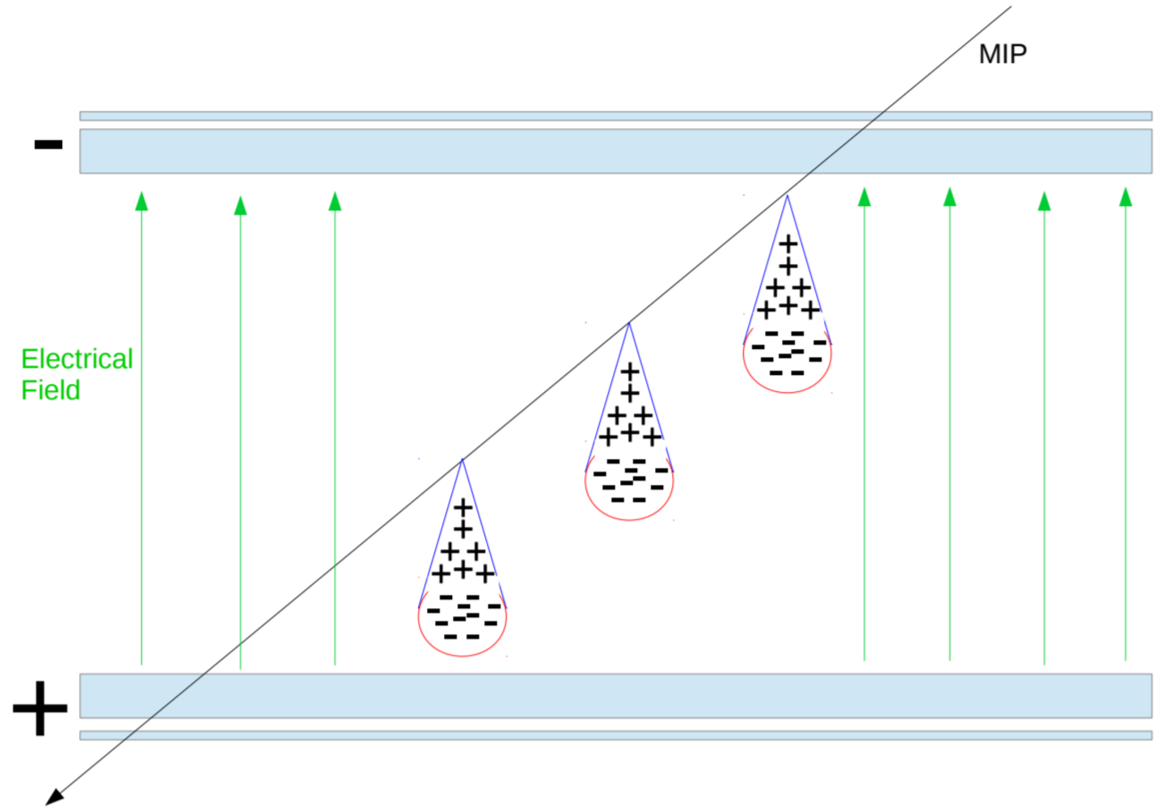


- The streamer curve is faster in the mixture containing 1% Cl-HFO
- The mixture with 1% Cl-HFO shows the lowest ionic charge for $\epsilon < 94\,\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge for $\epsilon > 94\,\%$

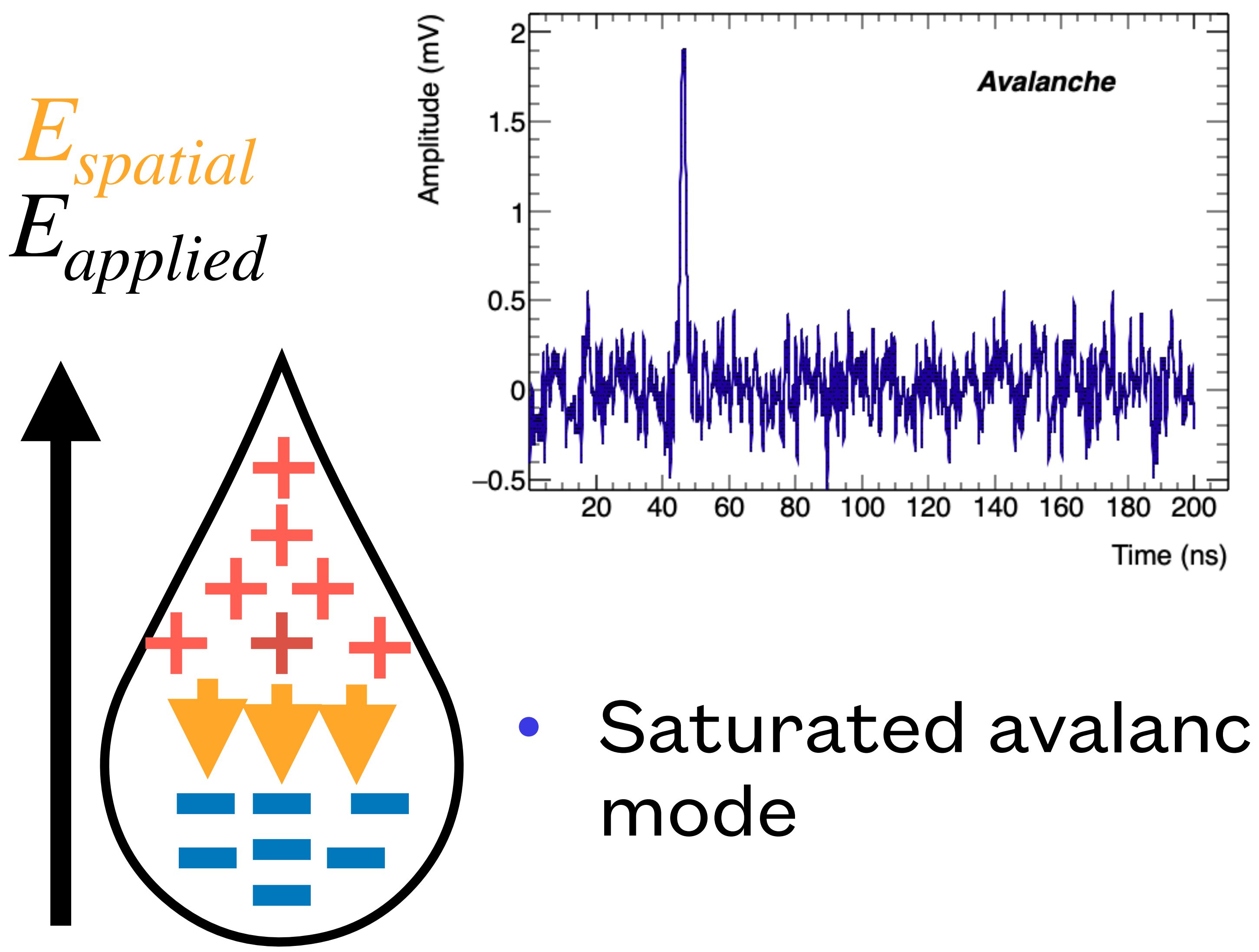
The Resistive Plate Chambers (RPC)



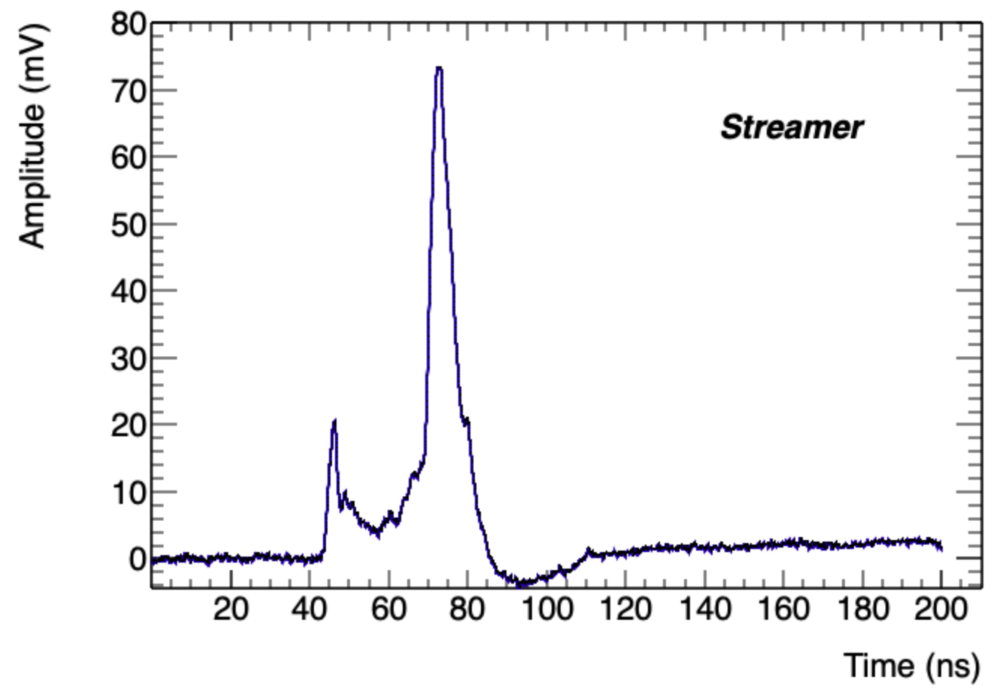
- Gas gap
- Parallel resistive electrodes
  - Internal surface: linseed oil
  - External surface: graphite
- Insulating layer
- Read-out strips



- Primary ionization
- Electron acceleration and avalanche charge formation



- Saturated avalanche mode



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