

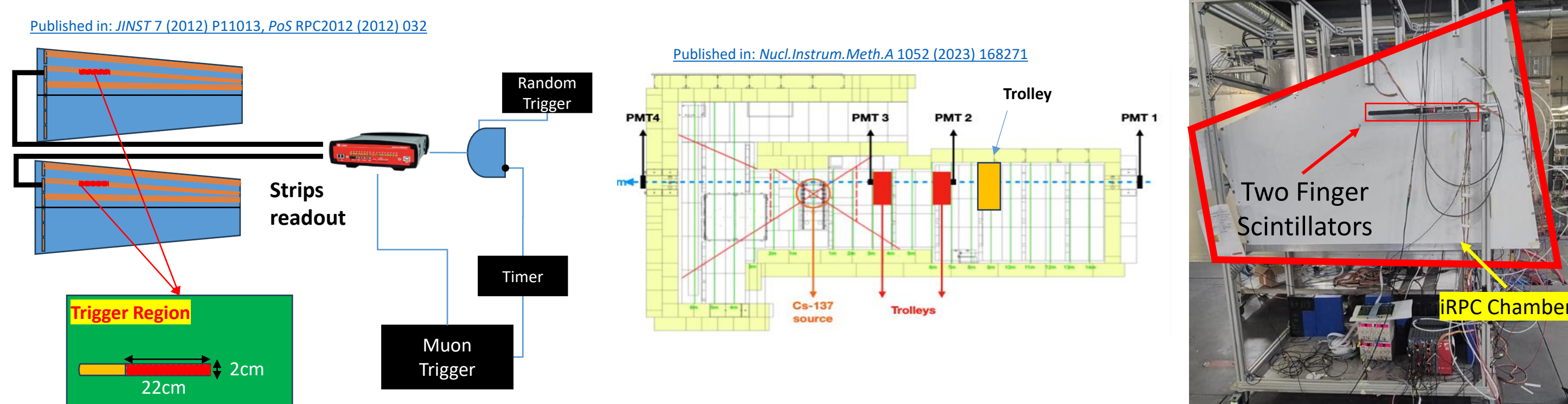
Temporal Waveform Parameters

Widely adopted in high-energy physics experiments, Resistive Plate Chambers (RPCs) face a significant challenge due to new regulations that severely limit allowable greenhouse gas emissions — including those typically used in RPC operation. As a result, identifying a low-global-warming-potential mixture has become a priority for the gas detector community. In this context, an investigation of iRPC waveforms obtained during a muon test beam at CERN’s Gamma Irradiation Facility was conducted in July 2026. The approach incorporates waveform analysis and machine-learning algorithms to classify signals from iRPC chambers operating on an HFO1233ZD-based mixture, as a candidate to replace SF₆. The machine learning model aims to improve the understanding of discharge mechanisms in candidate gases and to enrich insights from analytical methods

Experimental Setup

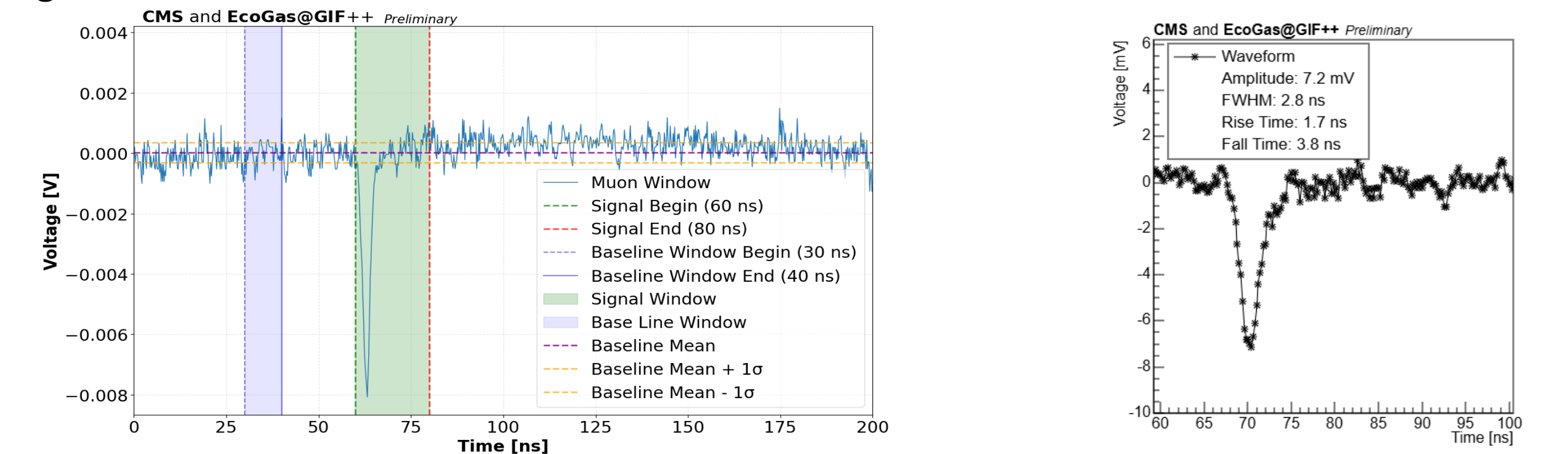
- Gamma Radiation Facility (GIF++)
- Muon Test Beam from July 2026
- CAEN DT5742 5GS/s
- Two iRPCs RE3/1
- Coincidence between two-finger scintillators
- Veto for the random trigger during the spill
- 4 gas mixtures tested

Published in: <i>Nucl. Instrum. Meth. A</i> 1066 (2024) 169580	HFO-1234ze	CO2	i-C4-H10	HFO-1233zd	R134a	SF6
Eco2_zd_0.5 [%]	35	59.5	5	0.5	0	0
Eco2_zd_2 [%]	20	73	5	2	0	0
Eco2 [%]	35	60	4	0	0	1
STD [%]	0	0	4.5	0	95.2	0.3
GWP	6	1	3	1	1430	23500



Waveform Data Analysis

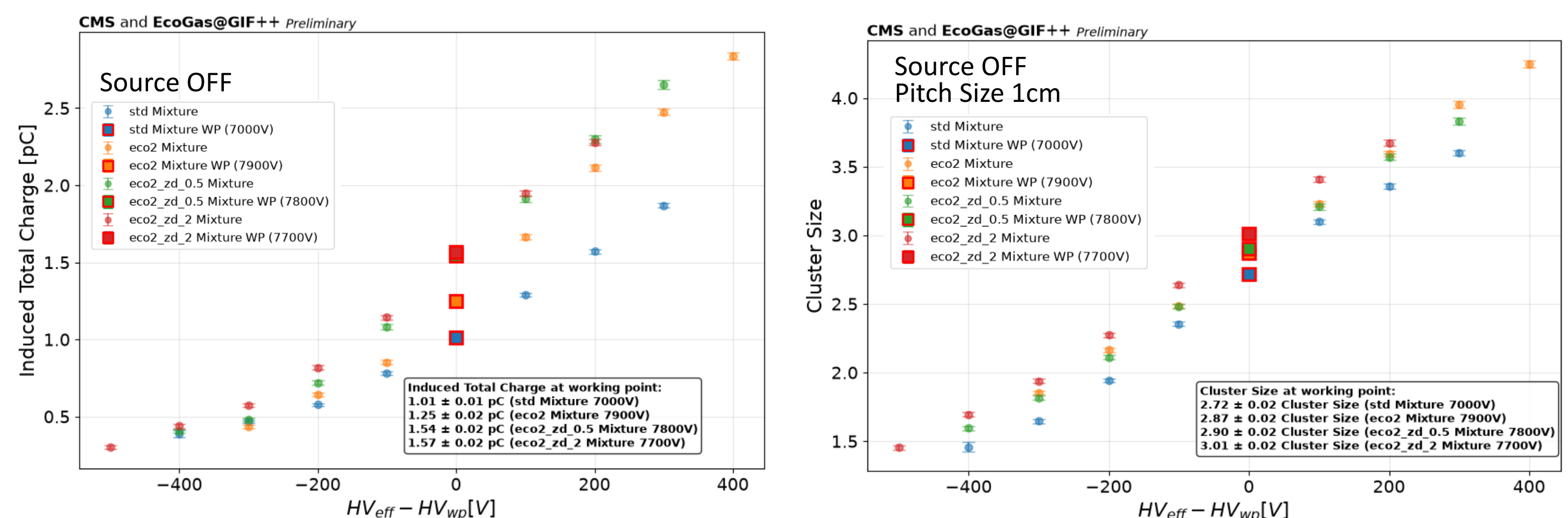
The first step is to identify the muon window and define a fixed 20 ns time window in this region. Set the baseline window before the muon window and use it to correct the waveform baseline to zero. The signal threshold is measured using the baseline window, defined as 5 sigmas from this window.



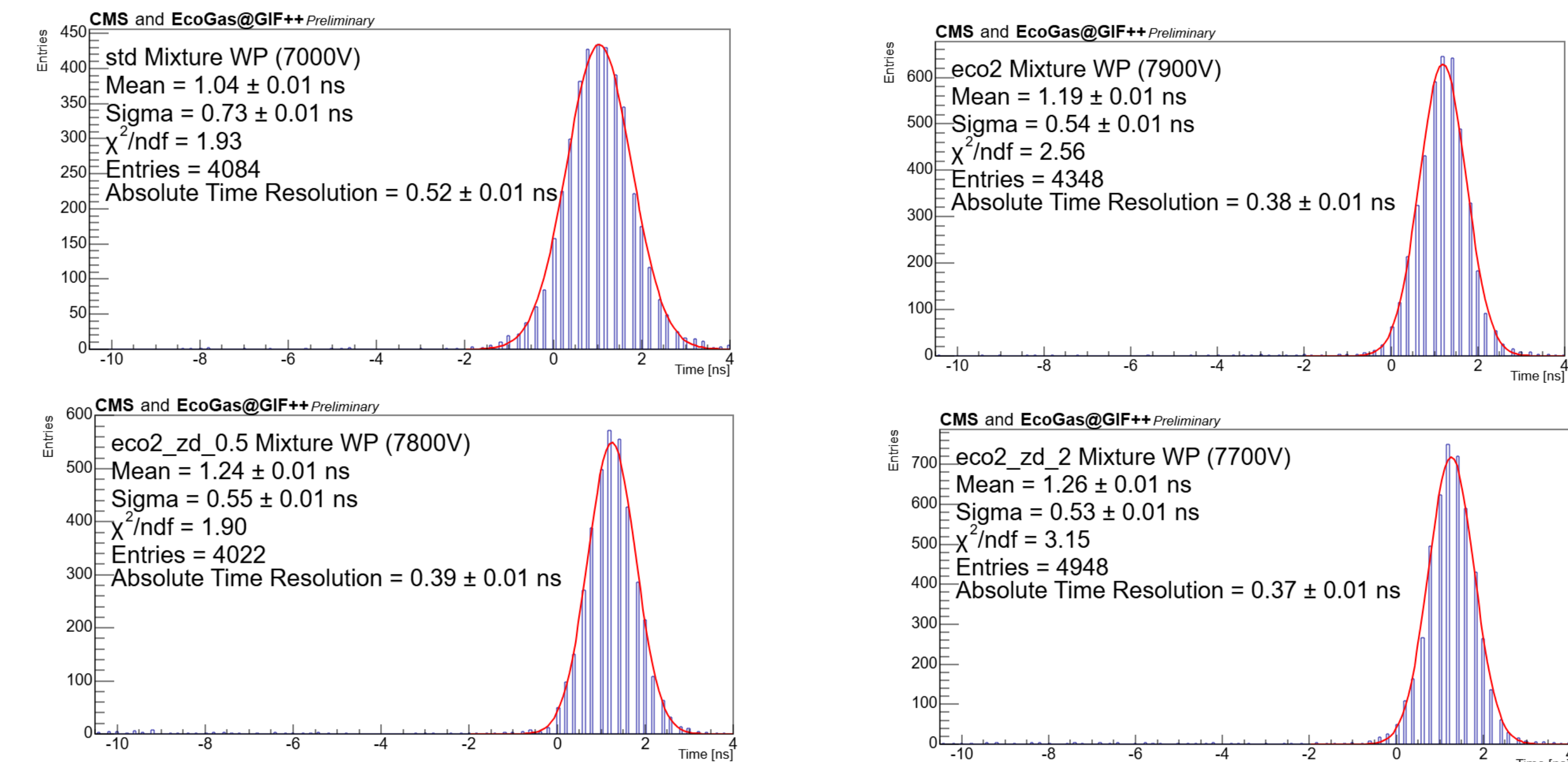
The efficiency curve is estimated using the 5 sigmas threshold, which is approximately 1.8 mV. From the efficiency curve, the work points calculated for the mixture std, eco2, eco2_zd_0.5, and eco2_zd_2 were 7000V, 7900V, 7800V, and 7700V, respectively, yielding efficiencies greater than $\approx 97\%$.

$$Eff = \frac{Eff_{max}}{1 + e^{s(HV - HV_{Eff})}} \quad WP = Knee + 150V$$

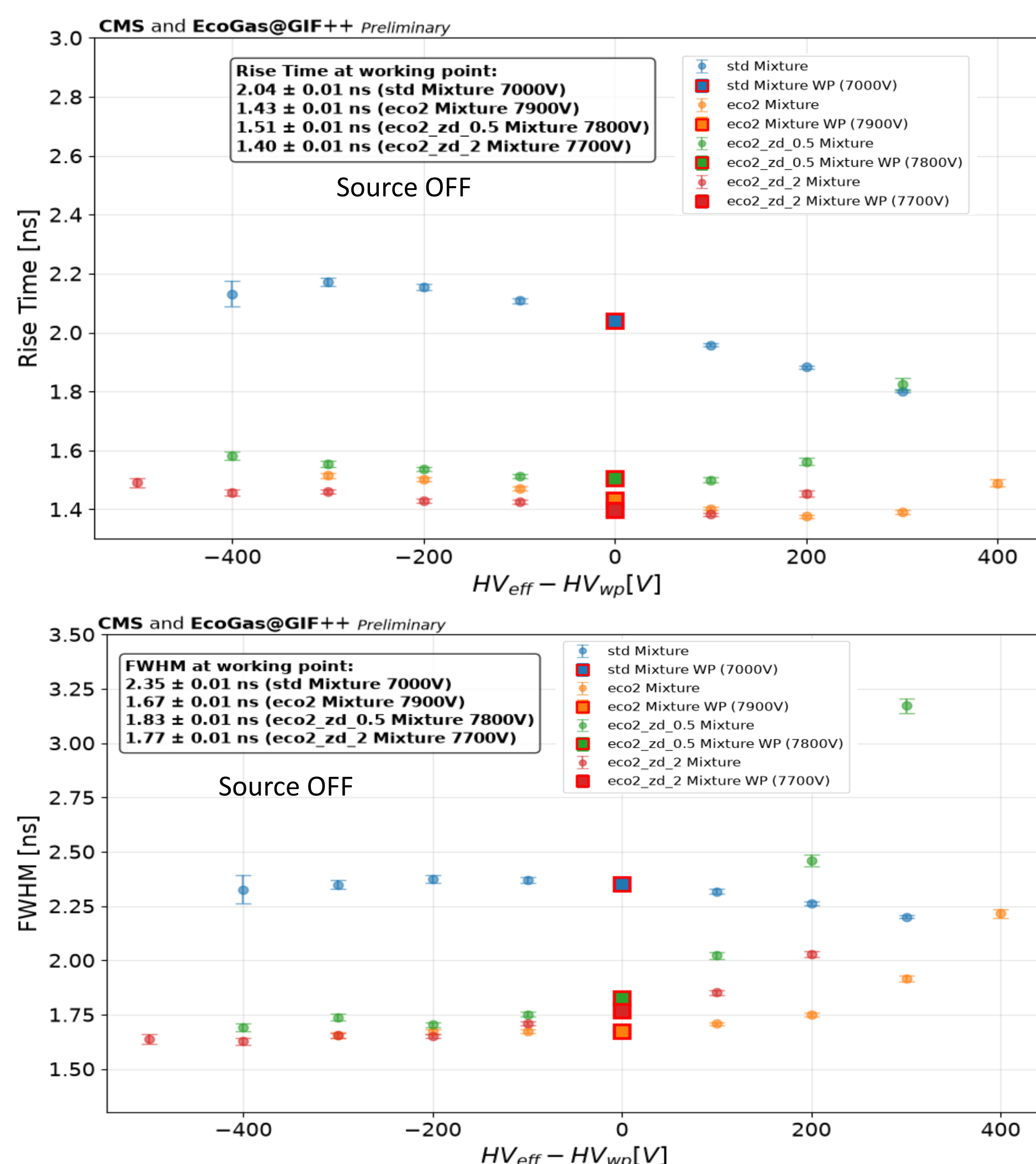
Observing the induced total charge (sum of the 8 strips subtracted by the pedestal charge) and the cluster size (number of adjacent strips fired), the HFO-1233zd presents a larger cluster size and greater charge than the standard mixture.



The absolute time resolution and all waveform time parameters are measured by seed strip selection (the strip with the highest charge in the event). Based on the seed strip selection, the time difference between the peaks of the two chambers is plotted, and a Gaussian function is fitted; the sigma from this fit, divided by the square root of two, is the absolute time resolution (chamber time resolution). When comparing the mixtures, the analysis indicates that the eco mixture shows improved time resolution.



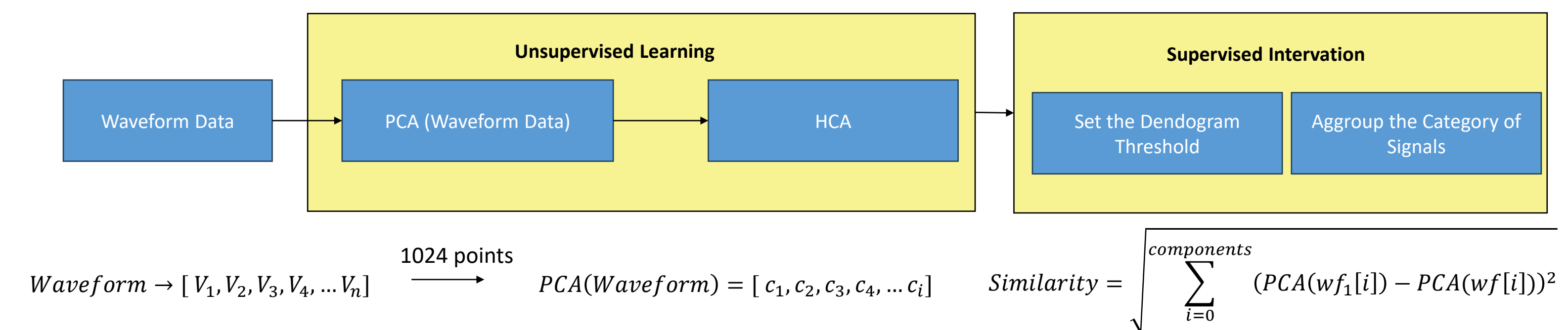
At the working point, eco mixtures exhibit a shorter rise time than the standard gas mixture, with eco2_zd_2 showing the fastest. Rise time decreases as voltage increases. However, at around 200 V above the working point, the eco mixtures began to increase the rise time.



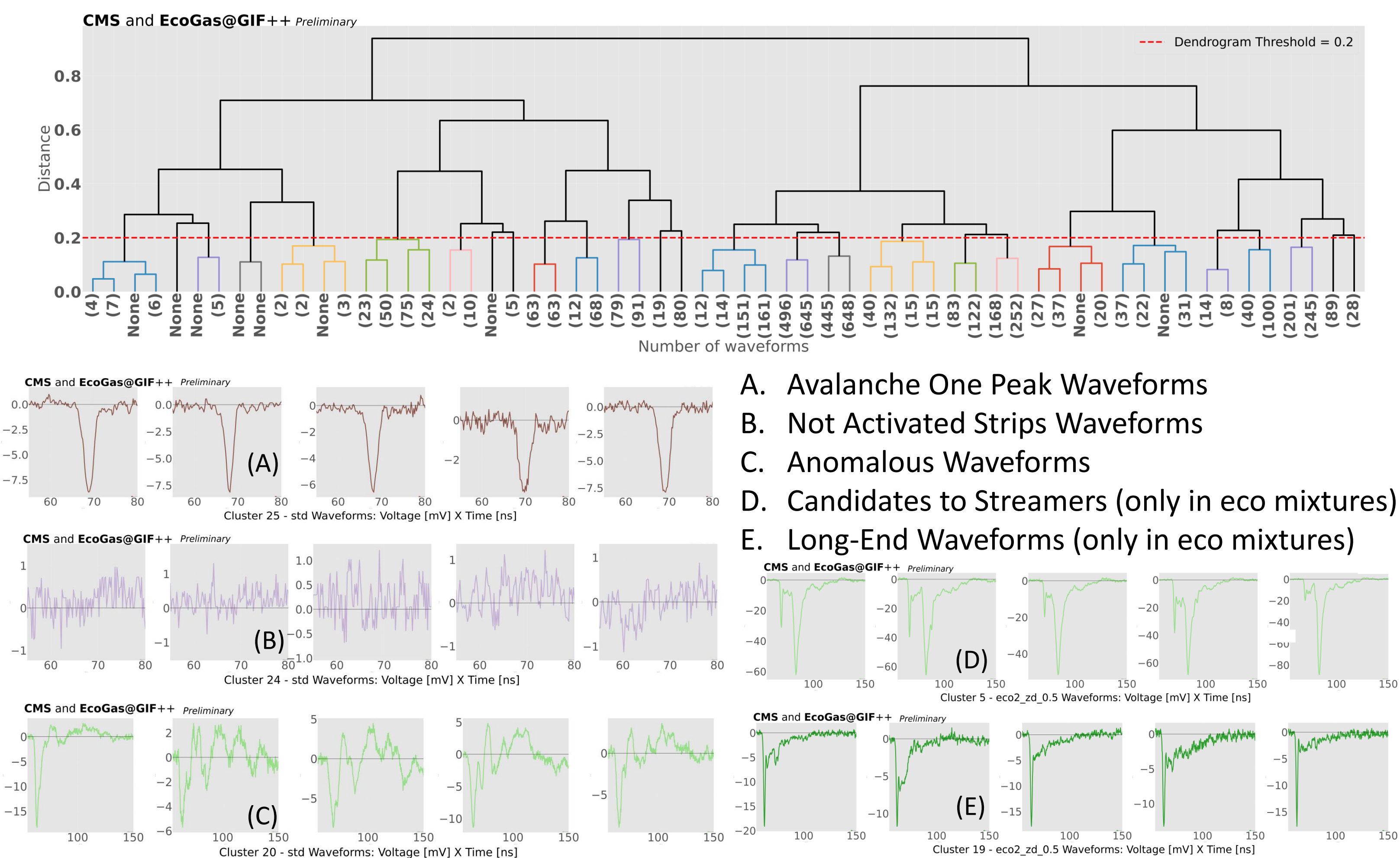
At the working point, the standard mixture waveforms show a larger signal than the eco mixtures. As the standard mixture decreases with increasing voltage, the eco mixtures show the opposite behavior, with eco2_zd.0.5 showing the greatest increase.

Unsupervised ML (HCA)

- **Principal Component Analysis (PCA)**, for dimensionality reduction.
- **Hierarchical Clustering Analysis (HCA)**, based on similarity.
- **HCA: implementing each mixture individually and the strip for more efficiency at the working point.**



Using the variance-explained ratio, the number of components is selected to account for at least 95% of the variance in the data. Using HCA, the distances between clusters can be verified in the cluster dendrogram. The threshold is defined as 0.2 to split the data into 26 clusters. Among the 26 clusters, only 3 waveform categories were detected, whereas the eco mixtures show 2 additional categories.



Waveforms Cluster Category	std	eco2	eco2_zd_0.5	eco2_zd_2
Avalanche One Peak Waveforms Population (A) [%]	53.7	37.26	27.76	41.068
Not Activated Strips Waveforms Population (B) [%]	44.68	46.32	51.54	44.9
Anomalous Waveforms Population (C) [%]	1.62	1.26	2.08	2.44
Candidates to Streamers Waveforms Population (D) [%]	0	0.02	3.04	1.07
Long-end Waveforms Population (E) [%]	0	15.14	15.58	10.522
Number of Clusters	26	46	66	62

Conclusions and Perspectives

The HFO-1233zd shows promising results in time-mixing experiments, outperforming the standard C₂H₂F₄-based blend with faster signals (as shown by rise-time measurements), narrower signal width at the working point, and improved chamber time resolution. It also offers a lower global warming potential, with the HFO-1233zd component being 23500 times less impactful. However, the trade-off between timing and rate capability should be considered due to the large cluster size and highest charge. The HCA might be a promising tool for classifying different waveform types, and with further refinement, it could become a valuable complement for studying detector response and providing statistical insights into signal behavior across different gas mixtures and parameters. As a next step, the plan is to extend the analysis to additional operating voltages, gas mixture ratios, and irradiated chamber conditions, and to investigate fall time, FWHM broadening mechanisms at high voltage, streamer probability, and seed strip selection in hierarchical clustering. It also intends to train supervised learning models (e.g., convolutional neural networks) using unsupervised learning outputs.