Eco-friendly RPCs for future HEP applications: an insight into signal shape and rate studies

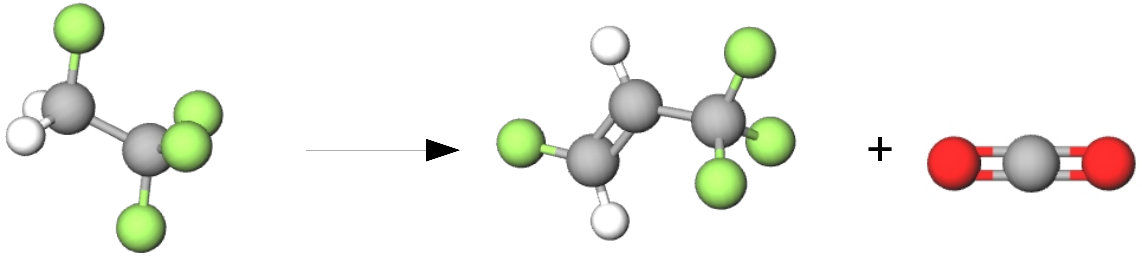
Luca Quaglia[1] on behalf of the RPC EcoGas@GIF++ collaboration

[1]INFN Torino

RPCs in HEP and their gas mixture

- **Resistive Plate Chambers** (RPCs)
  - Gaseous particle detectors with fast response + low-cost per unit area = ideal detectors for **muon triggering** and **identification** at LHC and future experiments

- Currently employed gas mixture in HEP: > 90% $\mathbf{C_2H_2F_4}$ + i-C_4H_{10} (5-10%) + SF_6 (< 1%)
  - $C_2H_2F_4$ and SF_6 are fluorinated greenhouse gases (F-gases) with a high GWP and are being phased out by the EU
    → Need to find an alternative RPC gas mixture in view of the future (HL-LHC and possibly FCC)
    → Possible solution explored: replace $C_2H_2F_4$ with $C_3H_2F_4$ (HFO) + CO_2



GWP ($C_2H_2F_4$) ~ 1430 GWP (**HFO**-1234ze) ~ 6 GWP (CO_2) = 1

The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

  → It includes **CMS, <u>ALICE</u>, ATLAS, ShiP/LHCb** and the **EP-DT** group of CERN

- Focus the effort for eco-friendly gas mixture studies

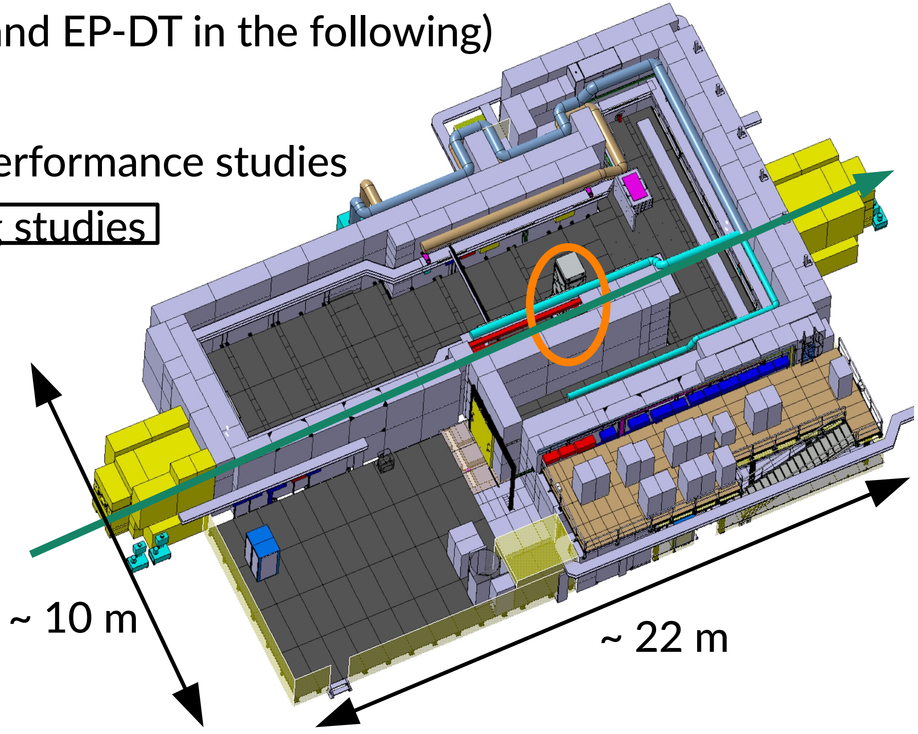
  → One RPC prototype per group (only results from ALICE and EP-DT in the following)

  → Experimental setup loacted @ GIF++ (CERN):

  1) High activitiy ^{137}Cs source for aging tests + μ beam for performance studies

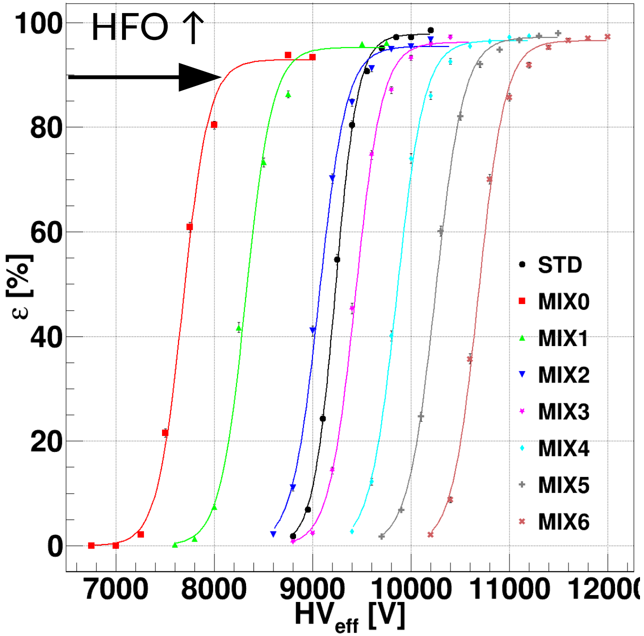
  2) Several mixtures beam-tested and one selected for aging studies

Mixture	$C_2H_2F_4$ %	HFO %	CO_2 %	i-C_4H_{10} %	SF_6 %	GWP
STD	95.2	0	0	4.5	0.3	1488
MIX0	0	0	95	4	1	730
MIX1	0	10	85	4	1	640
MIX2	0	20	75	4	1	560
MIX3	0	25	69	5	1	529
MIX4	0	30	65	4	1	503
MIX5	0	35	60	4	1	482
MIX6	0	40	55	4	1	457



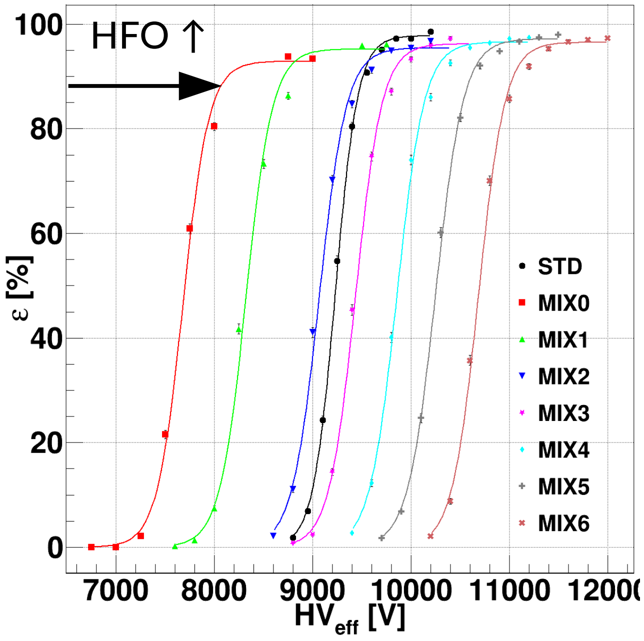
GIF++ facility layout

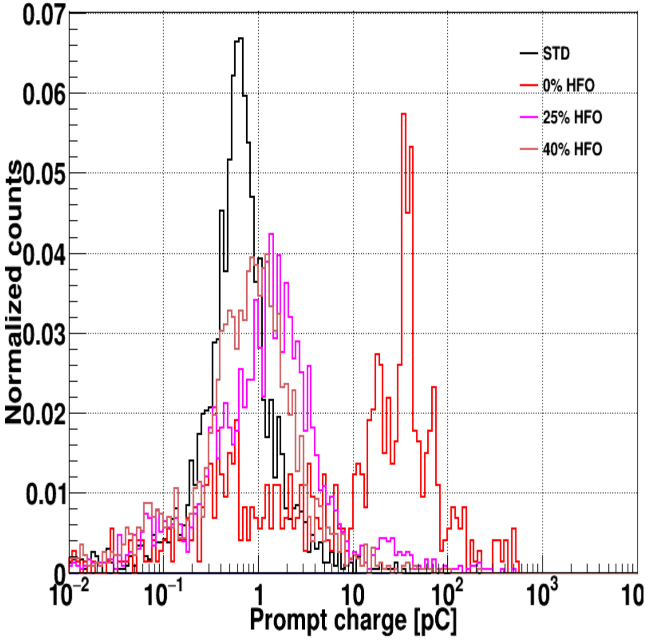
Baseline performance



- Efficiency curves fitted with logistic function to extract
  Working Point (WP) = knee (voltage where efficiency is 95% of its maximum) + 150 V
- Increasing value of **maximum efficiency as the HFO concentration increases** (denser mixture)
- Increase of **WP by ~1 kV for every 10% HFO added to the mixture**

Baseline performance

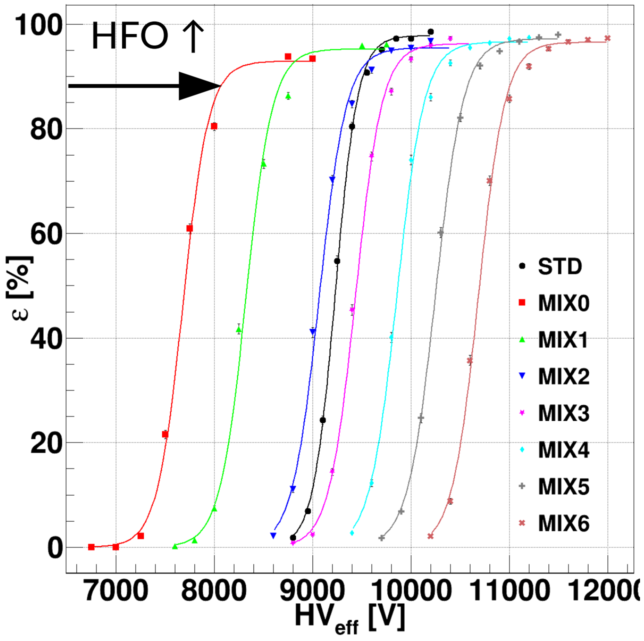


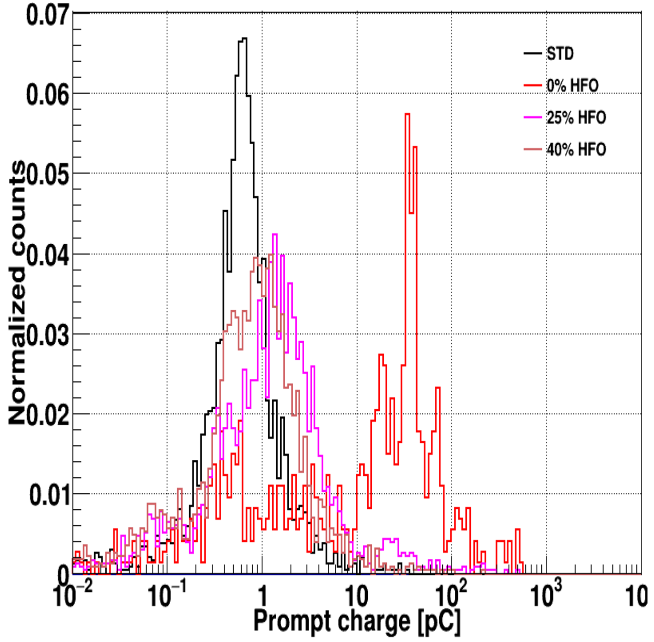


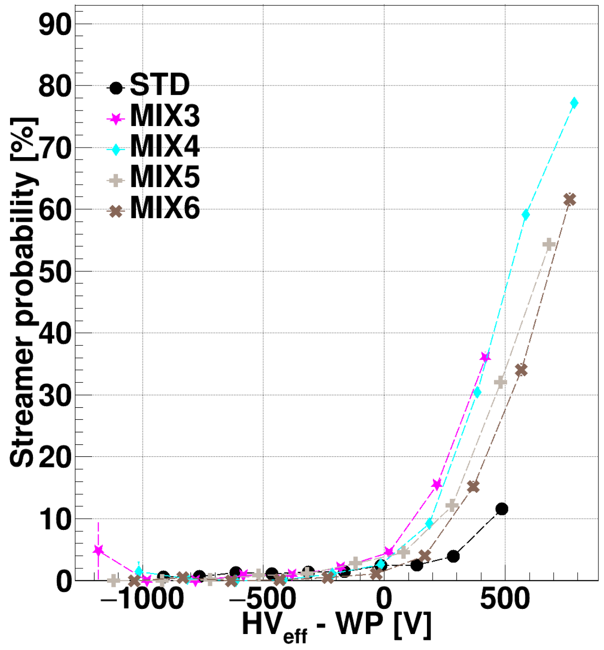
- For HFO-based mixtures, **small signal (avalanche) peak shifted towards higher values** wrt STD
  → Higher absorbed current

- **Large-signals peak generally more populated** than with STD
  → # of streamers decreases as CO_2 concentration decreases (**quenching** effect of more HFO)

Baseline performance







- Large-signal contamination at WP **improves with increasing HFO content**
- At **WP values are similar** to STD
- **Steeper rise** of the curve for voltages above the WP wrt STD

Performance evolution during aging

- **Aging test** ongoing since July 2022 (RPCs powered ON and exposed to ɣ's from the ^{137}Cs source)

- Periodic beam-test campaigns to monitor performance evolution. Example from a 2 mm single gap RPC after integrating ~115 mC/cm^2

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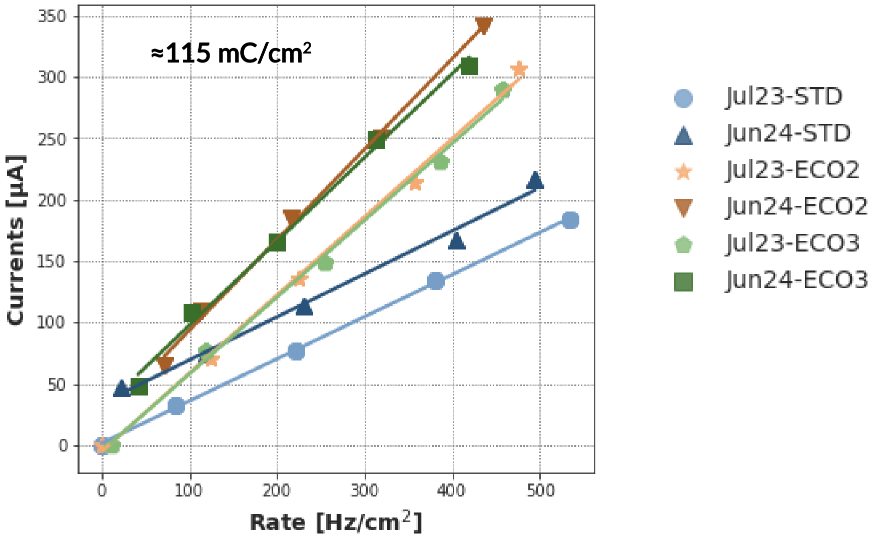
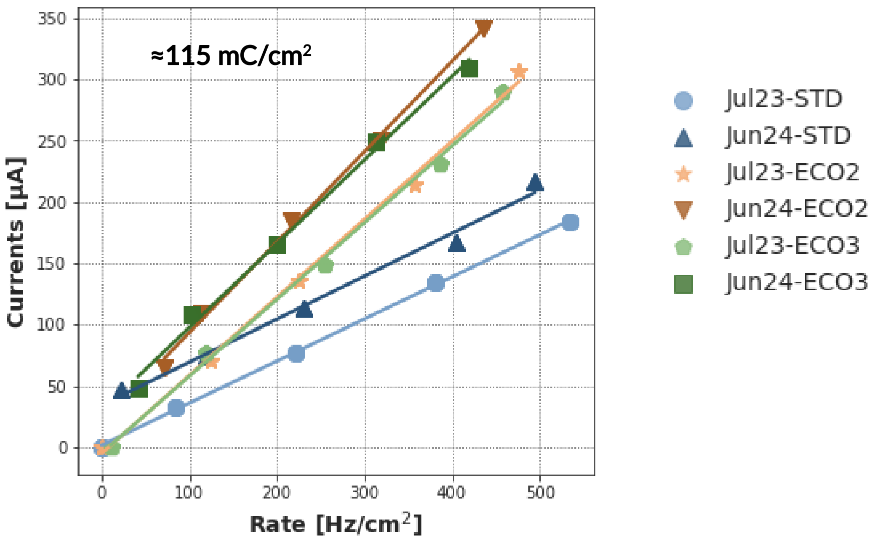
- **Currents under irradiation** slightly higher in 2024 wrt 2023
  → Visible for all mixtures
  → Ohmic current increase potentially related to electrode degradation



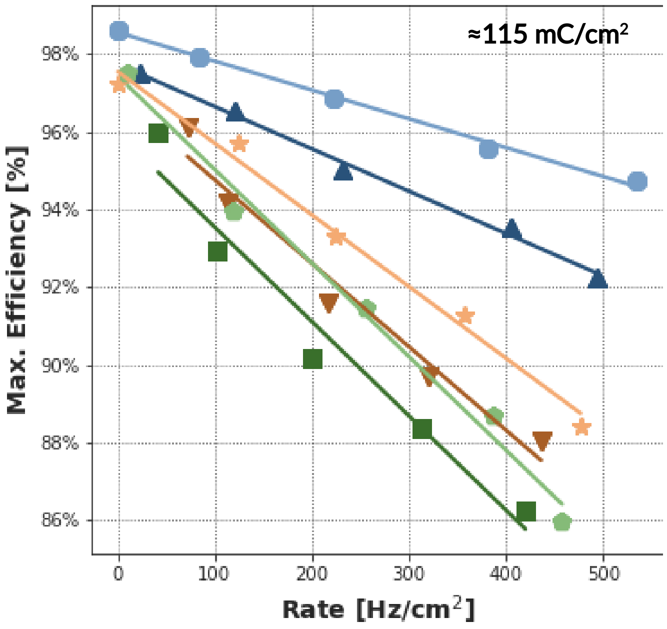
EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB

Performance evolution during aging

- **Aging test** ongoing since July 2022 (RPCs powered ON and exposed to ɣ's from the ^{137}Cs source)
- Periodic beam-test campaigns to monitor performance evolution. Example from a 2 mm single gap RPC after integrating ~115 mC/cm²
- **Maximum efficiency under irradiation** for same background reduced in 2024 vs 2023 for all mixtures
  - ~2% for all mixtures



EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB



EP-DT RPC maximum efficiency vs background rate.
Comparison between 2023 and 2024

Performance evolution during aging

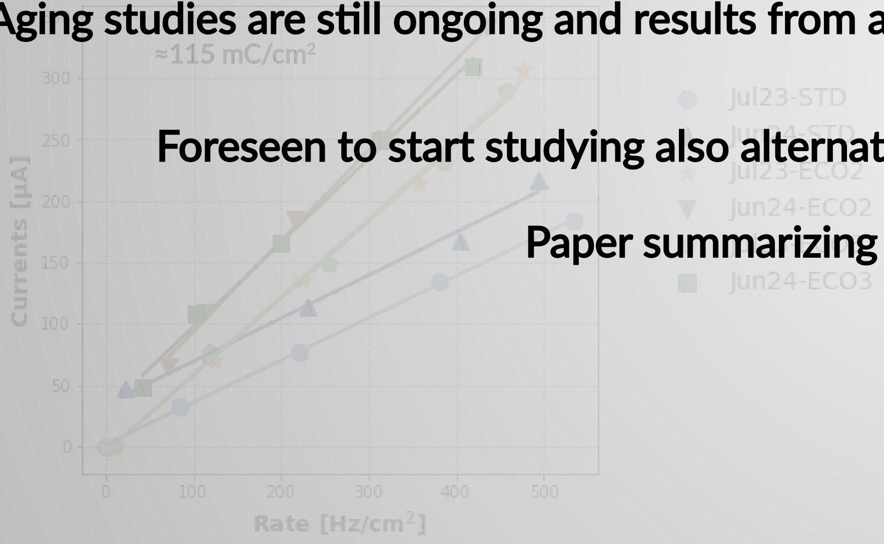
- **Aging test** ongoing since July 2022 (RPCs powered ON and exposed to ɣ's from the ^{137}Cs source)
- Periodic beam-test campaigns to monitor performance evolution. Example from EP-DT after ~115 mC/cm^2
- **Maximum efficiency under irradiation** for same background reduced in 2024 vs 2023 for all mixtures
  - ~2% for all mixtures

No significant performance degradation observed so far

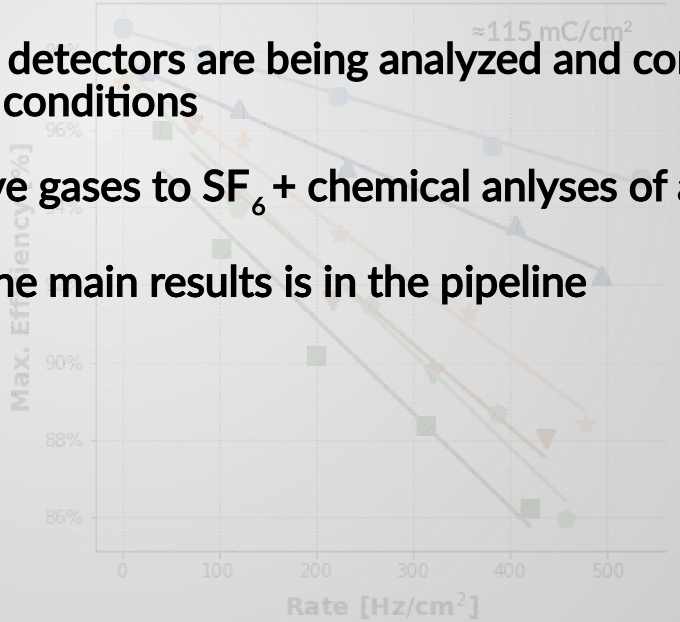
Aging studies are still ongoing and results from all detectors are being analyzed and compared for similar aging conditions

Foreseen to start studying also alternative gases to SF_6 + chemical anlyses of aged detectors

Paper summarizing the main results is in the pipeline



EP-DT RPC source on current vs rate at WP. Comparison between 2023 and 2024 TB

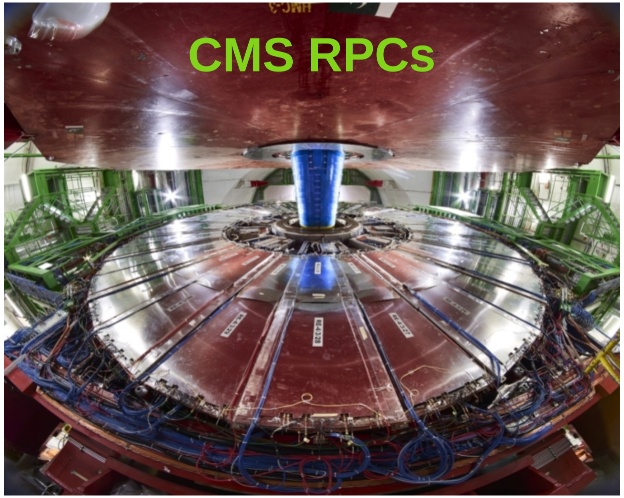


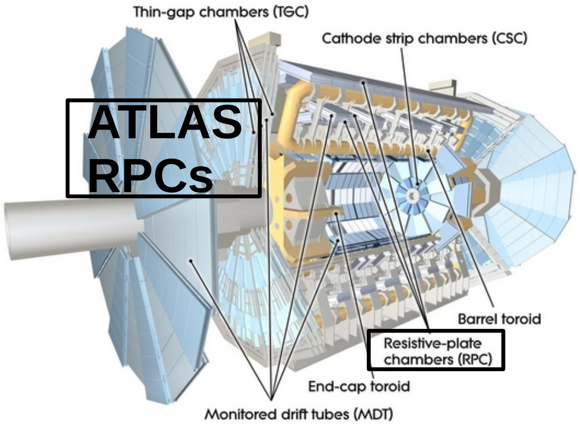
EP-DT RPC maximum efficiency vs background rate. Comparison between 2023 and 2024

Thanks for your attention!!!

Backup

RPCs in High Energy Physics





- **Resistive Plate Chambers** (RPCs)
  → Widely employed in HEP
- For **muon detection**
- Relatively cheap
  → **Large area coverage**
- Fast response
  → Used for **muon triggering** and **identification**

Issues with current gas mixture

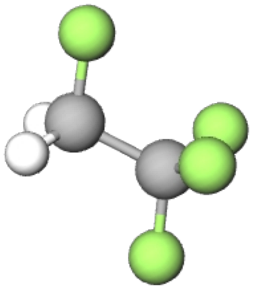
- Currently employed gas mixture in HEP (standard gas mixture/**STD** in the following)

  → Combination of **$C_2H_2F_4$, i-C_4H_{10} and SF_6** in different concentrations with ~ **90% $C_2H_2F_4$**

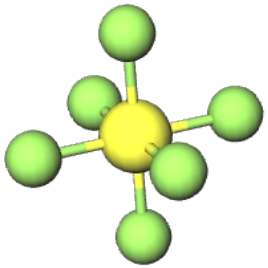
- Operated in avalanche mode

  → Time resolution **~ 1 ns** and space resolution **~ mm** ✓

  → $C_2H_2F_4$ and SF_6 are **fluorintated greenhouse gases** (F-gases) with a high GWP[1] X



GWP ($C_2H_2F_4$) ~ 1430



GWP (SF_6) ~ 22800

GWP of the standard gas mixture: 1350 ÷ 1430

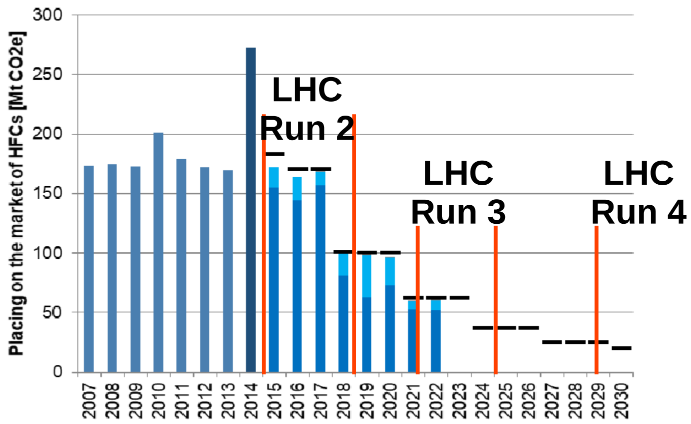
→ Is this a problem? Yes!

[1]GWP = global warming potential = measure of the heat trapped in the atmosphere by a ton of a given gas, if compared to a ton of CO_2 (GWP(CO_2) = 1)

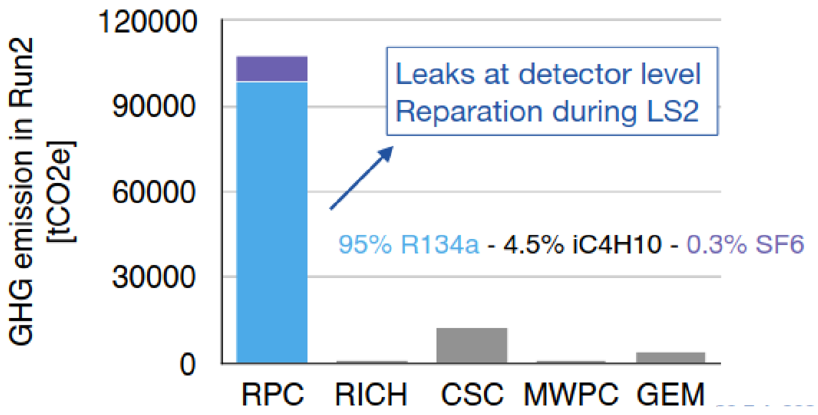
The need for an eco-friendly gas mixture

- EU regulations imposed a progressive phase down in the production and use of F-gases
  → Phase down of the production and consumption of such gases
  → Ban of the gases if a more eco-friendly alternative is available
  → Reduction of emissions from existing equipment

  Increase in cost and reduction in availability



F-gases placing on the market (POM) plan, from ETC CM Report 2023/04



B. Mandelli VCI 2022

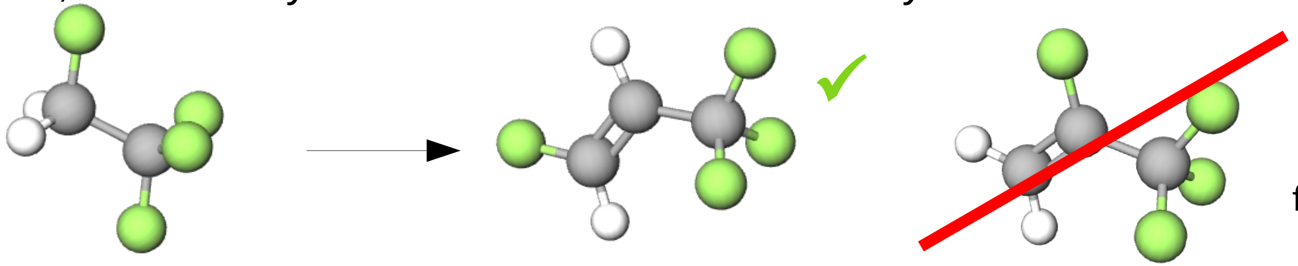
- RPCs are the main source of F-gases emissions at CERN (mainly due to gas leaks)
  → Need to find a more eco-friendly gas mixture

- Many laboratory studies using new gases have been carried out with cosmics
  → Now: **beam test** studies and **long-term performance evolution** under irradiation(aging tests)

Experimental approach

- First efforts of LHC RPC groups focused on R134a replacement

- **Industrial use:** from **R134a** to **hydro-fluoro-olefine** (HFO) family of gases
  → Similar chemical structure as R134a but lower Global Warming Potential
  → Among all HFOs, HFO-1234yf and HFO-1234ze are currently used



Not usable at LHC because of flammability-related safety concerns

GWP ($C_2H_2F_4$) ~ 1430 GWP (HFO-1234ze) ~ 6 GWP (HFO-1234yf) ~ 4

- 1:1 replacement of R134a with HFO not possible
  → Lower effective first Townsend coefficient
  → Working voltage of the detectors moves to over 15 kV

- HFO has to be diluted with other gases
  → Studies with cosmic muons by different LHC RPC groups [1-4]
  → CO_2 found to be the most promising candidate for dilution
  → **In-depth studies on RPCs long-term behavior with eco-friendly alternatives needed**

The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

  → It includes **CMS, <u>ALICE</u>, ATLAS, ShiP/LHCb** and the **EP-DT** group of CERN

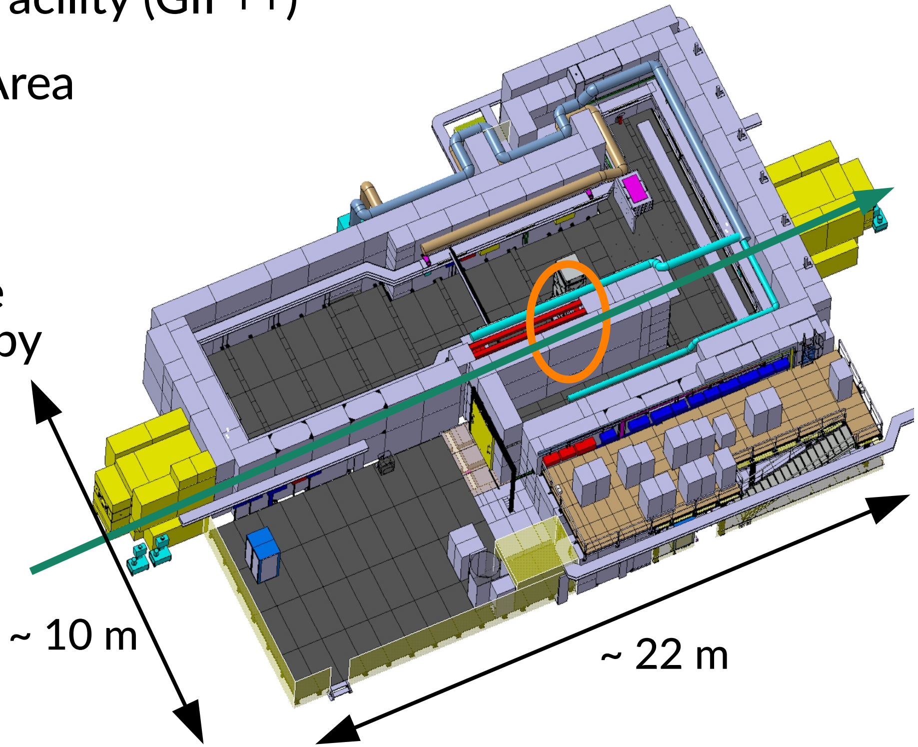
- Studies carried out at the CERN Gamma Irradiation Facility (GIF++)

  → Experimental facility located at the CERN North Area

- 12.5 TBq ^{137}Cs source, high activity allows one to simulate long operating periods in much shorter time spans (aging studies) – irradiation can be modulated by means of attenuation filters

- High energy (100 GeV/c) **muon beam** in dedicated beam time periods

→ Combination of muon beam with source: rate capability studies



GIF++ facility layout

Experimental setup - 1

- Each group provided an RPC prototype to be tested with eco-friendly gas mixtures
  → Installed on two setups, one at 3 m from the source and one at 6 m

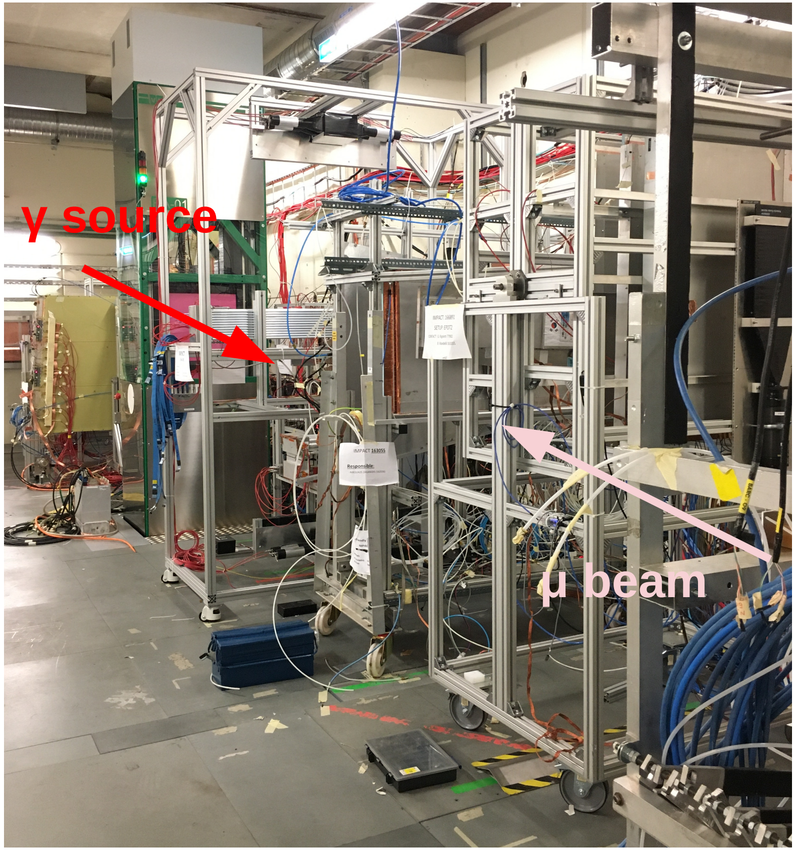
Group	Dimension (cm^2)	# of gaps	Gap/electrodes Thickness (mm)	Readout	# of strips
ATLAS	500	1	2 / 1.8	Digitizer	1
CMS	4350	2	2 / 2	TDC	128
CMS Upgrade	7000	2	1.4/1.4	TDC	32
EP-DT	7000	1	2 / 2	Digitizer[1]	7
ALICE	2500	1	2 / 2	Digitizer[2]	7
ShiP/LHCb	7000	1	1.6 / 1.6	TDC	64

Summary table of all the RPCs of the collaboration

- Two different readout methods for the different RPCs
  1) Front-end electronics + TDCs
  2) Digitizer

Subject of this presentation*

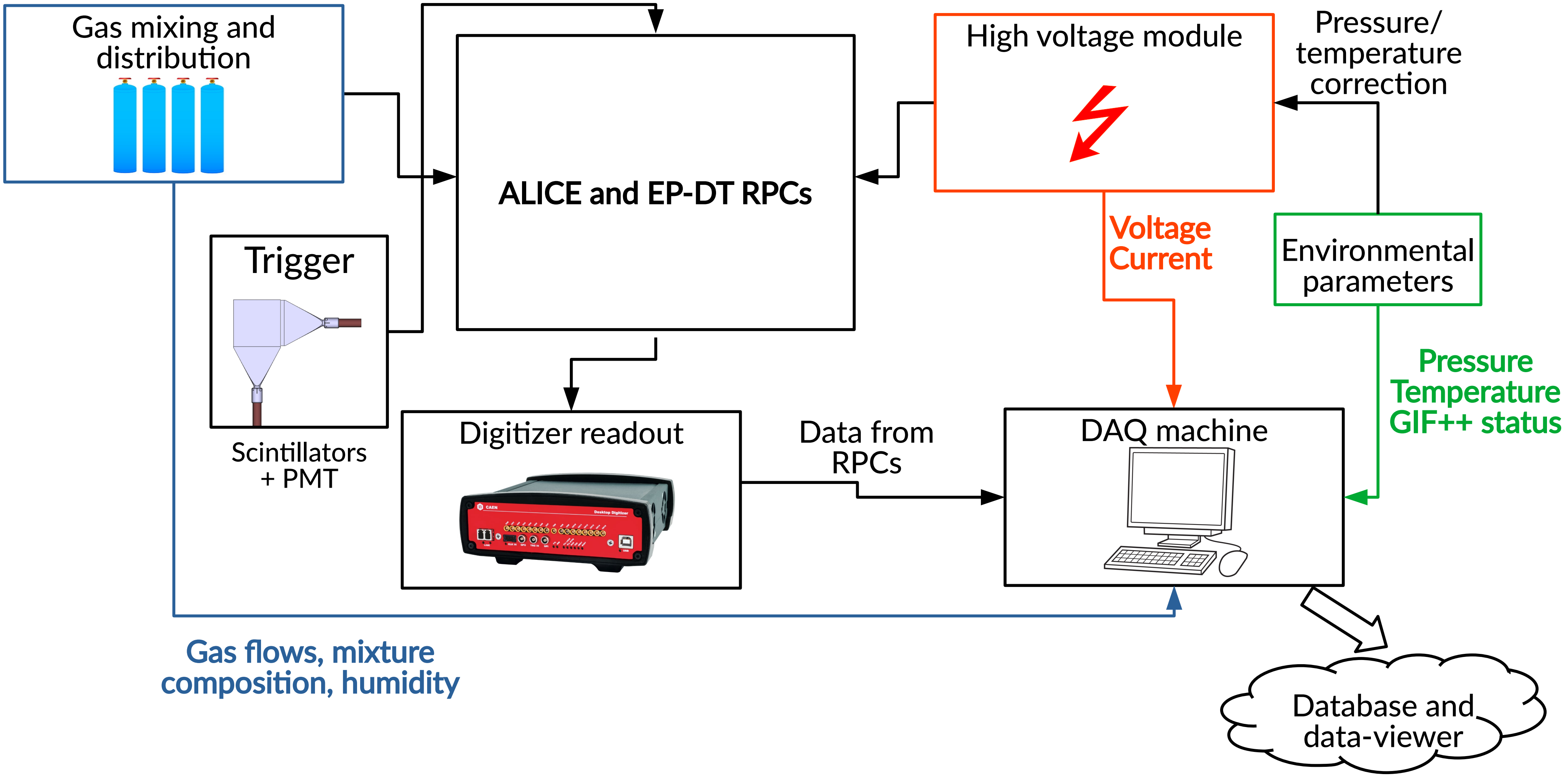
*Results from other detectors in M. Abbrescia's talk today @ 11:50 am



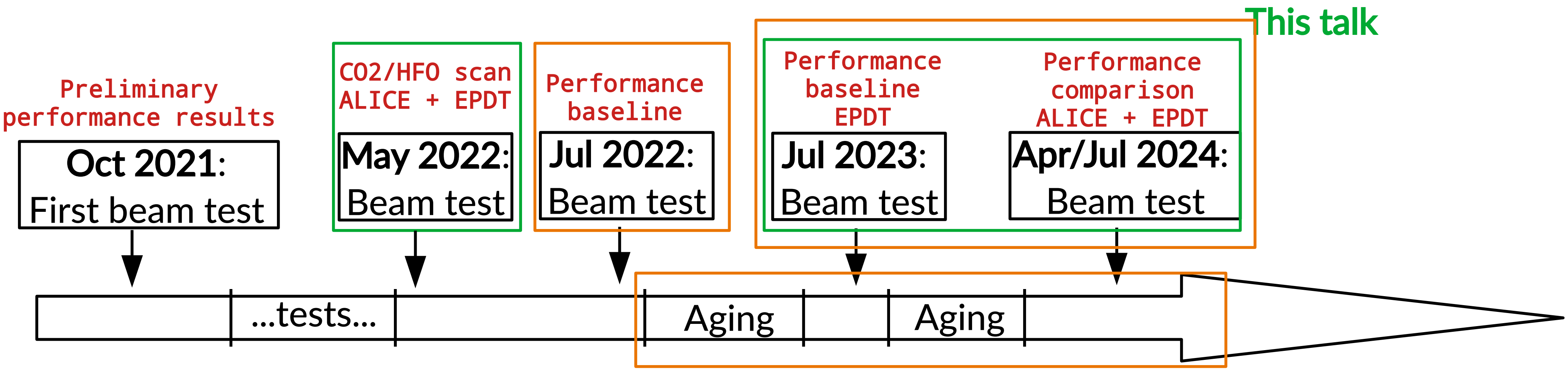
View of the setups inside the GIF++ bunker

[1]CAEN model V1730, 14-bit at 500 Ms/s, V_{pp} = 1 V
[2]CAEN model DT5742, 12-bit at 1-5 Gs/s, V_{pp} = 1 V

Experimental setup - 2



Timeline of collaboration activites



Marcello Abbrescia's talk today @ 11:50 am

Beam test measurements

- Mixtures with different ratios of HFO/CO_2 have been tested (from 0 up to 40% HFO)
- Study the interplay between these two gases and comparison to current gas mixture

	Mixture	$C_2H_2F_4$ %	HFO %	CO_2 %	i-C_4H_{10} %	SF_6 %	GWP
	STD	95.2	0	0	4.5	0.3	1488
	MIX0	0	0	95	4	1	730
	MIX1	0	10	85	4	1	640
	MIX2	0	20	75	4	1	560
(ECO3)	MIX3	0	25	69	5	1	529
	MIX4	0	30	65	4	1	503
(ECO2)	MIX5	0	35	60	4	1	482
	MIX6	0	40	55	4	1	457

CO_2 concentration decreases

HFO concentration increases

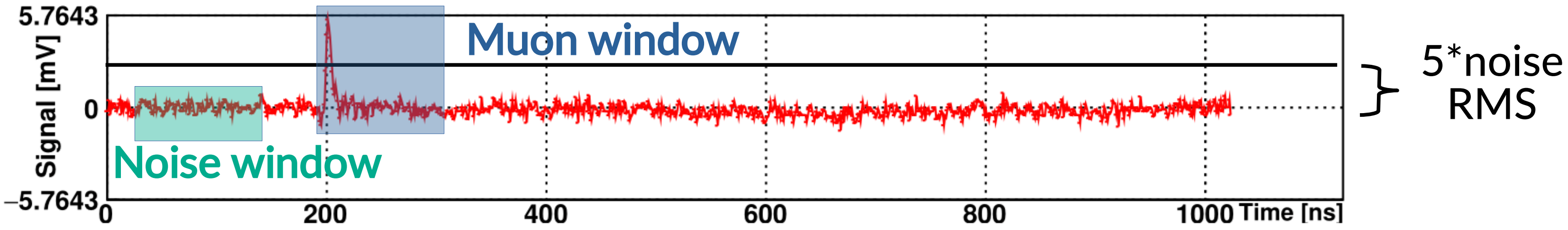
- Two readout methods employed:
  1) Detectors front-end electronics + TDCs
  → Realistic measurements of efficiency and cluster size

  2) Digitizer
  → Waveform/charge studies

- Goal of beam tests: measure RPC performance (using a muon beam) in terms of efficiency, cluster size, prompt charge, large-signal contamination and rate capability

Digitizer data analysis - 1

- Access to the waveform of each signal enables in depth characterization of RPC response



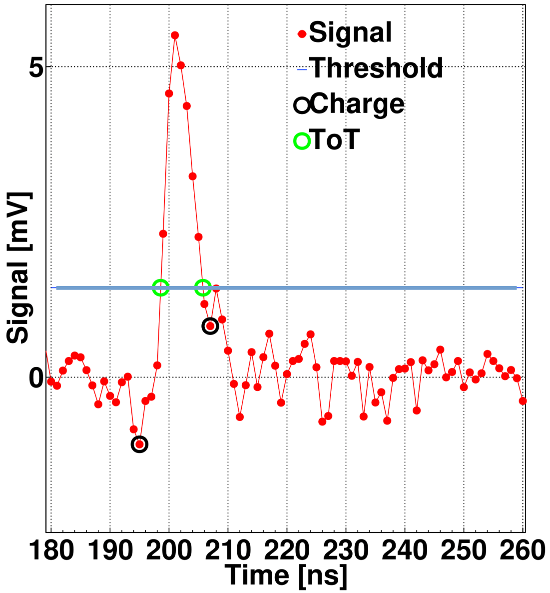
Example of RPC response when readout with digitizer – ALICE RPC

- **Analysis procedure** developed to

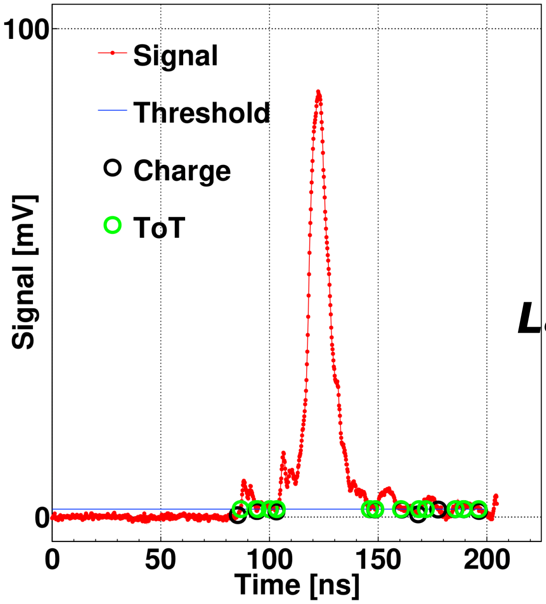
  1) Identify "efficient" strips for further processing
  ALICE: threshold = 5*RMS of the noise window. **EP-DT**: threshold = 2 mV
  → Reflection signals are identified and discarded (see backup)
  2) Find integration interval for prompt-charge calculation
  3) Compute large-signal probability
  4) Compute time-over-threshold
  5) Analyze run globally (efficiency, streamer probability… vs high voltage)

* Time window where NO muon signal is expected
** Time window where muon signal is expected

Digitizer data analysis - 2



Single-peak signal typical of STD – ALICE RPC

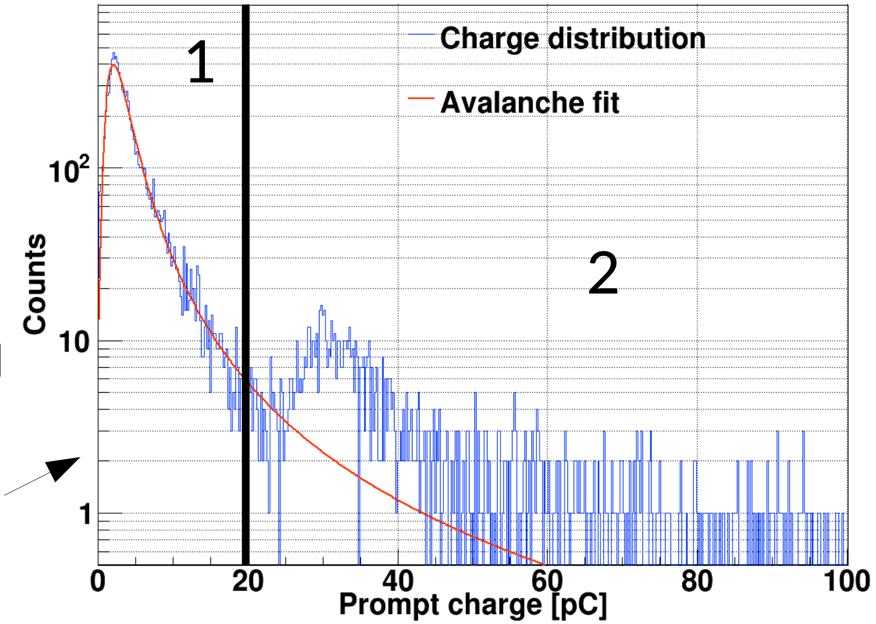


Multi-peak signal in HFO-based mixtures
ALICE RPC

- Two populations in the prompt charge distribution: 1) **avalanches** and 2) **large-signals**
- Two regions are separated at ~ 20 pC
→ Events with prompt charge > 20 pC tagged as "large-signals"

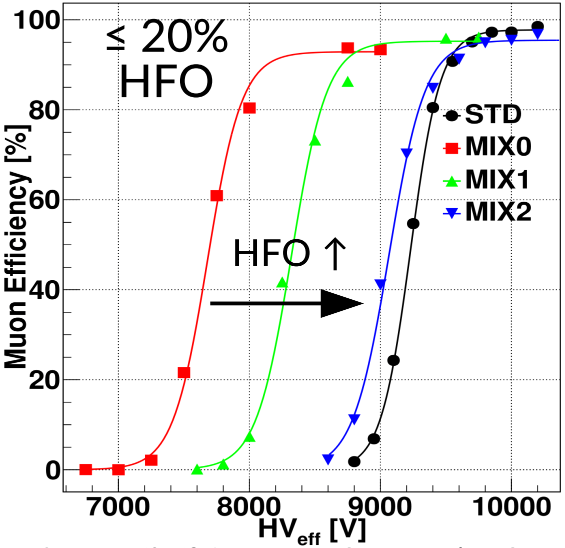
$$\boldsymbol{Large-signal\ probability = \frac{charge \geq 20\,pC}{tot_{events}}}$$

- Examples of **signal integration and time over threshold** calculation intervals
- For a fixed high voltage value, prompt charge distribution example

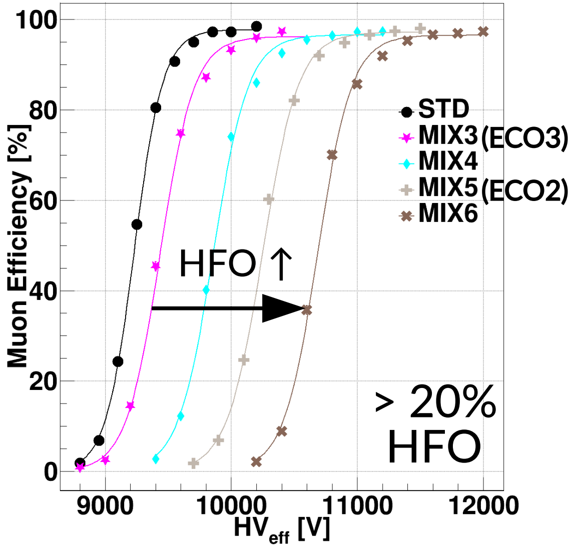


Prompt charge distribution at max efficiency - STD – ALICE RPC

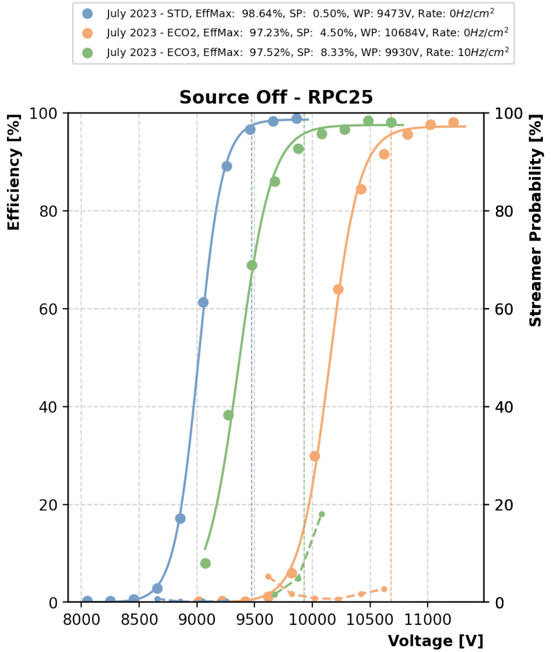
Efficiency vs HV at source off



Source off efficiency – ALICE unaged RPC



Source off efficiency – ALICE unaged RPC

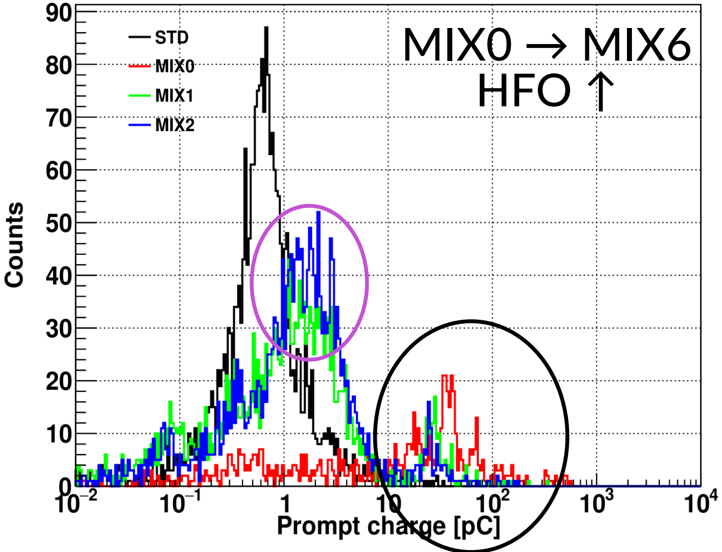


Source off efficiency – EPDT unaged RPC

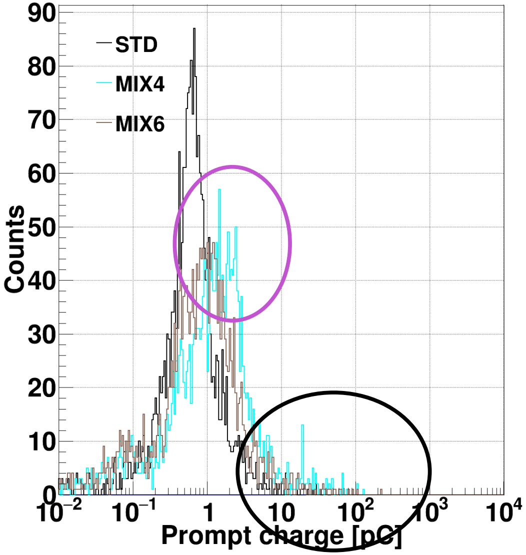
- **Trigger** provided by coincidence of 4 scintillators coupled with PMTs
- Efficiency curves fitted with logistic function to extract
  Working Point (WP) = knee (voltage where efficiency is 95% of its maximum) + 150 V
- Increasing value of maximum efficiency as the HFO concentration increases (denser mixture)
- Increase of WP by ~1 kV for every 10% HFO added to the mixture is observed in both detectors
- Differences between ALICE and EP-DT can be explained by the different threshold

Source-off prompt charge distribution

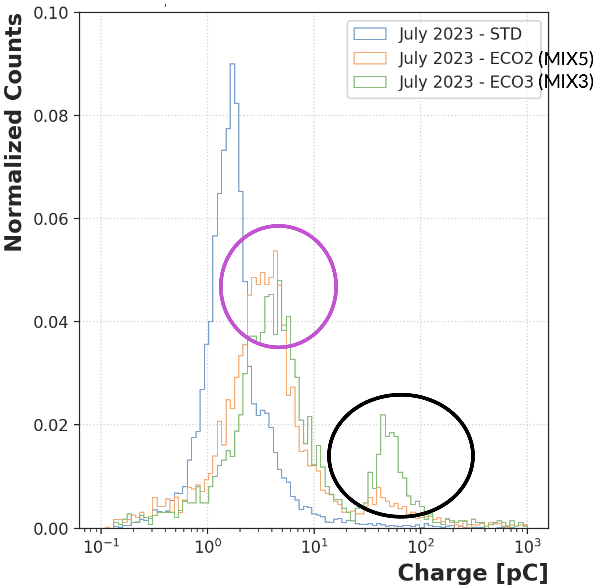
- Spectra shown correspond to the HV closest to the estimated WP



Source off prompt charge spectrum for MIX0 – MIX2
ALICE RPC



Source off prompt charge spectrum for
MIX4 and 6 - ALICE



Source off prompt charge spectrum for
ECO2 and ECO3 - EPDT

- For all HFO-based mixtures, avalanche peak shifted towards higher values wrt STD
  → Higher absorbed current

- Large-signals peak generally more populated than with STD
  → # of streamers decreases as CO_2 concentration decreases (quenching effect of more HFO)
  → Same observations for ALICE and EP-DT RPCs

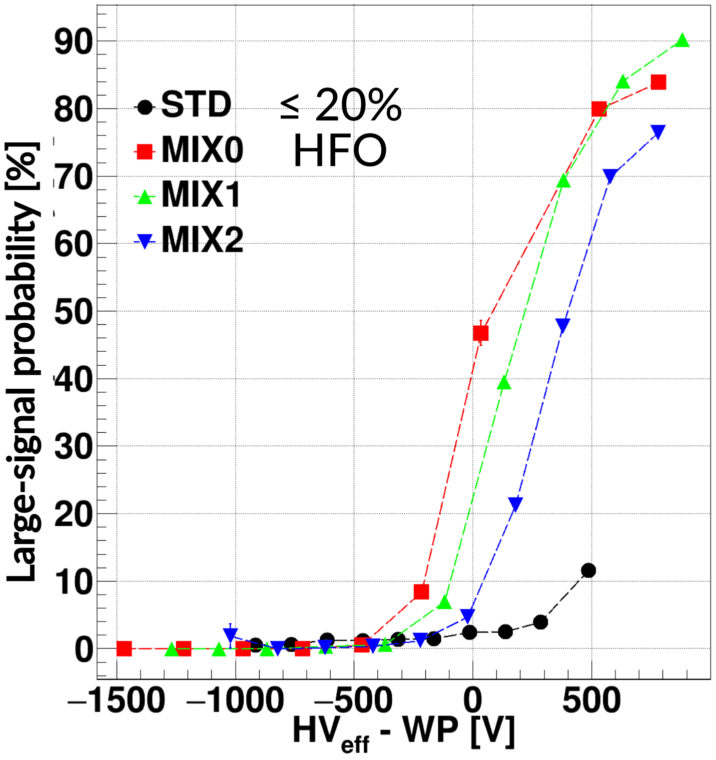
- Small differences between ALICE and EPDT can be explained by the different threshold

ALICE

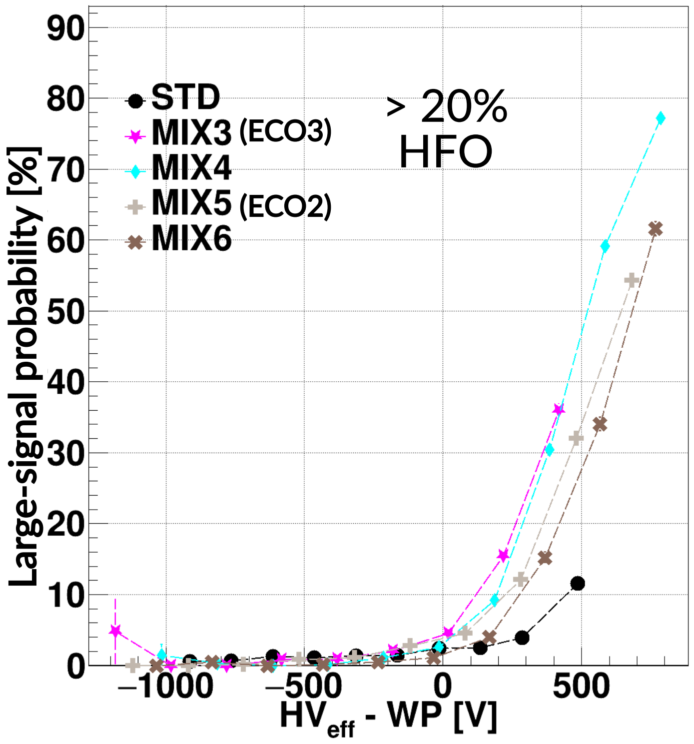
Source-off large-signals contamination

- Streamer contamination at source off, as a function of (HV - WP) for each mixture

- **STD** gas mixture:
  1) Streamer probability < 5% at WP
  2) Still < 10% 500 V above WP



Source off large-signal probability vs HV, MIX 0-2, ALICE



Source off large-signal fraction vs HV, MIX 3-6, ALICE

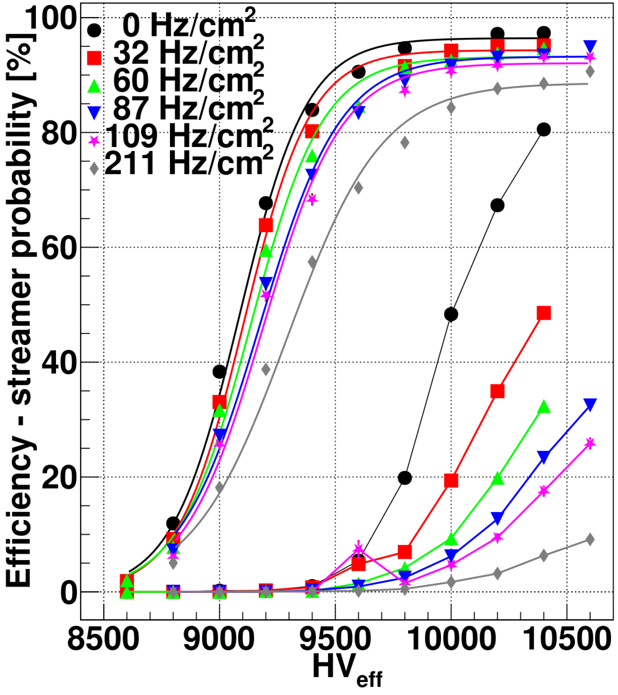
- Large-signal contamination at WP improves with increasing HFO content

- MIX5 (35% HFO) has similar contamination as STD at WP

- Steep rise of the curve for voltages above the WP (35% contamination 500 V above WP for MIX5)

Efficiency under irradiation

- RPC response to the muon beam was studied in combination with the ^{137}Cs source (source on) to study the rate capability
  → Results shown in terms of gamma cluster rate measured using a random trigger to periodically sample the RPC response



Unaged ALICE RPC response with source on and MIX2 (HFO/CO_2 20/75)

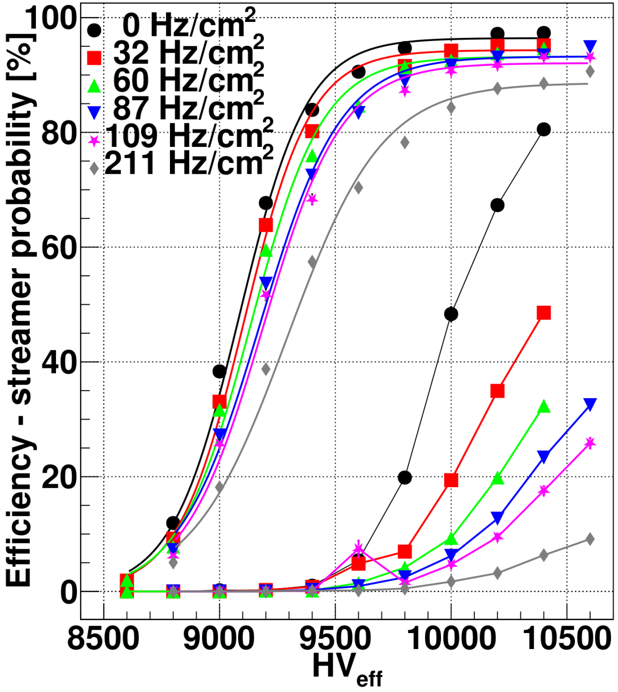
- MIX2 (HFO/CO_2 20/75) shown as an example but similar results with all mixtures

- Three effects under irradiation:
  1) Efficiency curves shift to higher voltages
  2) Maximum value of efficiency reaches lower values
  3) Reduction of large signal contamination

- They can be explained with a model considering voltage drop across resistive electrodes (more details in backup)

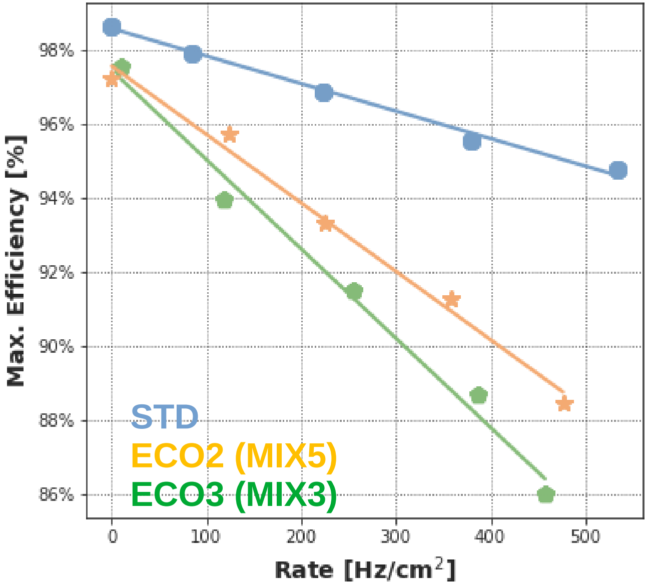
Efficiency under irradiation

- RPC response to the muon beam was studied in combination with the ^{137}Cs source (source on) to study the rate capability
  → Results shown in terms of gamma cluster rate measured using a random trigger to periodically sample the RPC response



Unaged ALICE RPC response with source on and MIX2 (HFO/CO_2 20/75)

- MIX2 (HFO/CO_2 20/75) shown as an example but similar results with all mixtures
- Three effects under irradiation:
  1) Efficiency curves shift to higher voltages
  2) Maximum value of efficiency reaches lower values
  3) Reduction of large signal contamination
- They can be explained with a model considering voltage drop across resistive electrodes (more details in backup)



Maximum efficiency vs gamma rate for unaged EP-DT RPC

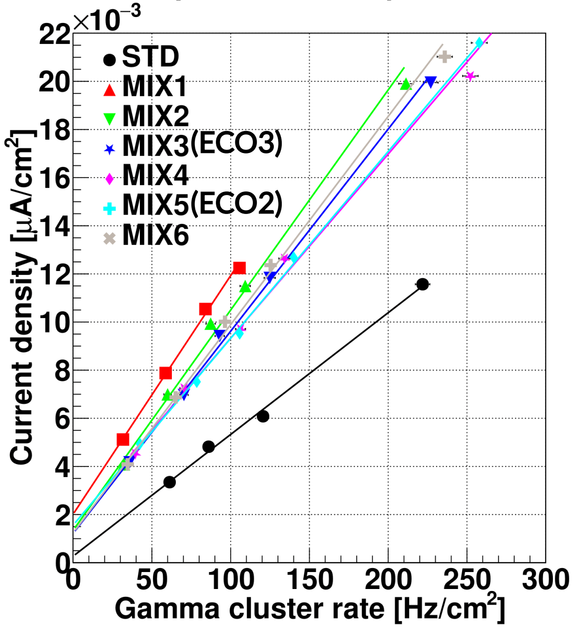
Larger efficiency drop for HFO-based mixtures, more HFO = less efficiency drop for the same background

Average charge per gamma cluster

ALICE

- Total charge per hit = total charge released by ionizing particle in the gas

- If RPC exposed to photon flux
  → Absorbed current (minus its dark component) is proportional to the rate of detected photons
  → Proportionality factor is the average charge per hit



Current density vs gamma cluster rate - ALICE

Current density

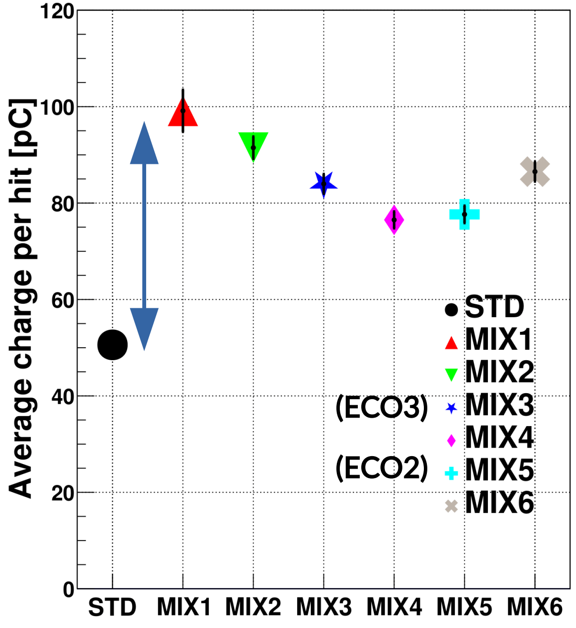
Gamma cluster rate

$$\frac{I}{A} = \langle Q \rangle \cdot \frac{N_{\gamma-detected}}{A\,\Delta t} + DCD$$

Average charge per hit

Dark current density

Linear fit



Average charge per gamma cluster - ALICE

- Current at given rate is 1.6/1.7 times higher for all the eco-friendly alternatives wrt STD gas mixture

- Same result obtained for the average charge per hit

RPC response evolution during aging

ALICE

- **Aging test with ECO2 (35/60 HFO/CO2)** gas mixture ongoing since 2022[1]
- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge

[1]See Marcello Abbrescia's talk today @ 11:50 am and Dayron Ramos' talk today @ 9:50 am

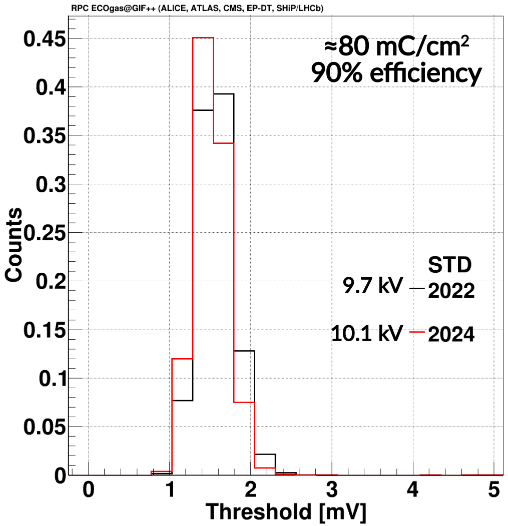
RPC response evolution during aging

ALICE

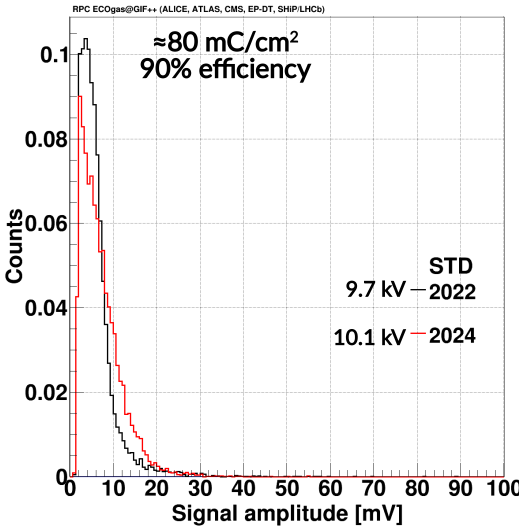
- **Aging test with ECO2 (35/60 HFO/CO_2)** gas mixture ongoing since 2022

Example for STD gas mixture (ECO2 under investigation)

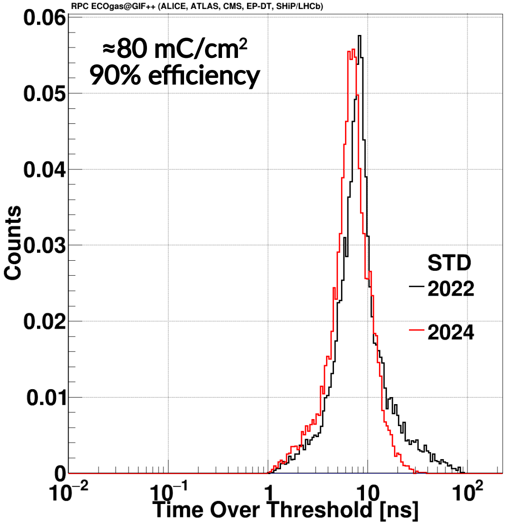
- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge



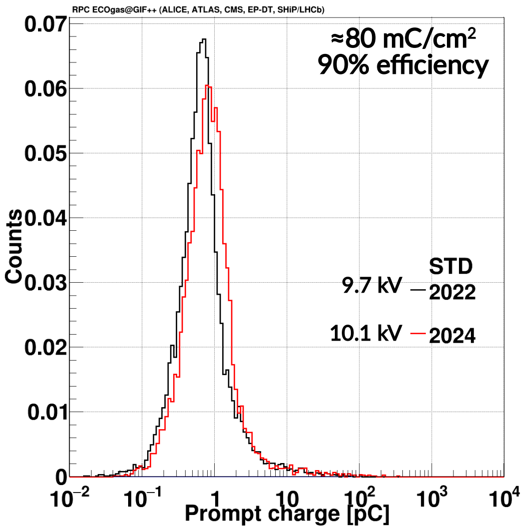
ALICE RPC threshold distribution at 90% efficiency - STD



ALICE RPC signal amplitude at 90% efficiency - STD



ALICE RPC time over threshold distribution at 90% efficiency - STD



ALICE RPC prompt charge distribution at 90% efficiency - STD

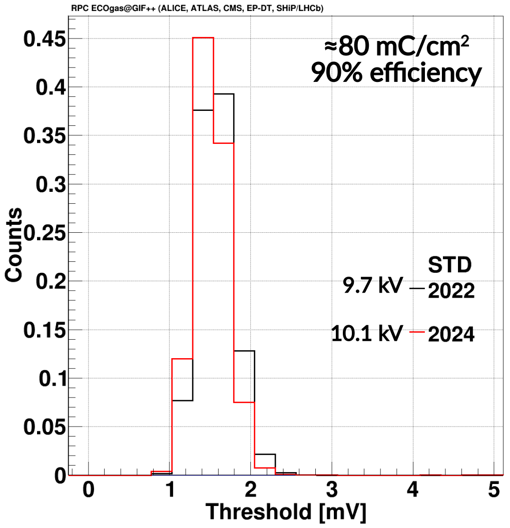
RPC response evolution during aging

ALICE

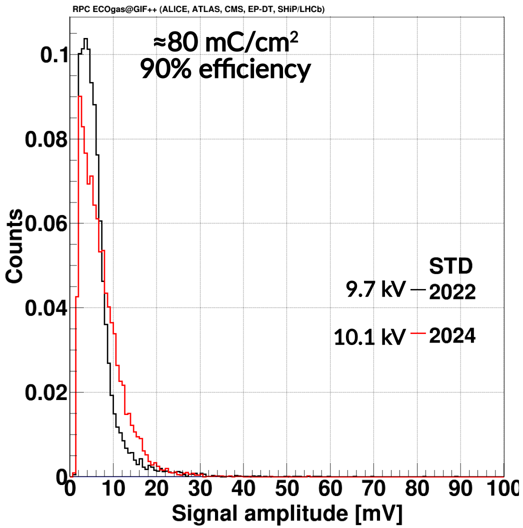
- **Aging test with ECO2 (35/60 HFO/CO2)** gas mixture ongoing since 2022

Example for STD gas mixture
(ECO2 under investigation)

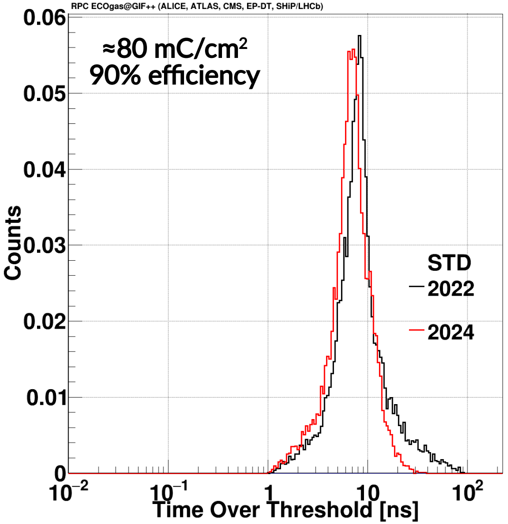
- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge



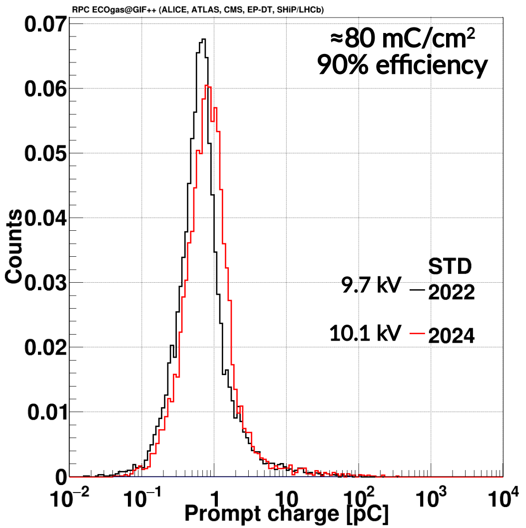
ALICE RPC threshold distribution at 90% efficiency - STD



ALICE RPC signal amplitude at 90% efficiency - STD



ALICE RPC time over threshold distribution at 90% efficiency - STD



ALICE RPC prompt charge distribution at 90% efficiency - STD

- **Threshold** is comparable between 2022 and 2024
- **Slightly larger prompt charge in 2024**
  → Similar large-signal fraction
- Can be explained by **larger average signal amplitude**
- **Slightly lower** average **time over threshold**

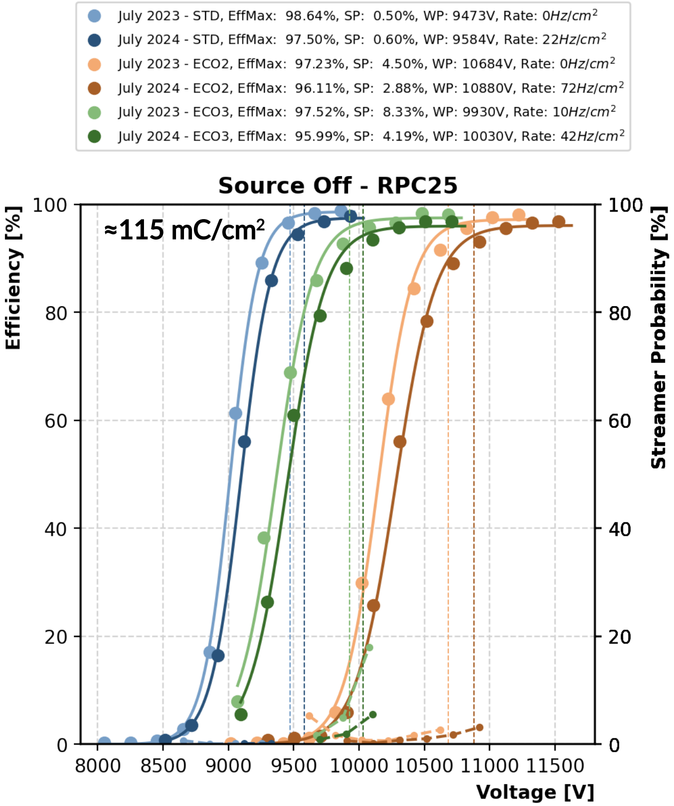
- Large current drift observed only in ALICE, shift of WP

→ Effects can partly be explained by **pre-existing issues with the ALICE RPC (under investigation)**

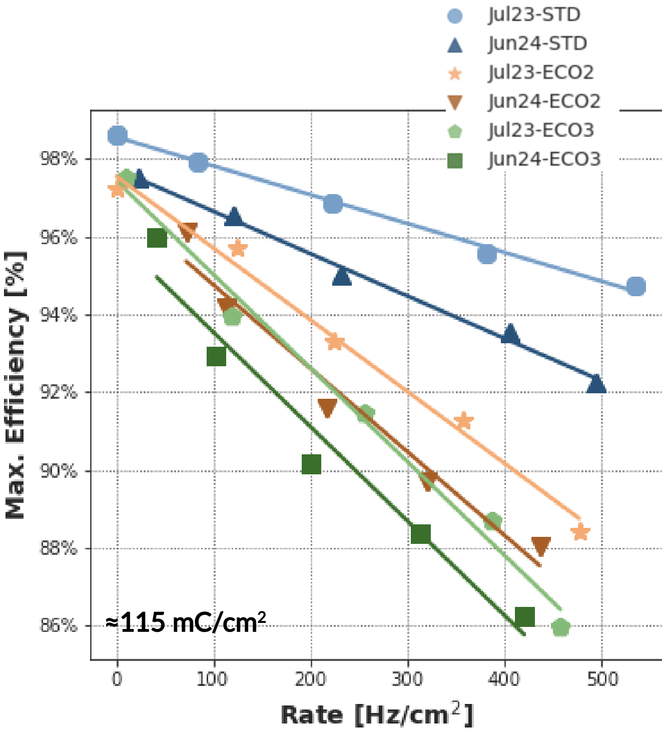
RPC response evolution during aging

EP-DT

- Comparison of performance for EPDT RPC before and after the aging studies with ECO2



EP-DT RPC source off efficiency vs HV curves. Comparison between 2023 and 2024



EP-DT RPC maximum efficiency vs background rate. Comparison between 2023 and 2024

- **Integrated charge** ~115 mC/cm²
- **WP increased** in 2024 wrt 2023, yet (~+100 V for STD, ~+200 V for ECO2 and ~+150 V for ECO3)
- Max **source off efficiency** decreases maximum by ~2% (could be due to alignment)
- Source off large-signal **probability reduced** for all the mixtures
- **Max efficiency under irradiation** for same background reduced in 2024 vs 2023 for all mixtures (~2% for all mixtures)

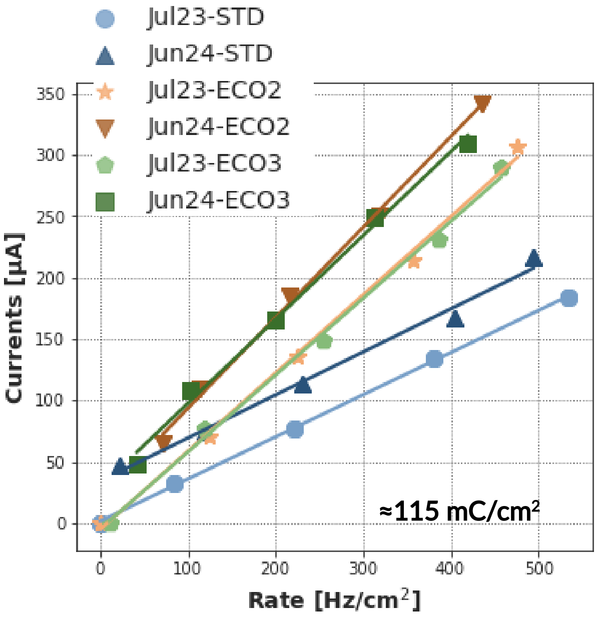
RPC response evolution during aging

EP-DT

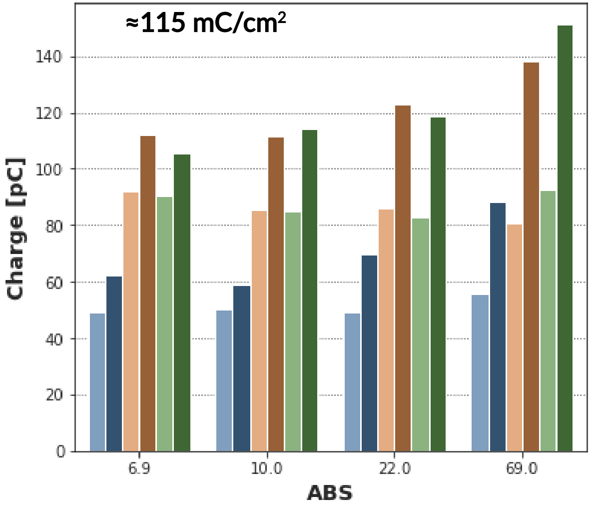
- **Currents under irradiation** slightly higher in 2024 wrt 2023
  → Visible for all mixtures

- Increase of dark current
  → Could be related to electrode degradation
  → Chemical analyses needed

- **Ratio between current and rate**
  → Estimation of total charge per gamma hit
  → Higher in 2024 wrt 2023
  → For all mixtures and for all ABS tested @ GIF++
  → Partly explained by higher dark current in this detector



EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB



EP-DT RPC average charge per gamma hit for different GIF++ ABS filter.
Comparison between 2023 and 2024 TB

Conclusions and outlook

- **RPC ECOgas@GIF++** collaboration is performing beam tests and aging studies on RPCs where the **R134a** is fully replaced using different concentrations of **HFO and CO_2**

- **RPC response** studied using a **digitizer** with ALICE and EPDT RPCs:
  - In general:
    → More HFO in the mixture, better performance (but higher WP)
  - **Average charge** per gamma cluster **increases** by 1.6/1.7 times wrt R134a-based mixtures

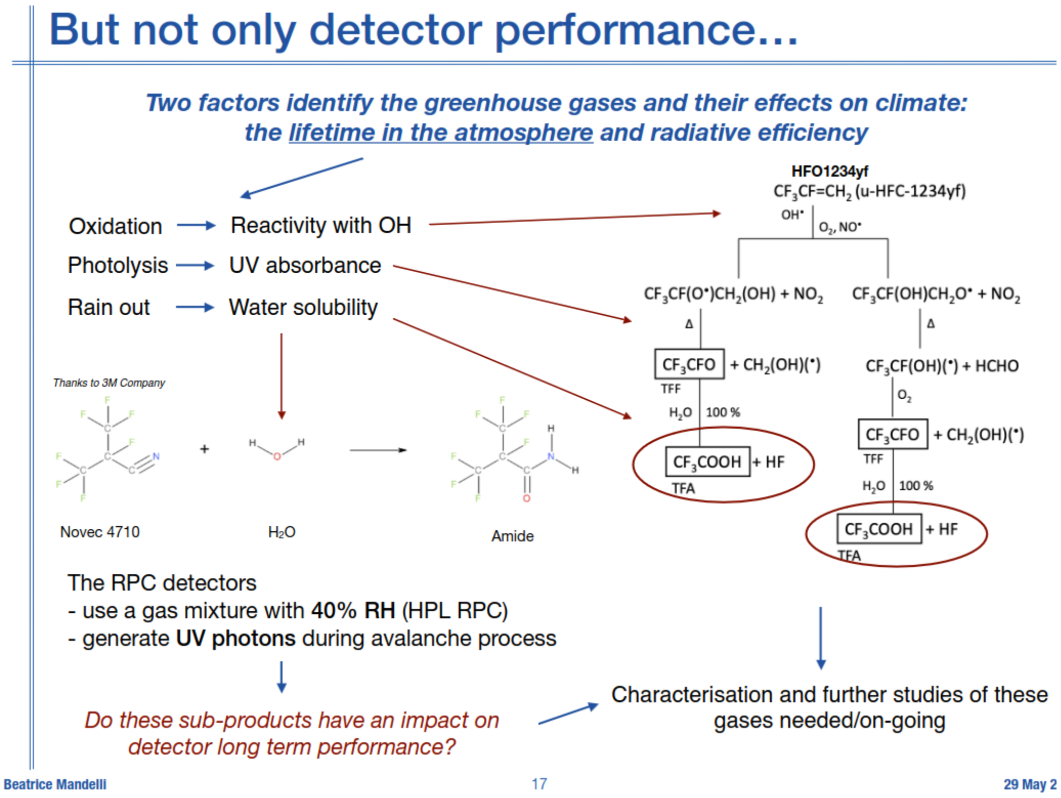
- Following the **aging** campaign:
  - **ALICE** RPC: integration of ~80 mC/cm^2
    → Increase in absorbed current, muon prompt charge, and signal amplitude

  - **EPDT** RPC: integration of ~ 115 mC/cm^2
    → Slight increase of WP and decrease of maximum effciency under irradiation
    → No significant performance degradation but higher current and charge per gamma hit to be monitored

- Aging campaign continuing for the **other detectors** of the collaboration. ALICE RPC removed from irradiation and dedicated studies ongoing to further investigate the observations

On the HFO ecology - 1

B. Mandelli
https://indico.cern.ch/event/1263322/



- HFO dissociation in atmosphere might leas to the creation of TFA (toxic chemical for humans)
- Deposition on land following rain fall and consequent exposure to humans
- Studies on the matter (such as those reported in [5-7]) are not yet conclusive
- Research work on this direction is ongoing and we are studying these gases since for now they are not deemed as pollutants

On the HFO ecology - 2

B. Mandelli
https://indico.cern.ch/event/1263322/

- PFAs: Per- and polyfluoroalkalyl substances:

  - Group of synthetic substances consisting of carbon chain + fluorine

  - Widely used in the industry and can leak into water/air/soil

  - Prolonged exposure harmful for humans

  - More than 15k PFAs identified

- Possible new regulations to ban PFAs

  - Not yet clear if HFO will be included + not clear if the ban will be immediate or if derogations are foreseen

A possible new regulation?

PFAS: Per- and polyfluoroalkyl substances

- PFAS are a large class of synthetic chemicals considered environmental pollutants with links to harmful health effects.
- They all contain carbon-fluorine bonds: they resist degradation when used and also in the environment.
- Concern is growing on their use as they pollute the environment: PFAS have been frequently observed to contaminate groundwater, surface water and soil.

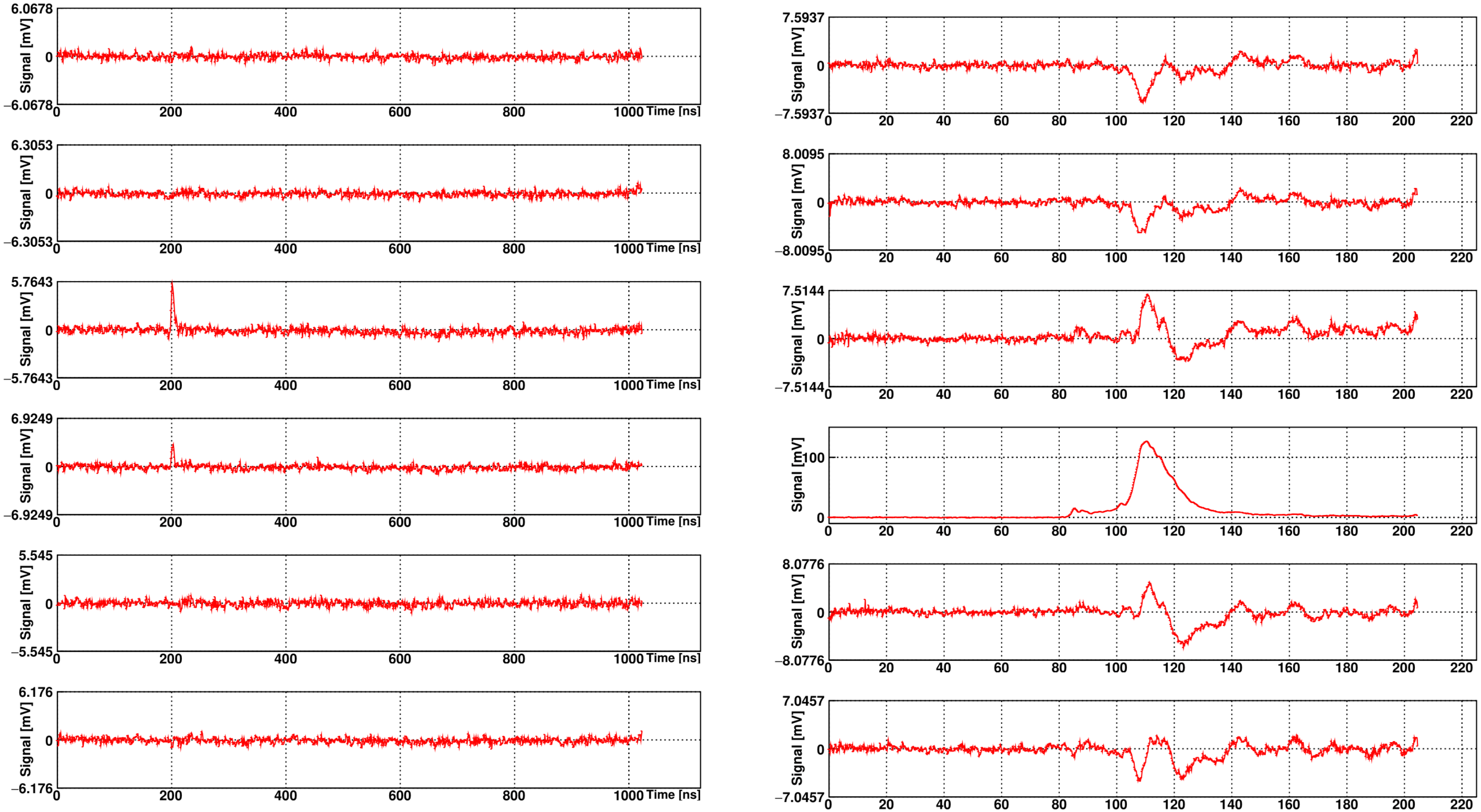
PFAS Regulation

- On February 7, 2023, the European Chemicals Agency (ECHA) released a proposal regarding PFAS restrictions:
  - It aims to be biggest chemical ban out of health considerations.
  - The proposal sets concentration limits below which the presence of PFAS would not be restricted: but which products?
  - None of the proposed restrictions will occur immediately: but when? Possible derogations?

More on Roberto Guida's talk

Beatrice Mandelli 19 29 May 2023

Efficiency/charge calculation with digitizer



Example of signals from RPC when readout with the digitizer. Left: STD gas mixture; right: MIX0 gas mixture

- RPC response when readout with the digitizer
- Algorithm developed to discriminate efficient strips
- Would tag strips 3 and 4 in the left case
- Would tag strip 4 in the right case because other signals would be classified as reflections (see next slide)

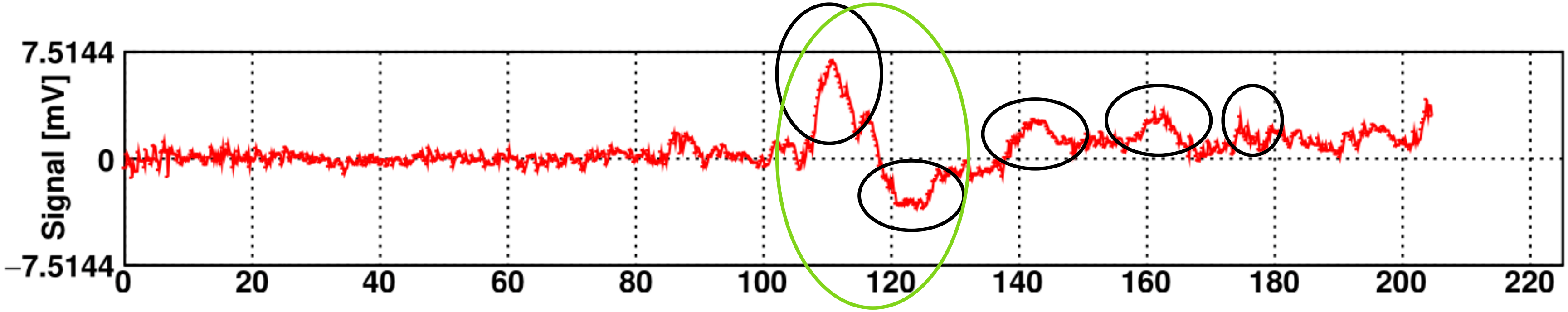
How to find "real signals" with digitizer? - 1

- All the strips which have a signal above 5*RMS in the muon window (arbitary window defined by looking at the muon time of arrival distribution) are deemed as potentially efficient

- The algorithm goes through all the data of the waveform (amplitude vs time with a sample every 1 or 0.4 ns (according to digitizer sampling frequency)) and it finds all the "peaks" (i.e. portions of signal above the threshold)

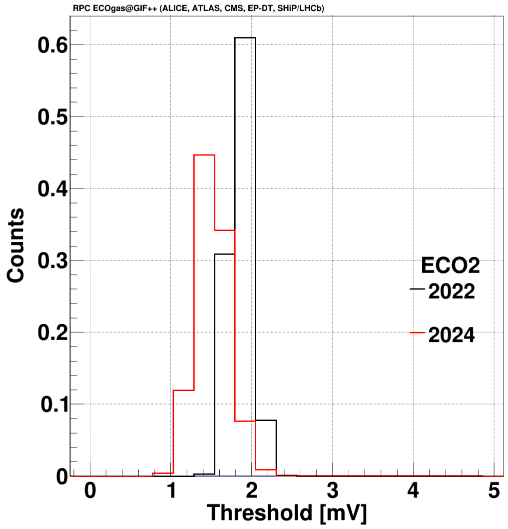
- If more than one peak is found, they are divided into peak-groups (if time difference between two peaks is < 40 samples)

- With eco-friendly mixtures with low HFO content, often more than one peak and many times they are due to cross-talk effects
  → These peaks are characterized by two opposite-polarity peaks with same absolute value of amplitude

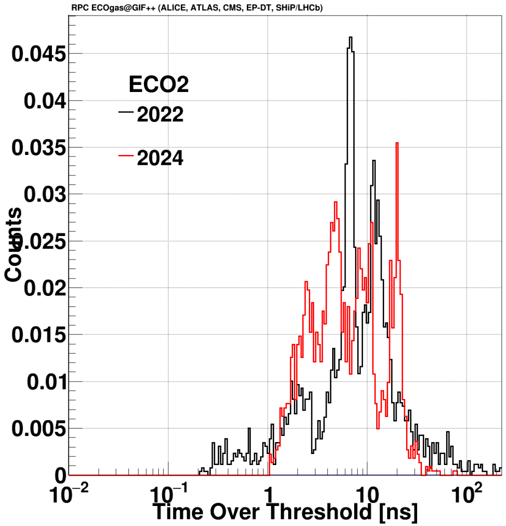


RPC response evolution during aging - 2

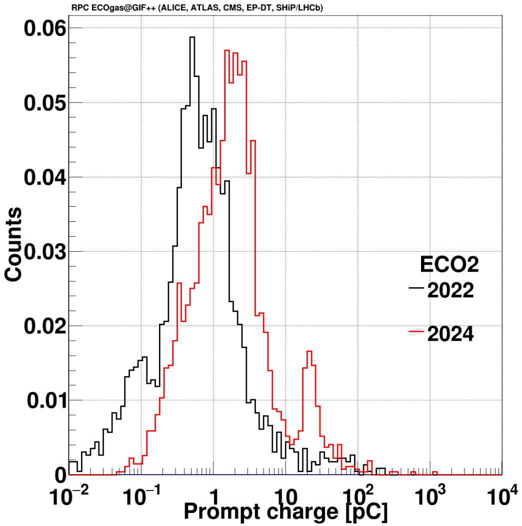
- Comparison of RPC response between 2022 and 2024
  → Taken at 90% efficiency (different HV but same gas gain)



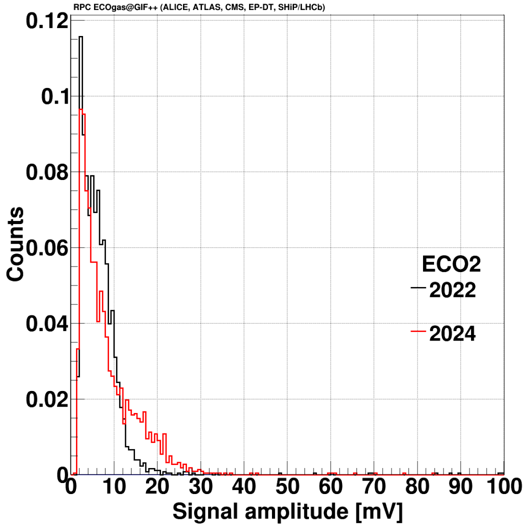
ALICE RPC threshold distribution at 90% efficiency – ECO2



ALICE RPC time over threshold distribution at 90% efficiency - ECO2



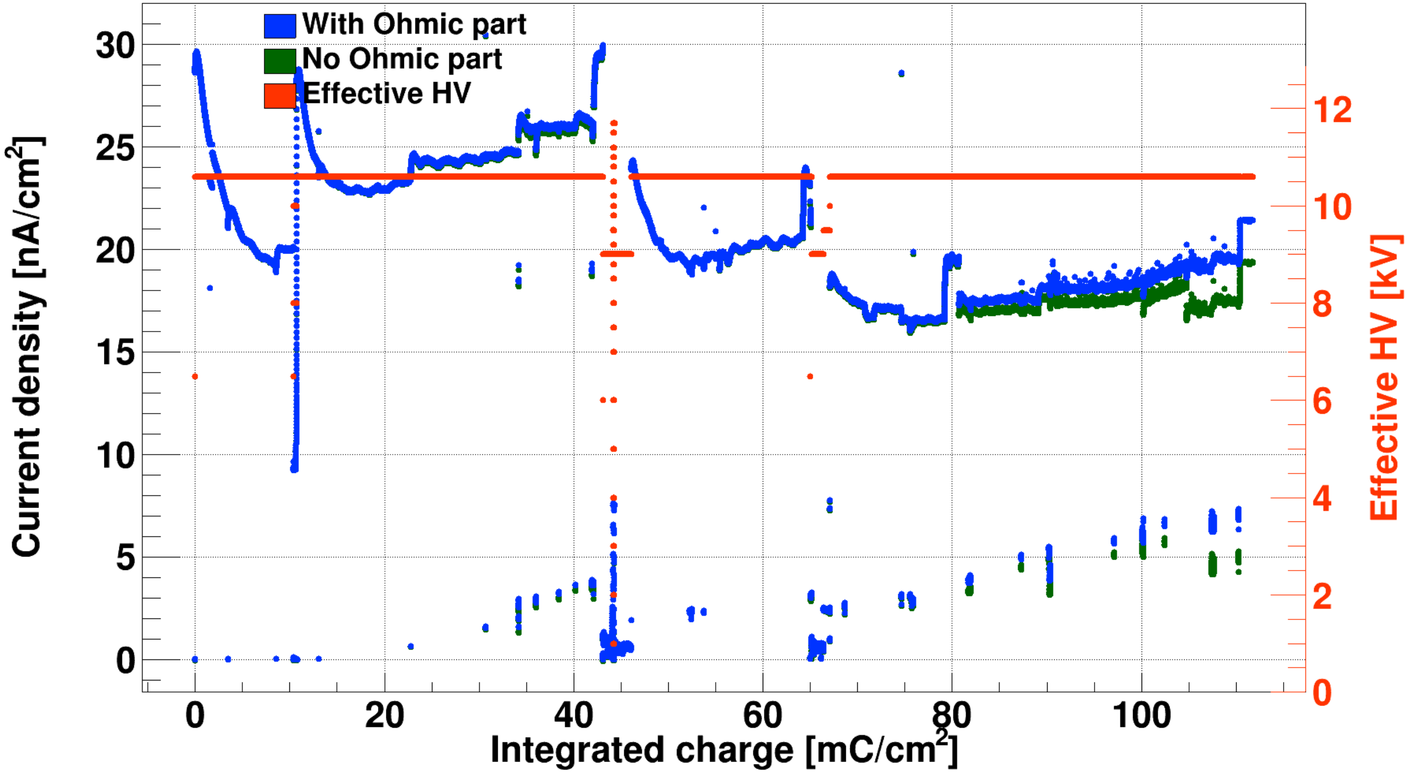
ALICE RPC prompt charge distribution at 90% efficiency - ECO2



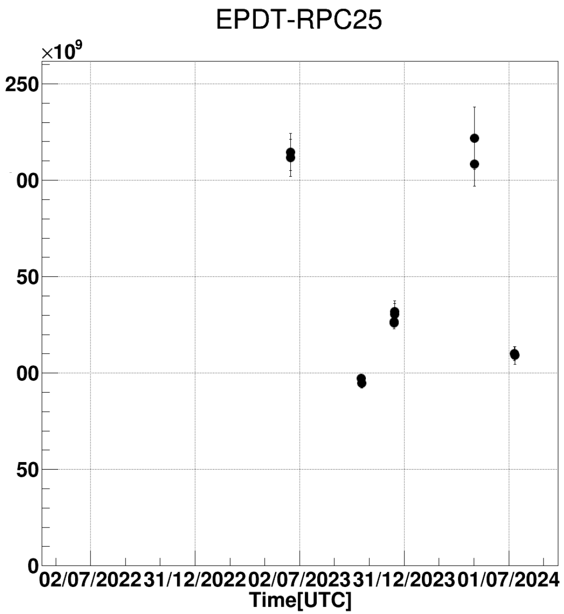
ALICE RPC signal amplitude at 90% efficiency - ECO2

- **Threshold** is similar between 2022 and 2024
- **Larger prompt charge in 2024**
  → Together with larger fraction of streamers
- Can be explained by **larger average signal amplitude and time over threshold**

Aging campaign results - EPDT

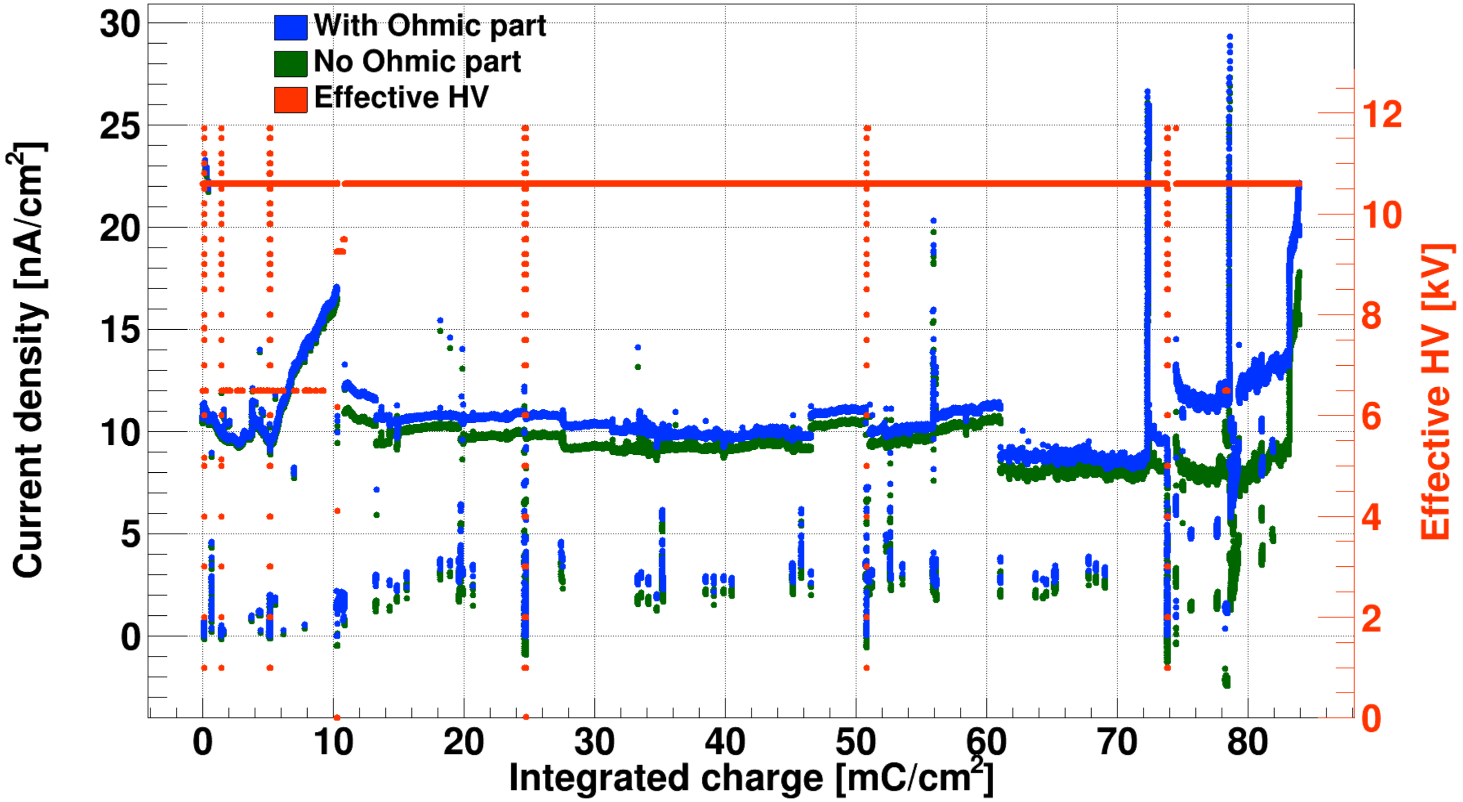


Evolution of the absorbed current as a function of the integrated charge during the aging test

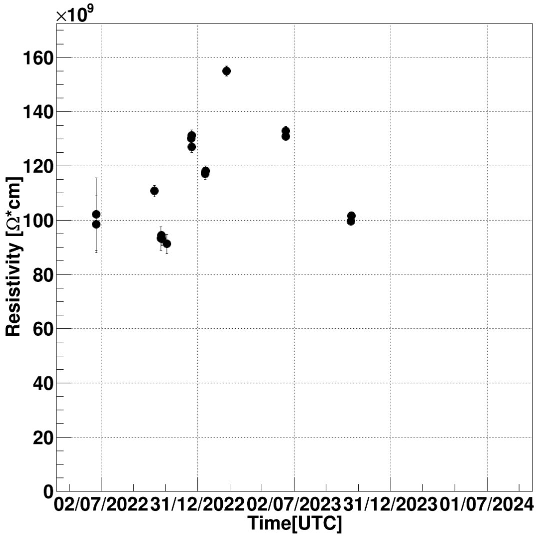


Resistivity measurements during aging – measured with the Ar method

Aging campaign results - ALICE



Evolution of the absorbed current as a function of the integrated charge during the aging test



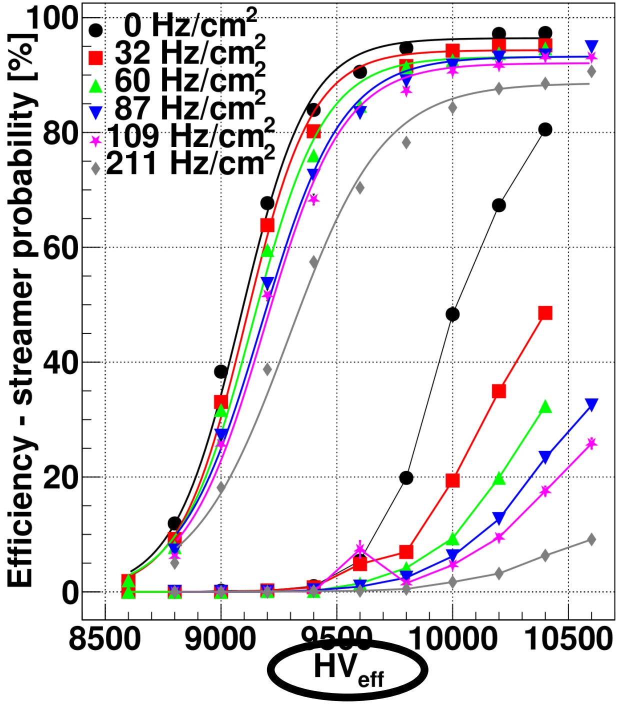
Resistivity measurements during aging measured with the Ar method

ALICE

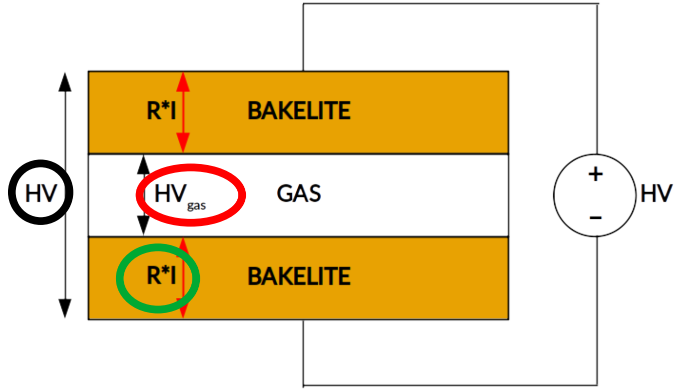
Efficiency under irradiation

N.B. This works only up to rates ~ 250/300 Hz/cm²

- When gamma rate increases, current also increases
- Current flowing through the Bakelite electrodes leads to a voltage drop ($\Delta V_{electrode}$)
  → Can be calculated as the product of electrode resistance and current

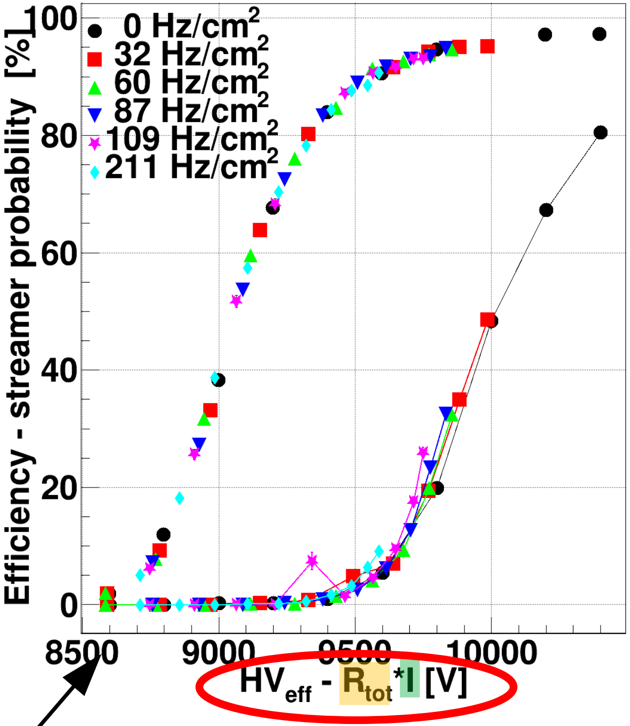


RPC response with source on and MIX2 (HFO/CO_2 20/75)



$$HV_{eff} = HV_{gas} + 2*\Delta V_{electrode}$$

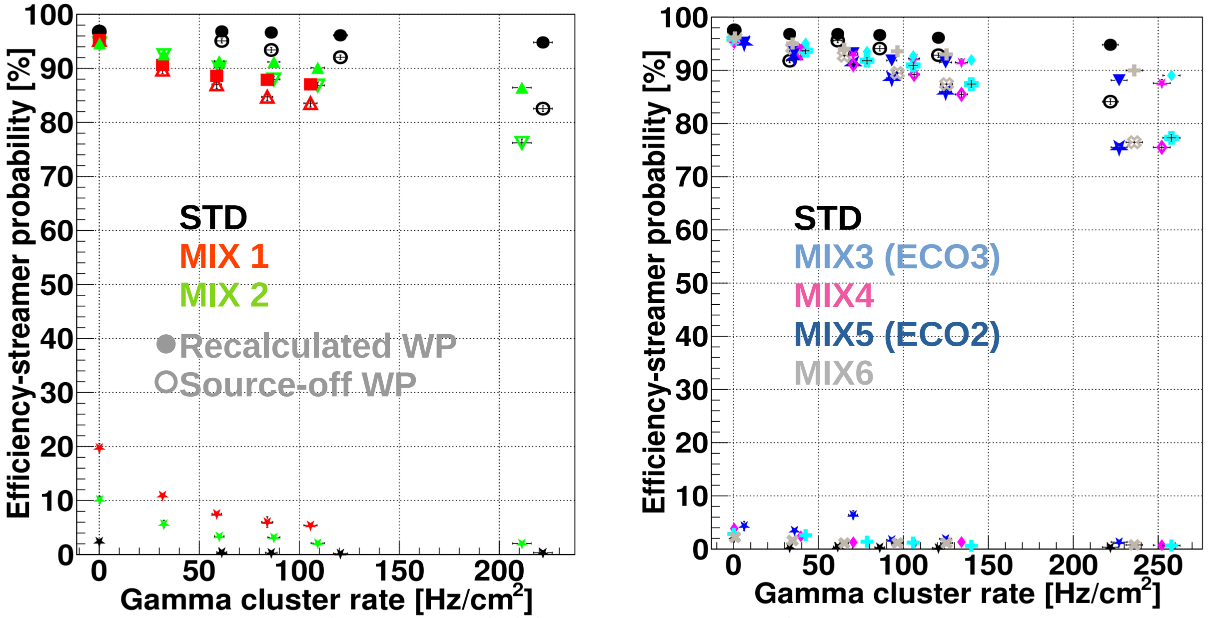
- Current is known, resistance can be measured with Ar method
- Current-induced voltage drop ($\Delta V_{electrode}$) can be calculated
  → Plot of efficiency vs HV_{gas} shows that all curves align



RPC response with source on and MIX2 vs HV_{gas}

Beam test results – under irradiation

- Evolution of the efficiency and streamer probability estimated at the working point (recalculated for each value of gamma cluster rate) as a function of the gamma cluster rate



Efficiency and streamer probability at WP vs gamma cluster rate – ALICE RPC

- Open markers in the plot refer to the quantities measured at the source-off working point

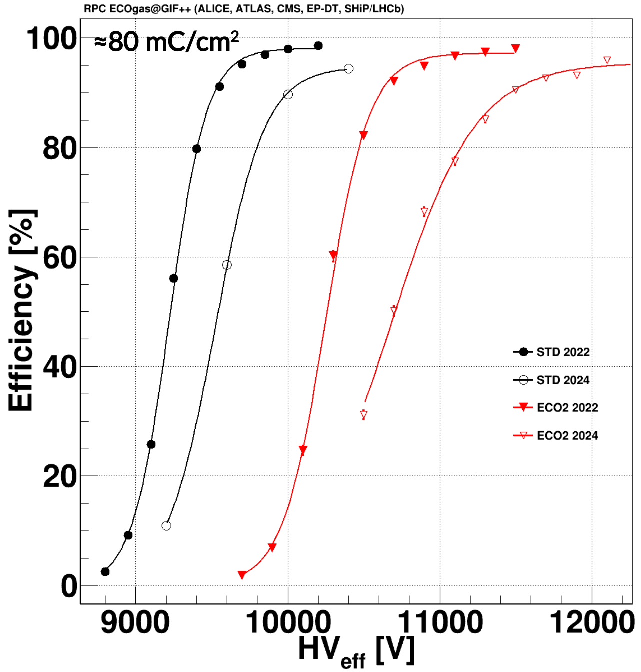
- Efficiency drop at recalculated WP and ~ 100 Hz/cm^2 cluster rate (RUN3/4 ALICE)
  1) **STD ~ 1** percentage points (pp)
  2) **Eco-friendly alternatives**: from ~ **8 pp** (lowest HFO concentration) to ~ **3 pp** (highest HFO concentration)

- Observed also in EP-DT:

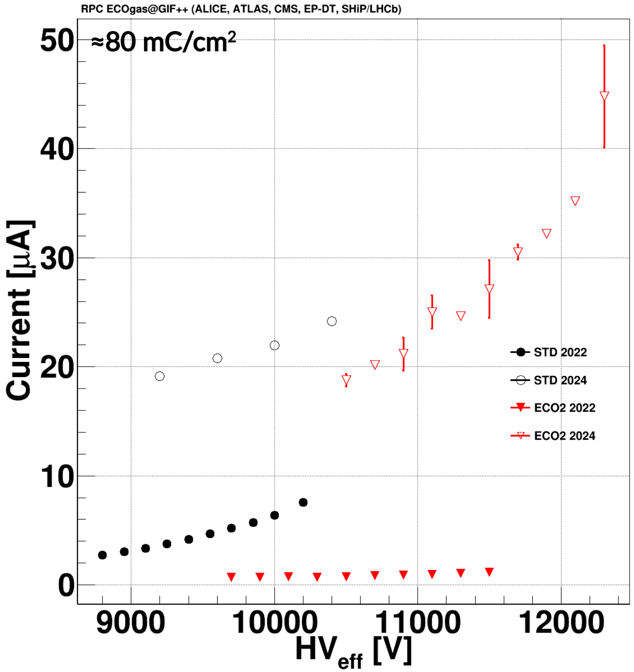
RPC response evolution during aging

ALICE

- **Aging test with ECO2 gas mixture** ongoing since 2022[1]
- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge



ALICE RPC source off efficiency – STD and ECO2 2022 vs 2024



ALICE RPC source off current – STD and ECO2 2022 vs 2024

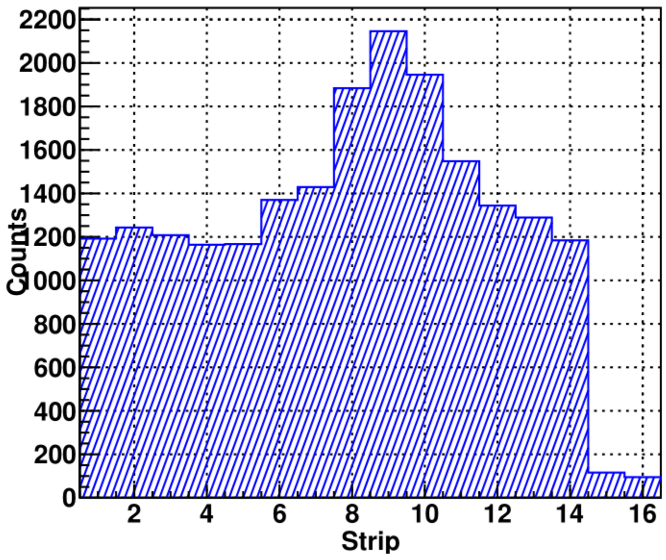
- Comparison **at source OFF** with **STD** and **ECO2** (ECO3 missing in 2024)
- **Shift of the WP** by ≈ 400 V with STD and 700 V with ECO2

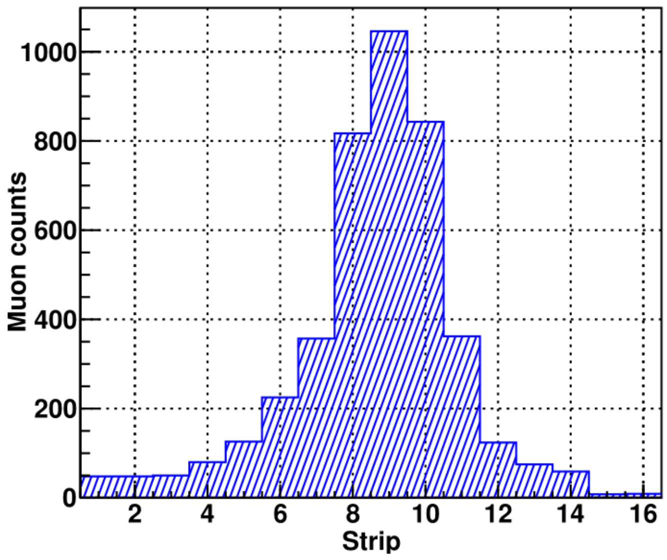
  → Readout on the same RPC region, same signal polarity and same data analysis
- **Increase in absorbed current with both mixtures**
- **Slight decrease in maximum efficiency**
- Effects can partly be explained by **pre-existing issues with the ALICE RPC**

[1]See Marcello Abbrescia's talk today @ 11:50 am

Efficiency calculation with FEERIC

- TDC data format:
  - Two vectors, filled everytime a trigger is issued
  - One vector contains the strips that fired while the other one the time of the signal
  - Muon events are tagged as 0 while gamma events with a 1
- TDC time profile:
  - Contains the time of all hits
  - Peak corresponds to muons (since their arrival time is fixed wrt trigger arrival time)
  - Located via Gaussian fit, muon window = mean ± 3σ (obtained from the fit)
- RPC is efficient in a given trigger if at least one hit in both strip planes inside the muon window





Selecting only the signals in the muon widnow allows one to remove background created by gamma source

Considerations on efficiency fit

- Example of RPC response to the muon beam, wen operated with the STD gas mixture to highlight the main features

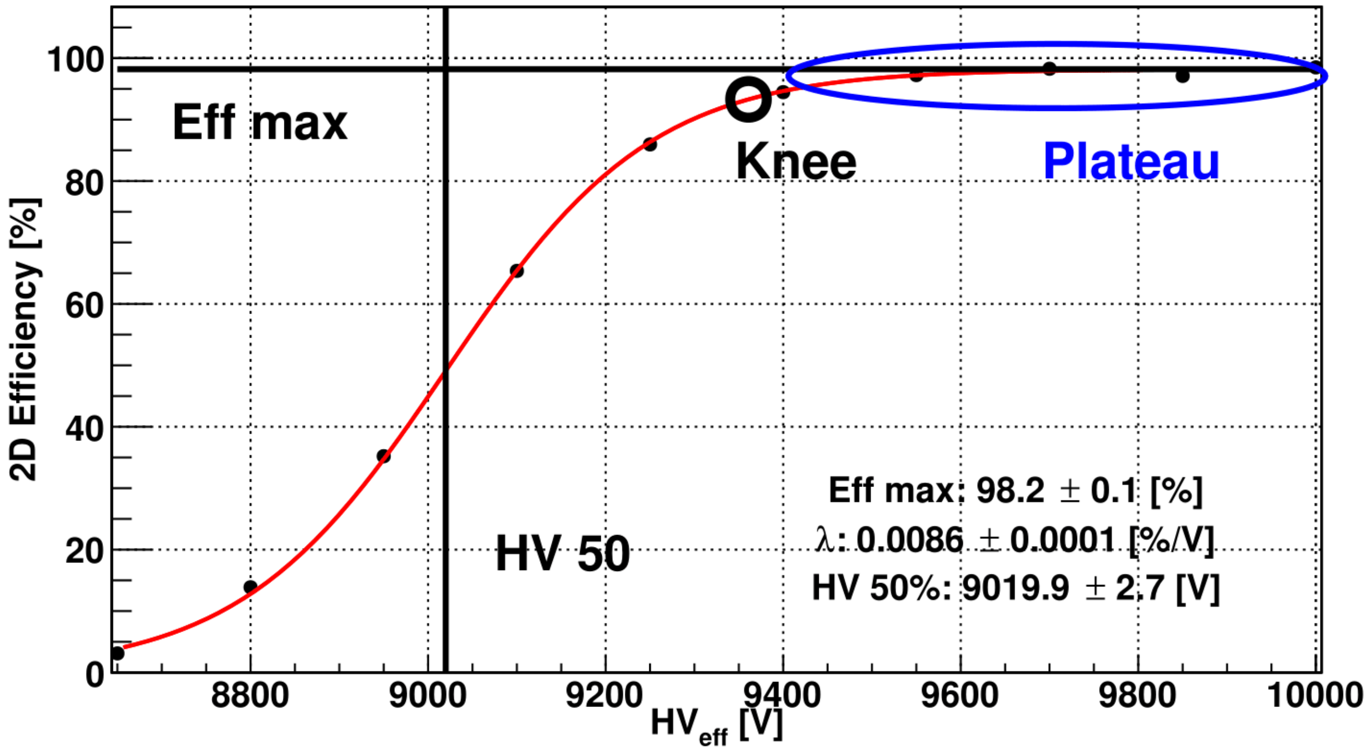
- Efficiency(HV) curve fitted with the logistic function:

$$\epsilon(\boldsymbol{HV}) = \frac{\epsilon_{\boldsymbol{Max}}}{\boldsymbol{1}+\boldsymbol{e}^{\lambda(\boldsymbol{HV}-\boldsymbol{HV}_{\boldsymbol{50}})}}$$

1) ε_{Max} = maximum efficiency

2) HV_{50} = voltage where efficiency is 50% of its maximum

3) λ = steepness of the efficiency curve rise

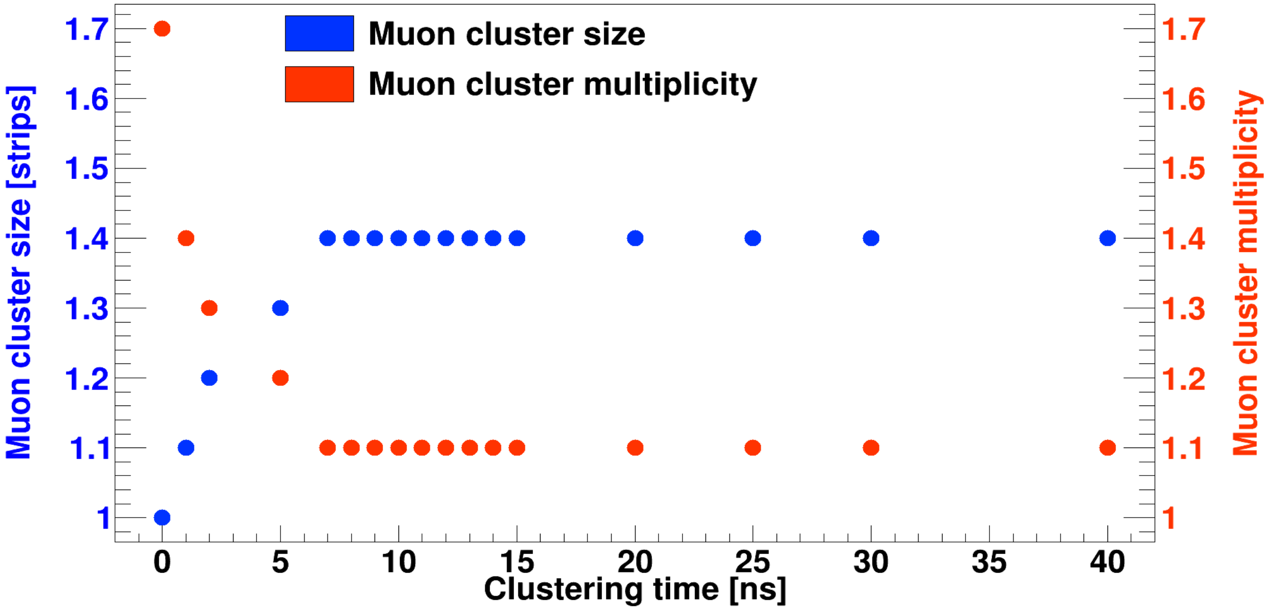


Typical efficiency(HV) curve with main response parameter highlighted

- **Working point (WP)** = operational voltage with given mixture = knee (HV where efficiency is 95% of the maximum) + 150 V
- Important value when studying a new gas mixture

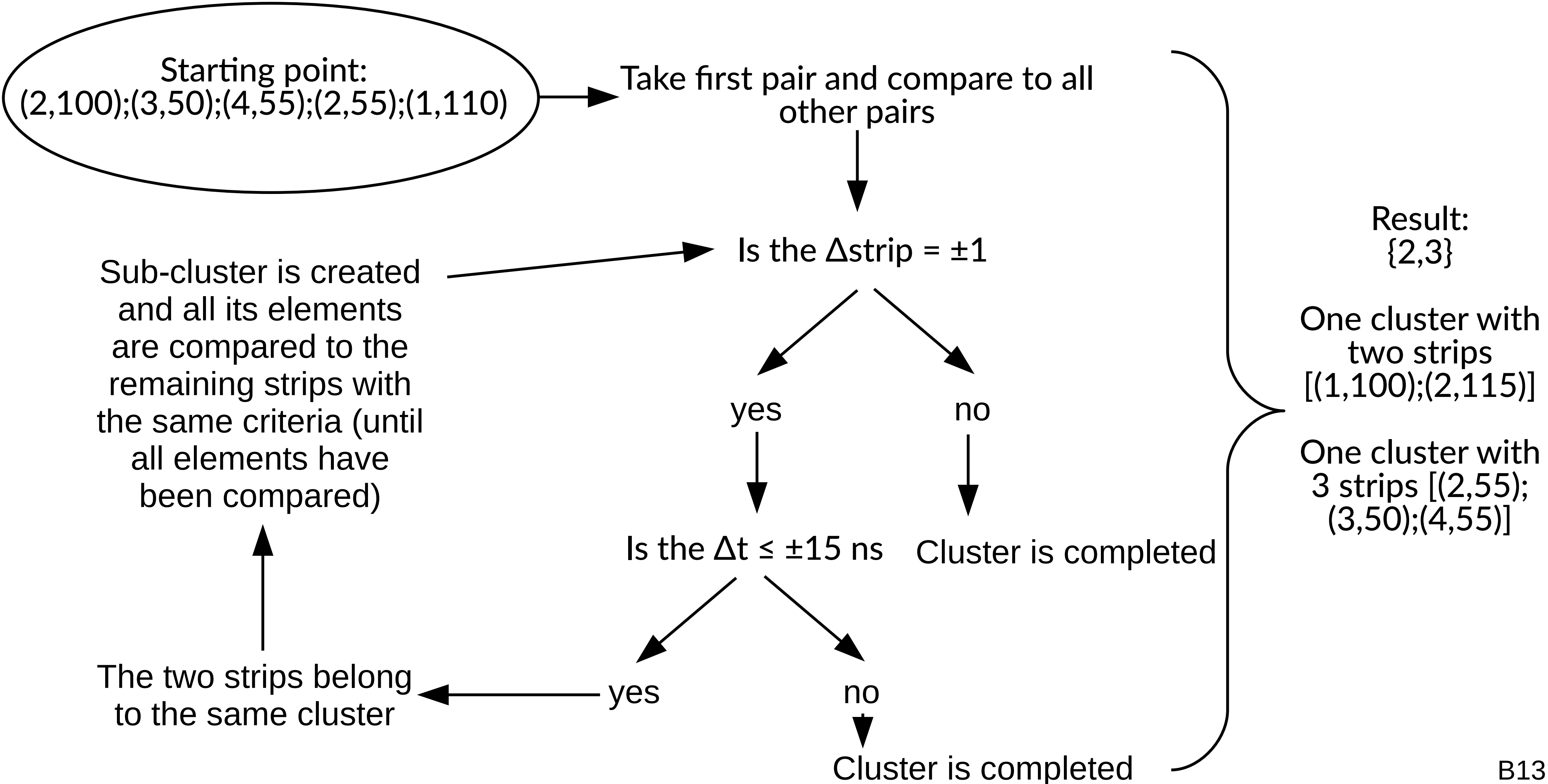
Clustering algorithm - 1

- We have 2 information on each hit, time and strip
- Need to find clusters (i.e. adjacent strips in a given trigger) while keeping in mind also time informaton (clustering time)
- Developed clustering algorithm and tested it for different clustering times
- For clustreing times > 7 ns
  → Cluster size and multiplicity are constant
  → Clustering time set to 15 ns to be on the safe side



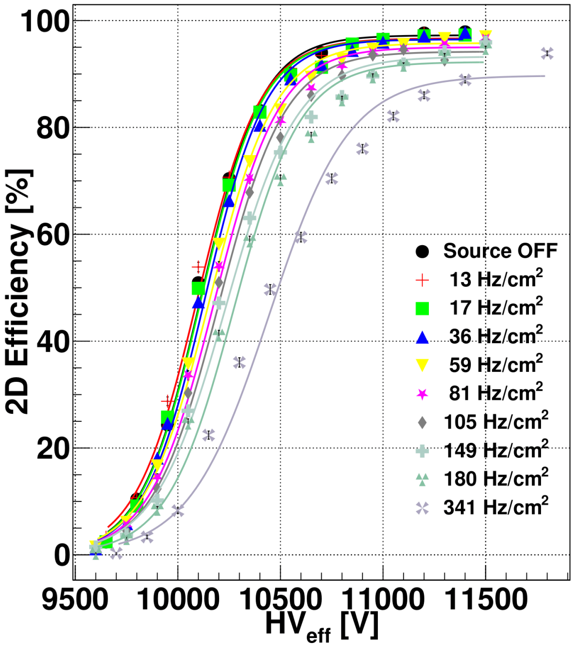
Variation of cluster size and multiplicity for different clustering times

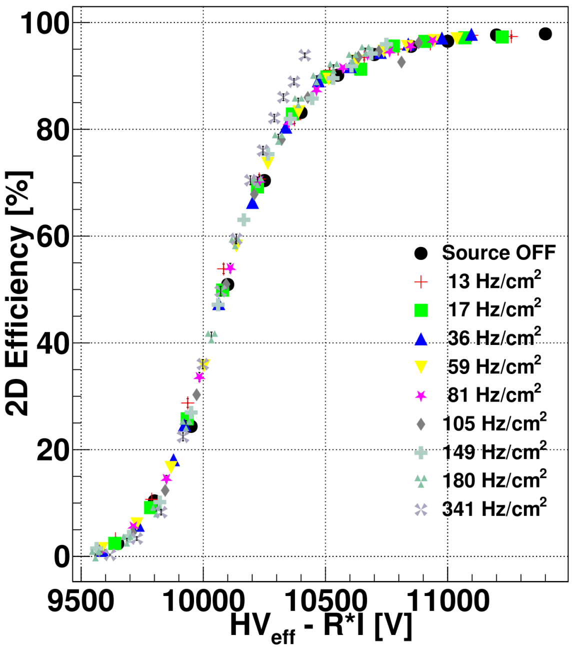
Clustering algorithm - 2



Efficiency under irradiation – FEE data

- Efficiency(HV) curves under irradiation, when FEE is used
- Streamer probability cannot be calculated in this case but higher maximum rate reached wrt digitizer case





RPC response with source on and MIX5 (HFO/CO_2 35/60)

- Same shift effects shown when analyzing digitizer response
- "Correction" of the applied voltage for the drop on the Bakelite aligns the curves
- Not true for the highest rate
  → Might be due to secondary effects not easily measurable
- Similar behavior observed in all the eco-friendly mixtures studied with FEERIC