In-beam performance of a Resistive Plate Chamber operated with eco-friendly gas mixtures

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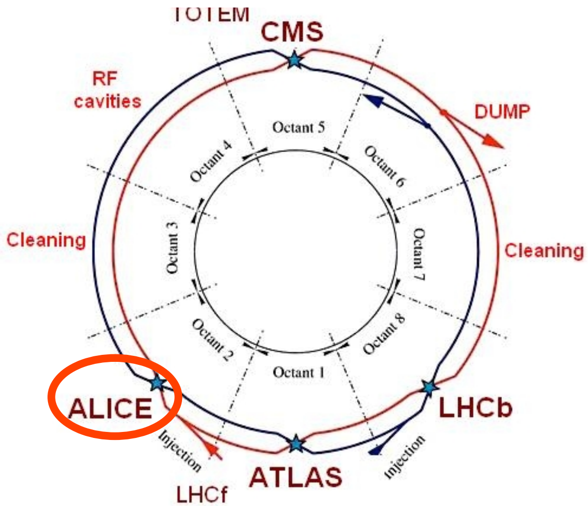
[1]INFN Torino

Overview

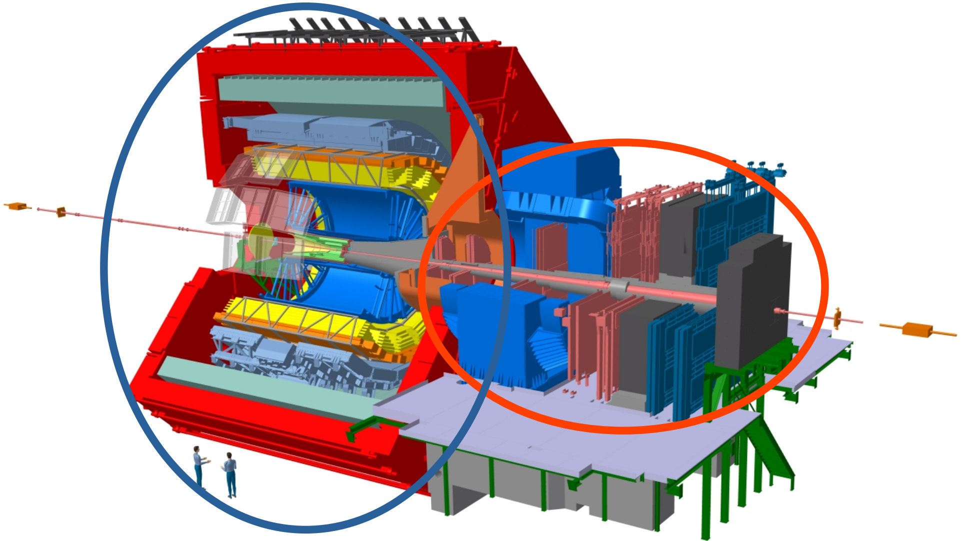
- The ALICE detector at CERN and its muon spectrometer
- The need for an eco-friendly gas mixture for Resistive Plate Chambers (RPCs)
- Test set-up at the CERN GIF++
- Beam tests with $C_3H_2F_4$-based gas mixtures
- Conclusions and outlook

The ALICE detector at CERN

- A Large Ion Collider Experiment (ALICE) is one of the four experiments located at the CERN Large Hadron Collider (LHC)
- Multi-purposed detector, taking data in all colliding systems: pp, Pb-Pb and p-Pb
- Mainly focused on the study of quark-gluon plasma (QGP) in heavy-ion collisions



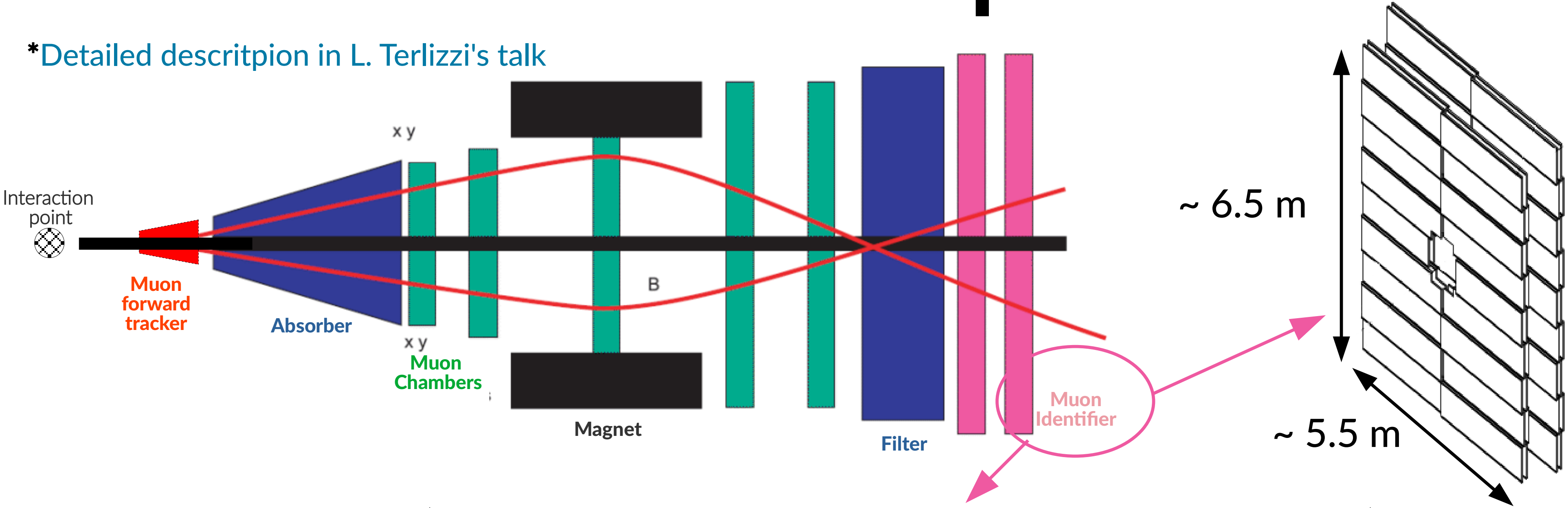
Scheme of the LHC ring


Rendering of the ALICE detector

- Two spatially distinct detection regions
- Central barrel
  - Particle identification
  - Hadron tracking, e^-/γ detection
- Muon spectrometer
  - Located at forward rapidity
  - Muon tracking and **identification**

The ALICE muon spectrometer*

*Detailed descritpion in L. Terlizzi's talk



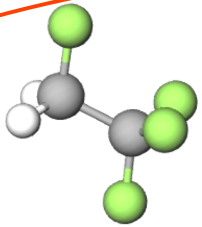
- 72 single gap RPCs (2 mm single gas gap and 2 mm thick Bakelite electrodes) to provide muon identification
- Resistivity ~ 10^9-10^{10} Ω·cm
- Located at 16 and 17 m from the IP, 18 RPCs per plane, total area covered ~140 m^2
- Readout provided by the FEERIC front-end electronics (with signal pre-amplification) , installed from Run 3 onwards
- Average total charge per hit (at working point) ~ 40 pC

The currently employed gas mixture

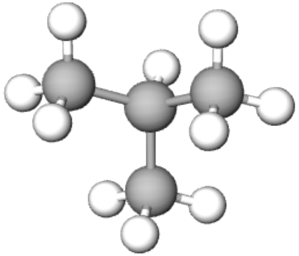
- RPC working parameters depend on the gas mixture employed

- The currently-used gas mixtures at the LHC grant the following properties:

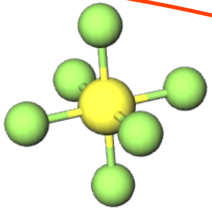
  1) High density of primary ion-electron pairs
  2) Relevant quenching properties
     → Ability of capturing recombination photons without further ionization
  3) Enough electronegativity to capture free electrons, reducing the avalanche size



$C_2H_2F_4$ (R-134a): provides primary electrons



i-C_4H_{10} - isobutane: quenching gas



SF_6 – sulfur hexafluoride: electronegative gas

→ Currently employed gas mixtures consist of these gases in different proportions

- Currently employed gas mixture in the ALICE MID RPCs

89.7% R-134a, 10% i-C_4H_{10}, 0.3% SF_6

The need for a new RPC gas mixture

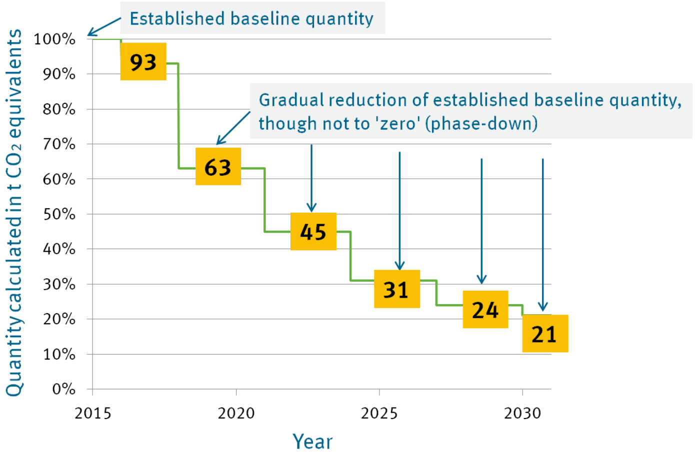
- All currently employed RPC gas mixtures contain different fractions of:

R-134a
SF_6 → Fluorinated greenhouse gases (F-gases)

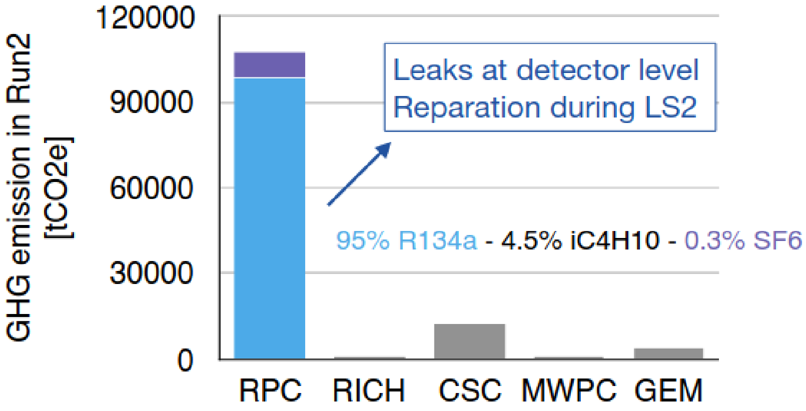
- New EU regulations to reduce the impact of greenhouse gases

→ Phase down of the production and consumption of F-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 phase down plan



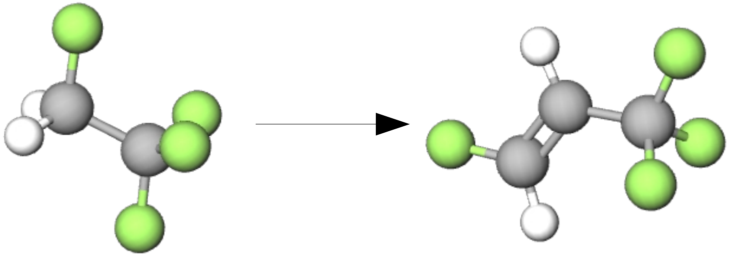
Emission of greenhouse gases from CERN - B. Mandelli VCI 2022

- RPC systems are the main consumer of F-gases at CERN
→ Need to find a more eco-friendly gas mixture

A possible solution

- First efforts focused on R134a replacement

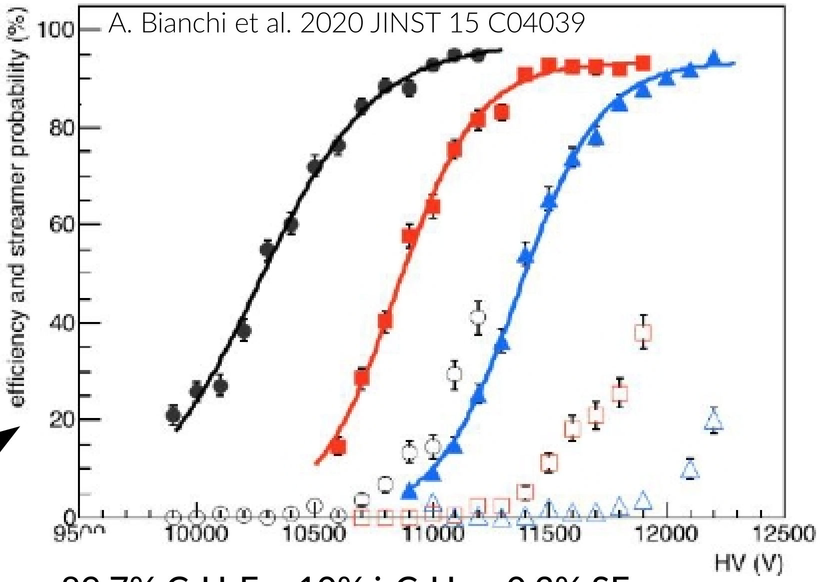
- Possible candidate (already used in industrial applications) is *tetrafluoropropene* ($C_3H_2F_4$, HFO-1234ze, HFO), with similar chemical structure as R134a but lower GWP[1] ~ 6



GWP ($C_2H_2F_4$) ~ 1430 GWP ($C_3H_2F_4$) ~ 6

- Replacement of R134a with HFO alone not possible due to its lower first Townsend coefficient
  → Working voltage above 15 kV
    → HFO has to be diluted to lower this value

- Promising gas mixtures pinpointed (among others) by the ALICE group in Torino and studied with cosmic muons
  → HFO diluted with CO_2
  → GWPs ~ **70**, **230** (vs **1470** for the current mixture)



89.7% $C_2H_2F_4$ - 10% i-C_4H_{10} - 0.3% SF_6
50% CO_2 - 39.7% HFO - 10% i-C_4H_{10} - 0.3% SF_6
50% CO_2 - 39.0% HFO - 10% i-C_4H_{10} - 1% SF_6

[1]GWP = Global Warming Potential = how much heat is trapped by a ton of given gas compared to a ton of CO_2 (GWP = 1)

The RPC ECOGas@GIF++ collaboration

- Cross-experiment collaboration to join forces and perform aging/beam test studies with eco-friendly gas mixtures for RPCs

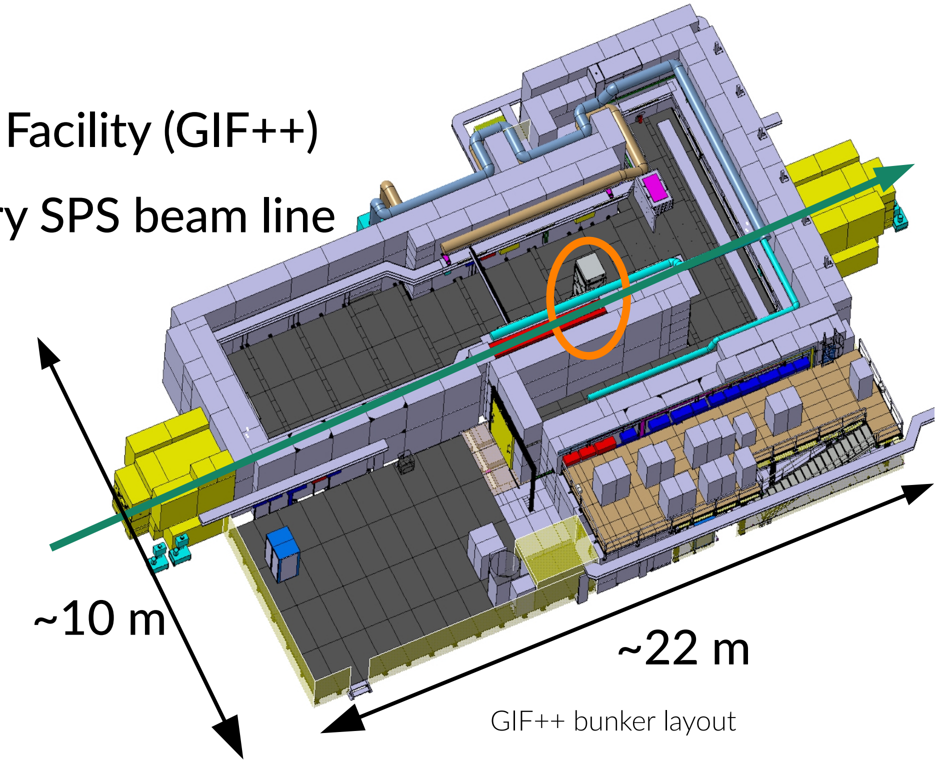
→ Includes CMS, ALICE, ATLAS, SHiP/LHCb and the detector technology group of CERN

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

→ Experimental facility located on the H4 secondary SPS beam line

- **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 (absorption factors)

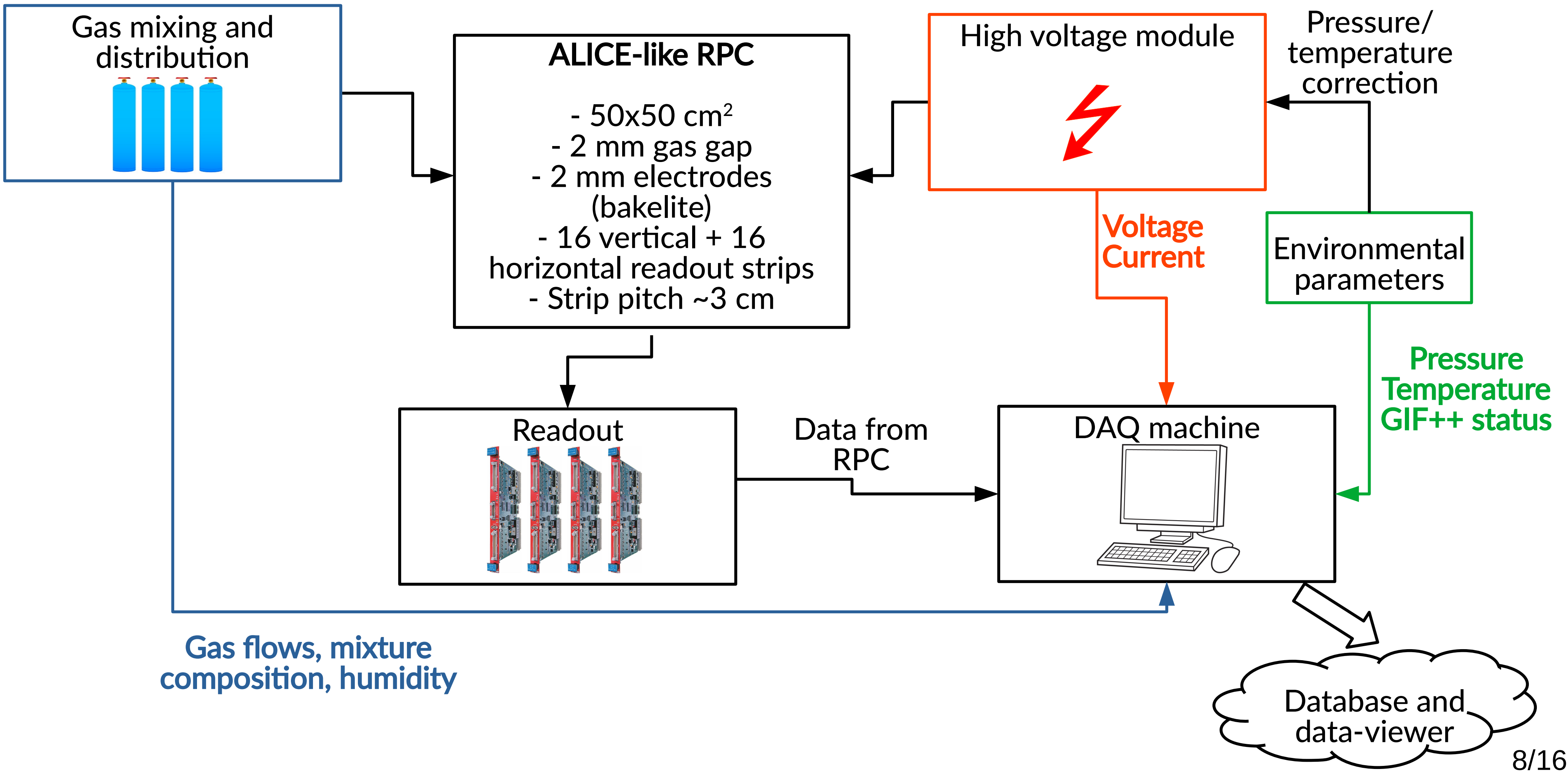
- **High energy** (~150 GeV/c) **muon beam** in dedicated beam time periods



GIF++ bunker layout

→ Combination of muon beam with source = study of detector rate capability

Experimental setup



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

NB: Lower isobutane concentration wrt mixtures previously tested with cosmic rays due to restrictions on flammable gases at GIF++

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

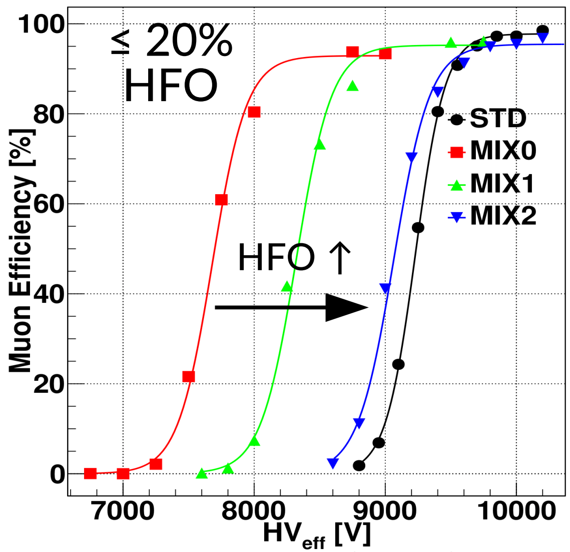
CO_2 concentration decreases

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

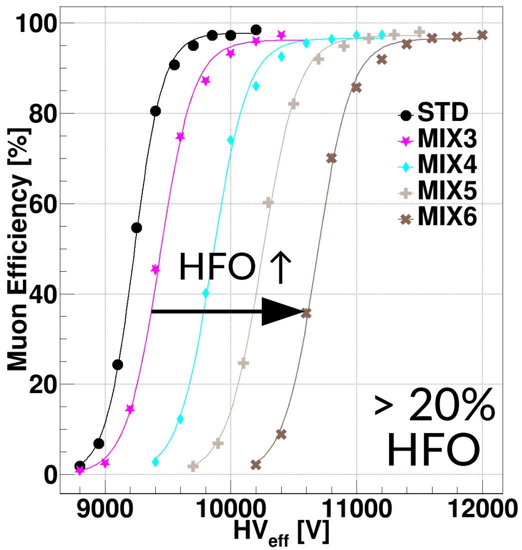
  2) CAEN digitizer
  → Waveform/charge studies

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

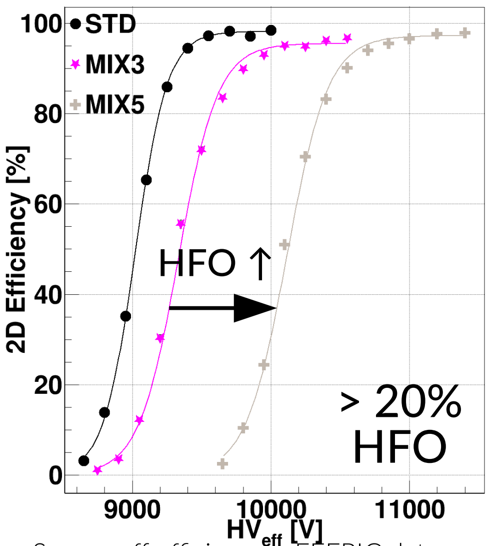
Efficiency vs HV at source off



Source off efficiency – digitizer data



Source off efficiency – digitizer data



Source off efficiency – FEERIC data

- **Trigger** provided by coincidence of 4 scintillators coupled with PMTs
- Threshold set on the FEERIC electronics = 100 mV after amplification (~ 150fC)
- Threshold used in digitizer analysis = 5*RMS of signal in noise window

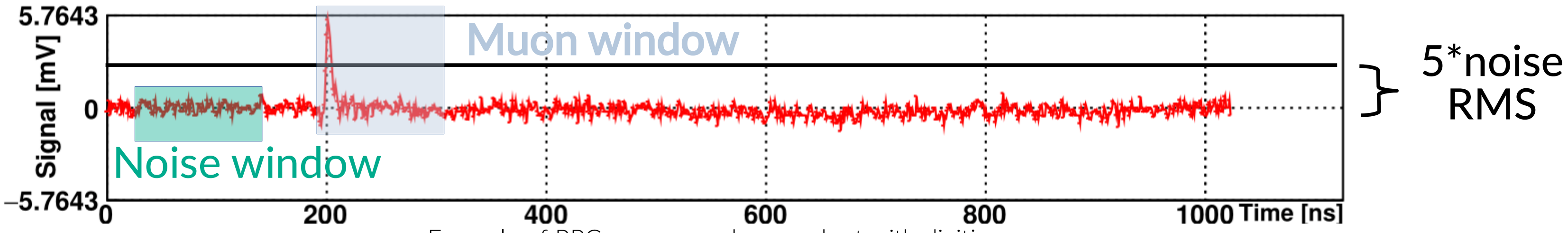
- Efficiency curves fitted with logistic function to extract **Working Point** (WP) = knee (voltage where efficiency is 95% of its maximum) + 150 V

- Increasing value of maximum efficiency as the HFO concentration increases (denser mixture)

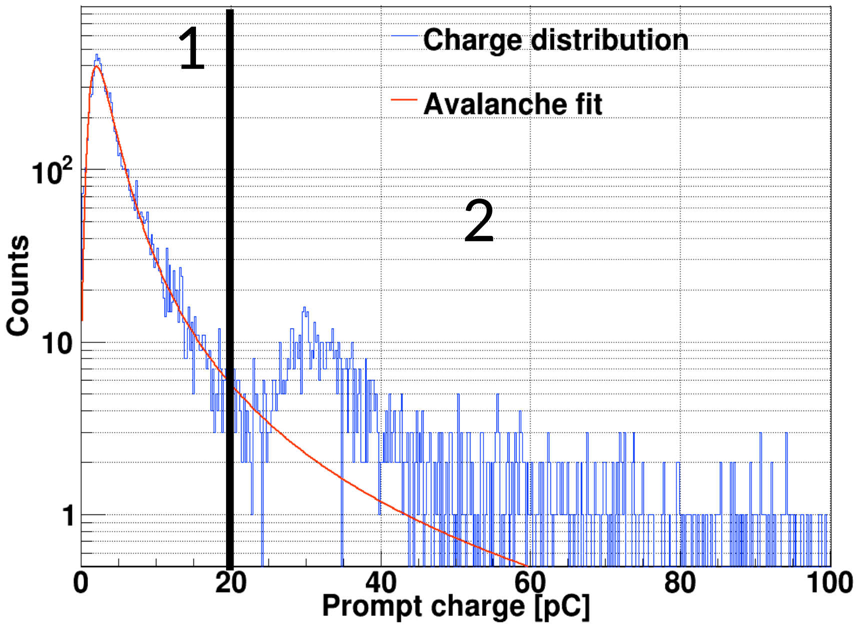
- Increase of WP by ~1 kV for every 10% HFO added to the mixture is observed with both readout methods

Exploiting the digitizer information

- Access to the waveform of each signal allows more in depth characterization of RPC response (e.g. in terms of signal prompt charge)



Example of RPC response when readout with digitizer



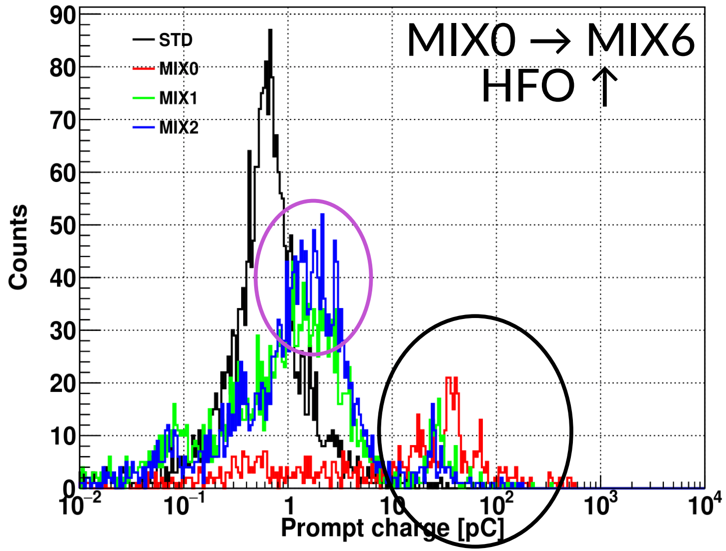
Prompt charge distribution with no irradiation – standard gas mixture

- Analysis procedure developed to
  1) Identify "efficient" strips for further processing
  2) Find integration interval for prompt charge calculation
- Prompt charge distribution for the standard gas mixture
  → Two populations appear
  1) **Avalanche signals**
  2) **Streamer signals**
- Two regions are separated at ~ 20 pC
  → Events with prompt charge > 20 pC tagged as streamers

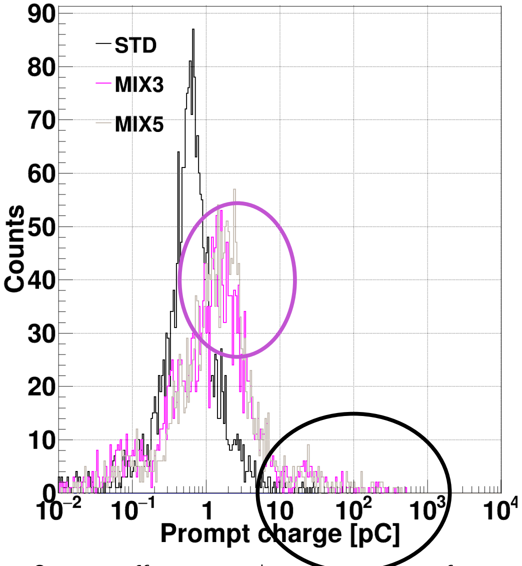
$$\textit{Streamer probability} = \frac{\textit{charge} > 20\,\textit{pC}}{\textit{tot}_{\textit{events}}}$$

Source-off prompt charge distribution

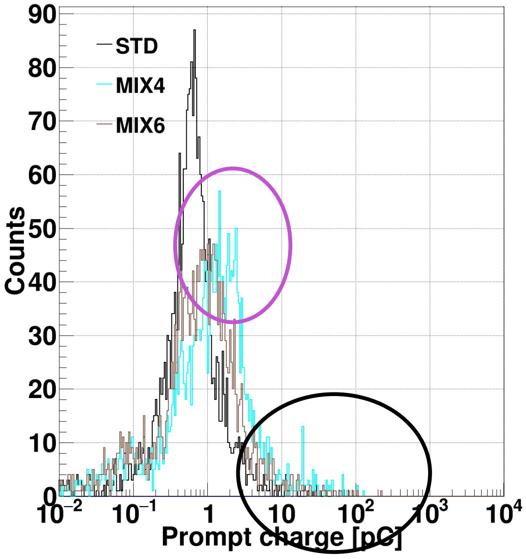
- Prompt charge calculated event-by-event as the sum of the prompt charge on all the efficient strips
- Spectra shown correspond to the HV closest to the estimated WP



Source-off prompt charge distribution at HV closest to the WP for STD + MIX0-2



Source off prompt charge spectrum for MIX3 and 5



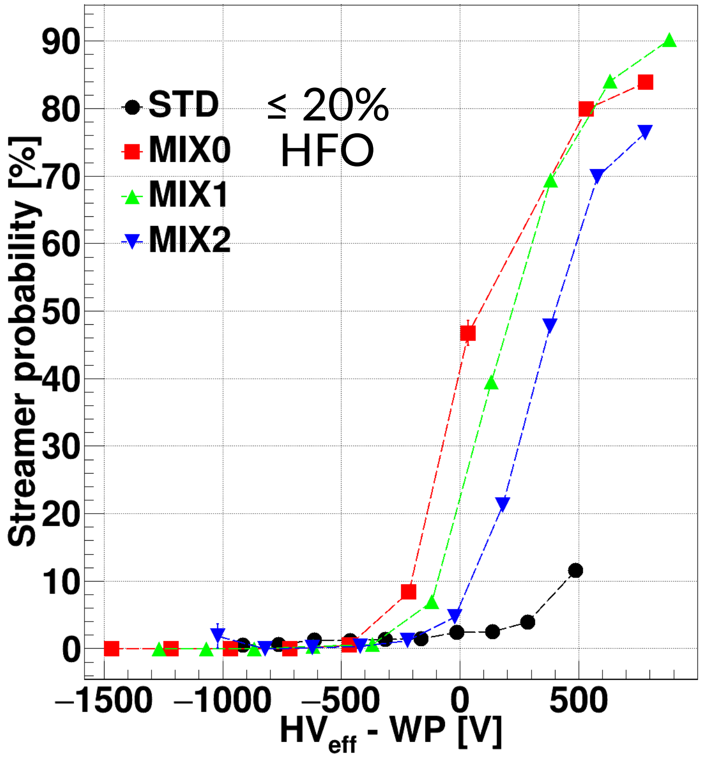
Source off prompt charge spectrum for MIX4 and 6

- For all HFO-based mixtures, the avalanche peak is shifted towards higher values wrt STD
  → Higher absorbed current
- Streamer peak generally more populated than with STD
  → Decreases as CO_2 concentration decreases (quenching effect of more HFO)

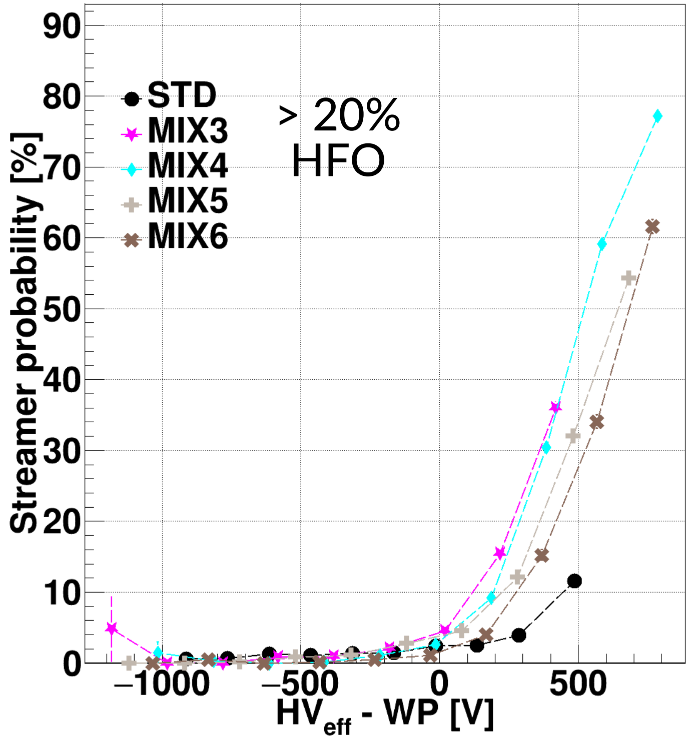
Source-off streamer contamination

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

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



Source off streamer probability (HV), MIX 0-2



Source off streamer probability (HV), MIX 3-6

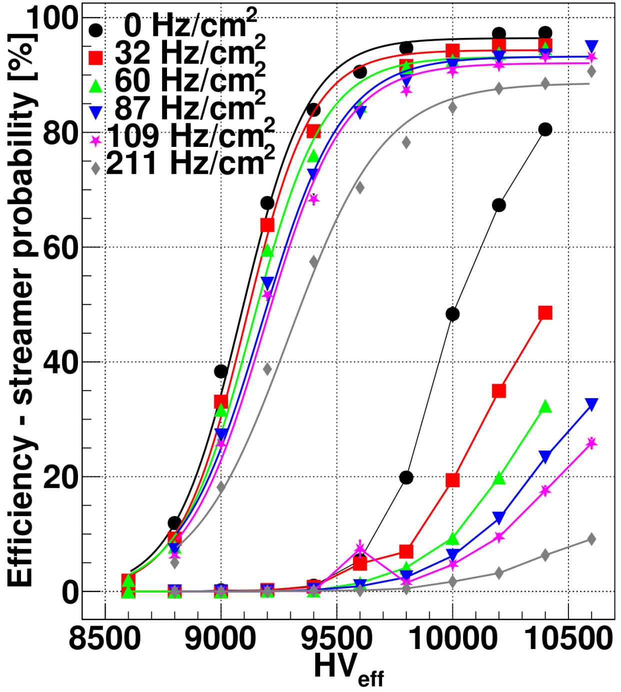
- Streamer contamination at WP improves with increasing HFO content

- 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



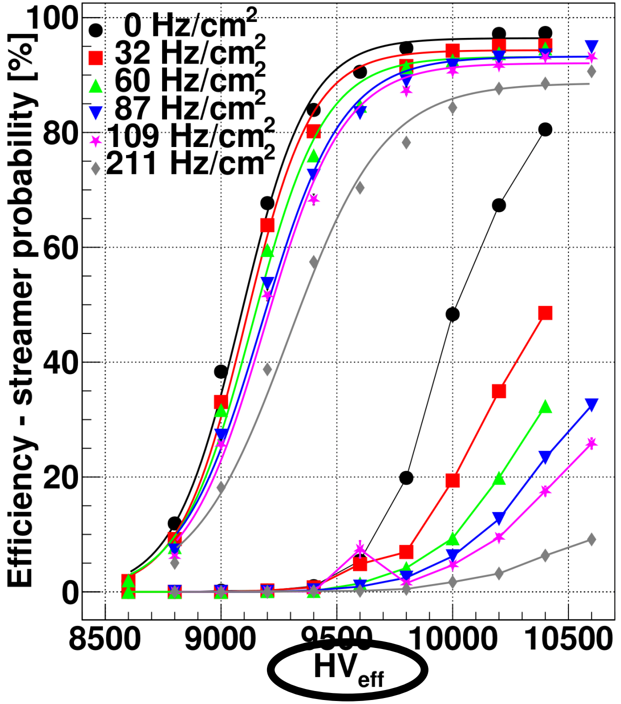
RPC response with source on and MIX2 (HFO/CO_2 20/75)

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

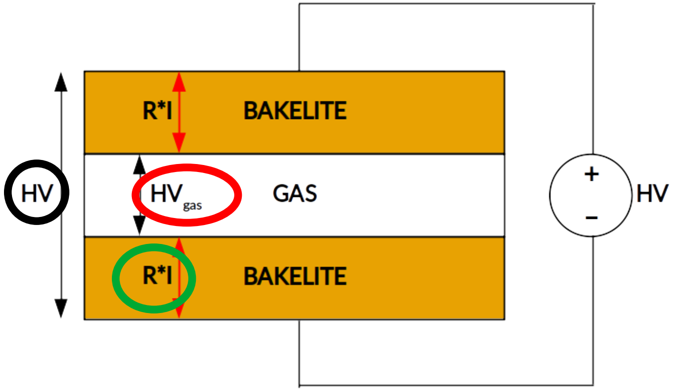
- Three effects under irradiation:
  1) Efficiency curves shift to higher voltages
  2) Maximum value of efficiency reaches lower values
  3) Reduction of streamer contamination

Efficiency under irradiation

- 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

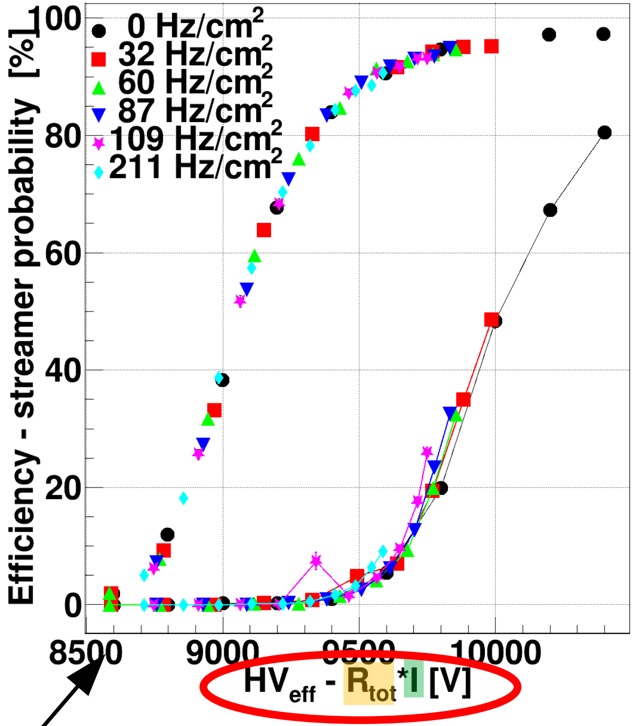


RPC response with source on and MIX2 (HFO/CO_2 20/75)



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

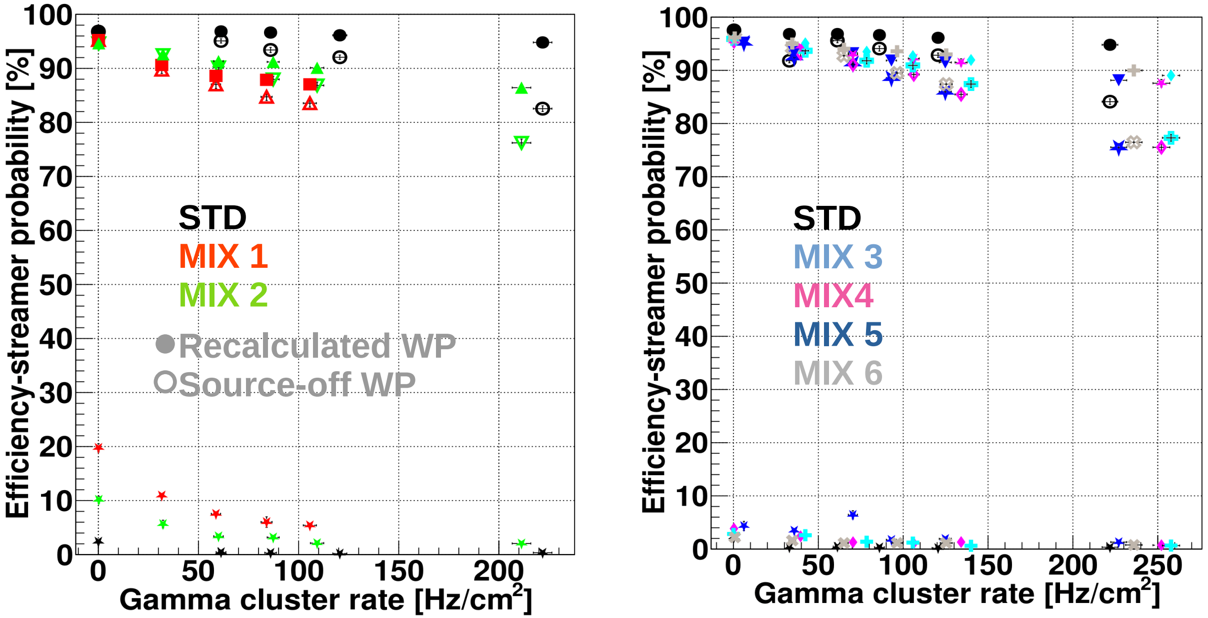
- Current is known, resistance can be measured with Ar method
- Current-induced voltage drop ($\Delta V_{electrode}$) can be calculated
  → Plot of efficiency vs HV_{gas} shows that all curves align



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 – Digitizer data

- 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
(conditions of ALICE MID most exposed RPCs in RUN3/4 with safety factor 2):

1) **STD ~ 1** percentage points (pp)
2) **Eco-friendly alternatives**: from ~ **8 pp** (lowest HFO concentration) to ~ **3 pp** (highest HFO concentration)

Conclusions

- The search for eco-friendly alternative gas mixtures for RPC detectors is a hot topic in the CERN community, especially due to new regulations imposing a progressive phase-out of F-gases
- Several eco-friendly mixtures, where R134a is replaced with HFO/CO_2 in variable proportions, were beam-tested at the CERN GIF++
- Working point increases by ~1 kV for every 10% HFO added to the mixture
- Streamer contamination decreases if HFO concentration increases
- Mixtures with 30-40% HFO provide similar streamer contamination at WP as STD but the contamination grows faster than STD above WP
- Efficiency curves under irradiation are shifted to higher voltages
→ Explained by the current-induced voltage drop on the bakelite electrodes
- Efficiency drop at ALICE-like background rates (~100 Hz/cm^2) is ~1 pp for standard gas mixture and 3-4 pp for eco-friendly alternatives

Thank you for your attention!

Backup

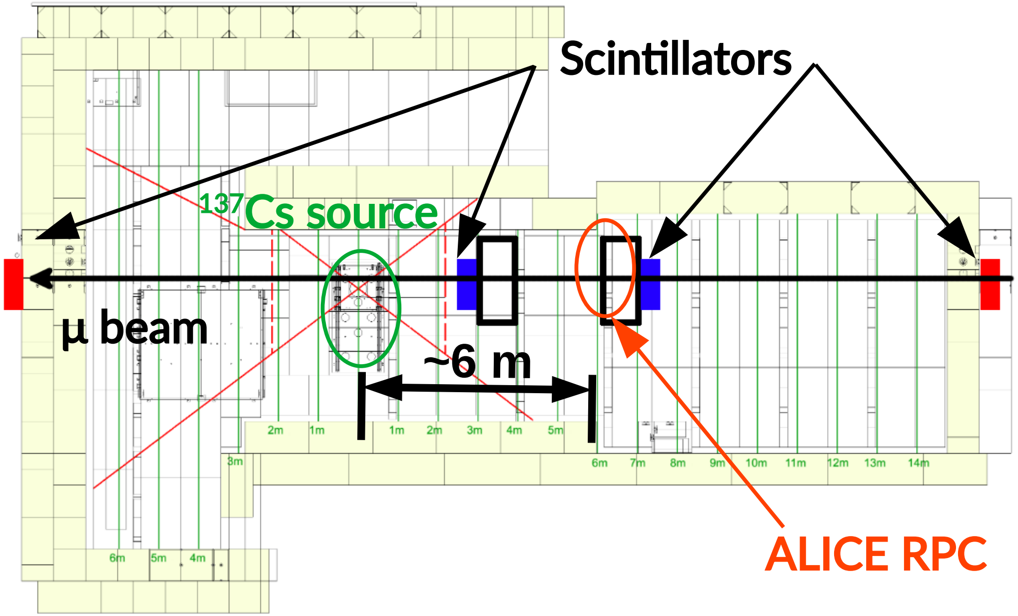
Experimental setup

- Two main beam test objectives:

  1) Collect muon signals, for RPC performance studies
  2) Measure the gamma rate on the detector for rate capability studies

  1) Trigger provided by coincidence of 4 scintillators
  → 10x10 cm^2 trigger area

  2) Random trigger to periodically sample RPC response



Sketch of the beam test setup @ GIF++

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

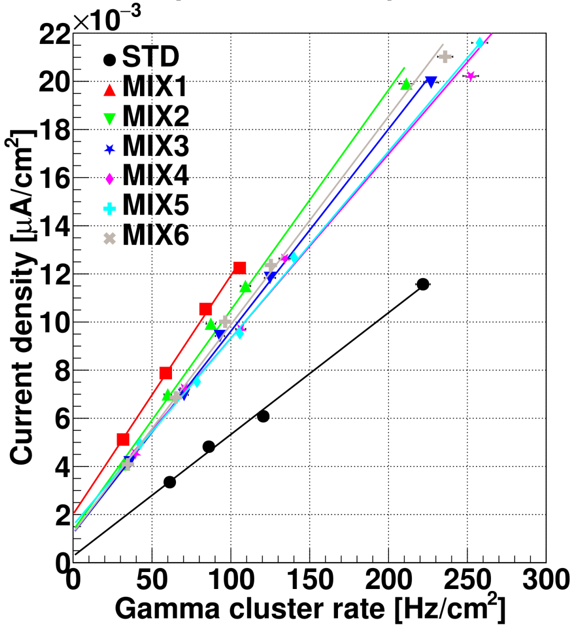
  2) CAEN digitizer
  → Waveform/charge studies

- TDC: CAEN V1190, 128 ch, 100 ps time resolution
- Digitizer: CAEN V5742, 16 input channels, 1/2.5/5 Gs/s, 12 bit with V_{pp} = 1 V

Average charge per gamma cluster

- 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

Linear fit

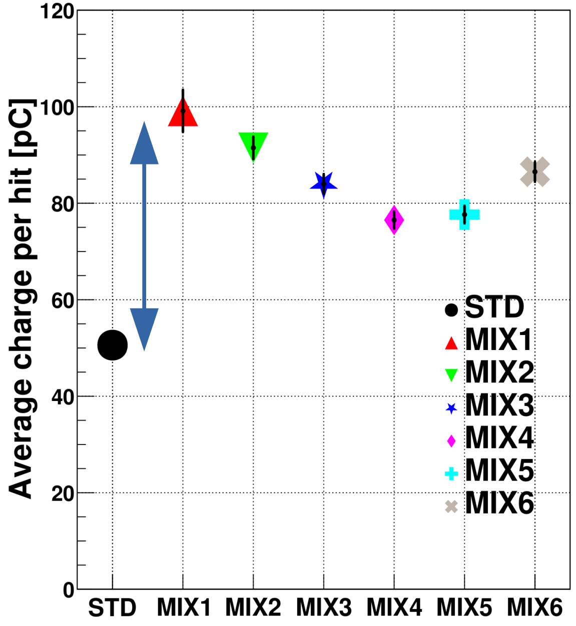
Current density

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



Average charge per gamma cluster

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

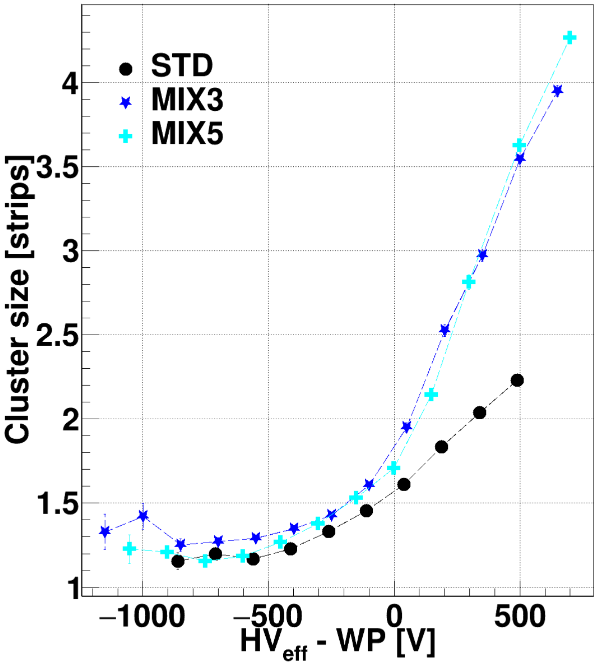
- Same result obtained for the average charge per hit

Cluster size for muons

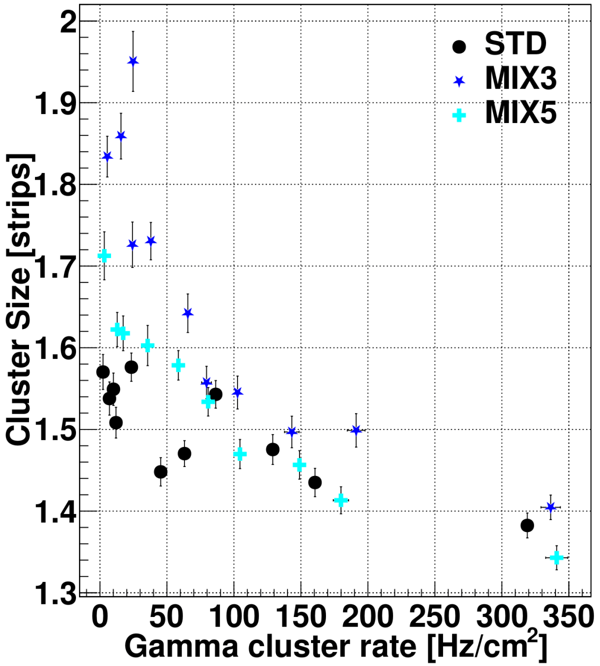
- Cluster size (CS) = number of adjacent strips with a signal above threshold for a given muon trigger
- CS computed with FEERIC data as the average of CS in the two readout planes

- CS at source off
  → Similar values for all mixtures at WP
  → For HV above the WP, CS for HFO-based gas mixtures shows steeper rise wrt STD

- CS at source on
  → Value at the recalculated WP shows a decreasing trend (for all mixtures) for increasing gamma cluster rate
  → May be explained by the current-induced voltage drop discussed earlier



Source off cluster size vs HV



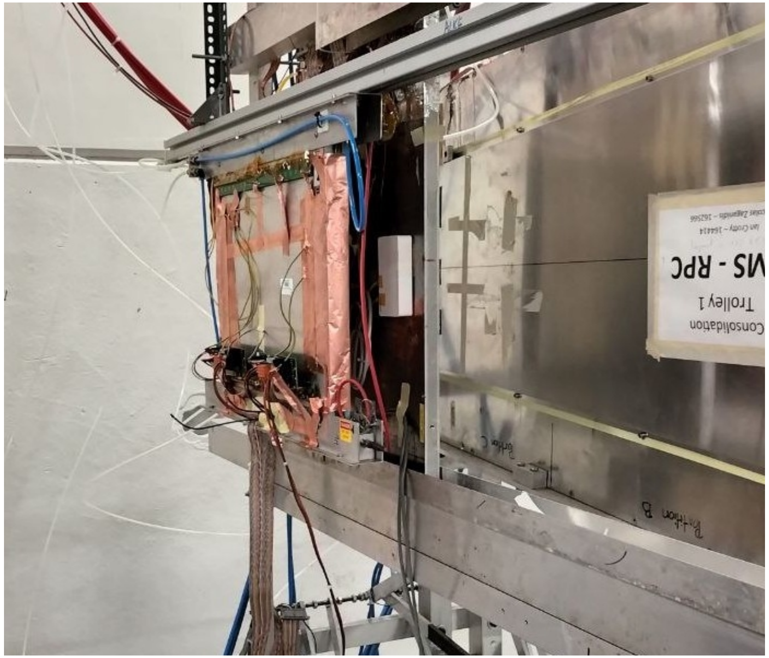
Cluster size at WP vs gamma cluster rate

Experimental setup

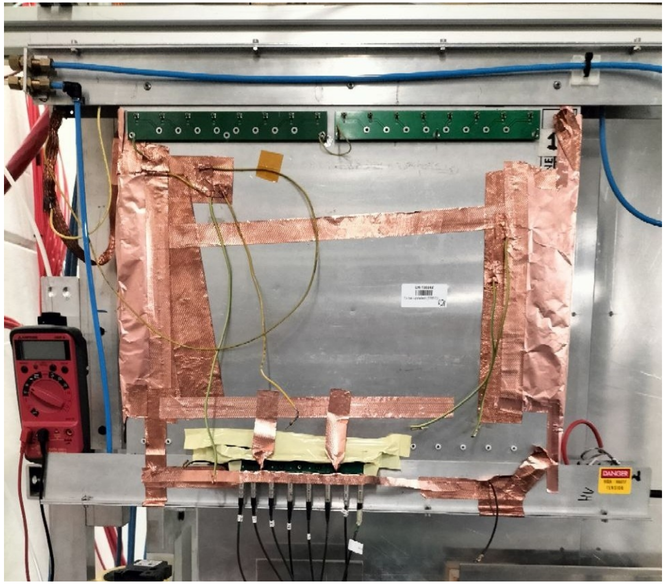
ALICE RPC

ALICE-like prototype

- 50x50 cm^2
- Single gas gap (2 mm thick)
- Bakelite electrode (2 mm thick)
- Double linseed oil coating of inner electrode surface
- 32 total readout strips (16 vertical and 16 horizontal)
- Strip pitch ~ 3 cm



ALICE RPC hanging from the GIF++ trolley 1



Front view of the ALICE RPC

“Safe” transport of the RPC to the GIF++ bunker