Searches for eco-friendly gas mixtures for the RPCs of the ALICE muon identifier

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66th ELOISATRON workshop: new gas mixtures for RPC and MRPC detectors **21/11/2022**

Overview

- The ALICE detector at the LHC
  - RPCs in ALICE

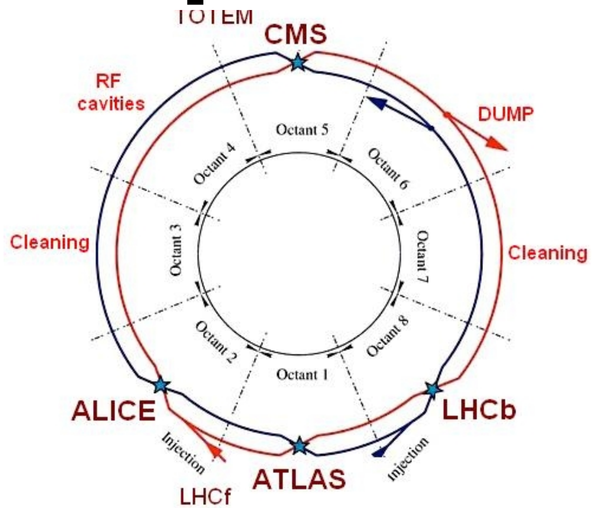
- Searches for an eco-friendly gas mixture
  - Laboratory studies with cosmics
  - The ECOgas@GIF++ collaboration
  - Beam test studies at the CERN Gamma Irradiation Facility

- Conclusions and future perspectives

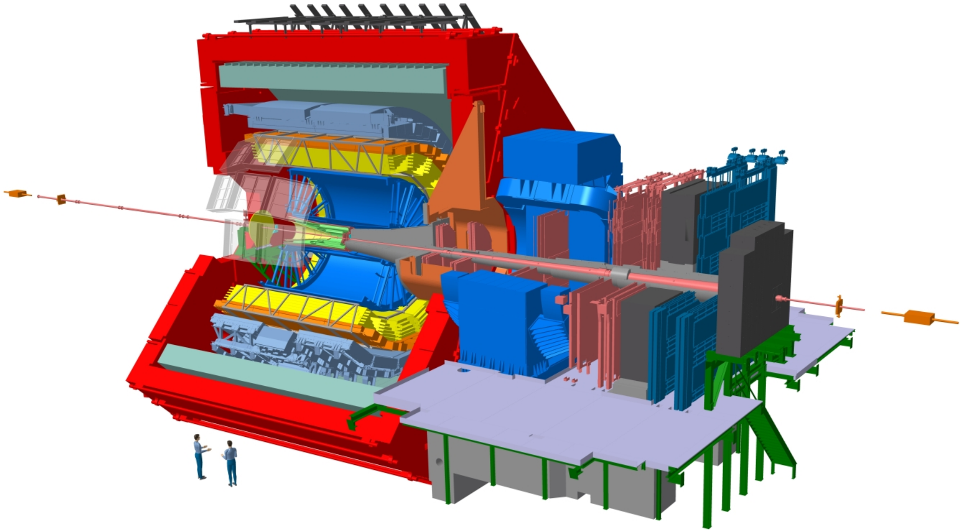
The ALICE detector

A Large Ion Collider Experiment

- ALICE is one of the 4 main experiments located on the LHC ring at CERN
- Multi purposed detector
  - Focused on **Pb-Pb** collisions
  - Taking data in **pp** and **p-Pb** (not only) for reference

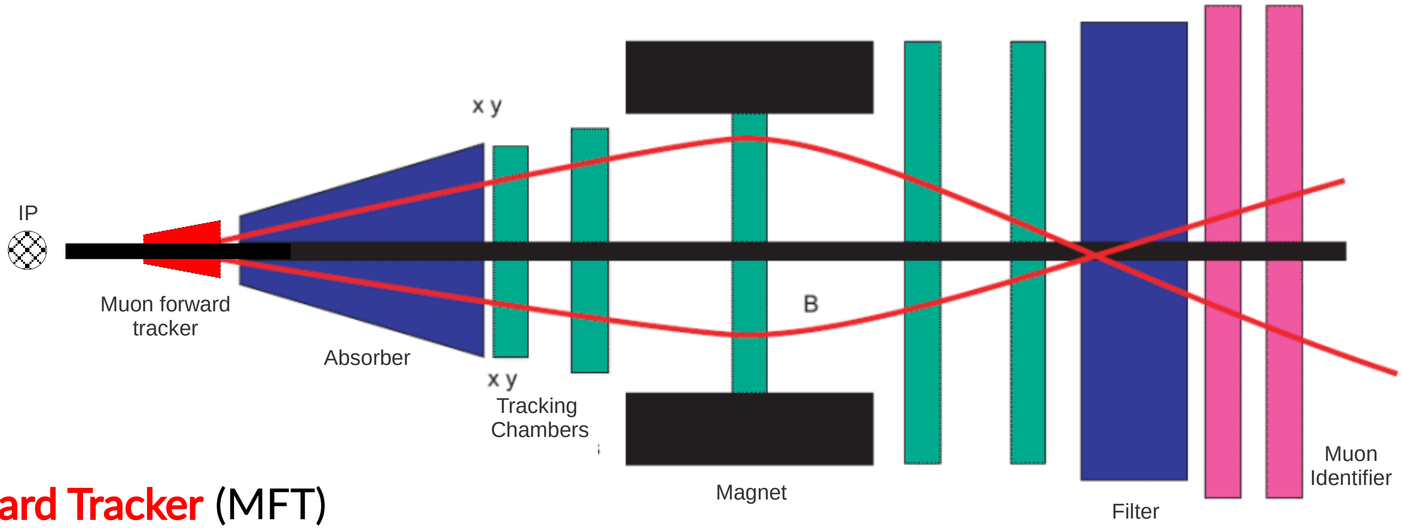


Scheme of the LHC ring


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



Muon Identifier

- Two stations of RPCs
- Provides muon identification

Muon Forward Tracker (MFT)

- Silicon pixel detector
- Added before the start of RUN3 to improve tracking in the spectrometer

Hadron absorbers

- Front absorber: composite concrete cone to reduce hadron contamination
- Filter: iron wall to stop residual hadrons

Tracking chambers

- Five stations of cathode pad/strip chambers
- Provides muon tracking

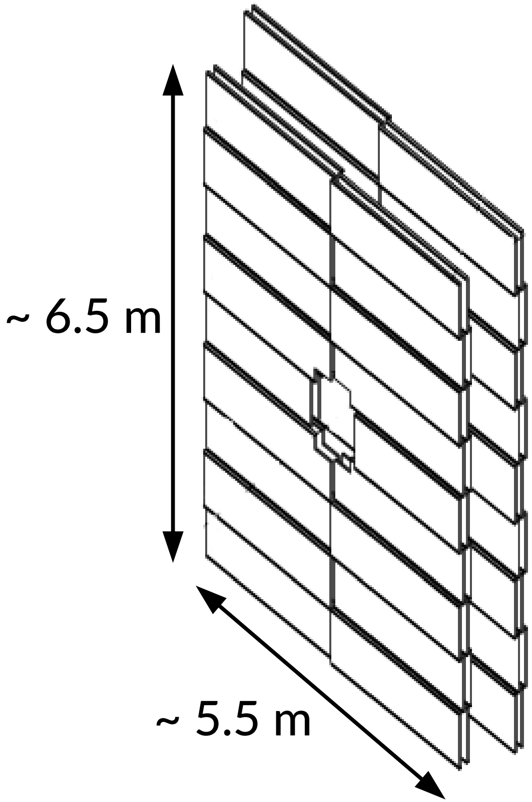
Muon Identification System (MID) - 1

- 72 single gap RPCs
- 2 mm gas gap and 2 mm thick bakelite electrodes
- Low resistivity ~ 10^9-10^{10} Ω·cm
- Two stations of two planes each (18 RPCs per plane), total area covered ~140 m^2
- Located at 16 and 17 m from the IP
- Operated in avalanche mode with the following gas mixture

$$89.7\%\ C_2H_2F_4 - 10\%\ i\text{-}C_4H_{10} - 0.3\%\ SF_6$$

- Average charge per hit ~ 25 pC
- Readout provided by means of the FEERIC [1] front-end cards, installed from RUN3 onwards

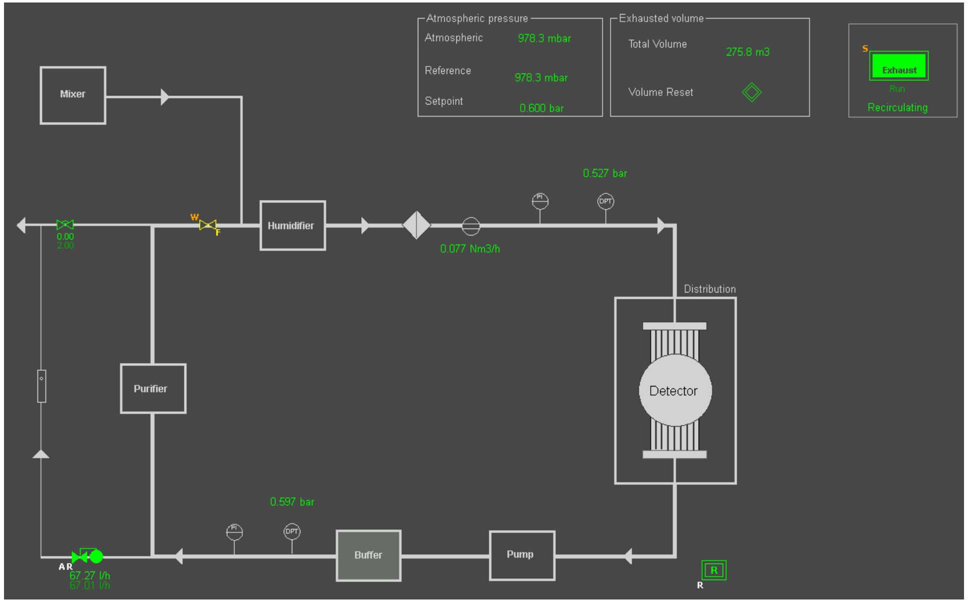
  → Pre-amplifies the signal, allowing one to reduce HV at working point and average charge per hit



Sketch of the Muon Identifier RPCs

[1] https://ieeexplore.ieee.org/document/6829539

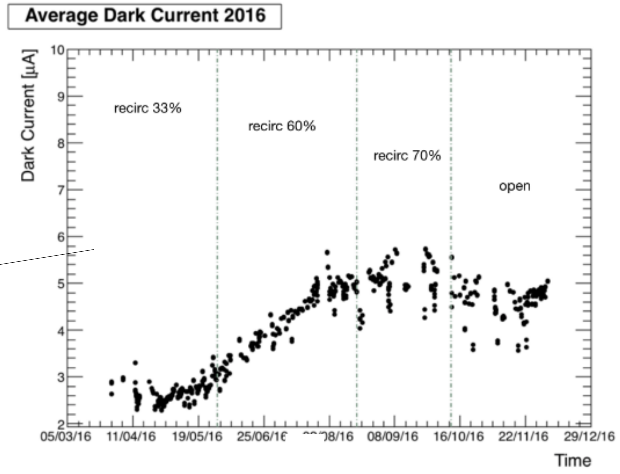
Muon Identification System (MID) -2



General scheme of the ALICE Muon Identifier RPC gas system

- Total gas volume of detectors plus piping ~ 0.3 m³
- Total gas flow ~ 150 l/h (0.5 vol/h change)
- First effort to reduce gas consumption:
  - From RUN1 to RUN2 the system was moved from open loop to closed loop (see Roberto's talk today)
  - Current recirulation fraction: 75% (only 25% of the total gas flow is fresh gas)

- Trend of dark current during recirculation studies
- No clear correlation between dark current and higher recirculation fractions
- Higher fraction chosen



B. Mandelli, RPC workshop 2018, Puerto Vallarta

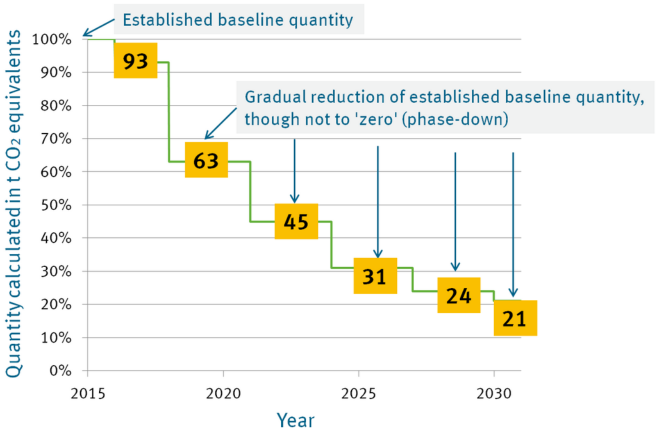
Searches for eco-friendly gas mixtures

- Motivation for the research
- Laboratory studies with cosmics
- Beam test studies @ GIF++

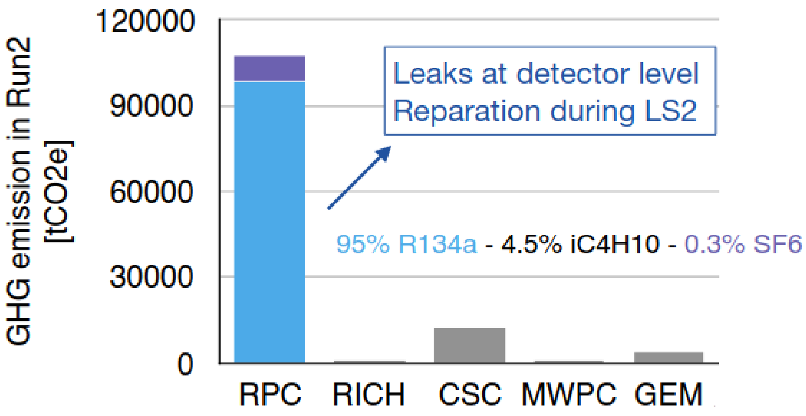
Why eco-friendly gas mixtures?

- New EU regulations have 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 phase down plan



B. Mandelli VCI 2022

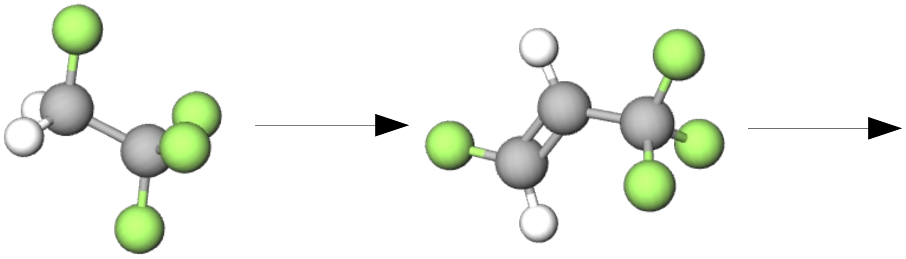
- RPCs are the main source of F-gases emissions at CERN (mainly due to gas leaks)
  → Need to find a more eco-friendly gas mixture

Experimental approach

- ALICE RPC gas mixture has a high GWP ~ 1400 due to the presence of $C_2H_2F_4$ (R134a) and SF_6

- $C_2H_2F_4$ is the main contributor to the gas mixture GWP

- First step: try to find a replacement for R134. Possible candidate: *tetrafluoropropene* ($C_3H_2F_4$, HFO-1234ze) → HFO in the following
  → Similar chemical structure to $C_2H_2F_4$ and lower GWP ~ 6



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

- Replace completely $C_2H_2F_4$ with $C_3H_2F_4$?
  → Not possible because HFO has a lower Townsend coefficient
  → Working point goes to over 15 kV
- Dilute HFO with "space-holder gas" to lower the working point
  → CO_2 is a promising choice

Running conditions in ALICE (Runs 3/4)

- Search of a new mixture in the context of the ALICE data taking
- During RUN 3 (2022-2025) and RUN 4 (2030-2032) peak Pb-Pb collisions ~ 50 kHz

pp average	pp Most exposed RPC	Pb-Pb average	Pb-Pb Most exposed RPC
5 Hz/cm^2	13 Hz/cm^2	48 Hz/cm^2	90 Hz/cm^2

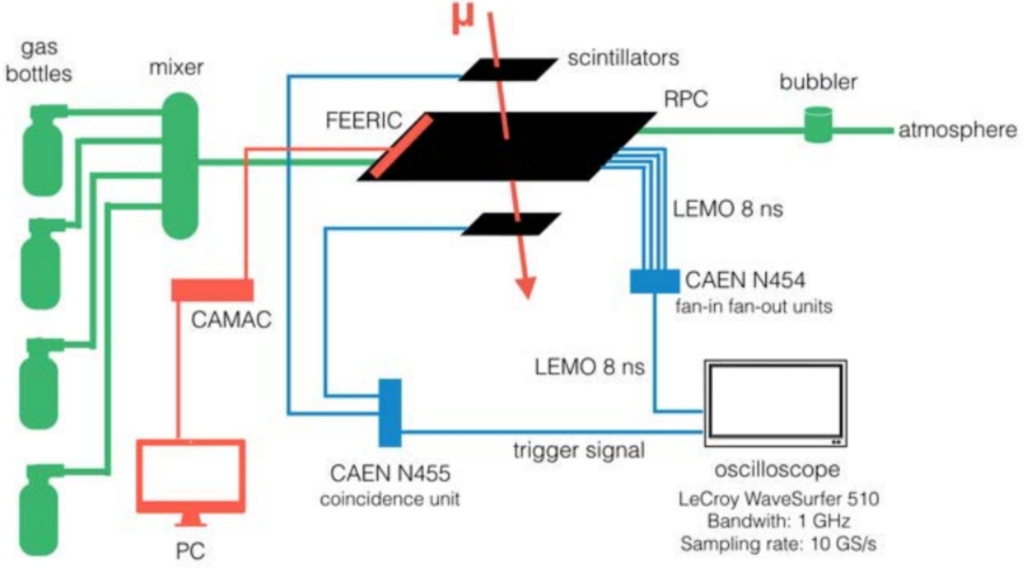
A. Ferretti, The upgrade of the RPC-based ALICE Muon Trigger – RPC 2018

- 90 Hz/cm^2 maximum hit rate on the most exposed RPCs, with a safety factor 2
- Goal: find an eco-friendly gas mixture that can satisfy the running conditions by the start of RUN 4

Preliminary results with cosmics - 1

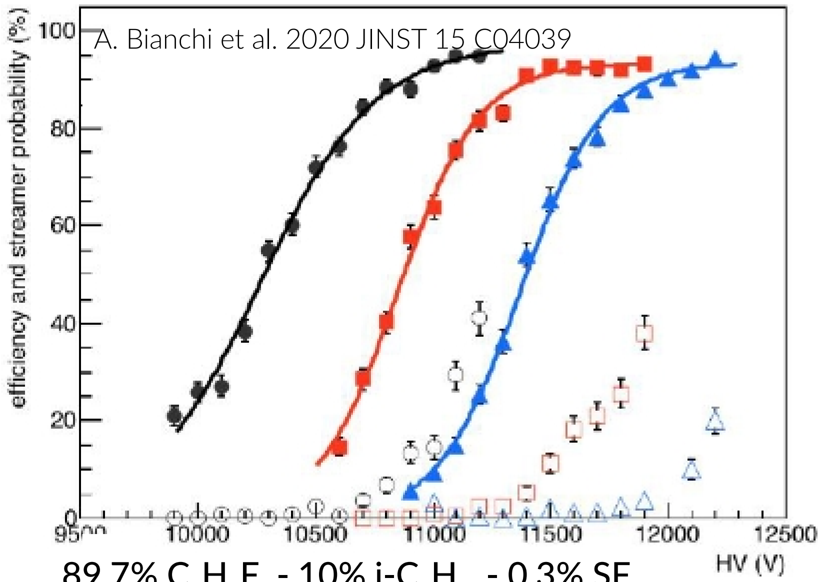
- Small cosmic setup in Torino
- Two 50x50 cm^2 ALICE-like RPCs installed in the Torino INFN laboratory
- Gas system allows one to mix up to 4 gases

- Cosmic trigger provided by the coincidence of 4 scintillators (10x10 cm^2 active area)
- Strips readout both with FEERIC boards and oscilloscope
- Complete characterization of various gas mixtures with HFO and different gases used as placeholders
- CO_2 was found to be the most promising one



Sketch of the experimental setup in the Torino laboratory
A. Bianchi et al. 2020 JINST 15 C04039

Preliminary results with cosmics - 2



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

- Promising results in terms of detector performance
  → Lower streamer probability and signal charge wrt other space holder gases

  → No current instabilities observed in the short term (observed with O_2 for example)

  → GWP ~ **1470**, **70**, **230**

- **Now:**

- Study long-term behavior of RPCs operated with eco-friendly gases
  → Aging studies

- Study of performance in more controlled environments
  → Beam tests

The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

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

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

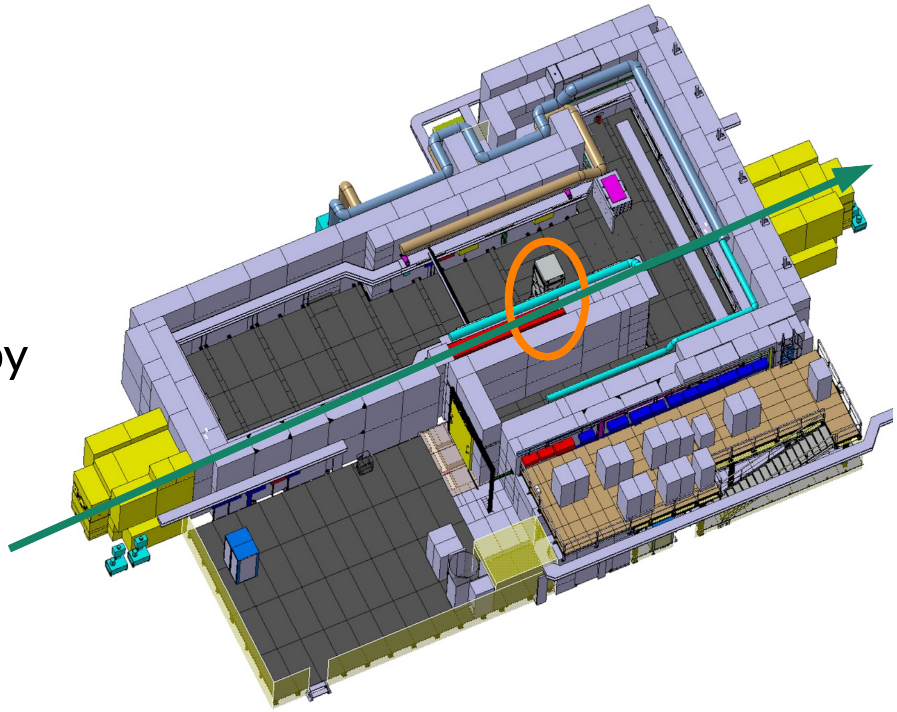
  → Experimental facility located on the H4 secondary beam line of SPS

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

  → Combination of muon beam with source

  → Study of detector rate capability



GIF++ bunker layout

Experimental setup and measurements

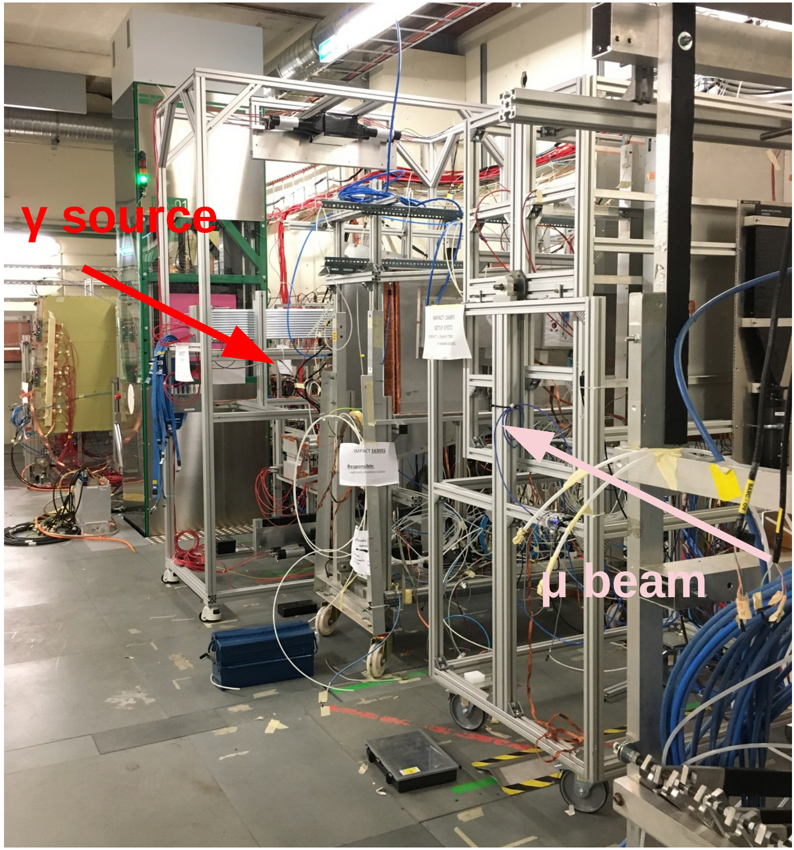
- Each group provided an RPC prototype to be tested with eco-friendly gas mixtures
  → Installed on two setups, one at 3 m from the source and one at 6 m

- Common gas and HV systems

- Results shown in the following: ALICE RPC
  → Signal acquired and digitized with new ALICE front-end electronics (FEERIC[1])

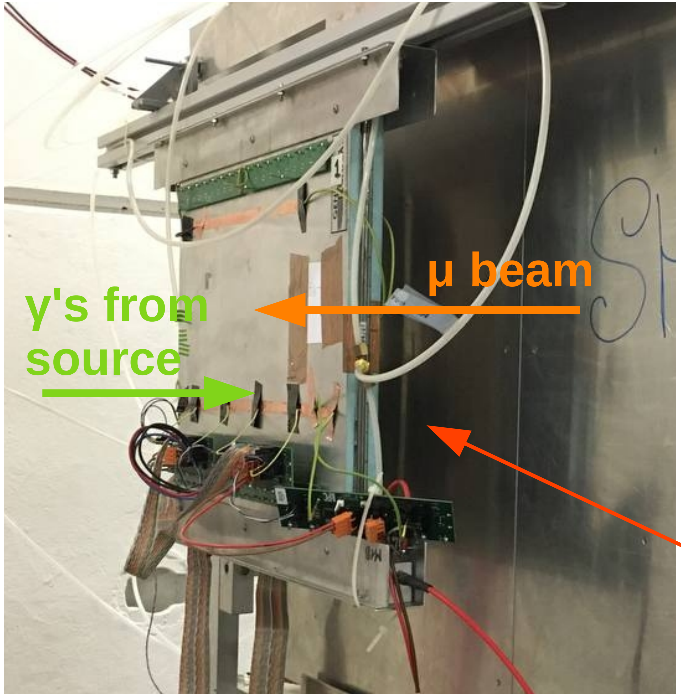
  → Direct strip readout directly w/o amplification using a CAEN DT5742 digitizer (**analysis still ongoing**)

Readout type	Front-end	# of strips	Strip readout
TDC	FEERIC	32	2D
Digitizer	–	7	1D



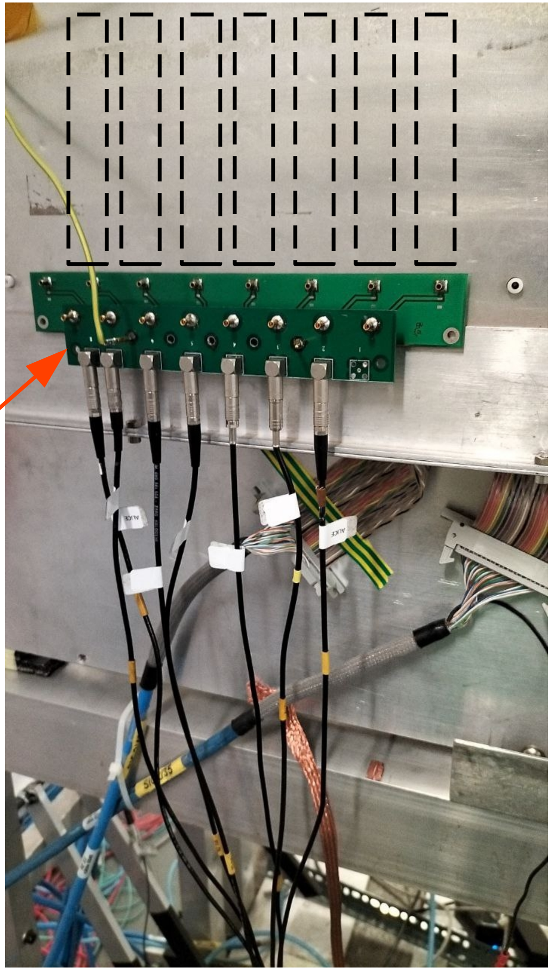
View of the setups inside the GIF++ bunker

The ALICE ecogas RPC



View of the ALICE RPC with FEERIC boards

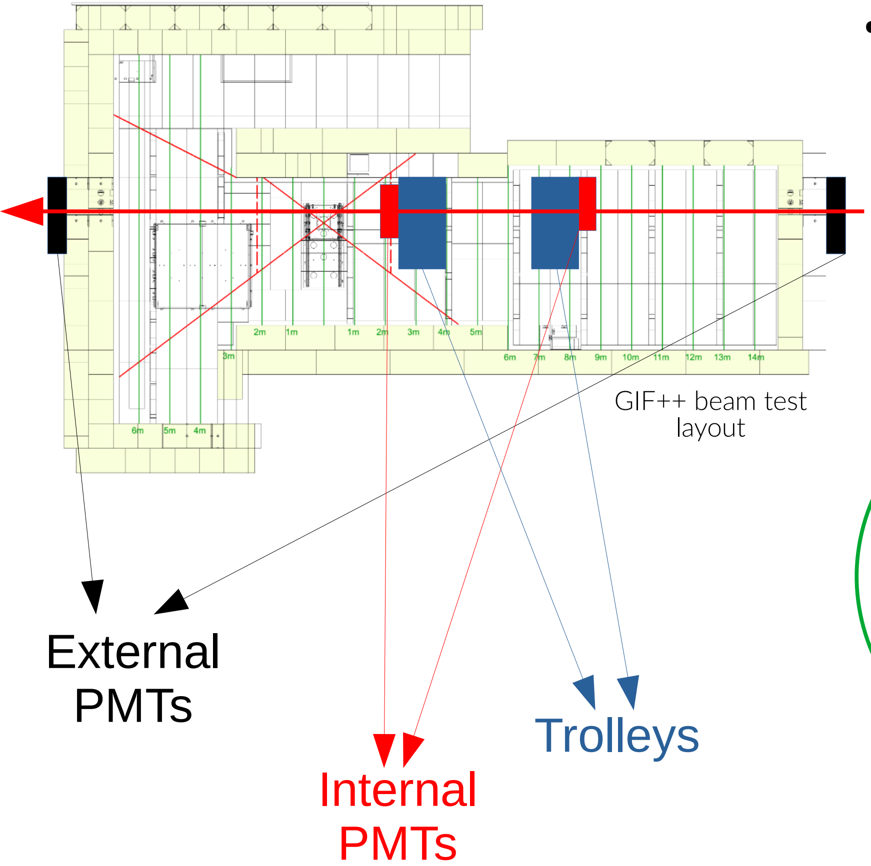
- 50x50 cm^2 single gap bakelite RPC
- 16 strips in two perpendicular directions (allowing 2D readout)
- Strip pitch ~ 3 cm
- Mechanical frame allows one to connect the strips either to the front-end boards or directly to the digitizer


Direct strip connection

- Signal from FEERIC are read out with a VME TDC, using a common DAQ system
- Digitizer DAQ is standalone

Beam test setup

- Trigger provided by coincidence of 4 scintillators (2 inside the facility and 2 outside)
- Need to acquire both the signals from muon and gammas

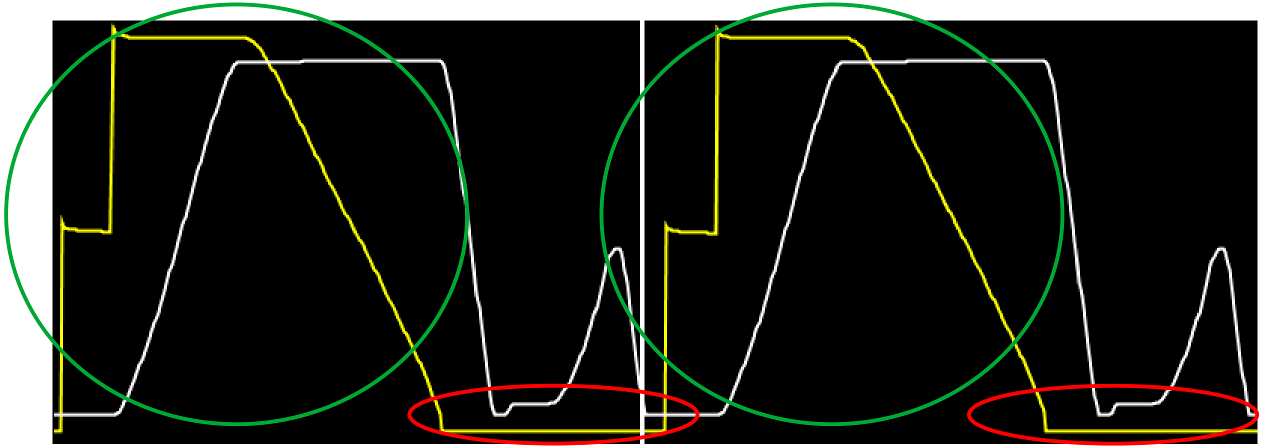


GIF++ beam test layout

- How?
  → Split trigger windows

  1) **During μ spill** → PMT trigger → efficiency measurement

  2) **Outside spill** → random trigger → rate measurement



SPS spill cycle

Studied gas mixtures

- Different gas mixtures, varying the ratio between HFO and CO_2, have been studied in beam tests

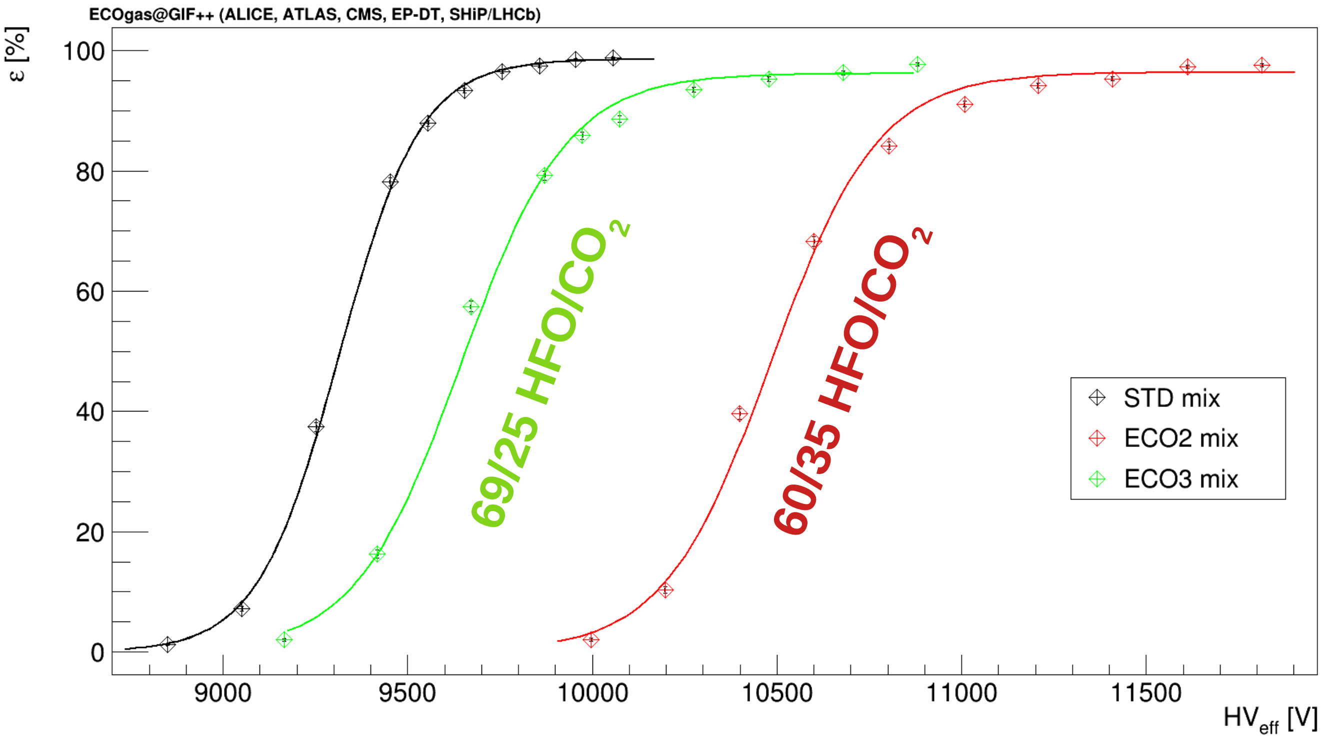
- CMS/ATLAS standard gas mixture taken as a reference (the standard ALICE mixture is flammable and can not be used @ GIF++)

Mixture name	R134a (%)	HFO (%)	CO2 (%)	i-C4H10 (%)	SF6 (%)	Other name	GWP
STD	95.2	0	0	4.5	0.3	STD	1430
MIX0	0	0	95	4	1	//	229
MIX1	0	10	85	4	1	//	230
MIX2	0	20	75	4	1	//	230
MIX3	0	25	69	5	1	ECO3	230
MIX4	0	30	65	4	1	//	231
MIX5	0	35	60	4	1	ECO2	231
MIX6	0	40	55	4	1	//	231

- Two mixtures (**ECO2** and **ECO3**) have been tested by the whole collaboration (ALICE using FEERIC boards)

- Other mixtures tested only on ALICE detector, with digitizer

FEERIC results

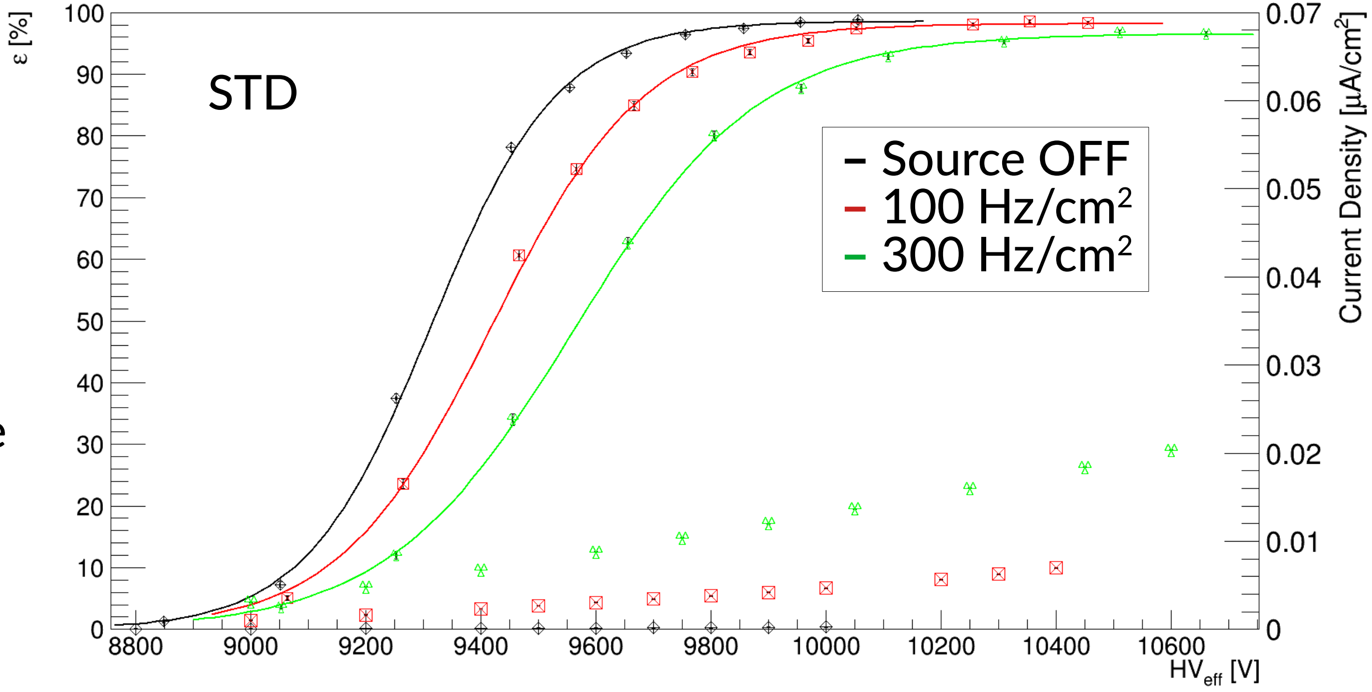


- 2D efficiency
  → Hit in x and y plane
- Definition of knee as the voltage where efficiency reaches 95% of its maximum value
- The curves shown are taken with source OFF (no irradiation)

- Shift of the efficiency curve to higher voltages wrt standard gas mixture
  → Expected due to HFO
  → Higher if HFO fraction is higher
- Plateau shift wrt STD: ~ 1.2 kV for ECO2 and ~ 0.4 kV for ECO3

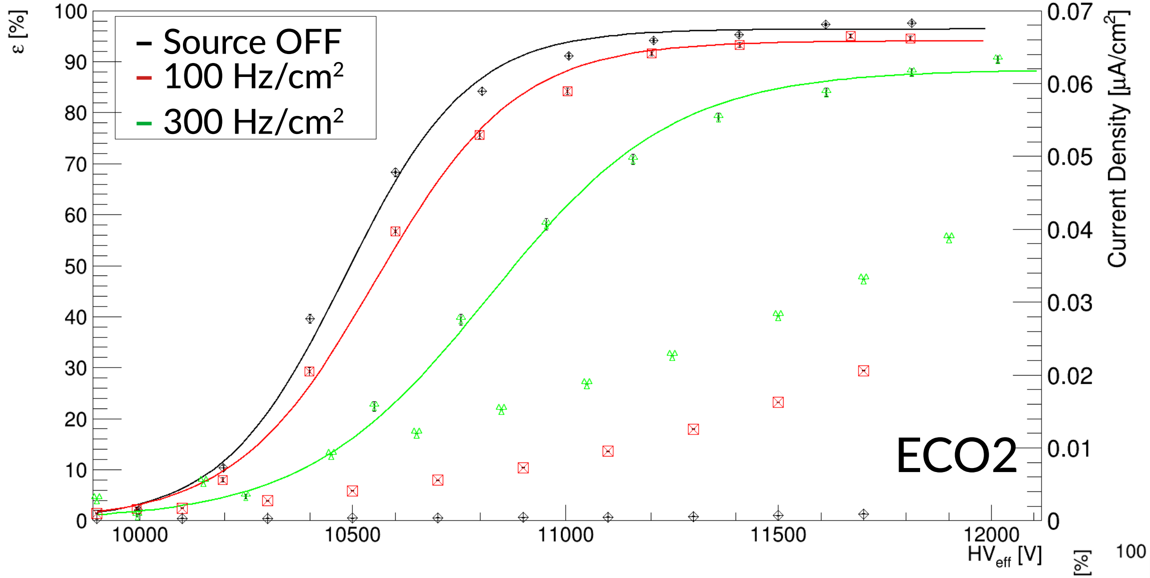
Efficiency under irradiation (STD)

- Efficiency and surface current density curves with STD gas mixture
- Three irradiation conditions have been chosen: source OFF, ABS 10 and ABS 2.2
- Cluster rate measured by the RPC in interspill (i.e. no beam). Defined as gamma strip rate divided by gamma cluster size



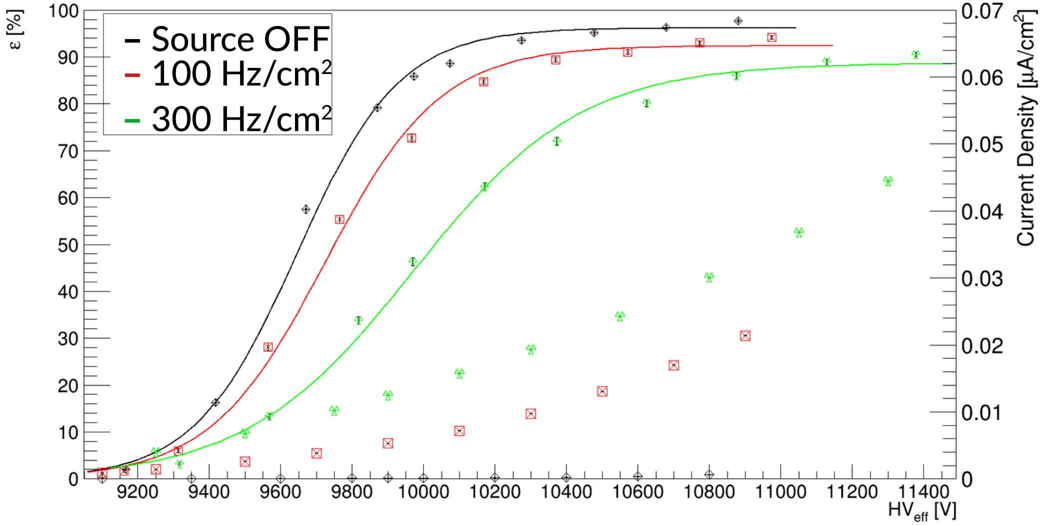
- Efficiency plateau shifts to higher voltages if gamma rate increases
  → Rate capability
- Maximum value of efficiency decreases
- To be compared with ECO2 and ECO3 gas mixtures

Efficiency under irradiation (ECO2 vs ECO3)

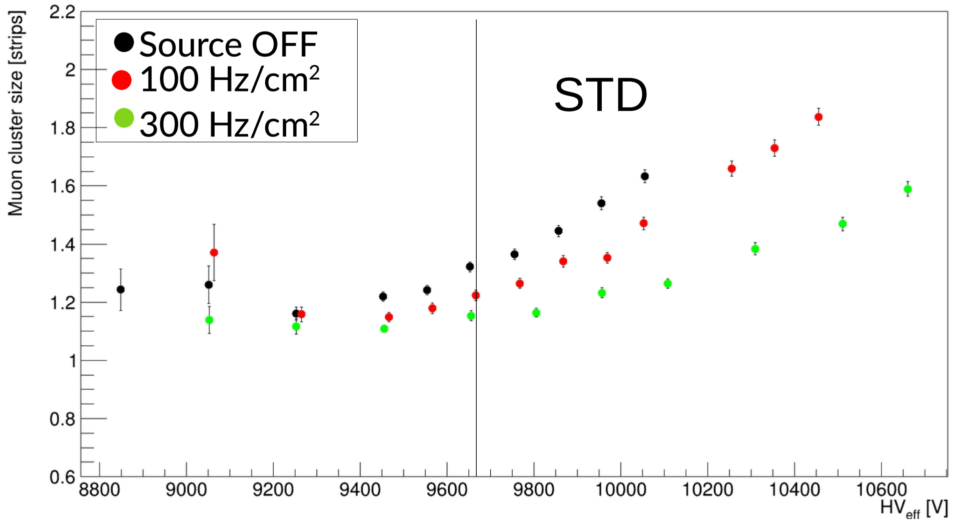


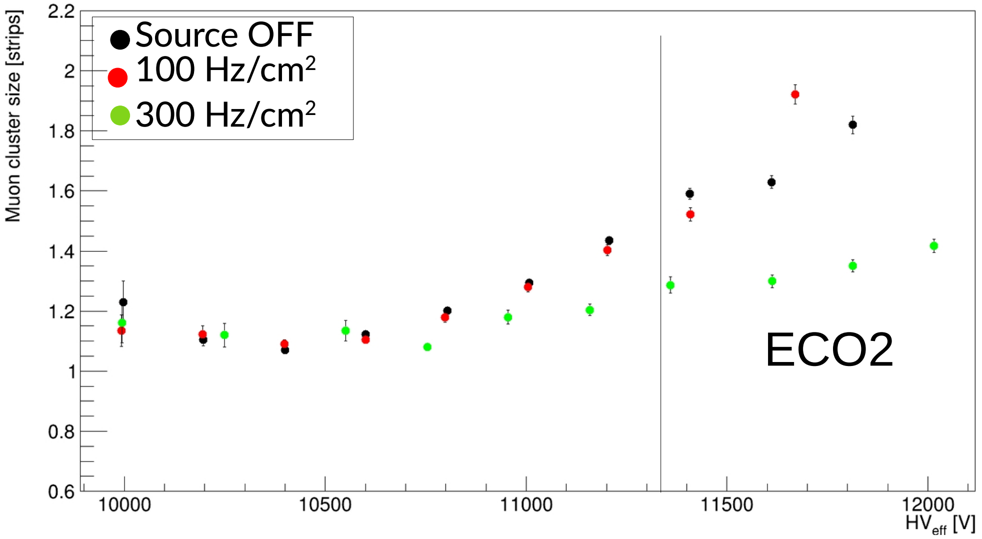
- Efficiency plateau reached for both mixture even under high irradiation conditions
- Higher (2x) currents wrt STD (double) gas mixture
  → New irradiation campaign to understand if this poses any problems

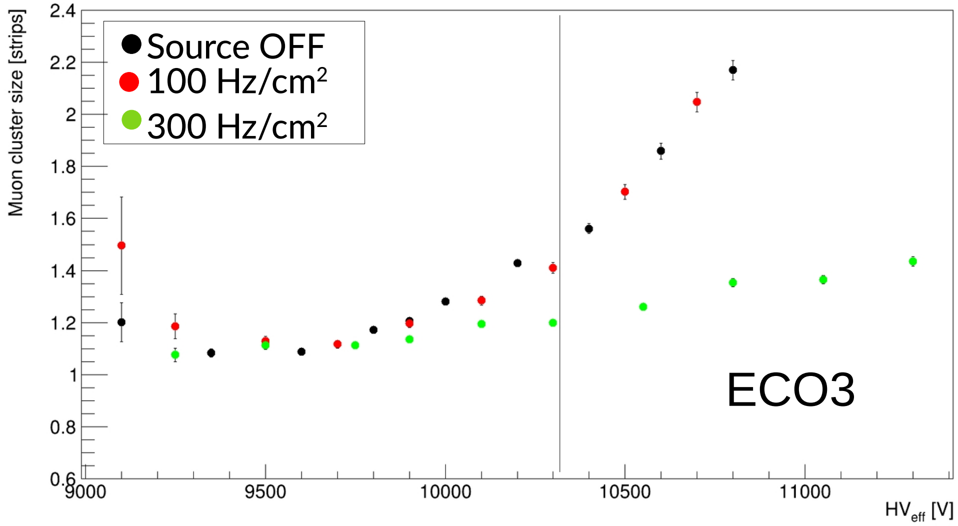
- Higher drop if the maximum efficiency wrt STD
- From gamma rate estimation (using data from ALICE RPC)
  → Curve at 100 Hz/cm^2 of gamma rate (red) simulates best ALICE running conditions
- 300 Hz/cm^2 (green) is a condition that will never be reached in ALICE



Cluster size

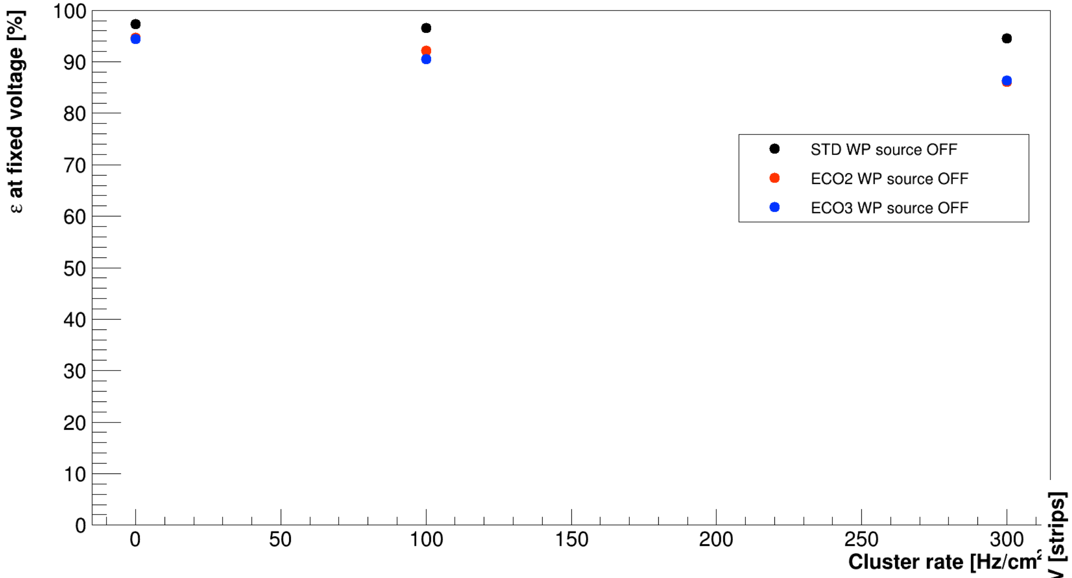






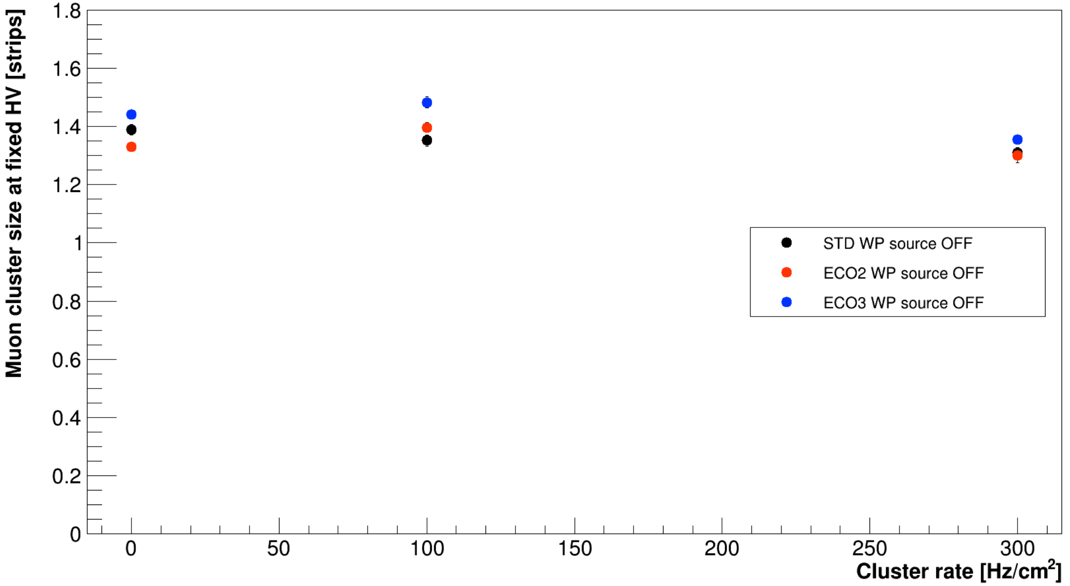
- Mean muon cluster size for the three tested gas mixtures for the three different irradiation conditions
- Vertical line is the working point at source OFF
- Comparable for the three mixtures and for the three irradiation conditions
- Average cluster size values slightly decrease with increasing irradiation

Main results with FEERIC



- Efficiency at fixed HV as a function of the gamma rate
- Value chosen to be the working point at source OFF
  → Knee of the efficiency curve + 150 V
  → Different for the three mixtures
- Efficiency drop of around 4% at 100 Hz/cm^2 and 10% at 300 Hz/cm^2 (could possibly be recovered with a lower FEERIC threshold?)
  - Similar between ECO2 and ECO3

- Cluster size at fixed HV as a function of the gamma rate
- Value chosen to be the working point at source OFF
- Constant trend for all the gas mixtures and all irraditaion conditions



PRELIMINARY!!

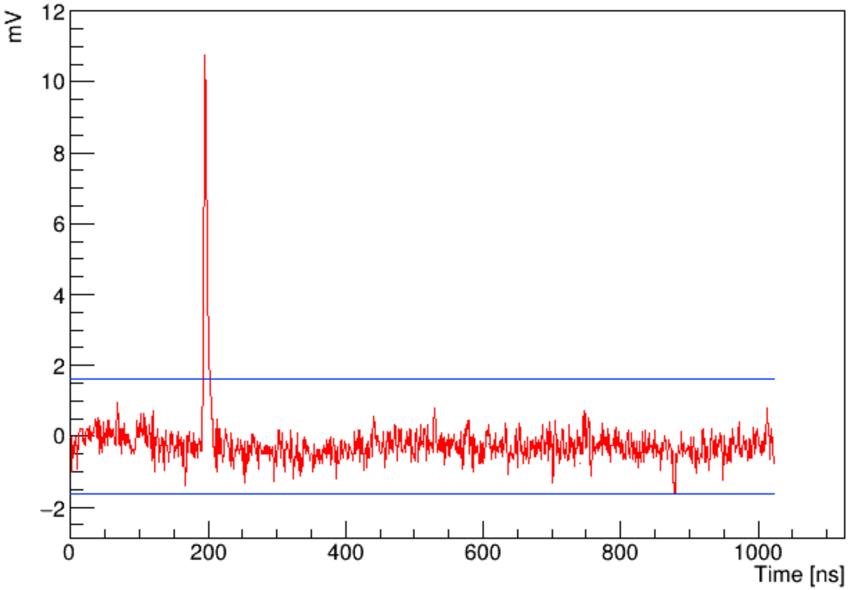
Digitizer studies

- Setup and analysis method
- Charge distributions
- Ecogas studies with digitizer

Why using a digitizer?

PRELIMINARY!!

- It allows to sample the nude signal coming from the RPC
  → Signal shape
  → Prompt charge
  → Time Over Threshold
  → Efficiency, muon cluster size, gamma rate are also measurable
  → More complete study of the signal



Example of digitizer signal obtained from a fired strip

- Digitizer model: CAEN DT5742

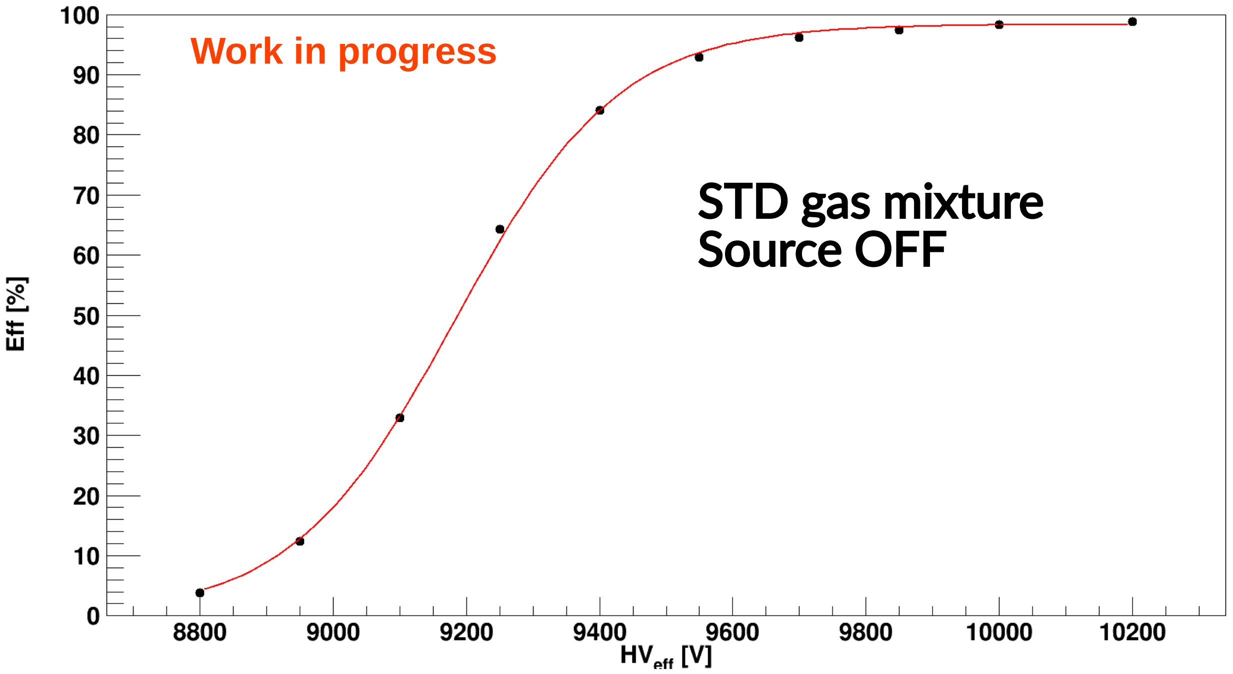
  → 1024 samples per trigger @ 1 Gs/s
  → Acquisition window = 1024 ns
  → 16 channels
  → 12 bit resolution (V_{pp} = 1V)

  → Trigger as with FEERIC boards (muon signal during spill and gamma signal out of the spill)

Signal analysis and example

PRELIMINARY!!

- RMS of the signal estimated in fixed noise window before muon signal
- Muon window = time interval where a muon signal is expected
- If any of the 7 strips is above 5RMS in the muon window
  → RPC is efficient (no spatial cut for now)



Important: necessary to know the conversion factor between FEERIC threshold and signal amplitude to exactly compare FEERIC and digitizer results (5RMS threshold assumed for preliminary studies)

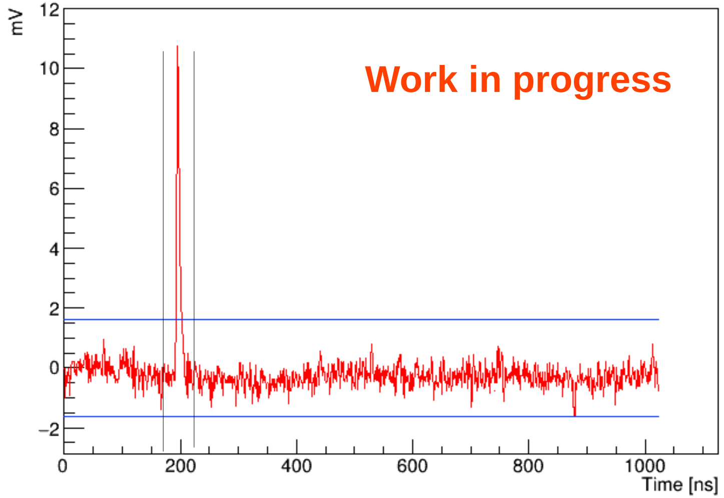
- Efficient events are then further processed:
  → Prompt charge calculation (streamer contamination)

  → Cluster size

  → Time Over Threshold

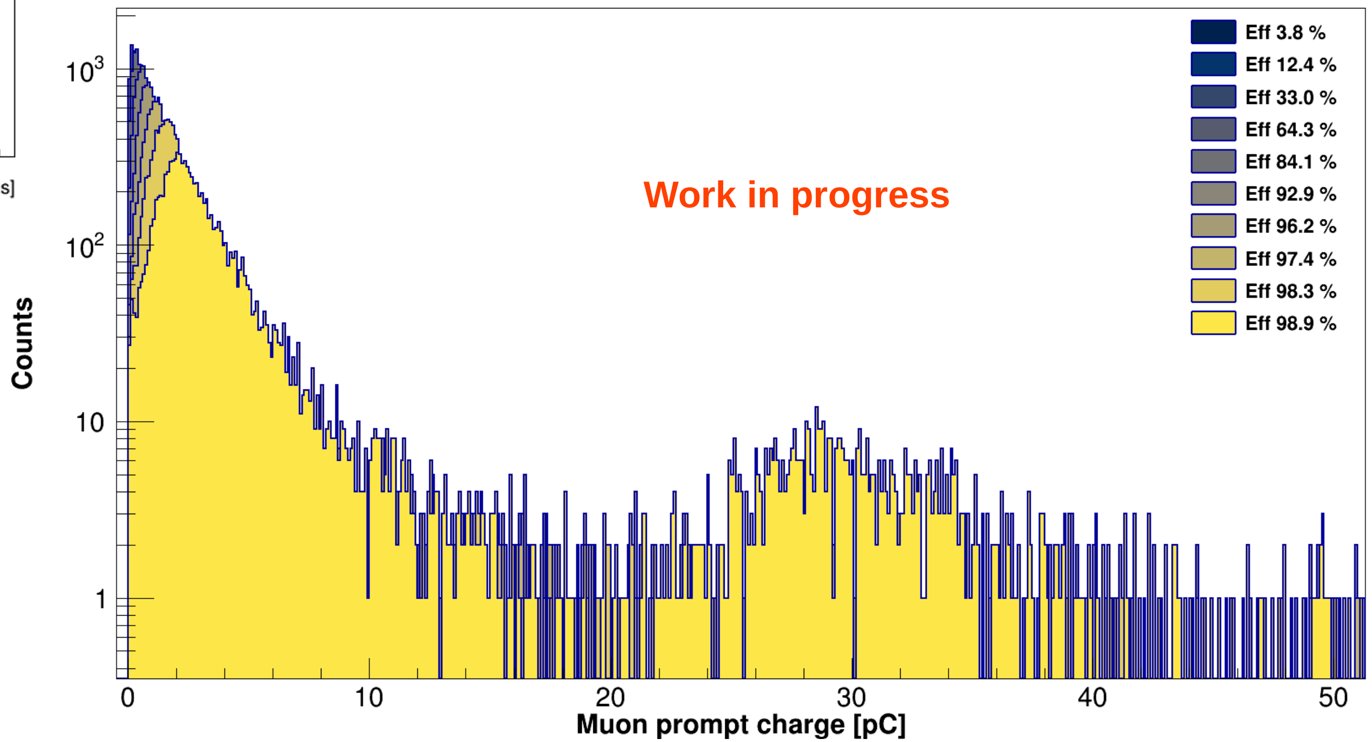
Prompt charge calculation

PRELIMINARY!!



- For each trigger the charge is summed over all the strips
- Evolution of the prompt charge spectrum for the standard gas mixture at source OFF
- O(10^4) triggers per HV point in enough to measure streamer contamination

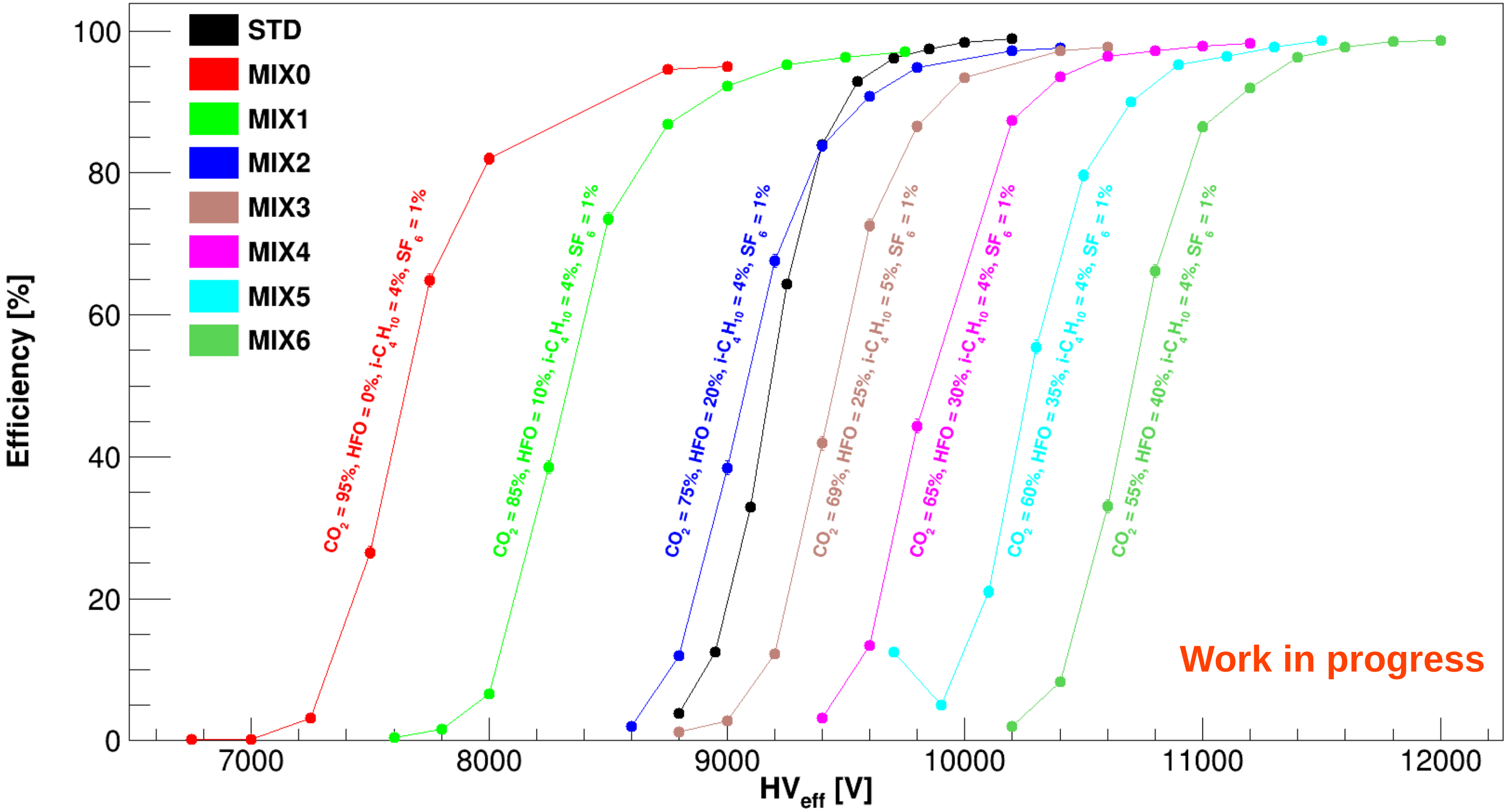
- Algorithm developed to integrate each signal
- For each efficient event the integration region is found and the integral is computed



Source OFF results - 1

PRELIMINARY!!

- 7 gas mixtures tested (plus standard for reference), decreasing the CO_2 percentage from 95% down to 45% (HFO varying accordingly and other % fixed)
- Aim of the study: understand the interplay between CO_2 and HFO

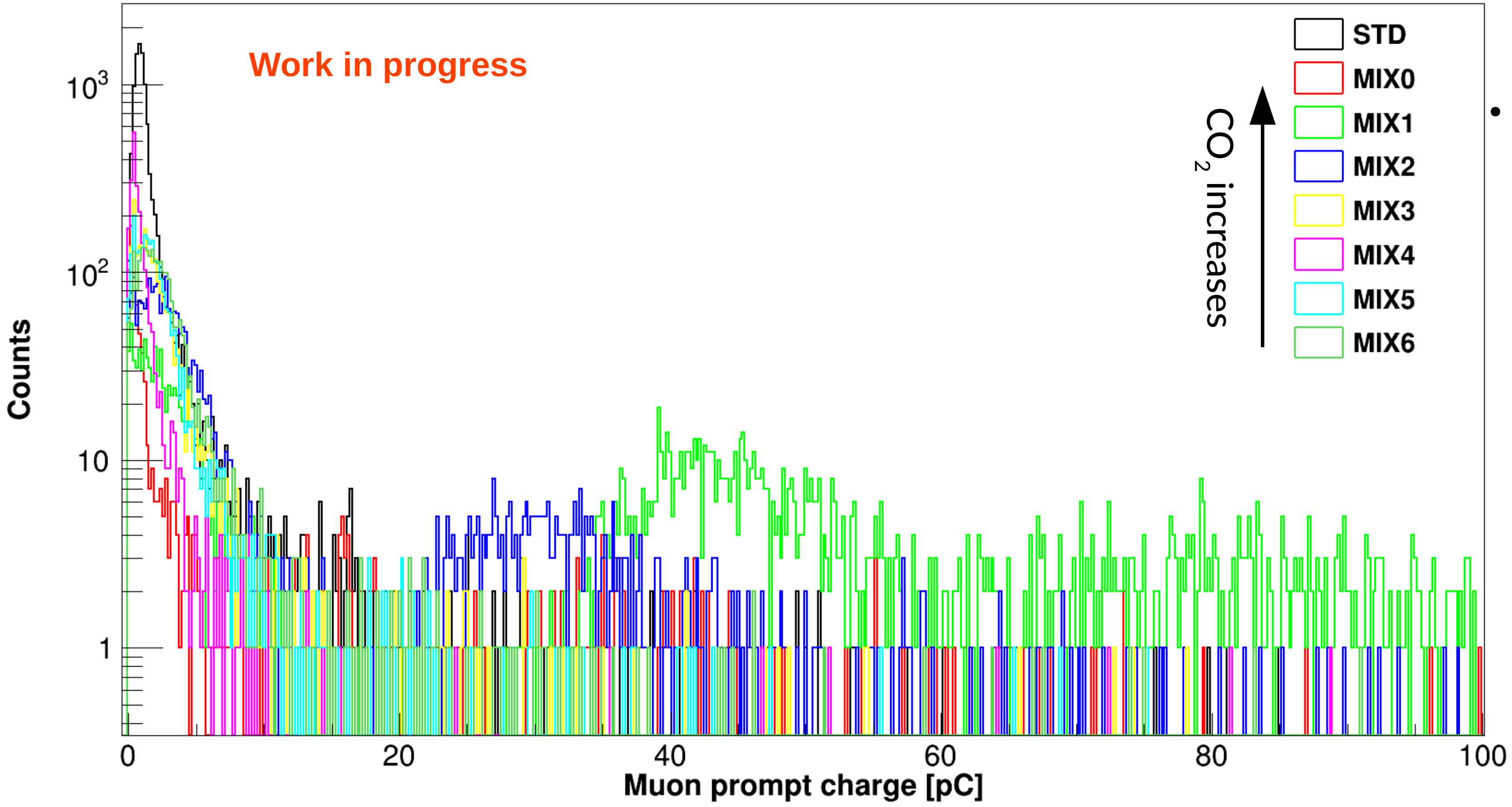


- Efficiency curves as a function of the HV
- With the digitizer we can dig deeper than just efficiency curves

Source OFF results - 2

PRELIMINARY!!

- Charge spectra for the different gas mixtures at fixed efficiency value (95%)



- Different shape of the spectra wrt standard gas mixture:

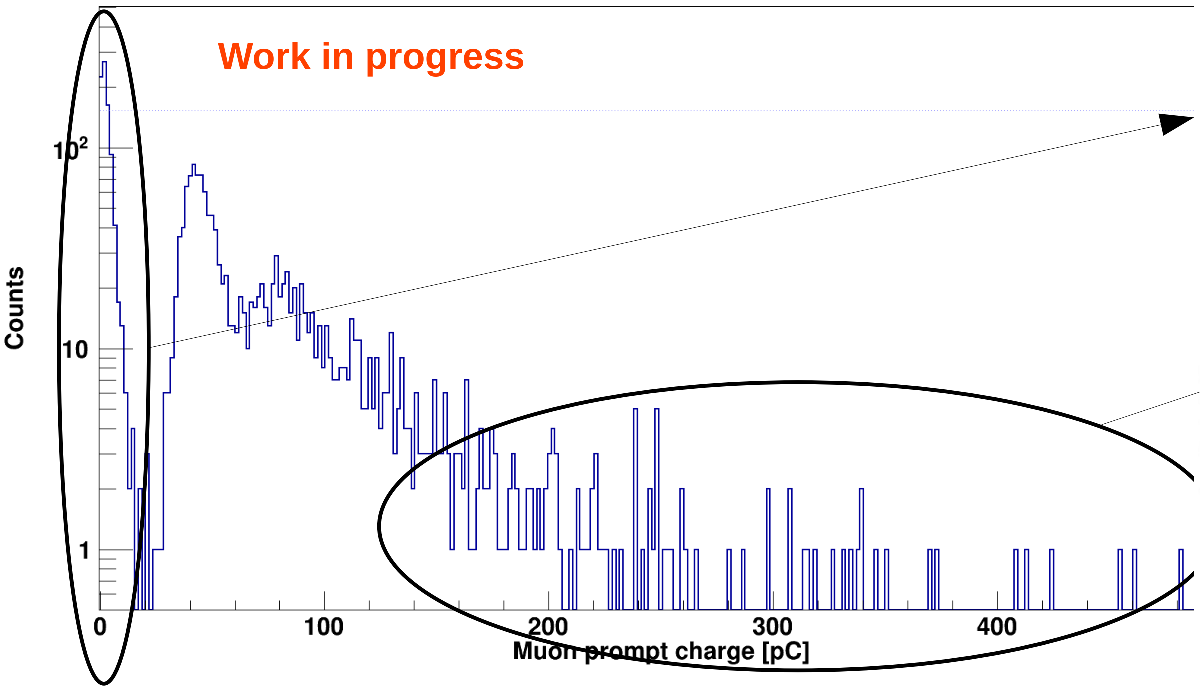
  → From peaked to exponential distribution at low charge (the more CO_2 the more this is evident)

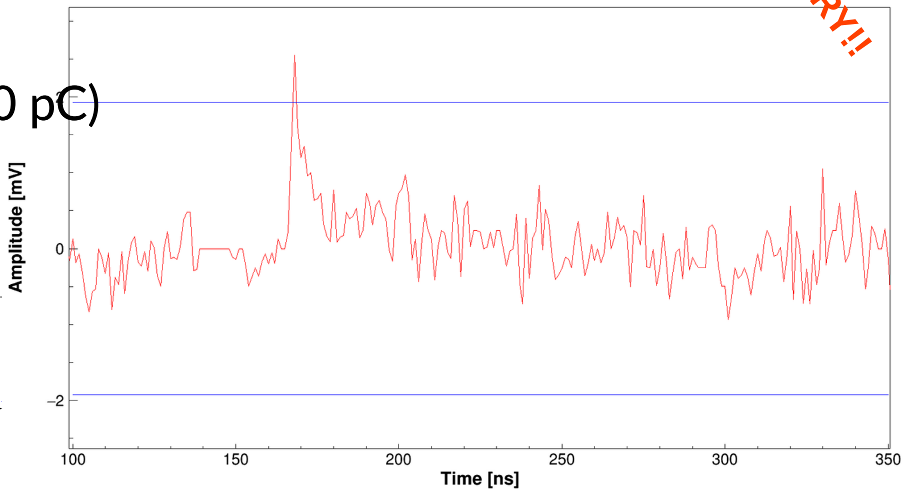
  → "Streamer" region becomes more populated as CO_2 increases

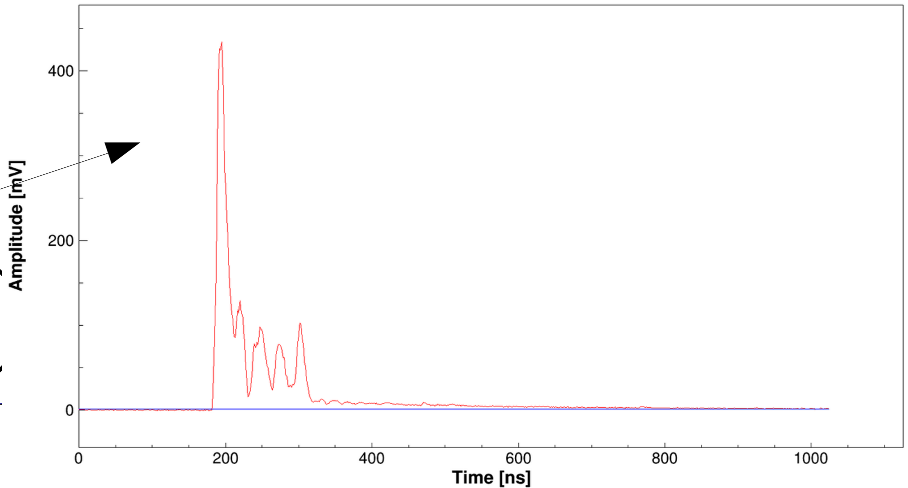
Source OFF results - 3

PRELIMINARY!!

- To really be sure that signal with charge close to 0 pC are not noise we can look at the signal shape
- Same can be done for signals with a big charge (> 100 pC)
- Spectrum of charge for MIX1 (85% CO_2 - 10% HFO) at WP



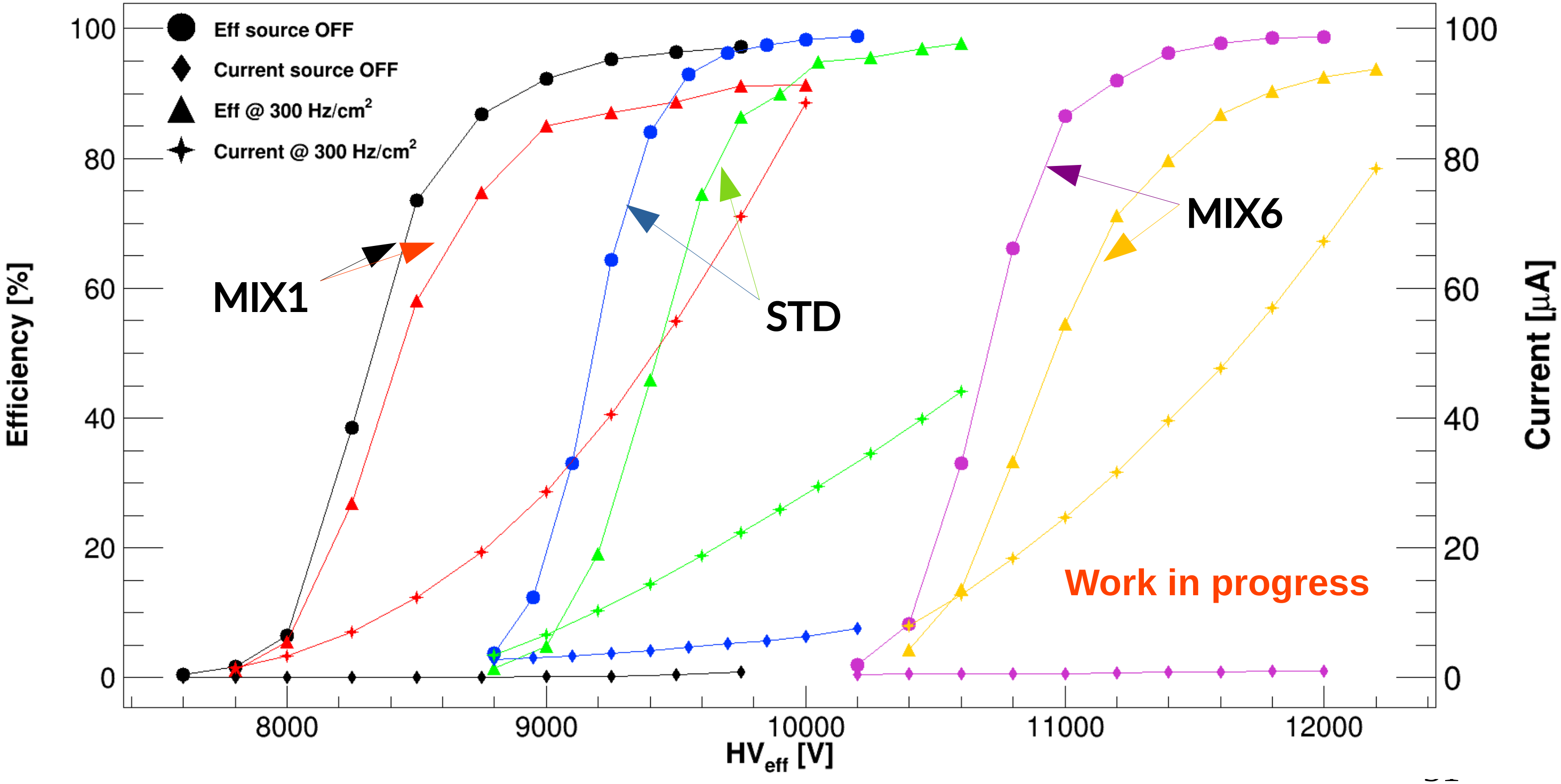




Source ON results - 1

PRELIMINARY!!

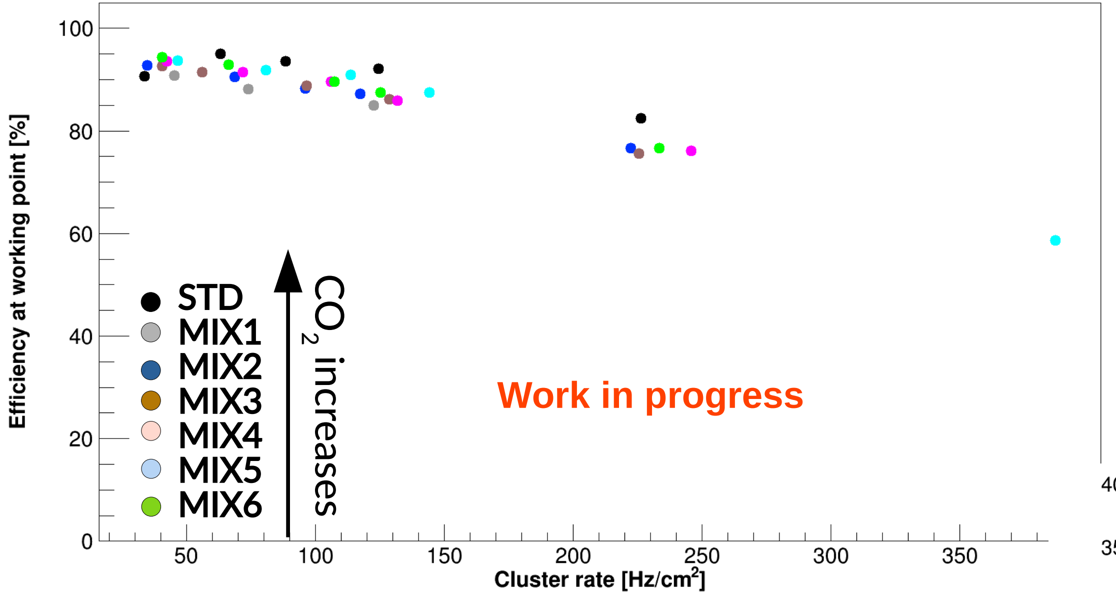
- Efficiency and current curves for three different gas mixtures (**STD**, **MIX1** (85% CO_2) and **MIX6** (55% CO_2)
- 4 or 5 different irradiation conditions (2 shown) for each mixture (0 to 300 Hz/cm²) have been studied
- Curve positions are different for the different mixtures
- MIX1 does not reach the same efficiency as the other two (for same irradiation condition)
- Spread of the curves with increasing irradiation seems to increase if more HFO is added



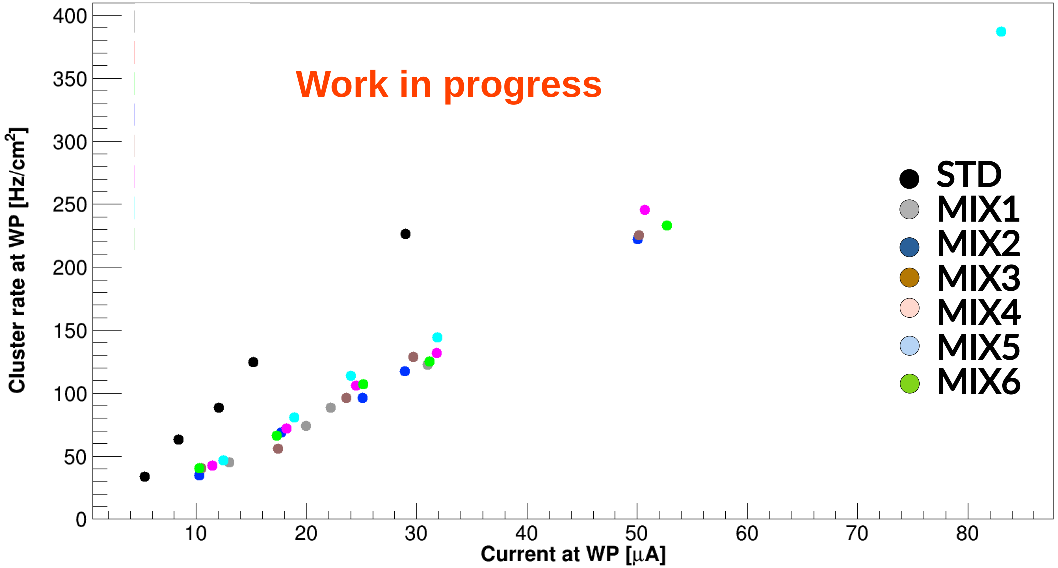
HFO % increases

Source ON results - 2

PRELIMINARY!!



- Efficiency value at fixed HV (source OFF working point) as a function of the gamma cluster rate
- All gas mixtures tested
- Efficiency drop more pronounced for eco gases wrt standard gas mixture



- Gamma cluster rate at working point (for given irradiation condition) as a function of the absorbed current
- Linear trend for all the tested gas mixtures
- Slope of the line passing by the points = average charge per hit

Conclusions

- The **search for an eco-friendly gas mixture for the ALICE RPCs** (and for RPCs in general) is an ongoing effort

- RPC **EcoGas@GIF++ collaboration** born to perform in-depth studies on more eco-friendly gas mixtures for RPC detectors
  → **Studies under gamma irradiation** for aging purposes
  → **Beam test studies** to better characterize the operation of RPCs with new gas mixtures

- Focused on the study of **full replacement of R134a with HFO**-1234zd and **CO_2**

- **Promising results** obtained with at least one of the tested eco-friendly mixtures
  → Long term stability studies ongoing at GIF++ now carried out by EcoGas@GIF++ collaboration

- Study of **charge spectra** with the digitizer opens insights into the streaming contamination and allows one to fully characterize a given mixture

- **To analyze more precisely digitizer data**: measure correspondence of FEERIC threshold and digitizer signal amplitude

Thank you for your attention!