INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

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Assessing long-term performance of eco-friendly RPCs

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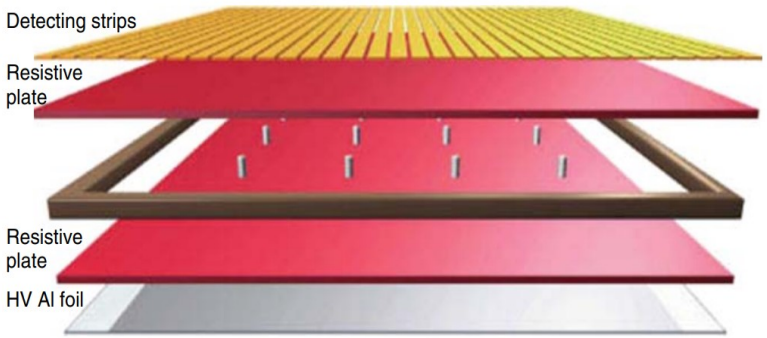
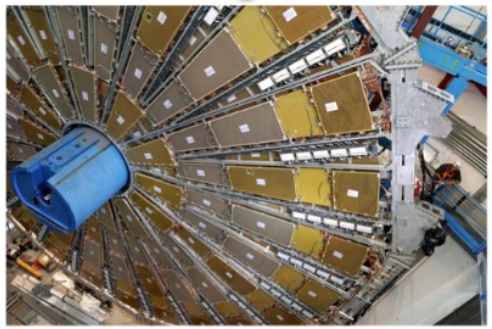
Resistive Plate Chambers



Gaseous detectors widely employed in HEP experiments for triggering and particle ID purposes:

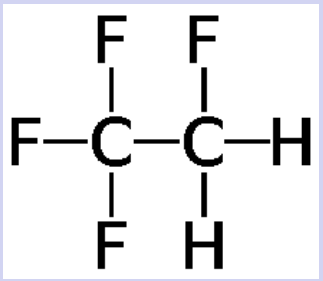
- low cost per unit area;
- high efficiency and time resolution;
- ease of construction and robustness.

Total area currently covered by RPCs at the LHC experiments: ~7000m^2

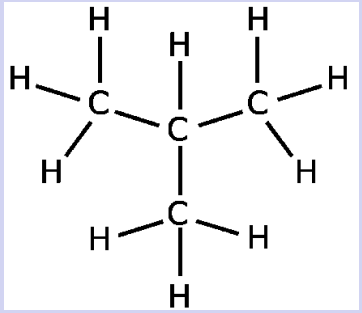


«Standard» gas mixture for RPCs

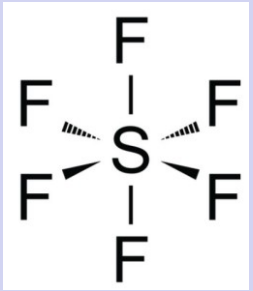
- High density of primary ion-electron pairs:
  high RPC efficiency
- Good quenching properties and electronegativity
  good rate capability and "slow" detector ageing



R134a (>90%)



iC_4H_{10}



SF_6 (<1%)

However, R134a and SF_6 are Fluorinated Greenhouse gases (F-gases) having high **Global Warming Potential (GWP)***
[e.g. the main component for standard gas mixture (R134a) has GWP as high as 1430]

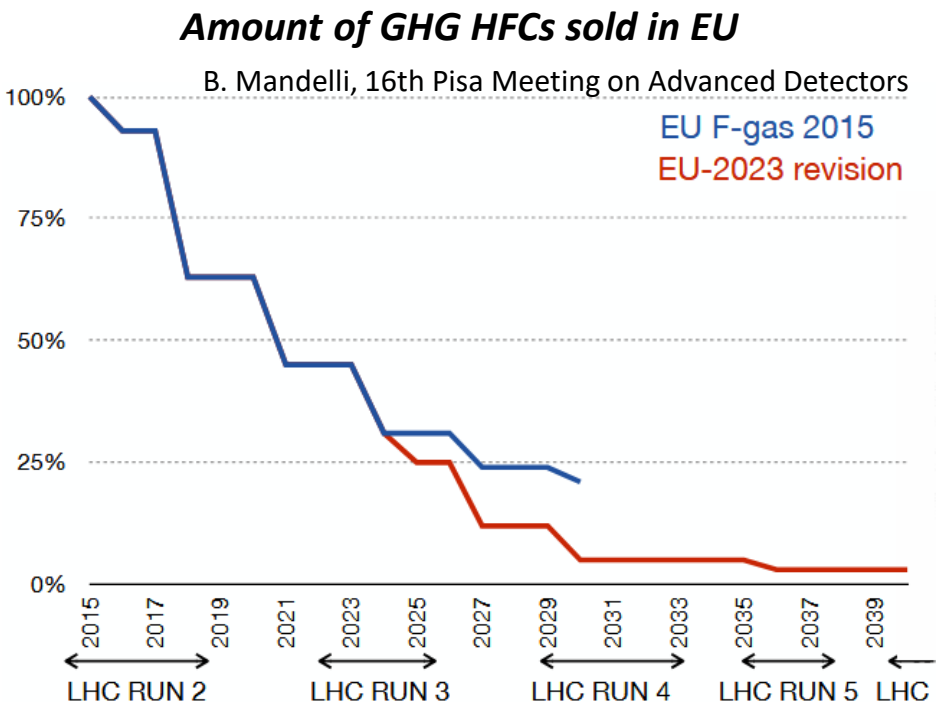
**measure of the heat trapped in the atmosphere by a ton of a given gas, if compared to a ton of CO_2*

Greenhouse gases: EU regulation

The sale and the use of Fluorinated greenhouse gases (GHG) have been limited in EU [EU regulation 517/2014].

Further restrictions due to the recent EU F-gas regulation 2024/573:

- reduction of 55% GHG emissions by 2030 w.r.t. 1990
- total elimination of HFCs (such as R134a) by 2050
- new restrictions in the use of SF_6 and other high GWP gases



- The Fluorinated GHG availability is being reduced and their price is increasing.
- CERN is committed to reducing its direct GHG emissions [CERN enviromental report]: goal: -28% of CERN GHG emission by the end of LHC RUN3.

Greenhouse gases at CERN

The major contribution to the CERN direct GHG emissions is due to the LHC particle ID mainly affected by R134a, the main component of RPC std gas mixture

Strategies to reduce GHG emissions:

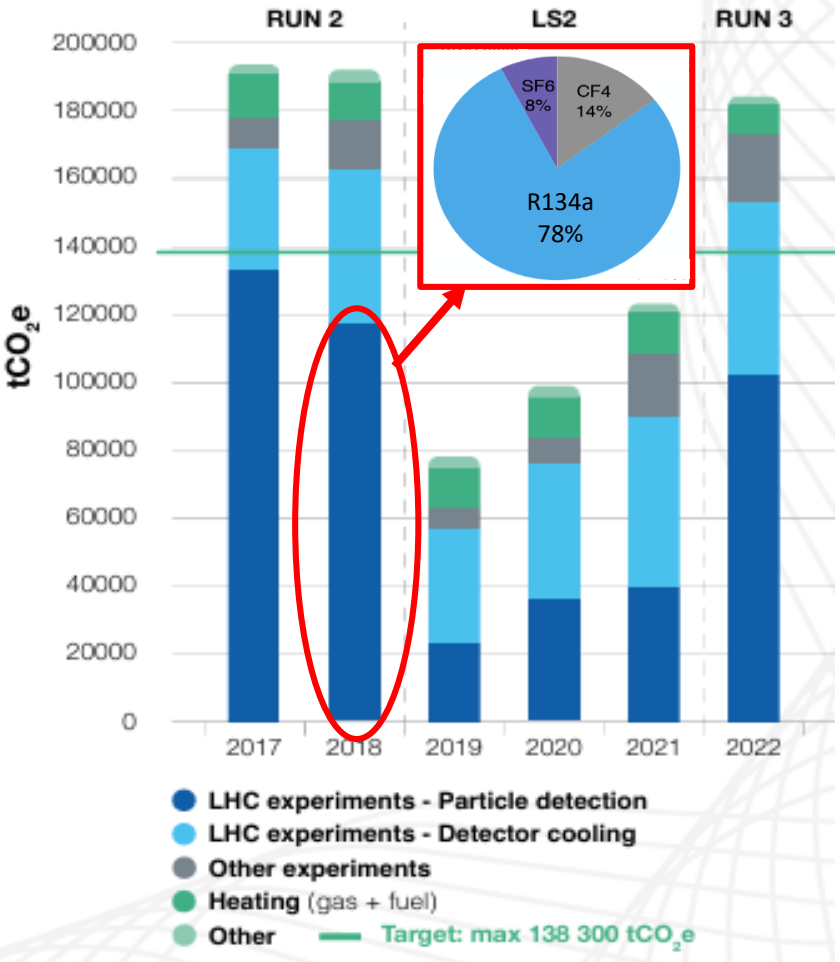
- Optimization of current detector systems
- Gas recirculation and recuperation
- **Search for new eco-friendly gas mixtures**

RPC groups from different experiments [ALICE, ATLAS, CERN Gas team, CMS, LHCb/SHiP] have joint efforts in the **RPC ECOGAS@GIF++ Collaboration**

goal: study of alternative eco-gas mixtures for RPCs with *low GWP, low toxicity and flammability guaranteeing detector performance comparable with std mix.*

CERN direct GHG emissions

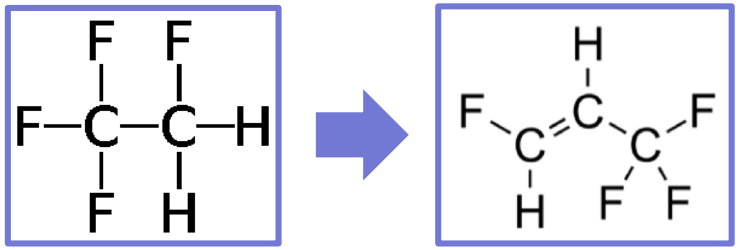
CERN env. Rep. 21-22



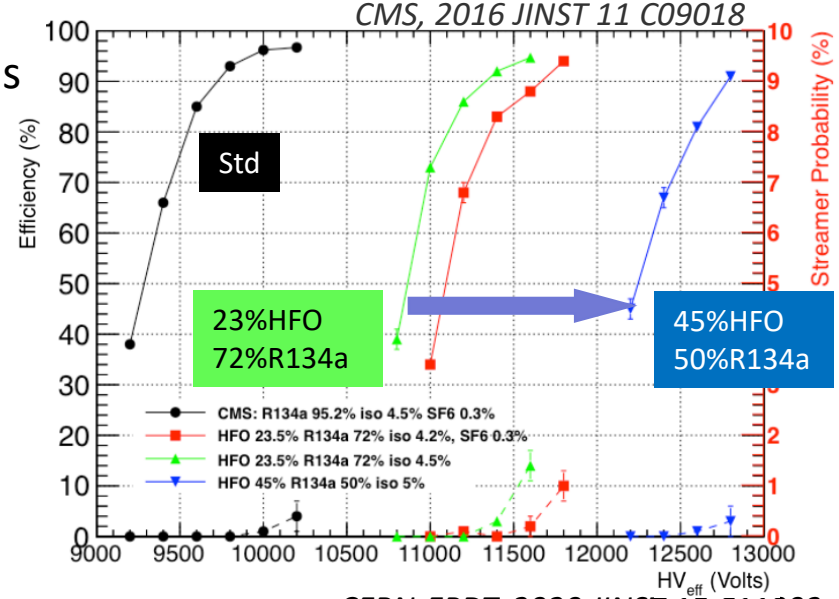
Towards eco-friendly RPCs

- R134a is being replaced in industrial applications with HydroFluoro-Olefins (HFOs)
  ➡ similar chemical structure but lower GWP.

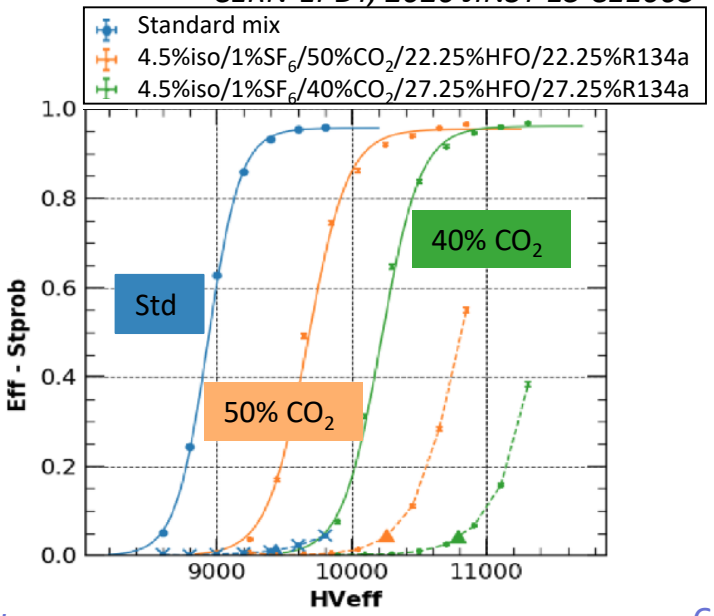
R134a, GWP=1430 **HFO-1234ze, GWP=6**



CMS, 2016 JINST 11 C09018



CERN-EPDT, 2020 JINST 15 C11003



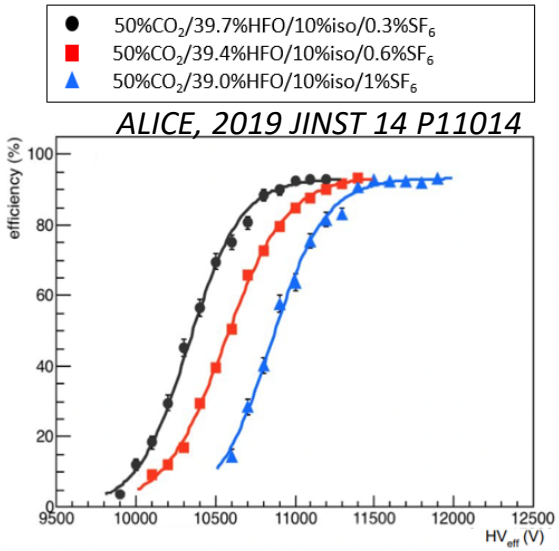
- Several tests performed in laboratories from different institutes of the Collaboration:

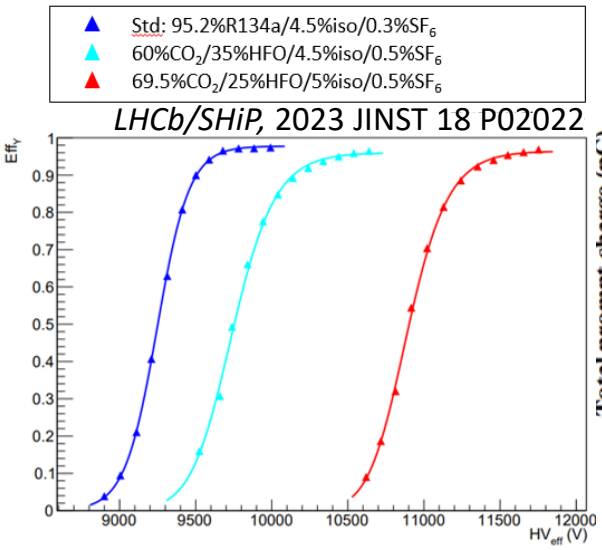
  - The replacement of R134a with HFO moves the operating voltage to very high values (>13kV for 2mm gaps).

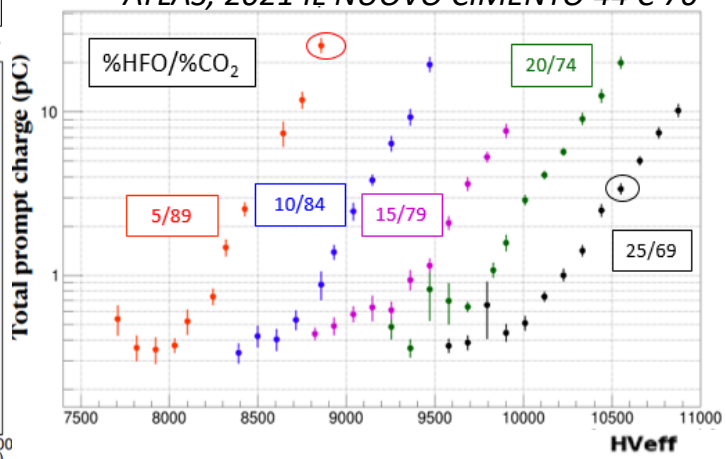
  - The addition of CO_2 helps in decreasing the WP.

Towards eco-friendly RPCs

Several R134a-free mixtures with CO_2/HFO/iC_4H_{10}/SF_6 tested in the various laboratories







Promising results have been obtained with the gas mixtures:

ECO1: 45% HFO / 50% CO_2 / 4% iC_4H_{10} / 1% SF_6
ECO2: 35% HFO / 60% CO_2 / 4% iC_4H_{10} / 1% SF_6
ECO3: 25% HFO / 69% CO_2 / 5% iC_4H_{10} / 1% SF_6

} GWP reduced by 1/3 w.r.t. the std mixture!

These mixtures have been tested by the Collaboration with different RPC detectors at various background conditions at the CERN Gamma Irradiation Facility (GIF++).

RPC EcoGas@GIF++ Collaboration timeline

RPC EcoGas@GIF++ Collaboration

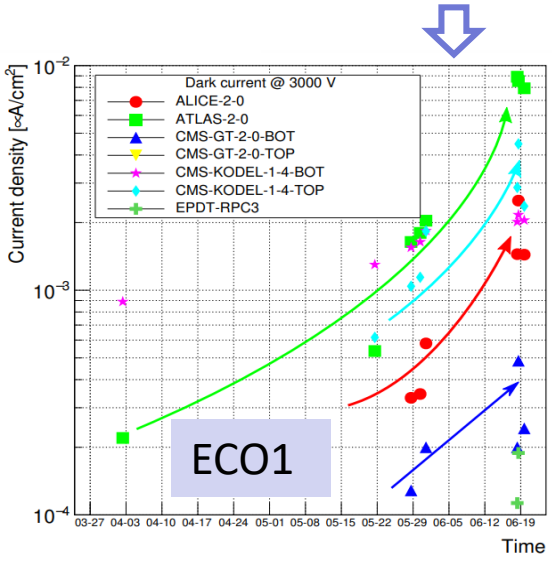
AidaInnova Startup

Irradiation campaign for ageing studies

2018 Studies in different laboratories
Setup of the system at GIF++ and first HFO/CO_2 based gas mix. under irradiation

2021 TB | 2022 TB | 2023 TB | 2024 TB | 2025 TB

2021 **Performance baseline** | **Performance comparison**

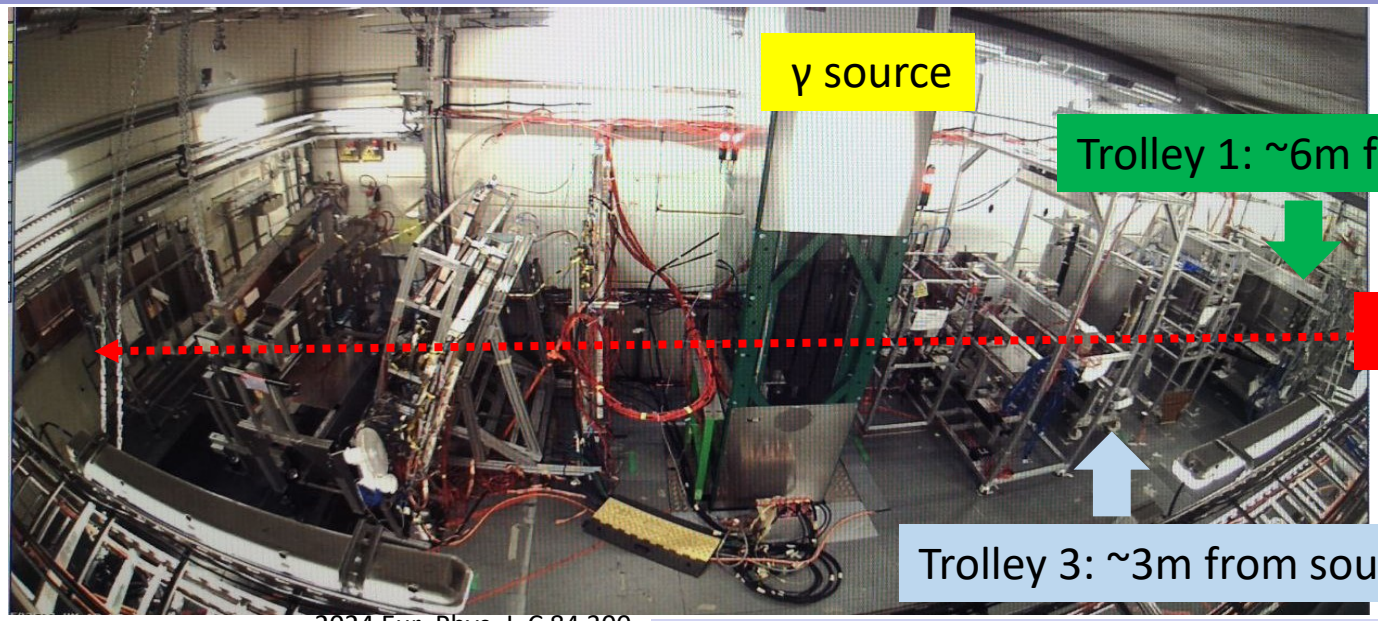


ECO1 discarded due to high current increase after ~20 mC/cm² integrated charge

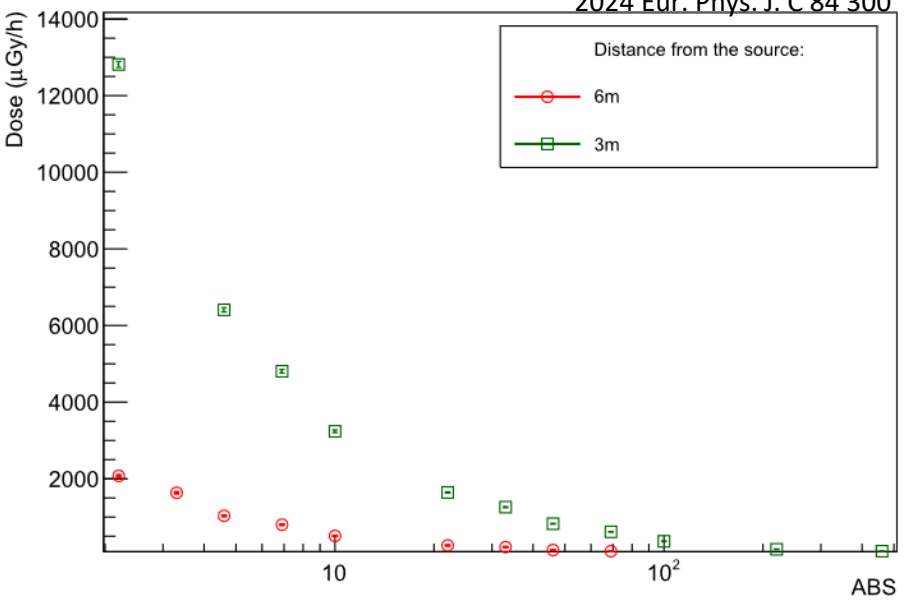
Std, ECO2 and **ECO3** mixtures tested under irradiation. Current results in papers *[1][2][3].*

[1] "High-rate tests on resistive plate chambers operated with eco-friendly gas mixtures", 2024 Eur. Phys. J. C.
[2] "Performance of thin-RPC detectors for high rate applications with eco-friendly gas mixtures", 2024 Eur. Phys. J. C.
[3] "Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility" – 2025 EPJPlus.

Setup at GIF++



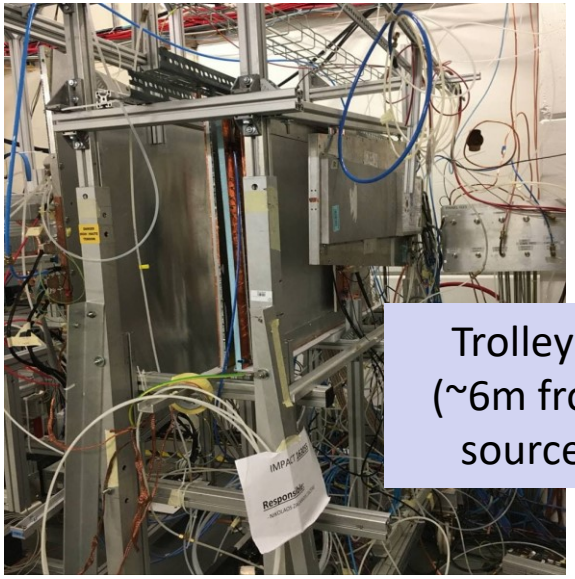
2024 Eur. Phys. J. C 84 300



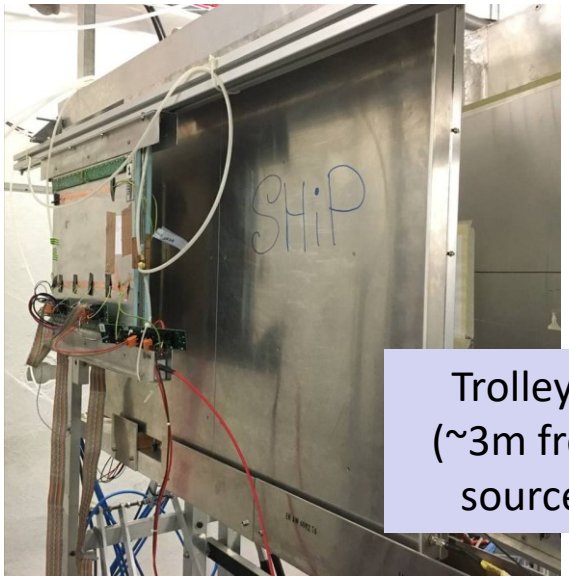
- 12.5 TBq ^{137}Cs source producing γ (at ~660keV) + adjustable filters (24 possible attenuation factors, ABS);
- Two mechanical frames (Trolleys 1 and 3) installed inside the GIF++ bunker hosting RPCs.
- Periodical beam tests of the detectors: muon beam (~100 GeV/c) from the secondary CERN SPS H4 beam line;
  beam trigger provided by the coincidence of two scintillators positioned on Trolley 1 and 3 with the GIF++ external scintillators.

Setup at GIF++

RPC	Gap thickness	Electronics
ALICE	2mm	FEERIC + TDC
ATLAS	2mm	Digitizer
CMS	2mm – double gap	CMS FEB + TDC
CMS upgrade	1.4mm – double gap	CMS FEB + TDC
EP-DT	2mm	Digitizer
LHCb/SHiP	1.6mm	FEERIC + TDC



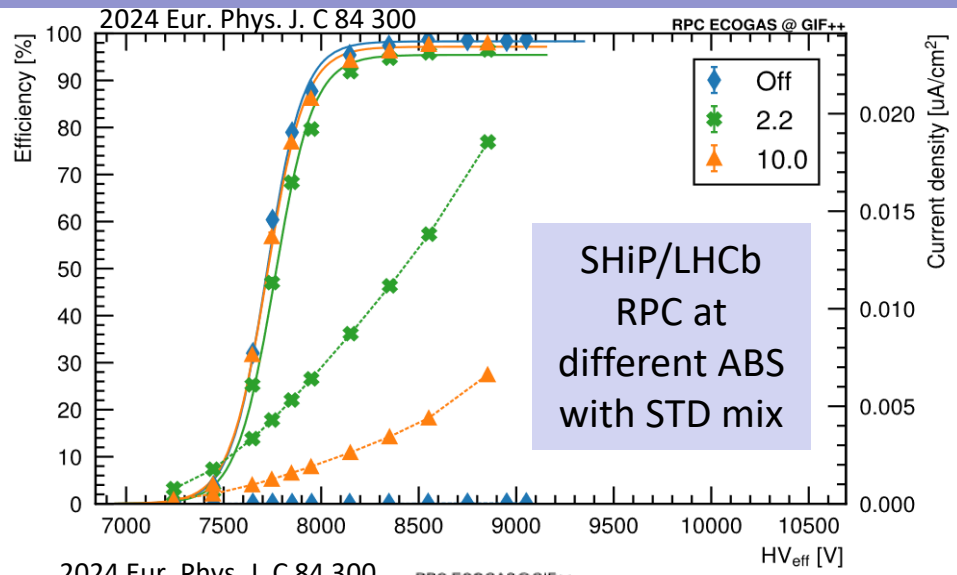
Trolley 1 (~6m from source)



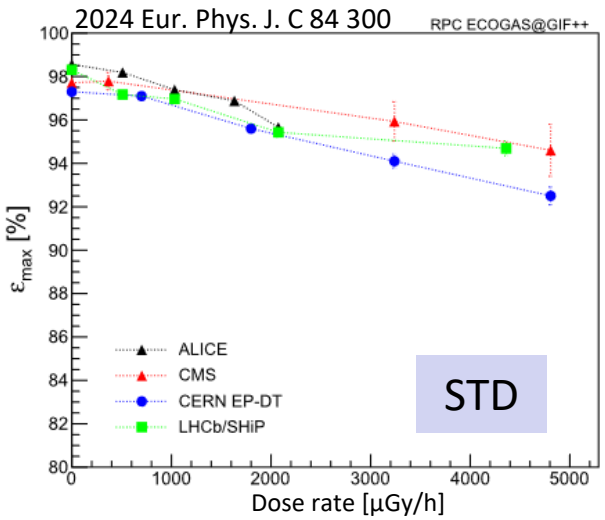
Trolley 3 (~3m from source)

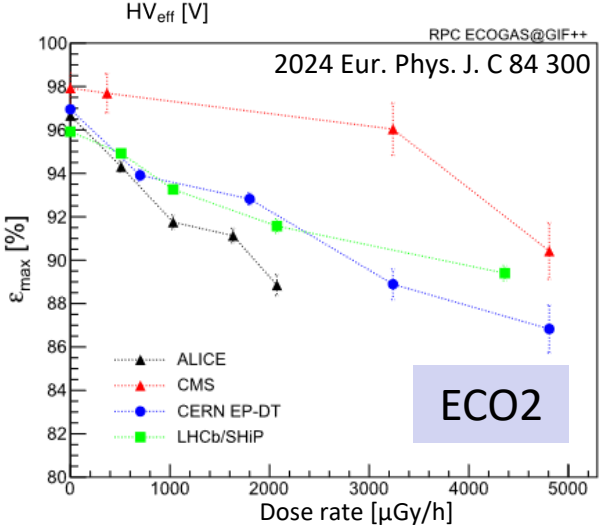
- RPCs with different dimension, gap thickness and features installed on Trolley 1 and 3.
- Dedicated HV modules and readout electronics for each RPC
- Gas mixer unit to provide up to 4 component gas mixture (humidified) to all the RPCs.
  [gas mix currently under test: Std, ECO2, ECO3]
- Flowmeter to monitor gas flow for each RPC
  → keep a stable flow in the detectors.

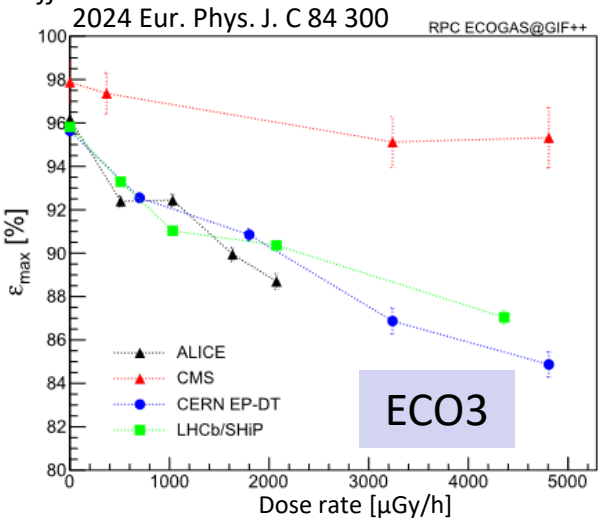
RPC performance under irradiation: baseline



- HV is corrected for temperature and pressure variations*
  *[1995 Nucl. Instrum. Meth. A 359 603-609]
- Fit of efficiency curves with logistic function: $\varepsilon(HV_{eff}) = \frac{\varepsilon_{max}}{1 + e^{-\gamma \cdot (HV_{eff} - HV_0)}}$
- The working point is defined as:
  WP = HV_{knee} + 150 V
  ↳ *[HV_{eff}(@eff=95%)]*



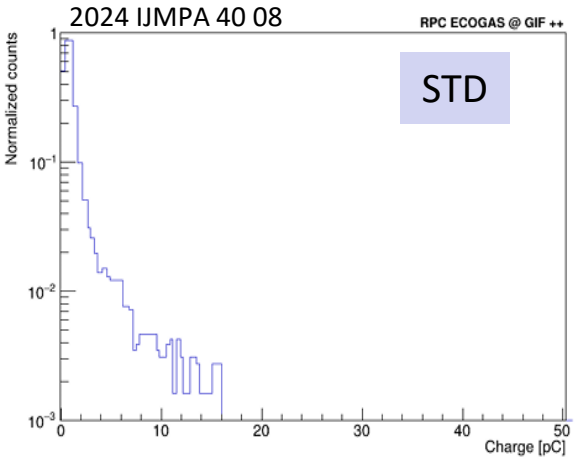


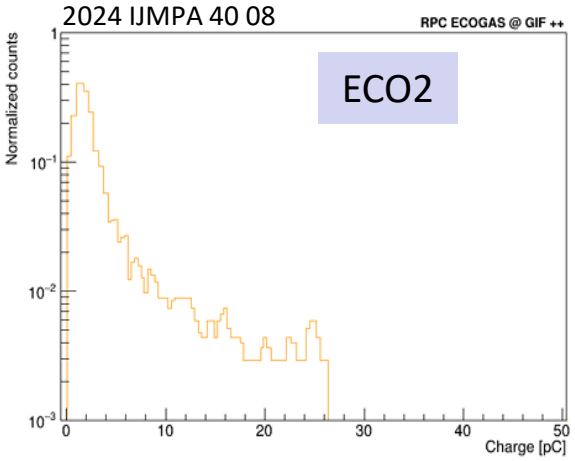


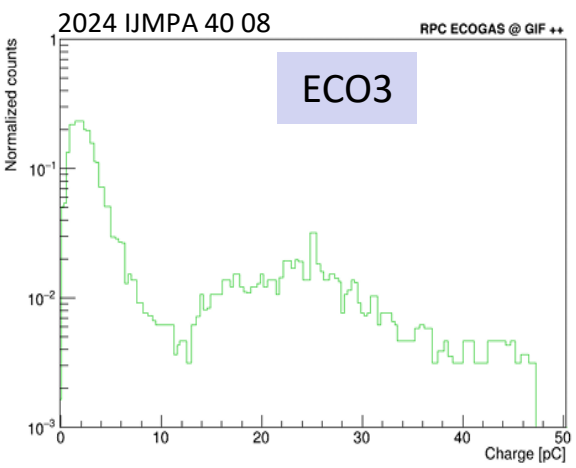
From 0 to the maximum irradiation (5000 µGy/h, i.e. several hundreds of Hz/cm^2):
eff decrease with std ~5% further decreased by a few % with eco-gas

RPC performance under irradiation: baseline

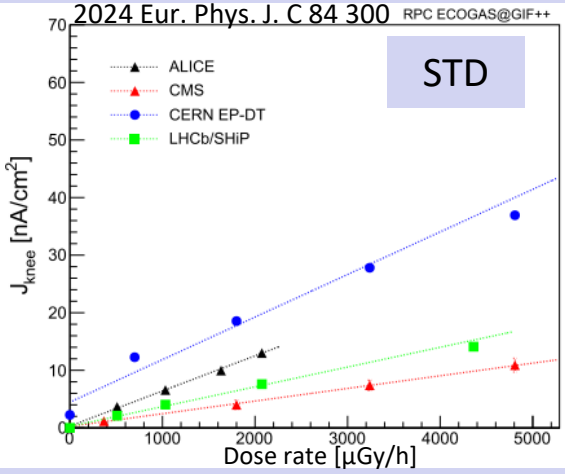
Charge distributions of the signals induced on ATLAS RPC at HV_{knee} without source.
Increase of events with large charge for eco-gas w.r.t. std.

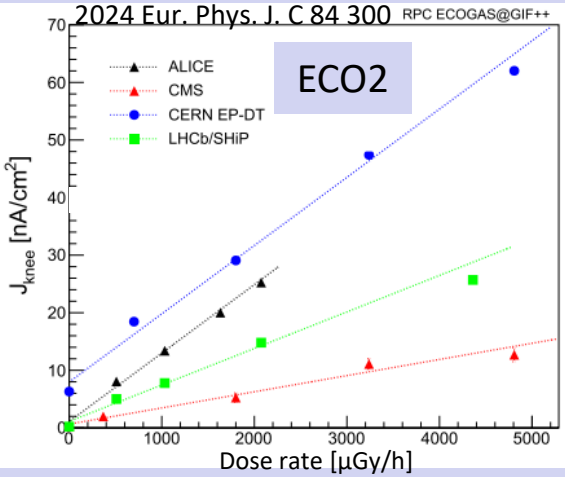


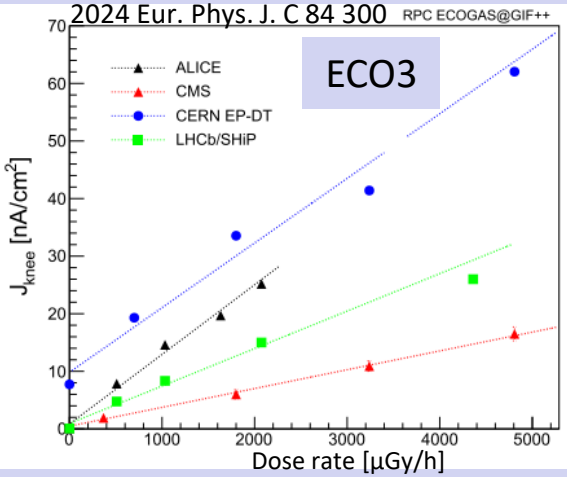




At the same irradiation, the current density J_{knee} at HV_{knee} is a factor of ~2 higher for eco-gas w.r.t. std.







Higher currents and charge with eco-gas ➡ higher pollutant production and faster RPC ageing?

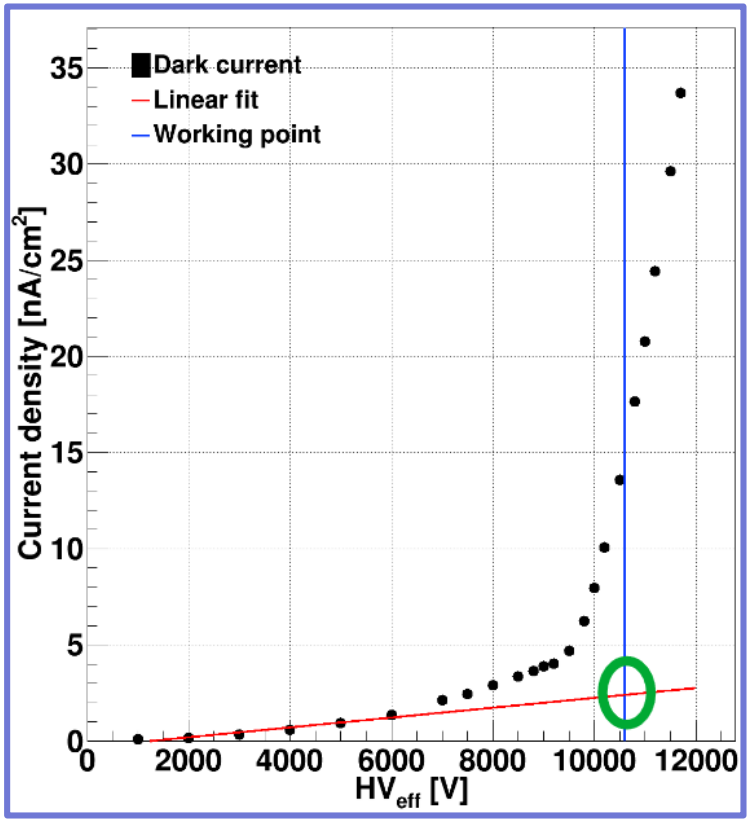
Ageing study: methodology

- RPCs flushed with ECO2, switched on at fixed HV (irradiation voltage) value and continuously irradiated with a background rate of several hundreds of Hz/cm^2

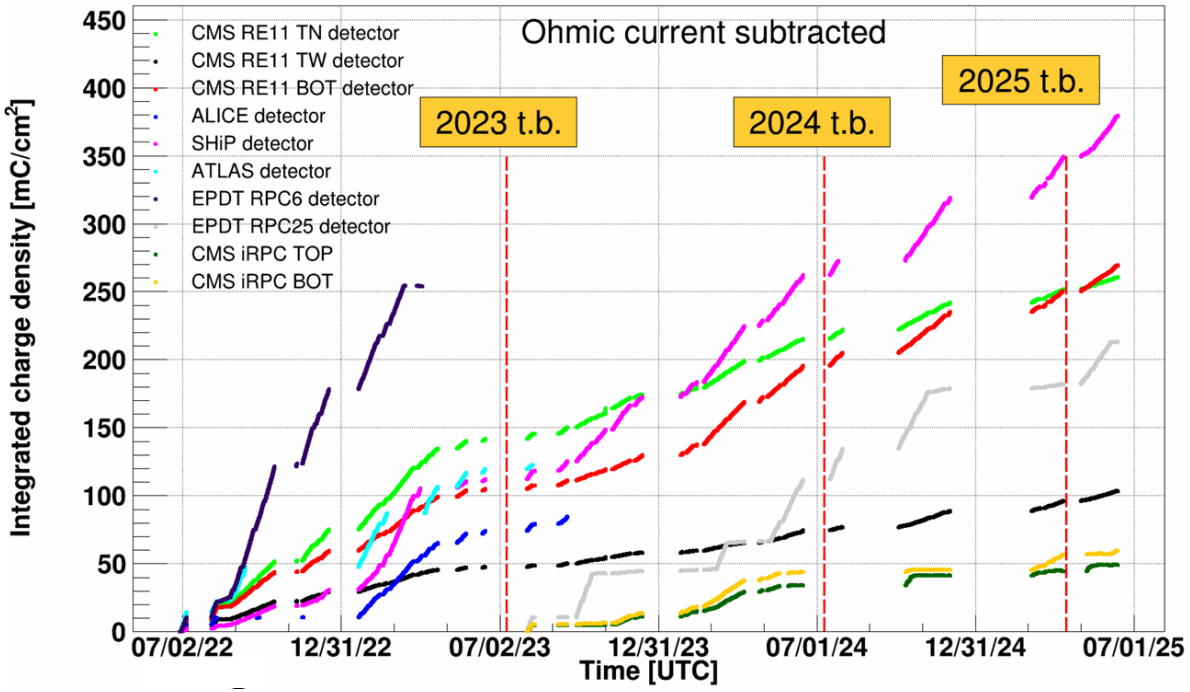
  Monitoring of HV and absorbed current ⟹ data stored every 30 s

- Weekly current vs HV scan to monitor the absorbed current without irradiation (**dark current**)
- Calculation of the charge integrated by each RPC under irradiation from the current flowing through the gas $I_{tot} - I_{Ohmic}$

  Ohmic current *(could flow through other conductive paths in the detector)*
- Monitoring of electrode resistivity
- Periodical check of detector performance during beam tests



Ageing study: integrated charge

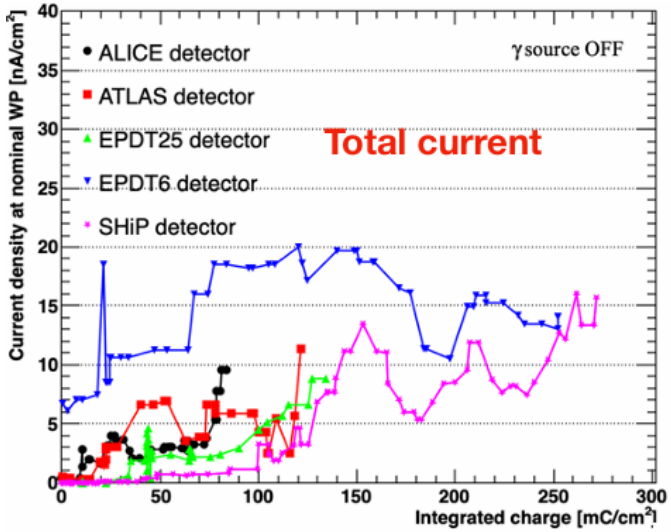


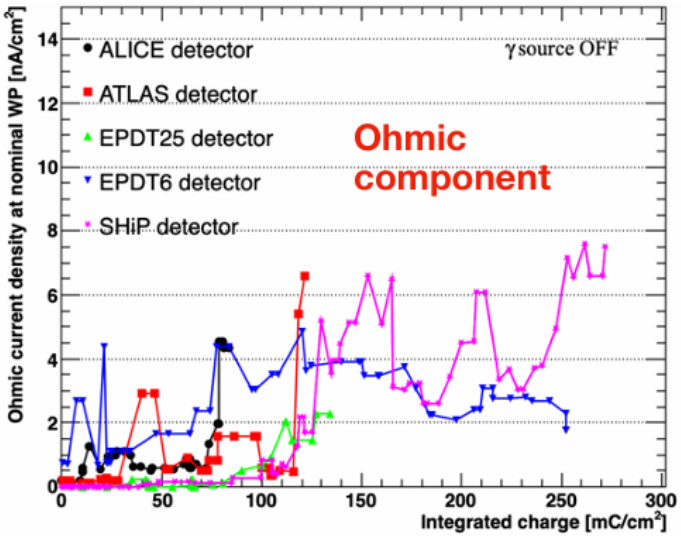
Between ~50 and ~400 mC/cm^2 integrated up to now. Different integrated charge values for the detectors due to:

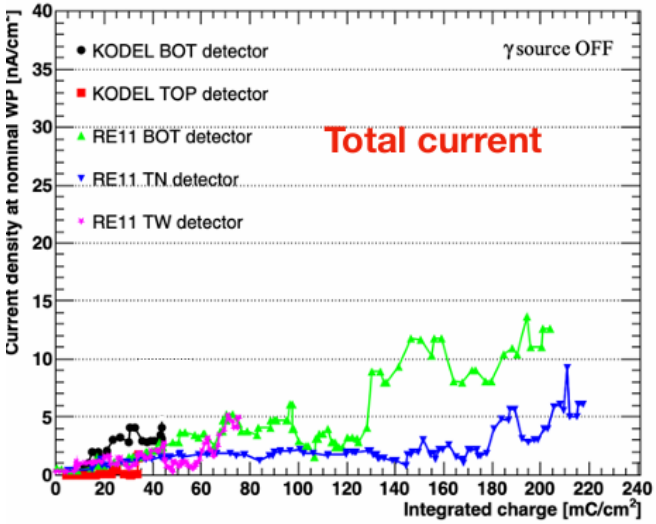
- different irradiation periods and distances from source;
- efficiency corresponding to irradiation voltage is not the same for all RPCs.

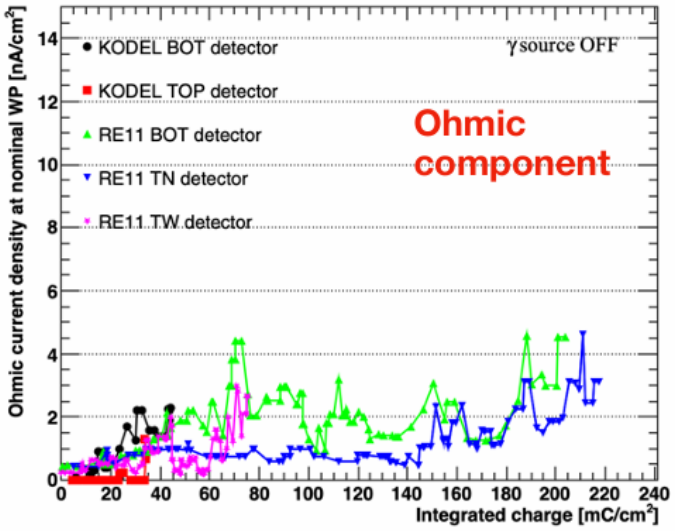
Each LHC experiment has a different “target” for the integrated charge, e.g. for ALICE it is 100 mC/cm^2 and for CMS 1C/cm^2 including a safety factor of 3.

Ageing study: currents









- General trend: After 50-100 mC/cm^2 of integrated charge, both total and Ohmic currents increase and show fluctuations.

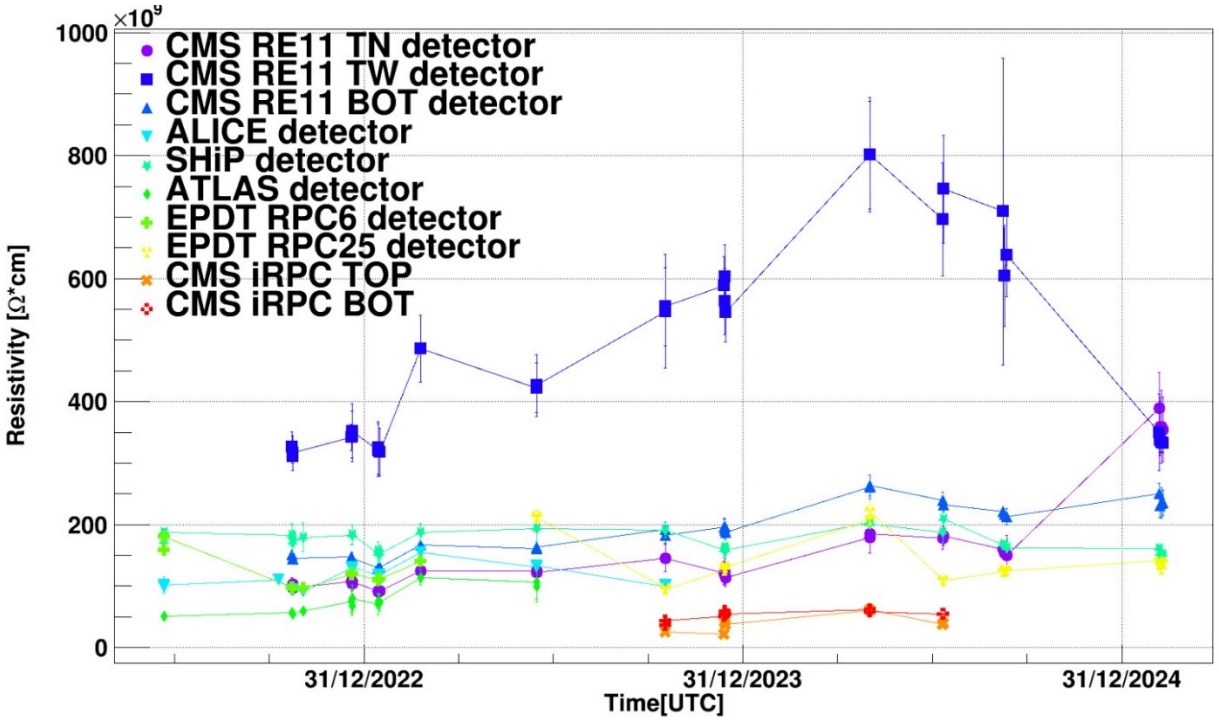
- Increase of the ohmic currents could be a hint of degradation of the internal surfaces of the detectors.

RPCs will be opened and internal surfaces will be examined. Chemical analysis could also be useful.

Ageing study: resistivity

An eventual electrode deterioration could also induce a variation of electrode resistivity. It is thus periodically measured with the Argon method:

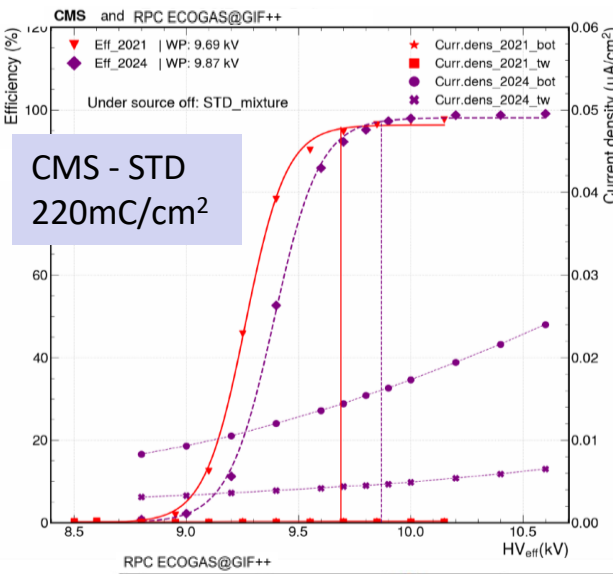
Gaps filled with Ar -> applying HV of few kVs, a discharge between electrodes is generated. The only contribution to the RPC resistance is thus due to electrodes.
Electrode resistivity is extracted from the HV vs I plot



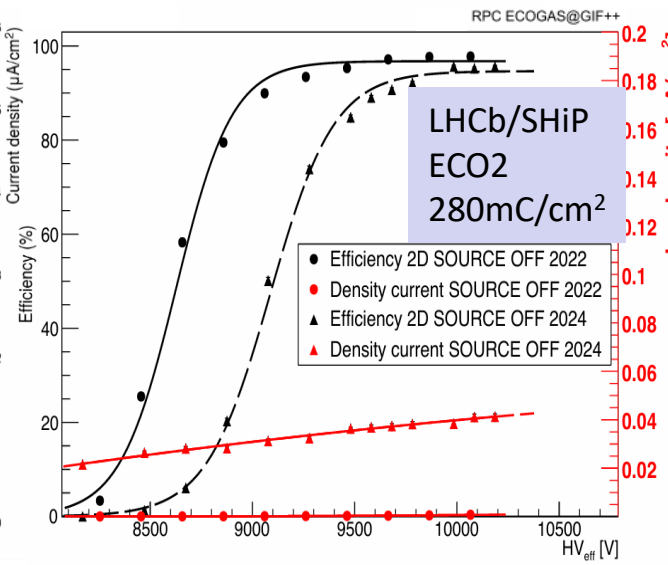
No clear general trend observed for all the RPCs

RPC performance after irradiation campaign

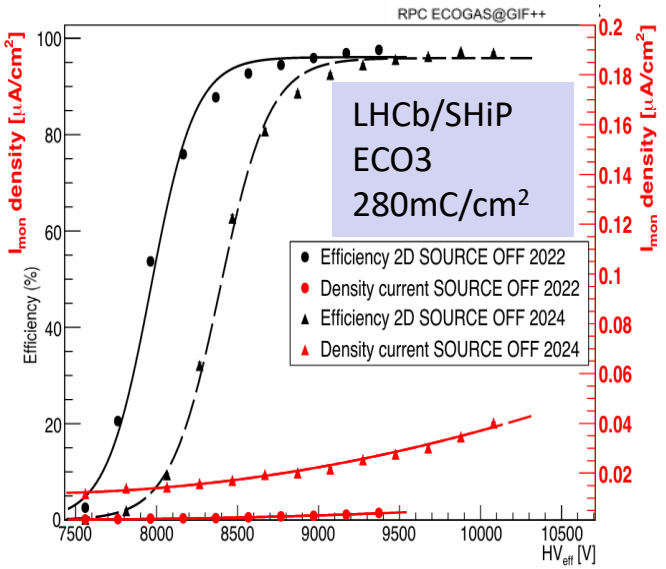
Source OFF



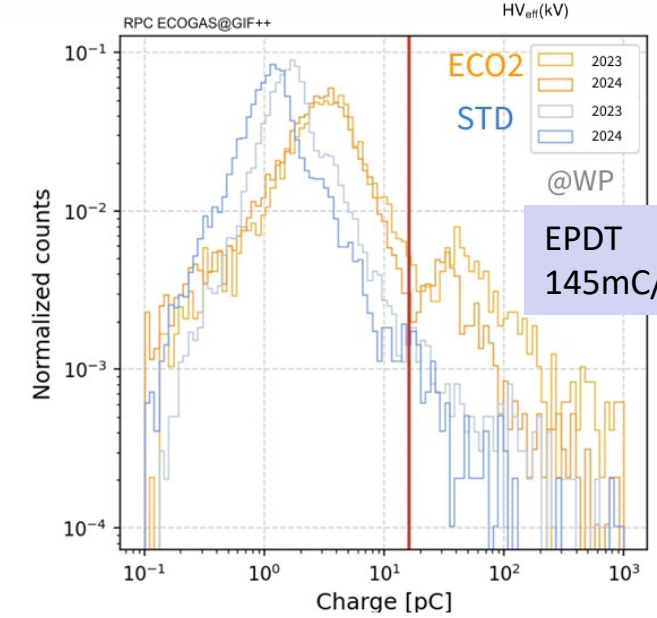
CMS - STD
220mC/cm²



LHCb/SHiP
ECO2
280mC/cm²



LHCb/SHiP
ECO3
280mC/cm²



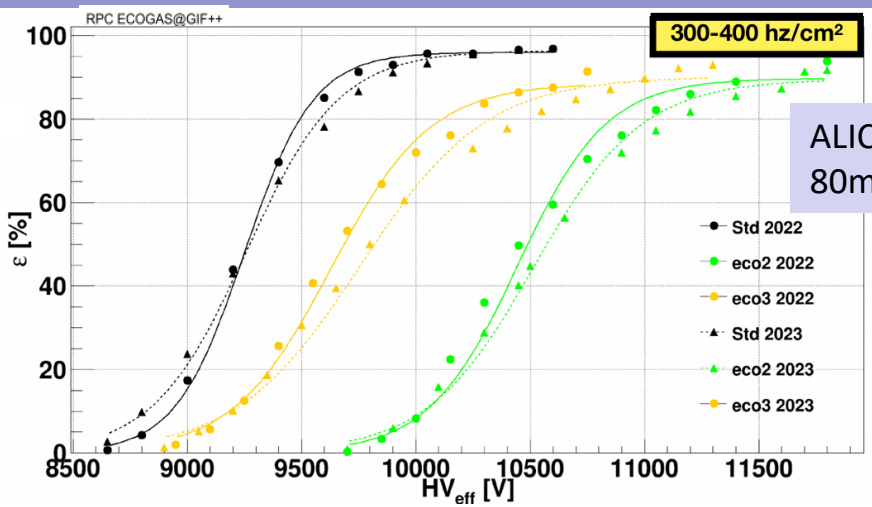
EPDT
145mC/cm²

Comparing the efficiency curves before/after irradiation:

- the plateau efficiency is stable both with std and with eco-gas mixtures for all the detectors;
- WP shifts observed, affected by the increase of currents after irradiation.

Charge distributions before/after irradiation comparable

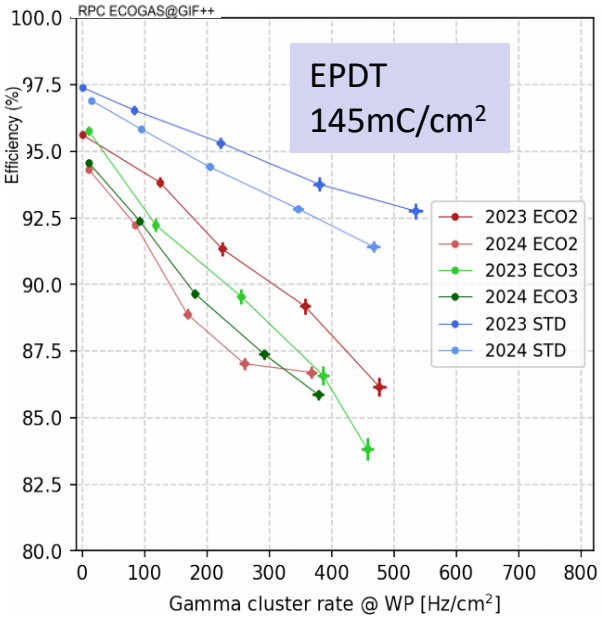
RPC performance after irradiation campaign



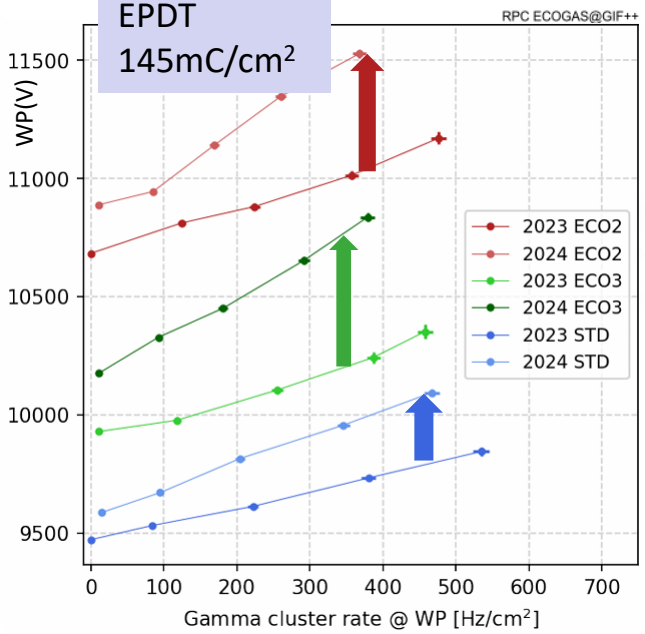
ALICE
80mC/cm²

Also with source ON at different background conditions:

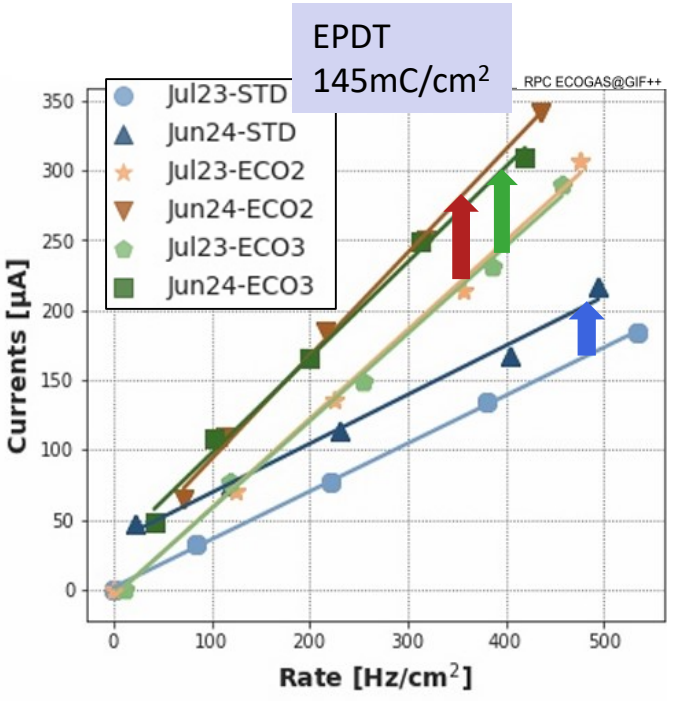
- No efficiency degradiation is spotted after irradiation campaign;
- WP shift and higher currents observed.



EPDT
145mC/cm²



EPDT
145mC/cm²



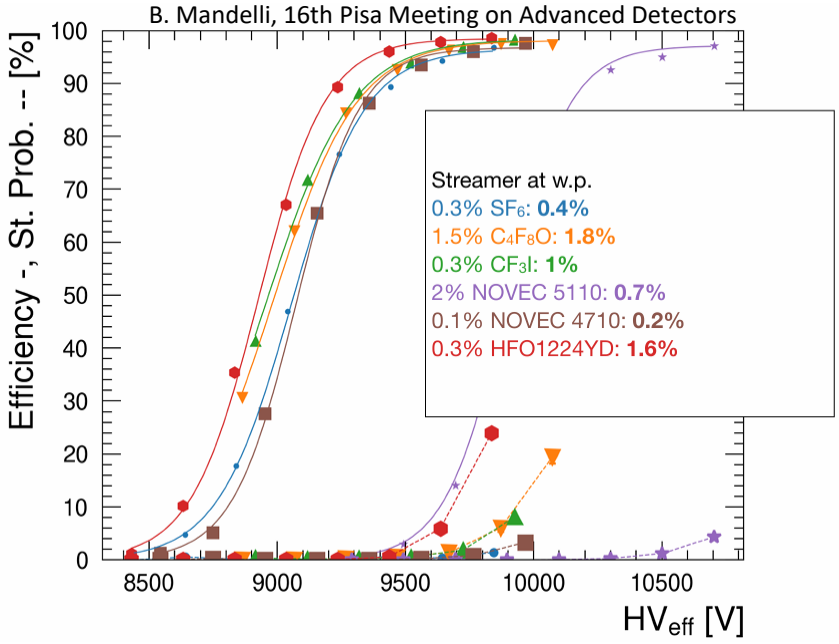
EPDT
145mC/cm²

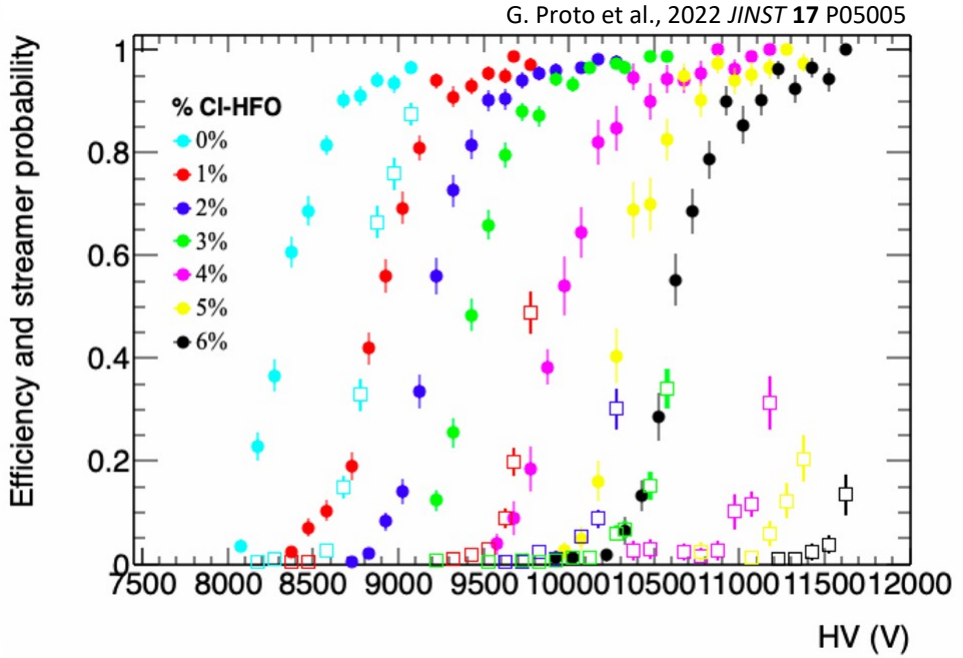
Outlook: The SF_6 replacement

SF_6 is an electronegative gas component of the RPC standard gas mixture with very high GWP (22800). Possible alternatives with low GWP:

- Novec dielectric fluids: operated for the replacement of SF_6 for arc quenching and insulation applications;
- Alternative electronegative gases.

Several candidates tested in laboratory by CERN EPDT group, Rome Tor Vergata group and at MPI (Munich) showing interesting performance.





Conclusion

The RPC ECOGAS@GIF++ Collaboration [ATLAS, ALICE, CERN Gas team, CMS, LHCb/SHiP] is commited in an intensive research of new eco-friendly gas mixtures for RPCs.

- Alternative R134a-free eco-gas mixture tested with several RPCs in various background conditions at the GIF++.
- Gas mixture candidates based on HFO/CO_2 in relative fractions 60%/35% and 69%/25% selected.

An ageing test campaign of RPCs operated with the new eco-gas mixtures was launched in 2022 for a long-term performance study.

- Promising results observed up to now, with no degradation of the RPC performance in terms of efficiency after 3 years of irradiation (few hundreds of mC/cm^2 integrated by the RPCs). The eco-gas mixtures could be good comprimises for the RPCs operated at LHC.
- Some observed phenomena are currently under investigation.
  Shift of the WP and an increased trend of currents ➡ a possible contribution could be due to a deterioration of the electrode inner surface which will be examined.
- A final beam test is ongoing.

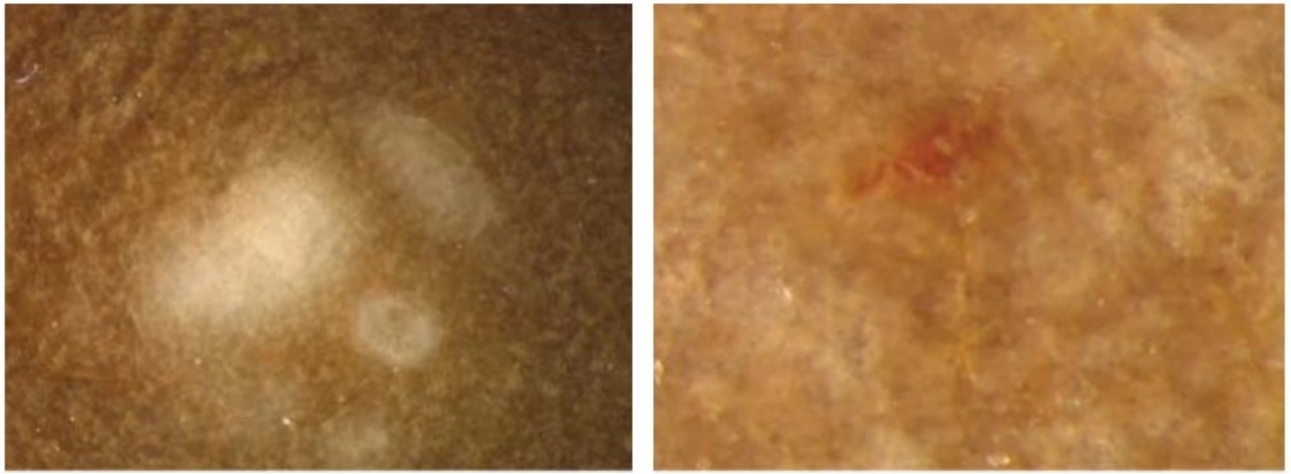
A new R&D phase is foreseen focussing on eco-friendly SF_6-free gas mixtures for RPCs.

XIV International Conference
on New Frontiers in Physics
17-31 July 2025, OAC, Kolymbari, Crete, Greece

Thank you for your attention!

RPC ageing

The decomposition of F-rich gas molecules (such as R134a and HFO) could led to the production of fluoride (F^-). It combines with H_2O, producing HF acid that could damage the inner surface of RPC electrodes.

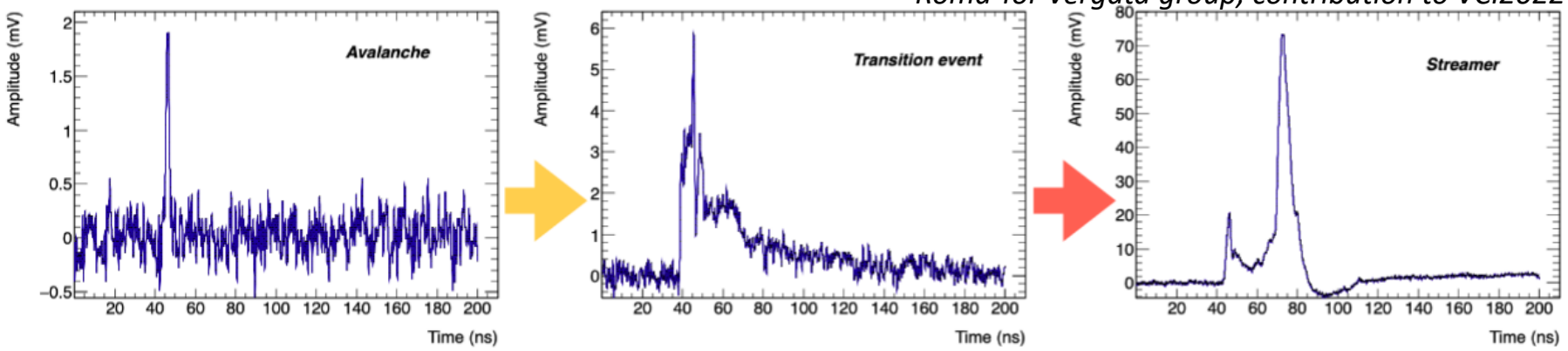


Pictures of spots, appearing on the inner surfaces of Bakelite electrodes that could be due to the chemical interaction with HF

M. Abbrescia et al., Resistive Gaseous Detectors, 2018 WileyVCH.

Event classification

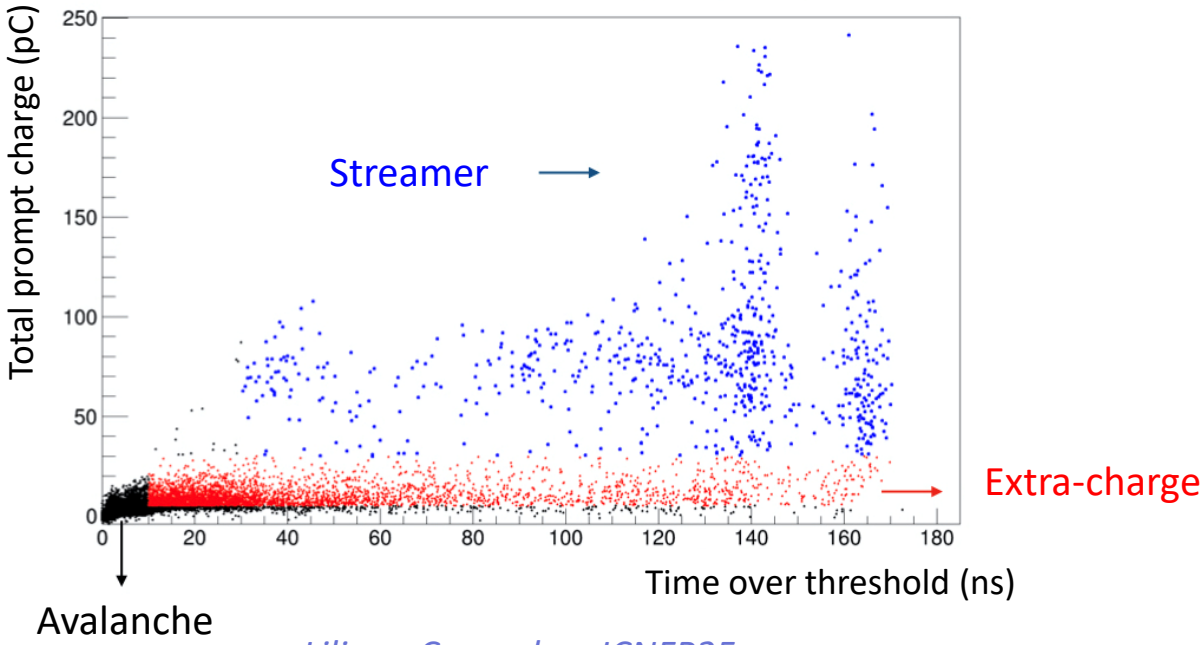
Roma Tor Vergata group, contribution to VCI2022



Avalanche: very short signal

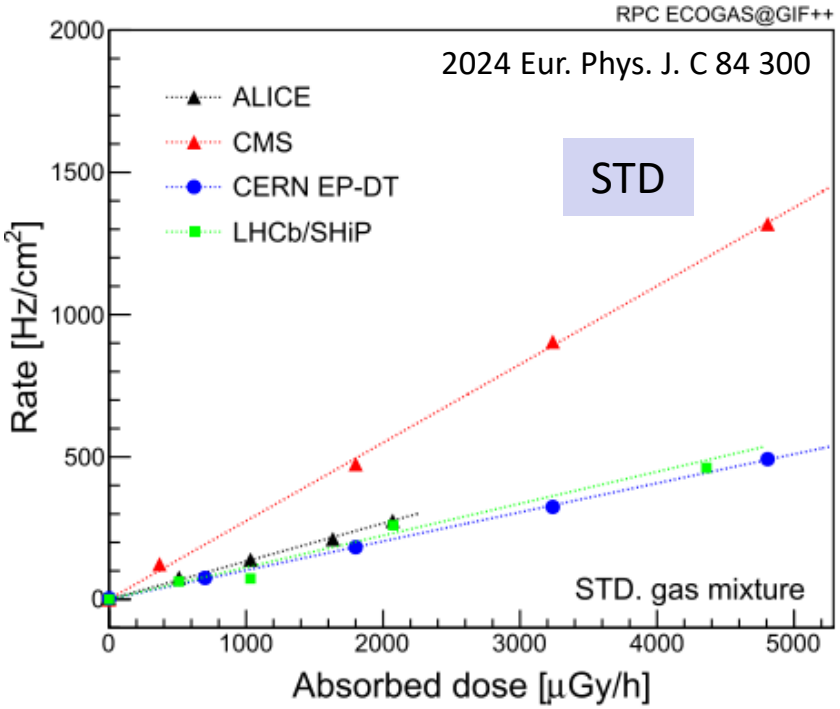
Extra-charge events: multiple avalanche signal and/or large tail following the avalanche precursor

Streamer events: avalanche signal precursor followed by a signal lasting tens of ns



Gamma rate

- Gamma cluster rate -> number of clusters related to γ photons from the Cs source per unit of area and unit of time
- It is measured with random triggers during beam interspill



up to several hundreds of Hz/cm^2