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# Performance and ageing studies on Eco-Friendly Resistive Plate Chamber detectors

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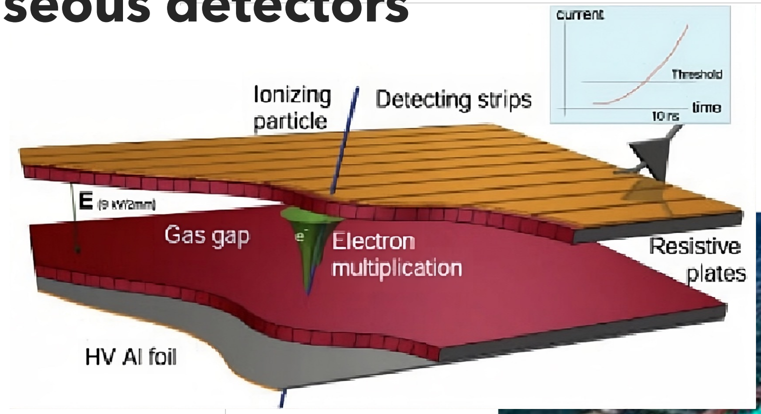
# RPCs in High Energy Physics experiments

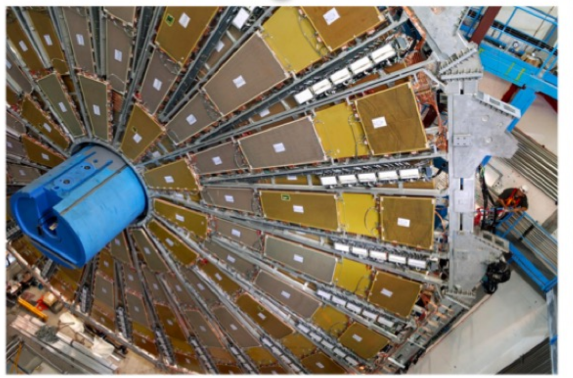
**Gaseous detectors**

**Fast response**: used for triggering and identification purposes, widely employed in **High Energy Physics** experiments

**High efficiency** and **time resolution**

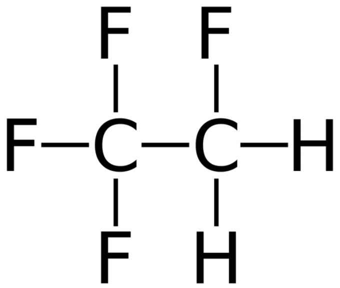
**Relatively cheap** to cover large areas

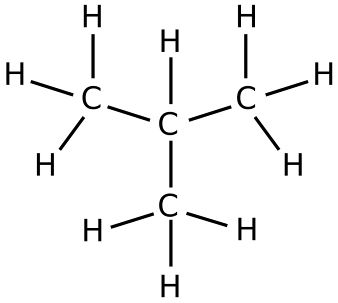


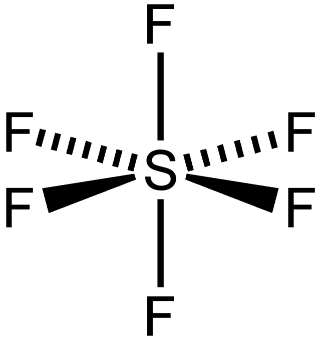


# Gaseous mixture for RPC operation at CERN

TFE ($C_2H_2F_4$) ~ 95% + $iC_4H_{10}$ ~ 4-5% + $SF_6$ < 1%







- High density of primary ion-electrons pairs → high RPC efficiency
- Good quenching properties and electronegativity → very low streamer probability
- High rate capability

**Nowadays increased attention on GHGs emissions:** F-gas regulation aims in limiting emissions, GHGs availability, price, **GHGs are used because needed to achieve specific detector performance and/or long-term stability**

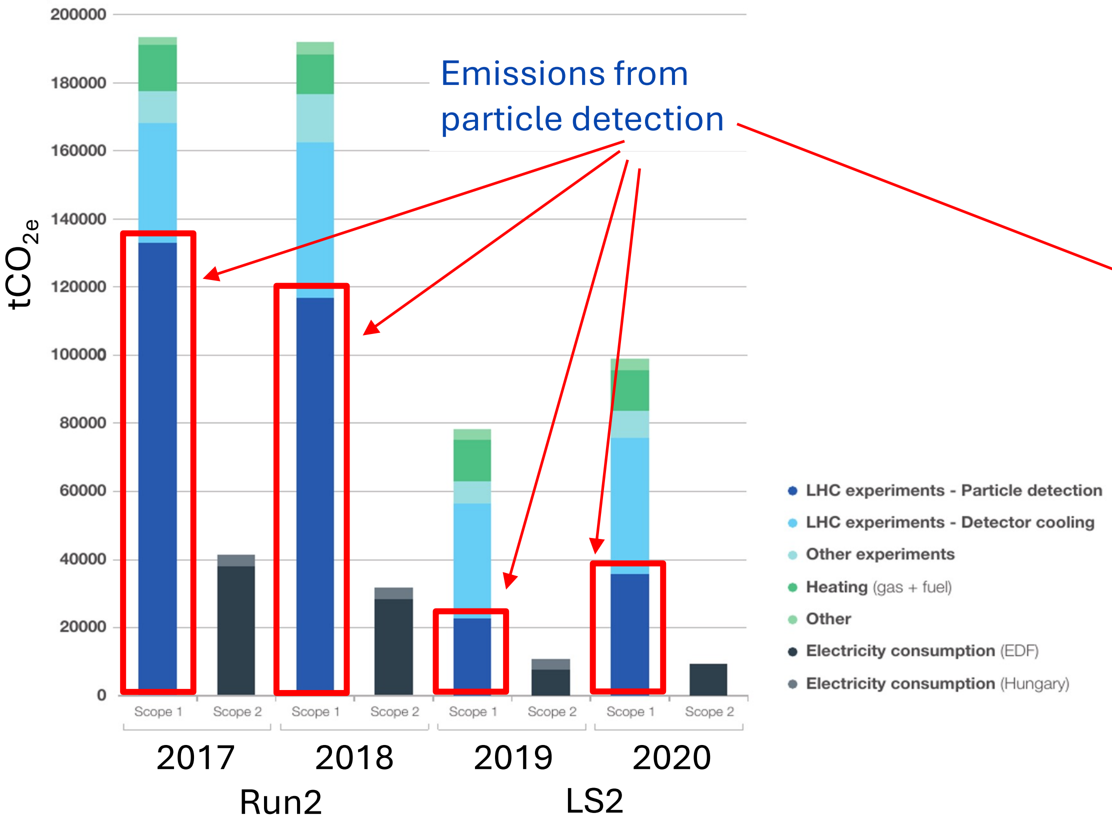
# Greenhouse gas usage at CERN (1)

- CERN Environment Report 2019-2020
- 2021: CERN’s Year of Environmental Awareness.
- CERN Environment workshop: 12 and 13 October 2022
- CERN Environment Report 2021-2022

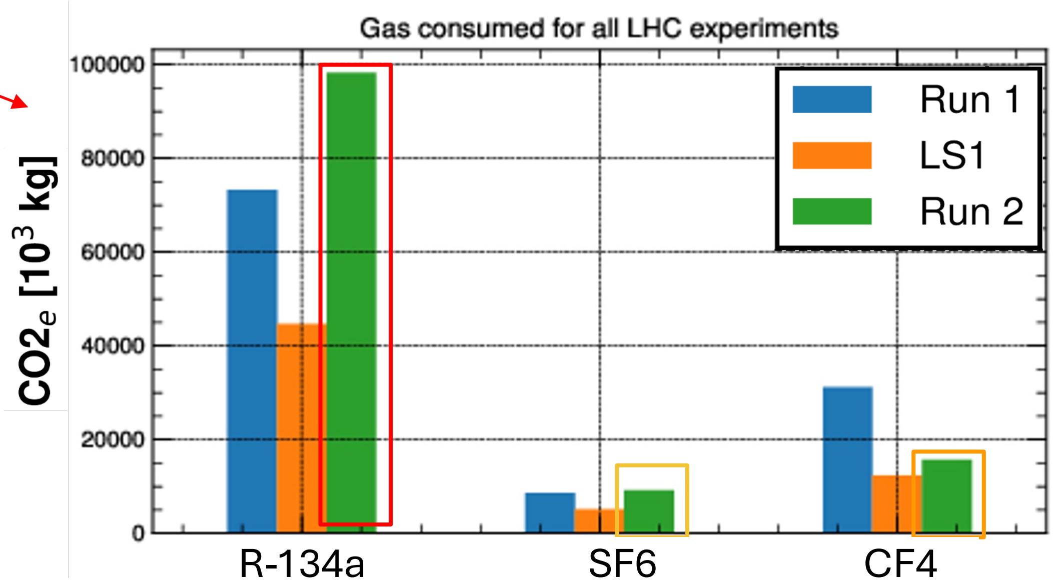
Total CERN emissions during 1 year of Run 2 ~ **200 000 tCO2e**

***~ 50%*** from particle detectors

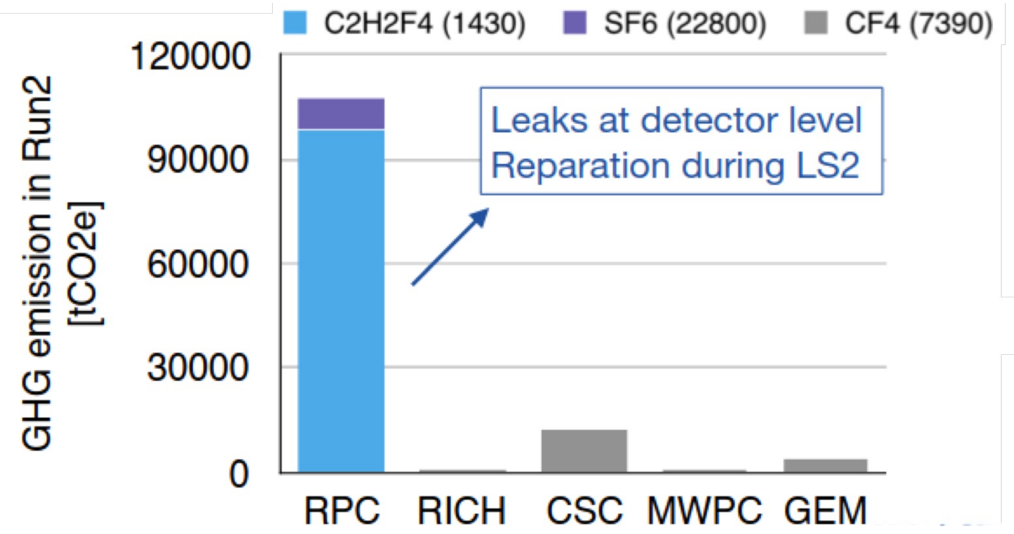
- **$C_2H_2F_4$/R-134a** biggest contributor → leaks from RPC detector, used for ALICE, ATLAS and CMS systems
- **$CF_4$** → due to operation of CSC and RICH systems
- **$SF_6$** → Related to RPCs as R-134a

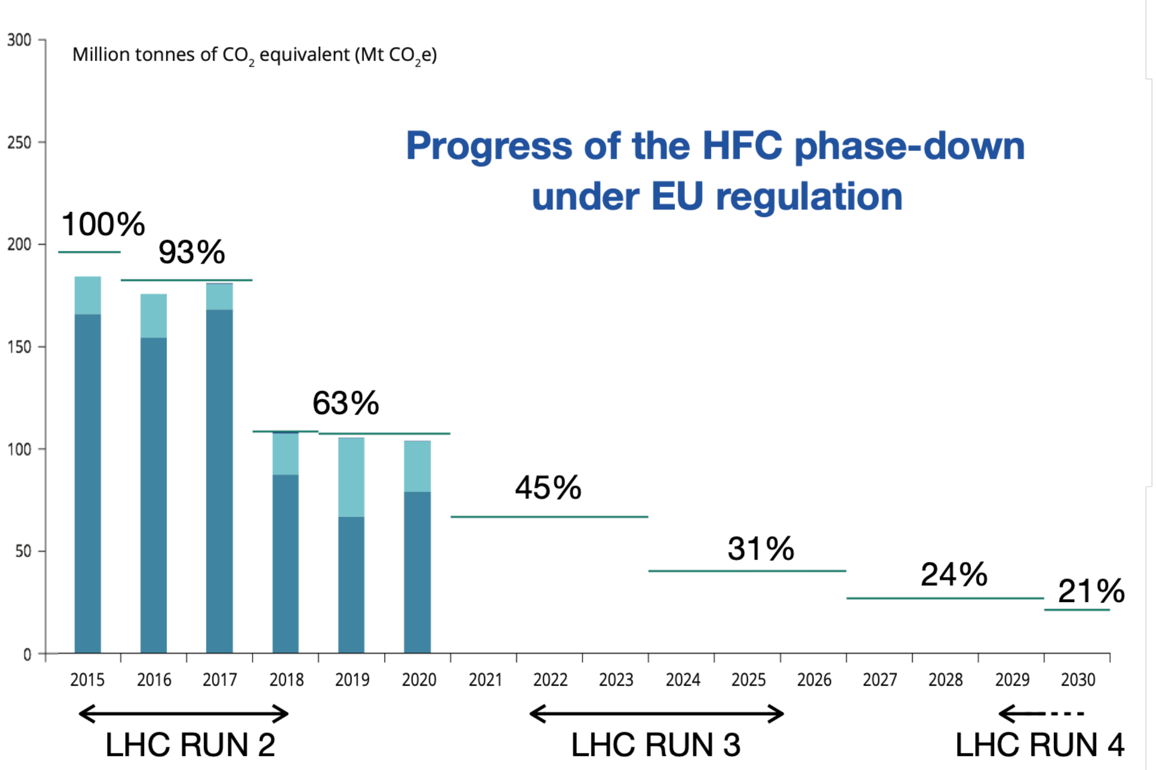


Emissions from particle detection



# Greenhouse gas usage at CERN (2)





**Limiting the total amount** of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030.

**Banning the use** of F-gases where less harmful alternatives are widely available.

**Preventing emissions** of F-gases from existing equipment by requiring checks, proper servicing and recovery

# New gaseous mixtures candidates

- Requirements: low GWP, low toxicity, not flammable and detector performance comparable with standard one

In industrial applications $C_2H_2F_4$ is being replaced with HydroFluoro-Olefins (HFOs)

- the replacement of C2H2F4 with HFO moves the operating voltage at much higher values (es. >13kV for 2mm gap)
- the addition of CO2 helps in decreasing the WP

**Hydro-Fluoro-Olefin (HFO)**

C=C double bond

fluorine-containing

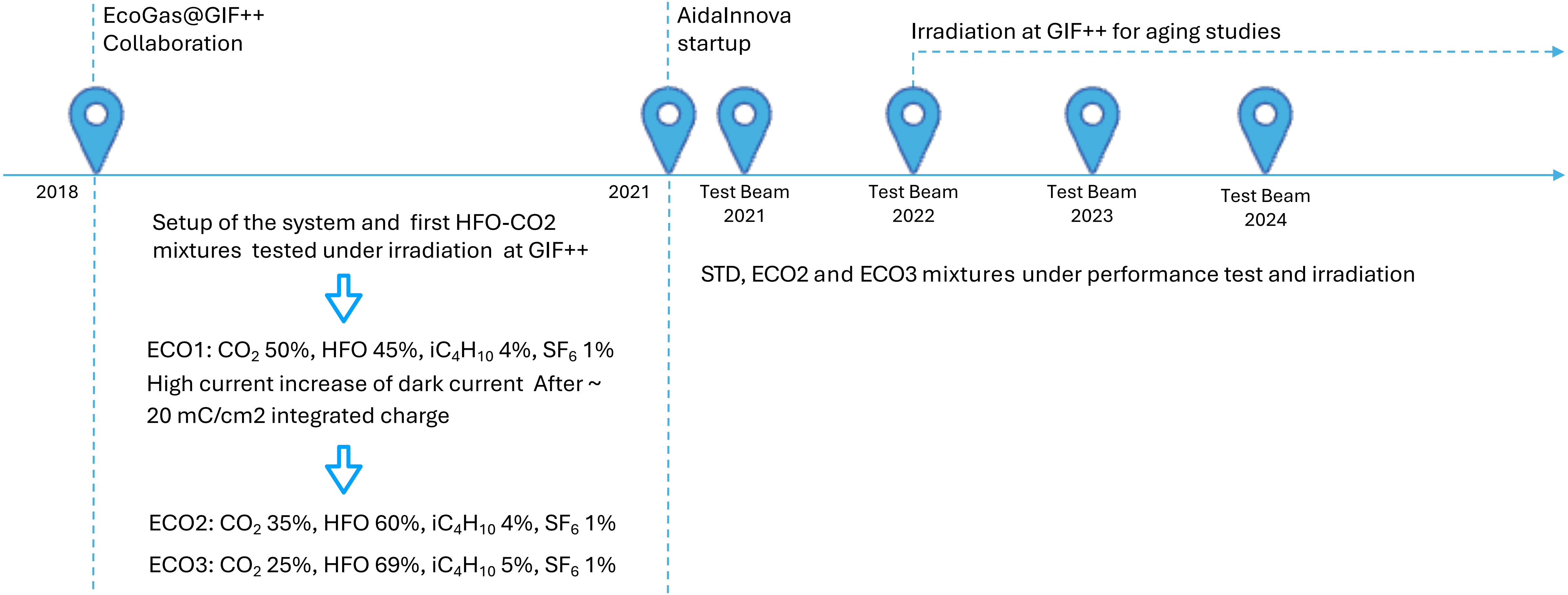
hydrogen-containing

| | TFE (%) | HFO-1234ze (%) | $CO_2$ (%) | $iC_4H_{10}$ (%) | SF6 (%) | GWP | $CO_2$e (g/l) |
|---|---|---|---|---|---|---|---|
| STD | 95.2 | - | - | 4.5 | 0.3 | 1485 | 6824 |
| **ECO2** | **-** | **35** | **60** | **4** | **1** | **476** | **1522** |
| **ECO3** | **-** | **25** | **69** | **5** | **1** | **527** | **1519** |
| Density (g/l) | 4.68 | 5.26 | 1.98 | 2.69 | 6.61 | - | - |
| GWP | 1430 | 7 | 1 | 3 | 22800 | - | - |

GWP with respect to CO2, and their CO2e, in grams, for one litre of mixture

**Values mainly driven by SF6**

# EcoGas at GIF++ collaboration timeline



EcoGas@GIF++
Collaboration

2018

Setup of the system and first HFO-CO2 mixtures tested under irradiation at GIF++

ECO1: $CO_2$ 50%, HFO 45%, $iC_4H_{10}$ 4%, $SF_6$ 1%
High current increase of dark current After ~ 20 mC/cm2 integrated charge

ECO2: $CO_2$ 35%, HFO 60%, $iC_4H_{10}$ 4%, $SF_6$ 1%

ECO3: $CO_2$ 25%, HFO 69%, $iC_4H_{10}$ 5%, $SF_6$ 1%

AidaInnova
startup

2021

Irradiation at GIF++ for aging studies

Test Beam
2021

Test Beam
2022

Test Beam
2023

Test Beam
2024

STD, ECO2 and ECO3 mixtures under performance test and irradiation

# ECOG… la… timeline

**Transversal collaboration** to find an ecological gas mixture replacement for RPC operation at CERN
**Beam tests and irradiation campaigns, performance analysis** of chambers from each experiment

ALICE

2018

2021

startup

Test Beam
2021

Setup of the system and first HFO-CO2 mixtures tested … rradiation at GIF++

STD, ECO2 a

$CO_2$ 50%, HFO 45% … $F_6$ 1%

er ~

1%

1%

2024

Around 24 universities, institutes and research centers!!!

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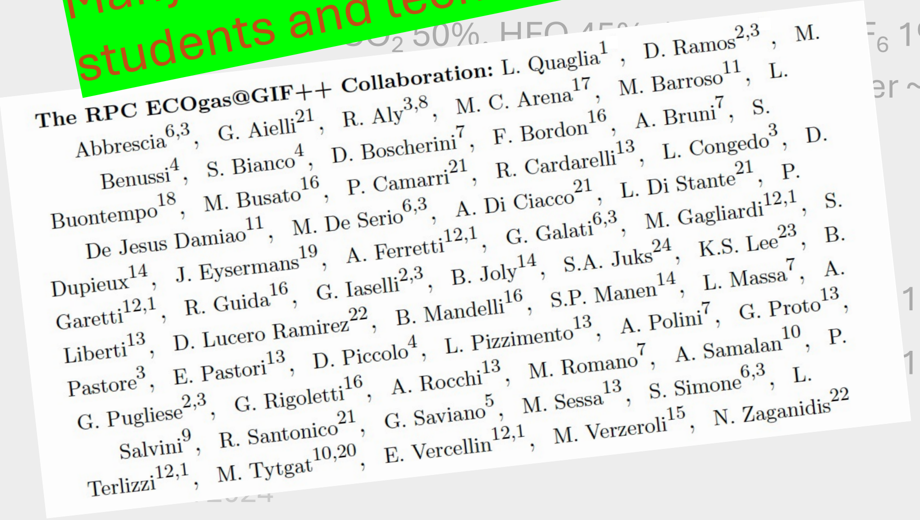
Many colleagues, PhDs, students and technicians!!!



**The RPC ECOgas@GIF++ Collaboration:** L. Quaglia[1], D. Ramos[2,3], M. C. Arena[17], M. Barroso[11], L. Abbrescia[6,3], G. Aielli[21], R. Aly[3,8], M. C. Arena[17], F. Bordon[16], A. Bruni[7], S. Benussi[4], S. Bianco[4], D. Boscherini[7], R. Cardarelli[13], L. Congedo[3], D. Buontempo[18], M. Busato[16], P. Camarri[21], A. Di Ciacco[21], L. Di Stante[21], P. De Jesus Damiao[11], M. De Serio[6,3], G. Galati[6,3], M. Gagliardi[12,1], S. Dupieux[14], J. Eysermans[19], A. Ferretti[12,1], B. Joly[14], S.A. Juks[24], K.S. Lee[23], B. Garetti[12,1], R. Guida[16], G. Iaselli[2,3], S.P. Manen[14], L. Massa[7], A. Liberti[13], D. Lucero Ramirez[22], B. Mandelli[16], A. Polini[7], G. Proto[13], Pastore[3], E. Pastori[13], D. Piccolo[4], L. Pizzimento[13], A. Samalan[10], P. G. Pugliese[2,3], G. Rigoletti[16], A. Rocchi[13], M. Romano[7], S. Simone[6,3], L. Salvini[9], R. Santonico[21], G. Saviano[5], M. Sessa[13], N. Zaganidis[22] Terlizzi[12,1], M. Tytgat[10,20], E. Vercellin[12,1], M. Verzeroli[15],

Some papers!!!

High-rate tests on resistive plate chambers operated with eco-friendly gas mixtures

Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility

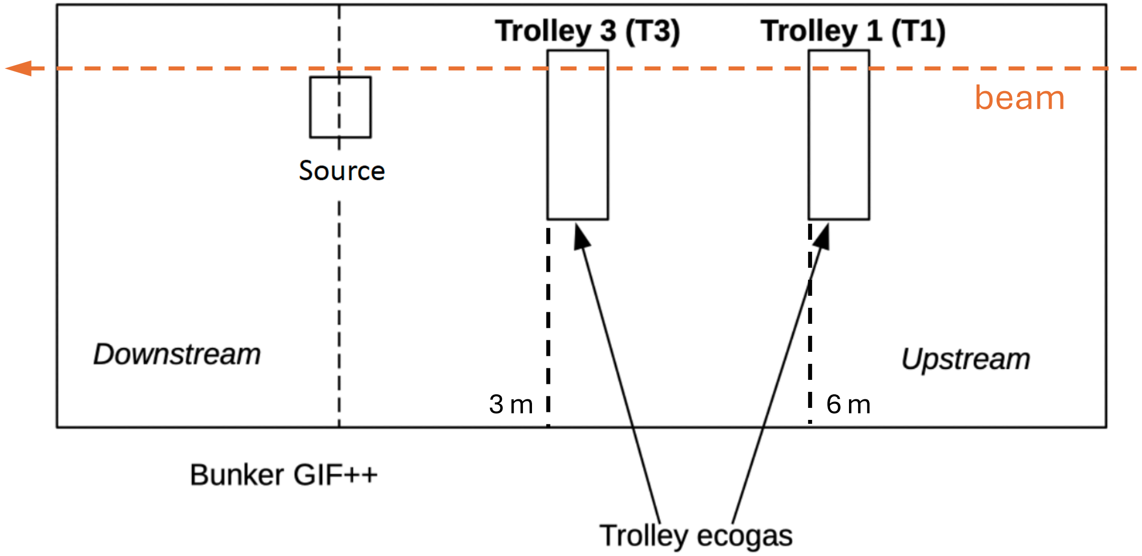
Performance of thin-RPC detectors for high rate applications with eco-friendly gas mixtures

# Setup at GIF++

- 12.2 TBq $^{137}Cs$ + H4 SPS beam line
- Radiation intensity attenuated by combination of filters

Gas mixer unit to provide up to 4 component gas mixture (humidified)

- $C_2H_2F_4$, $iC_4H_{10}$, $SF_6$, $CO_2$, Ar, HFO



RPCs: ALICE (2 mm), EP-DT (2 mm), CMS (2mm, double gap), CMS_Upgrade (1.4 mm, double gap), LHCb/SHIP (1.6 mm), ATLAS (2 mm)

**Aging studies**

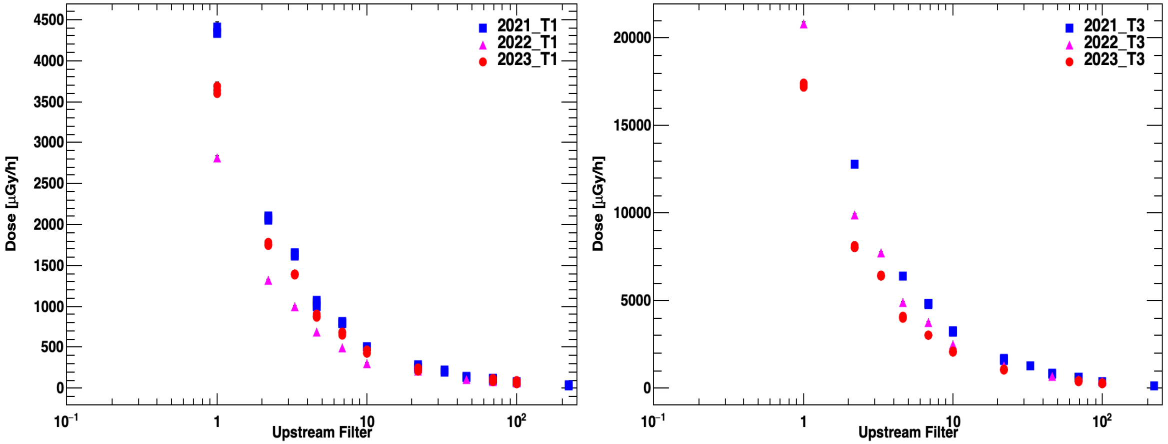
Monitoring of currents

**Detector performance (beam tests)**

CMS FEB for CMS RPC and KODEL FEB for CMS_Upgrade

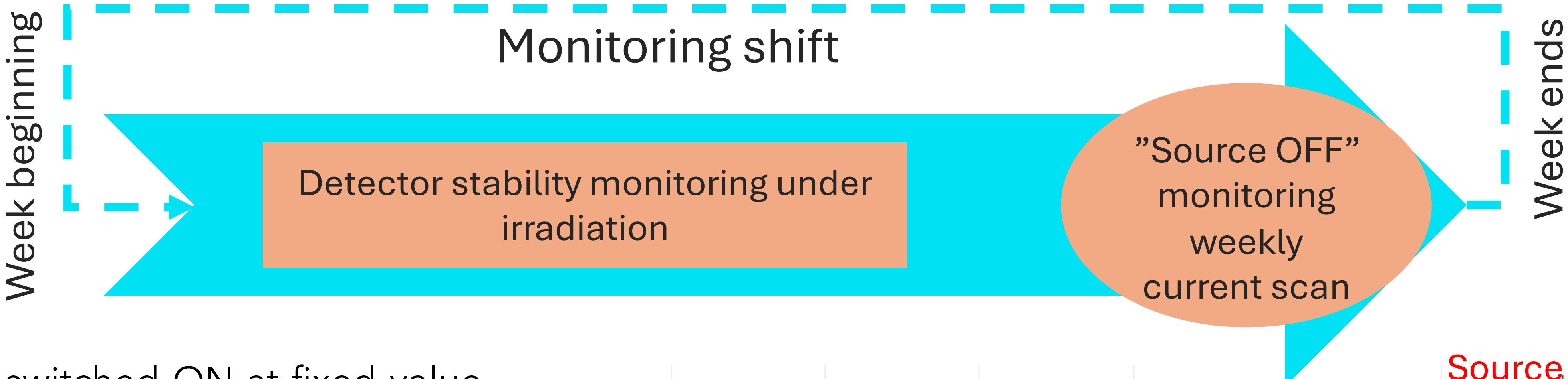
ALICE FEB FEERIC for ALICE and LHCb/SHIP RPCs

Dedicated digitizer for EP-DT and ATLAS RPCs



# Aging studies

# How our aging program works?



Week beginning

Monitoring shift

Detector stability monitoring under irradiation

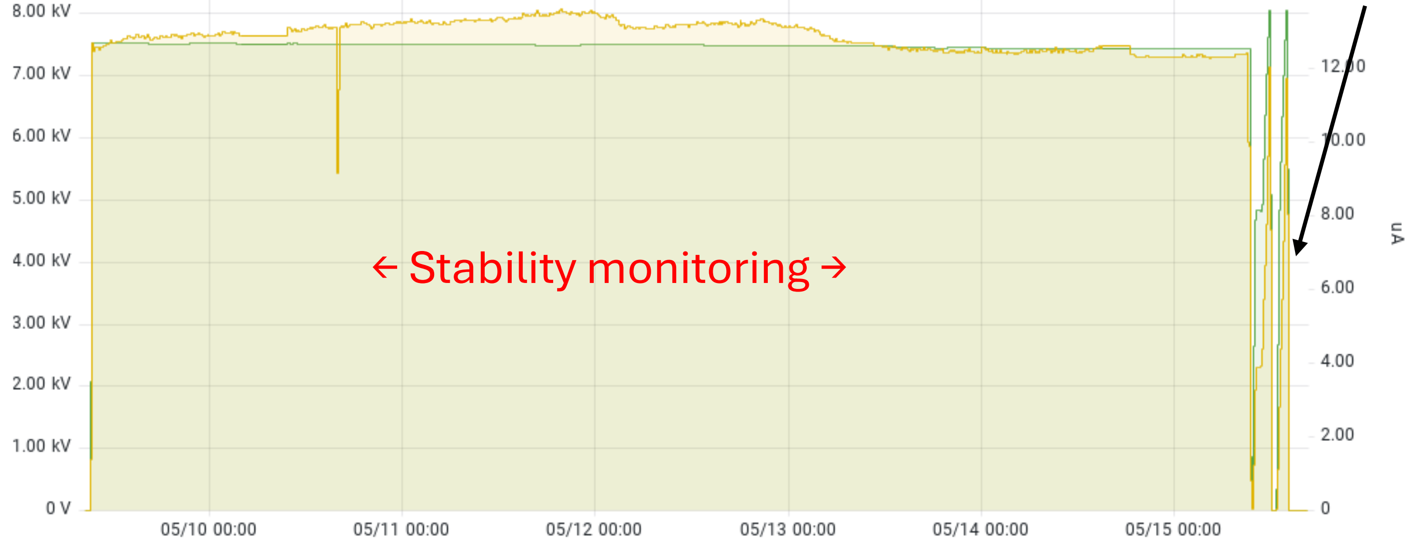
”Source OFF” monitoring weekly current scan

Week ends

- Detector HV switched ON at fixed value during all week → Stability monitoring
- HV is corrected every minute

$$HV_{app} = HV_{eff}\left[(1-\alpha)+\alpha\frac{P}{P_0}\frac{T_0}{T}\right]$$

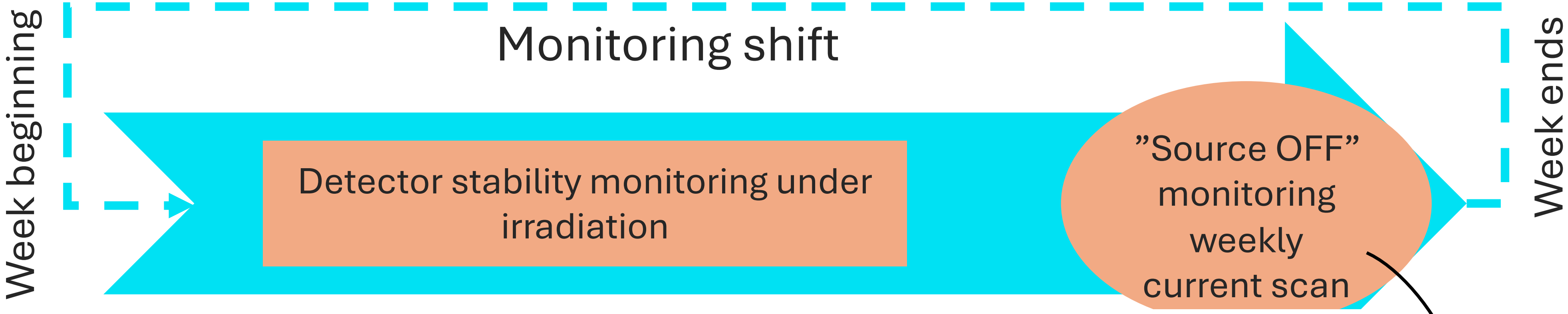
- Detectors are exposed to the γ flux from the $^{137}$Cs source → current and voltages are monitored by shifts



Source OFF scan

← Stability monitoring →

# How our aging program works?



Week beginning

Monitoring shift

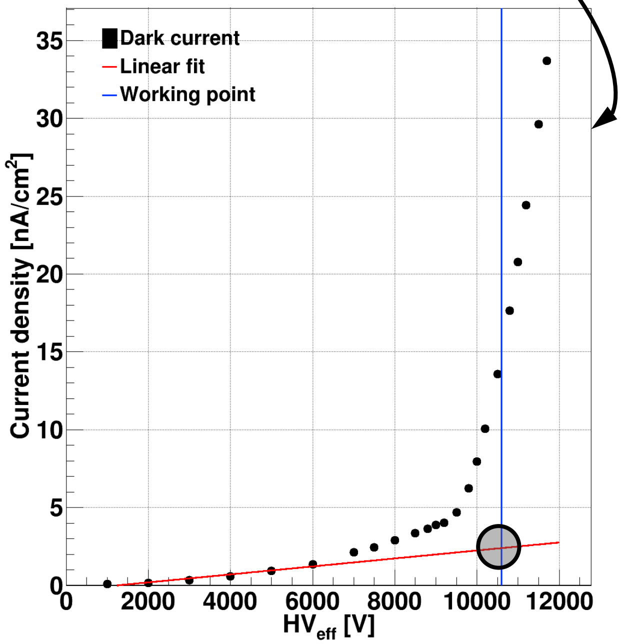
Detector stability monitoring under irradiation

”Source OFF” monitoring weekly current scan

Week ends

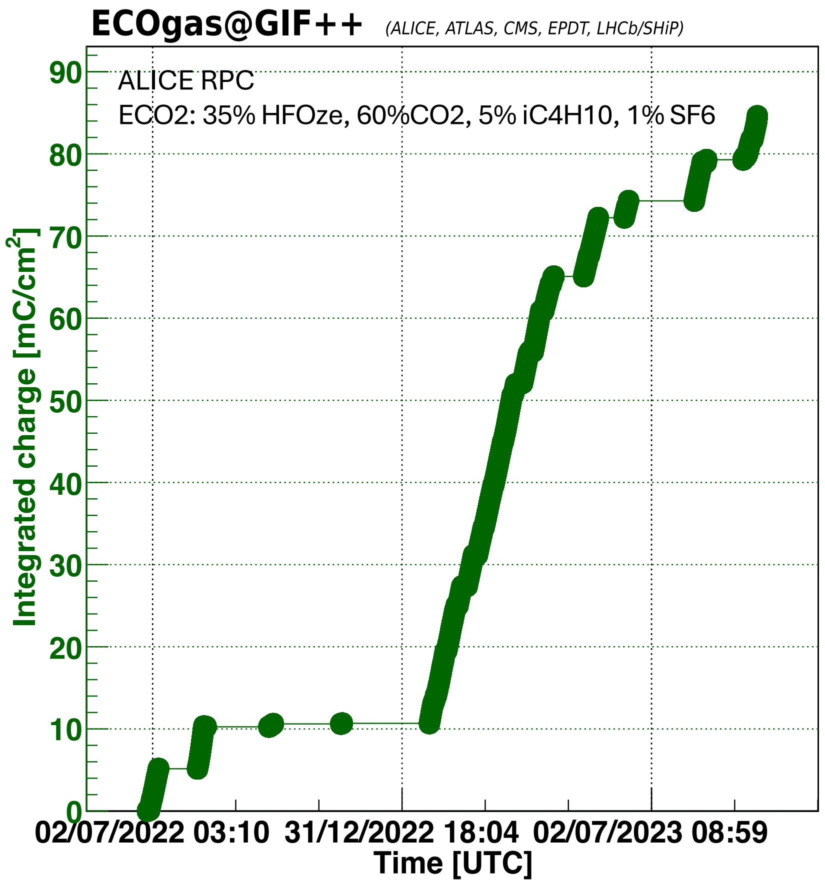
Linear fit between 0 and 5 kV to extrapolate Ohmic component of the dark current at the irradiation voltage
→ This current does not necessarily flow through the gas
→ Subtracted from the current absorbed under irradiation to calculate the integrated charge density

Current density monitoring over time as function of integrated charge density



# Integrated charge on time

By operating all detectors with ECO2



| GAP | $Q_{int}$ (mC/cm$^2$) | Period |
|---|---|---|
| ALICE | 85 | 2022-2023 |
| ATLAS | 125 | 2022-2023 |
| EPDT | 110 | 2023-2024 |
| CMS | ~200 | 2022-2024 |
| CMS_Upgrade | ~45 | 2023-2024 |
| LHCb/SHiP | 260 | 2022-2024 |

Total integrated (accumulated) charge by gaps by irradiation period

**Different maximum values of integrated charge** reached by the different RPCs
→ Efficiency corresponding to irradiation voltage is not the same on all detectors + different distances from the Cs source + different irradiation periods

# Aging studies results

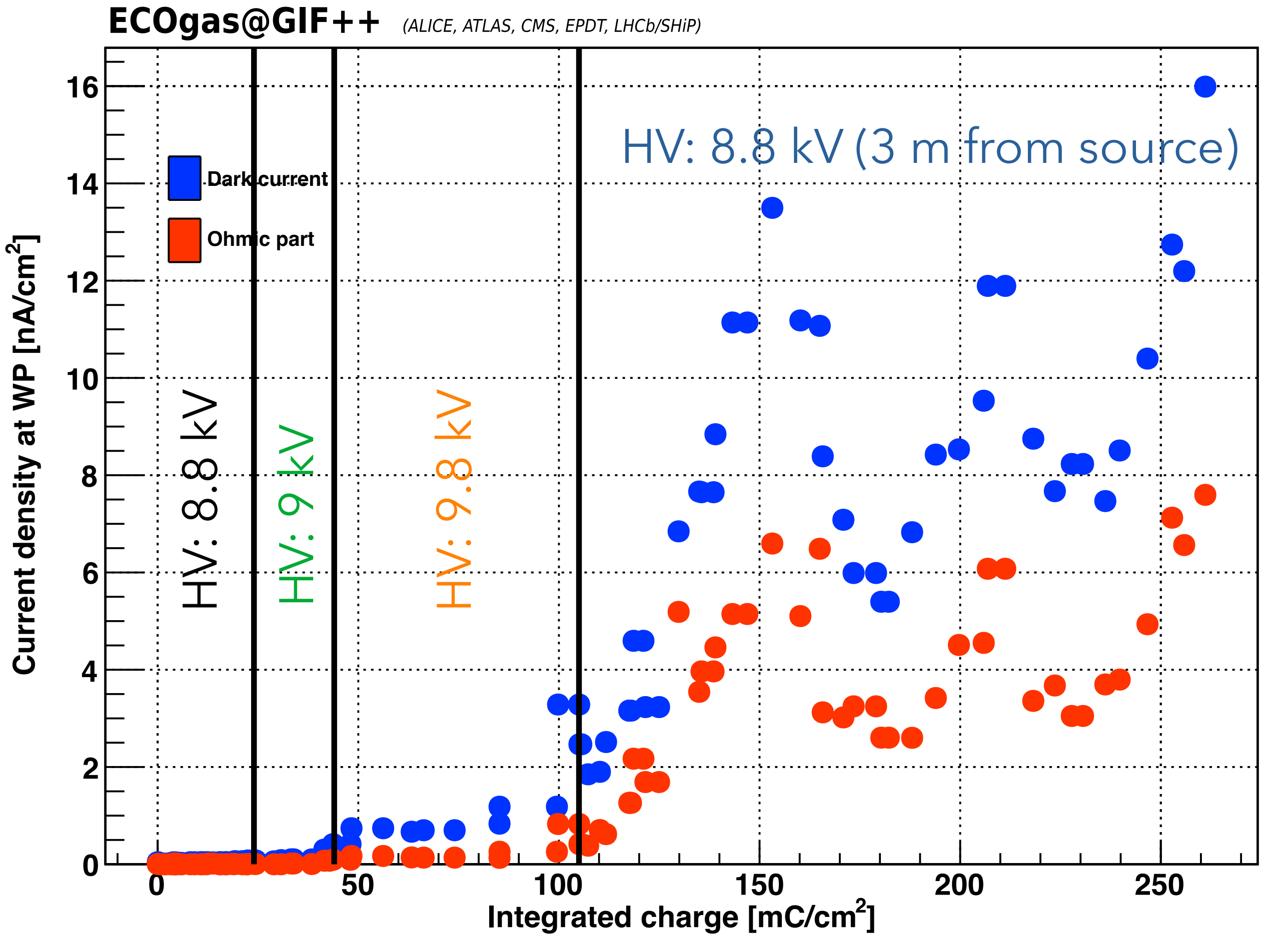
## LHCb/SHiP RPC

### Total and Ohmic dark currents

Effective high voltage of LHCb/SHiP RPC moved in steps up to 9.8 kV
→ Current trend stable over time
- When HV increased

→ Current increase + appearance of instabilities after 100 mC/cm$^2$ (under investigation)

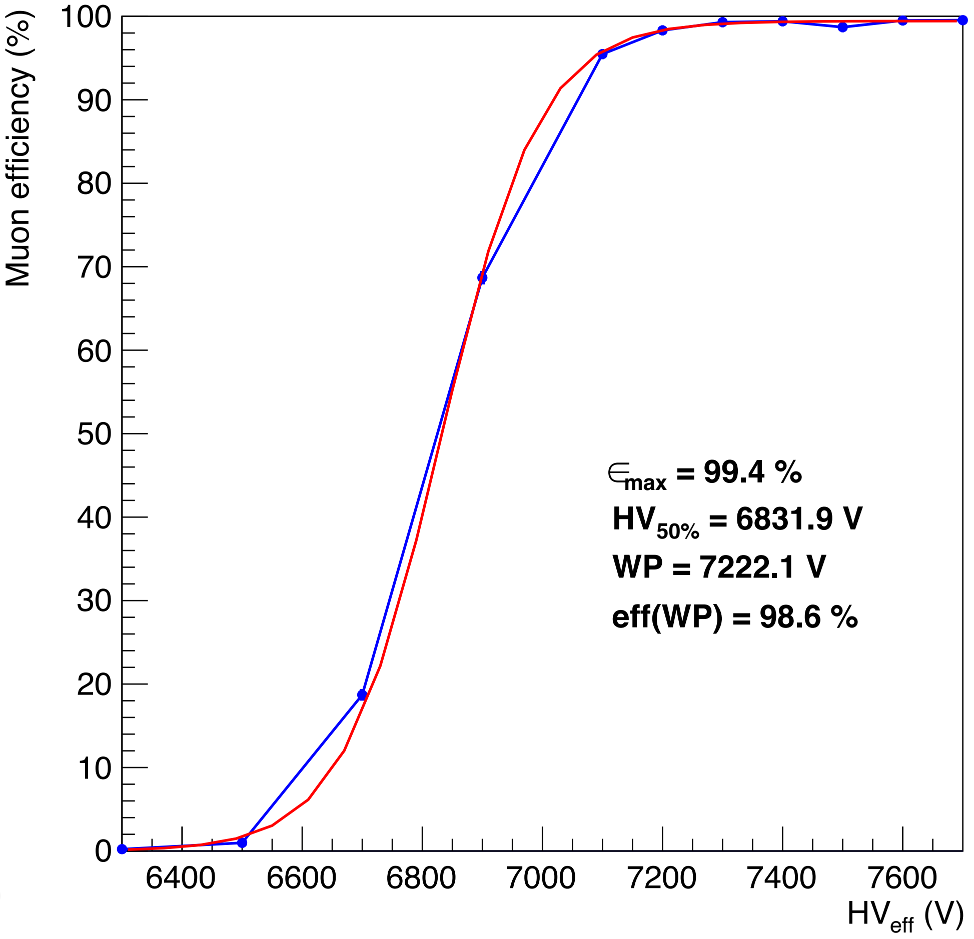
Similar trend for dark current and for all chambers in the collaboration



# Performance verification

# Some definitions

Example of high voltage scan of a chamber in absence of gamma background



Logistic function for efficiency fit

$$\varepsilon(HV) = \frac{\varepsilon_{max}}{1 + e^{-\beta(HV - HV_{50})}}$$

Working point

$$\mathrm{WP} = \frac{\log 19}{\beta} + HV_{50} + 150\ \mathrm{V}$$

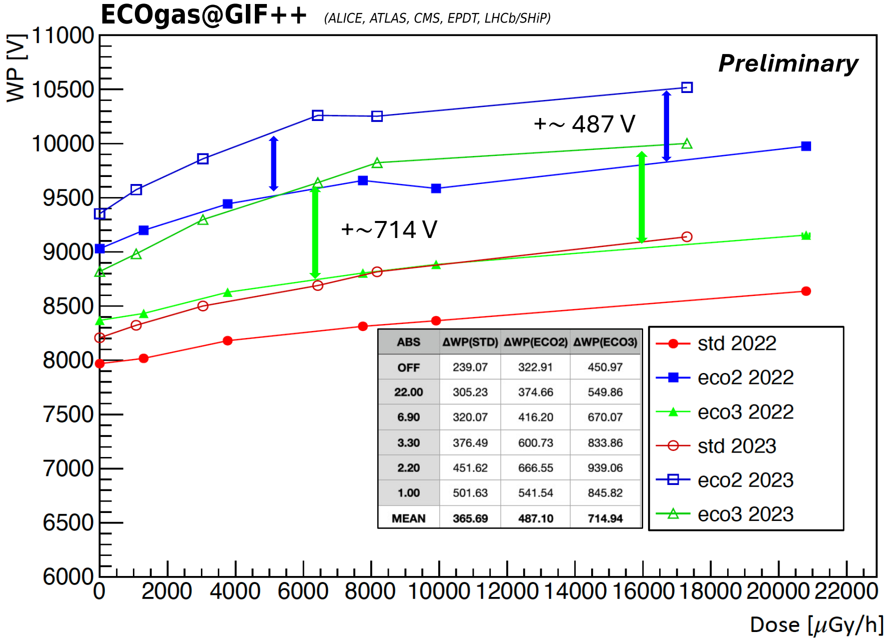
Effective high voltage corrected to be applied

Environmental correction to the high voltage also applied during irradiation (see slide 11)

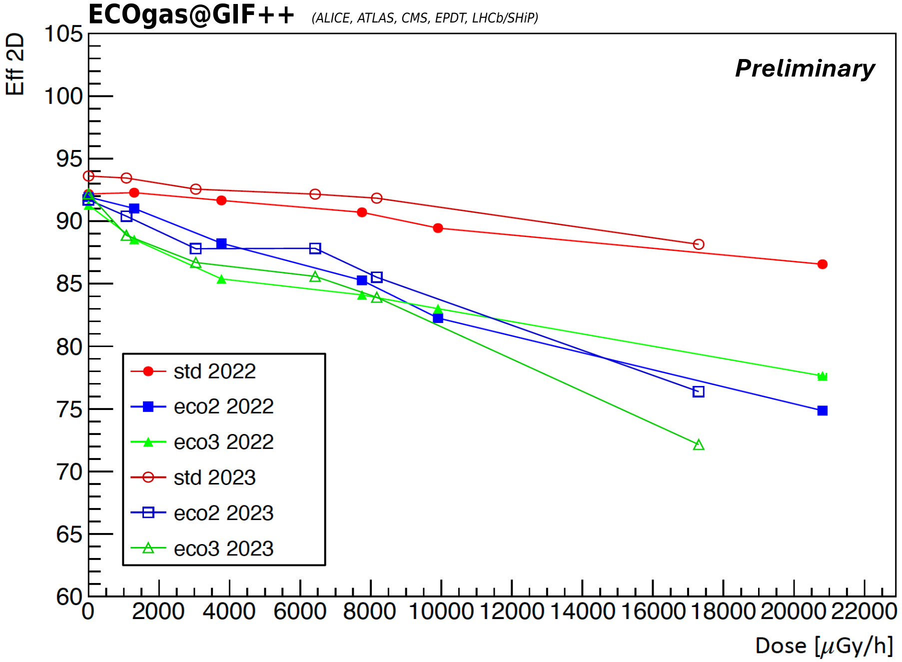
# Performance verification (1)

LHCb/SHiP RPC – 110 mC/cm$^2$

## Efficiency and Working Point



| ABS | ΔWP(STD) | ΔWP(ECO2) | ΔWP(ECO3) |
|---|---|---|---|
| **OFF** | 239.07 | 322.91 | 450.97 |
| **22.00** | 305.23 | 374.66 | 549.86 |
| **6.90** | 320.07 | 416.20 | 670.07 |
| **3.30** | 376.49 | 600.73 | 833.86 |
| **2.20** | 451.62 | 666.55 | 939.06 |
| **1.00** | 501.63 | 541.54 | 845.82 |
| **MEAN** | **365.69** | **487.10** | **714.94** |

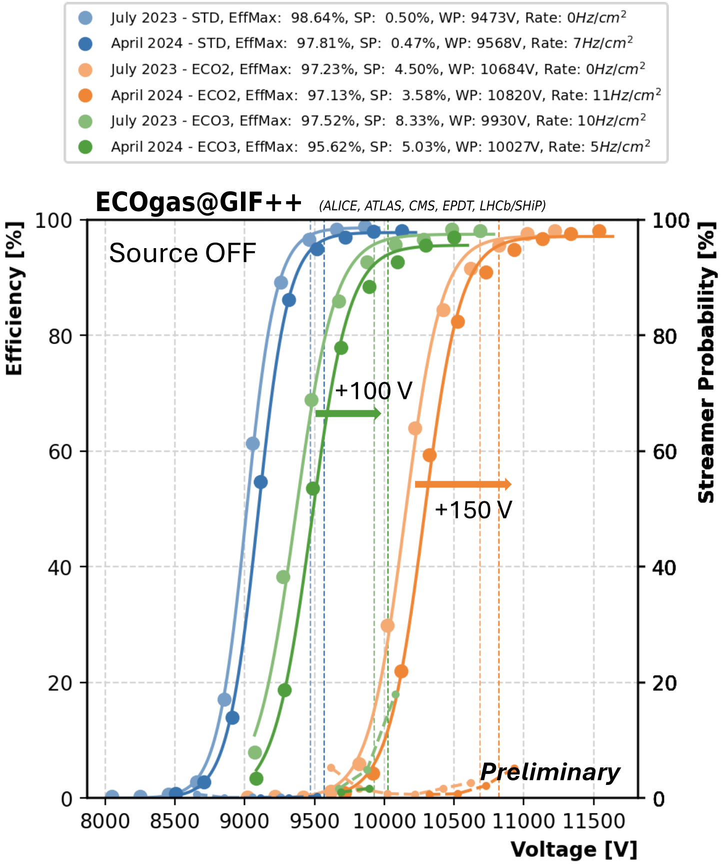


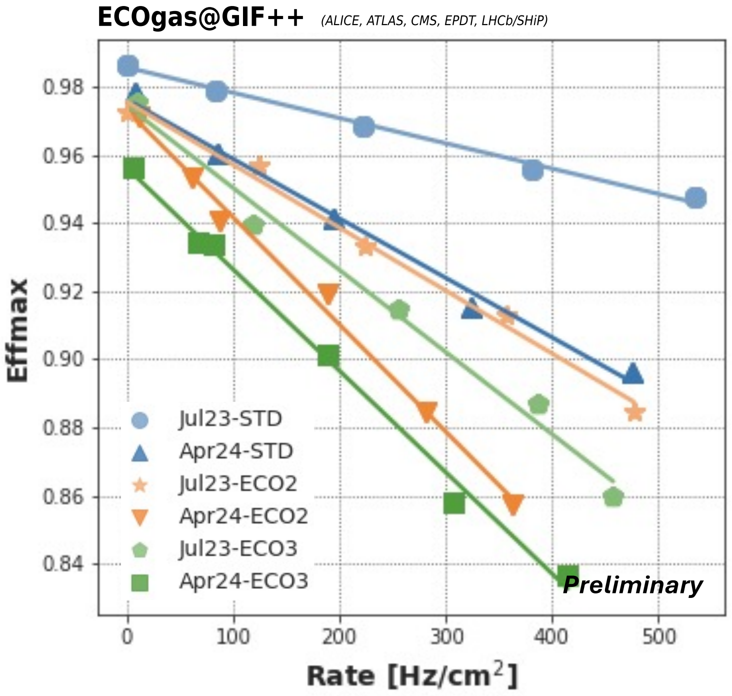
- **Increase of WP voltages** after 1 year of irradiation. In average higher increase when the operation was with ECO3, around 700 V, while with ECO2 around 500 V
- The **2D efficiency** shows similar trend for the ecological candidates and **not significant drop** is observed

# Performance verification (2)

## EP-DT RPC – 110 mC/cm$^2$

### Efficiency and Streamer Probability



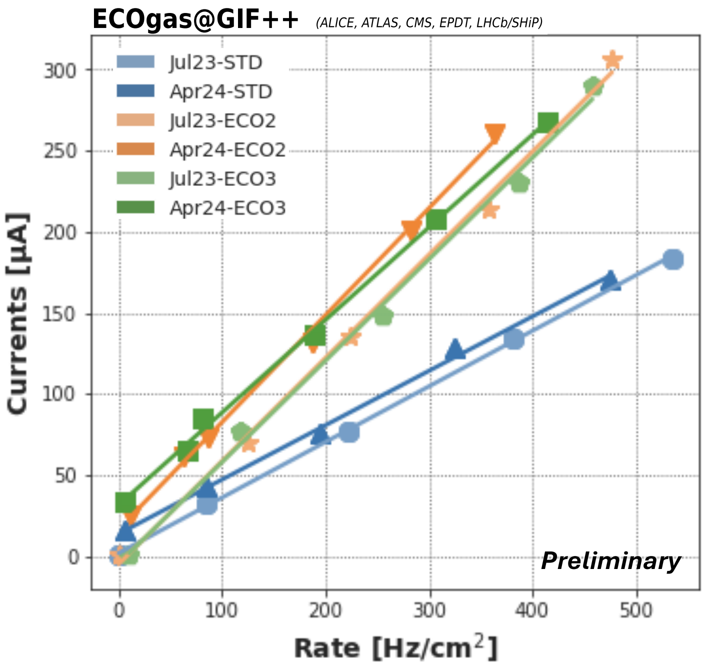


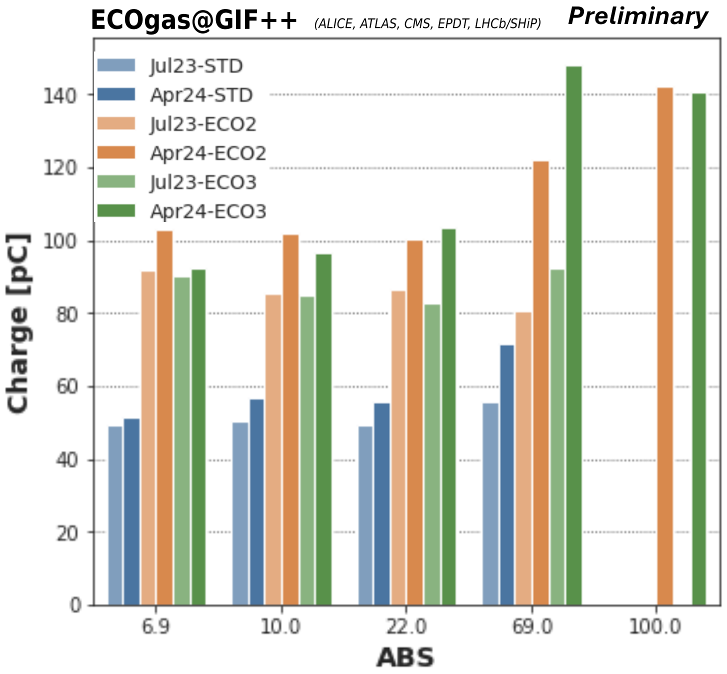
- Between the three mixtures, the efficiency drops at maximum ~2% (depending on the mixture and ABS filter) - which could result from the alignment
- The **streamer probability is reduced** for all runs for all the mixtures taken; the ECO3 shows more streamers than ECO2
- The **working point is increased, ECO2 shows a higher increase** in working point than ECO3
- The **maximum efficiency has dropped** compared to the last test beam for all mixtures

# Performance verification (3)

## EP-DT RPC – 110 mC/cm$^2$

### Currents and total charge





- The **currents** with respect to the rate are a **little higher than before irradiation**, for all rates tested → around **10% increase irrespective of the gas mixture**
- The slopes for the STD and ECO2 are similar to the last year, only for the ECO3 mixture, the currents are slightly decreasing at higher rates.
- In terms of charge per ABS filter, small increases have been observed, consistent with the higher currents.
- Between the mixtures, for the STD, the charge is lower, but for ECO2 and ECO3 they are similar on average.

# Summary

- Involved in the CERN phase-down of fluorinated GHG emissions, the RPC **EcoGas@GIF++ collaboration** has joined efforts to find a solution for the **environmentally friendly operation of RPCs**
- In 2022, a systematic **irradiation campaign** started, and the performance of each detector is annually verified during **beam tests**
- From aging studies, a **smooth increase trend of the total dark current** has been observed (also increases in ohmic contribution) → further discussion needed
- **No major degradation of the detector performance** has been verified from the beam test campaign at GIF++. **Increases in Working Point** values were observed in all RPCs after irradiation.

# THANKS!

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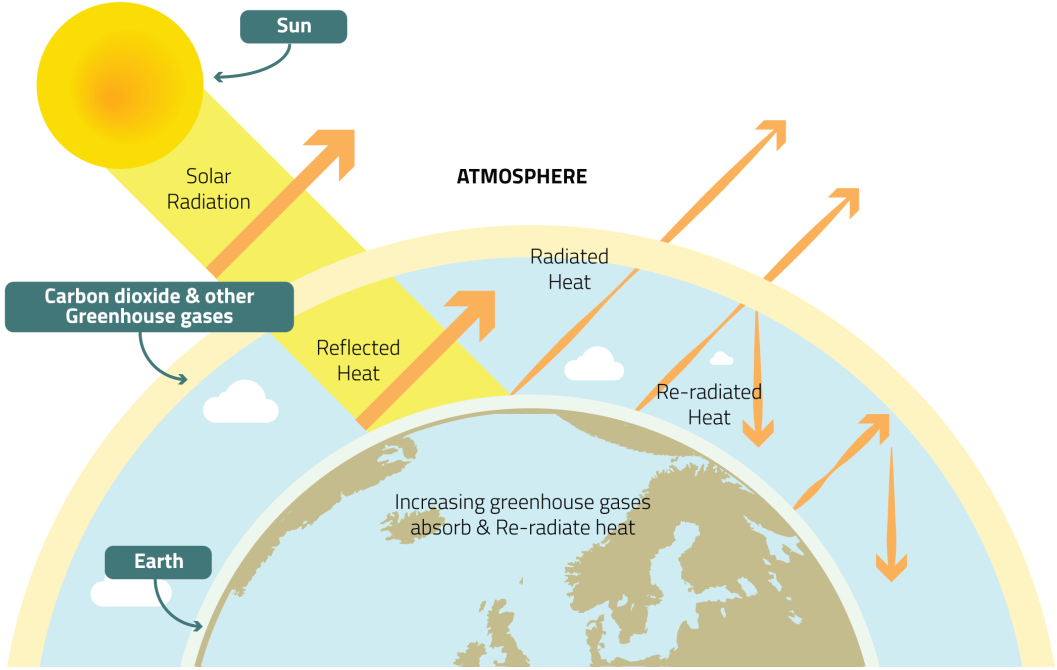
# Backup slides

# Global Warming Potential (GWP) and GHG emissions at LHC

**Greenhouse Gases** (GHGs) are gases in the earth's atmosphere that trap heat.



**Global warming potential (GWP)** is an index to measure of how much infrared thermal radiation a GHG would absorb over a given time. It is expressed as a multiple of the radiation that would be absorbed by the same mass of carbon dioxide, which is taken as a reference gas.

| **Gas** | **Atmospheric lifetime** | **$\mathbf{GWP_{100\ years}}$** |
|---|---:|---:|
| $CO_2$ | 50-200 years | 1 |
| R-134a | 14 years | 1430 |
| $CF_4$ | 50,000 years | 7390 |
| $C_4F_{10}$ | 2600 years | 9200 |
| $SF_6$ | 3200 years | 22800 |

Gases used at CERN with high GWP

# Resistivity monitoring by Ar scan

**Procedure**

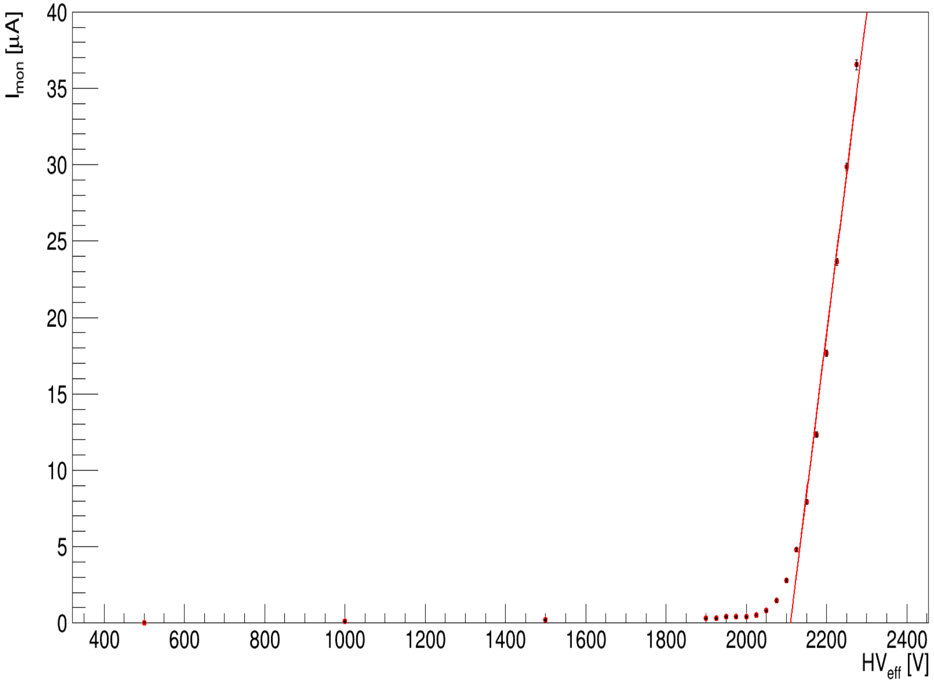
1. Linear fit to the ohmic part of the I(V) curve
2. Starting point of the fit is decided by the fit with the minimum chi square adding one point at a time
3. Function used y = a + bx, b = 1/R (R = resistance of the electrodes)

ρ(resistivity) = R*S(surface)/2d(electrode thickness) = 1/b*S/2d

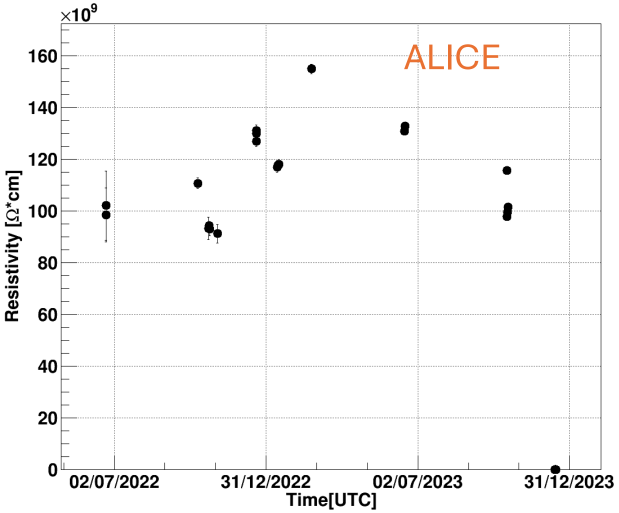
Resistivity values shown in the following are normalized to $T_0$ = 20°C using the following formula:

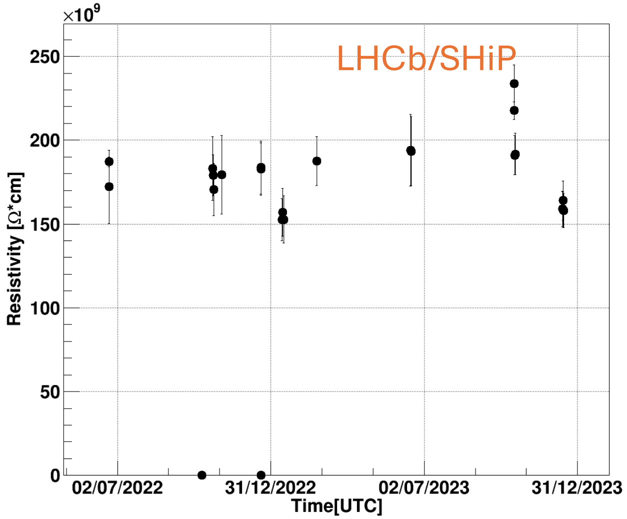
$$\rho(T)=\rho(T_0)*4.4^{\frac{T_0-T}{12°C}}$$

https://doi.org/10.1016/S0168-9002(00)00979-7



# Resistivity trend





- Resistivity monitoring by Ar scan (see backup slides)
- Slightly increase trend for CMS top RPCs while more constant behavior for the others
- Possible not uniform response in all detectors (under discussion, electrodes materials??)