Searches for Eco-friendly gases for gaseous detectors

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on behalf of the RPC ECOGAS @ GIF++ collaboration
with contributions from GEM, CSC, RICH communities

DRD1 kick-off meeting

CERN, January 31, 2024

The problem: use of Greenhous gases

We (basically) need to replace:

- $C_2H_2F_4$ = R134a mainly used in RPCs GWP = 1430
- SF_6 mainly used in RPCs GWP = 23400
- CF_4 used in CSCs, GEMs, RICH, etc. GWP = 6500

with more ecological gases, namely with a much lower Global Warming Potential.

Difficult problem: gases are **the core of gas-filled detectors.**

We also require:

- to get the **same performance**
- not to **change the electronics and HV** (for existing systems)
- to do everything at the **same cost**

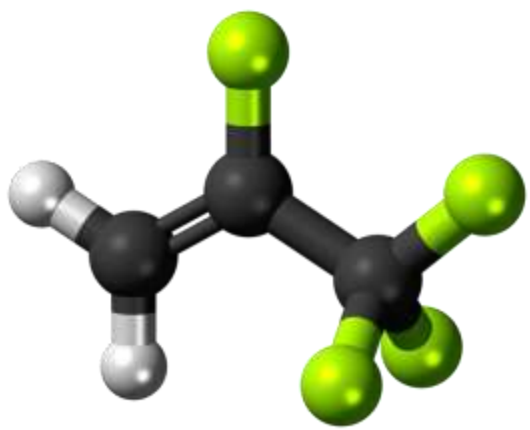
Of course we can also re-circulate the gases used, after purifying them → **see talk by G. Rigoletti**

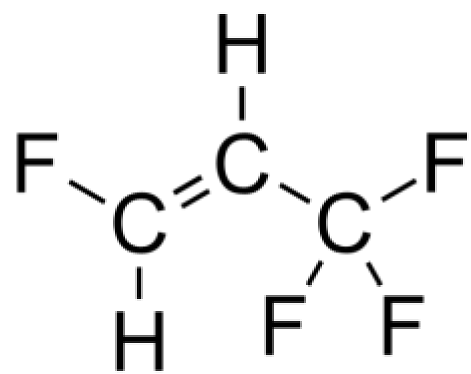
The smart (!?) idea

-Practically all research trendlines (with notable exceptions) concentrate around the idea of replacing:

- $C_2H_2F_4$ (GWP=1430)→ $C_3H_4F_4$ze (GWP=4)
  + CO_2 (GWP=1) or He (GWP<1)

CO_2 (or He) are added essentially to reduce the operating voltage.





$C_3H_4F_4$ze is the most similar molecule to $C_2H_2F_4$ but with a low GWP

Studies on the replacement of SF_6 are at an earlier stage, but interesting solution are on the table (see later on this talk).

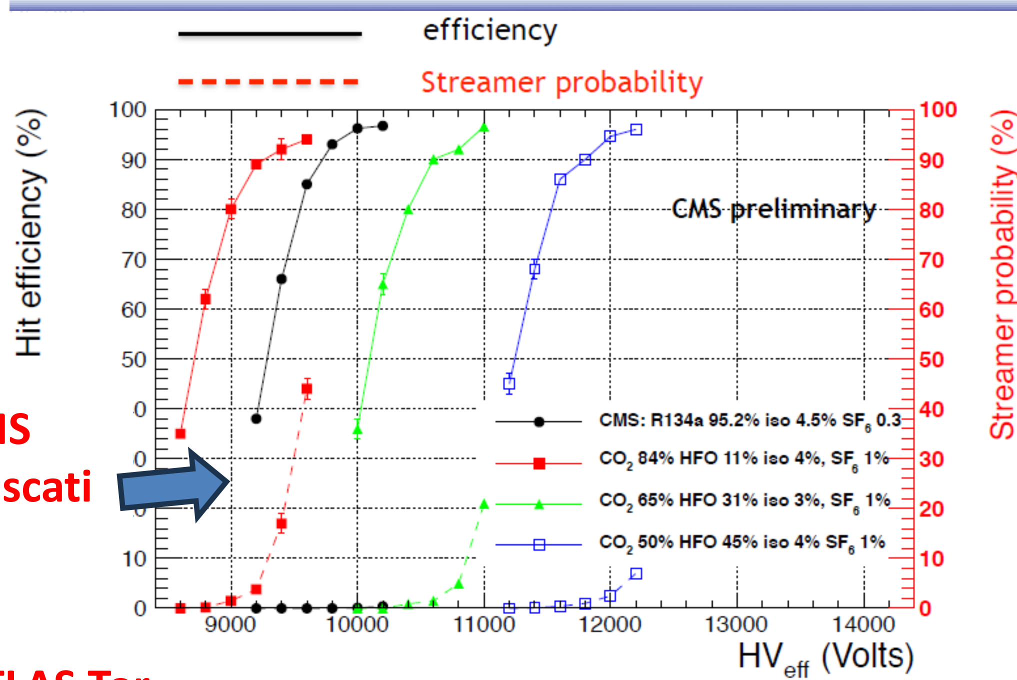
Test to be performed

RPCs filled with the desired gas mixture have to be operated and tested in terms of:

- -Efficiency (at low and high rate) and streamer fraction
- -Cluster size → direct impact on tracking capabilities
- -Time resolution → direct impact on triggering and TOF
- -Current absorbed (at low and high rate) → good indication of possible aging effect
- -Pollutants produced (e.g. HF, but NOT only HF) → direct impact on aging effect
- -Charge distribution →helps explaining many things

All high energy experiments (ALICE, ATLAS, CMS, LHCb, etc.) have started an intense R&D program to find suitable gas mixtures

Tests at the various home-labs

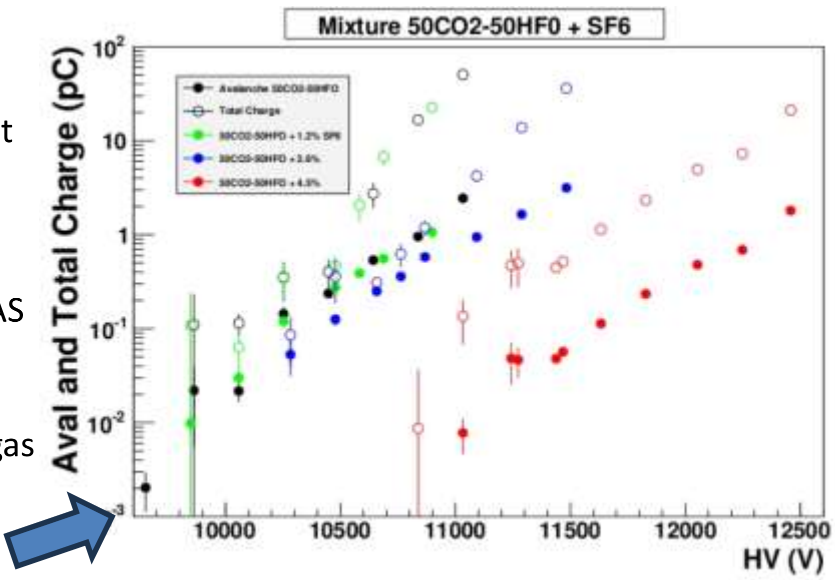


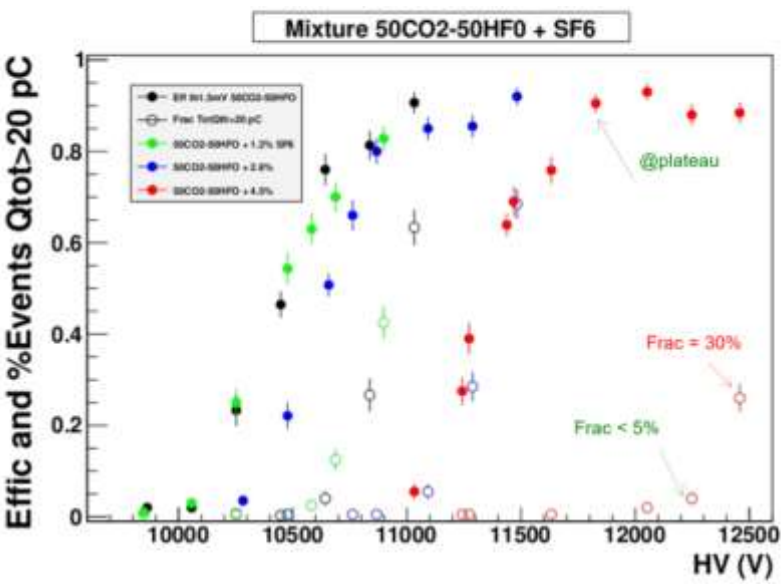
CMS Frascati

Preliminary results of Resistive Plate Chambers operated with eco-friendly gas mixtures for application in the CMS experiment, JINST 11 C09018 (2016)

ATLAS Tor Vergata

B. Liberti, "Recent results on environmental-friendly gas mixtures for ATLAS RPC", 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors

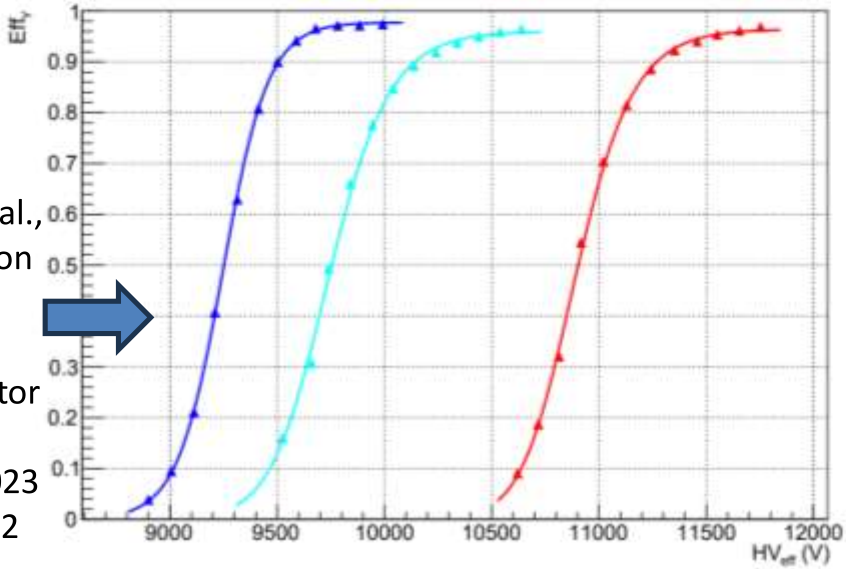




Tests at the various home-labs

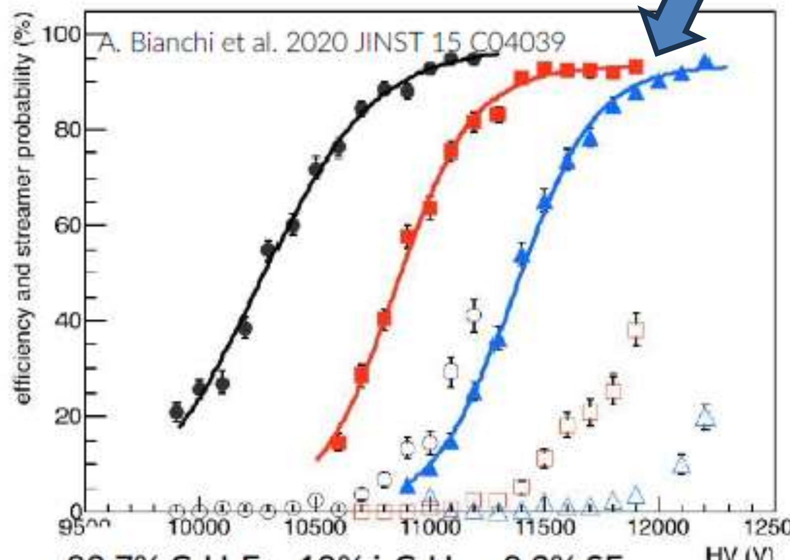
LHCb/SHip Bari

R. Albanese et al., RPC-based Muon Identification System for the neutrino detector of the SHiP experiment, 2023 JINST 18 P02022

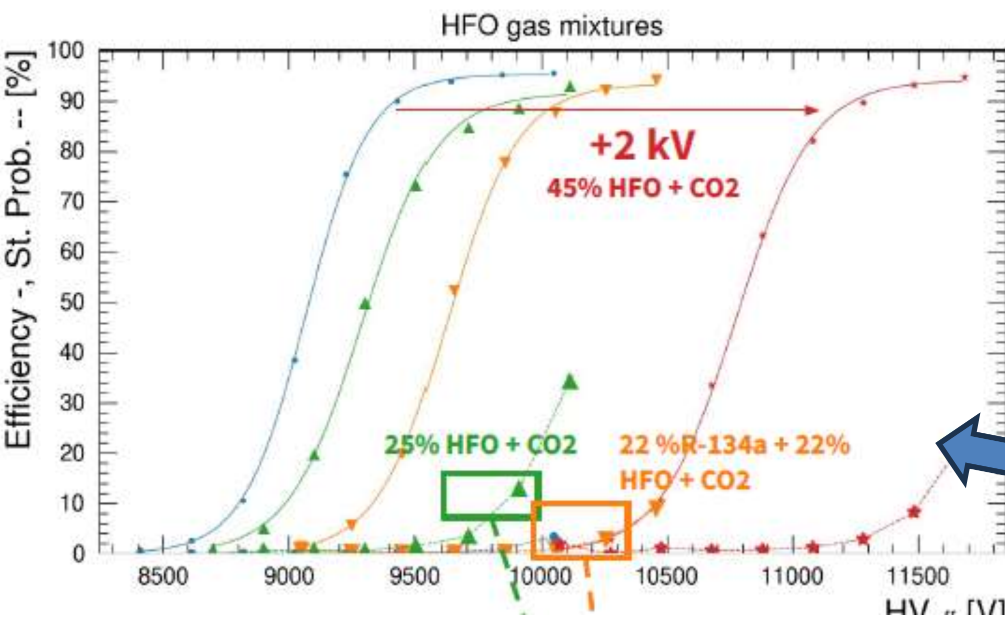


- 95.2% R134a/ 4.5% iC_4H_{10} / 0.3% SF_6 (standard)
- 60% CO_2/ 35% HFO/ 4.5% iC_4H_{10} / 0.5% SF_6
- 69.5% CO_2/ 25% HFO/ 5% iC_4H_{10} / 0.5 % SF_6

ALICE Torino



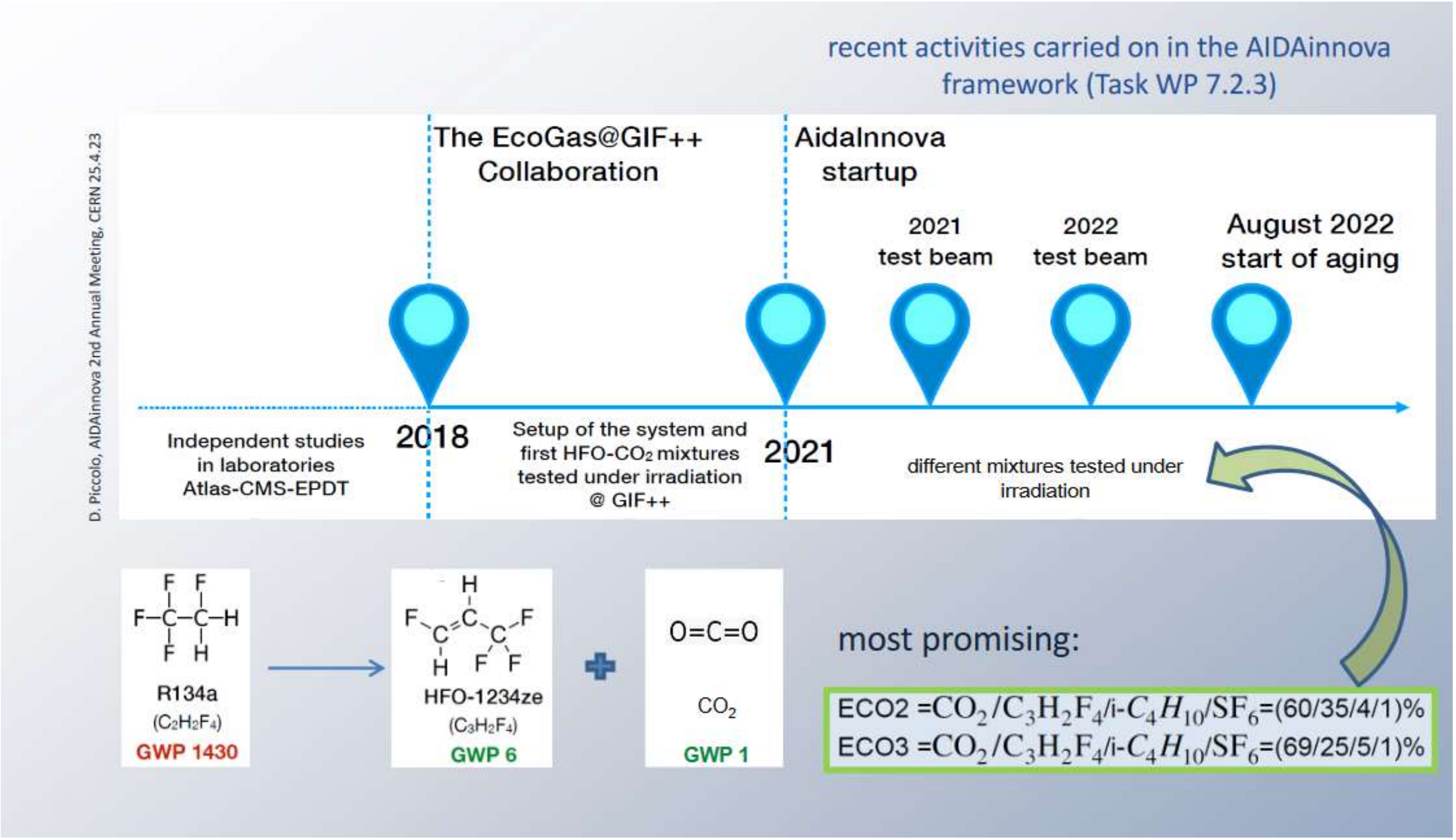
89.7% $C_2H_2F_4$ - 10% i-C_4H_{10} - 0.3% SF_6
50% CO_2 - 39.7% HFO - 10% i-C_4H_{10} - 0.3% SF_6
50% CO_2 - 39.0% HFO - 10% i-C_4H_{10} - 1% SF_6



CERN EP-DT

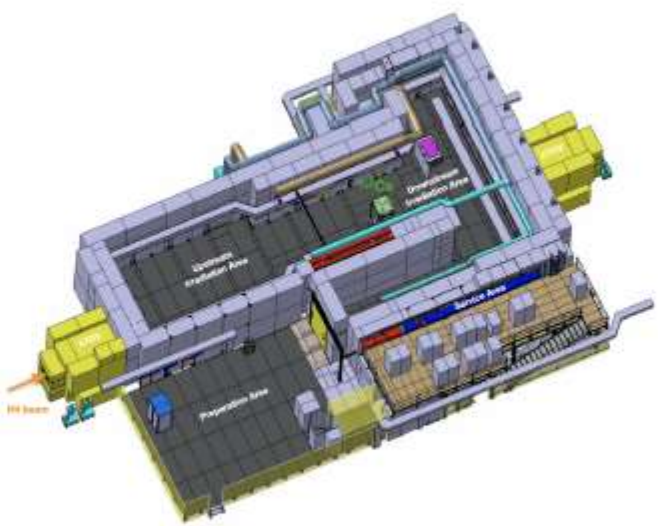
From: G. Rigoletti, “Environment friendly gas mixtures for Resistive Plate Chambers”, 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors

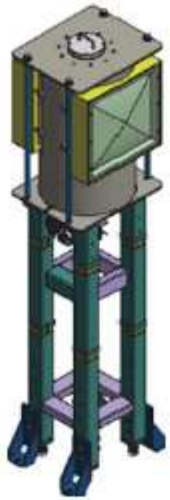
The RPC ECOGas@GIF++ experience



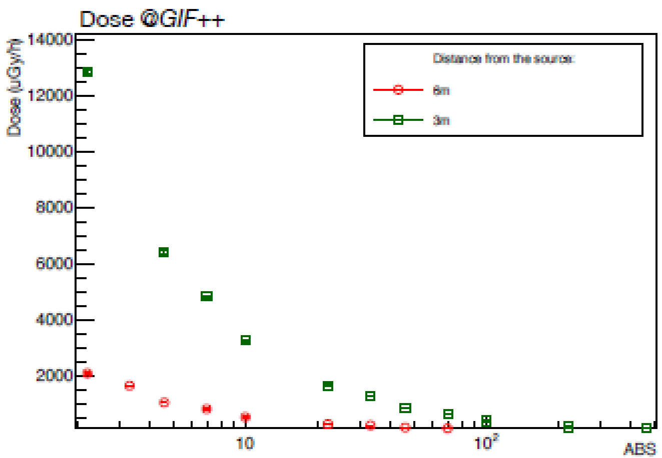
The RPC EcoGas@GIF++ is a collaboration **transversal to ALICE, ATLAS, CERN EP-DT, CMS**, **and LHCb** willing to put togethere expertise and resources in order to test different detectors and electronics, in the same conditions and 2-3 potential candidates of eco-friendly gas mixtures.

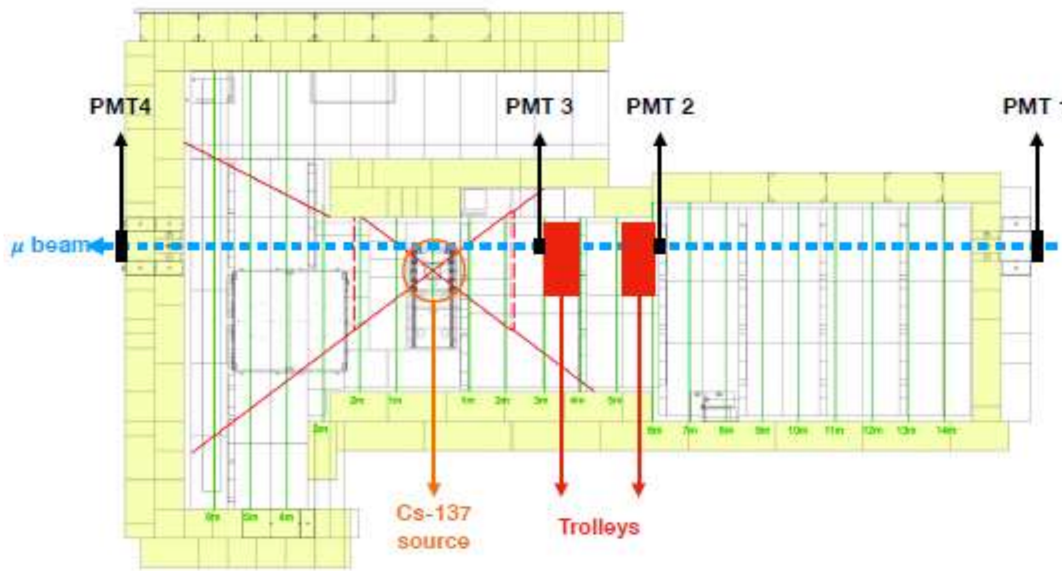
Tests at high rate: the Gamma Irradiation Facility





- H4 beam line in EHN1, CERN NA
- **Cs-137 gamma source** up to 12 TBq
- **Muon beam:** ≈ 150 Gev/c
- Gamma flux modulated independently using a system of six attenuation filters (ABS)





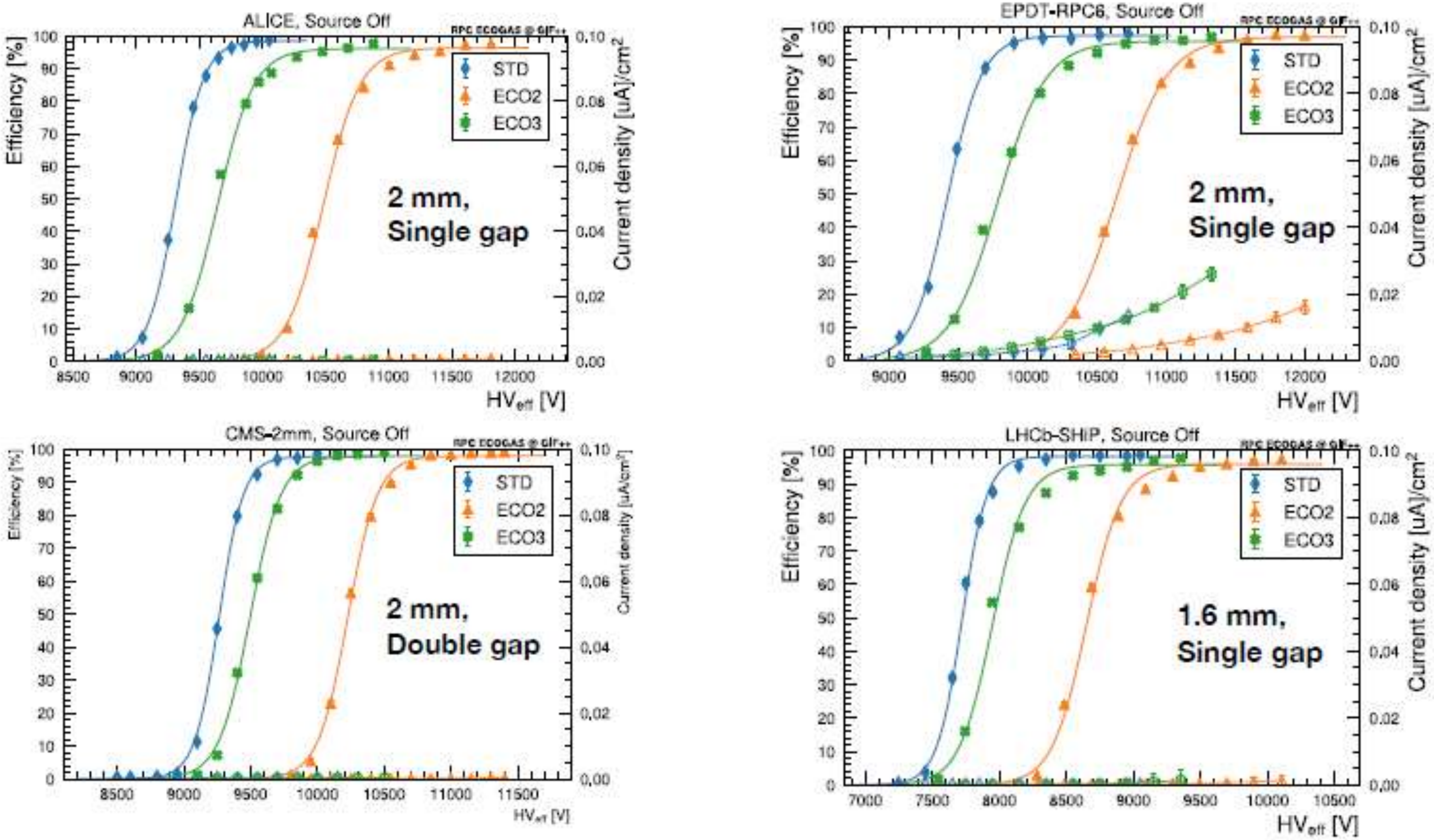
Detector Set-up at GIF++

	RPC characteristics	Readout
ALICE	50x50 cm^2 2 mm single gap 2 mm bakelite electrodes	2D readout (16+16 strips) 3 cm pitch TDC
ATLAS	10x55 cm^2 2 mm single gap 1.8 mm bakelite electrodes	1D readout (1 strip) 3 cm pitch Digitizer
CMS BARI-1p0	70x100 cm^2 1.0 mm single gap 1.43 mm bakelite electrodes	1D readout (32 strip) 0.5 cm pitch TDC
CMS	Trapezoidal (height 10 cm, bases 51cm and 33 cm) 2 mm double gap 2 mm bakelite electrodes	1D readout (128 strip) 1 cm pitch TDC
CERN EP-DT	50x50 cm^2 2 mm single gap 2 mm bakelite electrodes	1D readout (7 strips) 2.1 cm pitch Digitizer
LHCb-SHiP	70x100 cm^2 1.6 mm single gap 1.6 mm bakelite electrodes	2D readout (32+32 strips) 1 cm pitch TDC

5 different detectors, various electronics, use of digitizers

The RPC EcoGas@GIF++ collaboration **is a VERY nice example** of collaboration across various experiments.

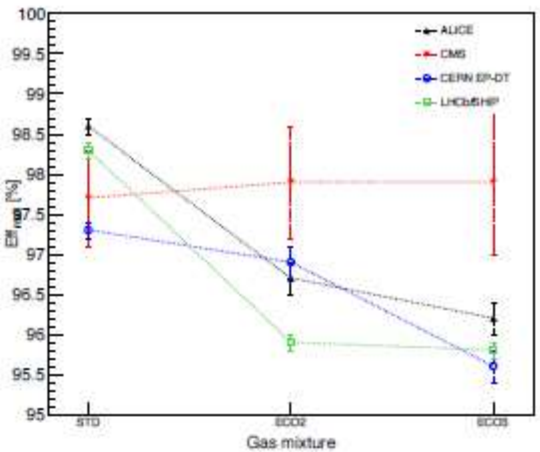
Performance without irradiation (no source)

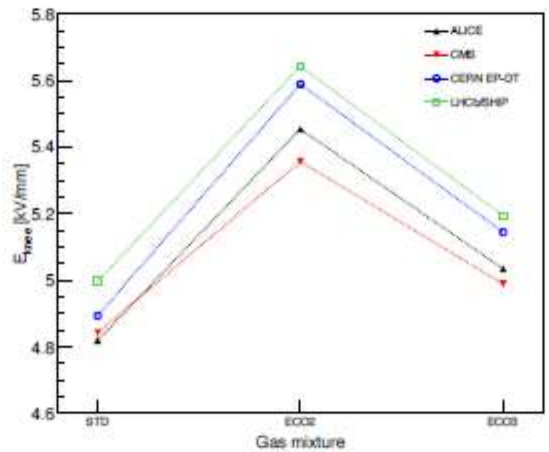


Gas mixtures tested:

	R134a (%)	HFO-1234ze (%)	CO_2 (%)	i-C_4H_{10} (%)	SF_6 (%)	GWP	CO_2e (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		

Performance without irradiation





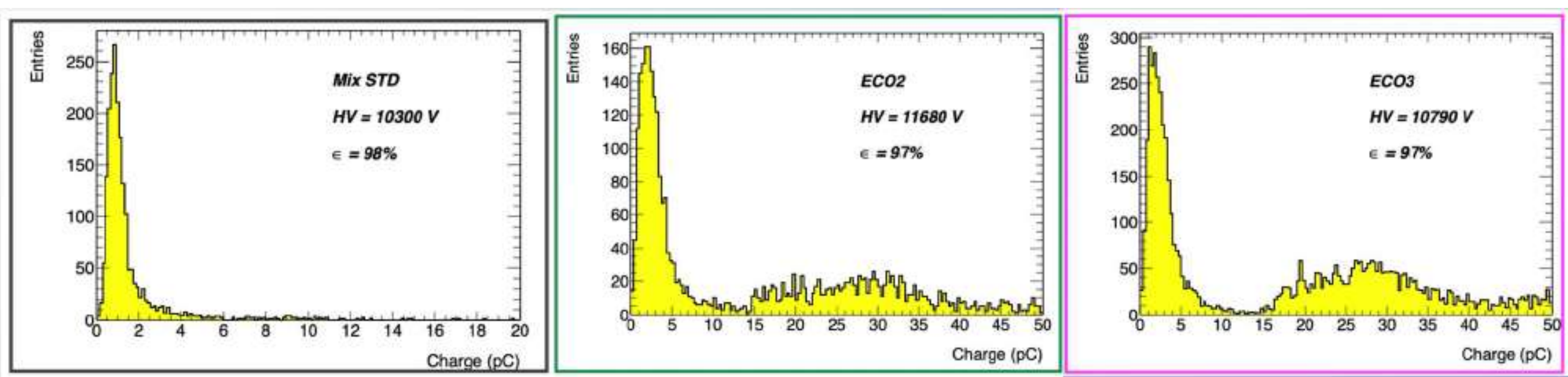
Efficiency curves fitted with sigmoid functions:

$$Eff(H_{Veff}) = \frac{Eff_{max}}{1 + e^{-\lambda^*(H_{Veff} - HV50)}}$$

Effmax well above 95% decreases for ECO2 and ECO3 (lighter target due to CO2)
Double gap CMS is less sensitive

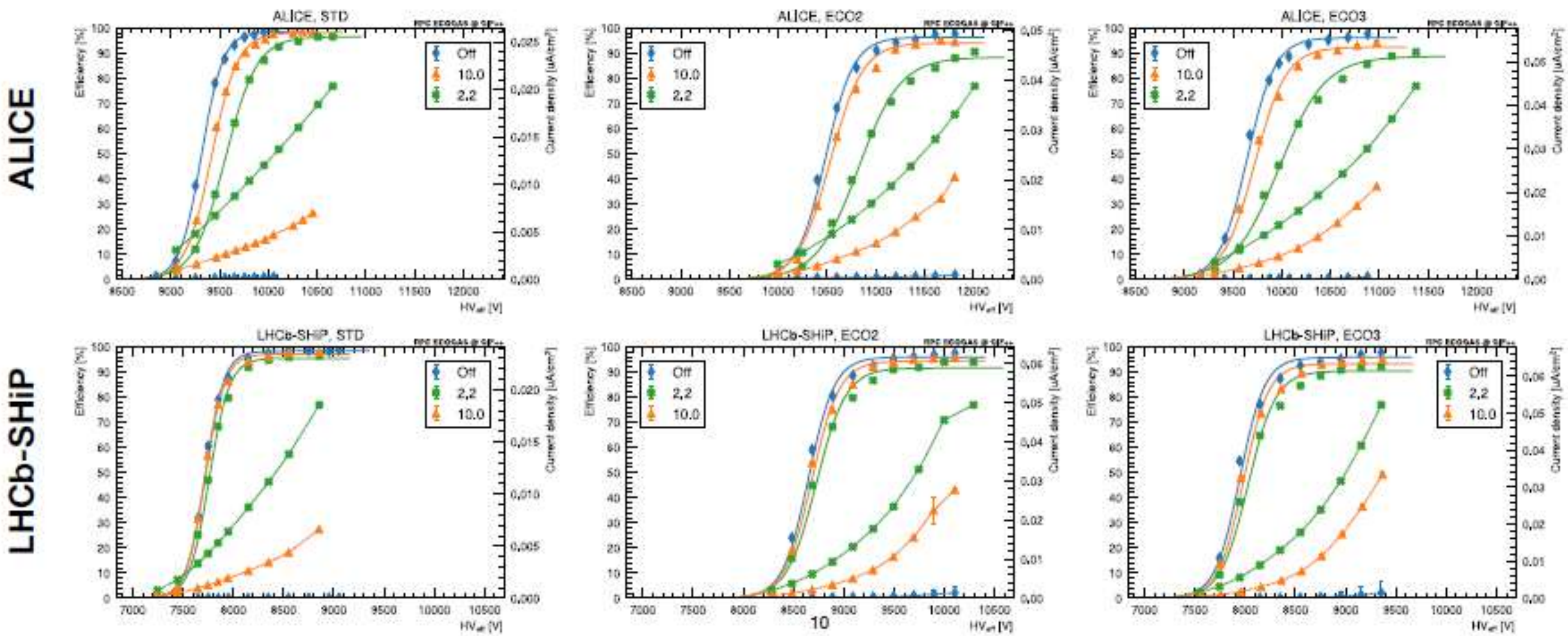
Electric field @ knee higher for ECO2 and ECO3

ATLAS RPC charge distributions



Larger streamer contamination for ECO2 and ECO3

Performance with irradiation



Efficiency and current density

Data taken at different ABS:

- ALICE-LHCb/Ship (6 m far from source)
    - OFF
    - ABS 10 (510 uSievert/hour; 70* Hz/cm² @knee)
    - ABS 2.2 (2070 uSievert/hour; 280* Hz/cm² @knee)

Data taken at different ABS:

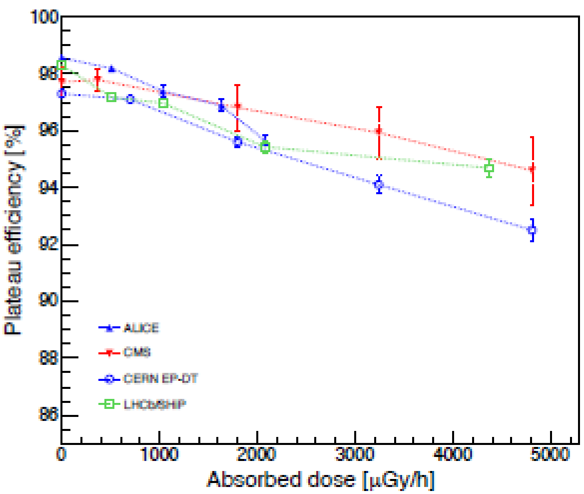
- CMS-EPDT (3m far from source)
    - OFF
    - ABS 69 (700 uSievert/hour; 80* Hz/cm² @knee)
    - ABS 22 (1800 uSievert/hour; 200* Hz/cm² @knee)

Performance with irradiation

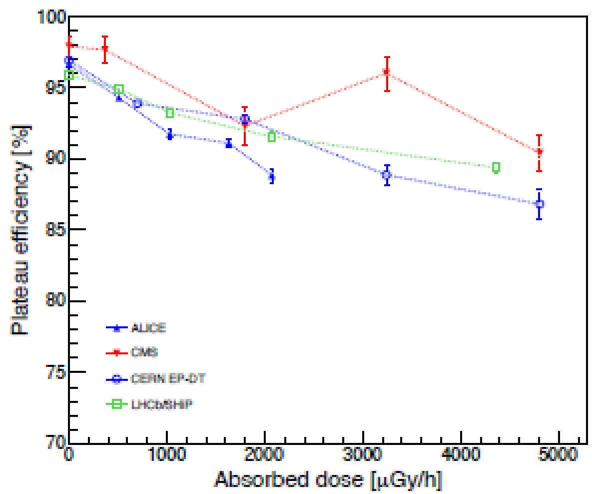
Efficiency summary for each gas mixture

Larger efficiency drop when using ECO2 and ECO3 mixtures

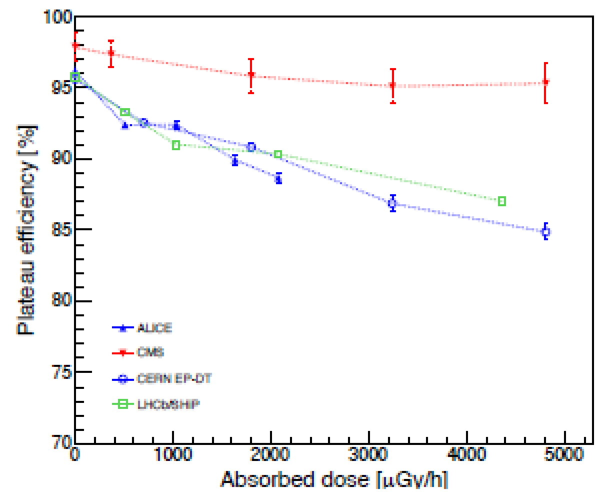
Plateau Efficiency vs. Dose with STD mixture



Plateau Efficiency vs. Dose with ECO2 mixture



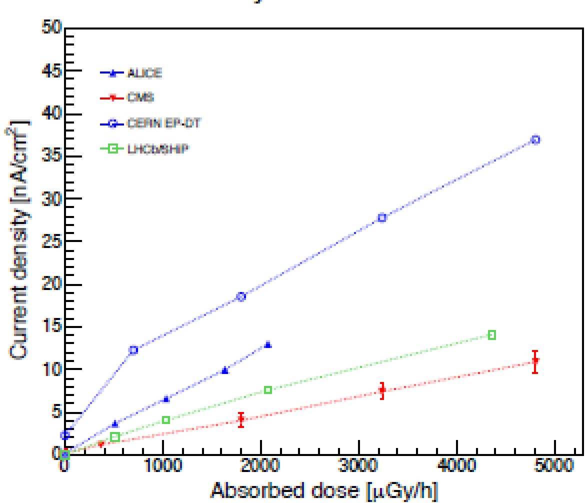
Plateau Efficiency vs. Dose with ECO3 mixture



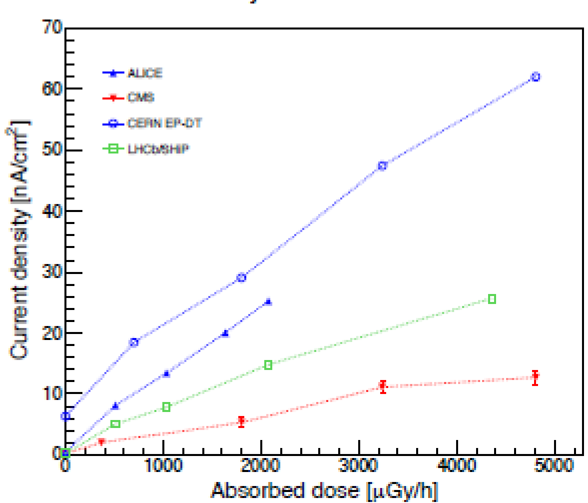
Current density summary for each gas mixture

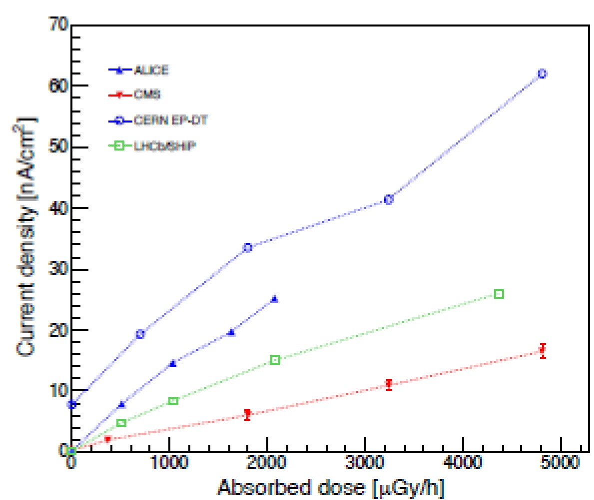
Slightly higher currents for at higher doses when using ECO2 and ECO3

Current density vs. Dose with STD mixture

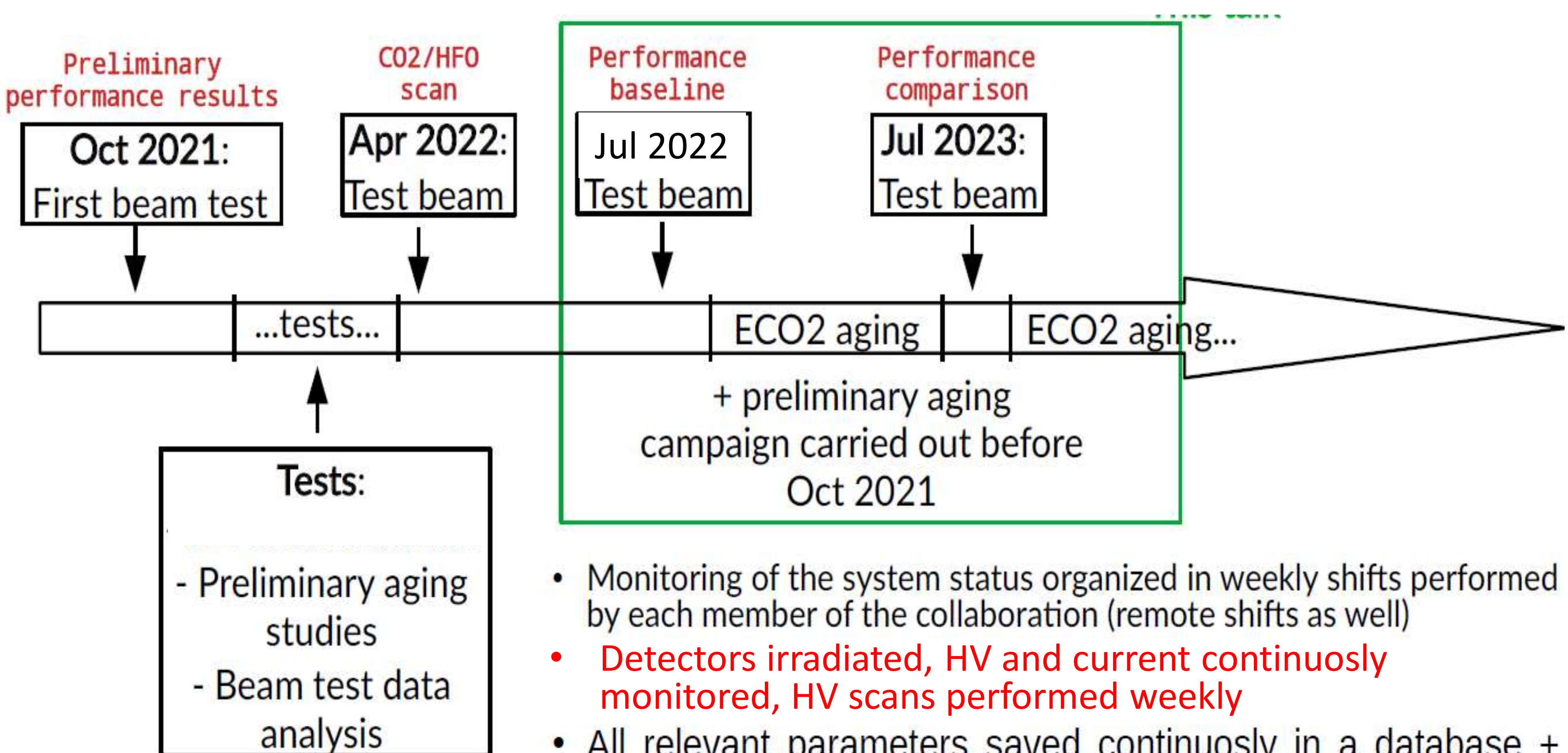


Current density vs. Dose with ECO2 r





Timeline of the aging tests @ GIF++



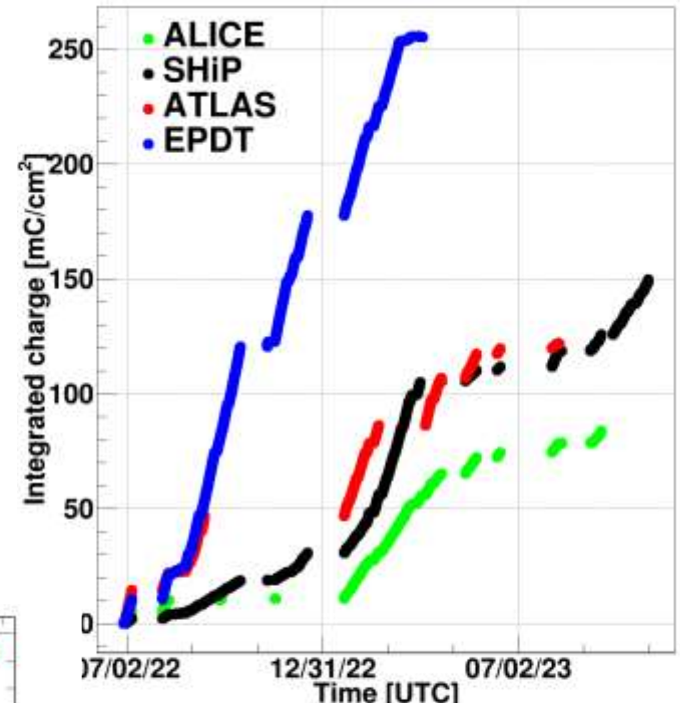
- Monitoring of the system status organized in weekly shifts performed by each member of the collaboration (remote shifts as well)
- Detectors irradiated, HV and current continuosly monitored, HV scans performed weekly
- All relevant parameters saved continuosly in a database + Grafana panel developed for ease of access and monitoring

Results of 2021 test beam in: High-rate tests on Resistive Plate Chambers operated with eco-friendly gas mixtures, ArXiV: 2311.08259, submitted to EPJ-C

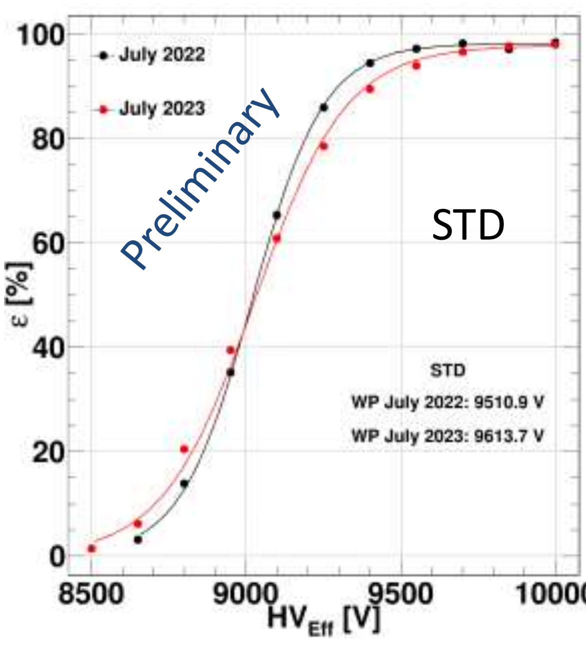
Preliminary results of aging tests

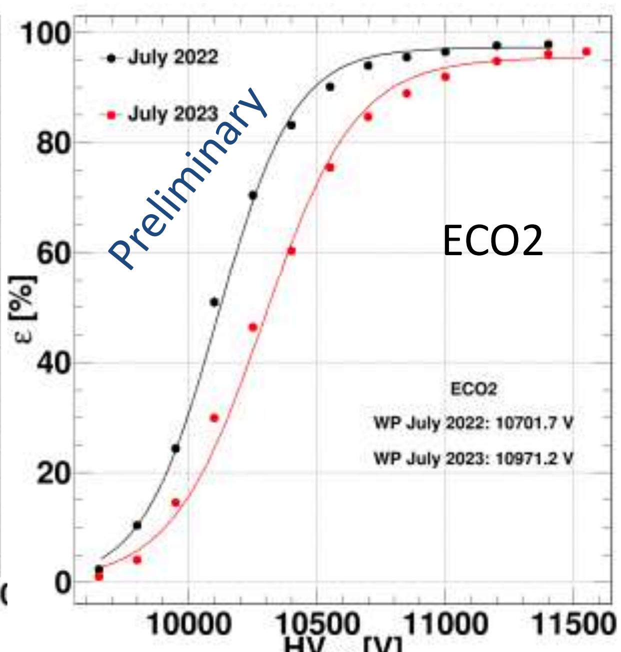
Different integrated charge from the various RPCs
- Because of different distance
- Charge at irradiation voltage not the same

Around 1.5 years of irradiation
Order of 100 mC/cm² of integrated charge



ALICE chamber



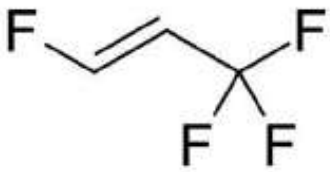


Efficiency shift with ECO2 could be explained by the observed increase in the absorbed current
- leading to larger efficiency drop on resistive plates
- effectively reducing the voltage applied to the gas

Looking for replacements for SF_6 (ATLAS)

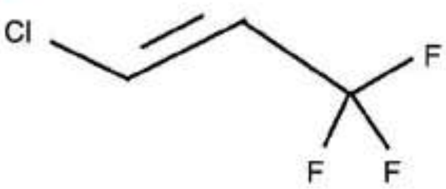
The standard gas mixture has a high Global Warming Potential (GWP)

- $C_2H_2F_4$ + i-C_4H_{10} + SF_6 → **GWP ~ 1450**



Substitute $C_2H_2F_4$ with an environment-friendly gas mixture

- CO_2 / $C_3H_2F_4$ **(HFO1234ze)** + i-C_4H_{10} + SF_6 → **GWP ~ 200**



Substitute the SF_6 with a different environment-friendly gas :the **Chloro-trifluoropropene** $C_3H_2ClF_3$ (HFO1233zd)

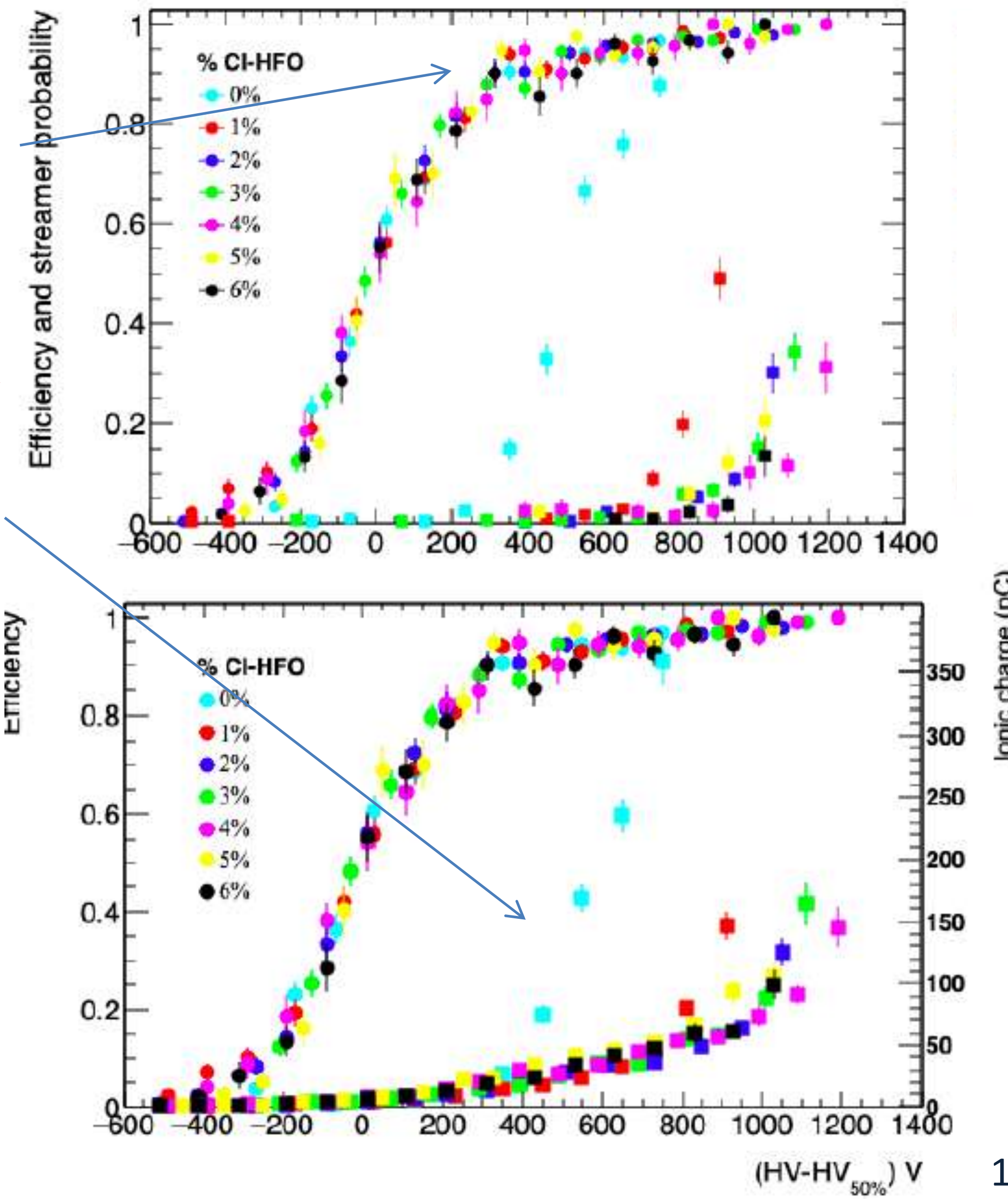
- CO_2 / $C_3H_2F_4$ **(F-HFO)** + i-C_4H_{10} + $C_3H_2ClF_3$**(Cl-HFO)** → **GWP ~ 10**

On a new environment-friendly gas mixture for Resistive Plate Chambers
G. Proto[1,2], B. Liberti[2], R. Santonico[1,2], et al. 2022 *JINST* **17** P05005

In terms of reduction of GWP, the replacement of TFE is just **part of the problem**; in the new eco-friendly gas mixture, the residual GWP is **almost ALL due to the presence of SF6.**

Tests with SF6 replaced with Cl-HFO for ATLAS

In general, **very promising results**.
-Efficiency always higher than 93%
-WP increases at a rate of 400V/1% of CL-HFO
-Avalanche/streamer separation ("useful" plateau) **larger than 400V**

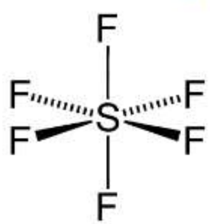


From: B. Liberti, "Recent results on environmental-friendly gas mixtures for ATLAS RPC", 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors

Other possible replacements for SF_6

(CERN EP-DT)

6 F

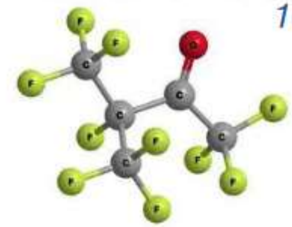


SF_6

GWP 23900

- Chemical inertness: extremely stable
- Exceptionally long lived in the atmosphere
- Excellent dielectric property
  - SF_6 x 2.5 than Air
- Non-flammable and toxic
- Gaseous form
- No major reactions
  - Ok with H_2O, Cl and acids

10 F



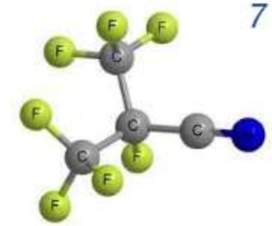
3M™ Novec™ 5110

($CF_3C(O)CF(CF_3)_2$)

GWP <1

Atm. lifetime 15 days

7 F



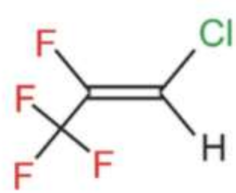
3M™ Novec™ 4710

($(CF_3)_2CFCN$)

GWP 2100

Atm. lifetime 30 years

4 F



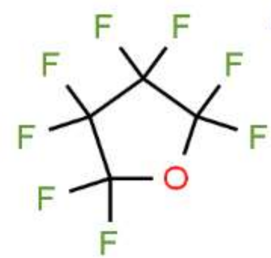
AMOLEA™ HFO-1224yd

(CF_3-CF=CHCl)

GWP <1

Atm. lifetime 20 days

8 F

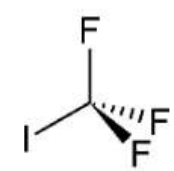


C_4F_8O

GWP 8700

Atm. lifetime >3000 years

3 F



CF_3I

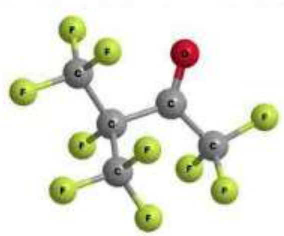
GWP 0.4

Atm. lifetime 6 days

Test performed by CERN EP-DT

See B. Mandelli, **Possible alternatives to SF6 for Resistive Plate Chambers** RPC2022

NOVEC5110

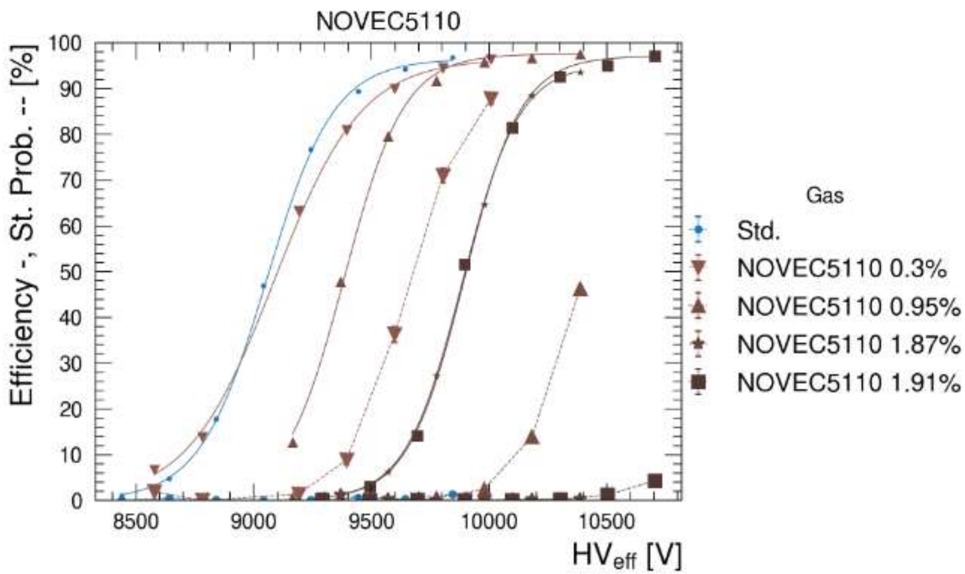


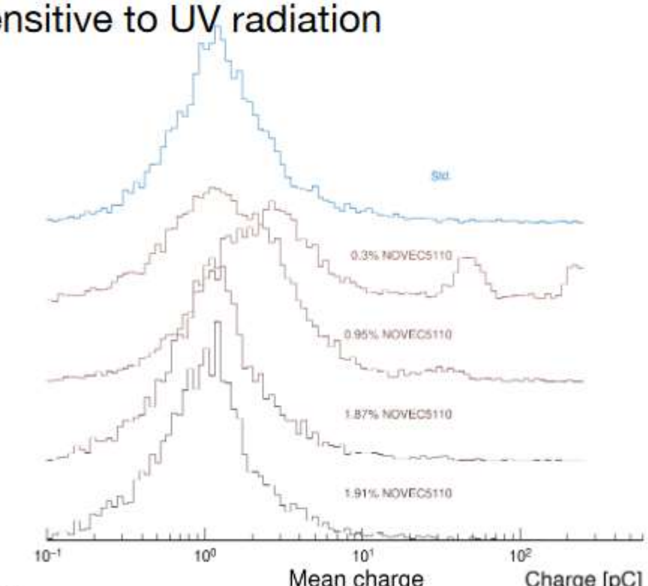
PRO

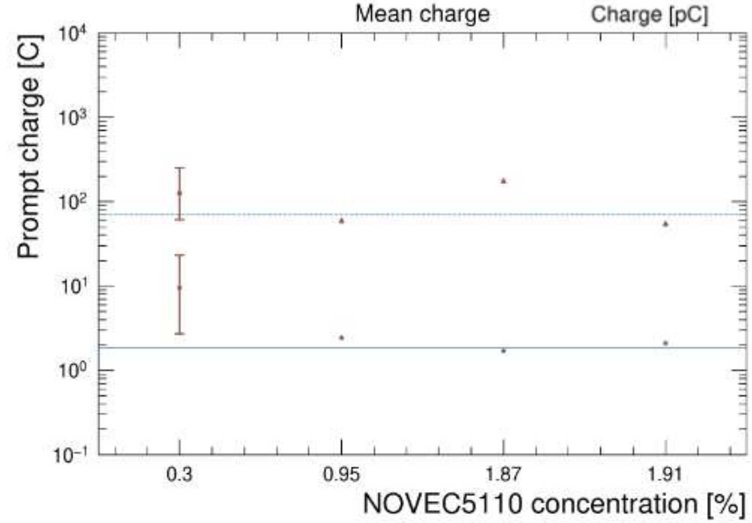
- Very low GWP: <1
- Application in industry
- High dielectric strength

CONS

- High boiling point: 27 C
- Sensitive to UV radiation







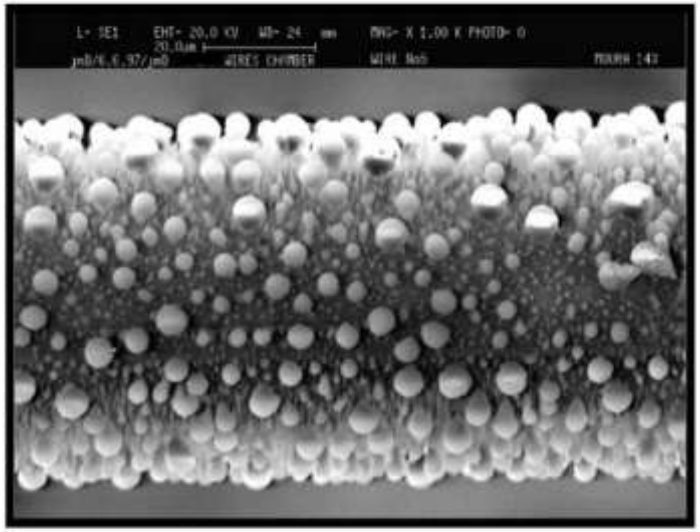
- High concentration (~2%) of NOVEC 5110 needed to obtain good streamer suppression
  - Suspect that NOVEC 5110 breaks inside the RPC
- Higher working point for concentrations > 0.3%
- Avalanche and streamer charge similar of std gas mixture from 0.9%
  - At 0.3% very large avalanche signals

What about CF_4?

Used in CSCs and GEMs

For instance, gas mixture used in CSCs of CMS:

- **40% Ar + 50% CO2 + 10% CF4**



- The main purpose of CF4 in the gas mixture – protection against anode wire aging : Si + 4 F → SiF4
(also breaking C-chains in polymer formation)

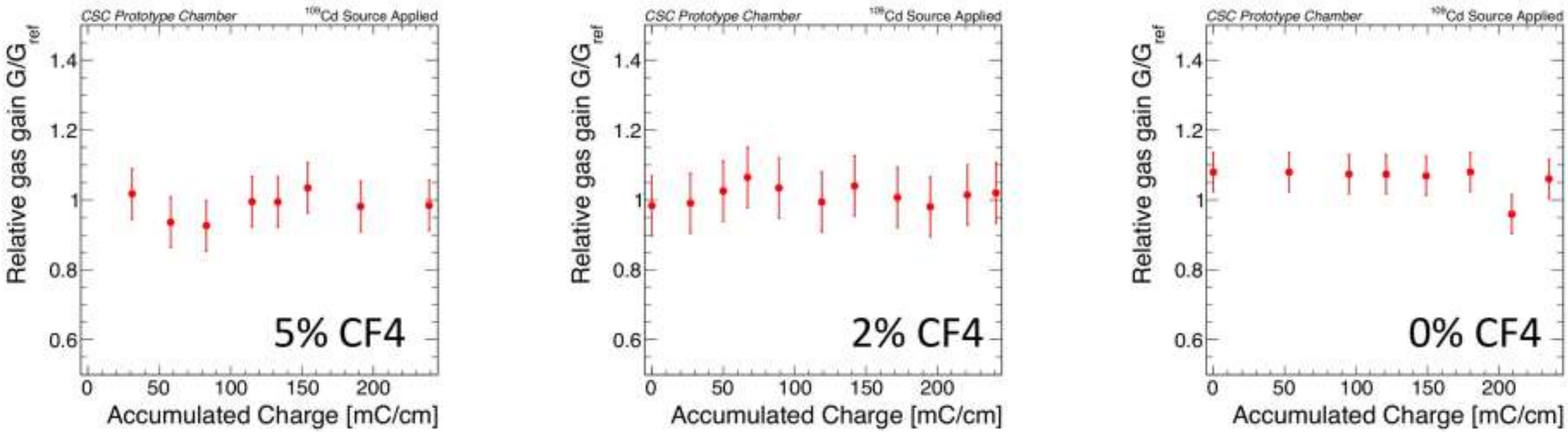
Used in GEMs basically to increase drift velocity → better time resolution. Anyhow without CF_4 time resolutions till within requirements,

Main ideas:

✓ Reduce (or eliminate) CF_4

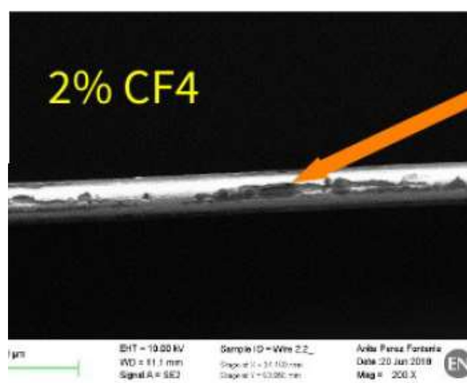
✓ HFO to replace CF_4, but this implies an increased HV → more studies needed

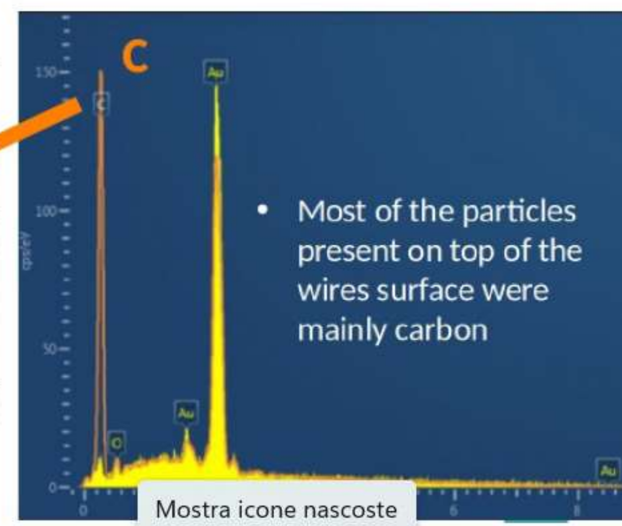
Reduction of CF_4



No significant degradation was seen, <u>in terms of performance</u>, in all longevity tests

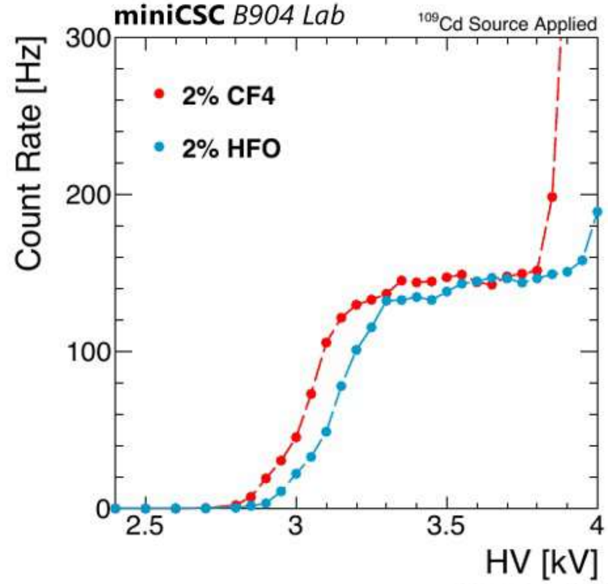
- However cathode modifications were seen in all cases.
- Anode surface depositions are seen with 0 and 2% CF4 even with naked eye.

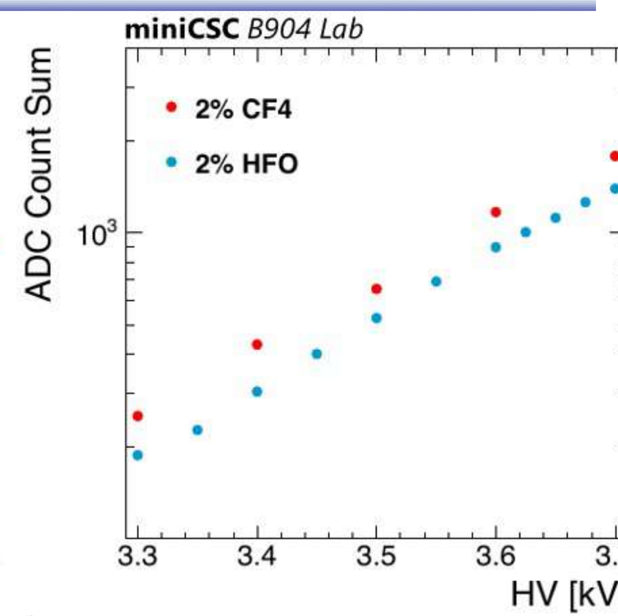


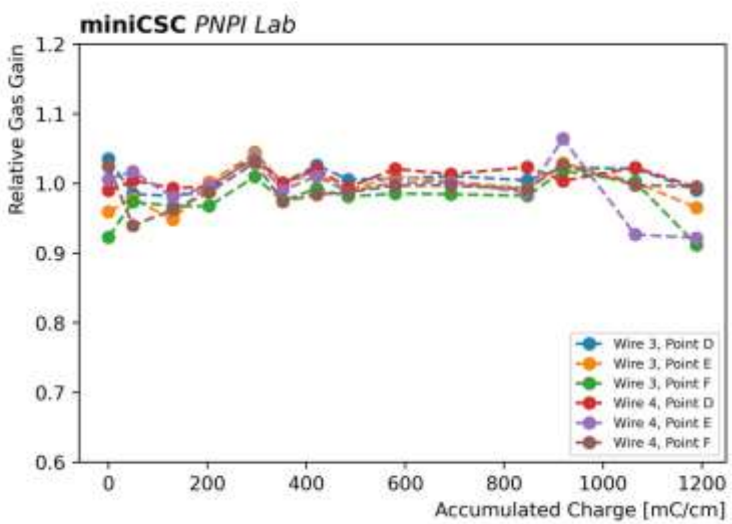


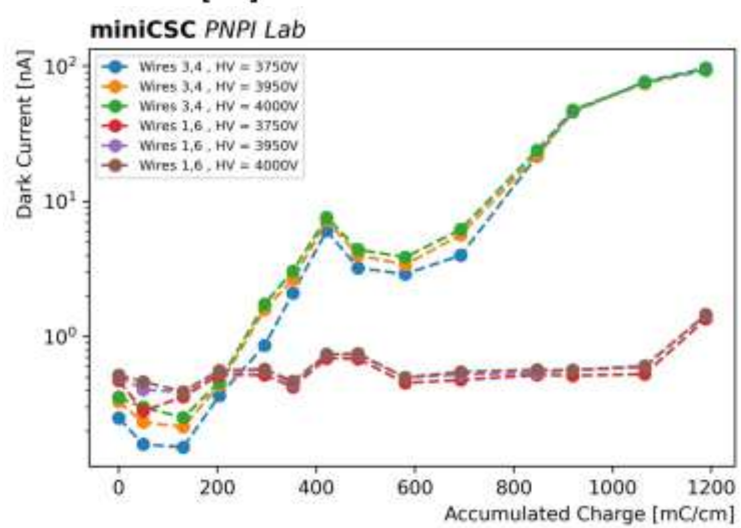
Replacement of CF_4 with HFO1234ze

Just 1000V increase in the operating voltage, good efficiency, reasonable plateau length









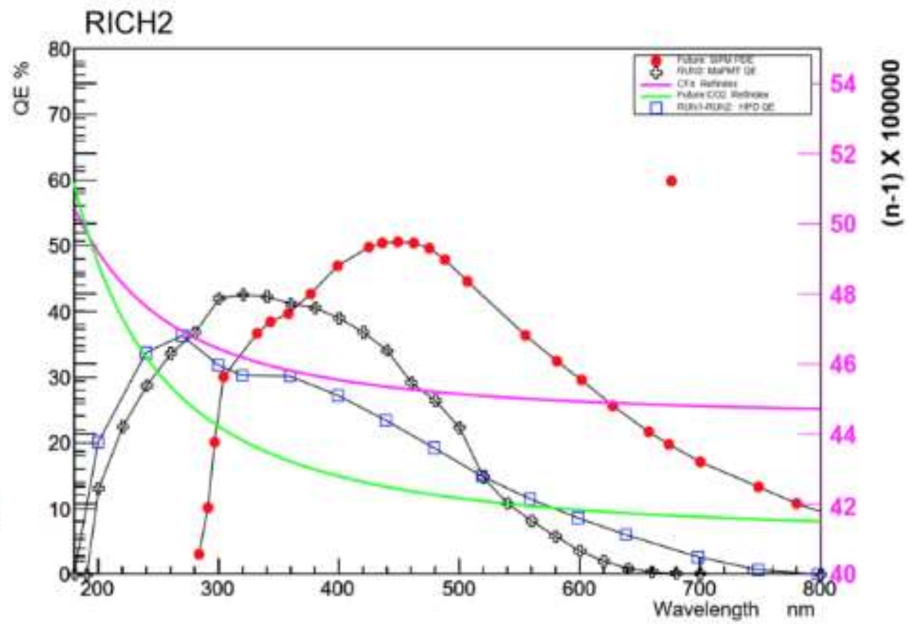
No gain reduction up to 1 C/cm, but significant increase in the dark current in first irradiation tests

Addendum: use of GHG in RICH detectors

- C_4H_{10} used in the LHCb RICH
- CF_4 used in the COMPASS RICH

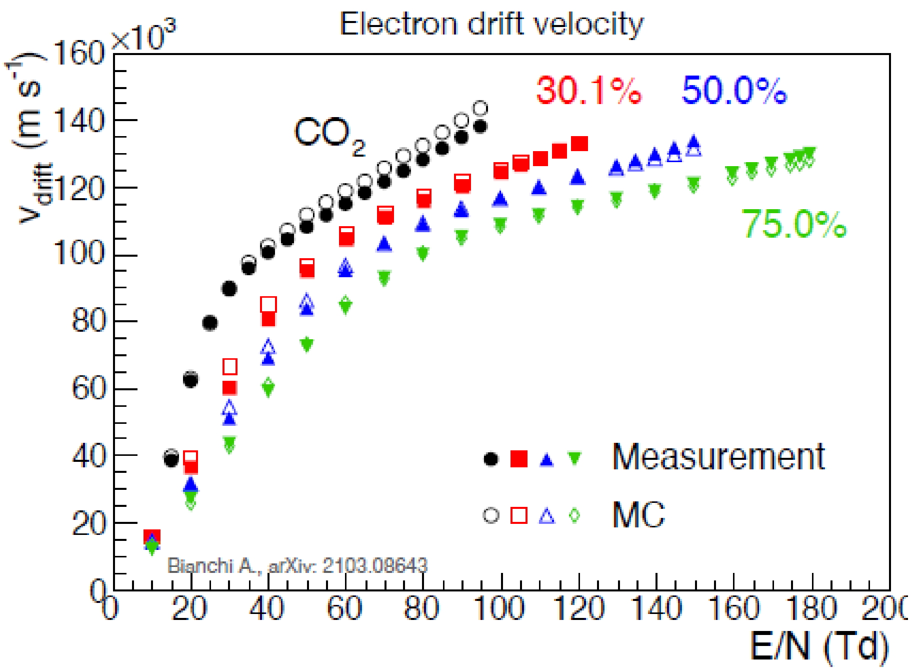
LHCb RICH studies

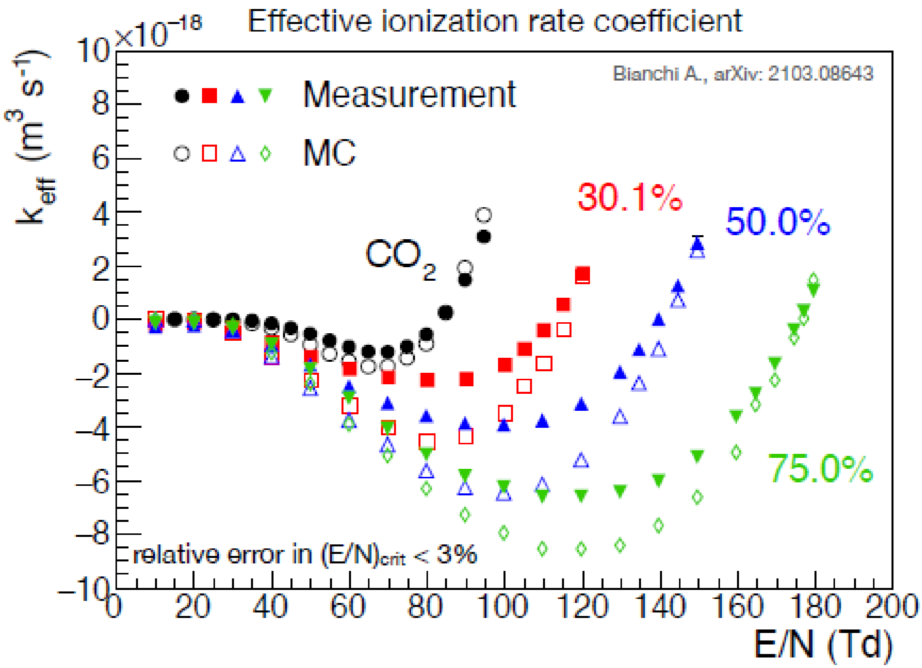
- RICH detectors use either CF_4 or C_4F_{10}
  - Necessary for good refractive index
- Replacement of C_4F_{10} with C_4H_{10}
  - Refractive index matches very well
  - But C_4H_{10} **flammable**
- Replacement of CF_4 with CO_2
  - Under investigation
- Use of SiPM to reduce the chromatic error and increase the yield



Simulation of gas and detectors parameters: how not to grope into the dark

From: A. Bianchi, "Simulation of Resistive Plate Chambers with C3H2F4 gas mixtures", 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors



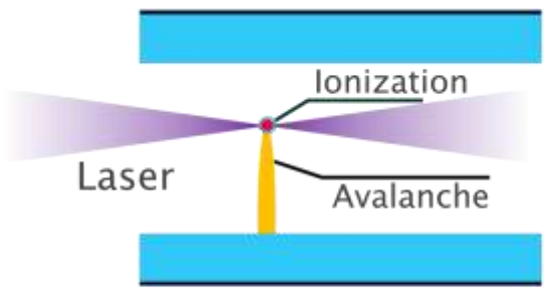


Simulation –both of the gas AND of the detector- is essential to correctly interpret detector performance and behaviour

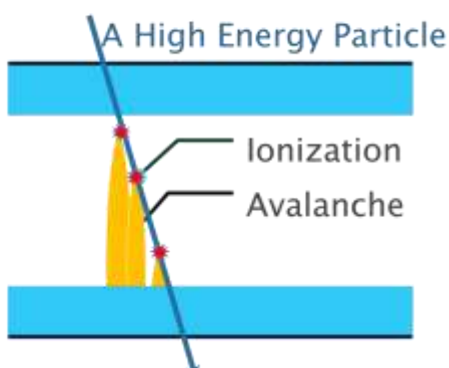
→ Connection with WP4

Second “fundamental” ingredient: direct measurements of gas parameters

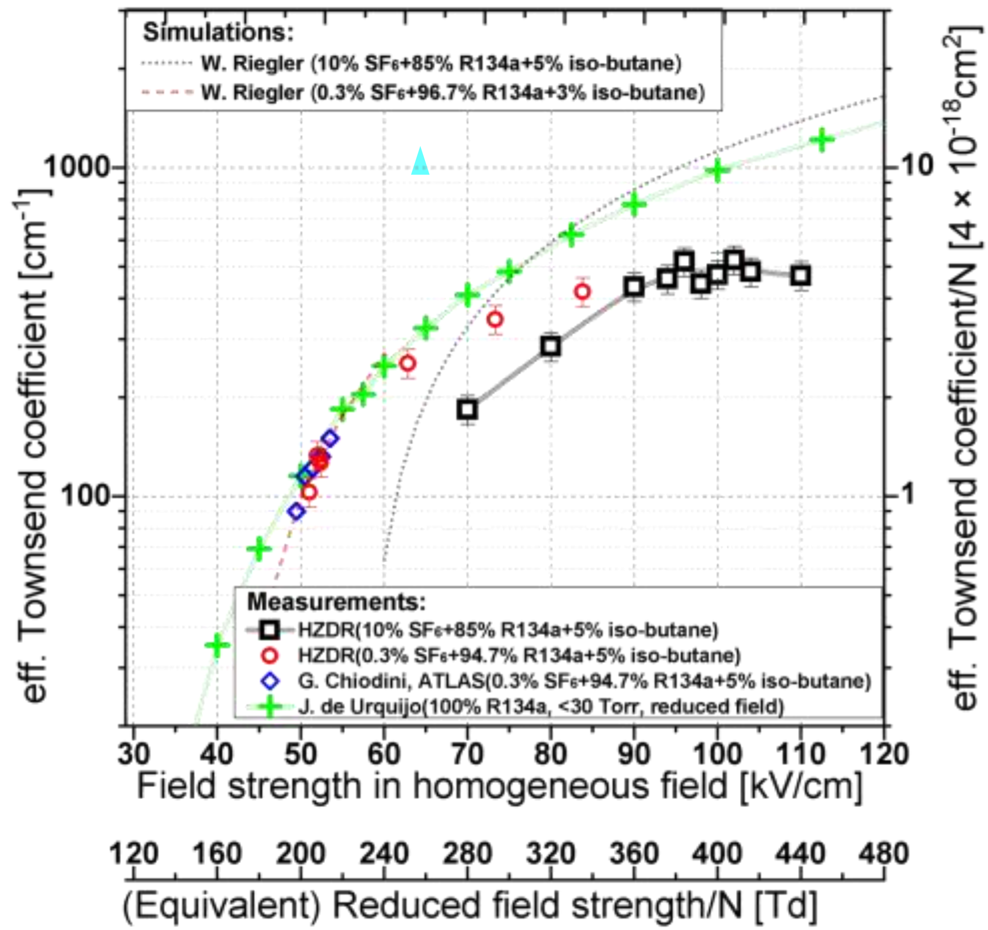
X. Fan, “Measurement of effective Townsend coefficient and drift velocity in RPC gas mixtures with UV Laser”, 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors



Focused UV laser:
controlled N_e , fixed position



High energy particle:
random N_e , random positions



Very nice work on TFE mixtures, **to be done with HFO**

Conclusions

- In general –within some limitations- the idea of replacing TFE with HFO (+CO_2 to reduce the operating voltage) seems to work.
  - **ECO2 and ECO3 might be good candidate gas mixtures**
- Of course, more severe tests are to be performed, in particular for what concerns aging effects, are due → stay tuned!
- First, encouraging results, on effectively replacing SF_6
  - It's responsible for most of GWP of ECO2 and ECO3
- The gaseous detector community is on the eve of its **ecological transition**