Performance and long-term ageing studies on eco-friendly Resistive Plate Chamber detectors

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on behalf of the RPC EcoGas @ GIF++ collaboration

RPC2024 - XVII Conference on Resistive Plate Chambers and related detectors

Santiago de Compostela (Spain)
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The problem: use of Greenhous gases in HEP

We need to replace:

- ✓ $C_2H_2F_4$ = R134a = TFE mainly used in RPCs
- ✓ SF_6 mainly used in RPCs
- ✓ CF_4 used in CSCs, GEMs, RICH, etc.

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

It's not a problem concerning just the RPC community

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

We also need:

- to get the same performance
- not to change the electronics and HV (for existing systems)

➢ HEP experiments, present and future, last several (dozens) of year
→ A good performance must be mantained for an adequate period of time
→ Aging tests are needed as well.

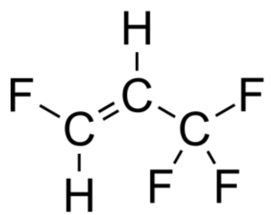
Of course we can also re-circulate the gases used, after purifying them

See talk by R. Guida

The importance of collaborative effort

- All high energy experiments (ALICE, ATLAS, CMS, LHCb, etc.) and the CERN gas group (CERN EP-DT) started, already several years ago, an intense R&D program to find suitable gas mixtures.

- Practically all research trendlines concentrate around the idea of replacing:
  $C_2H_2F_4$ (GWP=1430) → $C_3H_2F_4$ze (GWP=4)
  + CO_2 (GWP=1) or He → EEE



- ✓ $C_3H_2F_4$ (here indicated as HFO for short) is the molecule most similar to TFE but with low GWP
- ✓ CO_2 (or He) are essentially added to reduce the operating voltage.

The RPC EcoGas@GIF++ is a Collaboration **transversal to ALICE, ATLAS, CERN EP-DT, CMS**, **and LHCb** willing to put together expertise and resources in order to test potential candidates of eco-friendly gas mixtures with different detectors and electronics.

The RPC ECOGas@GIF++ timeline

RPC EcoGas@GIF++ Collaboration

AidaInnova Startup

Irradiation campaign for aging studies

2021 testbeam

2022 testbeam

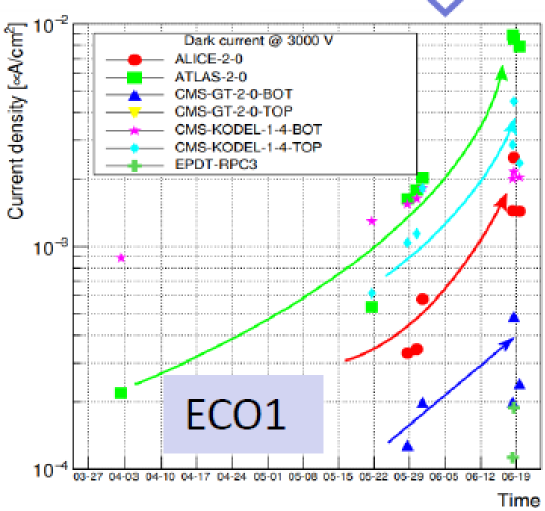
2023 testbeam

2024 testbeam

Assessment of the possibility of using HFO in place of TFE
→ ECO1, ECO2 and ECO3

2018

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



ECO1 discarded due to high current increase after ~20 mC/cm^2 integrated charge

2021

Performance baseline

Performance comparison

Std, ECO2 and **ECO3** mixtures tested under irradiation. First 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.

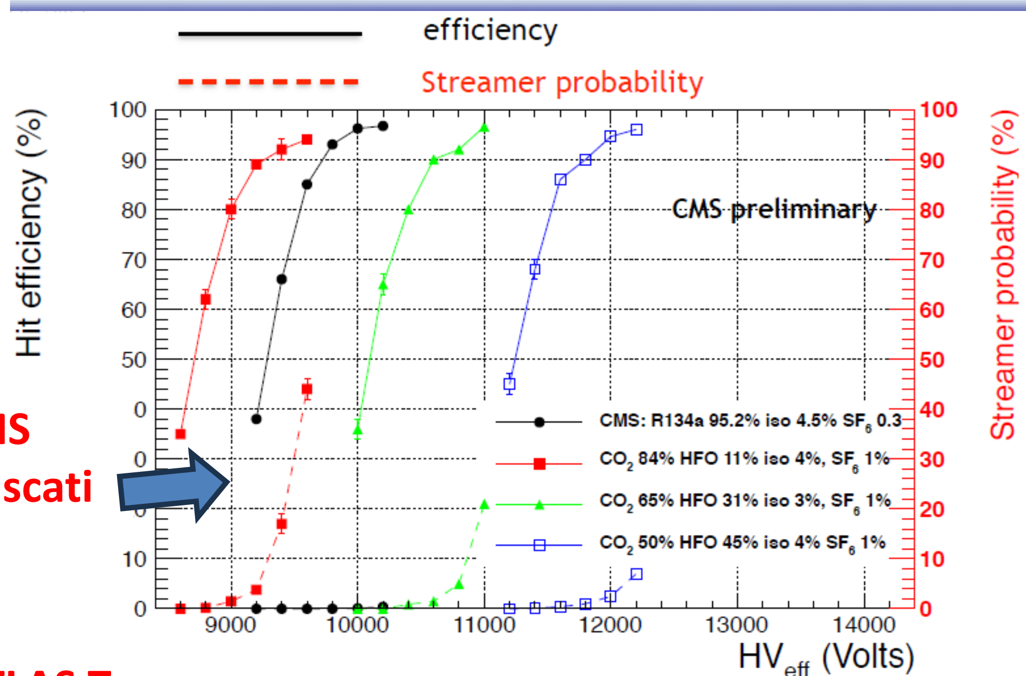
[2] "Performance of thin-RPC detectors for high rate applications with eco-friendly gas mixtures", 2024 Eur. Phys. J. C.

[3] "Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility" – submitted to EPJplus.

Tests at the various home-labs

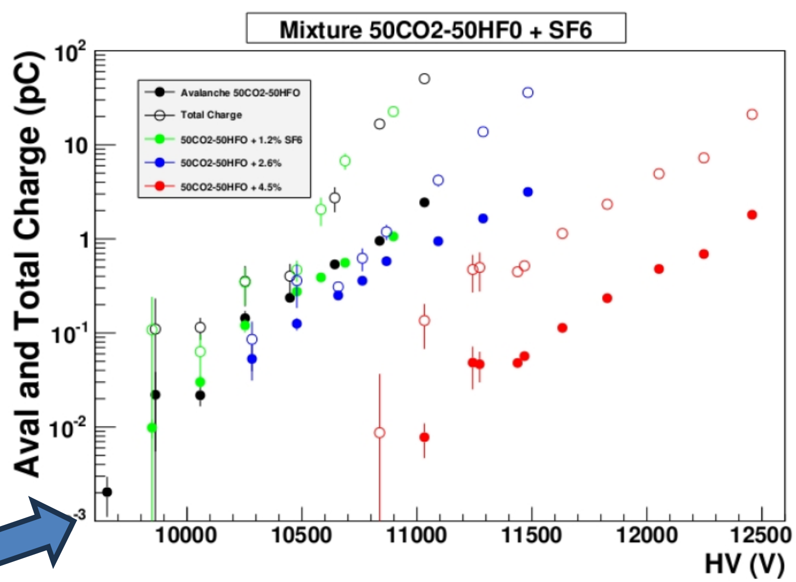
Preliminary results of Resistive Plate Chambers operated with eco-friendly gas mixtures for application in the CMS experiment, JINST 11 C09018 (2016)

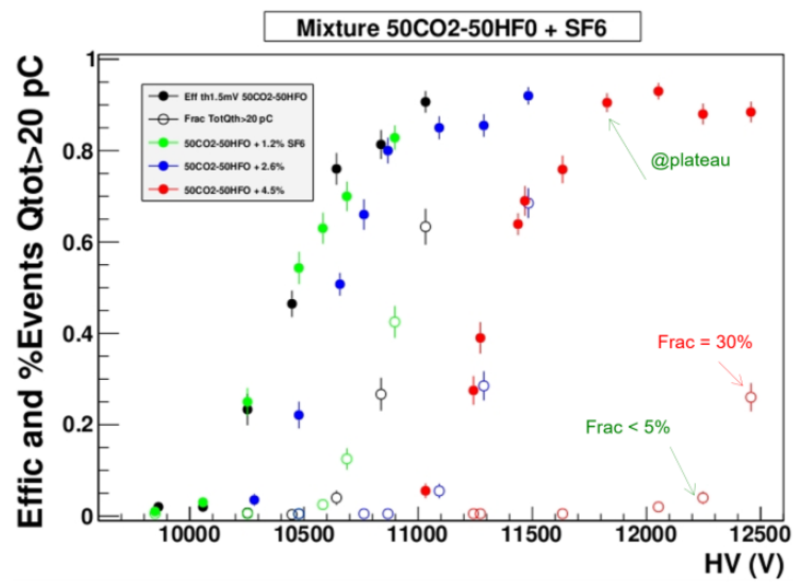
CMS Frascati



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

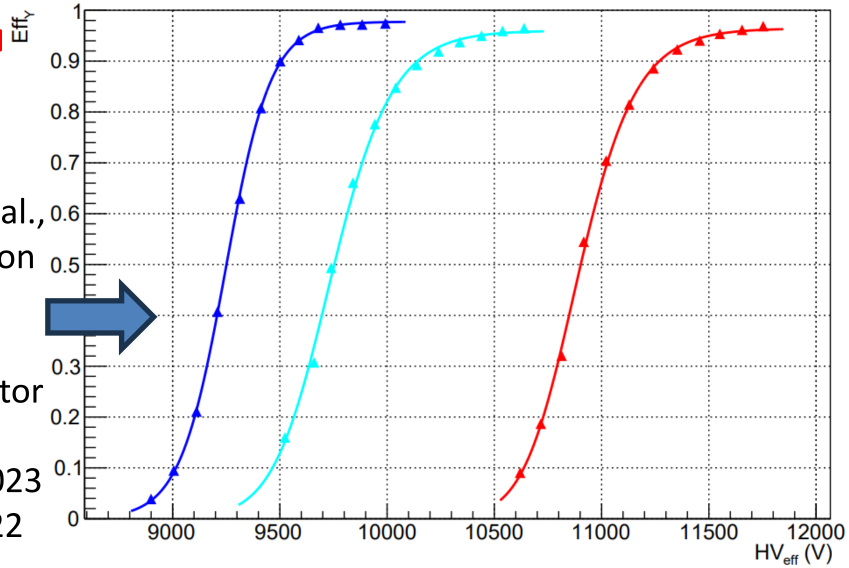




Tests at the various home-labs

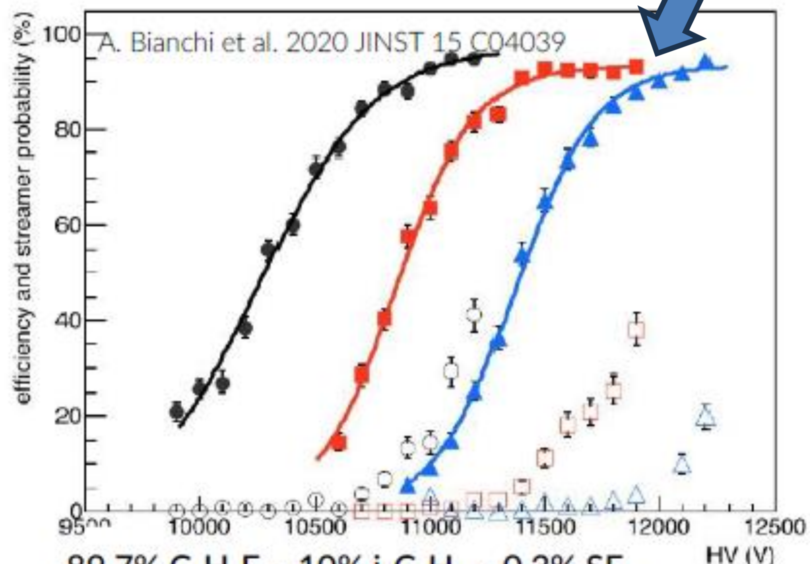
LHCb/SHip Bari

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

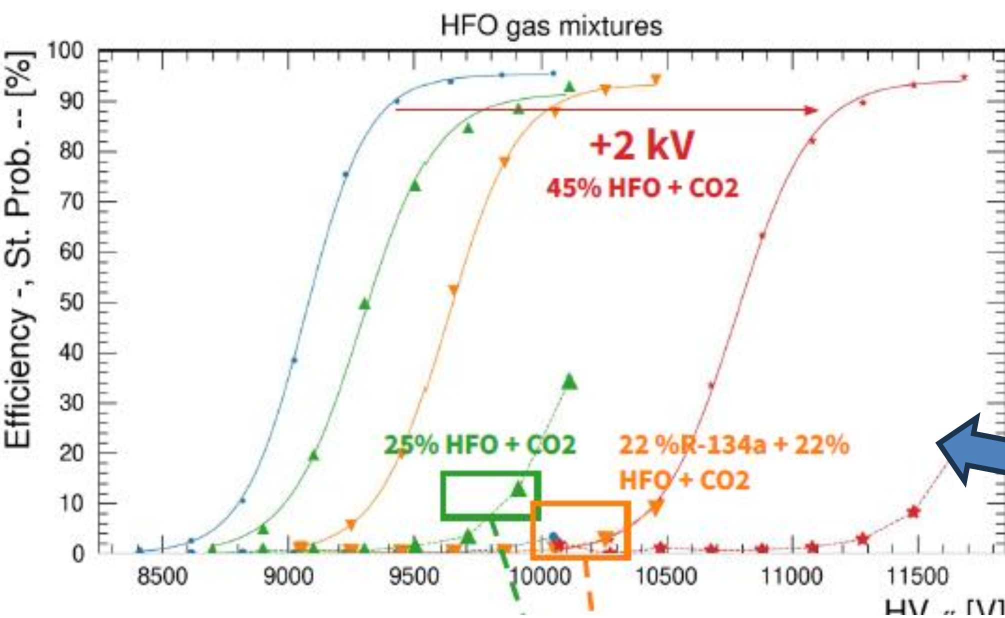


95.2% R134a/ 4.5% iC_4H_{10} / 0.3% SF_6 (standard)
60% CO_2/ 35% HFO/ 4.5% iC_4H_{10} / 0.5% SF_6
69.5% CO_2/ 25% HFO/ 5% iC_4H_{10} / 0.5 % SF_6

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

Experimental set-up @GIF++

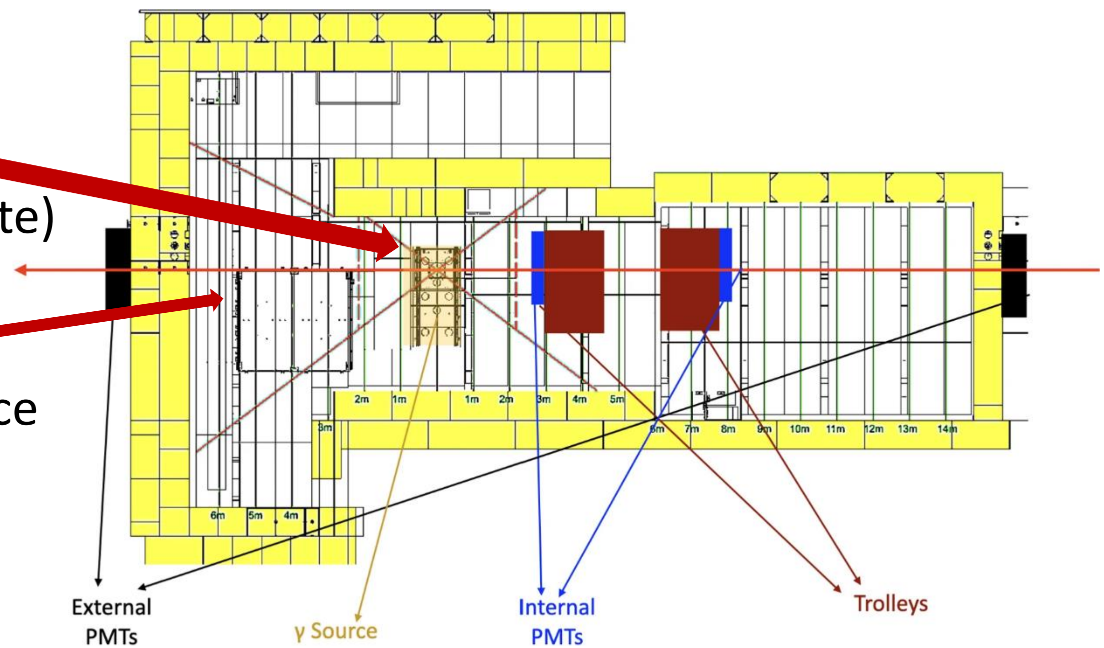
- Three gas mixtures identified, with various concentrations of HFO and CO_2.

ECO1: 45% HFO / 50% CO_2 / 4% iC_4H_{10} / 1% SF_6	GWP reduced by 1/3 w.r.t. the std mixture!
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	

Attention focussed on ECO2 and ECO3 because of the good stability and performance demonstrated in home-labs tests.

Aging tests performed at GIF++

- 12.5 TBq 137Cs source
- ✓ to generate background (high rate)
- ✓ to accelerate aging processes
- 100 GeV muon beam
- ✓ to measure detector performance



Detectors @ GIF++

- Various detectors, mounted on two trolleys, equipped with various electronics.

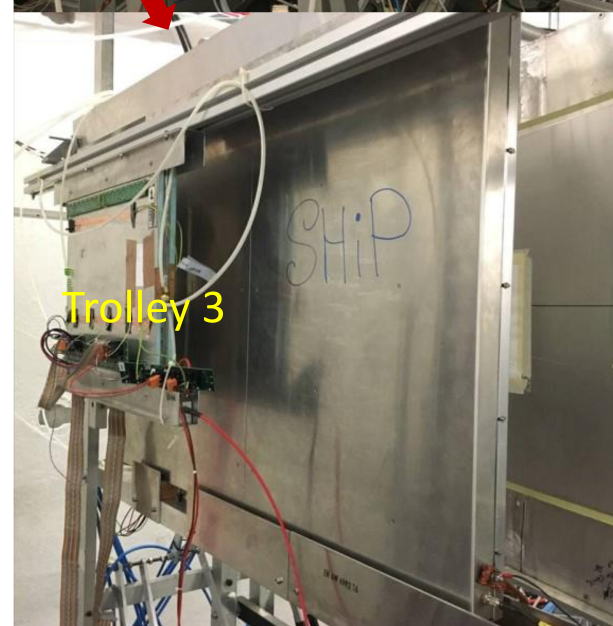
→ Help in disentagling common observed effect from effects specific of ONE detector

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

- The results presented here refer particularly to the detectors equipped with TDC

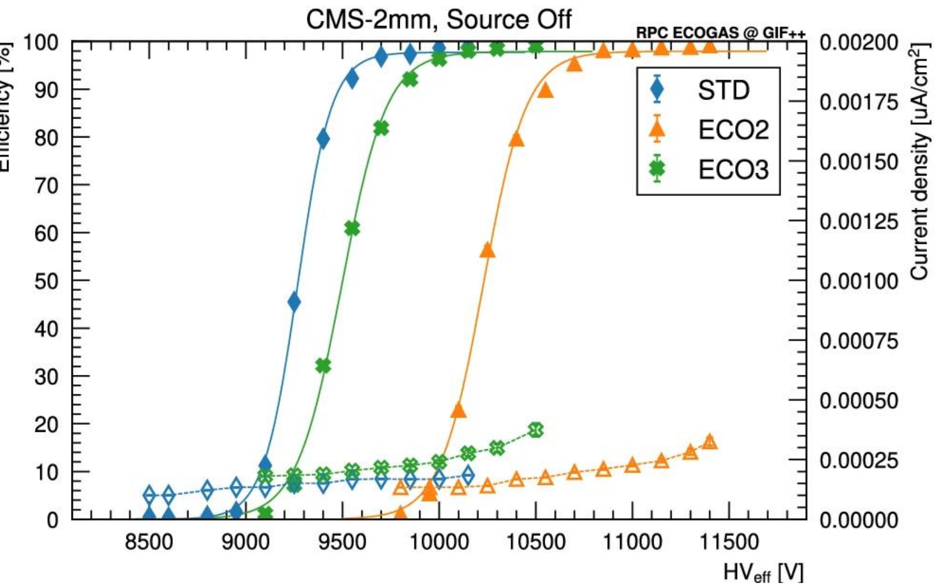
→ For other results, obtained with digitizers see talk by L. Quaglia

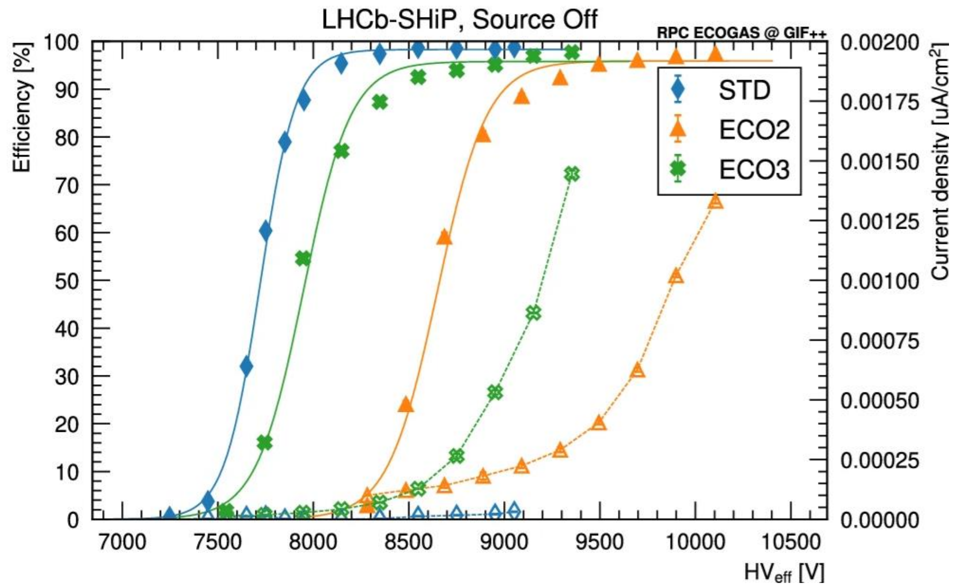
→ For other results, obtained with CMS upgrade chamber, see talk by D. R. Lopez



Determination of baseline perfomance

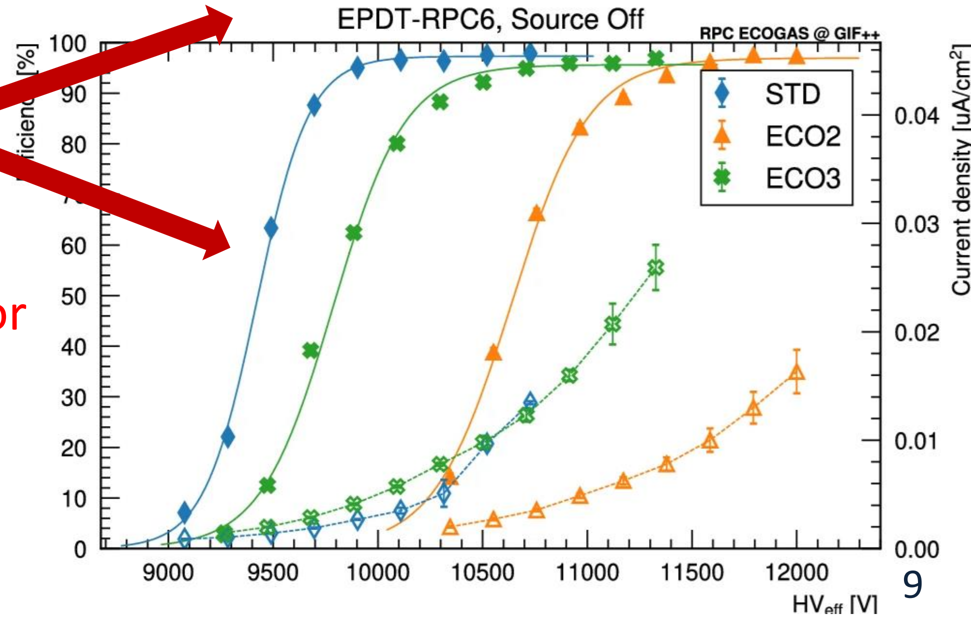
Source OFF, 2021 data





Fit of efficiency curves with a sigmoid:

$$\mathcal{E}(HV_{\mathrm{eff}}) = \frac{\mathcal{E}_{\max}}{1 + e^{-\beta(HV_{\mathrm{eff}} - HV_{50})}}$$



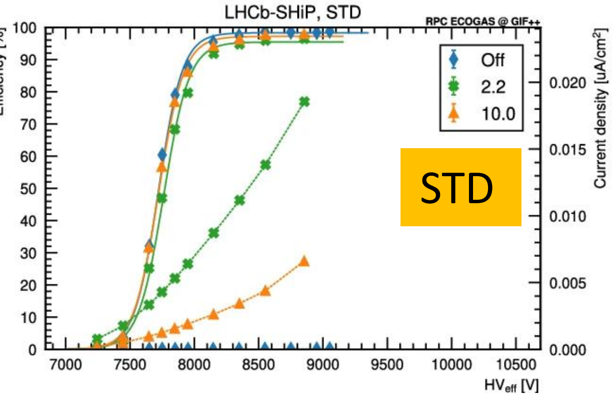
- Efficiency at plateau basically similar for STD, ECO2 and ECO3 > 95%
- Efficiency curves shifted at higher voltages depending on fraction of HFO

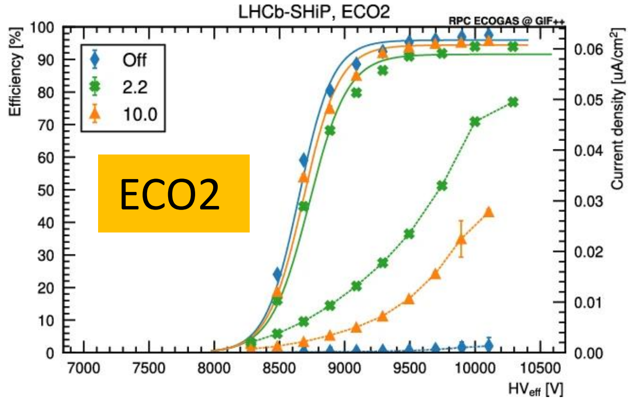
→ WP(ECO2) > WP(ECO3) > WP(STD)

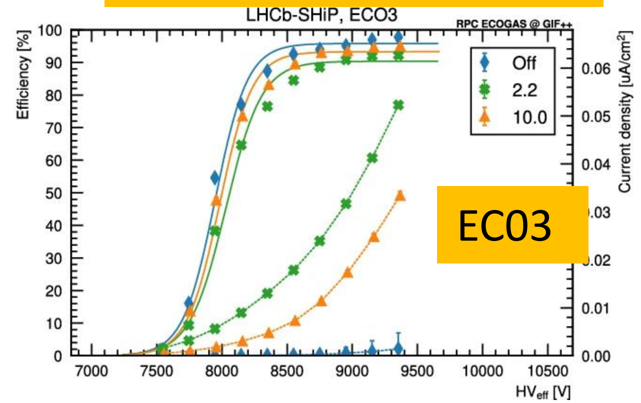
Efficiency and counting rate with irradiation

Source ON, 2021 data

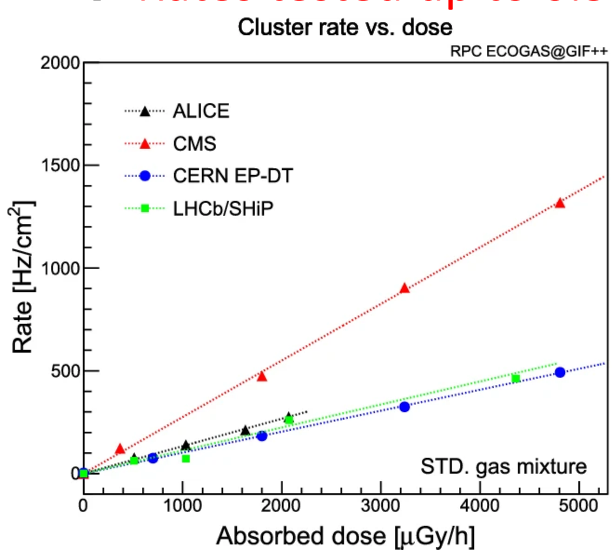
LHCb/SHiP (SG 1.6 mm)

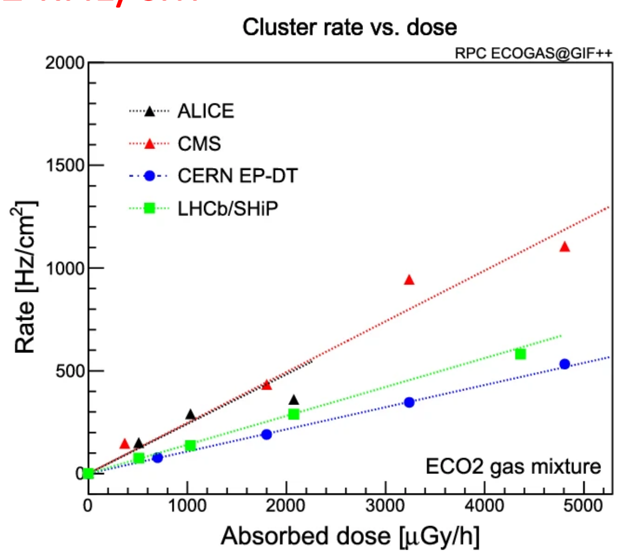


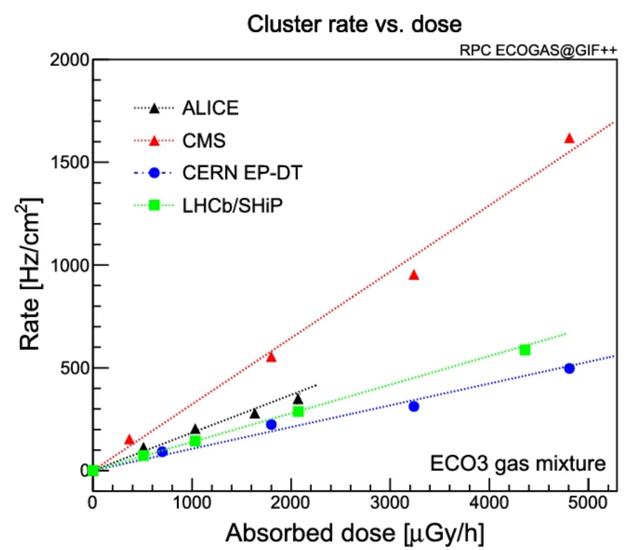




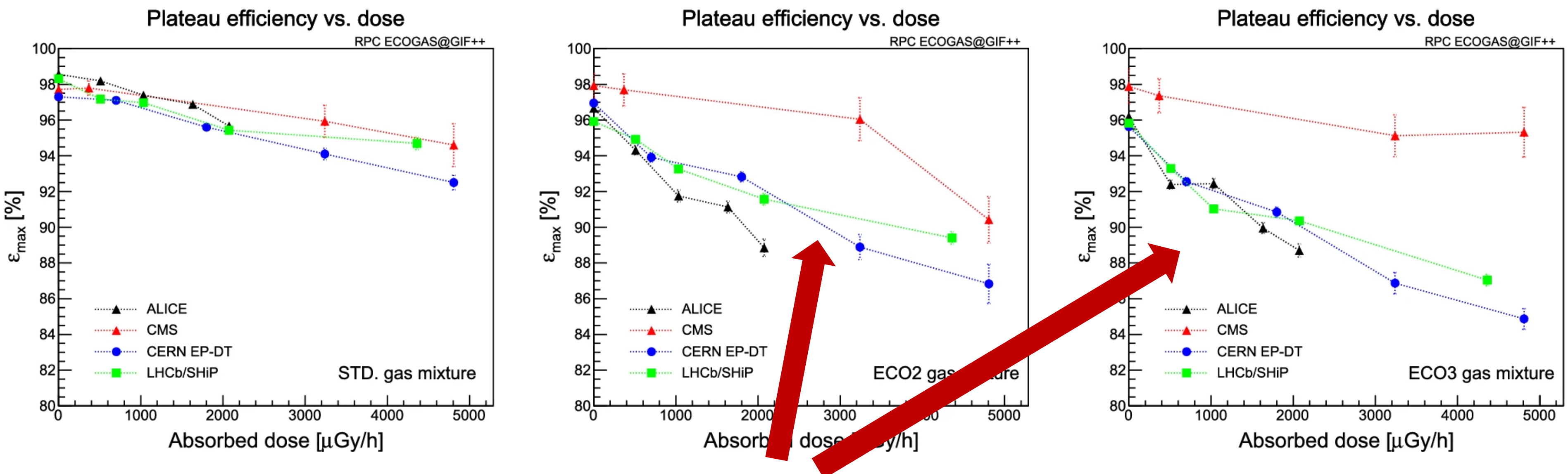
- ➢ Efficiency curves at high rate analogous for all detectors
- → featuring an efficiency > 90% even at the highest rates
- ➢ Counting rate vs. dose analogous for ALICE, CERN EP-DT, expt. for CMS (DG)
- → Rates tested up to 0.5- 1 kHz/cm^2



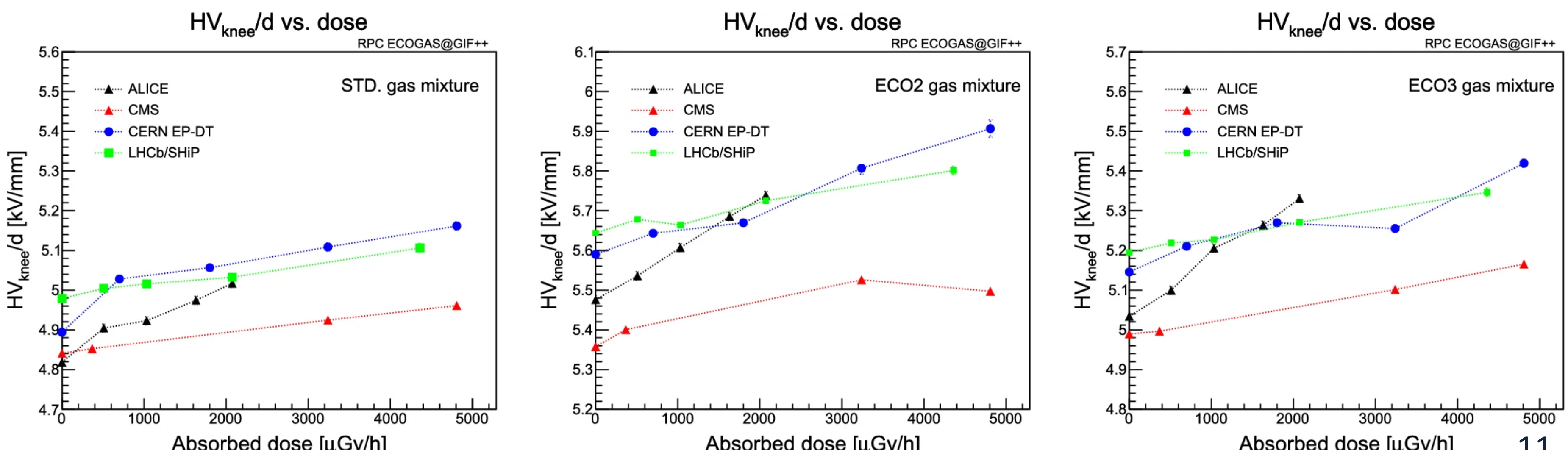




Performance with irradiation

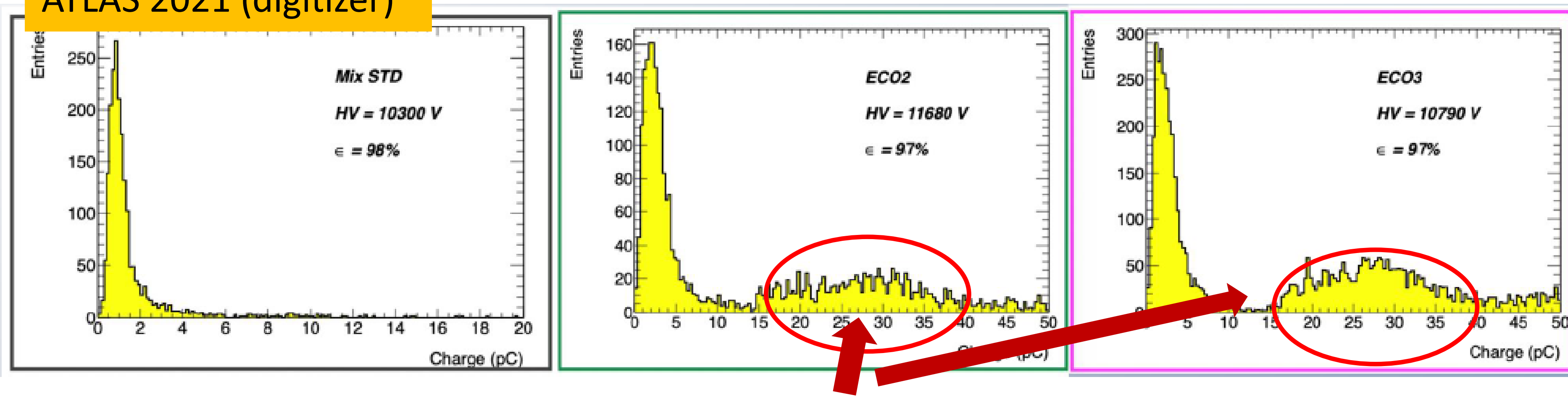


With ECO2 and ECO3 slightly larger efficiency drop and larger efficiency curves shift at high rate wrt. STD (CMS exception beause of the double gap).



Charge and current density

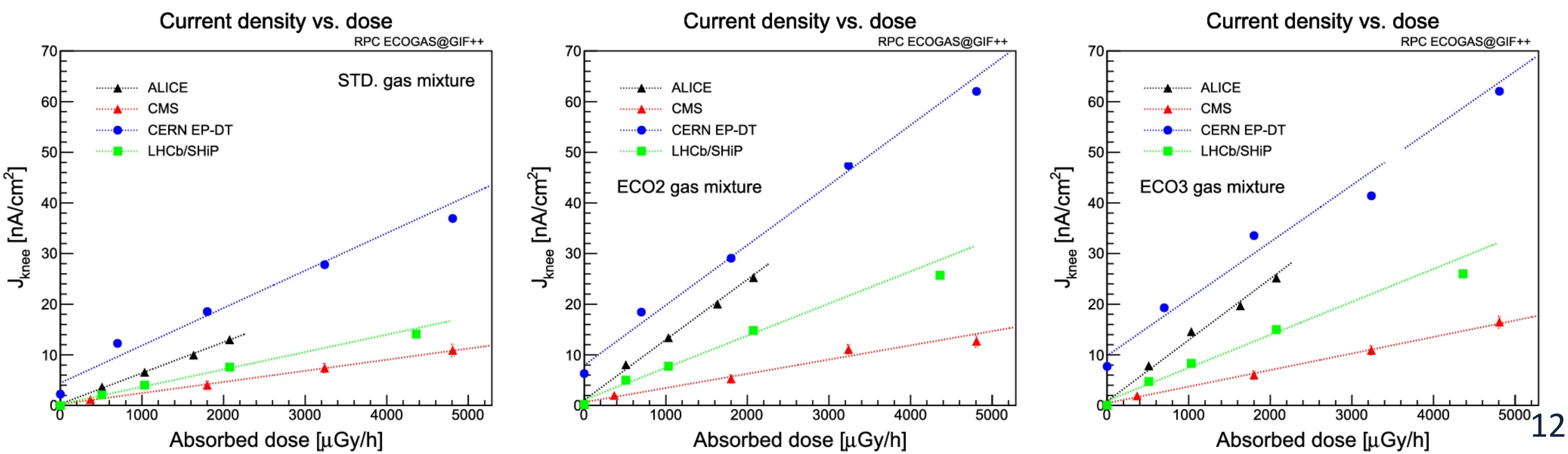
ATLAS 2021 (digitizer)



With ECO2 and ECO3 the presence of larger charge events (not streamers) observed

- Coherent with larger current density at WP for ECO2 and ECO3 under irradiation

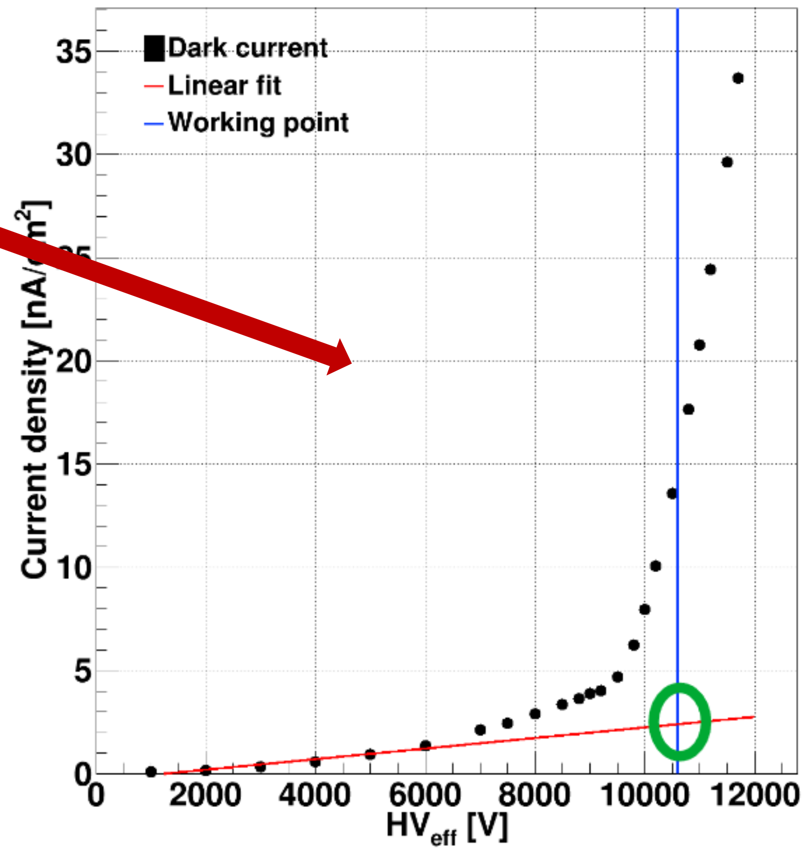
→ CMS exception because of the double gap



Aging tests: methodology

- All the detectors under test are flushed with the ECO2 gas mixture, while kept at fixed HV suitably chosen by the various groups: (irradiation voltage)
- They are irradiated so that, depending on their position, they absorb a dose typically between ≈ 1 and 5 mGy/h
  → they are subject to a background γ rate between 400 and 1000 Hz/cm^2
- The HV and absorbed current are continuously monitored and data stored every 30 s

- Weekly HV scans are performed to monitor the absorbed current without irradiation
- Both the ohmic and the total current are measured (the ohmic current by means of a linear fit in the low voltage range).

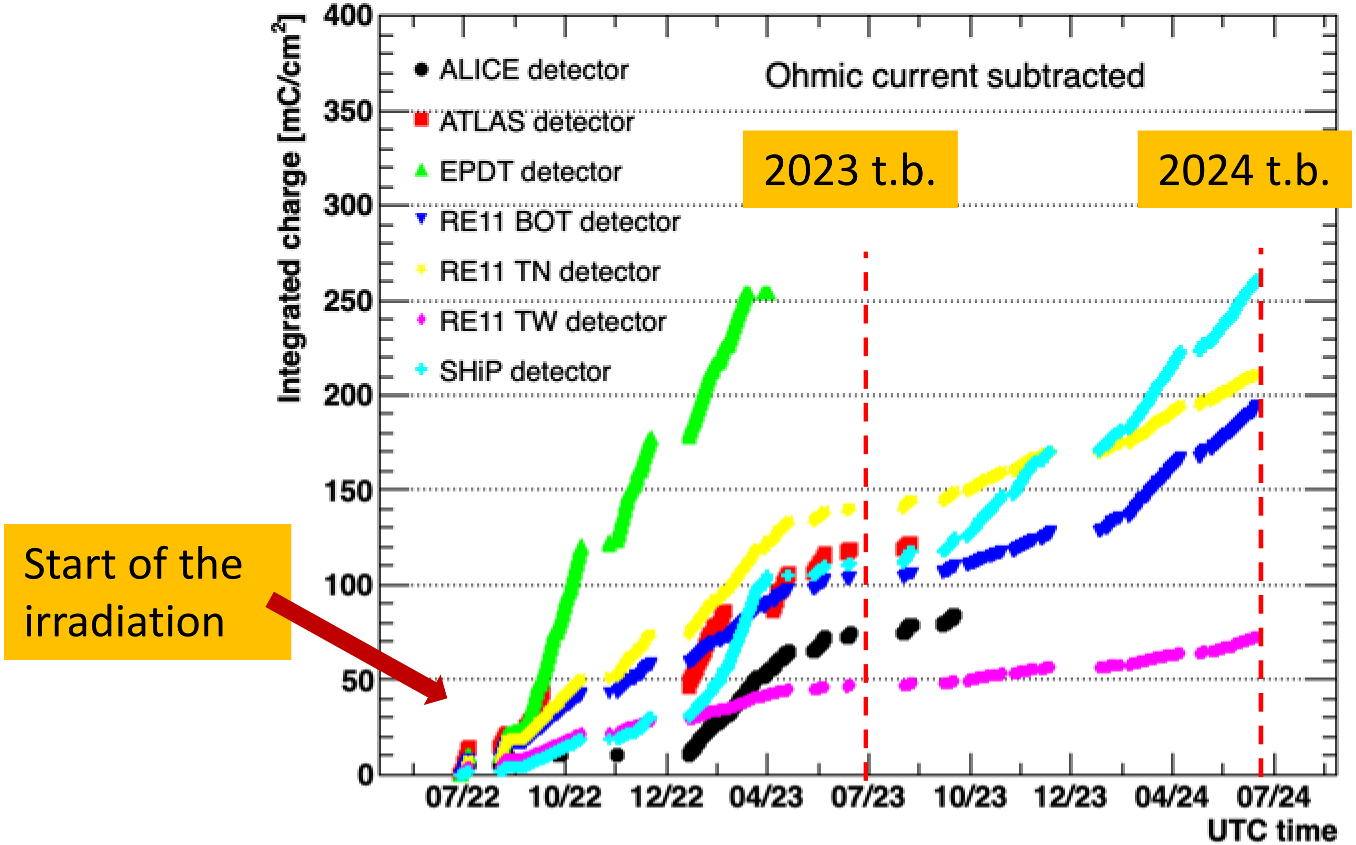


✓ Resistivity is measured by the Ar method 2-3 times/year

✓ Detectors performance is measured during dedicated beam tests 2-3 time/year

Causes for aging in RPCs

- Generally, the charge integrated along a certain elapsed time is considered the most important factor for aging in RPCs;
- The targets of integrated charge are different for various experiment: for instance, for ALICE is ≈ 100 mC/cm^2, for CMS is ≈ 1 C/cm^2 CMS, including a safety factor of 3.



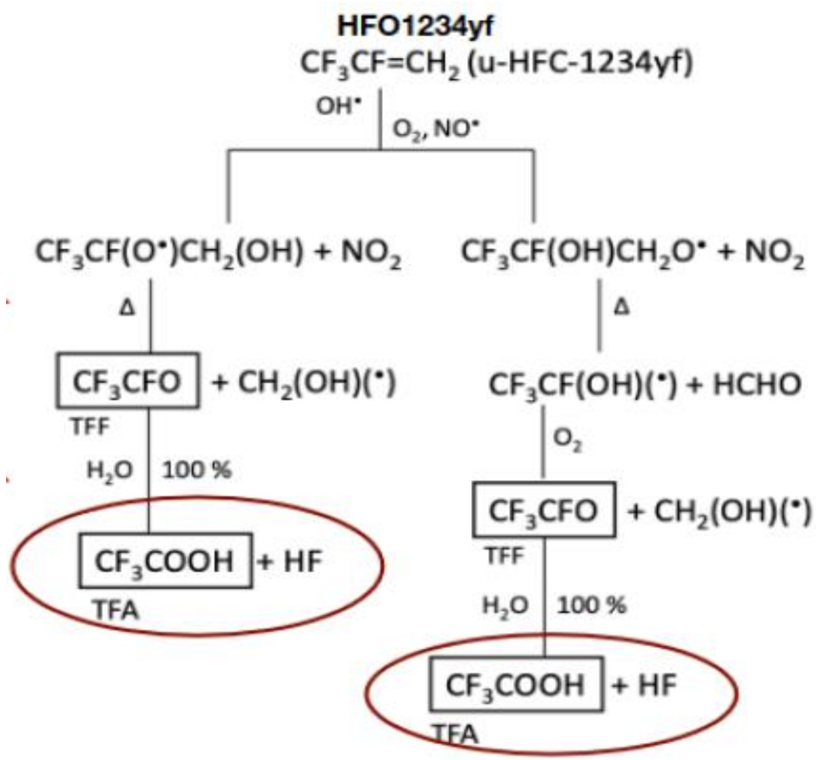
Further considerations about aging

Caveat: The importance of the integrated charge derives from the fact that production of HF was measured to be proportional to the integrated charge

→ Direct damage of the detector

- However, HFO typically dissociates producing TriFluoroAcetic acid

How TFA causes aging in RPCs and affects their performance on the long term is still to be investigated.



Aging is also caused by irradiation itself
→ Chemical modifications in the HPL electrodes

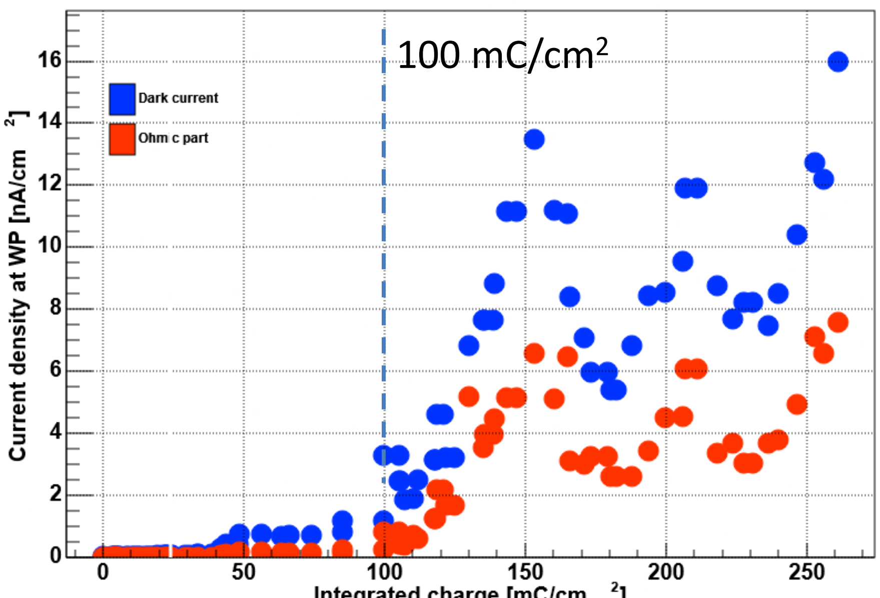
Aging is also caused by time itself
→ e.g. changed in HPL resistivity because of drying up.

Current density vs. integrated charge

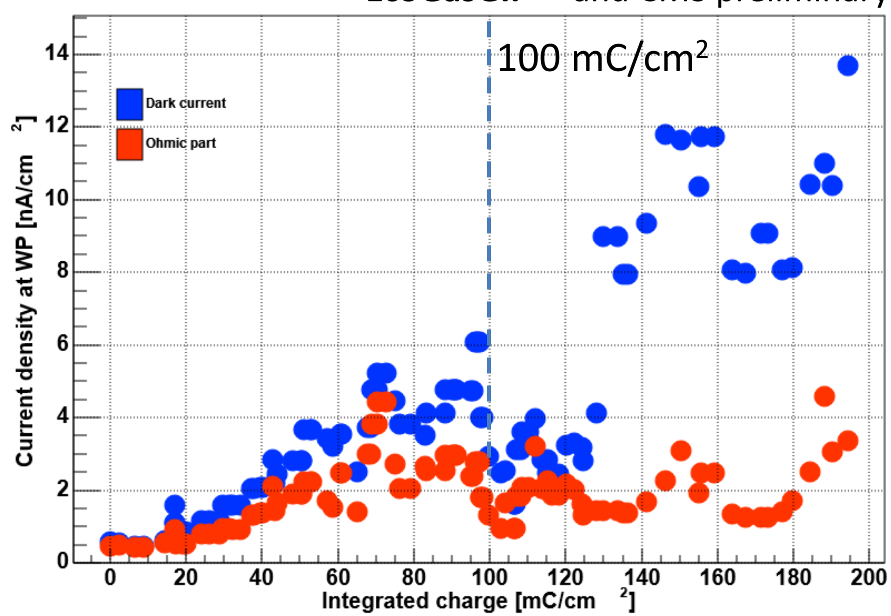
- Up to ≈ 100 mC/cm^2 of integrated charge (almost) all detectors present currents basically stable with time.
  - → CERN EP-DT detector 6 replaced by detector 25 in 2022 because of high currents, present already from the beginning (old detector).
- After ≈ 100 mC/cm^2 of integrated charge most detectors show the current fluctuations and slow rise with time.
  - → Behaviour similar in all detectors under test

Source OFF

EcoGasGIF++ and CMS preliminary



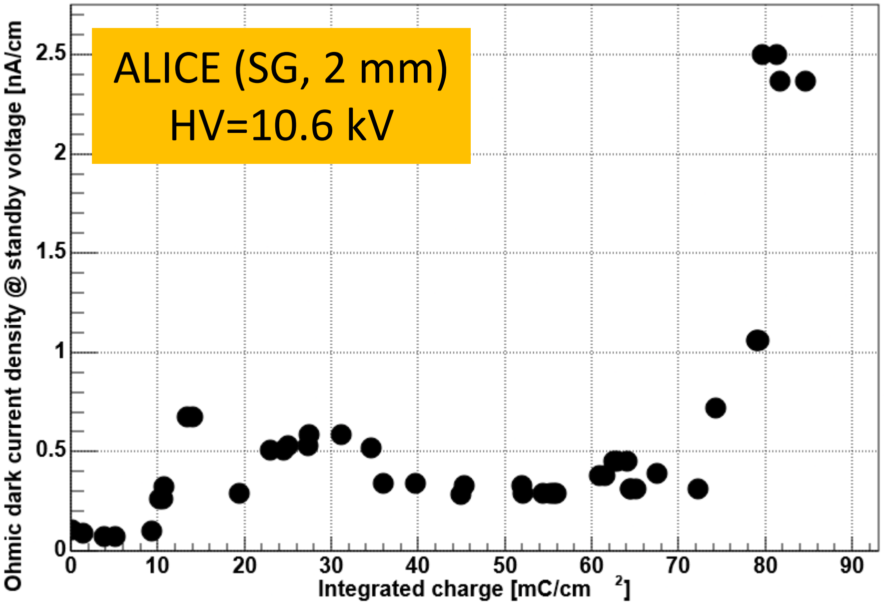
LHCb/SHiP
HV=8.7 kV

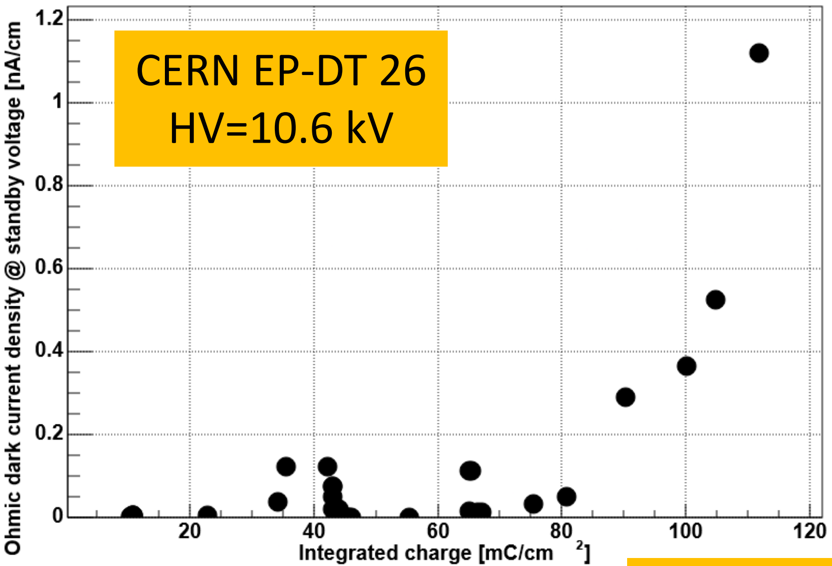


CMS (bottom gap)
HV=10.6 kV

Ohmic current density vs. integrated charge

- Note that some (not ALL) of the detectors under test feature also an increase of the ohmic part of the current density





Source OFF

The increase of the ohmic part of the current might be a hint of degradation of the internal surfaces of the detectors.

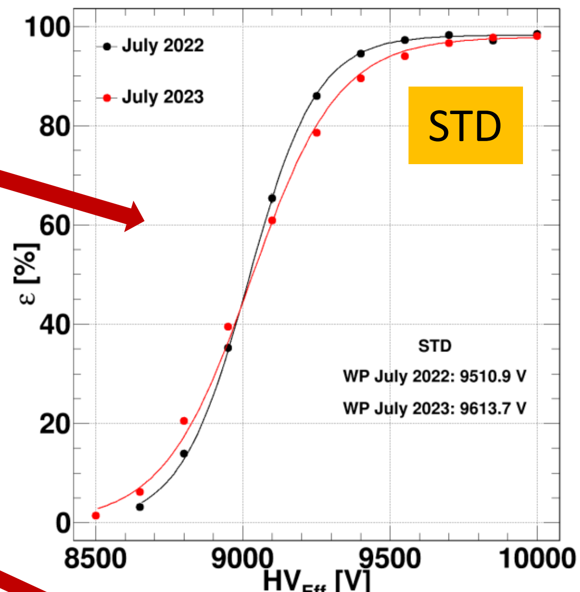
→ At the end of the tests, chambers will be opened and internal surfaces will be examined

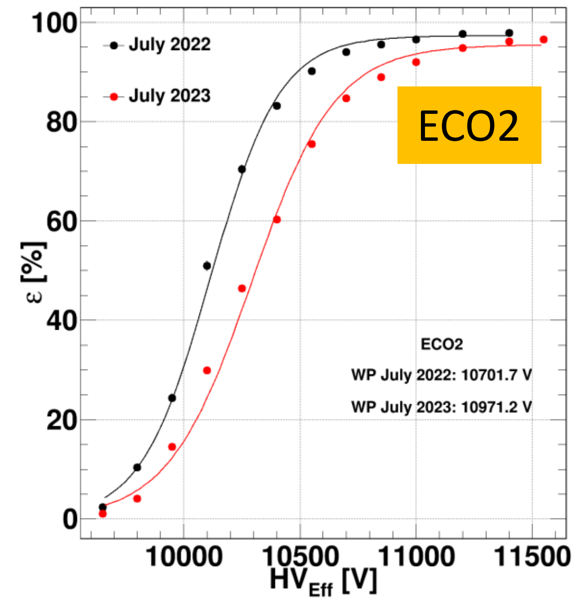
→ Chemical analysis could be useful to understand this issue

Efficiency before and after irradiation campaign

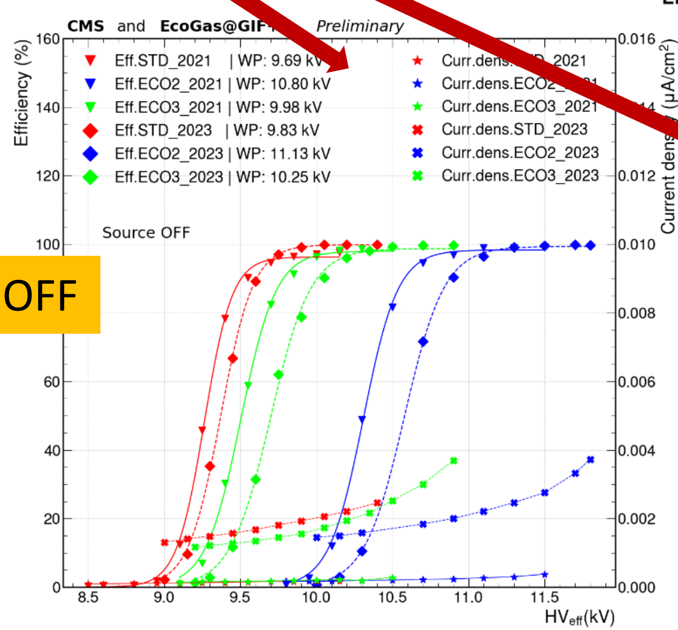
ALICE, comparison
2022 – 2023
SOURCE OFF

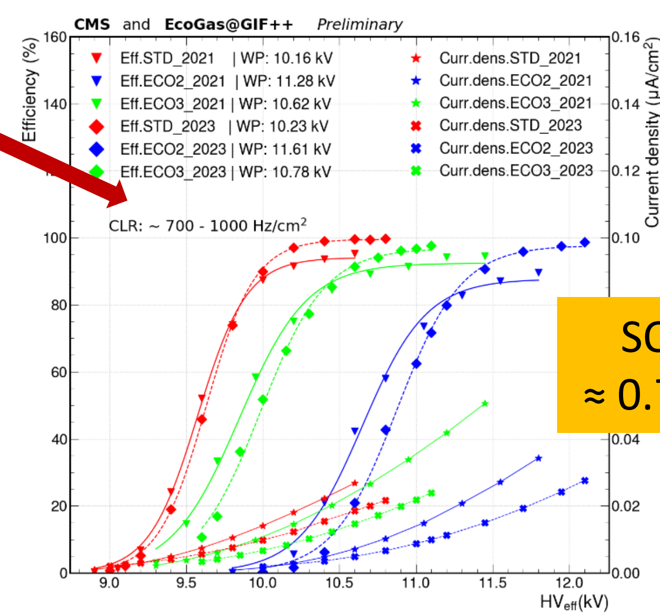
CMS (double gap),
comparison 2021 – 2023
Chamber OFF in 2022
because of low voltage
connector





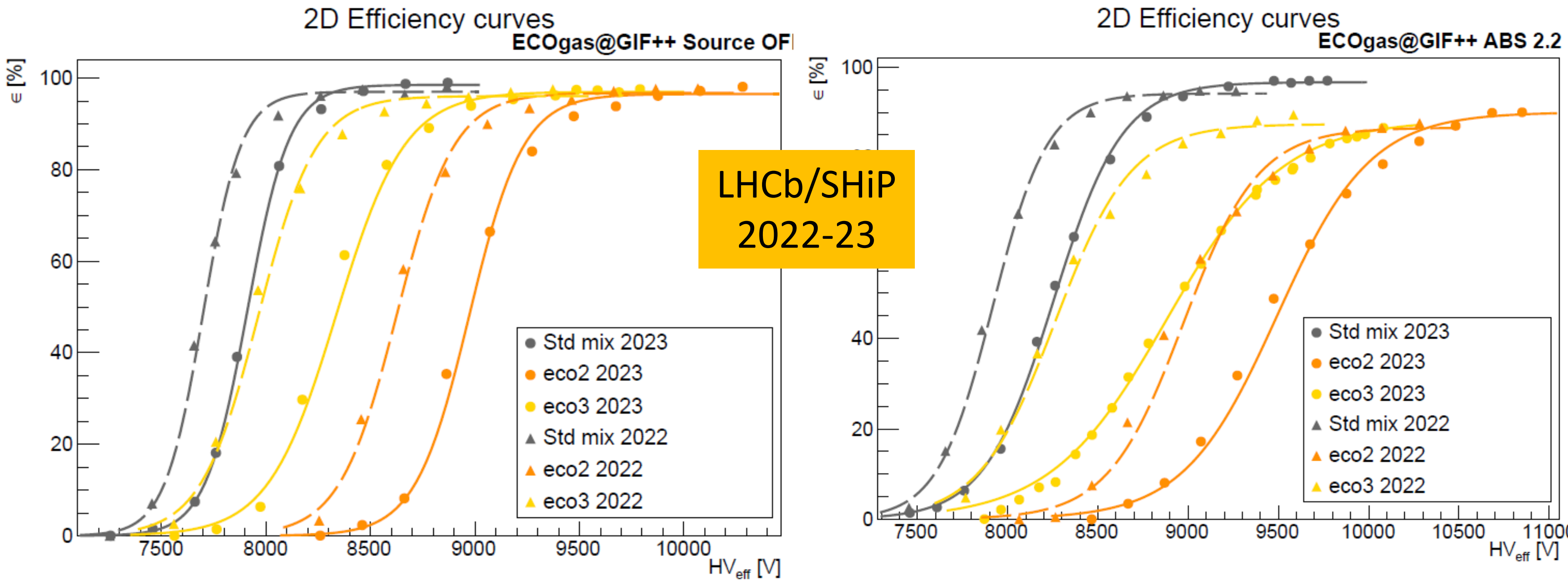
SOURCE OFF





SOURCE ON
≈ 0.7-1 kHz/cm^2

Efficiency before and after irradiation campaign



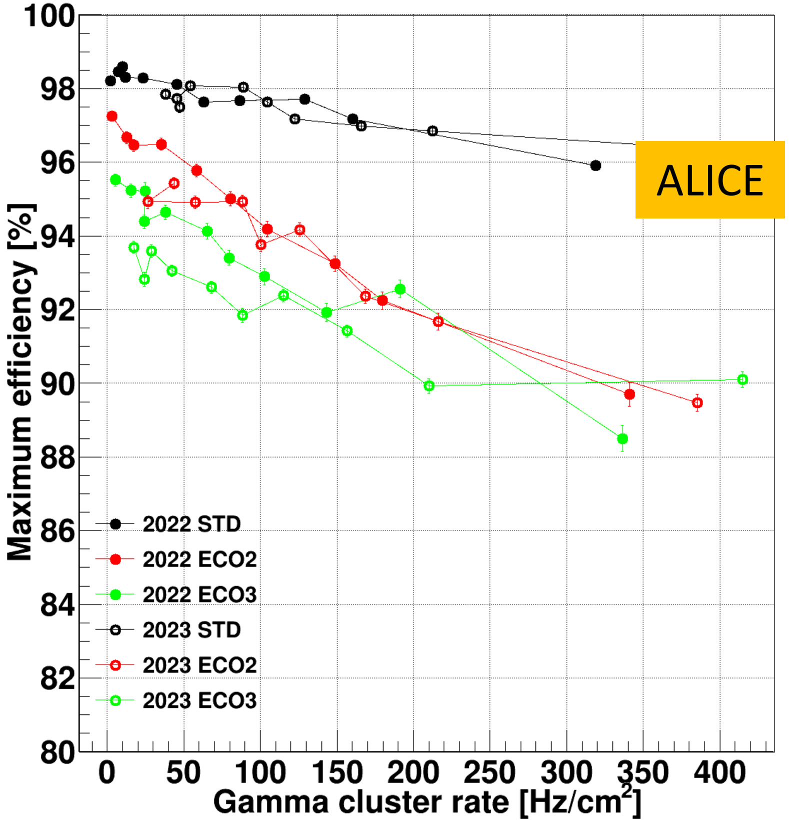
Other efficiency curves, obtained with digitizers, are contained in the presentation by L. Quaglia, this morning.

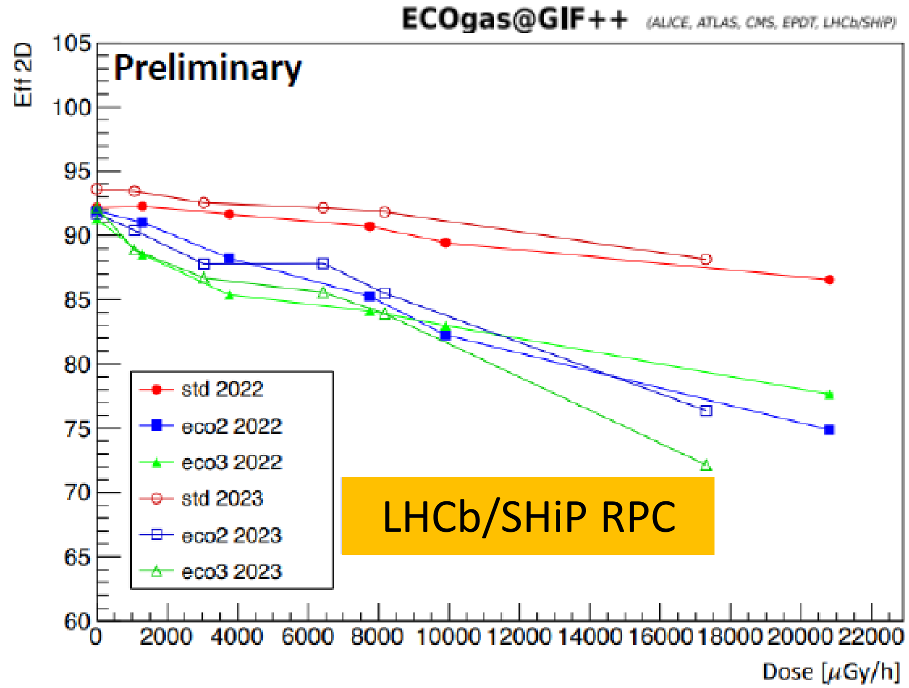
In general, for all detectors:

- A shift of the efficiency curves (few hundreds V) towards larger HV is observed
  - → For ALL gas mixtures used (so not directly caused by the gas)
  - → Smaller for STD with respect to ECO2 and ECO3
  - → Might be caused by changes in the HPL resistivity?
- Plateau efficiency remains approximately stable after the irradiation

Plateau efficiency before and after irradiation

Comparison 2022-2023 data
(2024 data still under analysis)

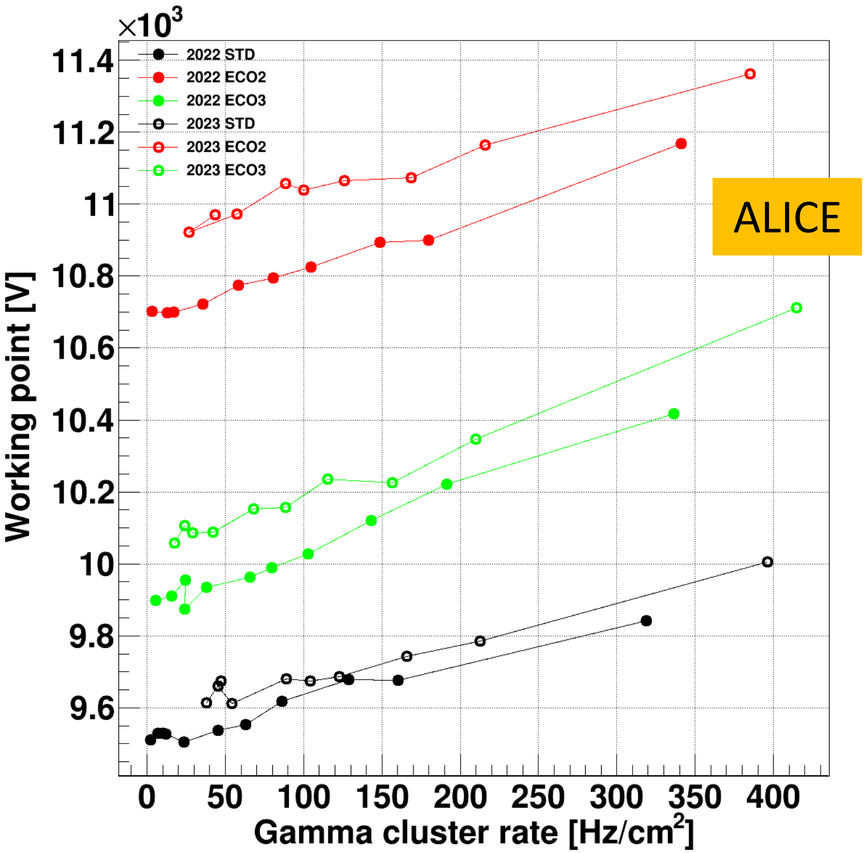


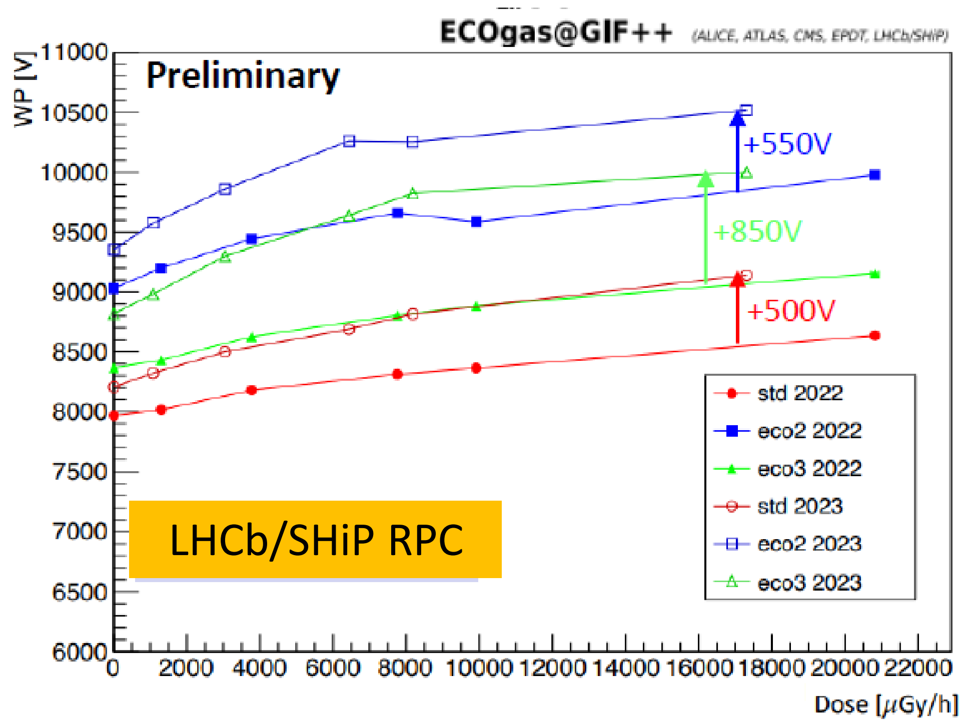


- The usual decrease of plateau efficiency with rate (or dose) is observed.
- Nevertheless, there seems NOT to be any efficiency degradation in the time lapse 2022-23

Shift of the WP before and after irradiation

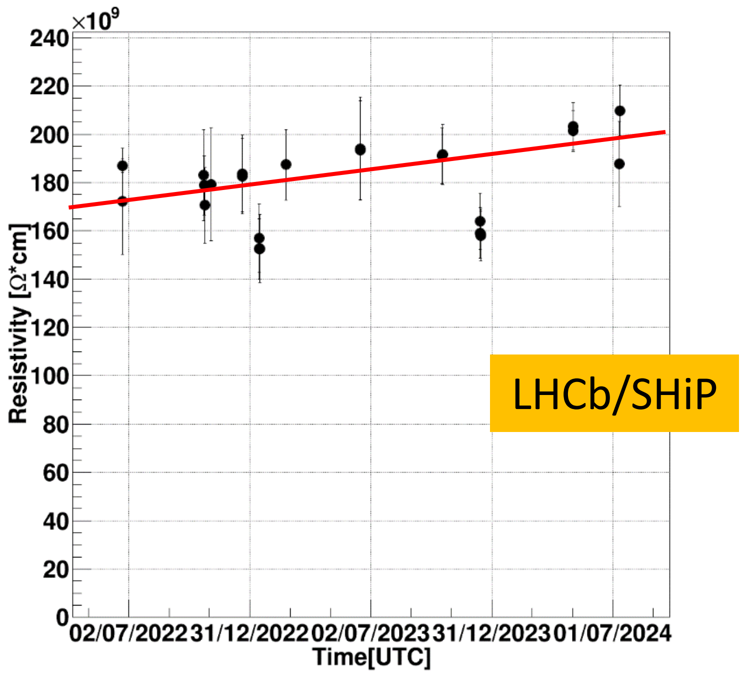
Comparison 2022-2023 data
(2024 data still under analysis)

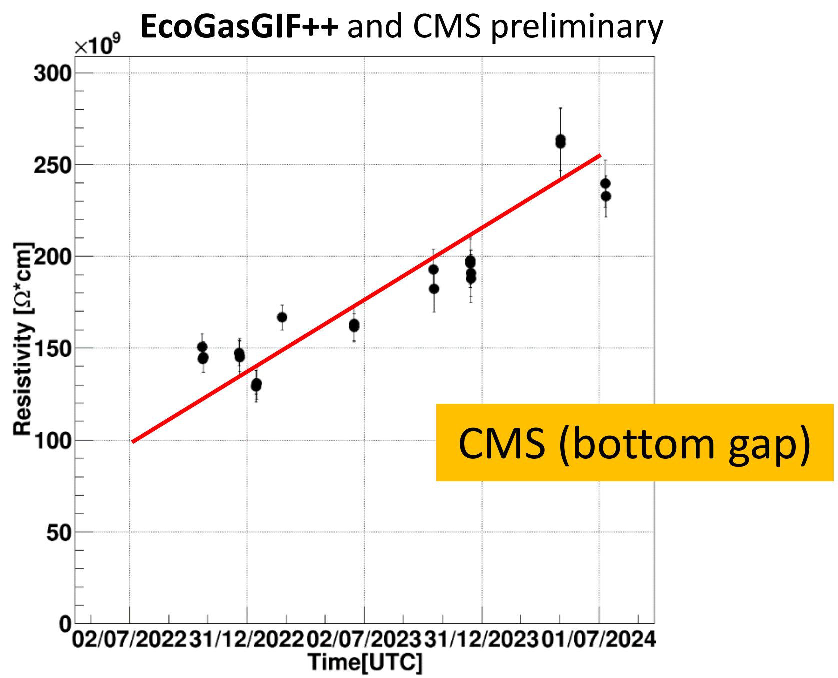




- Shift of the WP seems to be common to all detectors under test
  - → Variable amount, generally less for «standard» gas mixture
- To be checked if this will increase with time (2024 data)

Resistivity measurement campaign



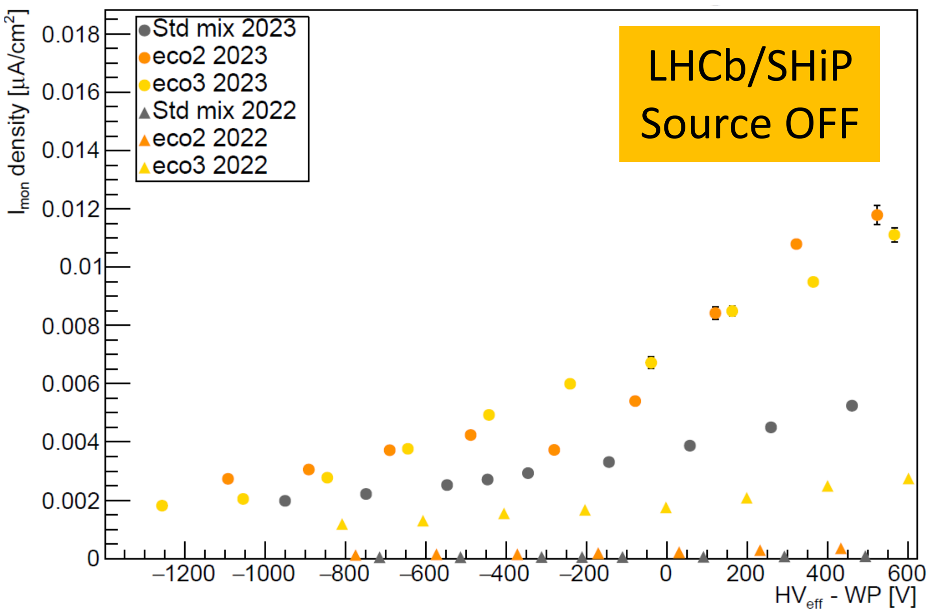


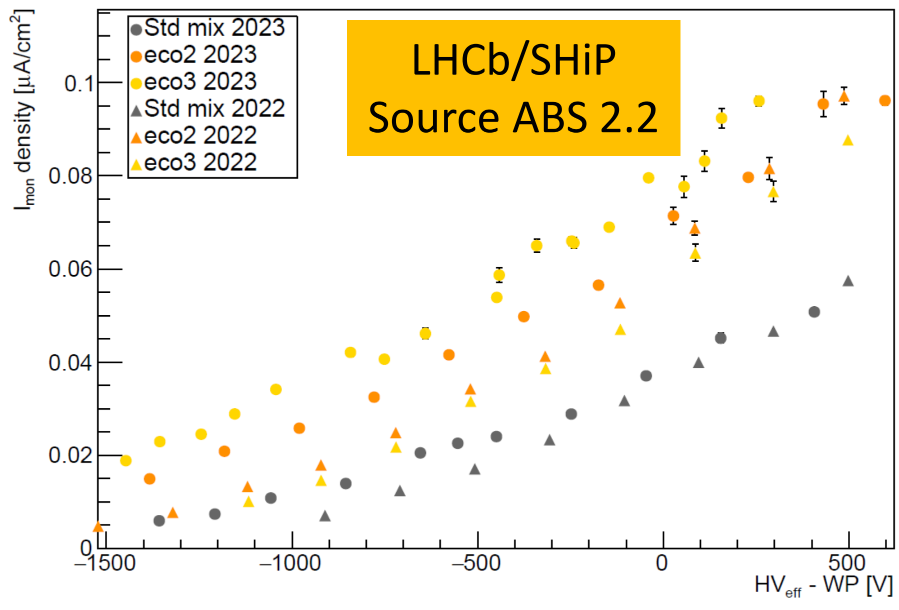
- The shift of the operating voltage observed might be related to the increase of bakelite resistivity and/or current observed.
- Indeed an increase of resistivity is observed when measured with the Ar method, with some differences across the detectors under test

→ A study to quantify these effects on WP and current will be done in the future.

Current density during beam tests

Comparison 2022-2023 data





Current density during TB (can be correlated to the WP)

→ mainly due to muons at Source OFF

→ mainly due to γ at Source ON

- Observed an increase both at Source OFF and ON, for all gas mixtures
- CMS is the exception (no significant increase observed)

The other piece of the puzzle

- The replacement of TFE is just **part of the problem**; in ECO2 and ECO3 the residual GWP is **almost ALL due to the presence of SF6.**

- Gas mixture replacement is generally done at constant number of gas volumes → CO2e is the parameter to consider when evaluating the reduction of the impact on greenhouse effects

Mixture	GWP (100 y)	CO2e (g/l)
Standard	1485	6824
ECO2	475	1522
ECO3	527	1529

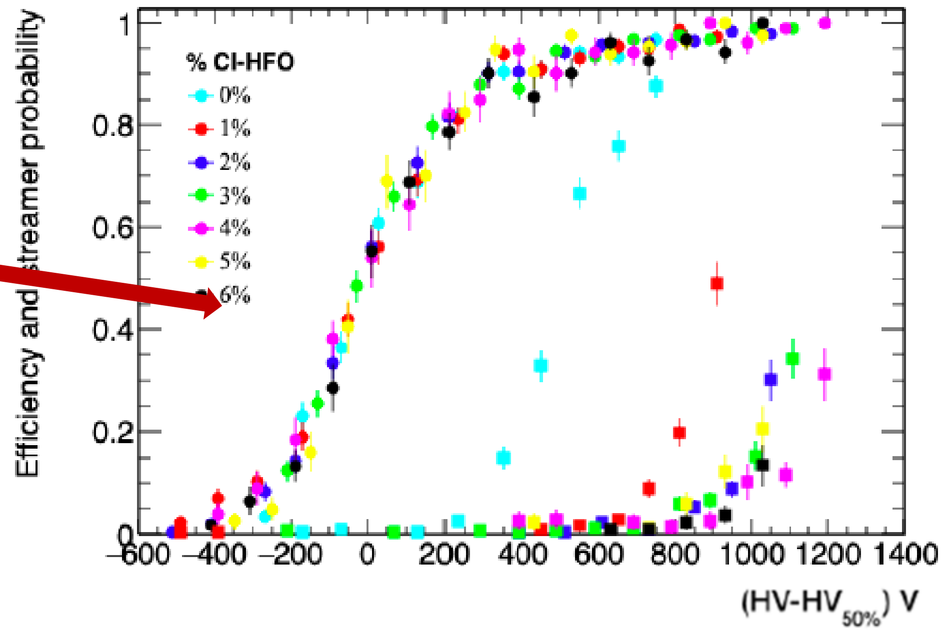
- With ECO2 and ECO3 achieved a reduction of 4 times the CO2e wrt. STD
- The residual CO2 is ALL due to SF6

→ Need to find replacement for SF_6, with low GWP and CO_2e, which could reduce the fraction of large charge events when in combination with HFO.

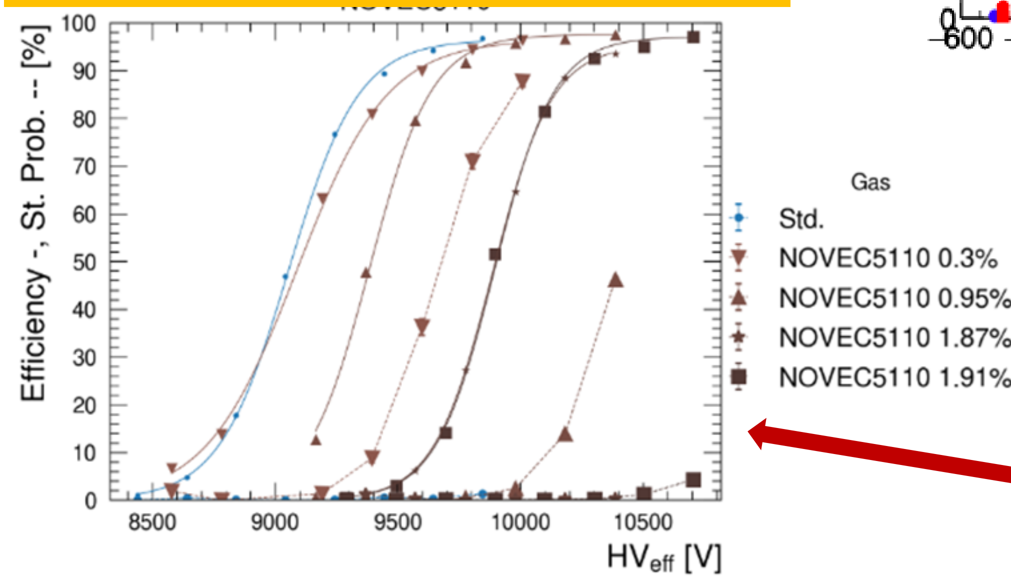
Looking for replacements for SF_6

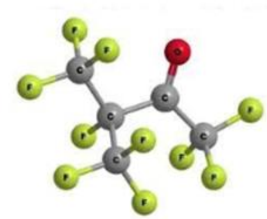
One proposed solution is Chloro-trifluoropopene $C_3H_2ClF_3$ (HFO1233zd)
Avalanche/streamer separation ("useful" plateau) **larger than 400V**
→ See talk by G. Proto

G.Proto et al, 2022 *JINST* **17** P05005



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





NOVEC 5110
- GWP < 1
- Atm. lifetime = 15 days
- Application in industry

→ See talk by. M. Verzeroli

Conclusions

- In general 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
- Interpretation of the effects observed not trivial
  → stay tuned!
- The effects observed migth be due to the increased presence of large charge events
  →check if the replacement for SF_6 will be better or worse
- Collaborative effors of paramount importance at this stage.