Towards more sustainable operation of Resistive Plate Chambers in the Compact Muon Solenoid

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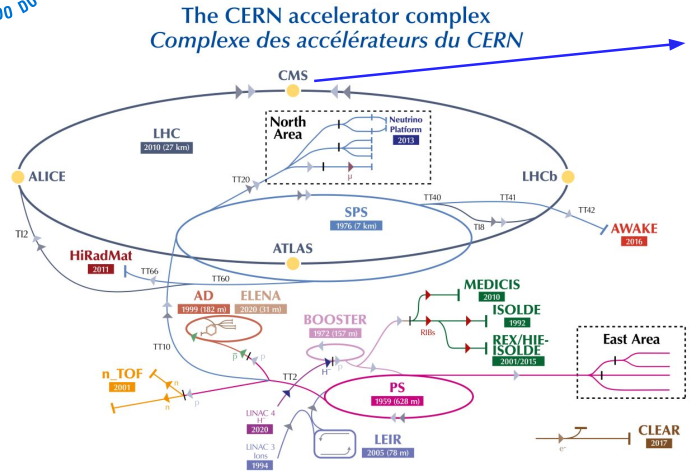
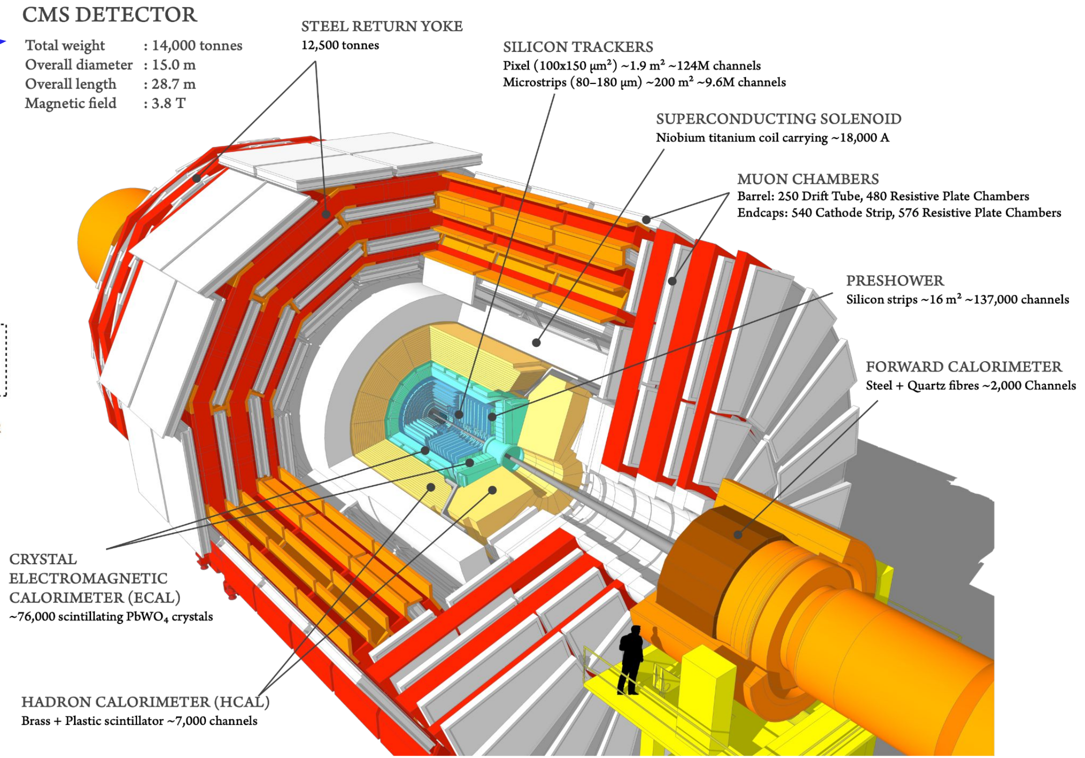
On behalf of CMS Muon Group

Sustainable High Energy Physics Conference 2026

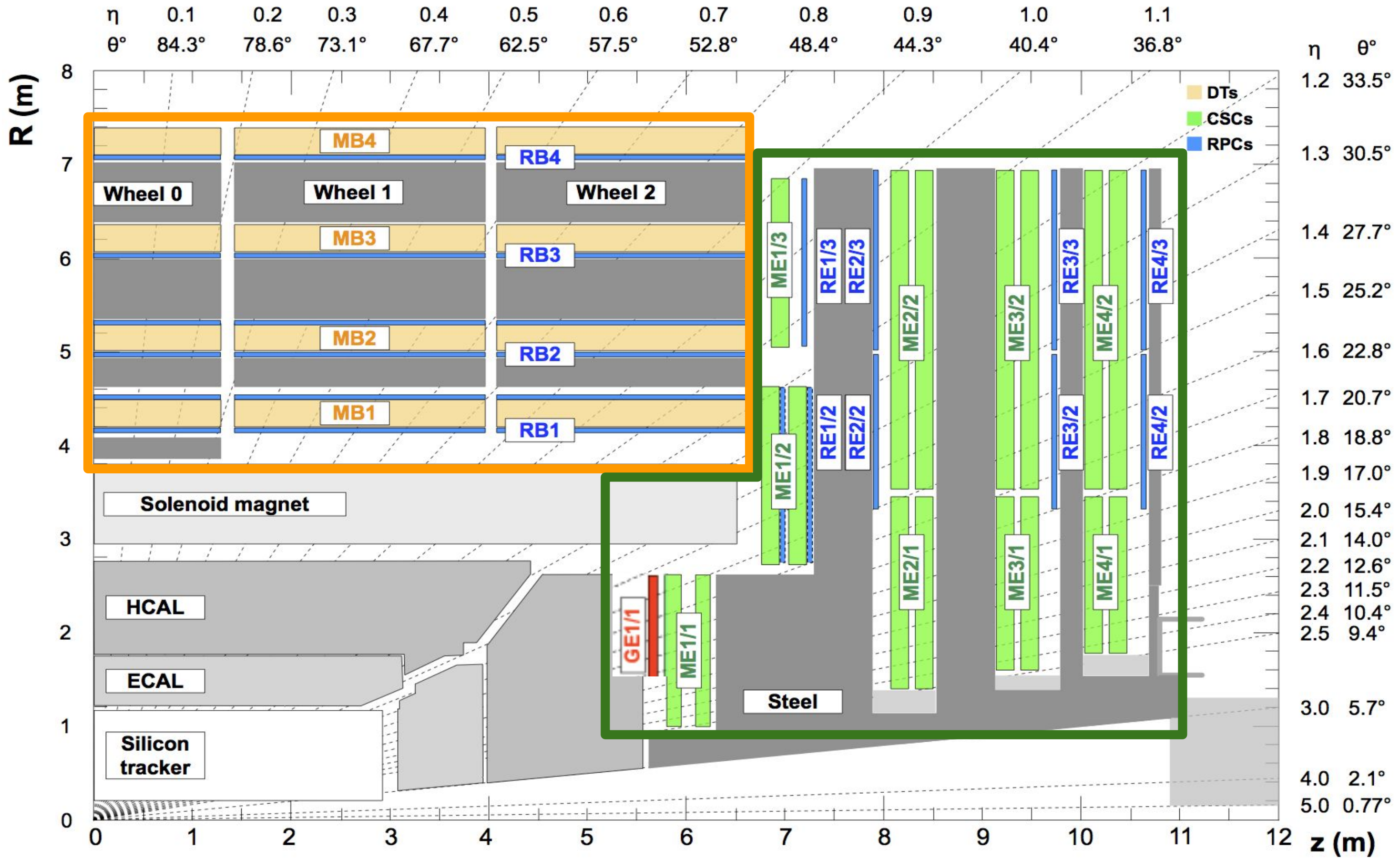
The Compact Muon Solenoid





Images: CERN Document Server courtesy

CMS Muon System during Run 3 (2022 - 2026)



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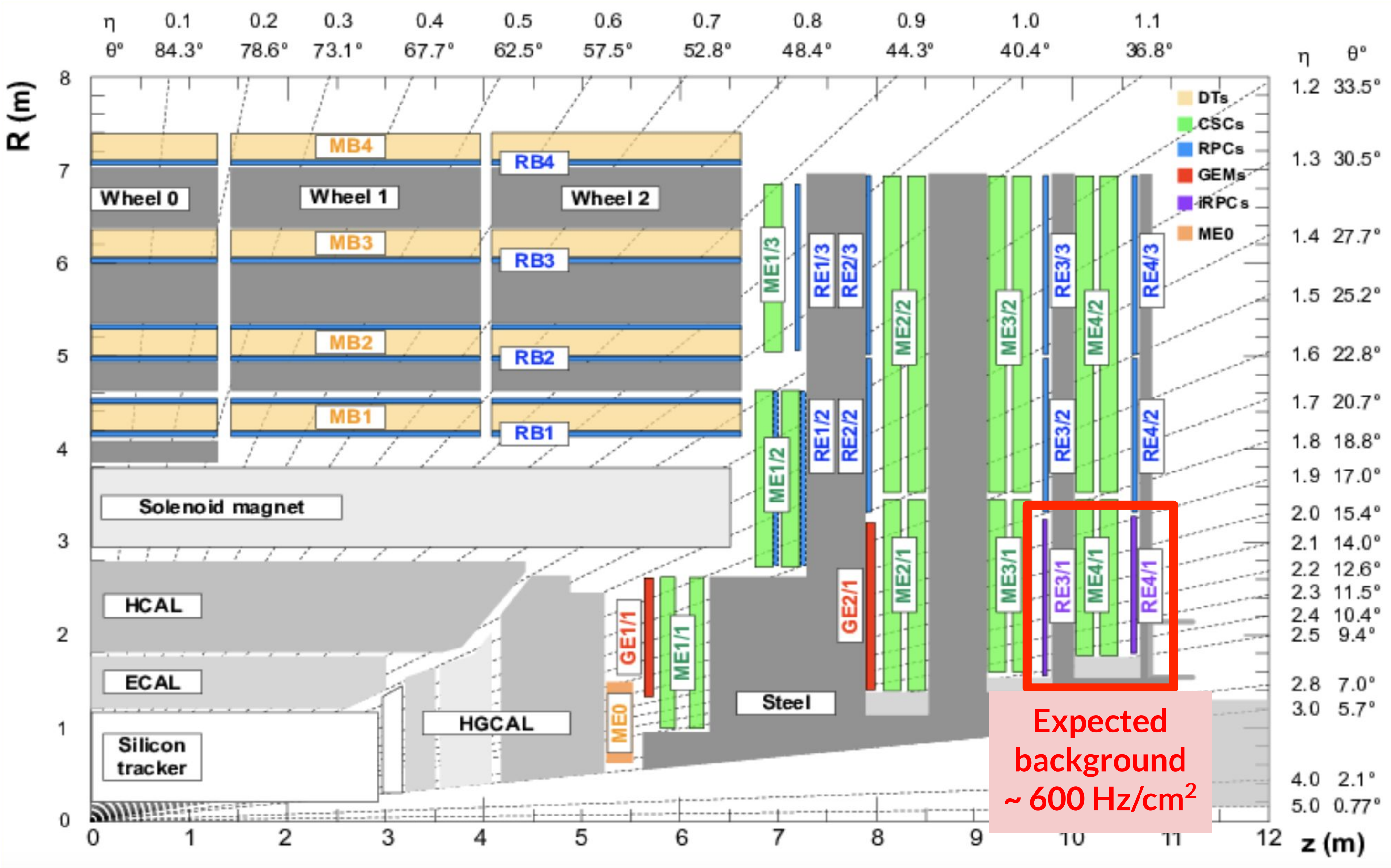
CMS Muon System for HL-LHC (2030)



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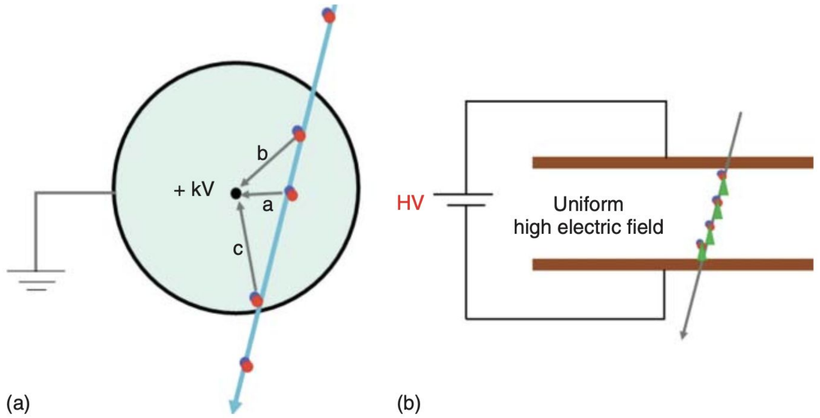
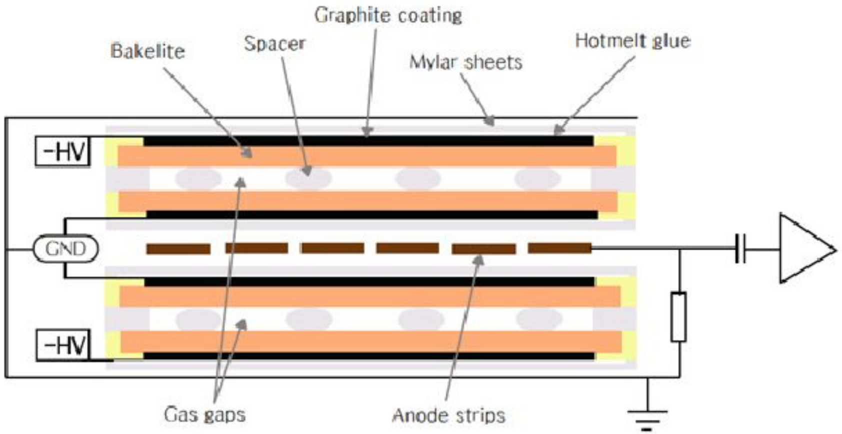
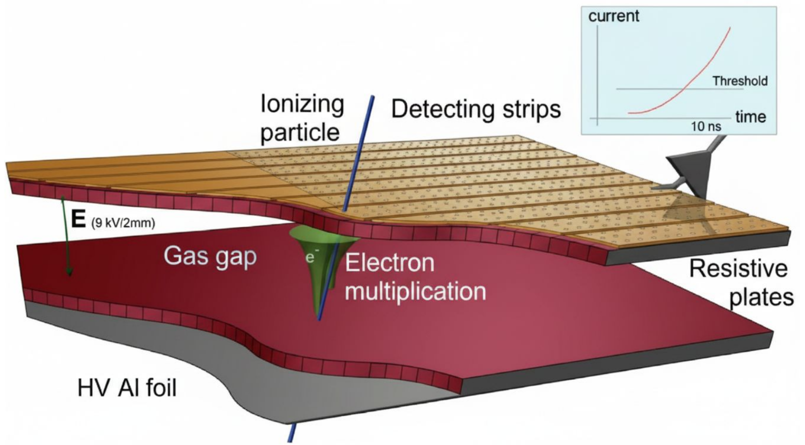
The Resistive Plate Chambers in CMS



Abbrescia et al, 2018



Park, S et al (2012). CMS endcap RPC gas gap production for upgrade. Journal of Instrumentation. 7. P11013. 10.1088/1748-0221/7/11/P11013.



Guiducci, Luigi & Montanari, Alessandro & Odorici, Fabrizio & Rossi, Antonio. (2006). Design and Test of the Off-Detector Electronics for the CMS Barrel Muon Trigger

Gas mixture used in CMS/RPC:

95.2 % of tetrafluoroethane (**$C_2H_2F_4$**) +

4.5 % of isobutane (**i-C_4H_{10}**) +

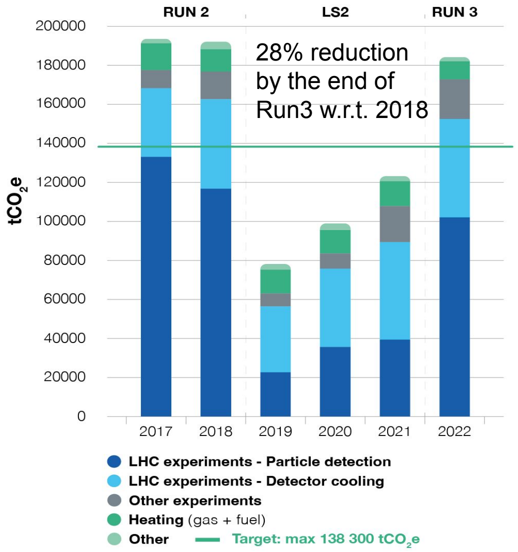
0.3 % of sulphur hexafluoride (**SF_6**)

Greenhouse gases emission at CERN

→ European Union has set targets to **reduce greenhouse gas (GHG) emissions by 55% by 2030** and achieving net-zero emissions by 2050.

→ The use of fluorinated gases (F-gases) like $C_2H_2F_4$ is tightly regulated due to their **high global warming potential (GWP)**.

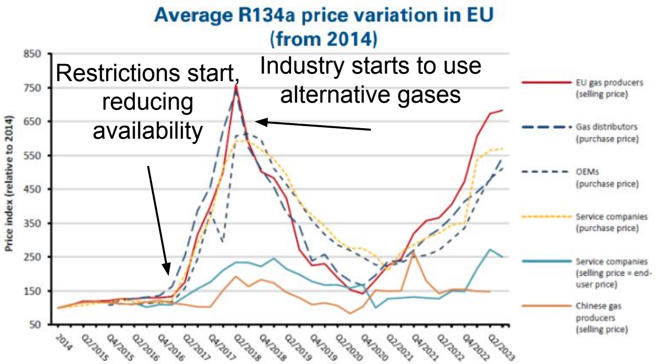
→ ~ 90% of direct emissions come from experiments, where more than 78% of GHG emission is a direct result of the use of F-gases.



CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY. "Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

CERN F-Gases Policy Condensed Summary **(July 24th, 2024):**

- **Promote R&D of alternatives gases**, replacing existing F-Gases where possible, and limiting their use in new installations.
- Prohibiting intentional releases, detecting and **reducing leaks**, and **training personnel**
- **Monitor and manage** F-Gas use and emissions across CERN

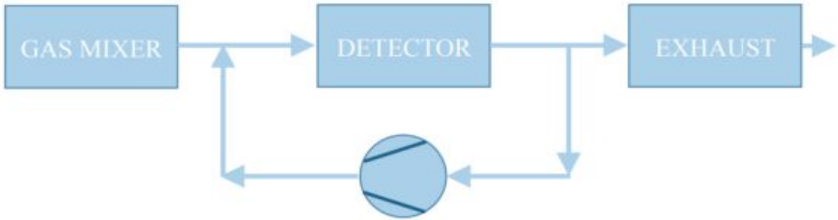


Strategies for F-gases reduction in CMS-RPC

- **Gas Recirculation**
  - Since LHC operation started (2010)
  - Stable performance
- **Gas Recuperation**
  - Operational since July 2023
  - 80 % efficiency in the recuperation of $C_2H_2F_4$
  - SF_6 recuperation under R&D studies ongoing
- **Gas Leak Repair**
  - Leak repair campaign during LS2
  - New procedure successfully applied during YETS 23/24
  - Massive repair campaign to be addressed in the next (E)YETS/LS
- **Alternative Gases**
  - HFO-1234ze + CO_2
    - Possible long term solution
    - Performance slightly affected
    - Longevity studies ongoing
  - $C_2H_2F_4$ + CO_2
    - Mid-term plan for $C_2H_2F_4$ mitigation
    - No performance degradation
    - Longevity studies ongoing

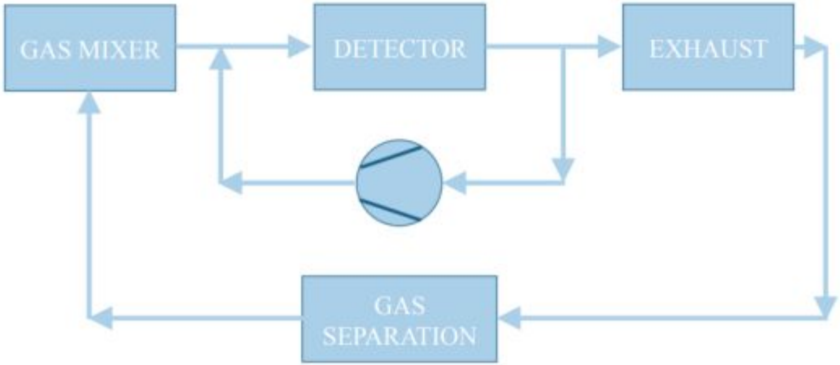
Recirculation and recuperation system at CMS/RPC

Recirculation system



- ~90% of the gas mixture is recirculated since the beginning of LHC operation (2010)
- Strongly reduces gas consumption
- Requires careful control of flow, pressure, and other parameters
- Impurities (as fluorides) accumulate over time

Recuperation system



- Further reduction of gas consumption by separating components via distillation
- Reinjects purified gas in the mixer with an efficiency of 80% since July 2023
- Increases system complexity and requires continuous R&D

Source: EP-DT group at CERN

Gas leak repair

→ The gas pipes break because polyethylene becomes brittle on time with radiation (bad batch of pipes)

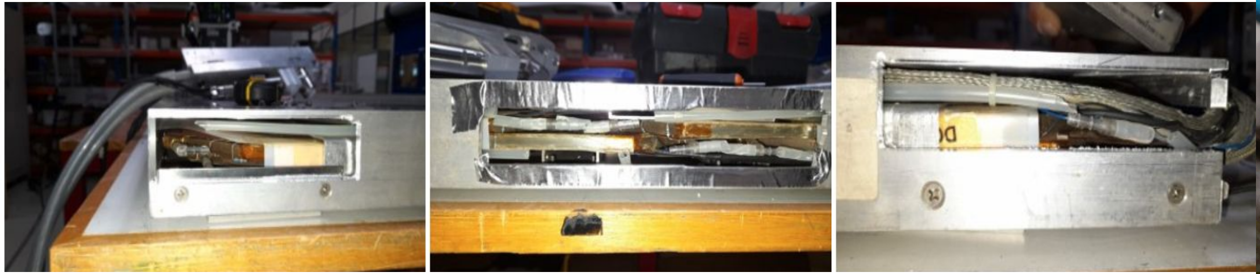
→ Since 2018, leaking chambers (> 10 L/h) have been disconnected

→ During LS2 (2019 – 2021) the leaks were repaired punctually at the source, but new leaks often appeared in other parts of the pipe

→ **More robust procedure (2023)**: replacing all pipes and connectors with full chamber extraction. 10 chambers repaired so far

→ Chambers show **stable performance** once gas flow is restored

Leak repair in P5 with chamber full extraction



Pilot leak repair in the laboratory with spare chamber

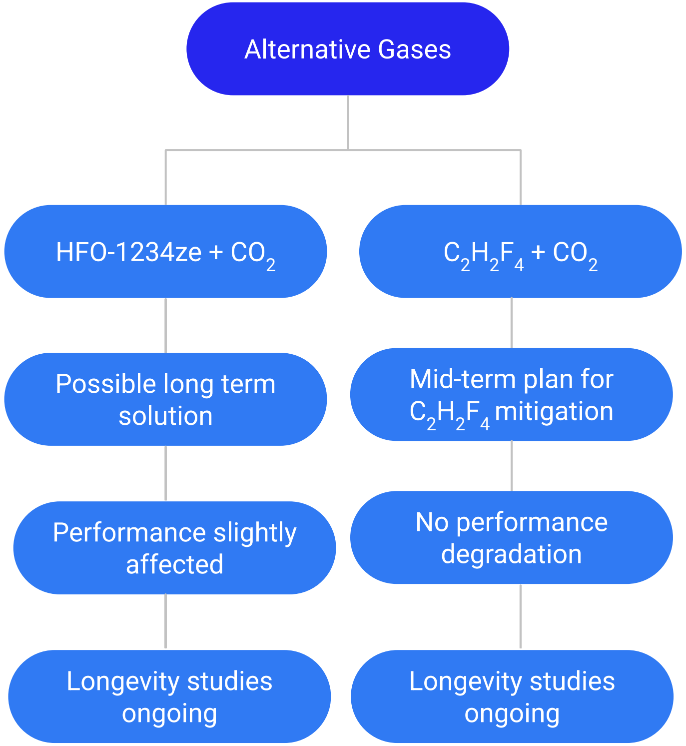
Alternative gases for GHG reduction: summary

→ HFO-1234ze, an isomer of $C_3H_2F_4$, is a leading industrial alternative to $C_2H_2F_4$

→ Possible candidate for the total replacement of $C_2H_2F_4$ in the RPCs

→ The higher operating voltage requires adding CO_2 to the mixture

→ Total GWP of the mixture is driven by SF_6



→ Mid-term solution is to partially replace the $C_2H_2F_4$ by CO_2

→ The ATLAS RPCs are adopting this alternative since 2023 to mitigate $C_2H_2F_4$ emission

→ Working point decreases with CO_2 addition

→ Gas recuperation system can bring the mixture GWP close to the standard one, and CO_2 molecule compatibility remains non-trivial.

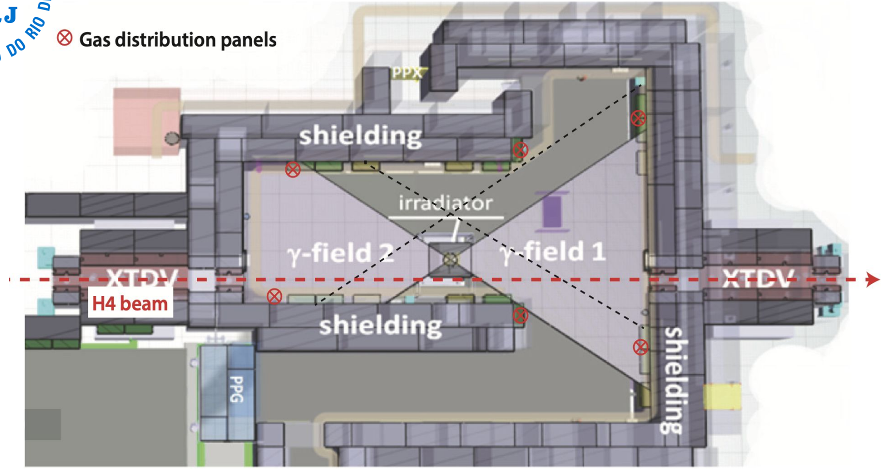
Alternative gas mixtures: more details

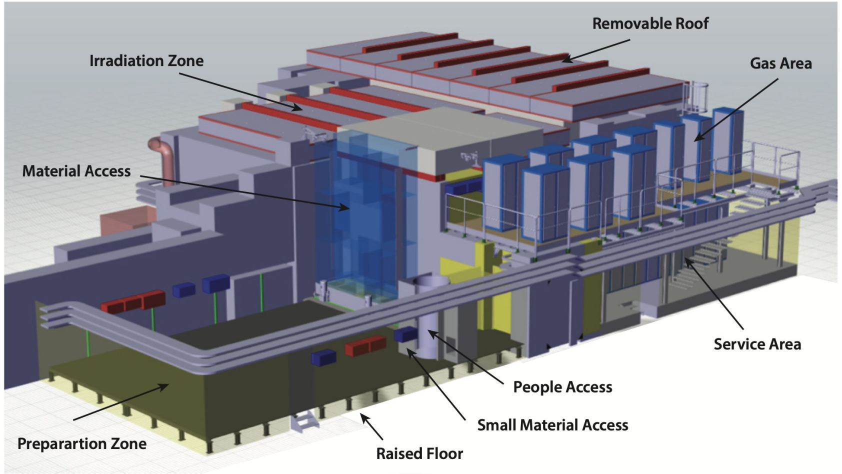
	TFE (%)	HFO-1234ze (%)	CO_2 (%)	$i\text{-}C_4H_{10}$ (%)	SF_6 (%)	GWP_{MIX}
GWP	1430	7	1	3	22800	
Density (g/L)	4.7	5.26	1.98	2.69	6.61	
STD	95.2			4.5	0.3	664
ECO2		35	60	4	1	149
ECO3		25	69	5	1	149
30%CO2+1%SF6	64		30	5	1	565
30%CO2+0.5%SF6	64.5		30	5	0.5	494
40%CO2+1%SF6	54.5		40	5	1	500

RPC ECOGAS@GIF Collaboration

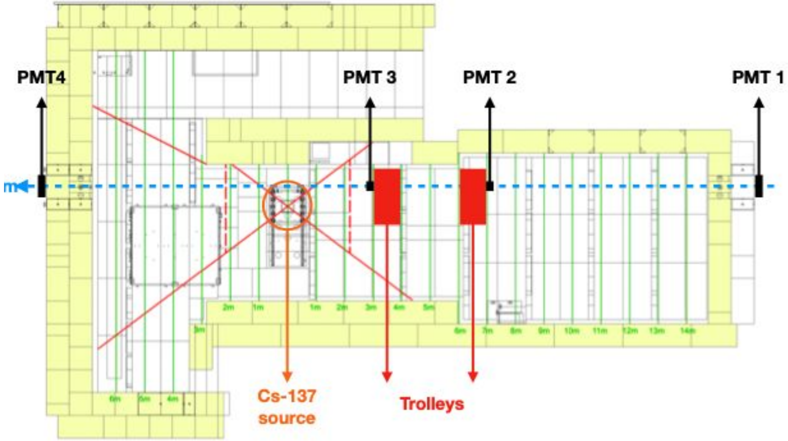
CMS collaboration with ATLAS-RPC and EP-DT Group

Experimental Setup: Gamma Irradiation Facility (GIF++)

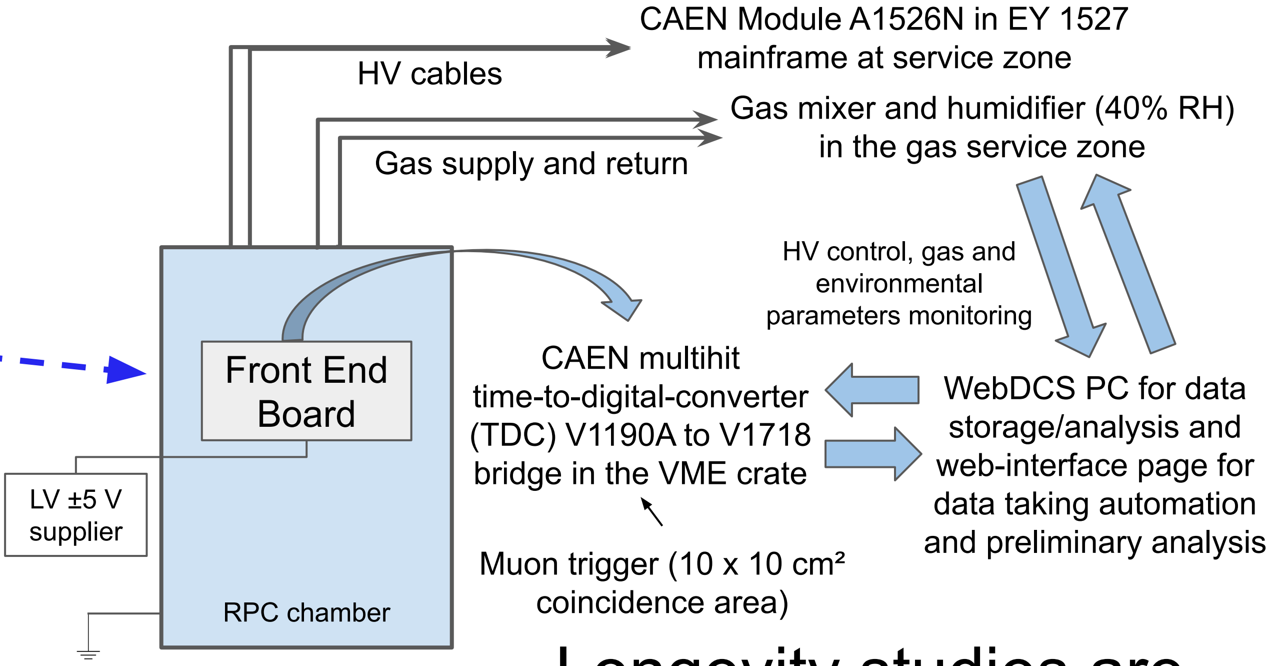




- 100 m² bunker with 11.5 TBq ^{137}Cs (Jan 24)
- 2 symmetric radiation field with an attenuator system with different absorption factors
- H4 beam line from SPS
- Muon beam 100 GeV/c, 10^4 muons / spill, every 400 ms
- Service zone with electronics and gas room
- Special gas line with CO2-based mixture from the mixer in the gas room
- Largely used for muon detector system of LHC experiments in the view of HL-LHC



Experimental Setup at GIF++: RPC prototype and electronics



RPC Prototypes:

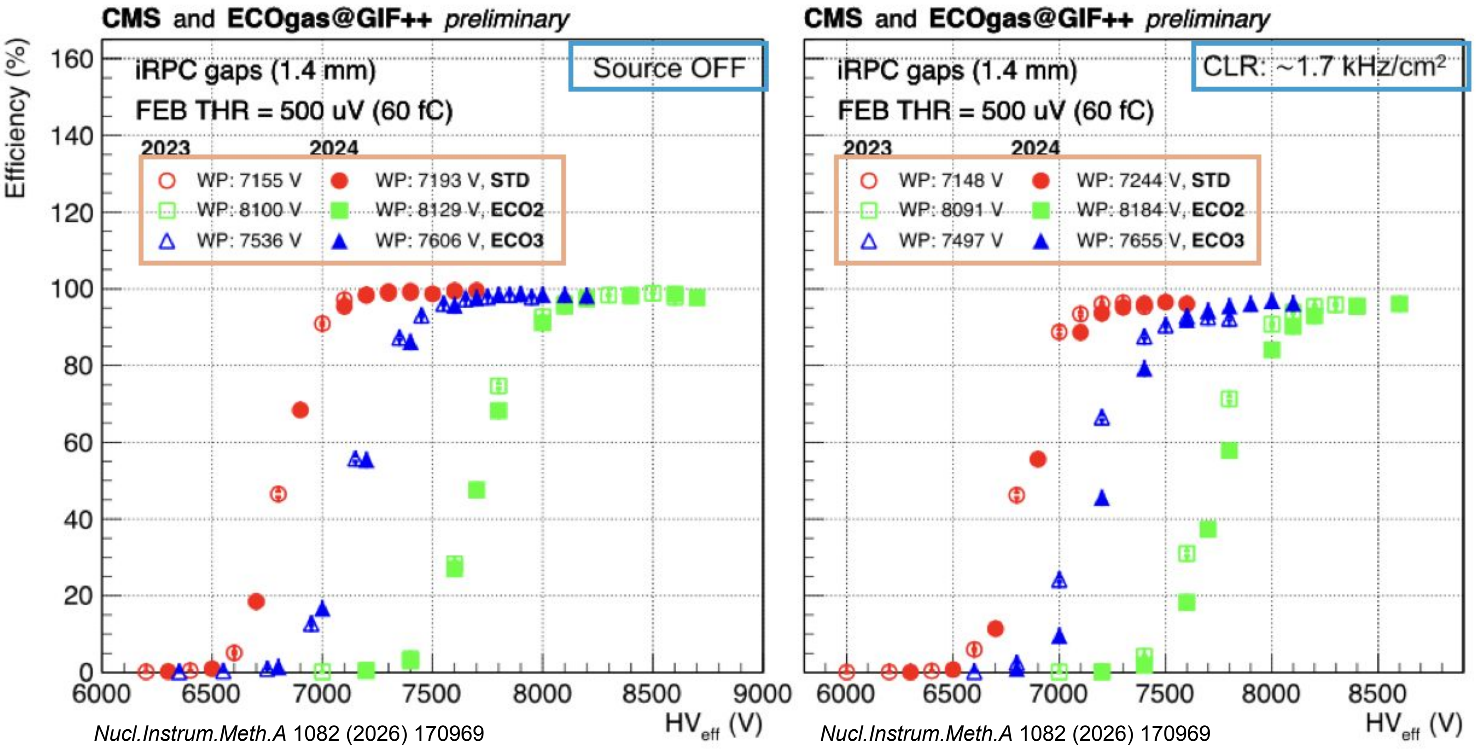
- Strips made with copper tape 16 strips plane,
- **double 1.4(2) mm 50 x 50 cm^2 gap**

Front-end Board (FEB) - KODEL adapted electronics:

- Current sensitive mode for input signals
- Input impedance = 20 Ω and amplification gain = 200
- LVDS width = 60 ns; **Threshold 0.5 mV ~ 60 fC**

Longevity studies are performed at GIF++: 4% of total HL-LHC integrated charge so far

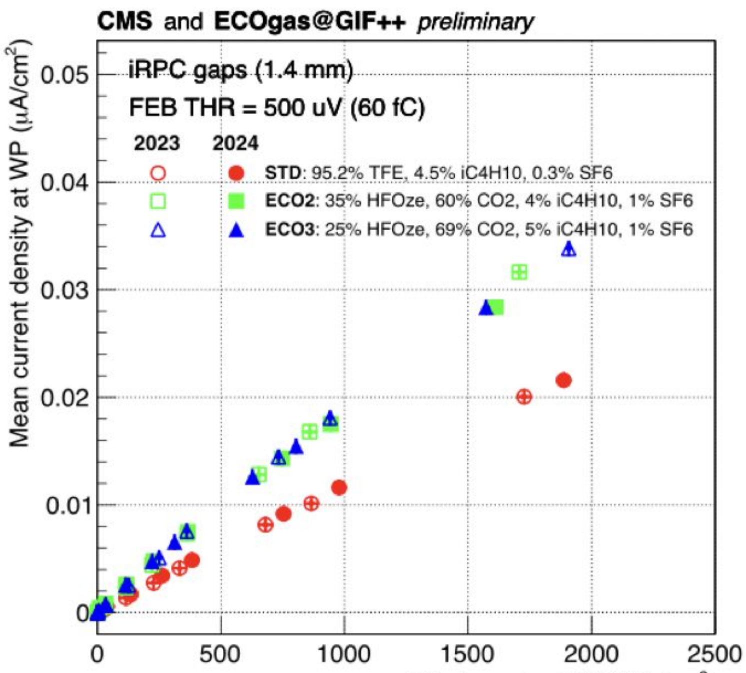
Alternative gas mixtures: HFO/CO2 mixtures

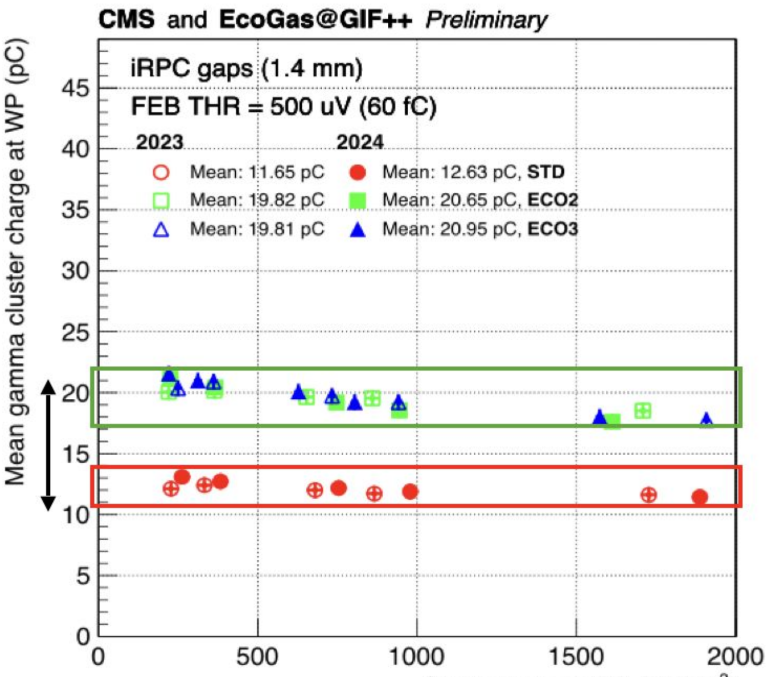


→ **Efficiency remains stable** up to highest background, with no drop after irradiation

→ The working point shifts slightly to higher voltages for ECO (defined in slide 10) mixtures being stable before and after irradiation

Alternative gas mixtures: HFO/CO2 mixtures





Nucl.Instrum.Meth.A 1082 (2026) 170969

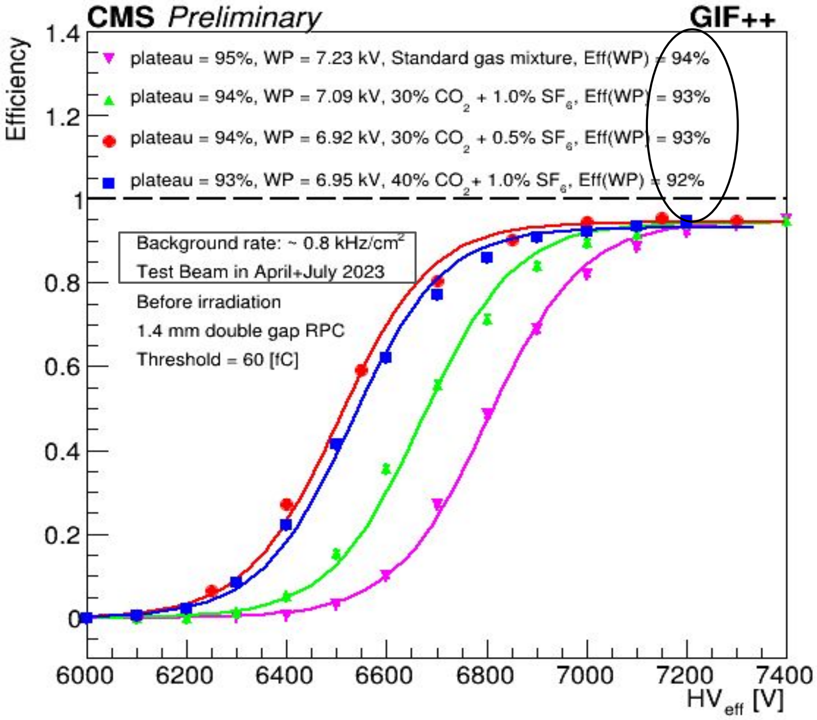
Nucl.Instrum.Meth.A 1082 (2026) 170969

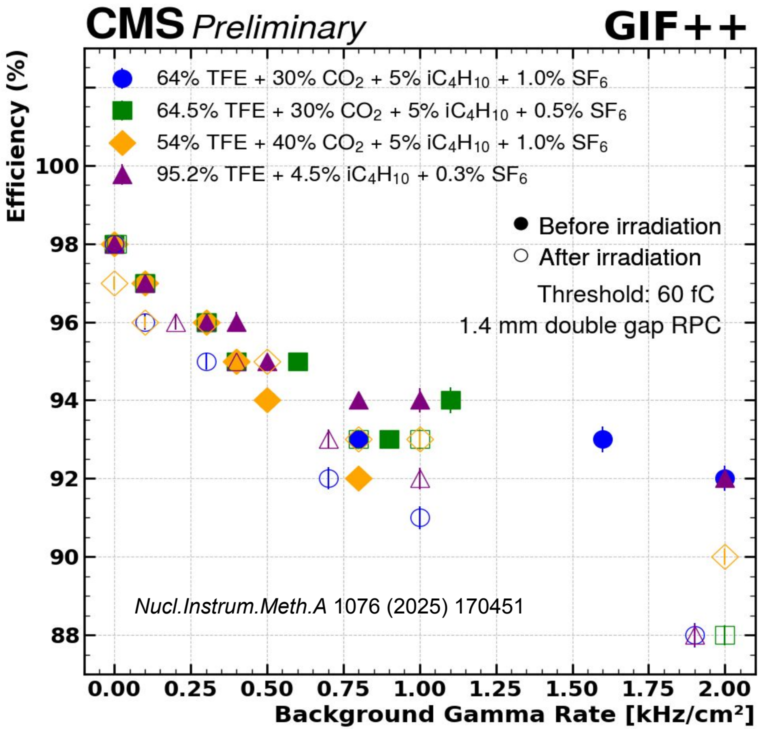
→ Current density slope is higher for ECO mixtures, remaining stable after irradiation

→ Cluster charge is about 40% higher with ECO mixtures, unchanged after irradiation

→ **No degradation** after 4% HL-LHC equivalent charge

Alternative gas mixtures: TFE/CO2 mixtures

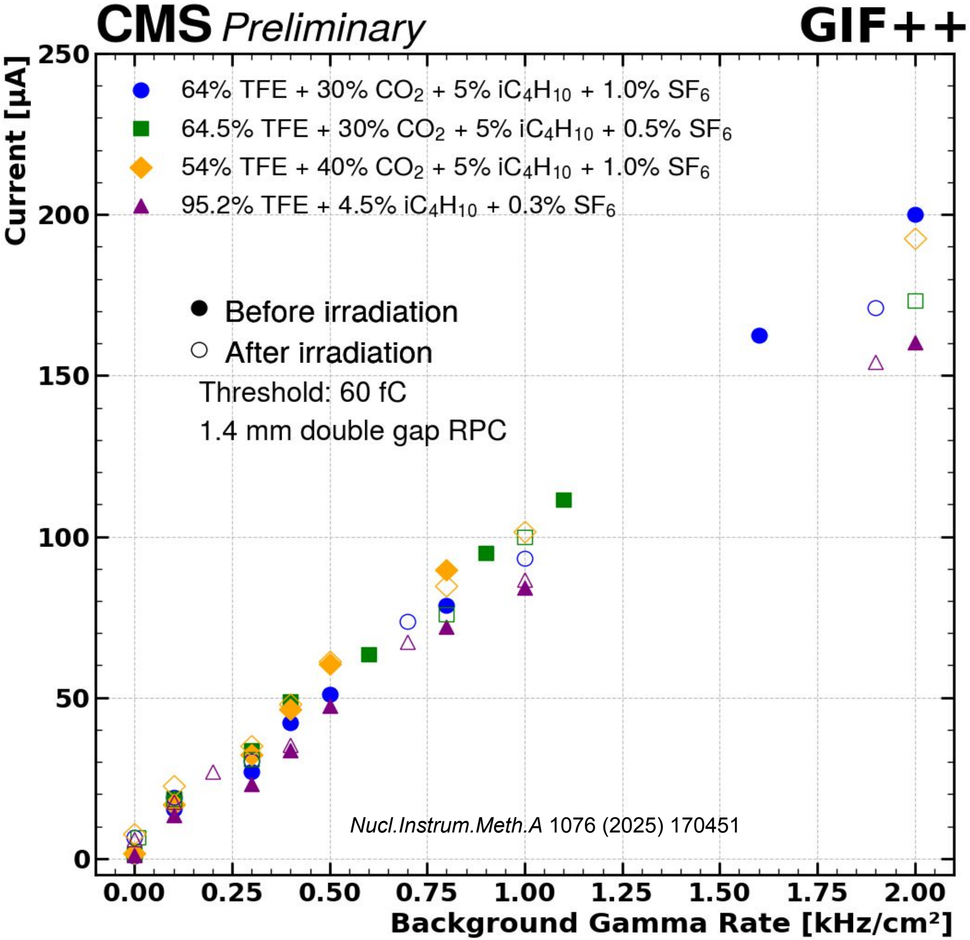




→ Efficiencies with background **are similar** before and after irradiation and across different gas mixtures

→ All CO_2- based mixtures show **lower working points** than the standard gas

Alternative gas mixtures: TFE/CO2 mixtures



→ **No degradation** after 4% HL-LHC equivalent charge

→ Currents and gamma charge are about 20% higher with CO_2-based mixtures, stable before and after irradiation

→ In long term operation, higher currents speed up gap surface degradation

→ It motivates the continuation of aging tests in irradiation environments

Summary

The replacement of the standard CMS-RPC gas mixture is a complex and non-trivial challenge

- Gas **recirculation, recuperation systems, and massive leak repair** remain essential for reliable CMS-RPC system operation

- **CO_2 - based mixtures** may represent a provisional mid-term strategy, providing resilience in case recuperation systems failure or leaky chambers cannot be accessed
- **HFO - based mixtures** cannot be considered a definitive solution yet: working point for 2 mm RPC close to HV board limit

- **No performance degradation** attributable to the alternative gas mixtures has been observed after irradiation equivalent to a few percent of the HL-LHC lifetime
- Challenges remain: **~ 40% higher cluster charge** with HFO-based mixtures and **~ 20 % higher currents** with CO_2-based mixtures → **more longevity studies are needed**
- The long-term operation of alternative gas mixtures remains uncertain, requiring substantial R&D with the RPC community

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Thank you

CAPES

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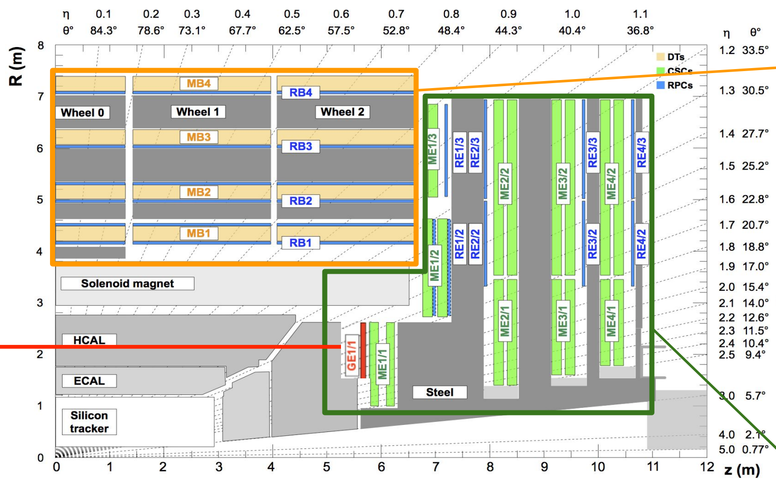
Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro

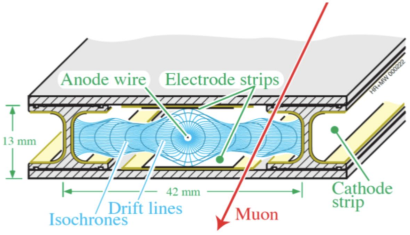
CMS Muon System during Run 3



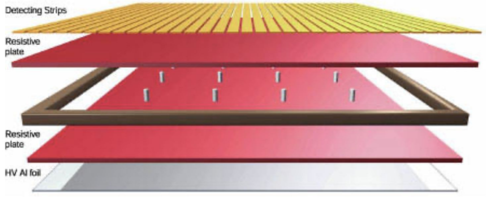
CERN Document Server courtesy

Good performance and **stable operation** of CMS Muon System during Run II of LHC (JINST 14 (2019) C11031)

Barrel of CMS: 250 Drift Tubes chambers
+ 480 Resistive Plate Chambers

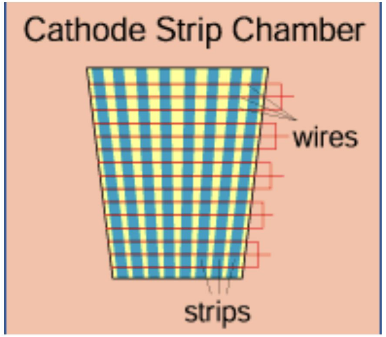


DT working principle

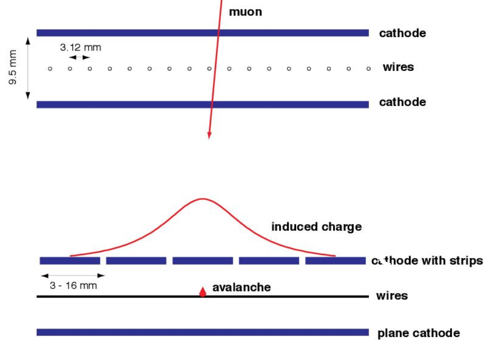


RPC gap layout

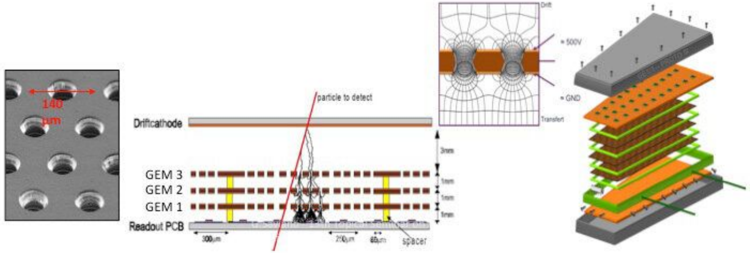
Endcap of CMS: 540 Cathode Strip Chambers
+ 576 Resistive Plate Chambers



CSC layout



CSC working principle

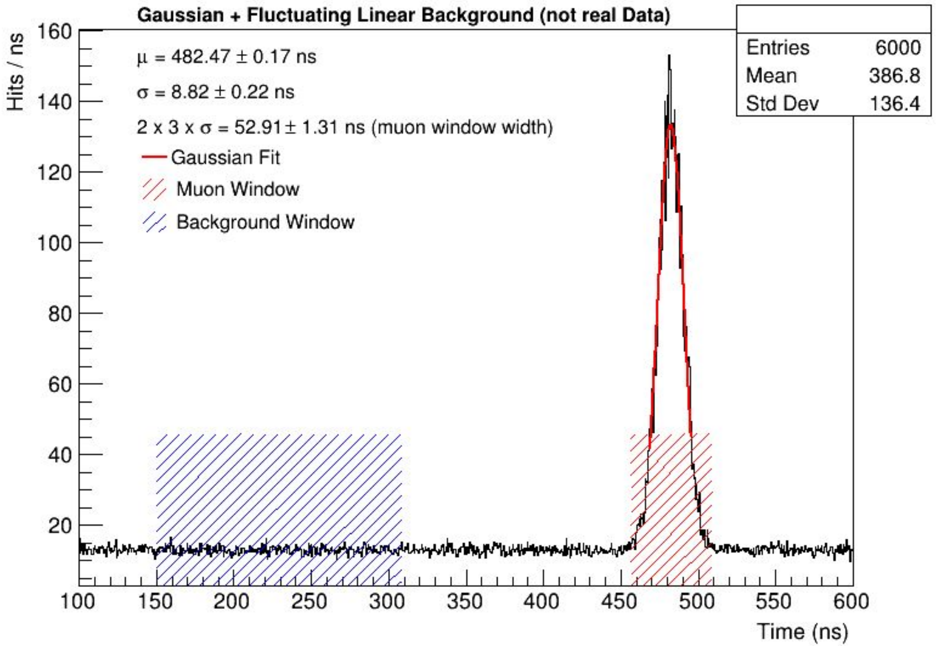


Verwilligen, Piet. (2023). GEM detectors for the CMS endcap muon system: status of three new detector stations. Journal of Instrumentation. 18. C07006. 10.1088/1748-0221/18/07/C07006.

72 triple-GEM chambers installed during Long Shutdown 2 (2019-2020) are having a **good performance** during Run III data taking period (CERN-LHCC-2015-012)

Analysis strategy

- Muons arrive in spills with a well-known frequency, while gamma contributions are homogeneous in both space and time
- Muon window is defined by a gaussian fit
- Hits outside the muon window are identified as background (noise/gamma), used to obtain the background rate
- Background contamination is removed during efficiency calculation using a window outside the muon hits



Muon window (all hits)

$$\epsilon = \frac{\epsilon_{tot} - \epsilon_{bkg}}{1 - \epsilon_{bkg}}$$

Background window

- Clusterization algorithm: a cluster (muon or gamma) is defined as the hits in adjacent strips inside a time window
- The time window is obtained with source OFF targeting a number of muon cluster per event equal to one
- It was found to be around 30 ± 5 ns
- Cross check with gamma clustering at low background rate

Analysis strategy

HV applied is PT corrected, as here

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

$\alpha = 0.8$ $P_0 = 990$ mbar $T_0 = 293.15$ K

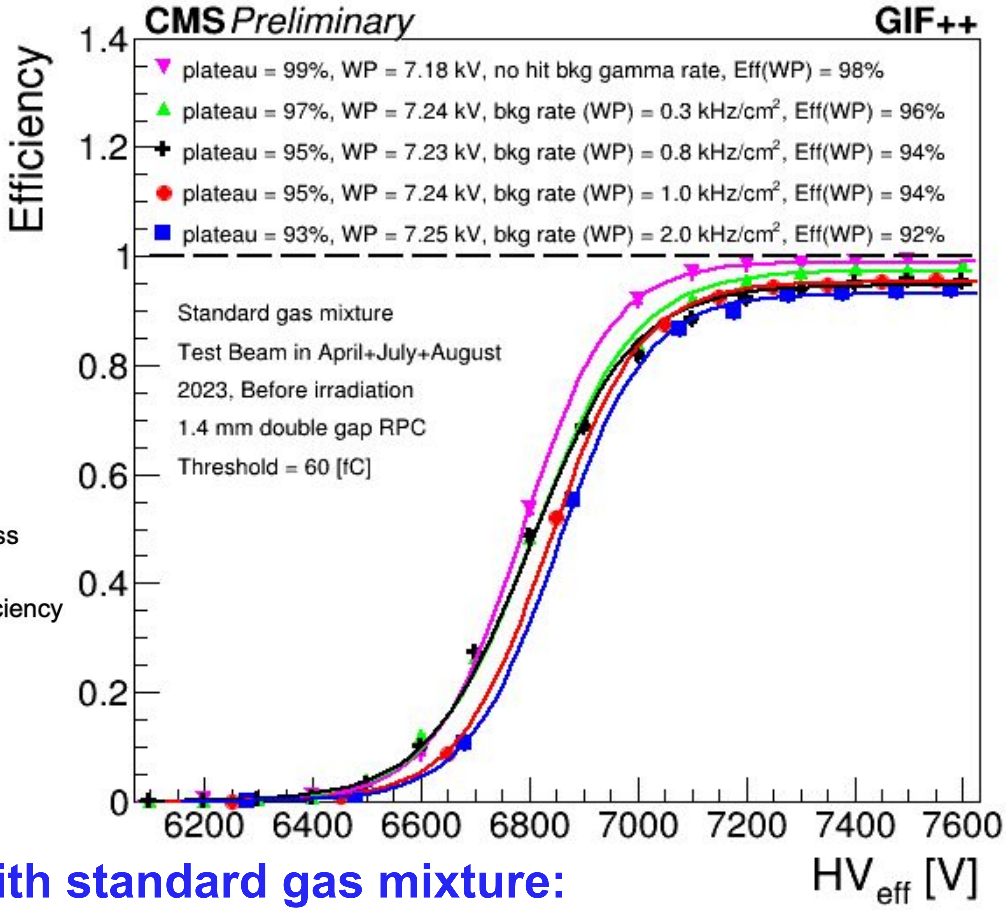
- Efficiency in each point is calculated using the method in previous slide
- S-curve is fitted by a sigmoid function

$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50\%})}}$$

λ : Slope or steepness
$HV_{50\%}$: $HV_{\epsilon=50\%}$
ϵ_{max} : maximum efficiency

- Working point defined as the HV where efficiency is 95% + 150V:

$$WP = \frac{\ln 19}{\lambda} + HV_{50\%} + 150V$$



Validation with standard gas mixture:
WP consistent around 7.2 kV and efficiency > 90 % up to 2 kHz/cm^2
(HL-LHC x 3)

Alternative gas mixtures: ECOgas Collaboration

RPC EcoGas@GIF++ Collaboration

AidaInnova Startup

Irradiation campaign for aging studies

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

2021 testbeam

2022 testbeam

2023 testbeam

2024 testbeam

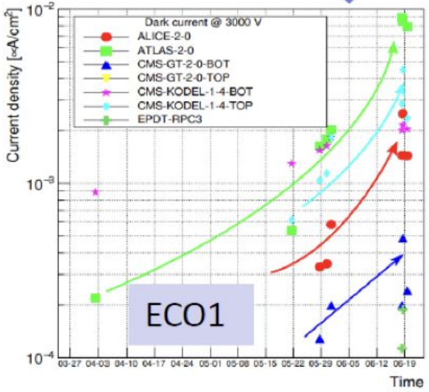
2018

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

2021

Performance baseline

Performance comparison



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

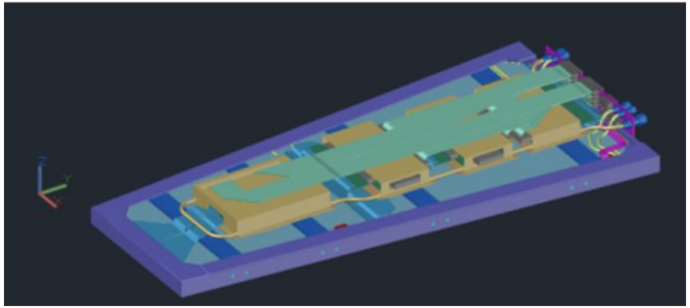
Std, ECO2 and **ECO3** mixtures tested under irradiation. First results in papers *[1][2][3]*.

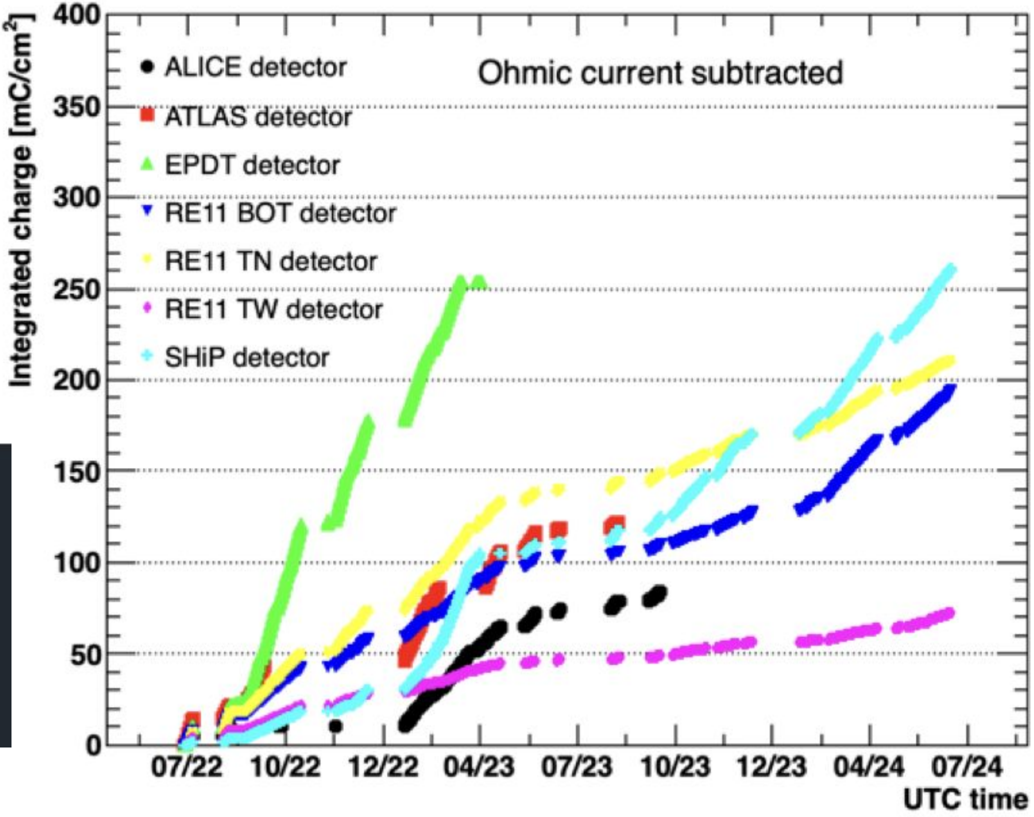
[1] "High-rate tests on resistive plate chambers operated with eco-friendly gas mixtures", 2024 Eur. Phys. J. C.
[2] "Performance of thin-RPC detectors for high rate applications with eco-friendly gas mixtures", 2024 Eur. Phys. J. C.
[3] "Preliminary results on the long term operation of RPCs with eco-friendly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

Alternative gas mixtures: ECOgas Collaboration

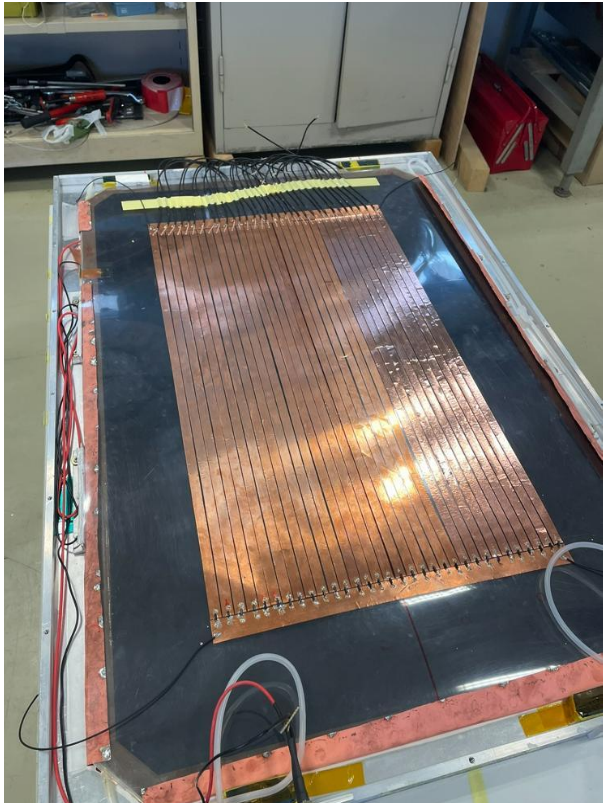
RE1/1

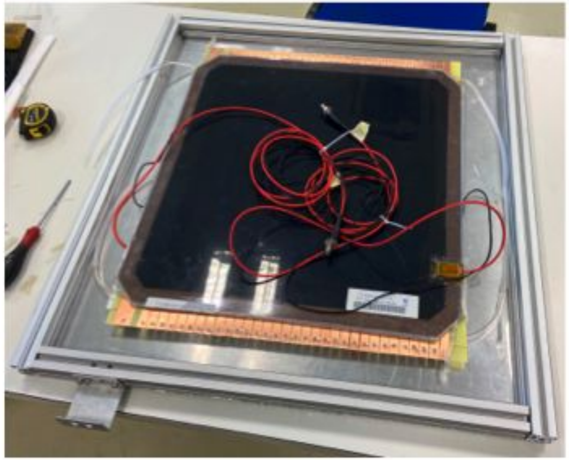
- Existing CMS-RPC 2mm double gap representative
- Target: 1 C/cm2 (3x safety factor)
- ~200mC/cm2 integrated so far





iRPC prototype: KODEL-H chamber

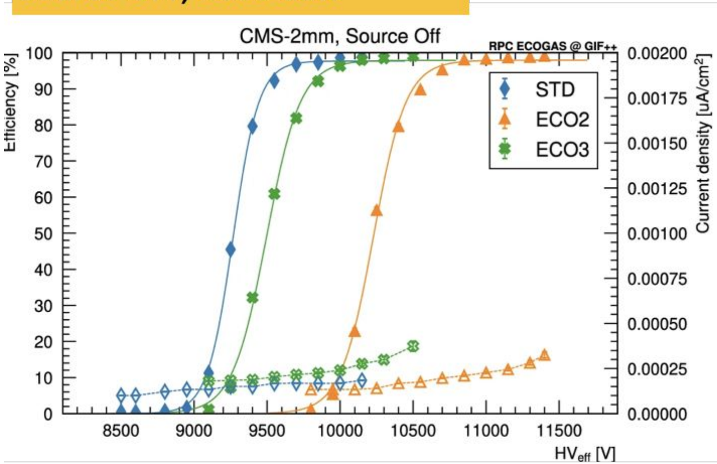


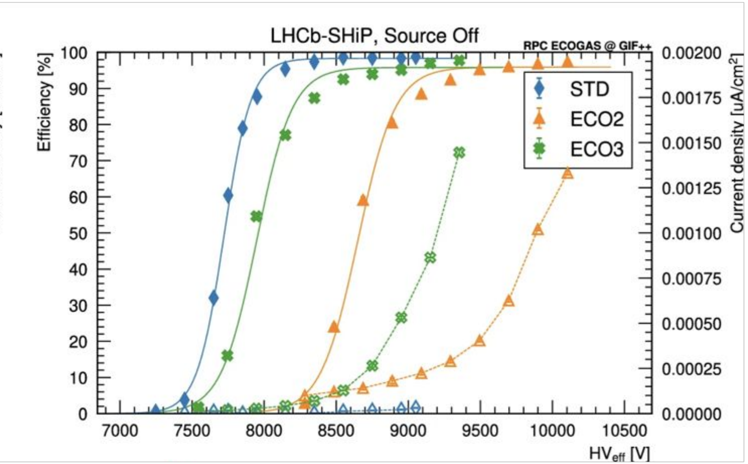


iRPC chamber prototype with adapted electronics (from KODEL)

RE11: Baseline perfomance

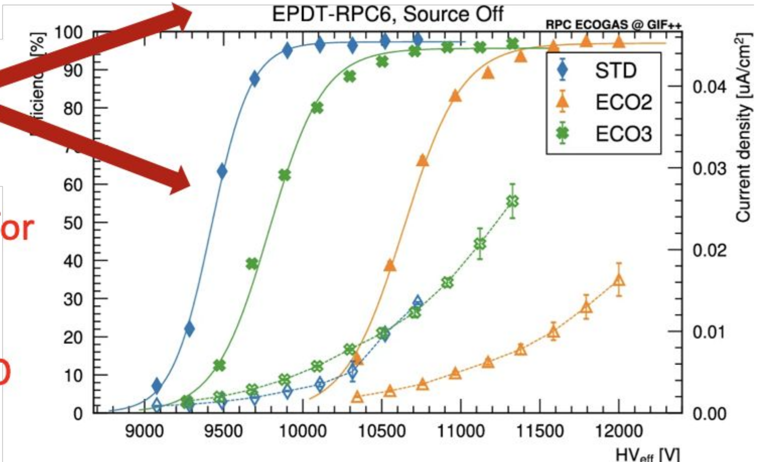
Source OFF, 2021 data





Fit of efficiency curves with a sigmoid:

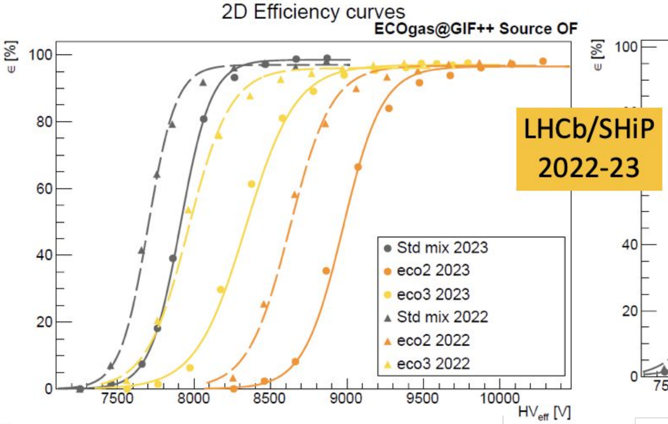
$$\mathcal{E}(HV_{\text{eff}}) = \frac{\mathcal{E}_{\max}}{1 + e^{-\beta(HV_{\text{eff}} - HV_{50})}}$$

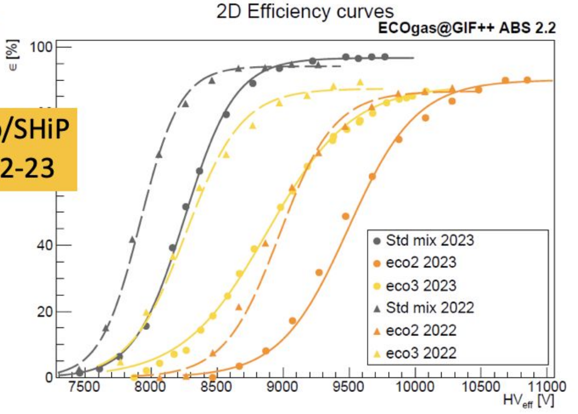


- ➢ Efficiency at plateau basically similar for STD, ECO2 and ECO3 > 95%
- ➢ Efficiency curves shifted at higher voltages depending on fraction of HFO

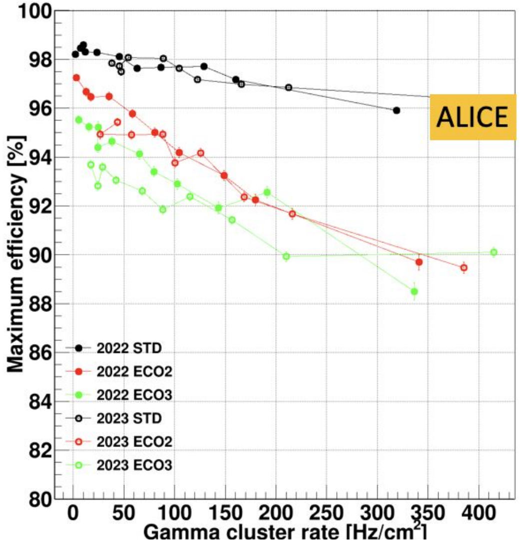
→ WP(ECO2) > WP(ECO3) > WP(STD)

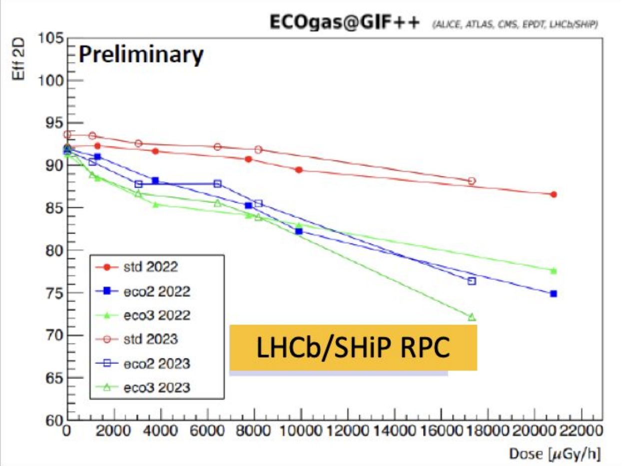
Before and after irradiation comparison





Similar shift in efficiency curve for LHCb/SHiP chambers

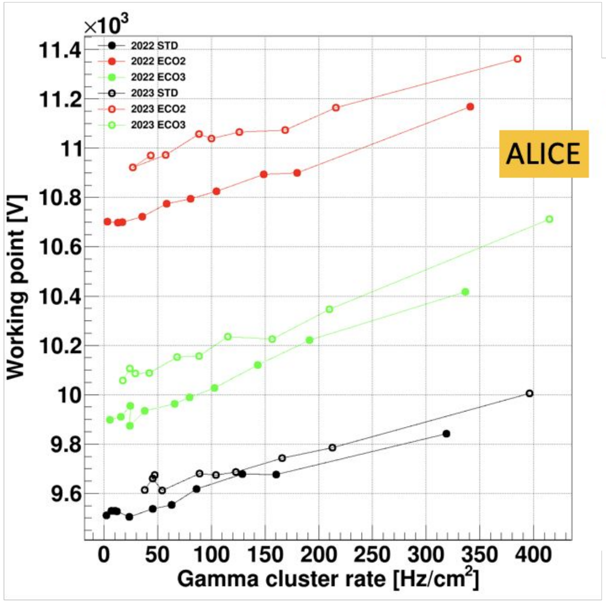


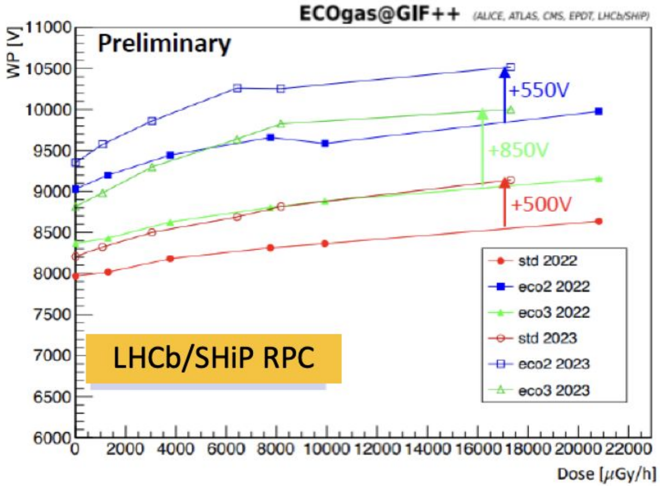


No efficiency degradation before/after irradiation

Shift of the WP before and after irradiation

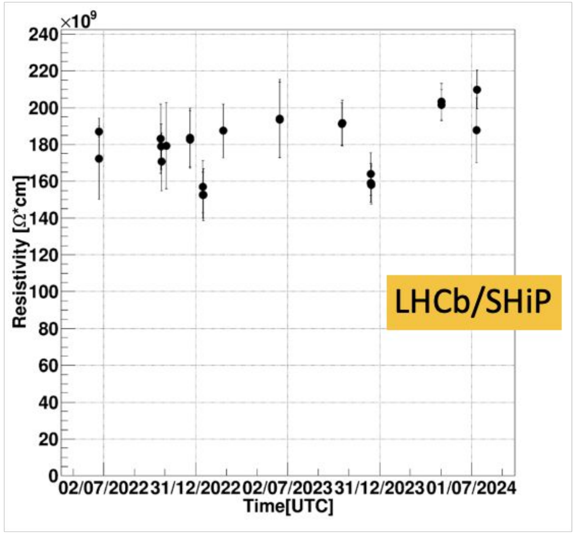
Comparison 2022-2023 data
(2024 data still under analysis)

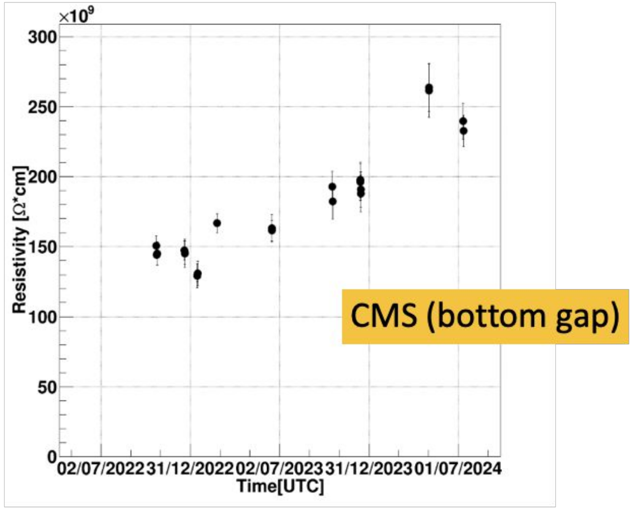




- Shift of the WP seems to be common to all detectors under test
  - → Variable amount, generally less for «standard» gas mixture
- To be checked if this will increase with time (2024 data)

Resistivity measurement campaign

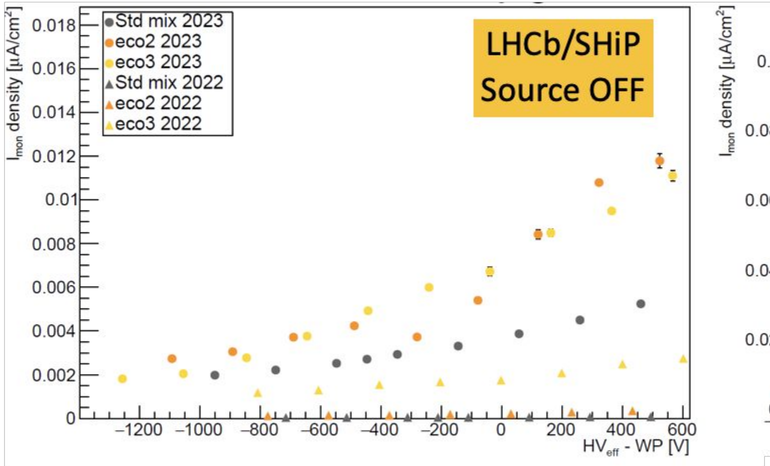


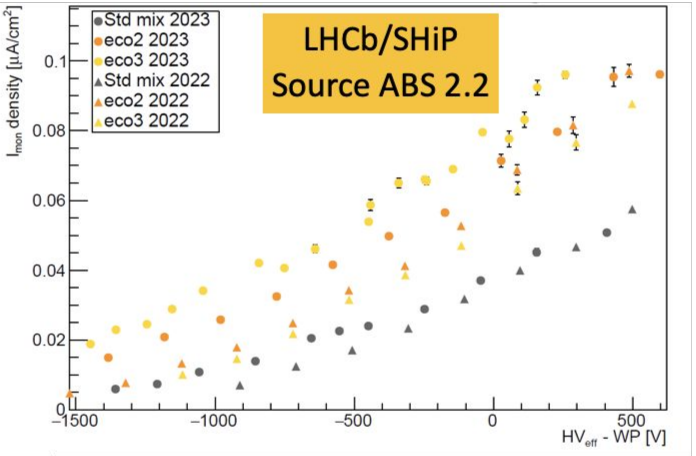


- ➢ The shift of the operating voltage observed might be related to the increase of bakelite resistivity and/or current observed.
- ➢ Indeed an increase of resistivity is observed when measured with the Ar method, with some differences across the detectors under test

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

Corrent density during beam tests





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)