

Long-term operation of CMS improved Resistive Plate Chambers with alternative CO₂-based mixture under high irradiation environment

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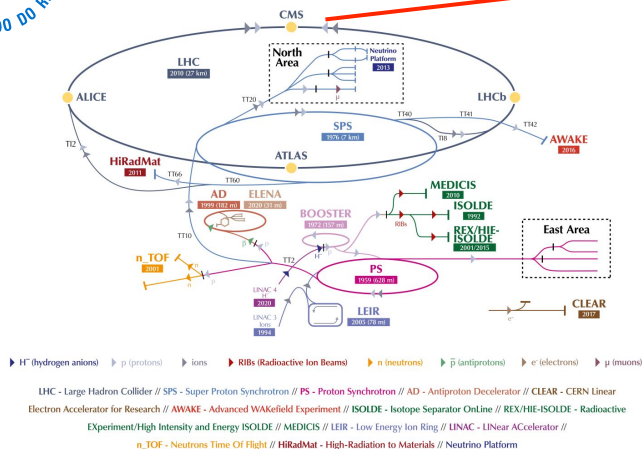
Outline

- **The Compact Muon Solenoid (CMS) for the HL-LHC**
 - iRPC for LHC Phase-II Upgrade
- **The Greenhouse emission in EU and at CERN**
 - Strategies for F-gases reduction in CMS-RPC
- **CO₂ based mixtures**
- **Experimental Setup**
 - Gamma Irradiation Facility (GIF++)
 - iRPC chamber prototype and electronics
- **Analysis strategy**
- **Results before and after irradiation campaign**
- **Conclusion and next steps**

The Compact Muon Solenoid for HL-LHC

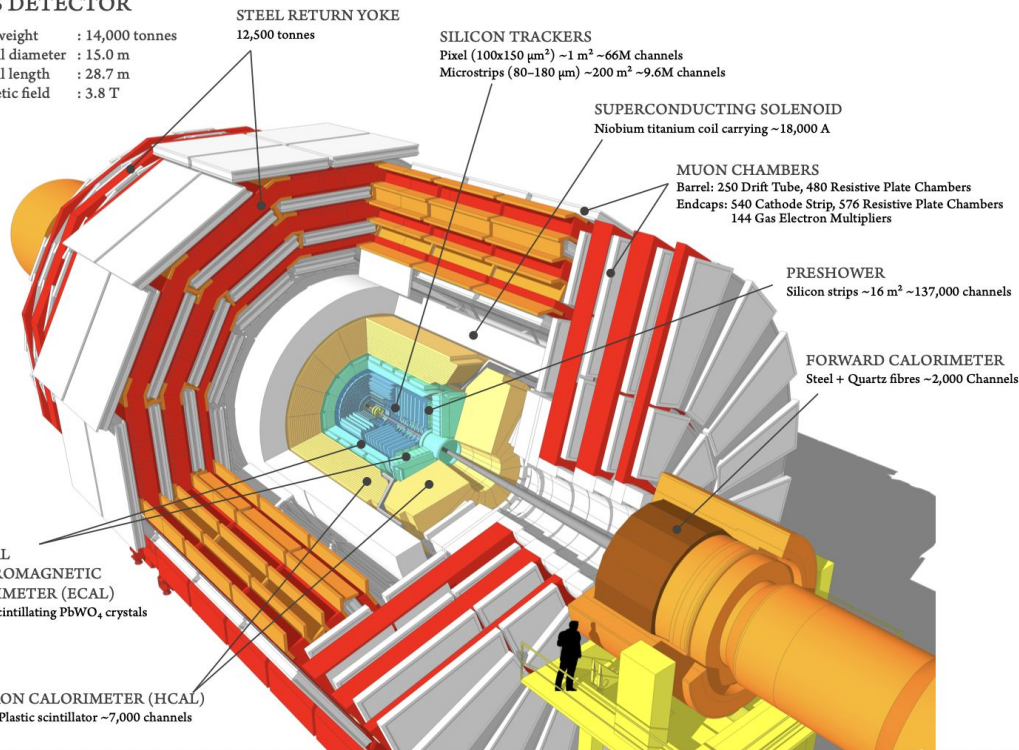
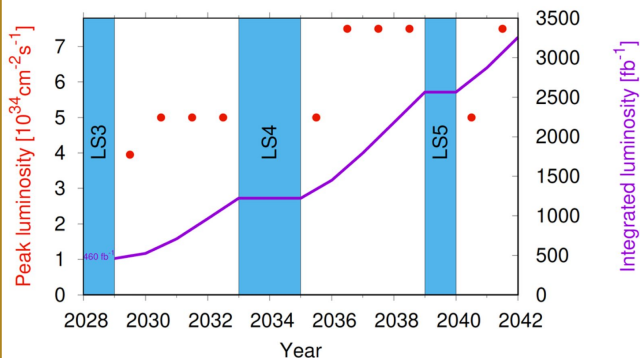


The CERN accelerator complex
Complexe des accélérateurs du CERN



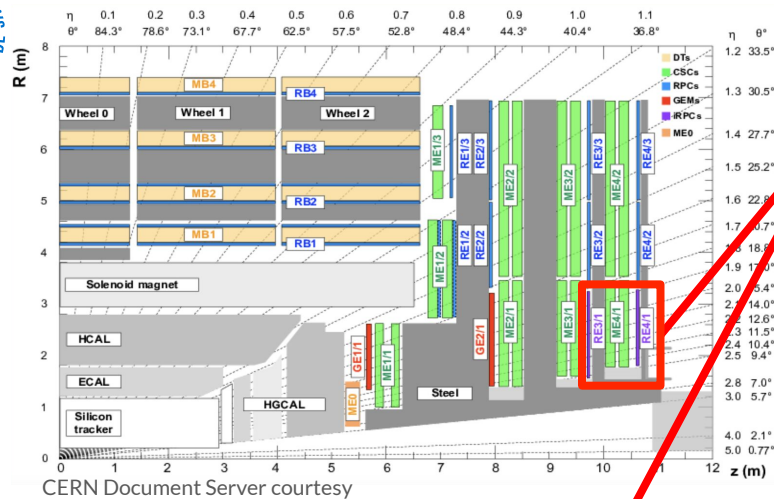
CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

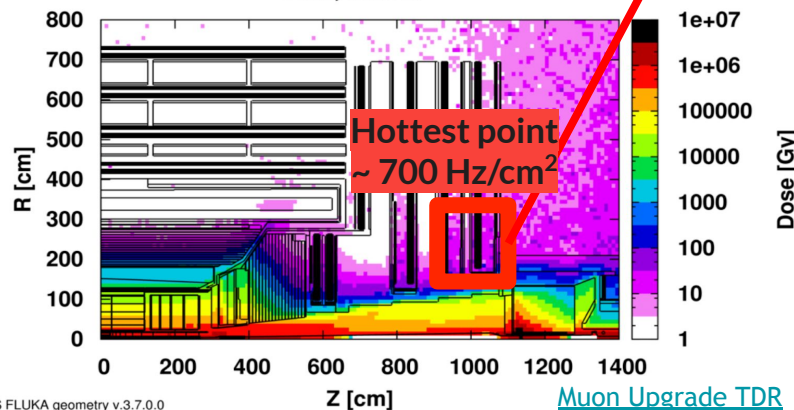


CMS is under Run 3 data taking phase and is preparing for the High-Luminosity (HL-LHC) period starting in 2030, anticipated to feature a higher Instantaneous Luminosity

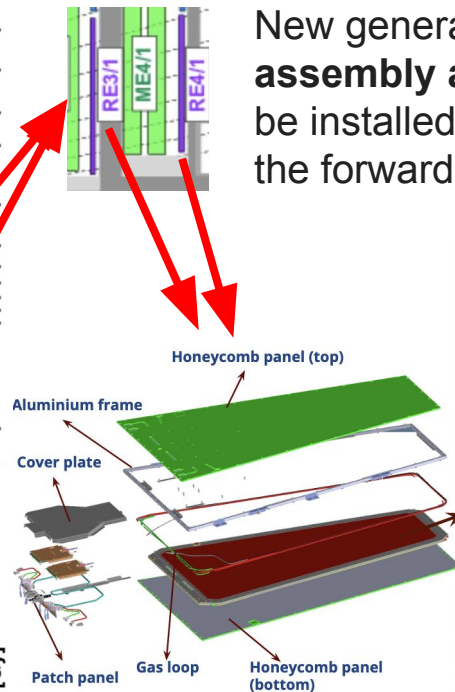
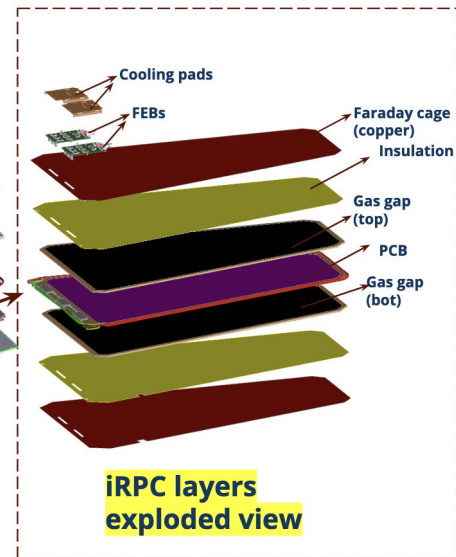
CMS iRPC for LHC Phase-II Upgrade



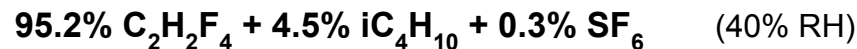
Dose, 3000 fb⁻¹



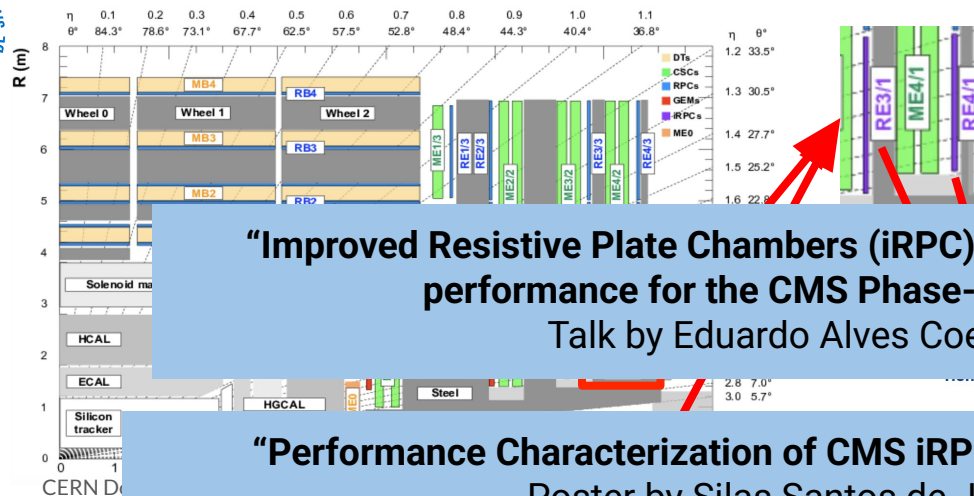
New generation of RPCs under assembly and quality control, to be installed for Run 4 data taking in the forward region of CMS endcap



Standard gas mixture of RPC and iRPC:



CMS iRPC for LHC Phase-II Upgrade



New generation of RPCs under assembly and quality control, to be installed for Run 4 data taking in the forward region of CMS endcap

“Improved Resistive Plate Chambers (iRPC) mass production and performance for the CMS Phase-II upgrade”

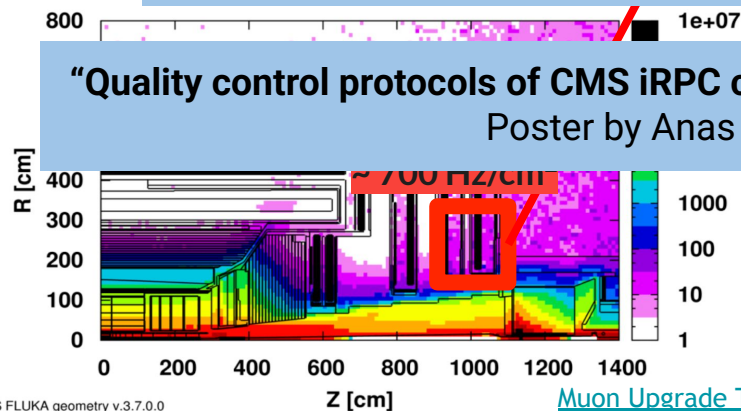
Talk by Eduardo Alves Coelho

“Performance Characterization of CMS iRPC detectors at GIF++”

Poster by Silas Santos de Jesus

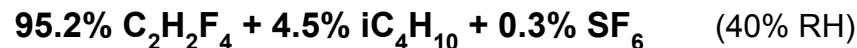
“Quality control protocols of CMS iRPC chambers for Phase-II CMS Muon System Upgrade”

Poster by Anas Idriss Laayouni El Oudghiri



iRPC layers exploded view

Standard gas mixture of RPC and iRPC:



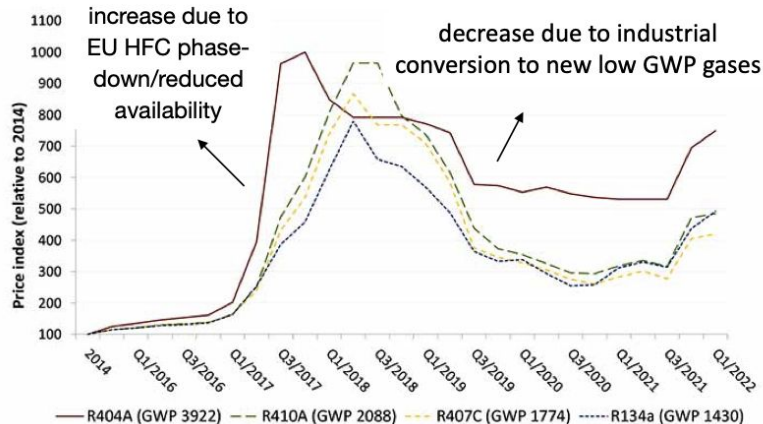
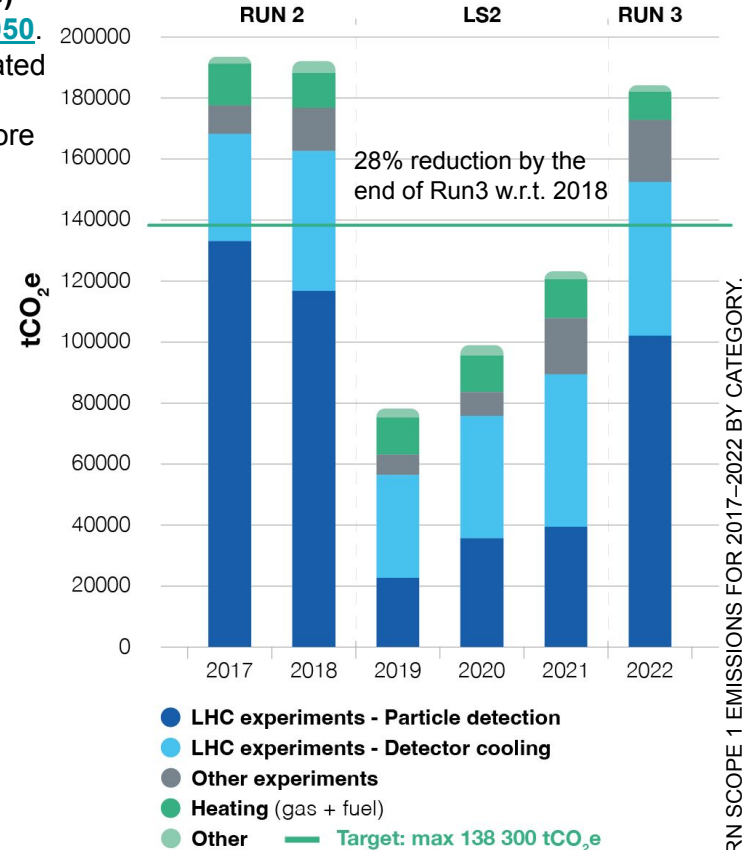
The Greenhouse emission in EU and at CERN

- European Union has set targets to **reduce greenhouse gas (GHG) emissions by 55% by 2030**, 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)**.
- Around 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 Fluorinated Gases (F-Gas) Policy (July 24th, 2024):

- Minimize F-gas use** through alternatives and substitution.
- Limit emissions** through leak detection and prevention.
- Monitor and manage** F-gas use.

Average purchase prices of the most commonly used HFC refrigerants



CERN SCOPE 1 EMISSIONS FOR 2017-2022 BY CATEGORY.

Strategies for F-gases reduction in CMS-RPC

Gas Recirculation

Since LHC started

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

"R134a recuperation and SF_6 recuperation plants: status and plan"
Talk by Roberto Guida

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

"CMS RPC system consolidation and upgrade for the LHC Phase-II programme"
Poster by Katherine Maslova

Alternative Gases

HFO-1234ze + CO_2

Performance slightly affected

Longevity studies ongoing

$C_2H_2F_4$ + CO_2

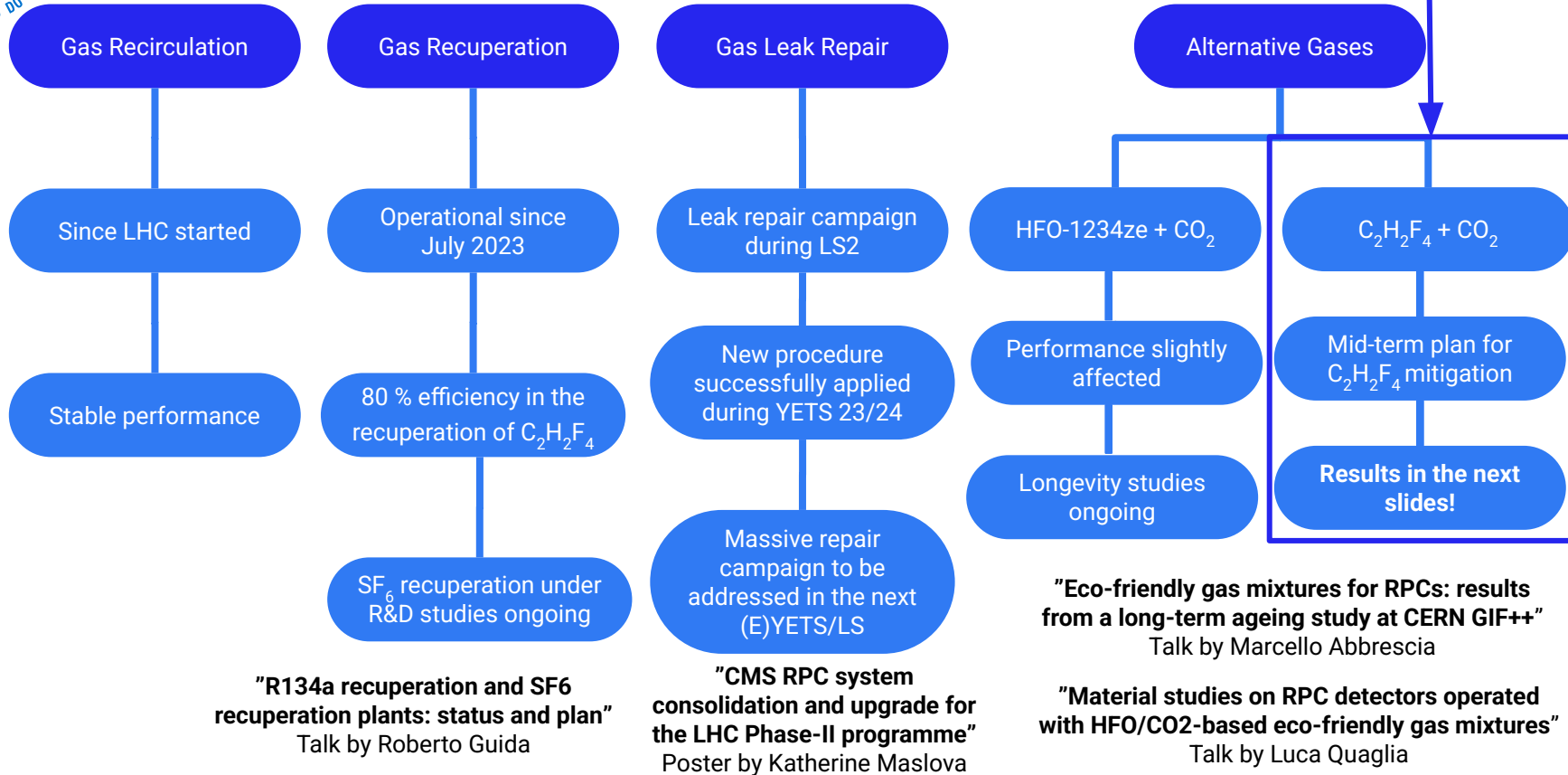
Mid-term plan for $C_2H_2F_4$ mitigation

Results in the next slides!

"Eco-friendly gas mixtures for RPCs: results from a long-term ageing study at CERN GIF++"
Talk by Marcello Abbrescia

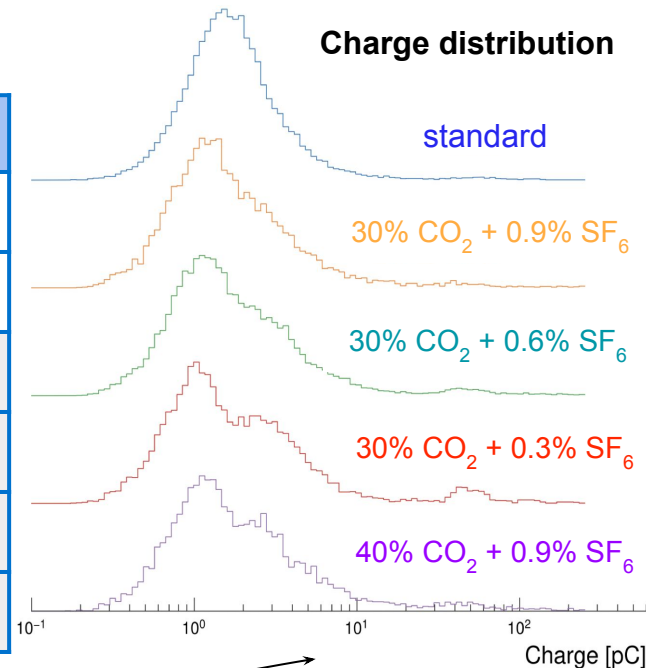
"Material studies on RPC detectors operated with HFO/ CO_2 -based eco-friendly gas mixtures"
Talk by Luca Quaglia

Strategies for F-gases reduction in CMS-RPC



CO₂-based mixtures

Gas components (%)	C ₂ H ₂ F ₄	CO ₂	iC ₄ H ₁₀	SF ₆	GWP* _{MIX}
GWP	1430	1	3	22800	
Density (g/L)	4.7	1.98	2.7	6.61	
STD	95.2	0	4.5	0.3	664
30% CO ₂ + 1.0 % SF ₆	64	30	5	1	565
30% CO ₂ + 0.5 % SF ₆	64.5	30	5	0.5	494
40% CO ₂ + 1.0 % SF ₆	54.5	40	5	1	500

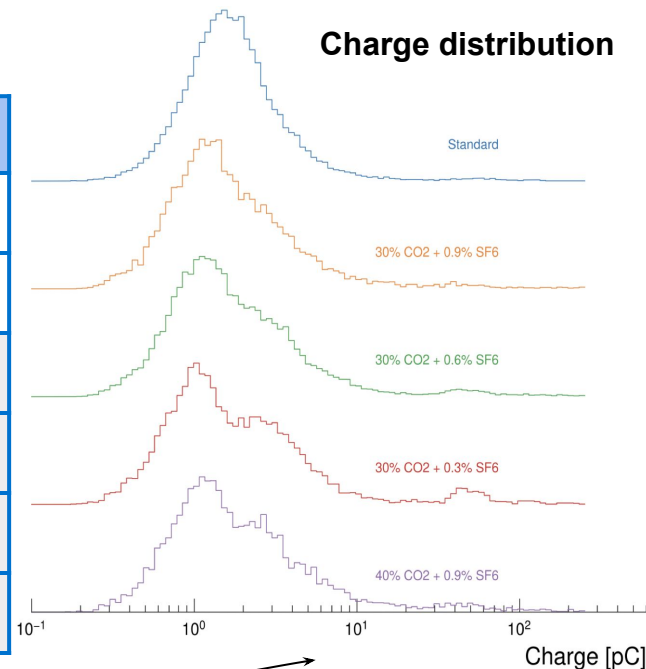


<https://doi.org/10.1016/j.nima.2023.168088>

- The mixtures used replaces C₂H₂F₄ by 30 - 40 % of CO₂, increasing SF₆ to 0.5 - 1.0 % in order to **decrease the streamer probability**, as shown in [previous EP-DT studies](#).
- The **price of the mixture is reduced** around 30 - 40 % and the **CO₂-e (exhaust volume related) is decreased** around 15 - 26 %
- Despite its small concentration, SF₆ becomes the dominant contributor to the mixture GWP due to its very high GWP.

CO₂-based mixtures

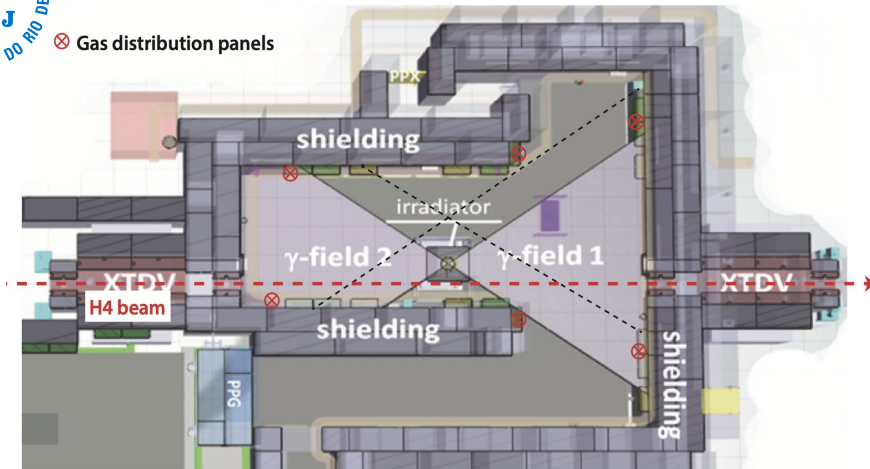
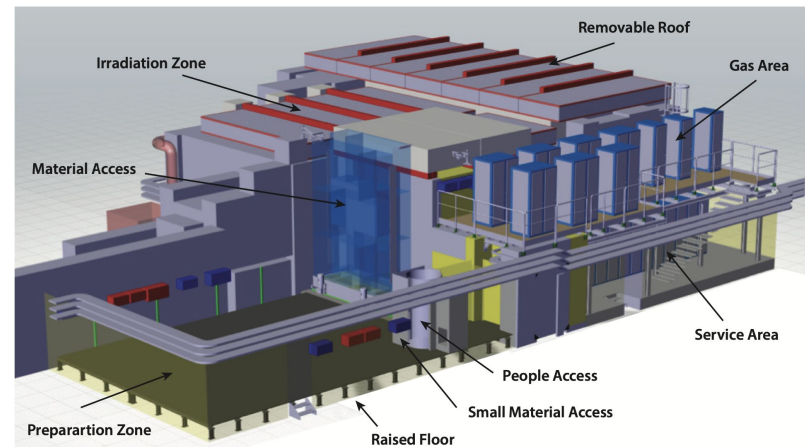
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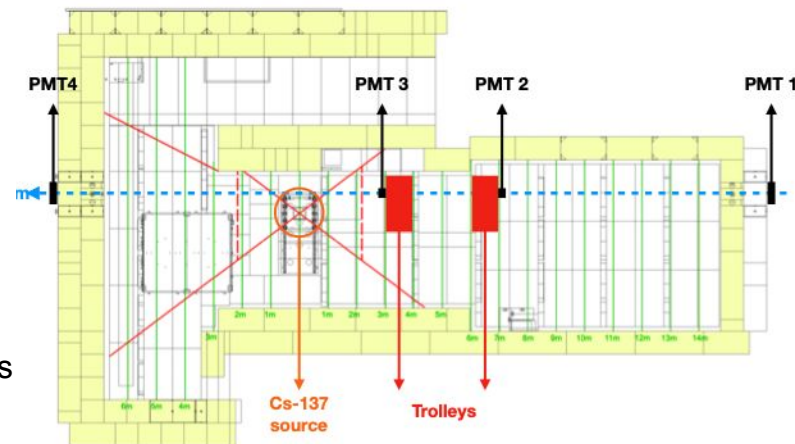
- **“Performance studies of HPL RPC detectors operated with alternatives to R-134a and SF₆”**
Talk by Luca Quaglia
- The **price of the mixture is reduced** around 30 - 40 % and the **CO₂-e (exhaust volume related)**
- **“Towards SF₆-free RPC operation: first results from the RPC ECOGas@GIF++ Collaboration”**
Talk by Luca Quaglia

Experimental Setup: Gamma Irradiation Facility (GIF++)



<https://doi.org/10.1016/j.nima.2017.05.045>

- 100 m² bunker with 11.5 TBq ¹³⁷Cs (Jan 24)
- 2 symmetric radiation field with an attenuator system with different absorption factors
- H4 beam line from SPS
- Muon beam 100 GeV/c, 10⁴ 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

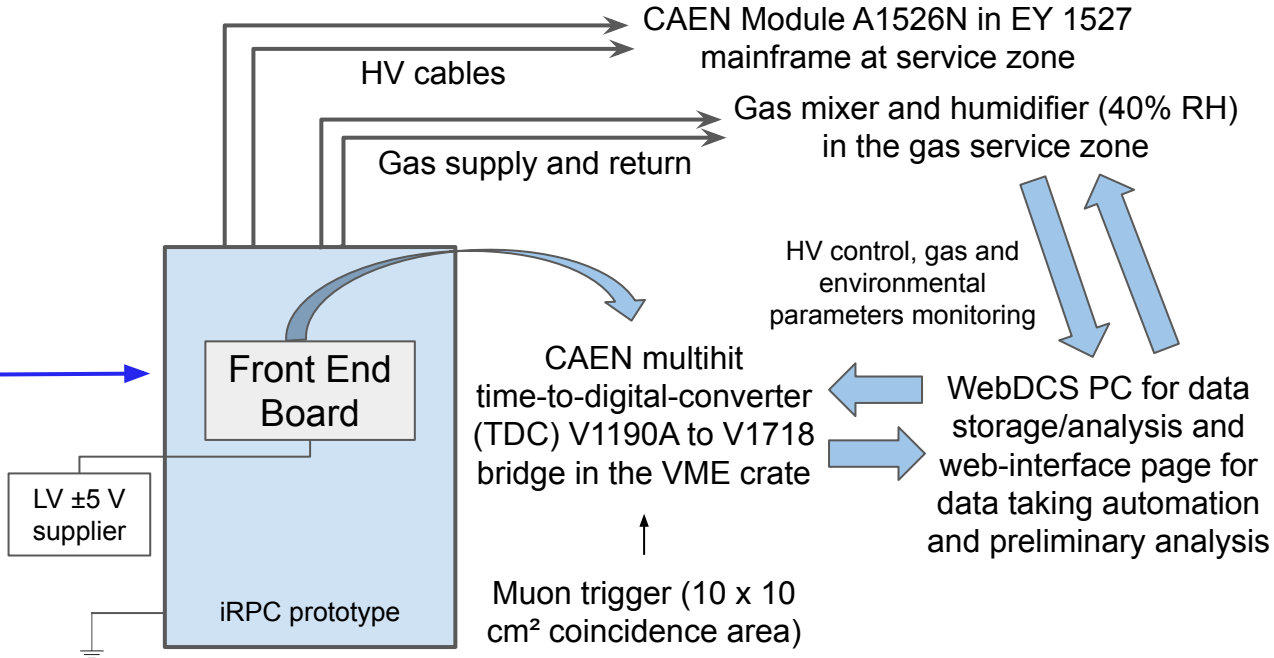


Experimental Setup: iRPC prototype and electronics



~3m from the source

Y-field upstream



iRPC Prototype

- Customized chamber with gaps from KODEL laboratory
- Made with copper tape strips plane (~1.8 cm pitch),
- **double 1.4 mm 50 x 50 cm² gap**
- 1.4 mm electrode HPL thickness
- $\rho \sim 1.2 (1.3) \times 10^{10} \Omega \cdot \text{cm}$ for bottom (top) gap
- **single strip plane readout with 16 or 32 strips**

Front-end Board (FEB):

- Customized electronics also from KODEL
- Current sensitive mode for input signals
- Input impedance = 20 Ω
- Amplification gain = 200
- LVDS width = 60 ns
- **Threshold 0.5 mV ~ 60 fC**

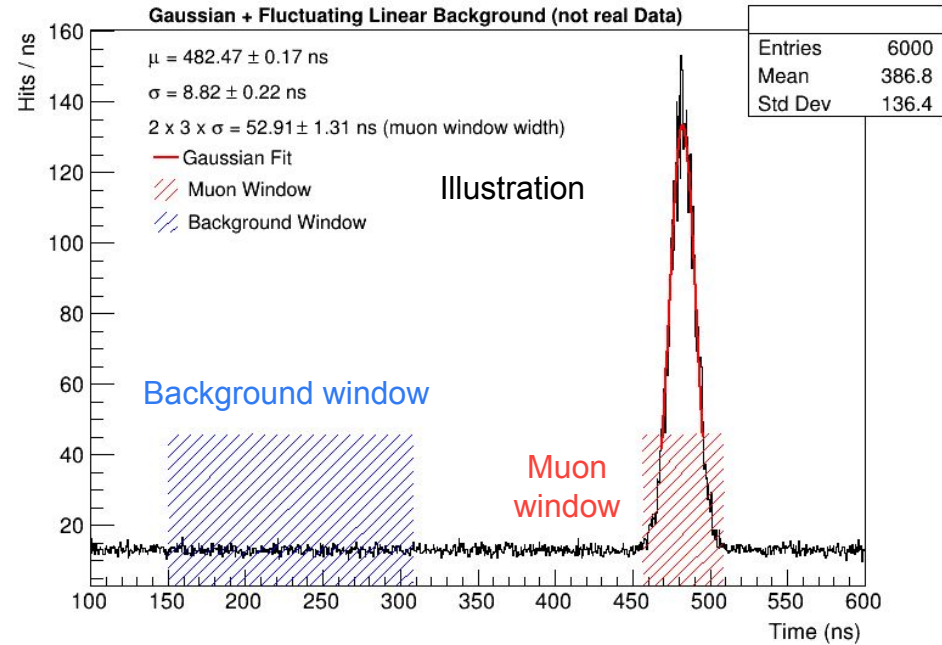
Analysis strategy

- 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](#)

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

$$\alpha = 0.8 \quad P_0 = 990 \text{ mbar} \quad T_0 = 293.15 \text{ K}$$

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

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

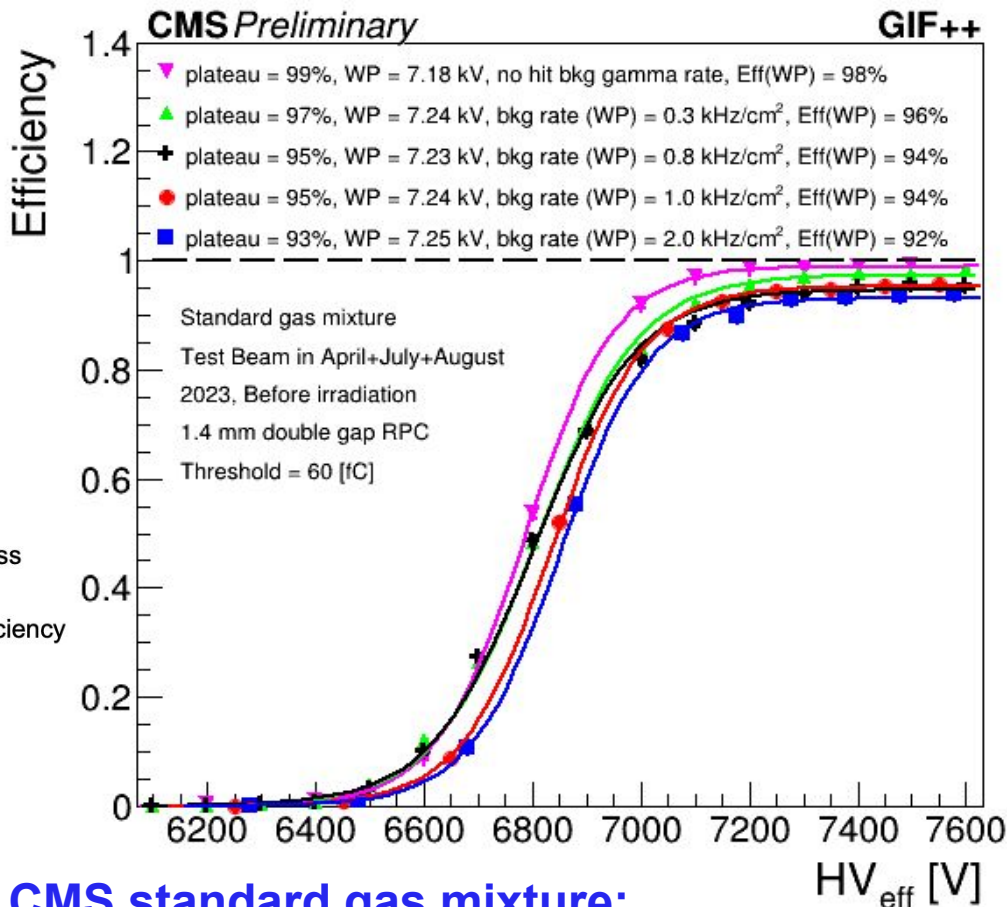
λ : Slope or steepness
 $HV_{50\%} : HV_{\epsilon=50\%}$
 ϵ_{max} : maximum efficiency

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

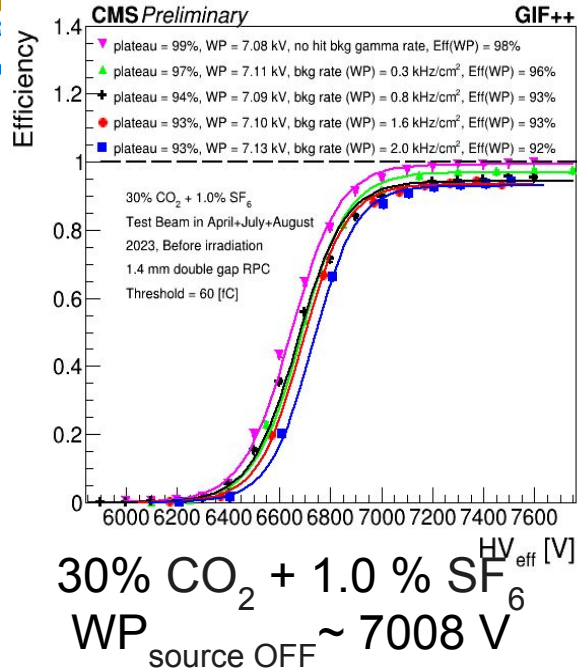
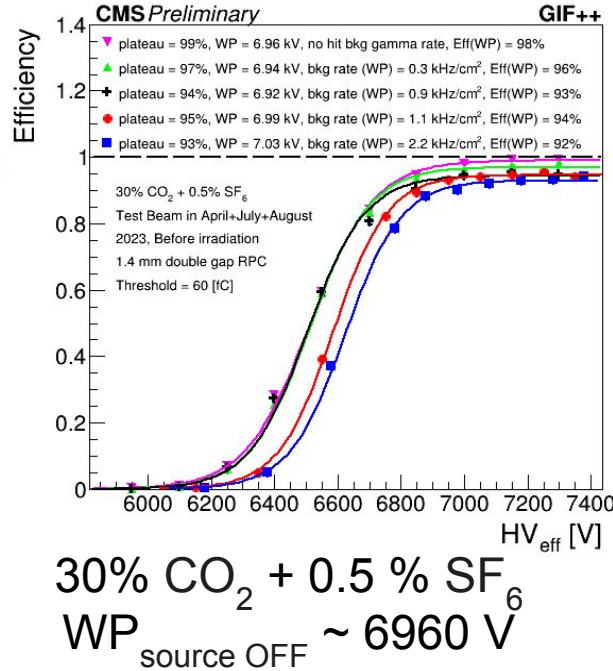
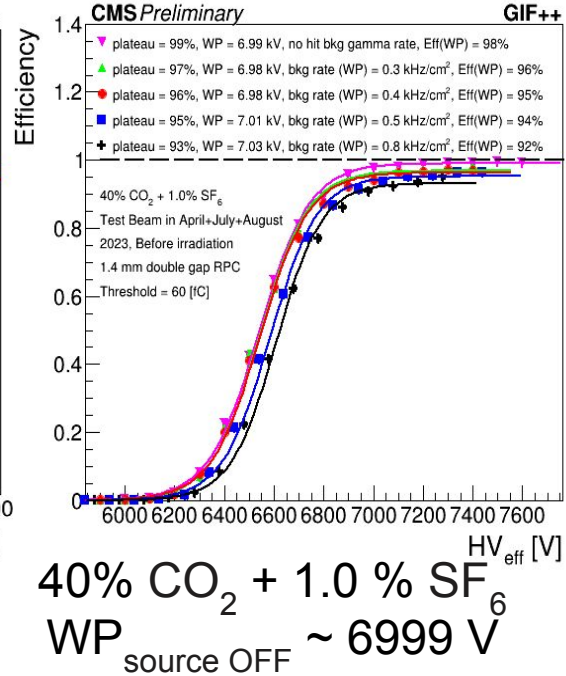
$$WP = \frac{\ln 19}{\lambda} + HV_{50\%} + 150V$$

Validation with CMS standard gas mixture:

WP consistent around 7.2 kV and efficiency > 90 % up to 2 kHz/cm² (HL-LHC x 3)



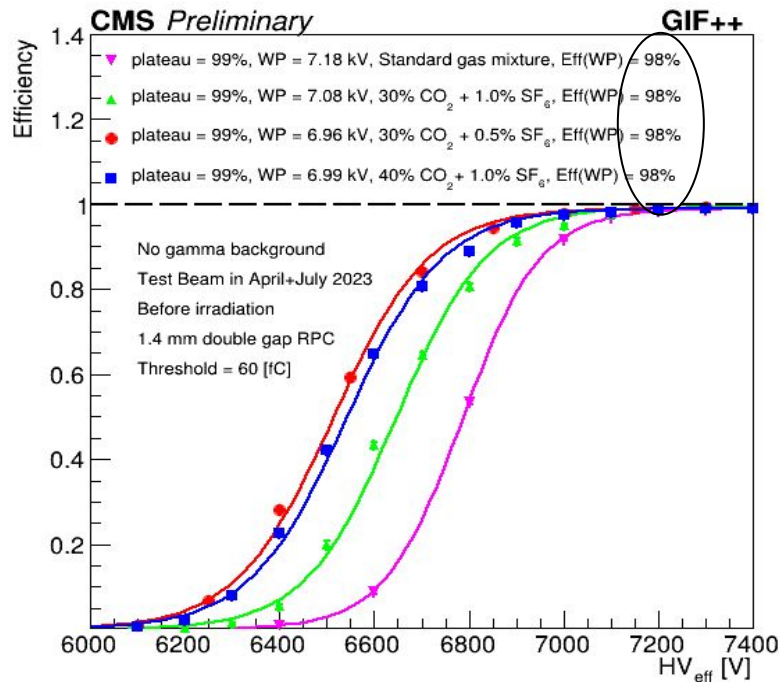
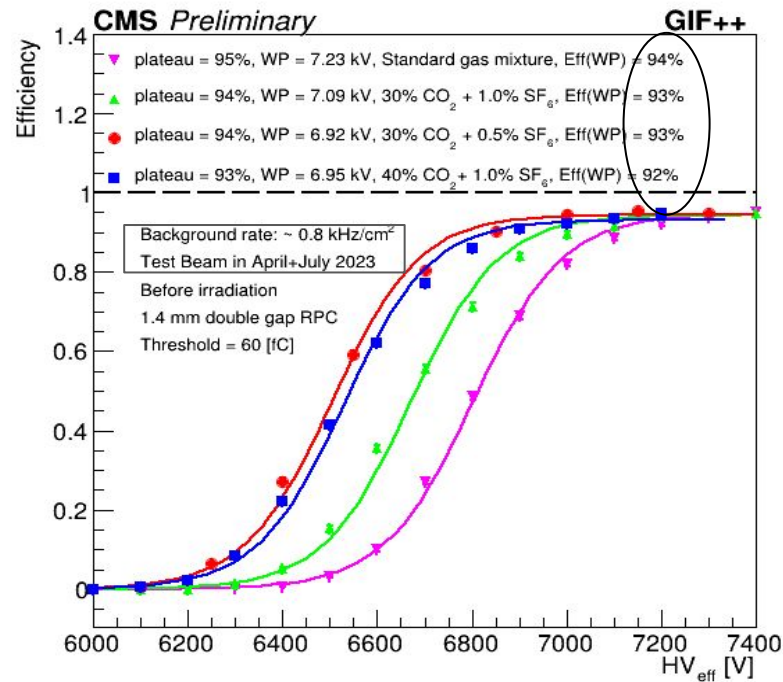
Results before the irradiation campaign



All gas mixtures are within the expectations with minor drop in efficiency due to the replacement of C₂H₂F₄ by CO₂

Overall efficiency drops (~ 4%) due to electronics dead time (~80 ns)

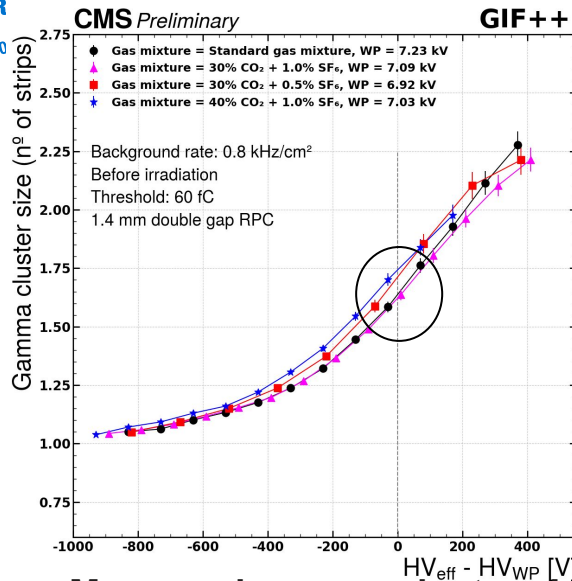
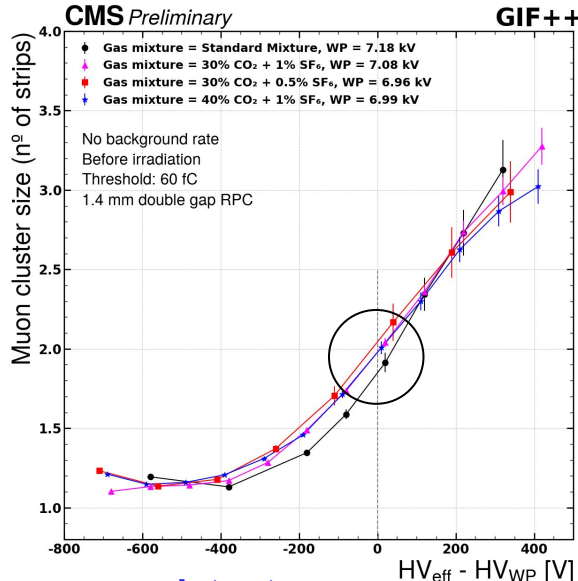
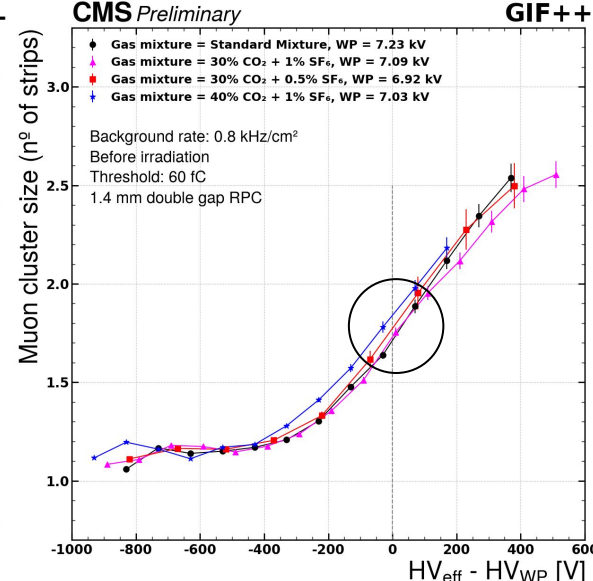
Results before the irradiation campaign



- Minor muon efficiency drop with the increase of CO_2
- Different WP in different mixtures:
 - CO_2 addition lower mixture density: lower WP
 - SF_6 has high electronegativity: higher WP

All the alternative mixtures show lower WP w.r.t the standard one!

Results before the irradiation campaign



Muon and gamma cluster size are consistent between the gas mixtures

→ SF₆ might be playing the role!

However, chamber resolution (1.8 cm chamber width) is not the same as CMS-iRPC chambers

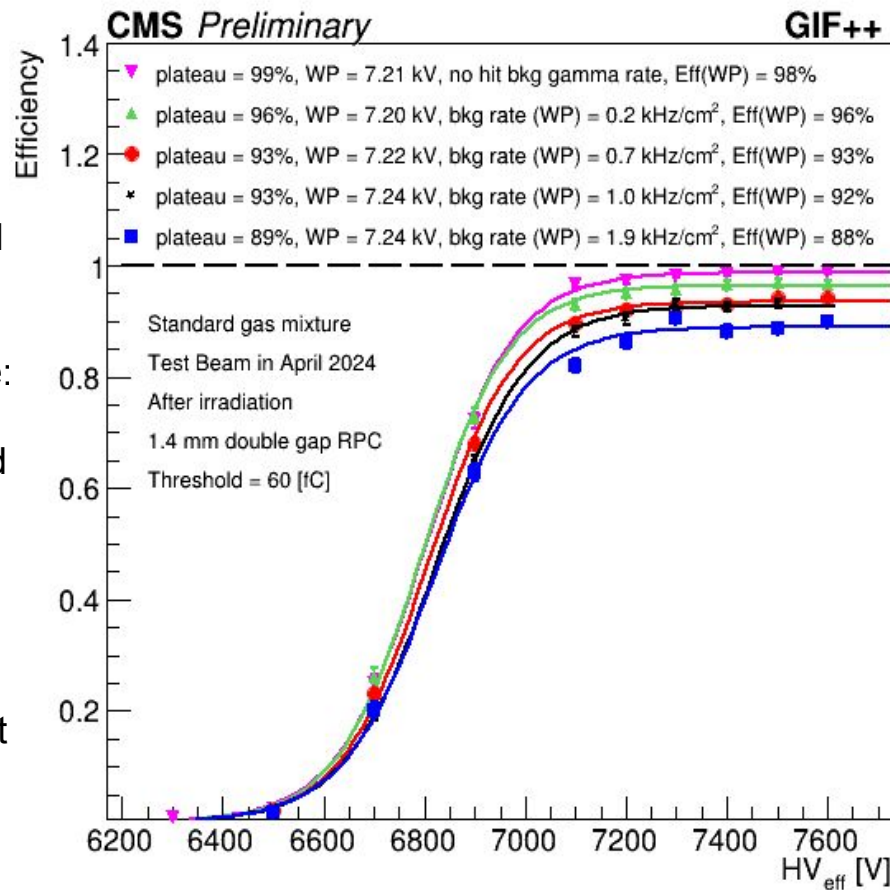
→ further tests are needed!

Background gamma rate (Hz/cm ²)	Average Muon Cluster Size	Average Gamma Cluster Size
0	2.0 strips	—
800	1.7 strips	1.7 strips

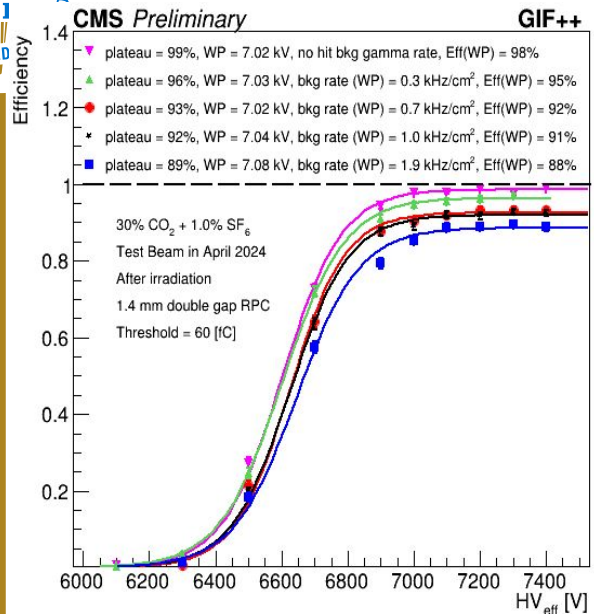
Results after the irradiation campaign



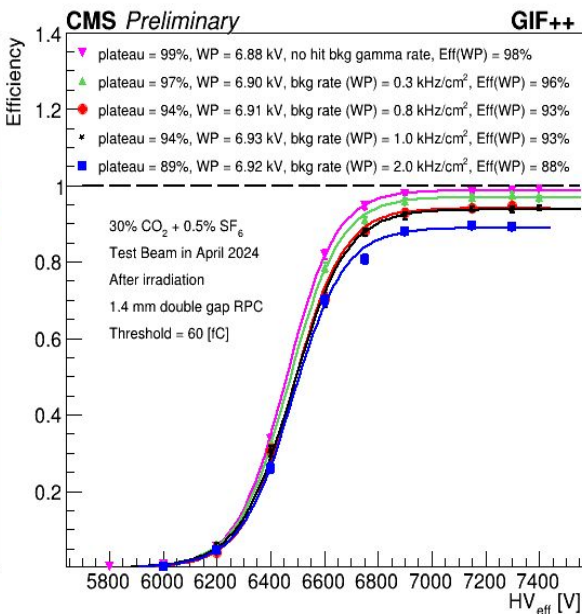
- During no beam period, a dedicated irradiation campaign took place at GIF++
- It was collected around **83 mC/cm²**, corresponding to **~ 30 %** of what is expected during HL-LHC
- Revalidation with CMS standard gas mixture:
 - **Consistent and stable efficiency** and Working Point (**~ 30 V** higher) for moderate background rate
 - Drop in efficiency for high background rate, **mostly driven due to the FEB aspects**, which is not designed for that high radiation environment



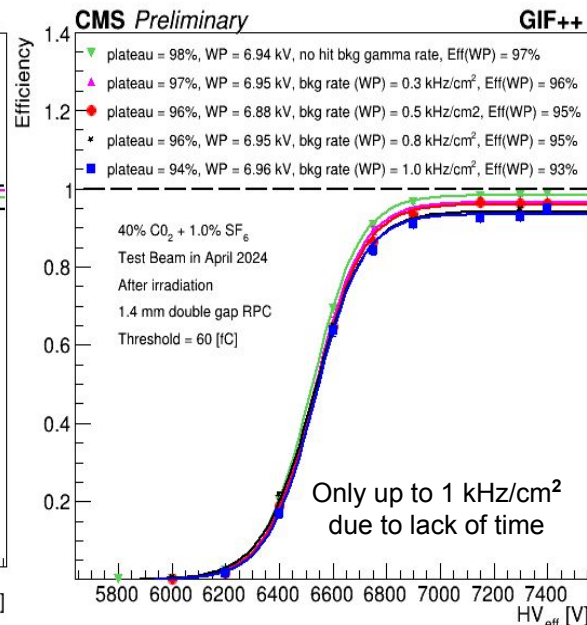
Results after the irradiation campaign



30% CO₂ + 1.0 % SF₆
WP_{source} OFF ~ 7020 V



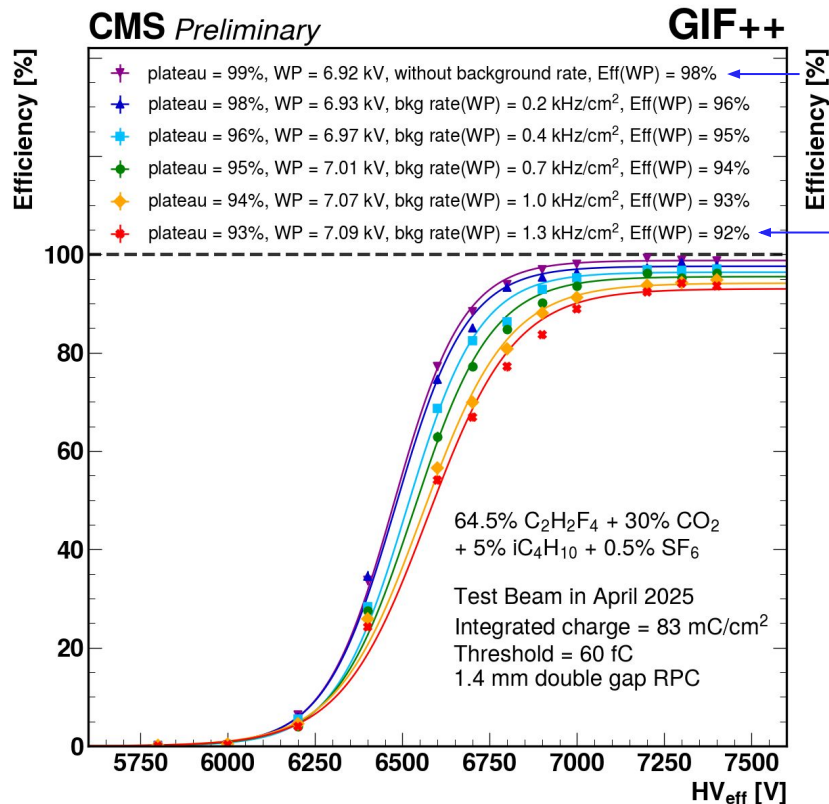
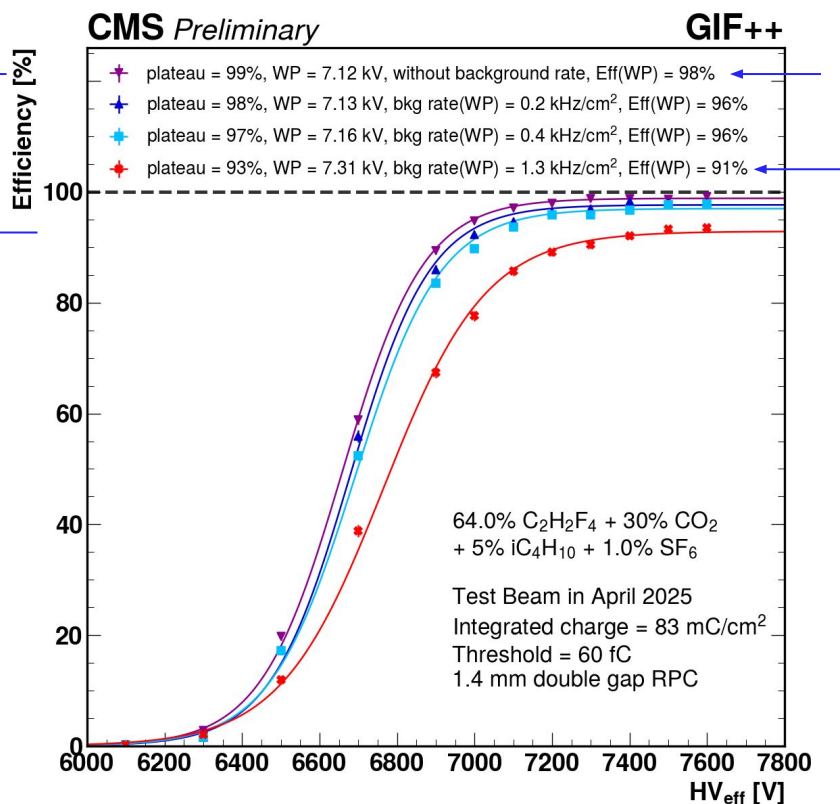
30% CO₂ + 0.5 % SF₆
WP_{source} OFF ~ 6880 V



40% CO₂ + 1.0 % SF₆
WP_{source} OFF ~ 6940 V

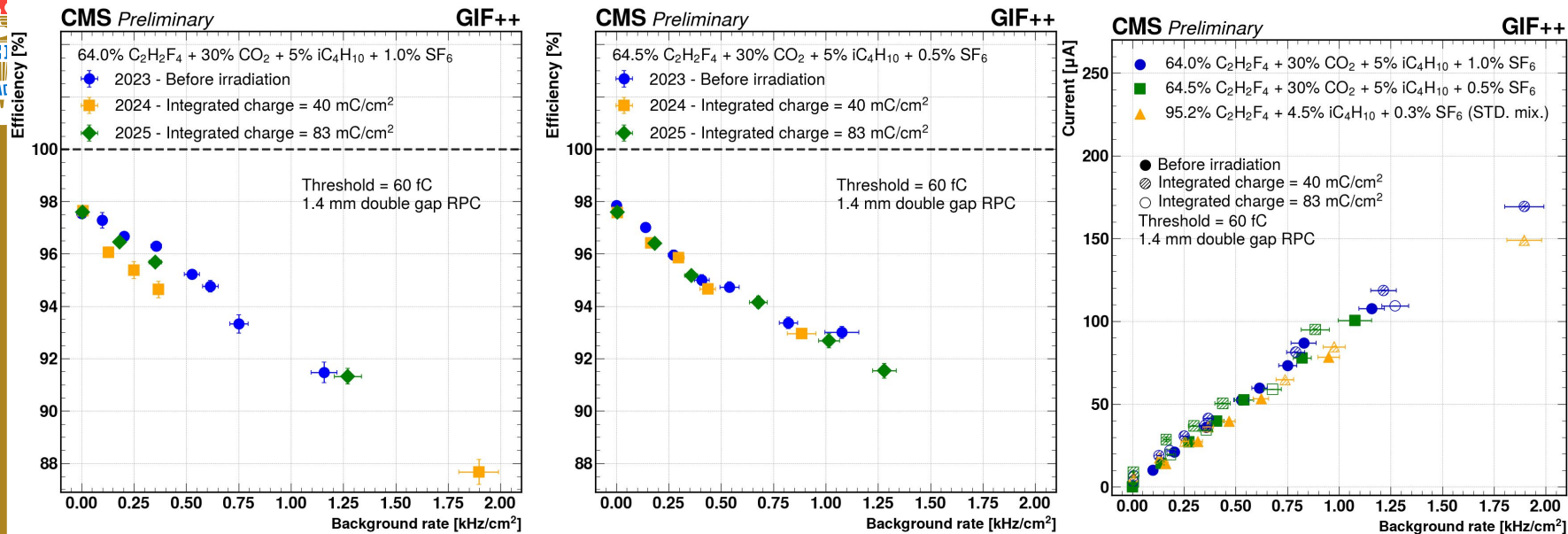
Consistent efficiency (same drop in background rate observed) and working point for different mixtures under background gamma rate up to 2 kHz/cm²

Results after the irradiation campaign



After 83 mC/cm², both 30% CO₂ mixtures still reach **~98% efficiency** without background and remain above 90% at ~1.3 kHz/cm²

Comparisons before and after irradiation



- Drop in efficiency with background **similar** before/after irradiation for moderate rates
- Current is shown to be **~20% higher** for CO₂ based mixtures, with similar results after and before irradiation

Conclusion and next steps

Gas replacement remains challenging; recirculation, recuperation, and leak repair are therefore essential for sustainable CMS-RPC operation.

- CO_2 based gas mixtures have good performance:
similar efficiency and lower working point w.r.t the standard one
- **Integrated charge around 30% of what is expected at HL-LHC**
 - No efficiency degradation related to the gas mixture was observed
 - No change in the working point was observed
 - **20 % higher currents, but no change with radiation**
- Studies will continue at GIF++ with the aim to integrate more charge during irradiation campaign
- The long-term operation of alternative gas mixtures remains uncertain, requiring substantial R&D with the RPC community

Conclusion and next steps

Gas replacement remains challenging; recirculation, recuperation, and leak repair are therefore essential for sustainable CMS-RPC operation.

"Strategies to reduce greenhouse gas emissions from particle detector operation at CERN"

Talk by Gianluca Rigoletti

"Monte Carlo Study of CO₂-Based, TFE- and SF₆-free gas mixtures for Resistive Plate Chambers"

Poster by Guilherme Lickel

○ **No efficiency degradation** related to the gas mixture was observed

"Neural Network-based prediction of CMS RPC efficiency with alternative gas mixtures"

Poster by Giulia Giannandrea

"Study of CMS RPC signal shape parameters by using HF01233ZD gas mixture"

Poster by Dalmo da Silva Dalto

during irradiation campaign

- The long-term operation of alternative gas mixtures remains uncertain, requiring substantial R&D with the RPC community



Thanks for your attention
Questions?





Backup

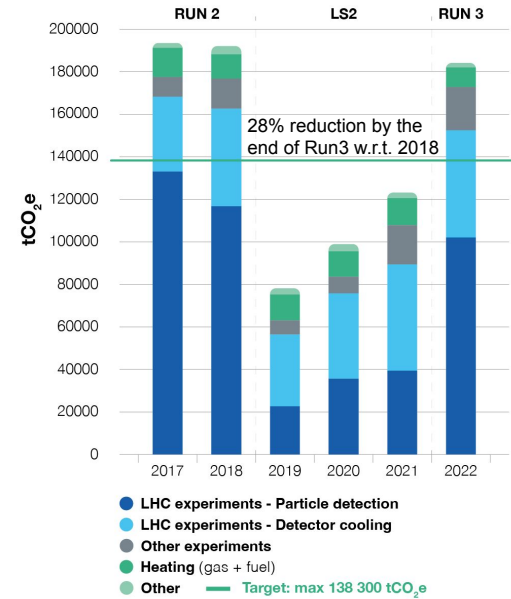


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- Around 90% of direct emissions come from experiments, where more than 78% of GHG emission is a direct result of the use of F-gases. [CERN Environment Report 2021-2022](#).

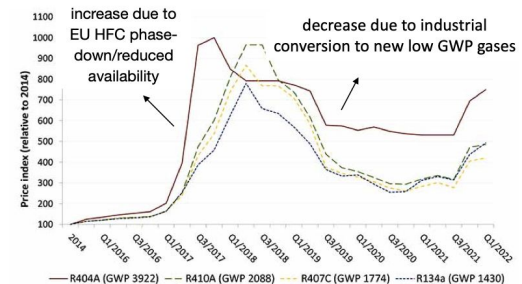
CERN Fluorinated Gases (F-Gas) [Policy](#) (July 24th, 2024):

- minimize the use of F-Gases at CERN, particularly by:
 - the promotion of research and development into F-Gas alternatives,
 - the replacement, to the extent possible, of F-Gases already used in its installations and activities with gases with no - or less - impact on the environment, and
 - the minimization, to the extent possible, the use of F-Gases in new installations and activities.
- limit its emissions of F-Gases, particularly by:
 - the prohibition of intentional releases,
 - the detection and reduction of leaks,
 - appropriate training of personnel concerned.
- monitor and manage the use and emissions of F-Gases within the Organization,
- establish and update appropriate internal procedures and regulations and monitor compliance with them,
- communicate proactively,
- collaborate with the Host States.



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.

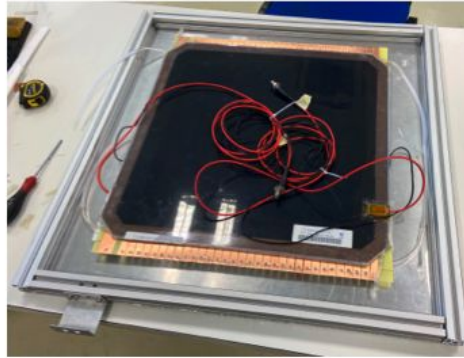
Average purchase prices of the most commonly used HFC refrigerants



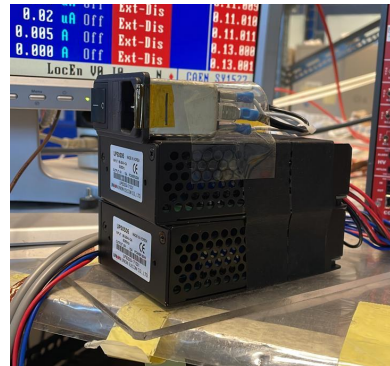
Experimental Setup: iRPC prototype and electronics



Chamber strip plane with copper tape example



iRPC prototype opened and KODEL electronics



Adapted LV ± 5 V supplier



TDC and VME bridge