Instituto de Física
ARMANDO DIAS TAVARES

DFNAE

UNIVERSIDADE DO ESTADO DO RIO DE JANEIRO
UERJ

Santiago de Compostela (Spain)
RPC 2024
XVII Workshop on Resistive Plate Chambers and Related Detectors

CMS

Performance and longevity of CO2 based mixtures in CMS Improved Resistive Plate Chambers in the HL-LHC environment

João Pedro Gomes Pinheiro [1], Thiago Rangel [2], Lucía Eiriz Sánchez [3]

[1] Rio de Janeiro State University - Brazil
[2] CERN - Summer Student 2024
[3] Dundee University - Scotland

CNPq

on behalf of CMS Collaboration

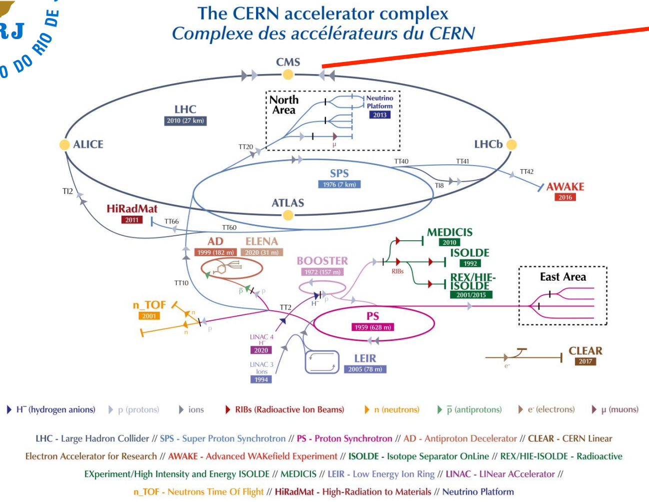
September 11th 2024

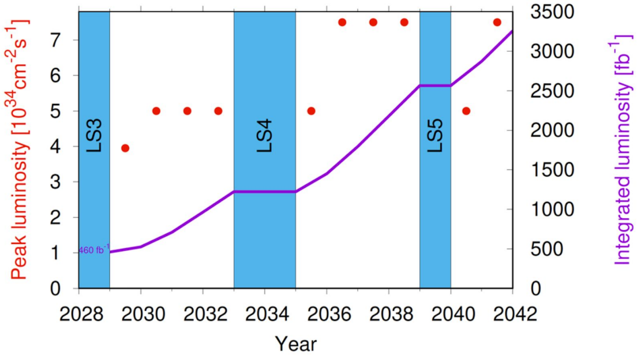
CAPES

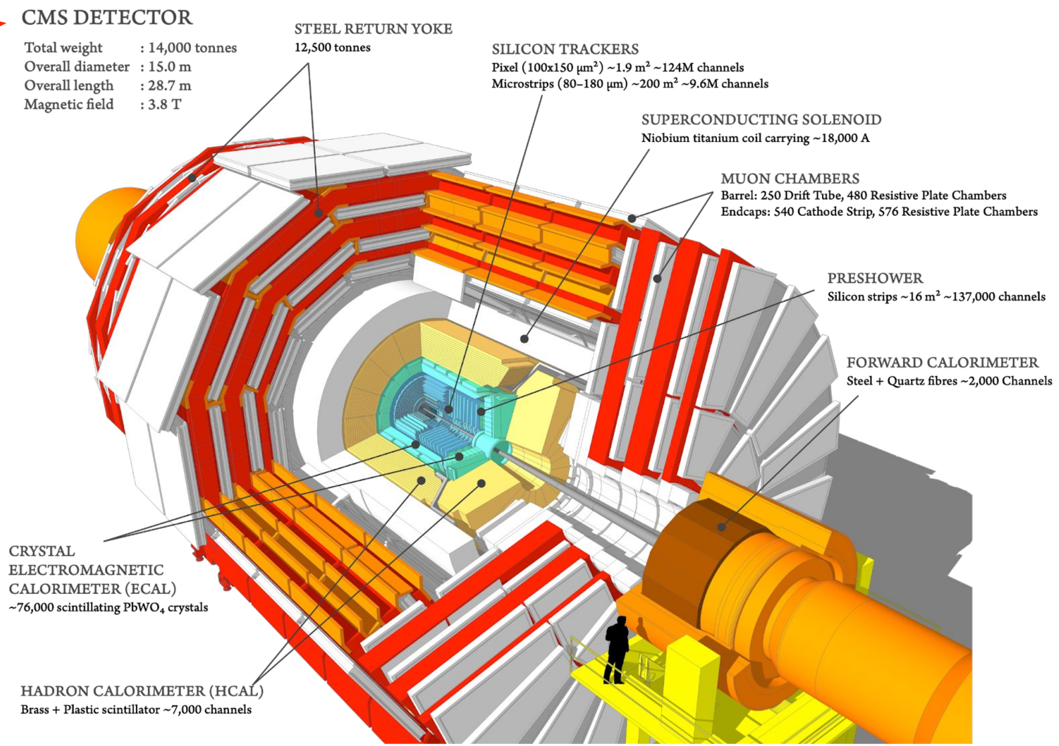
Outline

- **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



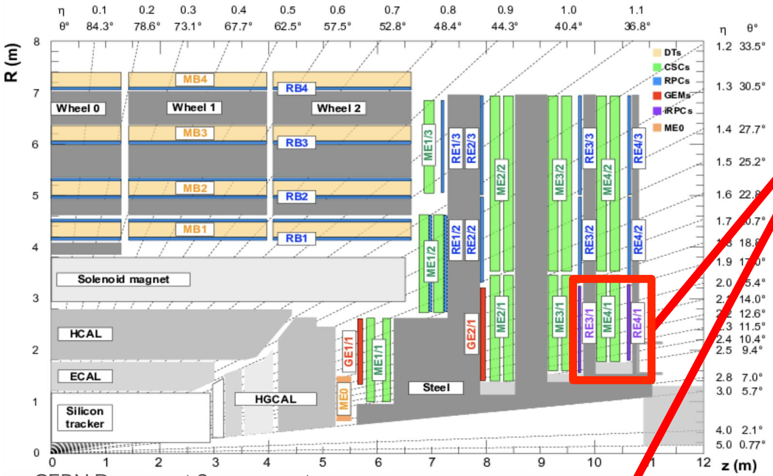




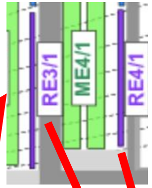
Images: CERN Document Server courtesy

CMS is under Run III data taking phase and is preparing for the High-Luminosity (HL-LHC) period starting in 2029, anticipated to feature a higher Instantaneous Luminosity

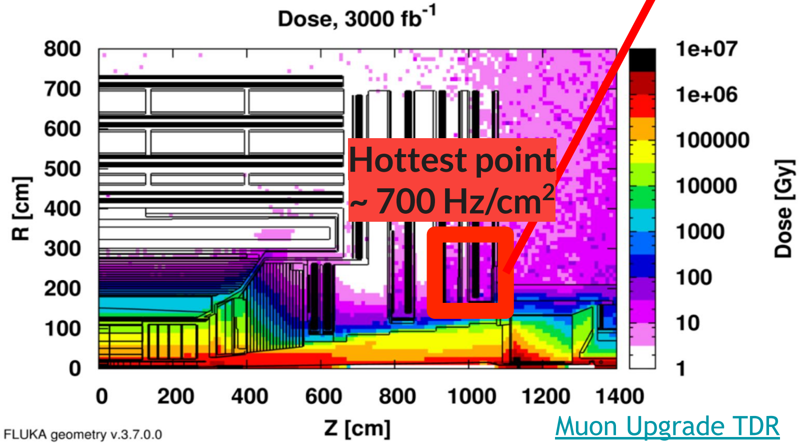
CMS iRPC for LHC Phase-II Upgrade



CERN Document Server courtesy

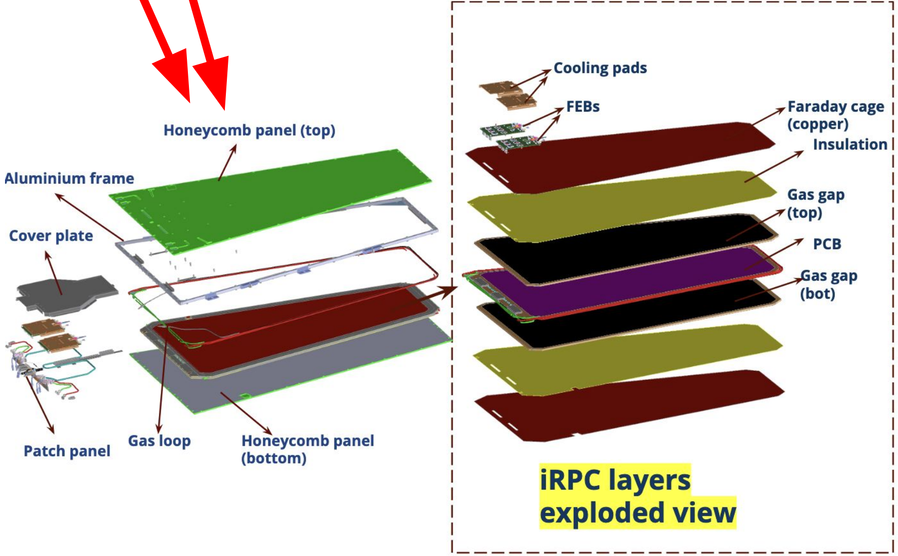


New generation of RPCs **under assembly and quality control**, to be installed for **Run 4 data taking** in the forward region of CMS endcap



CMS FLUKA geometry v.3.7.0.0

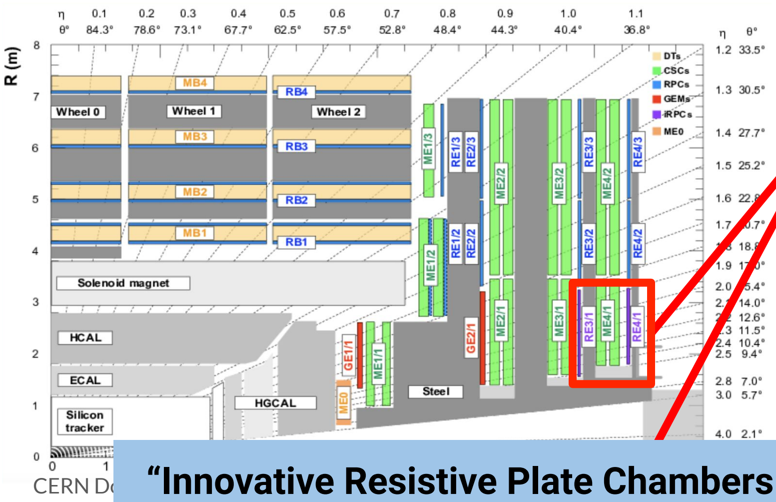
Muon Upgrade TDR

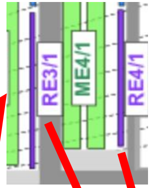


Standard gas mixture of (i)RPC:

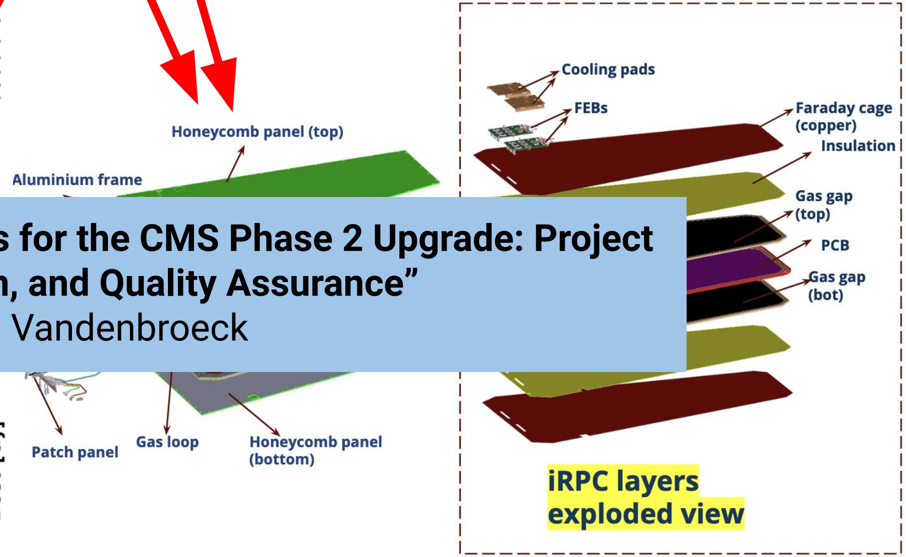
95.2% $C_2H_2F_4$ + 4.5% iC_4H_{10} + 0.3% SF_6

CMS iRPC for LHC Phase-II Upgrade

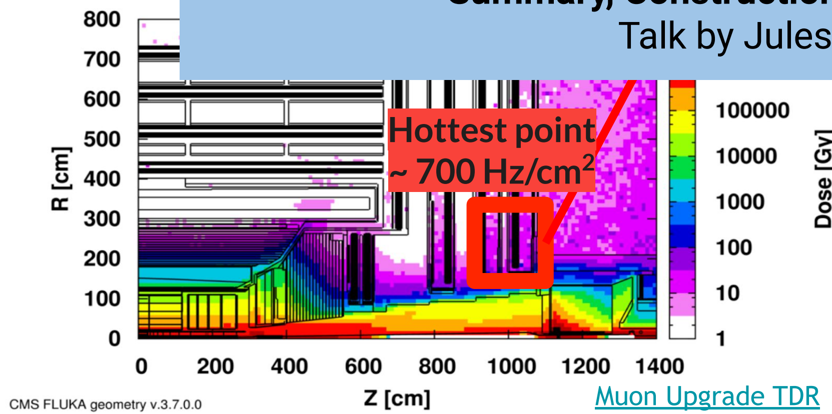




New generation of RPCs **under assembly and quality control**, to be installed for **Run 4 data taking** in the forward region of CMS endcap



“Innovative Resistive Plate Chambers for the CMS Phase 2 Upgrade: Project Summary, Construction, and Quality Assurance”
Talk by Jules Vandenbroeck



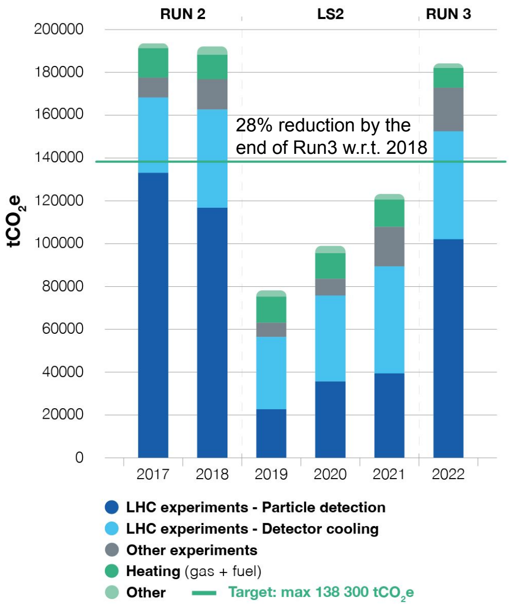
Muon Upgrade TDR

Standard gas mixture of (i)RPC:

95.2% $C_2H_2F_4$ + 4.5% iC_4H_{10} + 0.3% SF_6

The Greenhouse emission in EU and 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 European Green Deal.
- 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 Environment Report 2021-2022.

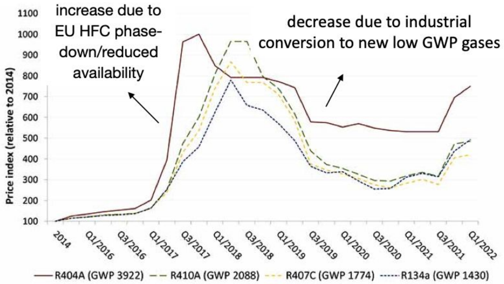


CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY. "Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

CERN 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.

Average purchase prices of the most commonly used HFC refrigerants



Strategies for F-gases reduction in CMS-RPC

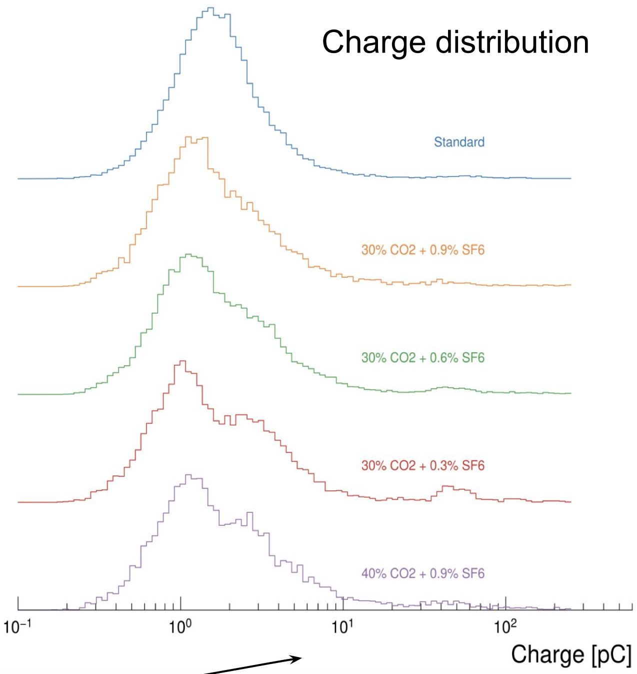
- **Gas Recirculation**
  - Since LHC started
  - Stable performance
- **Gas Recuperation**
  - Operational since July 2023
  - 80 % efficiency in the recuperation of $C_2H_2F_4$
  - SF_6 recuperation under R&D studies ongoing
- **Gas Leak Repair**
  - Leak repair campaign during LS2
  - New procedure 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
    - **Results in the next slides!**

"R134a recuperation and SF6 recuperation plants: status and plan"
Talk by Roberto Guida

"New RPC Gas Mixtures for Sustainable Operation in the CMS Experiment"
Talk by Dayron Ramos

CO_2 -based mixtures

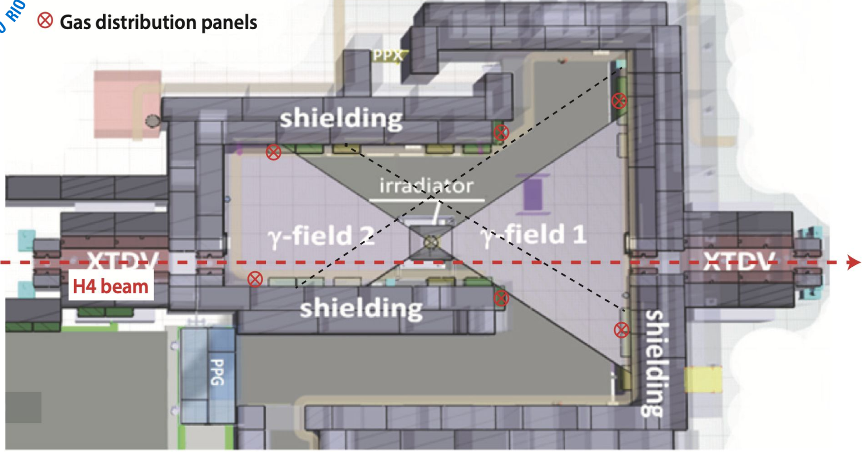
Gas components (%)	$C_2H_2F_4$	CO_2	$i\text{-}C_4H_{10}$	SF_6	GWP^*_{MIX}
GWP	1430	1	3	22800	
Density (g/L)	4.7	1.98	2.7	6.61	
STD	95.2	0	4.5	0.3	1486
30% CO_2 + 1.0 % SF_6	64	30	5	1	1529
30% CO_2 + 0.5 % SF_6	64.5	30	5	0.5	1337
40% CO_2 + 1.0 % SF_6	54.5	40	5	1	1353

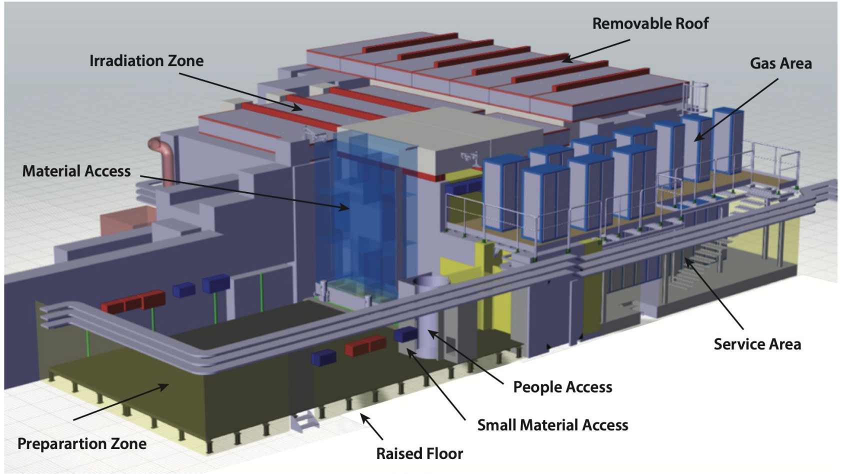


https://doi.org/10.1016/j.nima.2023.168088

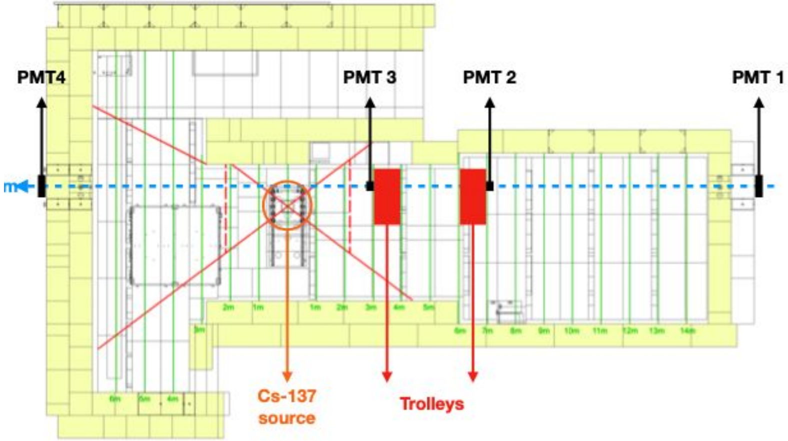
- The mixtures used replaces $C_2H_2F_4$ by 30 - 40 % of CO_2, increasing SF_6 to 0.5 - 1.0 % in order to **decrease the streamer probability**, as shown in previous EP-DT studies.
- The **price of the mixture is reduced** around 30 - 40 % and the **CO2-e (exhaust volume related) is decreased** around 15 - 26 %
- $C_2H_2F_4$ partially replacement by CO_2 also lead to less HF- ions produced due to ionization, meaning **a possible mitigation in the chemical aging of the bakelite gaps**

Experimental Setup: Gamma Irradiation Facility (GIF++)

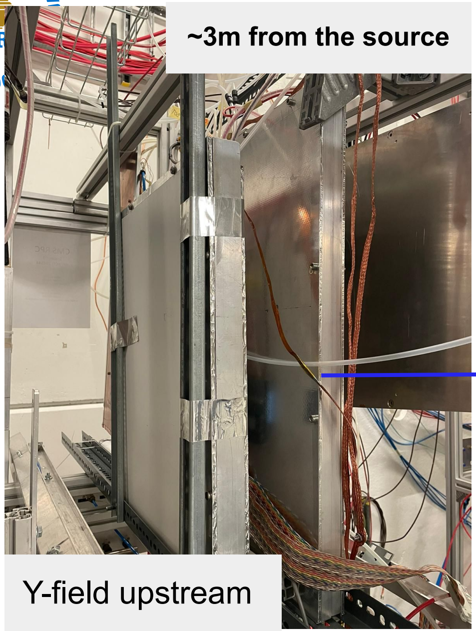


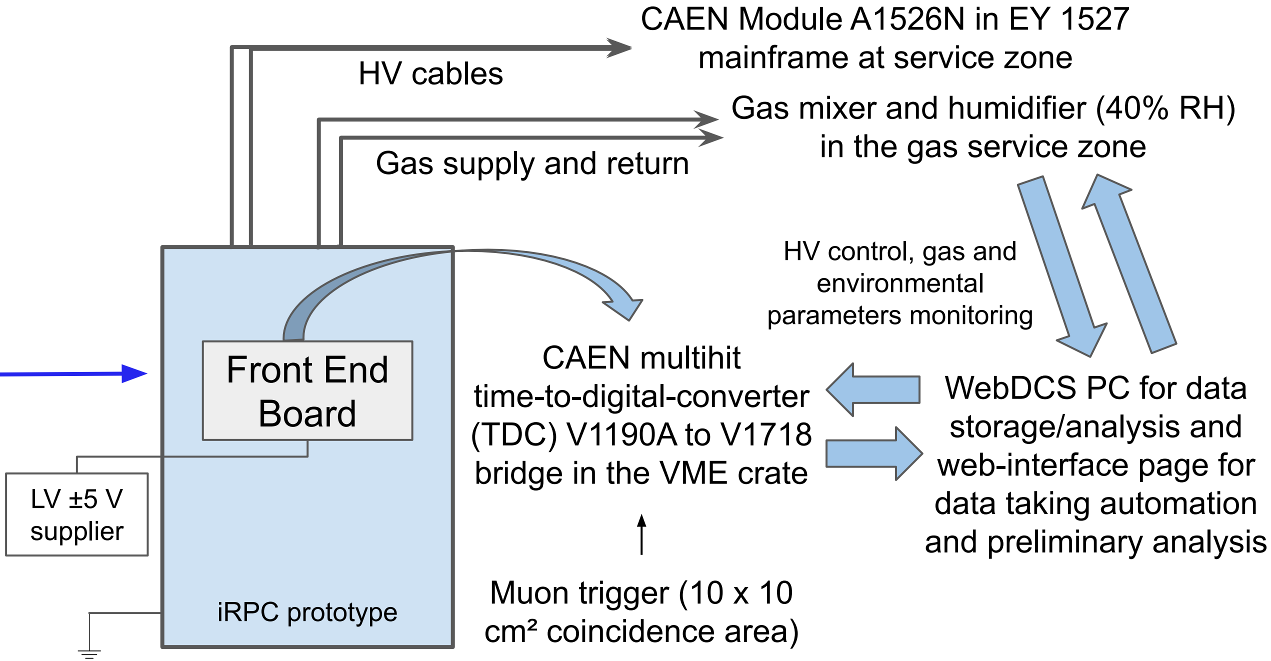


- 100 m² bunker with 11.5 TBq ^{137}Cs (Jan 24)
- 2 symmetric radiation field with an attenuator system with different absorption factors
- H4 beam line from SPS
- Muon beam 100 GeV/c, 10^4 muons / spill, every 400 ms
- Service zone with electronics and gas room
- Special gas line with CO2-based mixture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



Experimental Setup: iRPC prototype and electronics





iRPC Prototype

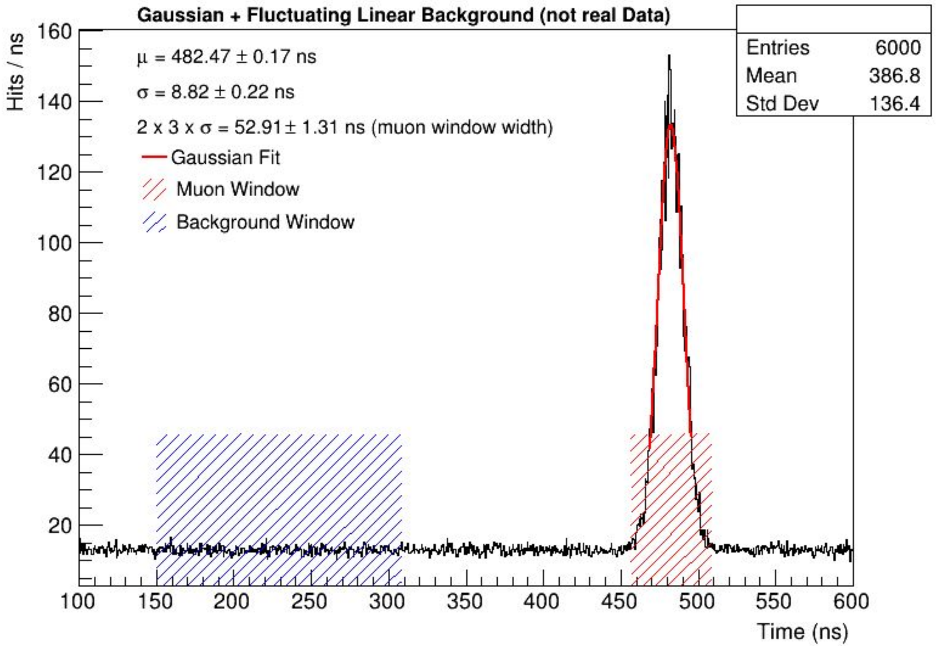
- Customized chamber with gaps from KODEL laboratory
- Made with copper tape strips plane (~1.8 cm pitch),
- **double 1.4 mm 50 x 50 cm² gap**
- 1.4 mm electrode HPL thickness
- $\varrho \sim 1.2\ (1.3) \times 10^{10}\ \Omega$.cm for bottom (top) gap
- **single strip plane readout with 16 strips**

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

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

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

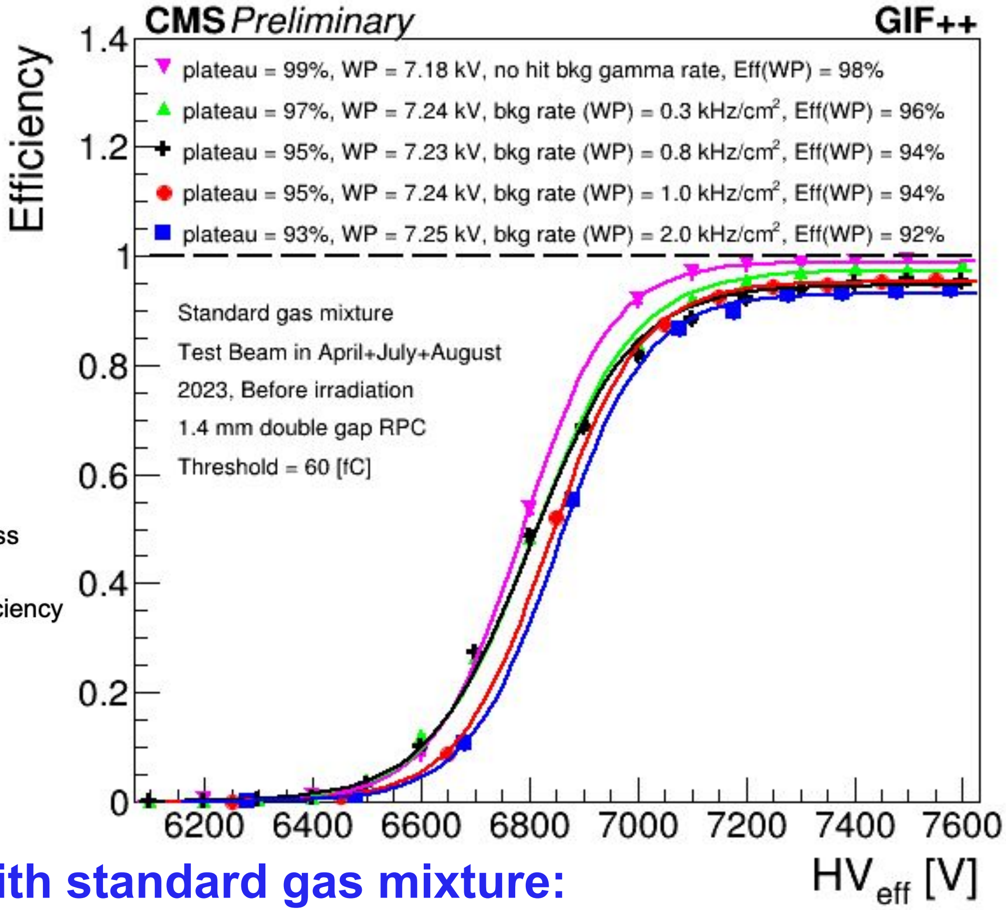
- Efficiency in each point is calculated using the method in previous slide
- S-curve is fitted by a sigmoid function

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

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

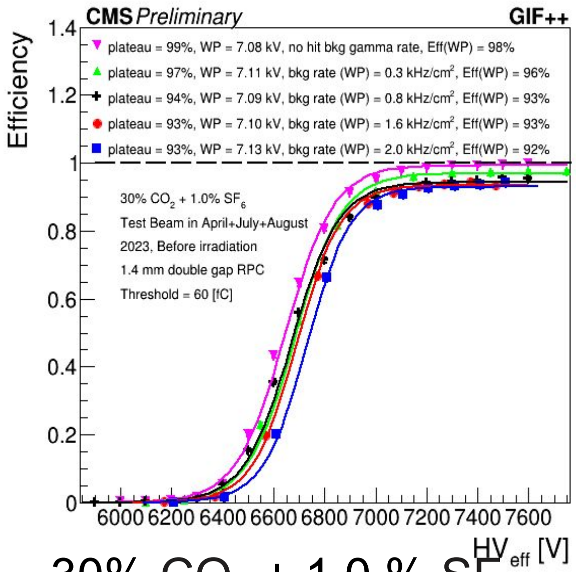
- Working point defined as the HV where efficiency is 95% + 150V:

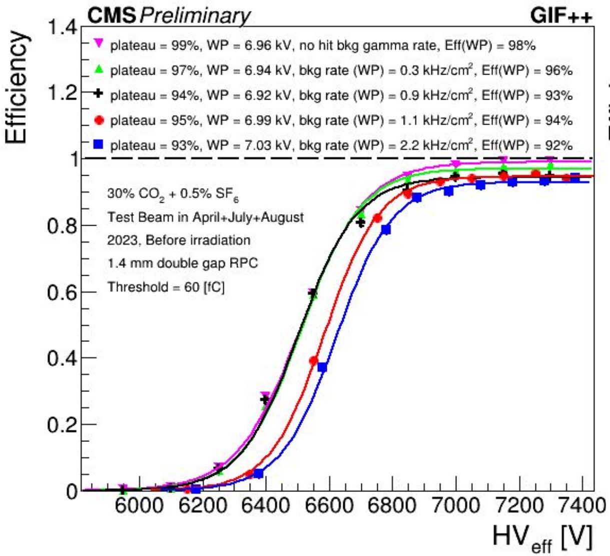
$$WP = \frac{\ln 19}{\lambda} + HV_{50\%} + 150V$$

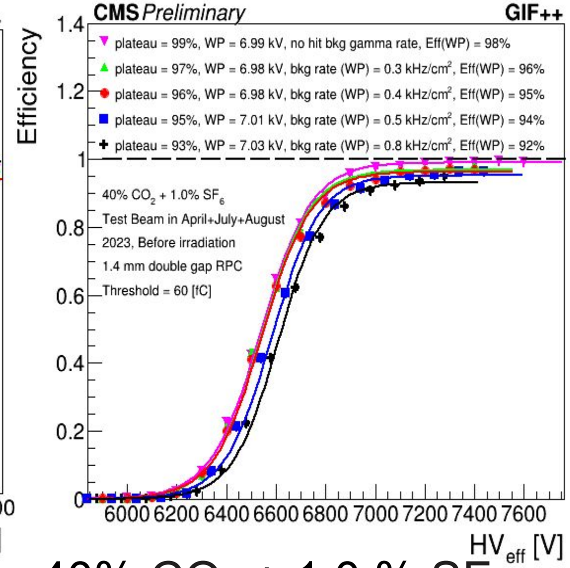


Validation with standard gas mixture:
WP consistent around 7.2 kV and efficiency > 90 % up to 2 kHz/cm^2 (HL-LHC x 3)

Results before the irradiation campaign







30% CO_2 + 1.0 % SF_6
$WP_{source\ OFF}$ ~ 7008 V

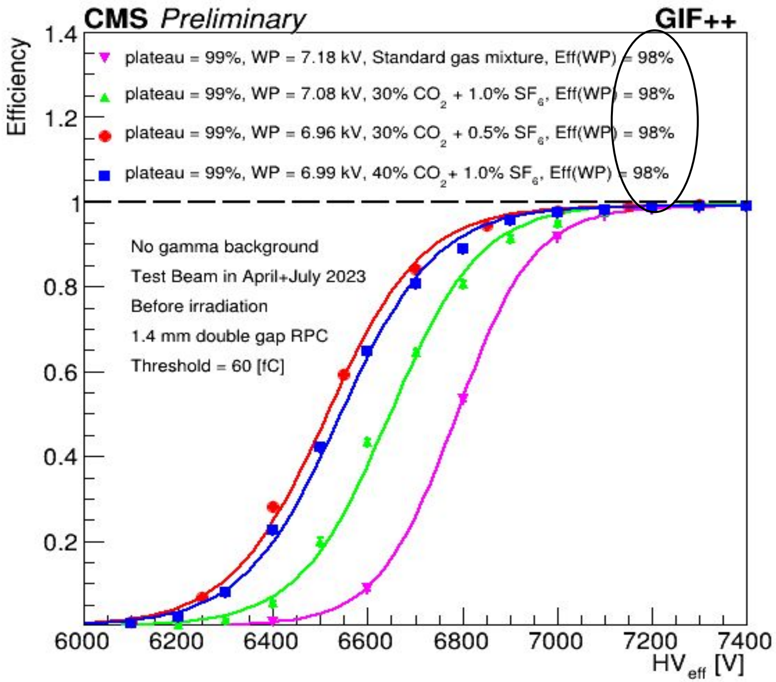
30% CO_2 + 0.5 % SF_6
$WP_{source\ OFF}$ ~ 6960 V

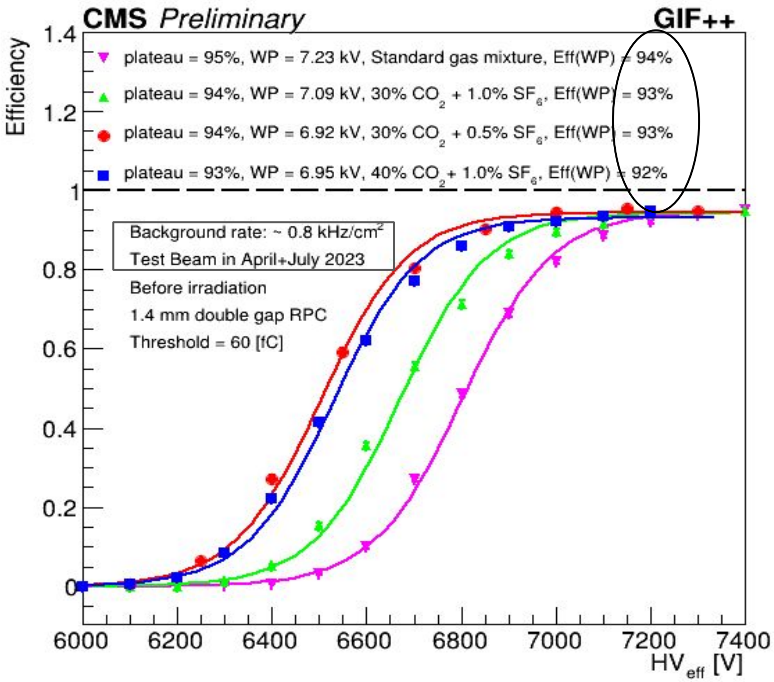
40% CO_2 + 1.0 % SF_6
$WP_{source\ OFF}$ ~ 6999 V

All gas mixtures within the expectations with minor drop in efficiency due to the replacement of $C_2H_2F_4$ by CO_2

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

Results before the irradiation campaign

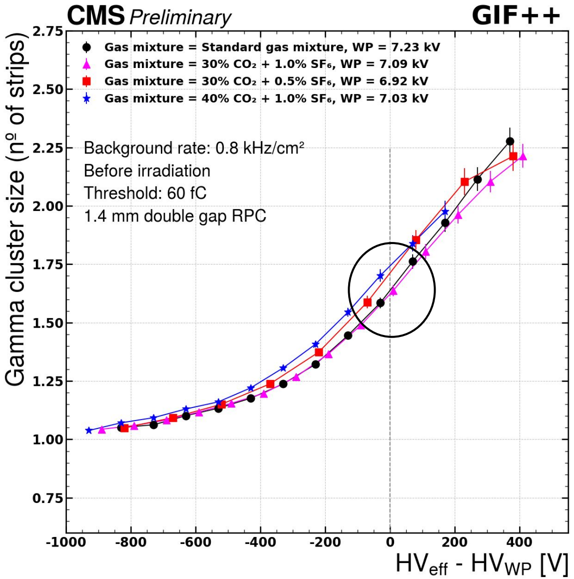


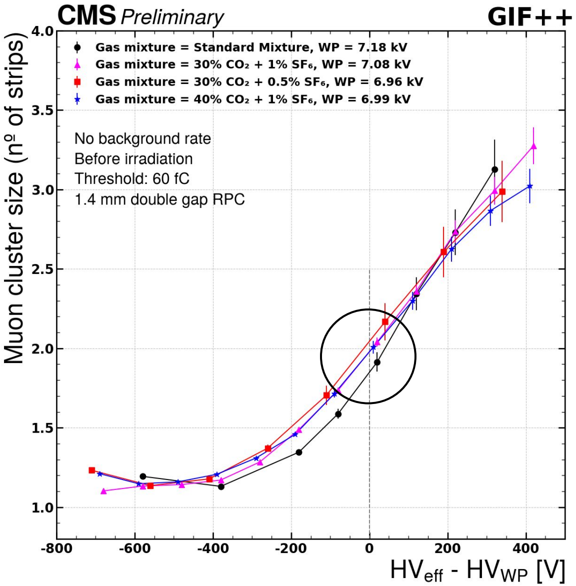


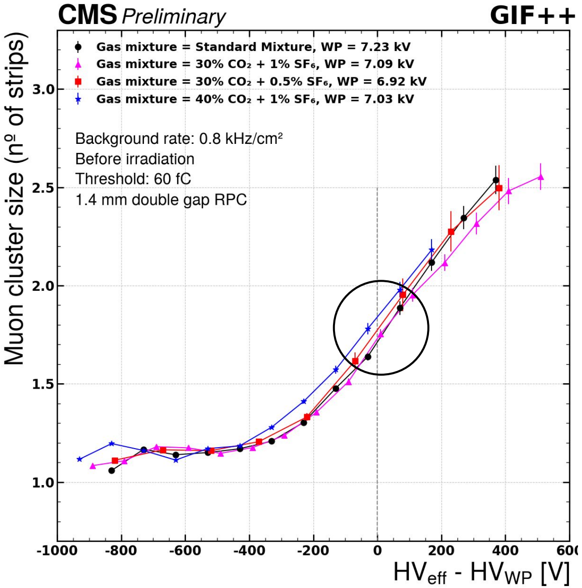
- **Minor muon efficiency drop with the increase of CO_2**
- **Different Working Point in different mixtures:**
  - **CO_2 addition lower mixture density: lower WP**
  - **SF_6 has high electronegativity: higher WP**

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

→ SF_6 might be playing the role!

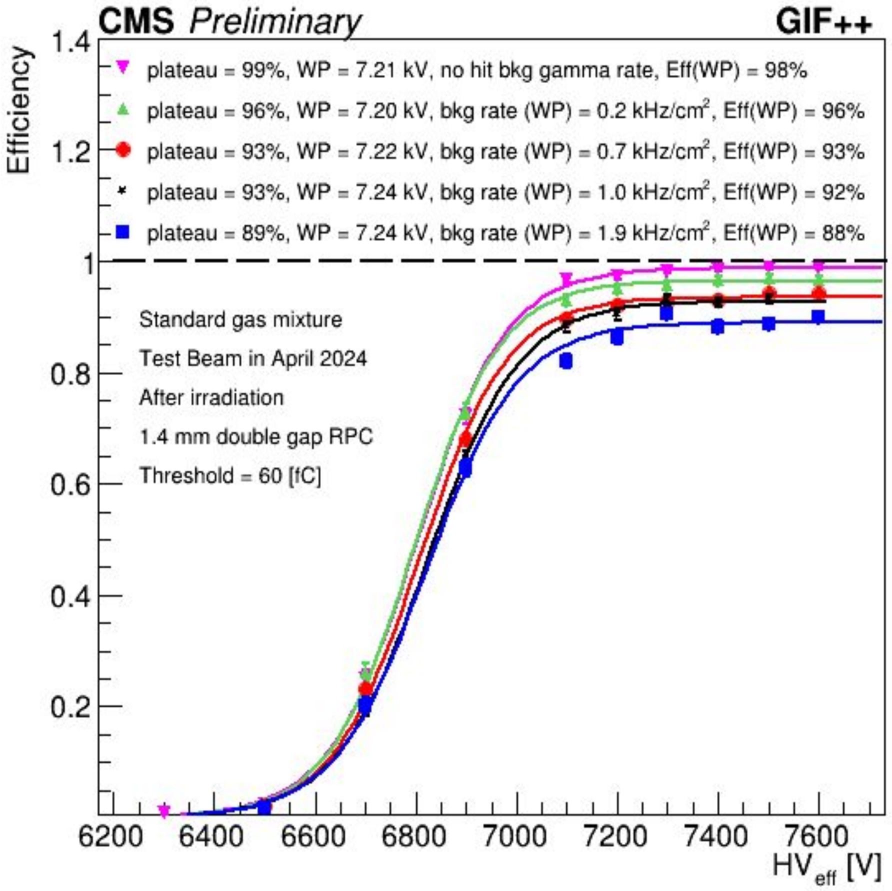
However, chamber resolution (1.8 cm chamber width) is not the same of CMS-iRPC chambers

→ further refinements are needed!

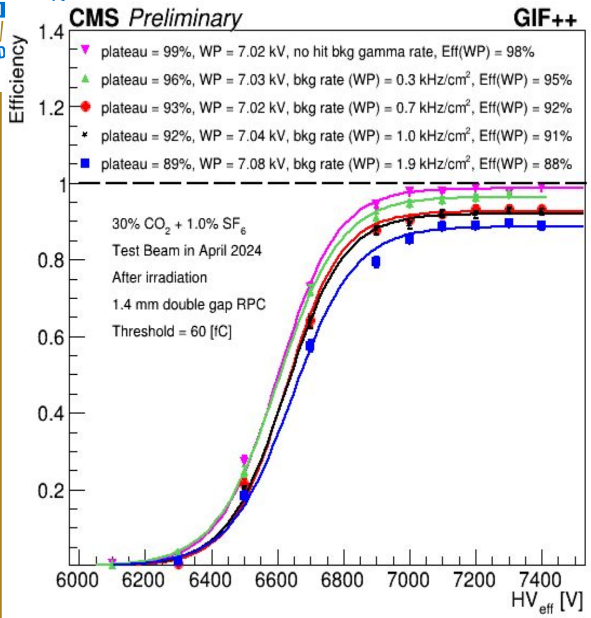
Background gamma rate (Hz/cm^2)	Average Muon Cluster Size	Average Gamma Cluster Size
0	2.0 strips	—
800	1.75 strips	1.7 strips

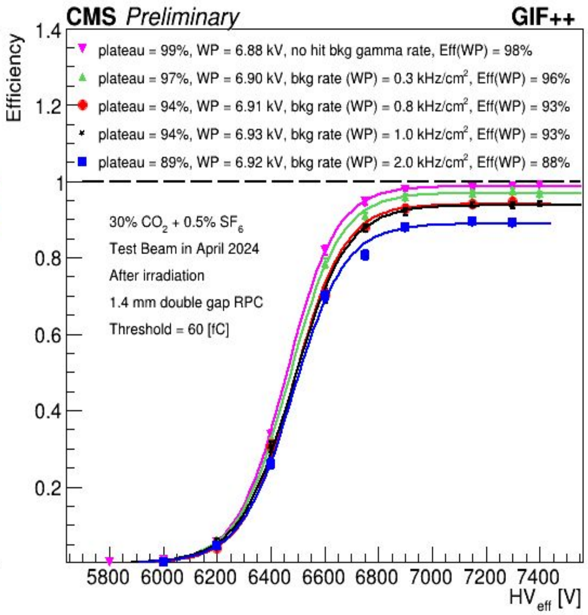
Results after the irradiation campaign

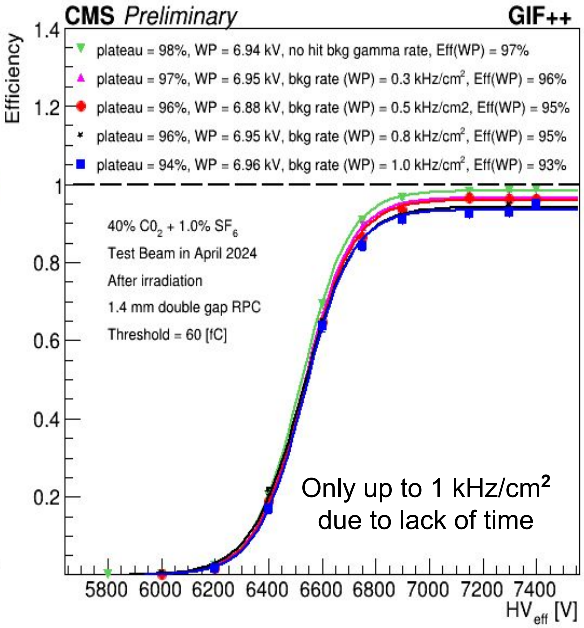
- During no beam period, a dedicated irradiation campaign took place at GIF++
- It was collected around **40 mC/cm²**, corresponding to **~ 4 %** of what is expected during HL-LHC within a safety factor 3
- Revalidation with standard gas mixture:
  - **Consistent and stable efficiency** and Working Point (~ 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







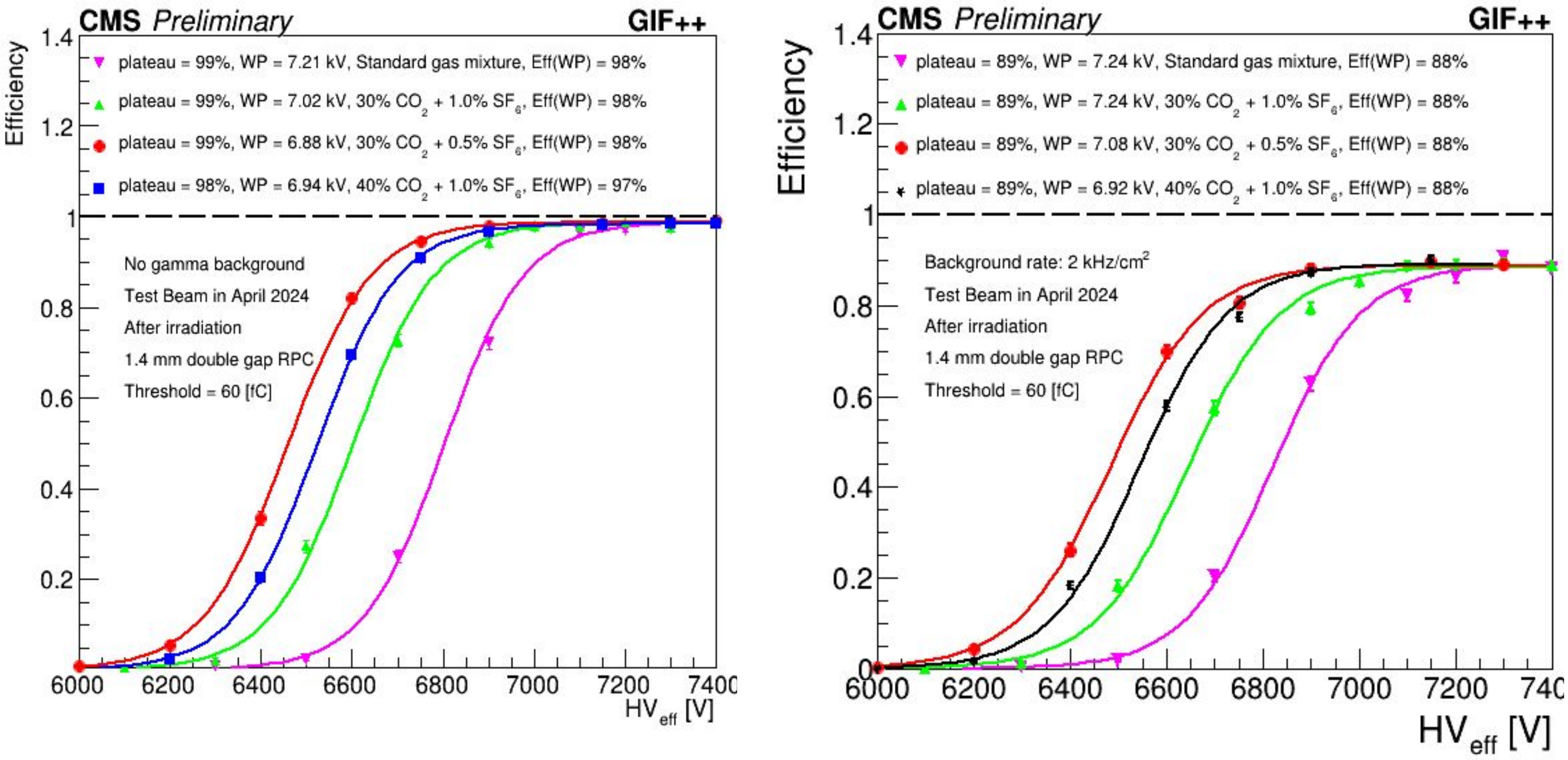
30% CO_2 + 1.0 % SF_6
$WP_{source\ OFF}$ ~ 7020 V

30% CO_2 + 0.5 % SF_6
$WP_{source\ OFF}$ ~ 6880 V

40% CO_2 + 1.0 % SF_6
$WP_{source\ OFF}$ ~ 6940 V

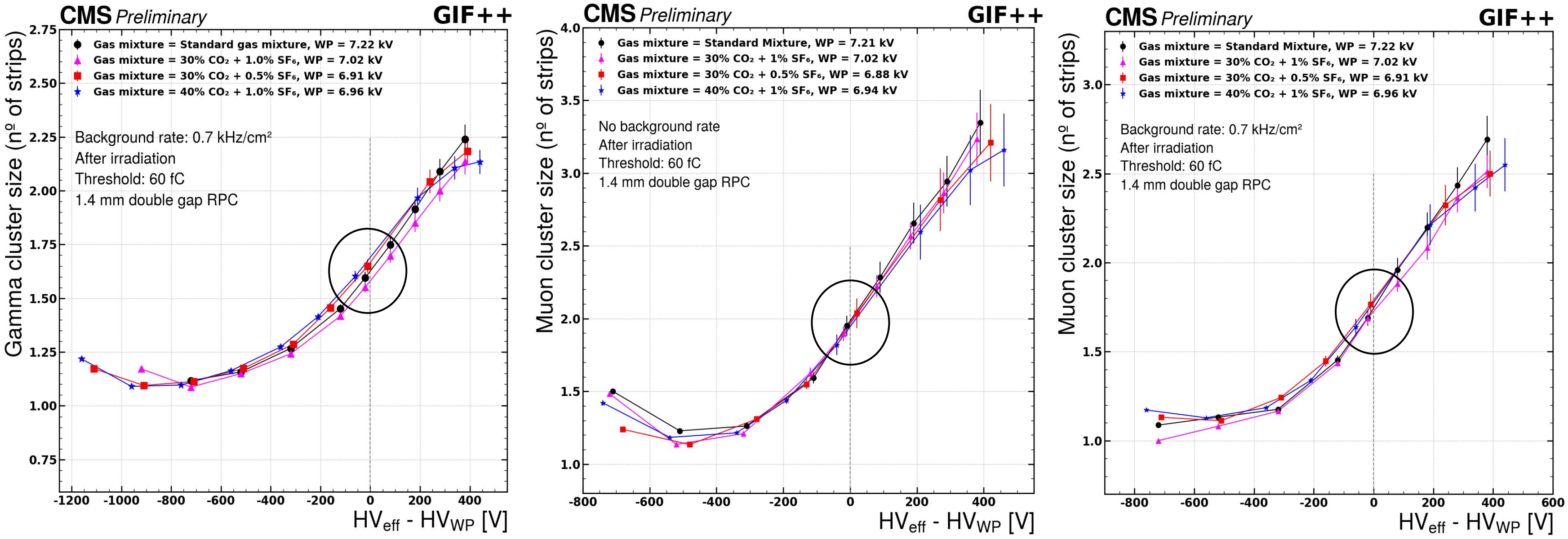
Consistent efficiency (same drop in background rate observed) and working point for different mixtures under background gamma rate up to 2 kHz/cm^2

Results after the irradiation campaign



No change in the efficiency without radiation,
but < 90% for 2 kHz/cm^2 (mostly FEB drive, no gas mixture related)

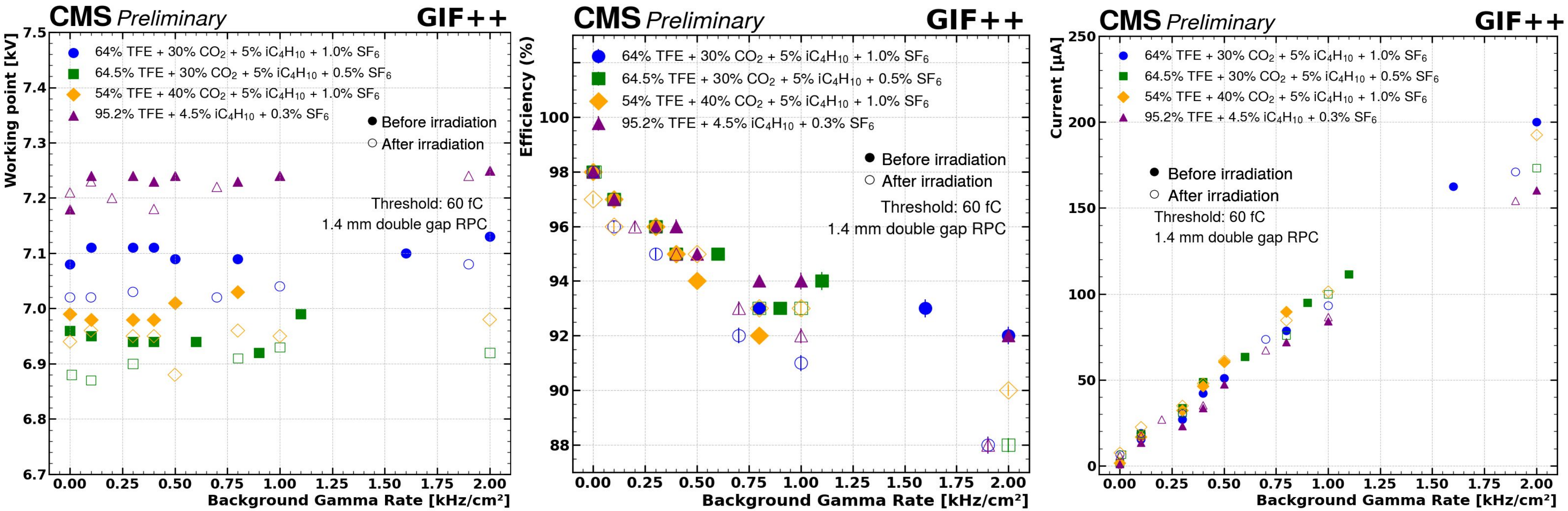
Results after the irradiation campaign



No difference between CO_2 based mixtures and also no changes w.r.t the results before irradiation!

Background gamma rate (Hz/cm^2)	Average Muon Cluster Size	Average Gamma Cluster Size
0	2.0 strips	—
700	1.75 strips	1.6 strips

Comparison



- **No change** in the working point after irradiation campaign
- Drop in efficiency with background **similar** before/after irradiation for moderate rates
- Current is shown to be **~20% higher** for CO_2 based mixtures, with similar results after and before irradiation

Conclusion and next steps

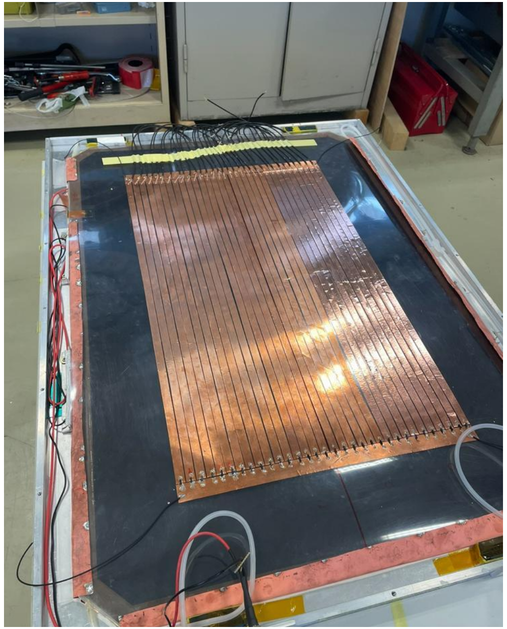
- **First results of an iRPC prototype with double 1.4 mm gap with CO_2 based gas mixtures**
- Similar efficiency and lower working point for all CO_2 based gas mixtures tested w.r.t the standard one
- **Integrated charge around 4% of what is expected at HL-LHC x 3**
- No efficiency degradation related to the gas mixture was observed
    - Efficiency drop is electronics related, similar for all tested mixtures
- No change in the working point was observed
- No change in the muon and gamma cluster size was observed
- 20 % higher currents for CO_2 based mixtures **- no change with radiation**

Studies will continue at GIF++ with the aim to integrate more charge during irradiation campaign, perform further studies, as timing resolution, and investigate better the efficiency drop observed

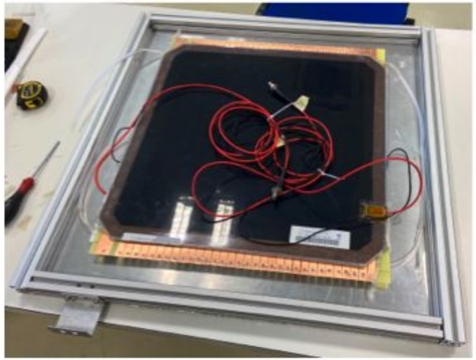
Thanks for your attention
Questions?

Backup

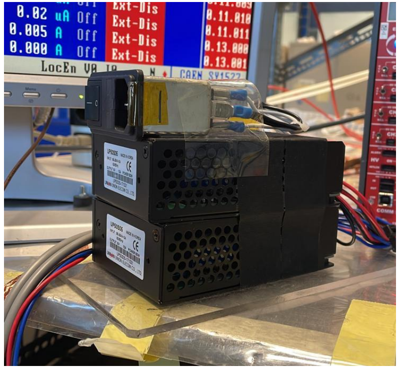
Experimental Setup: iRPC prototype and electronics



Chamber strip plane with copper tape example



iRPC prototype opened and KODEL electronics



Adapted LV ±5 V supplier

TDC and VME bridge