# Overview of CERN strategies for the reduction of greenhouse gas emissions from particle detectors

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CERN

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Detector Technologies

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# Outline

- Greenhouse gases for particle detectors at CERN
  - Gas requirements and consumptions
  - Gas regulations
- Strategies to reduce GHGs from particle detectors
  - Recirculating gas systems
  - Gas recuperation systems
  - Alternative gas mixture studies
- Conclusions

# Greenhouse gases for gaseous detectors at CERN

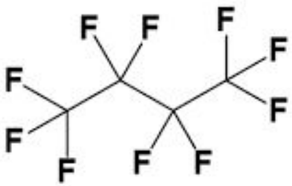
## Greenhouse gases

The strength of a GHG is defined by its Global Warming Potential **GWP** ($GWP_{CO2}$ = 1)

## GHGs are often required in gaseous detectors

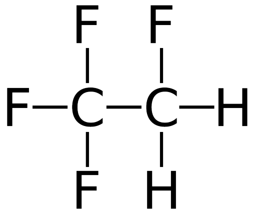
**Fluorinated** gases account for the **biggest emissions** at CERN

Most of F- gases were used before their environmental impact was understood



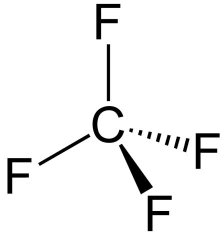
### C4F10 (GWP = 8860)

Used in **RICH** for optical properties



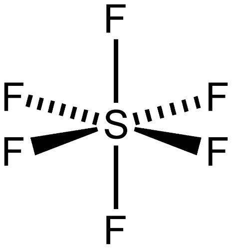
### C2H2F4/R-134a (GWP = 1430)

Used in **RPCs** for primary ionization and charge multiplication



### CF4 (GWP = 7390)

Used in **RICHs** (optical properties), **Wire** chambers (anti-polymerization) and **MPGDs** (time resolution)



### SF6 (GWP = 22800)

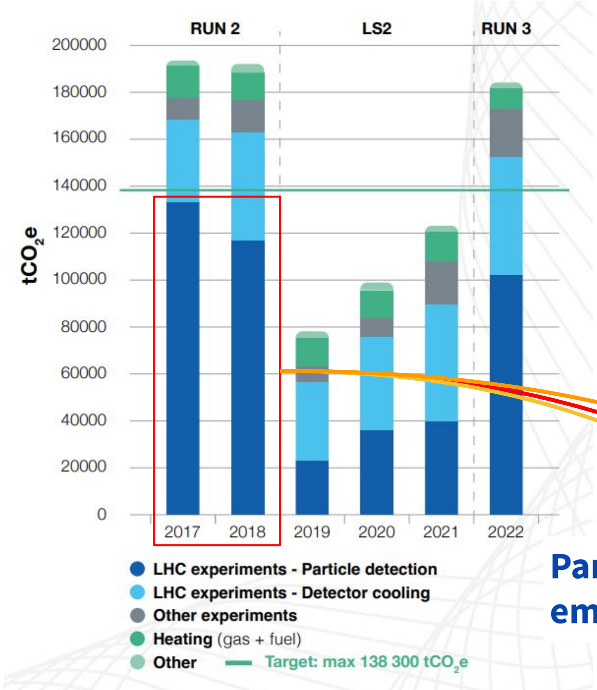
Used mainly in **RPCs** as electron quencher

# Greenhouse gases consumption from LHC

https://doi.org/10.25325/CERN-Environment-2023-003

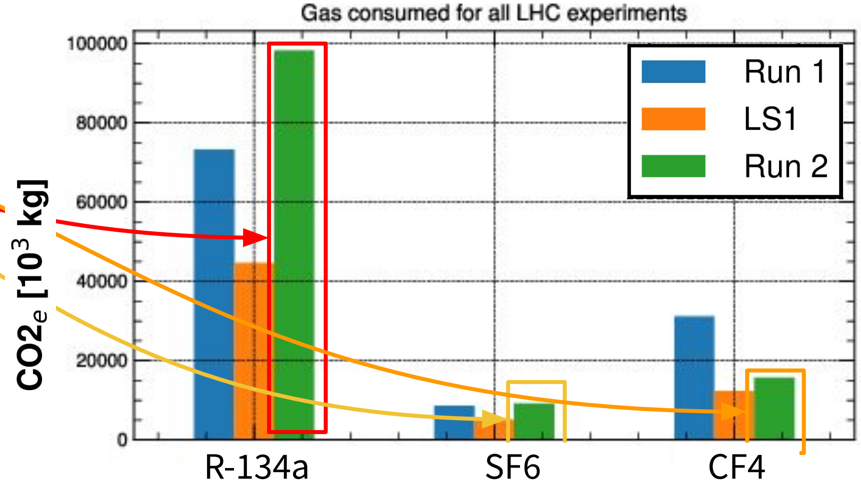
CERN emissions during 1 year of Run 2 ~ **220 000 tCO2e**
***Half*** of them from particle detectors → mostly due to leaks and operation

- **C2H2F4/R-134a** biggest contributor → leaks from RPC detector during operation
- **CF4** → due to operation of CSC, RICH, GEM systems
- **SF6** → Related to RPCs as R-134a




**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.

**Particle detection emissions**

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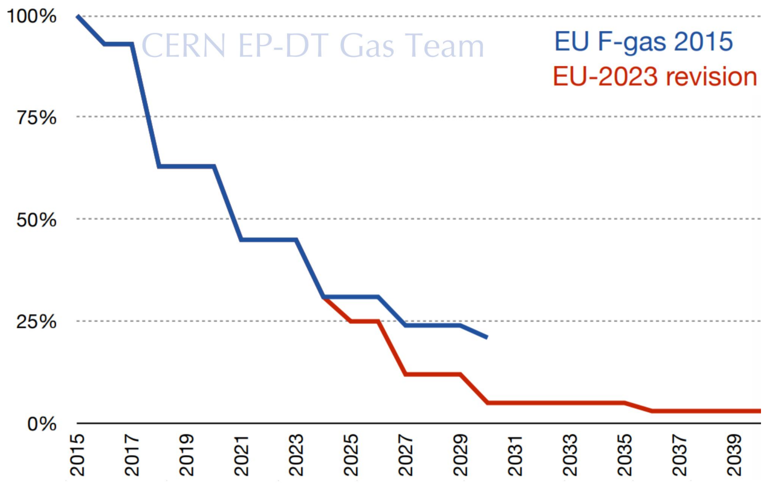
# F- gas regulations

## EU regulation on F- gases

Aim at **limiting** and preventing F- gases use

F- gas consumptions should be reduced:

- Environment
- Price
- Availability



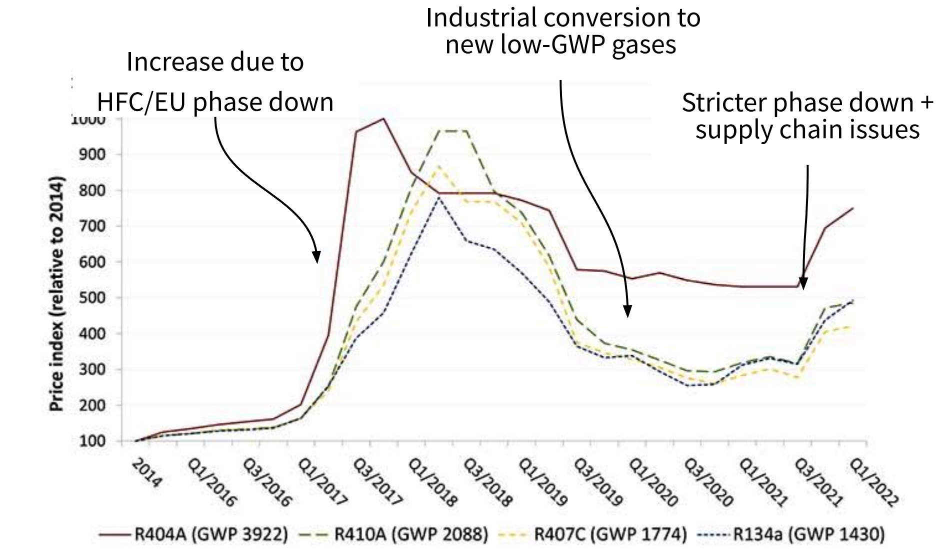

## Revised regulations + PFAS

PFAS: New regulation that includes F- gases

- EU Chemical Agency proposing to ban most of them

Revised regulations:

- EU F- gases
- Montreal Protocol on HFC



# GHG reduction strategies overview

**Goal: reduce GHG emissions from particle detectors at CERN**

### Smaller recirculating systems

*Gas recirculation for facilities and laboratory sized setups*

### Gas recuperation

*Distillation*
*Membrane absorption*
*Pressure swing*

### Detector performance with alternative gases

*RPC ECOGAS@GIF++ (AIDAInnova)*

*Mitigation of R-134a consumption with CO2*

*Alternatives to SF6*

### LHC gas recirculation

*Design and optimization of large LHC gas systems*

### Chemical studies

*Gas species qualification and quantification*

*Pollutants production studies*

### Future studies

*MPGDs performance with eco-friendly gases*

*Simulations of detector performance with new gases*

*Alternatives to GHGs for MRPCs*

*Pollutants production studies*

# Gas recirculation

# Gas recirculation

## Gas Systems at CERN can recirculate the gas

- For **large** volumes systems ~ 1-**100 m$^3$**
- Employed with **GHGs** or **expensive** gases
- ~15 recirculating systems for LHC
- Operating **24/7** with **99.99%** uptime (excluding interventions and external issues)

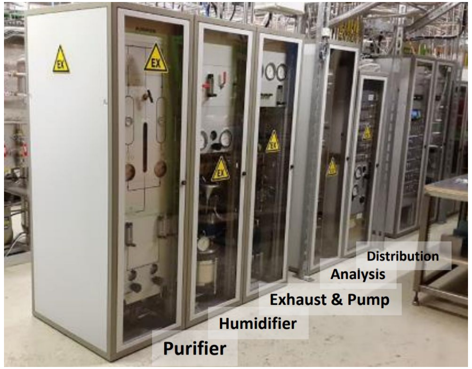
## Pros and Cons

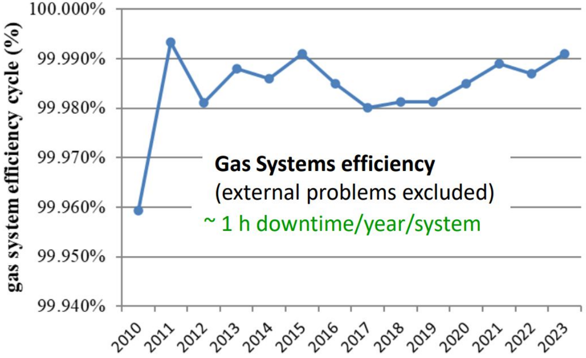
- *Gas consumption reduction up to **90-100%*** (10% fresh injection sometimes kept for detector performance)
- Higher system price **paid back** by the amount of gas saved
- **Large** installations ⇒ several euro racks installed in different areas
- Higher **complexity** of the system ⇒ more resources required also for maintenance and operation

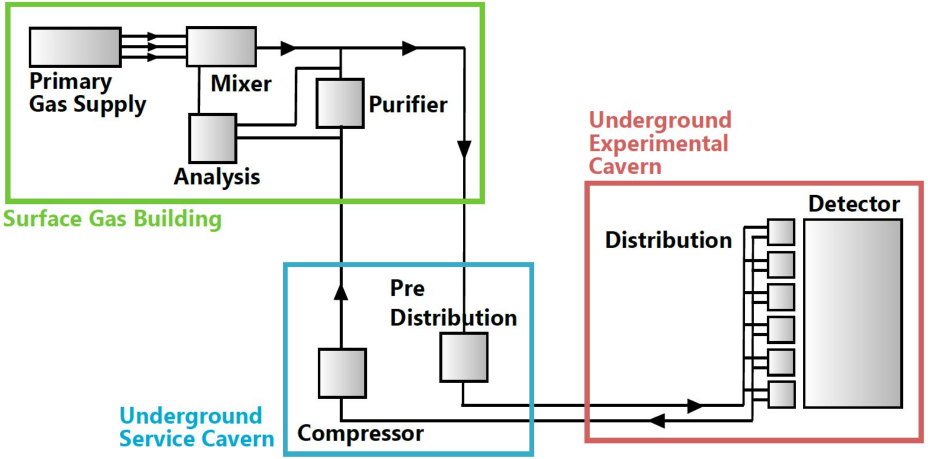
## Ongoing optimizations on gas recirculation

- **Mechanical** ⇒ modifications to improve gas systems operation and ensure better detector conditions
- **Software** ⇒ continuous improvement of monitoring and **control systems**

*ALICE MID gas system*



# Small and micro recirculating gas systems

## Several facilities and laboratories using GHGs

- The **sum** of contributions from **smaller facilities** is sometimes comparable with **LHC gas systems**

## Goal: design smaller recirculating gas systems

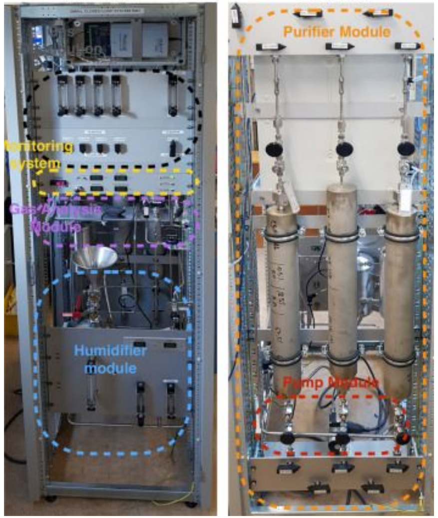
- **Target:** 1-10 detector, mL to a few liters volume
- **Size** of the gas systems: as small as possible
- **Price** of the components: should be reduced as much as possible for accessibility
- **Alternatives** to **industrial** controllers and components might be needed to reduce costs
- **Components** should be **validated** for their use with gaseous detectors

## Micro-loop

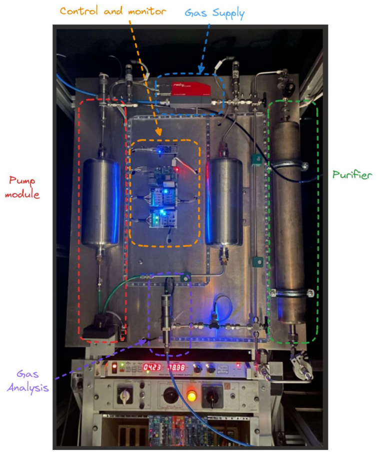
- **Portable** gas system for laboratory setups
- Ongoing effort to **standardize** the design to be flexible and simple ⇒ **knowledge transfer** to institutes and companies

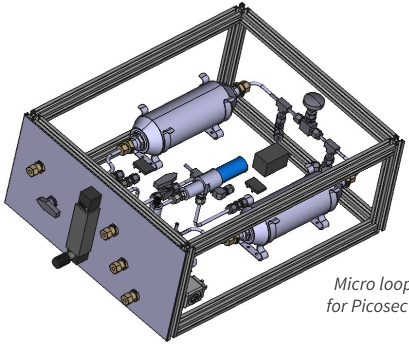
*Small recirculating systems for GIF++*

**Front View** **Rear View**



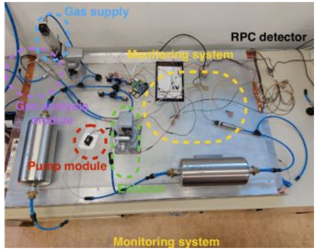

*micro loop for Spark Chamber @ CERN Science Gateway*



*Micro loop design for Picosec detector*

*RPC R&D prototype*



# Gas recuperation

# Gas recuperation systems: overview

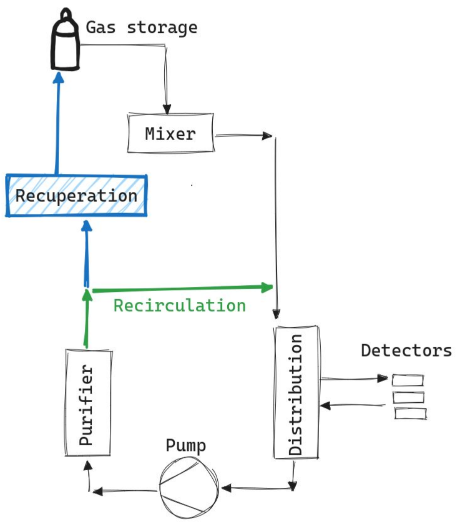
## Motivations for recuperation systems

In most systems, **not all the gas can be recirculated** due to detector requirements

The GHGs in a gas mixture can be recovered

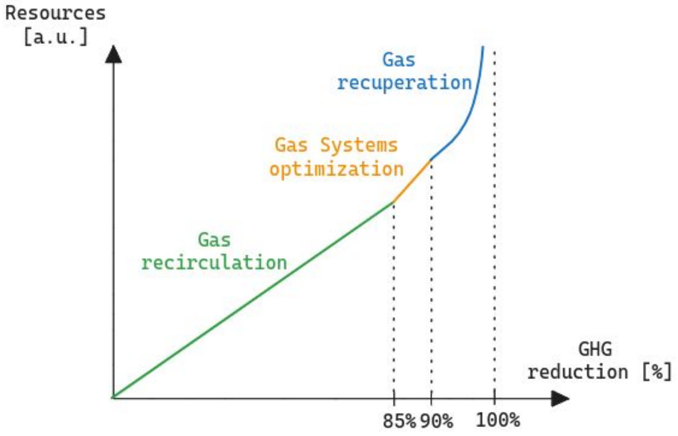
## Working principle

- Gas mixture at the **exhaust** sent to the recuperation
- GHG components of the gas mixture are **separated** from the other gas components using different techniques
- GHG is **stored** into bottles and reused as a **fresh gas** supply




## Pros and Cons

- Suitable for large LHC installations ⇒ ~$m^3$ spared, kCHF
- Non standard and **complex** systems
- Each recuperation system designed specifically for a gas mixture and a gas system
- Dedicated **R&D**, **maintenance** and **operation** needed




## Gas recuperation systems allow to reduce GHG emissions

- Up to 60-85% of the exhausted gas can be recuperated

# LHC recuperation systems

## CMS RPC R-134a

- Constantly operated
- Recovers **R-134a** from **CMS RPC** gas mixture
- Complex separation technique due to **azeotrope** between R-134a and isobutane
- Efficiency up to **85%, ~99.5%** quality
- Ongoing **R&D** to recuperate also **SF6** on a dedicated system

## CMS CSC CF4

- Constantly operated
- Recovers **CF4** with **membranes** adsorption and pressure swing cycles
- Several optimization underwent over the past 10 years
- **~70%** efficiency, **~90%** quality

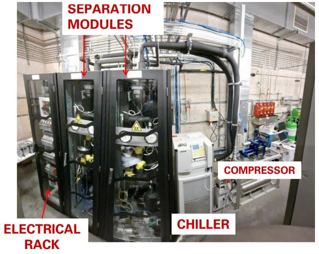
## LHCb RICH2 CF4

- Operated only when changing mixture in the detector
- ~**70%** efficiency, ~**95%** quality

## LHCb RICH1 C4F10

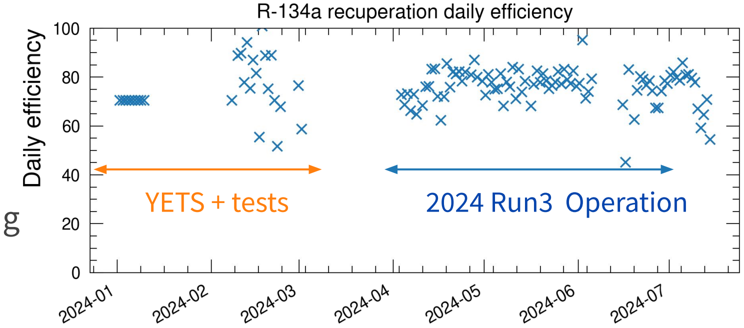
- Operated only during specific periods (cleaning, filling, emptying)
- Very old system, upgrade ongoing
- ~**80%** efficiency, ~**98%** quality

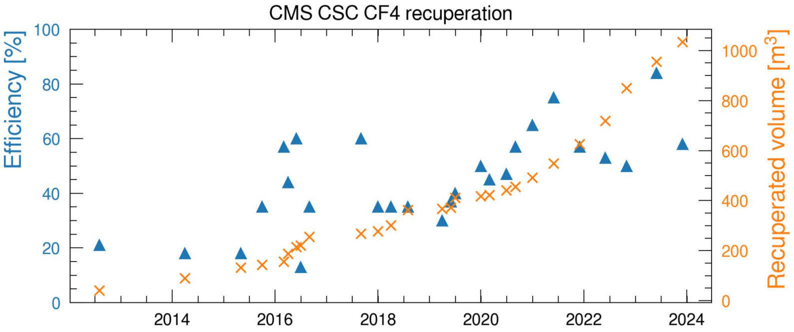
*CMS RPC R-134a recuperation*




*CMS CSC CF4 recuperation*

*LHCb RICH1 C4F10 recuperation*



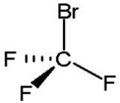



# Alternative gases

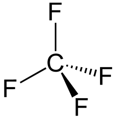
# Evolution of F- gases in detectors

*F- gases for particle detectors have always followed the industry and adapted to regulations*

**PFCs CFCs**



**R13B1**



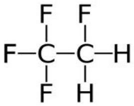
**CF4**

*Ozone layer issue*

**1987**

Montreal Protocol on CFCs

**HFCs**



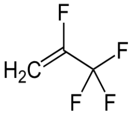
**R-134a**

*Global Warming becoming an issue*

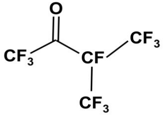
EU HFC regulation

**2014**

**Eco-friendly HFOs, PFKs**



**R-1234ze**



**C5F10O**

Montreal Protocol on HFCs

**2019**

*TFA, PFAS impact on health*

**2023**

EU PFAS Proposal

**Future?**

# Alternative gases for RPCs: experimental setup

**Detectors**

HPL-RPC, 2 mm gap, 2mm electrodes, ~70x100 $cm^2$

**Experimental setups**

Laboratory setup for detector characterization and gas mixture exploration

GIF++: muon beam tests, aging tests

**Gas System**

**6-components** gas mixer

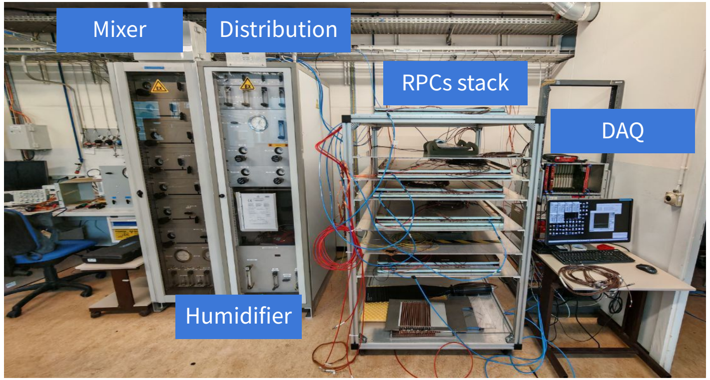
Same modules components of LHC gas systems

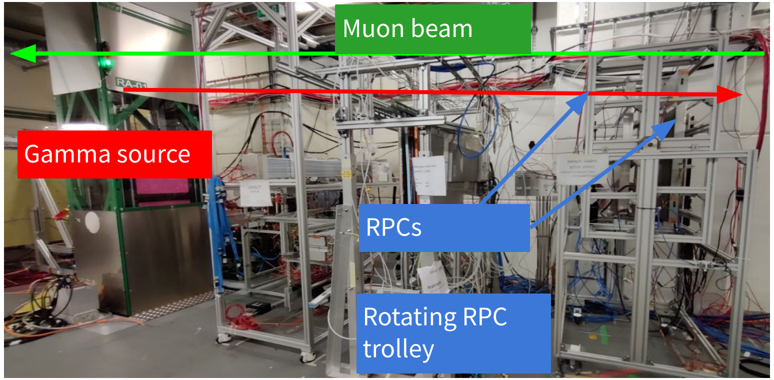
**Data acquisition**

Raw waveform: CAEN digitizers + offline analysis

**Gas mixture tests and validation**

1. **Several gas mixtures** explored and **tested** in lab conditions using the CMS RPC one as a reference
2. Few selected candidates tested during muon beam @ GIF++ with **LHC like background radiation**
3. One selected candidate undergoes **long term** performance **tests** on detectors



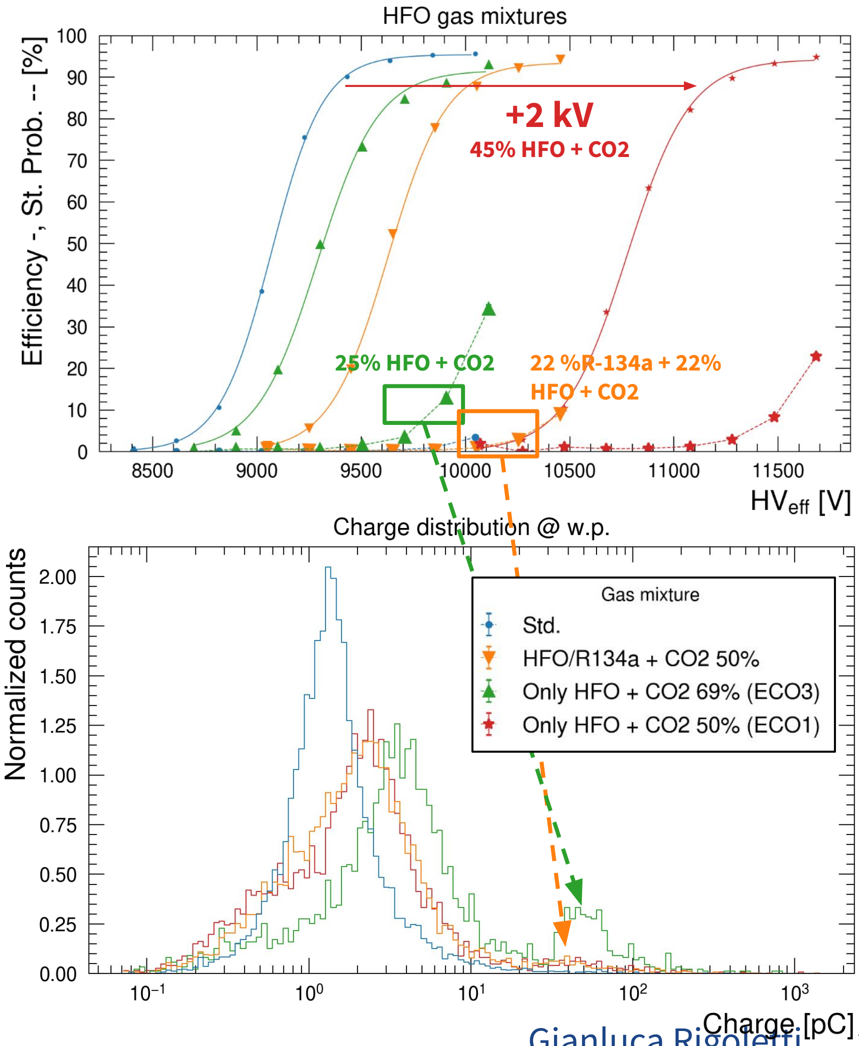
# R-1234ze + R-134a gas mixtures

## 4 components, (SF6 + iso.) + R-1234ze + CO2 gas mixtures

- **Muon** beam performance **extensively** studied
- Ongoing with a selected **HFO+CO2** gas mixture by RPC ECOGAS collaboration (see D. Ramos Talk ICHEP2024)
- In general, **currents with HFO higher** than with std. R-134a gas mixtures

## 5 components, (SF6 + iso.) + R-134a + R-1234ze + CO2 gas mixtures

- The addition **R-134a** helps **lowering** the background currents and prevents w.p. to be too high
- Gas mixture is **less eco-friendly** than HFO only gas mixtures



# Mid term solution: $CO_2$ to reduce R-134a consumption

**HPL-RPC gas mixture LHC ⇒ ~95% R-134a, 5% iso, 0.3% $SF_6$**

**2022 - Studies on replacing 95% R-134a with 30% $CO_2$**

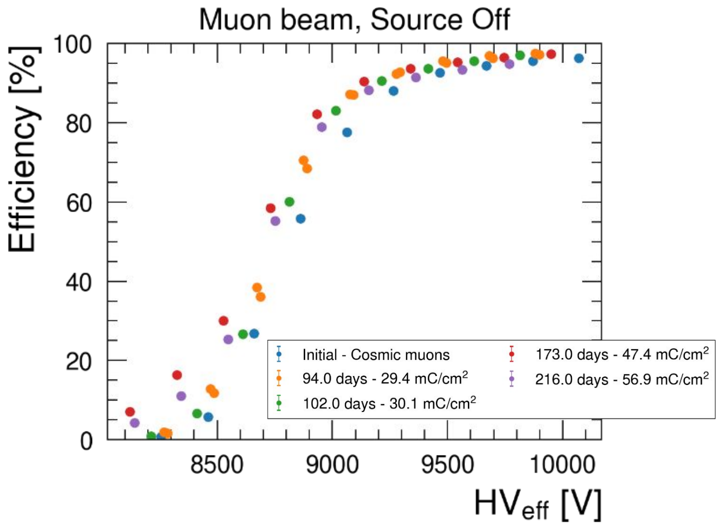
- $SF_6$ increased to 1% added to suppress streamers
- R-134a reduction of 30%
- GHG reduction of ~15%

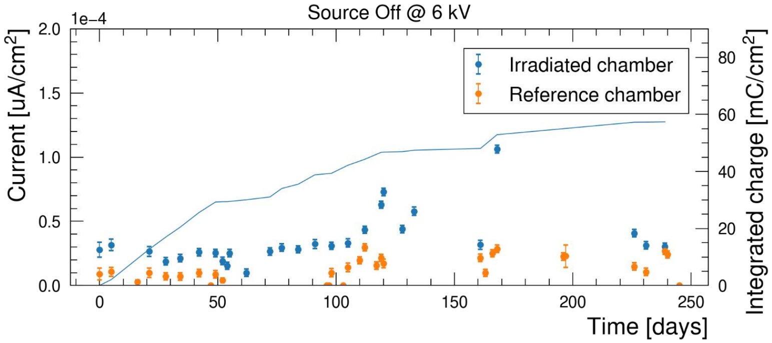
Nucl.Instrum.Meth.A 1049

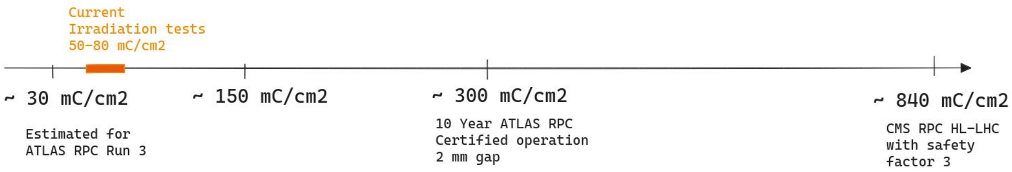
***Gas mixture is now used in ATLAS RPC!***

**2023- Muon beam tests and long term tests at GIF++**

- ~60 mC/cm2 integrated ⇒ ~ 2 x **ATLAS Run 3**
- Detector performance not significantly affected
- Further tests needed:
  - Integrated HL-LHC charge
  - Longer tests with **lower SF6** or **higher CO2**



# SF6 alternatives performance

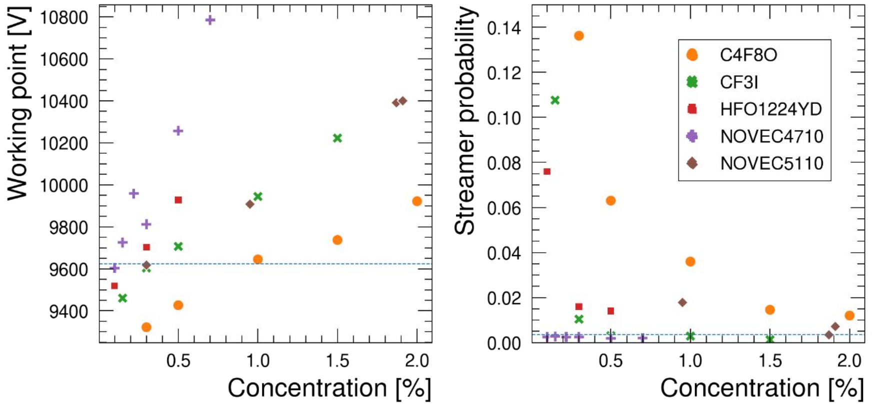
**Several gases tested in laboratory**

**C4F8O**, **CF3I**, **R-1224YD**, **Novec 4710**, **5110**

**C4F8O**, Novec **5110** ⇒ performance issues

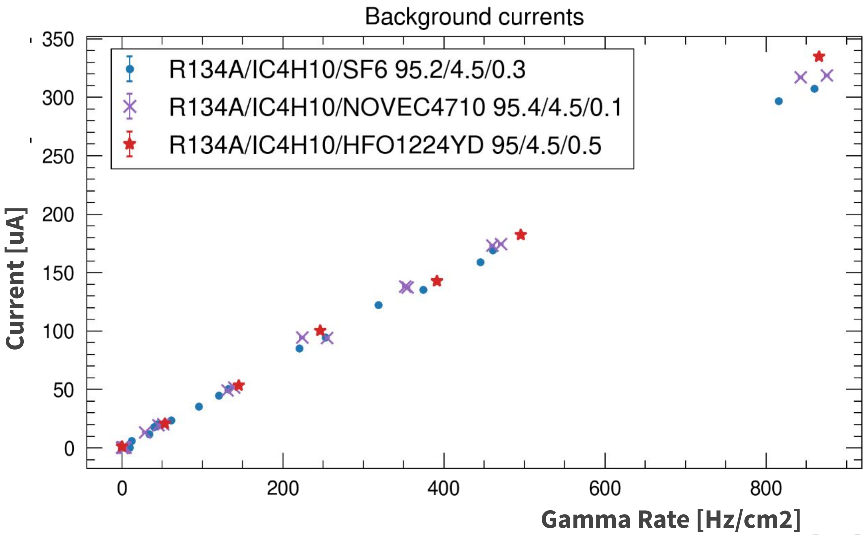
**CF3I** ⇒ safety issues (mutagenic toxicity)

**Novec 4710** and **Amolea 1224yd** selected for further studies with muon beam and gamma background




**GIF++ tests with muon beam and gamma background**

Novec 4710 **0.1%**, Amolea 1224yd **0.5%** matching performance of Std mixture with **0.3% SF6**




**Novec 4710** selected for its performance but may react with water → chemical studies ongoing

**Amolea 1224yd** most of them contain **Cl** → understanding possible **pollutants** formation



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# Not only detector performance: gas properties studies

## Not only detector performance

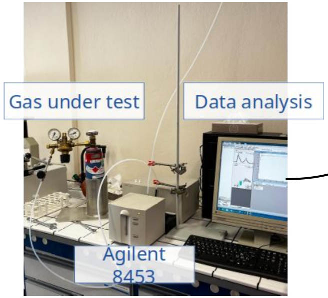
Understanding **physical** and **chemical** properties of gases is fundamental to detector operation

**Environmental chemistry** helps understanding pollutants formation

## Gas molecules interaction in the atmosphere and in the detector

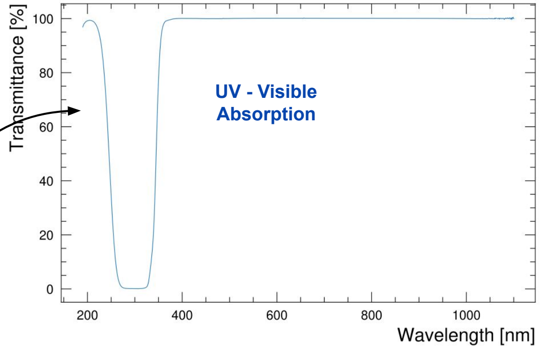
***Rain out*** → Water solubility → critical for humidified gas mixtures
***Oxidation*** → Reactivity with OH-
***Photolysis*** → UV (wavelength < 300 nm) → quenching properties

*UV spectrometry*

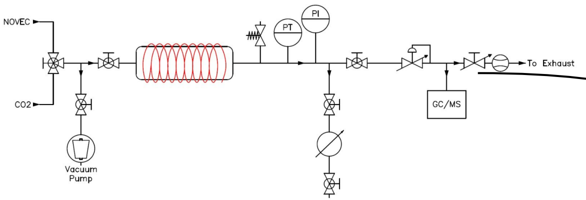



*Thanks to B. Teissandier for helping in the measurements and providing the instrument*

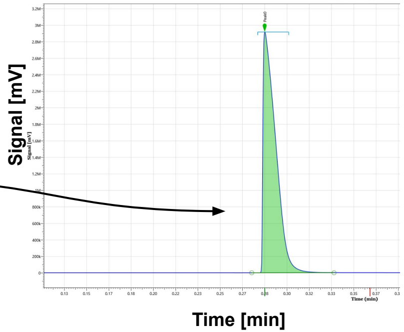
**Novec 5110 UV Transmittance**




Novec 4710 water solubility setup schema

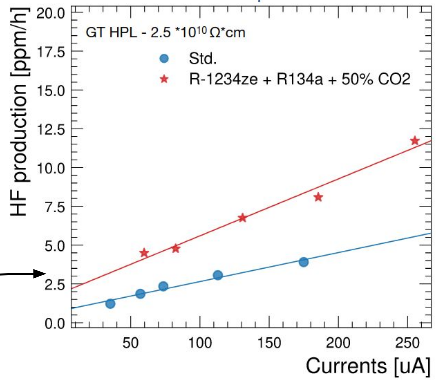



**Novec 4710 Chromatogram**





Measurements at w.p. for different ABS



# Conclusions

## Several strategies to reduce GHG emissions from RPCs

- Gaseous particle detectors contribute to a noticeable amount of CO2e emissions at CERN
- In the future the use of **F- gases** will likely be **more restrictive**

## Gas recirculating systems

- First approach towards reducing GHG emissions
- Some LHC detectors requires ~**10%** of **fresh gas** injection
- Gas recirculation is advisable also for **small, laboratory-sized setups**

## Gas recuperation systems

- Further approach, advisable for **large systems** where some gas needs to be exhausted
- Complex and non-standard: each gas systems requires a **specific design** to recuperate the GHG gas component
- They require a considerable amount of **resources** and deep **expertise**

## Alternative gases

- **Alternatives to R-134a** studies ongoing. **CO2** proved to be a gas to mitigate R-134a emissions
- **SF6 alternatives** extensively studied. Gas properties studied are needed to understand if gases could be used in detectors and gas systems
- Future studies on replacing **CF4** for MPGDs and new gas mixtures for MRPCs

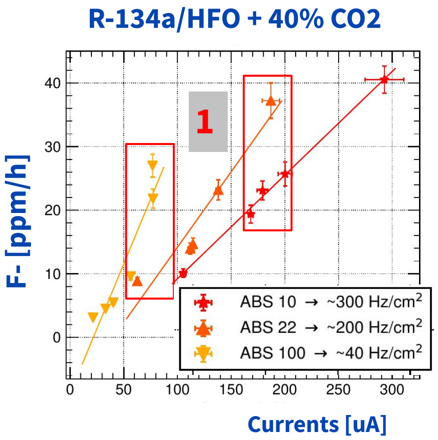
# Thank you

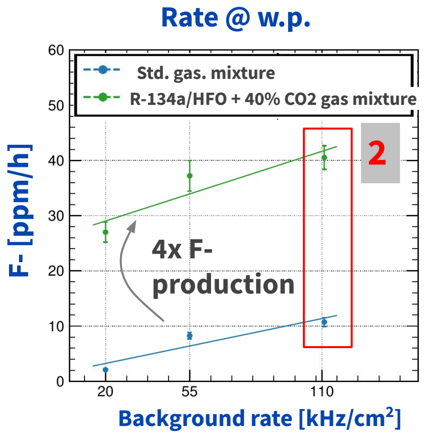
# Backup

# Impurities studies: F- measurements

**2019 ⇒ Std., HFO + R-134a + 40% CO2**

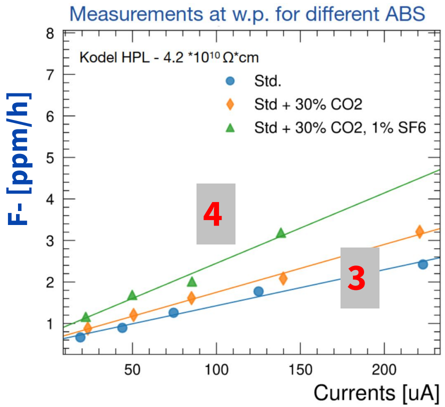
1. F- production does **not** depend **only** on the **currents** but also on the gap **electric field**
2. Tested **R-1234ze** gas mixture produced **4x more F-** than std. gas mixture

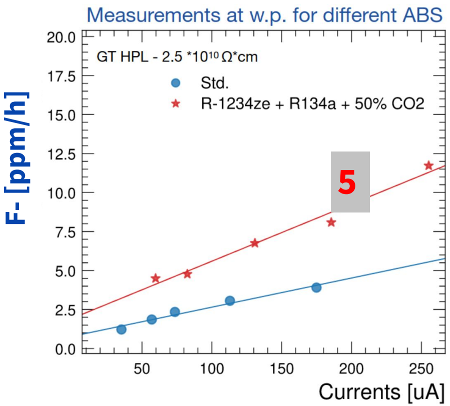



**2022 ⇒ Std, Std + CO2 (+1% SF6), HFO + R134a + 50% CO2**

3. 30% of CO2 in the standard gas mixture has the same F- production → **F- production** not **proportional** to R-134a
4. Using **1% SF6** to 30% CO2 + R-134a increases the **F- production** → under investigation
5. HFO + R134a + 50% CO2 produces **4x more F- than Std**

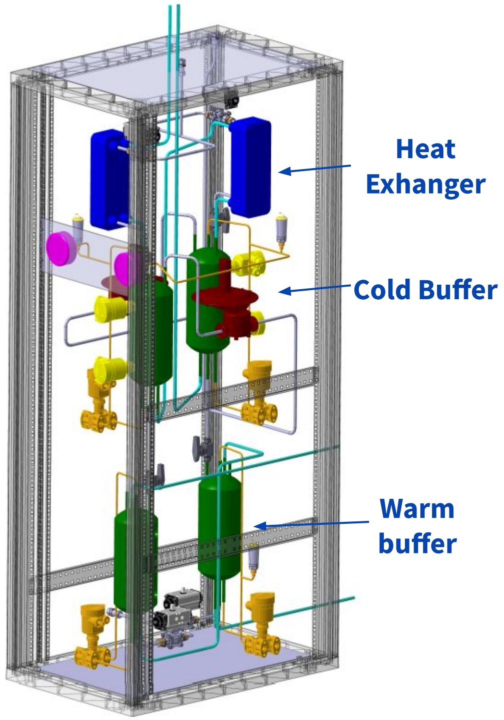


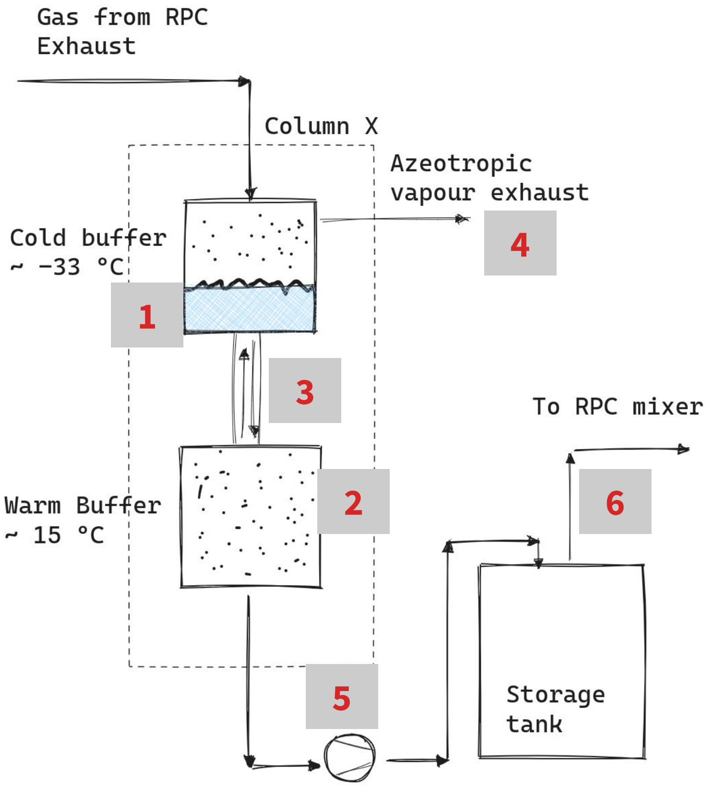



# R-134a Recuperation system

## Working design

1. **Gas mixture** completely cooled down **to liquid** in a “cold” buffer
2. **Liquid** mixture slowly heated up **to gas** into a “warm” buffer
3. Small thermodynamic **equilibrium** steps between **vapour** and **liquid**
4. **Azeotropic** vapour **exhausted** from cold buffer through a pressure controller
5. **R-134a liquid extracted** from cold buffer with a compressor
6. Compressor stores liquid in a tank ⇒ reused from CMS RPC mixer



# R-134a + R-1234ze + CO2/He gas mixtures @ GIF++

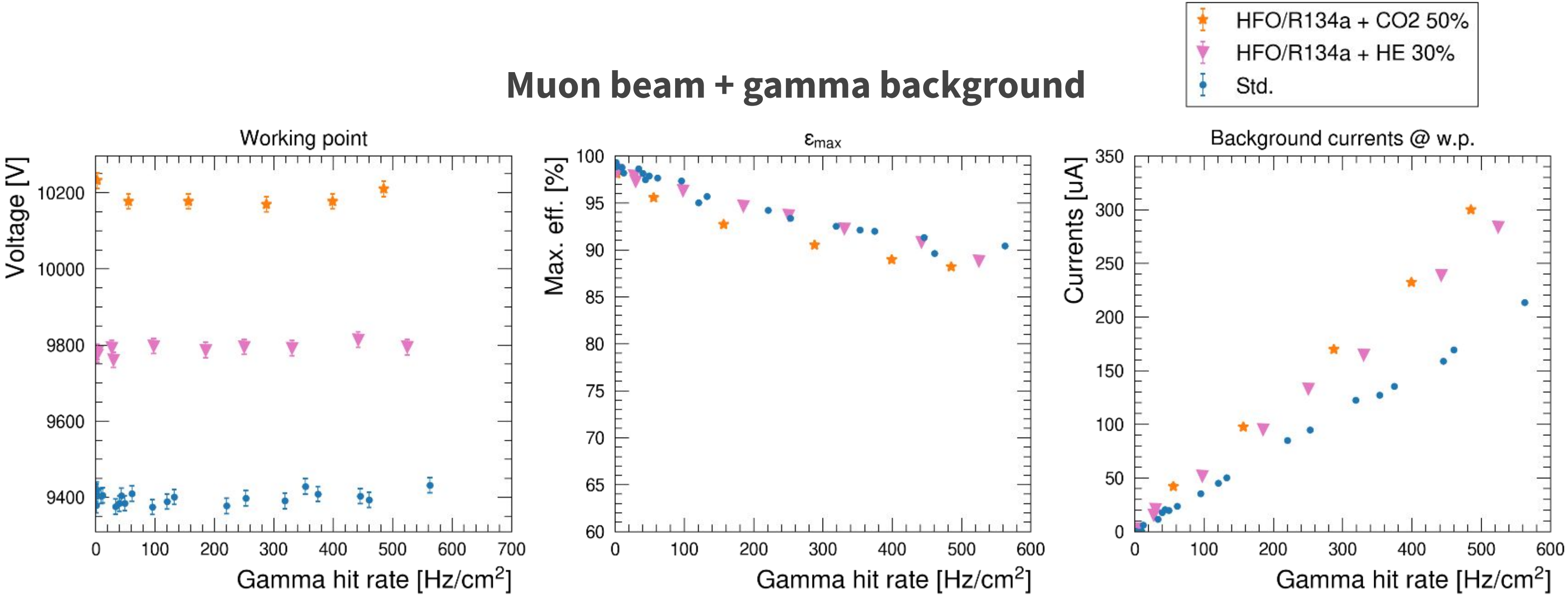
R-134a + R-1234ze: two gas mixtures at high rates (1 **CO2 50%**, 1 **He 30%**):

**He** gas mixture has lower working point than **CO2** one

**CO2 + R-1234ze** gas mixtures have slightly higher **efficiency drop** (-2 %)

**He** gas mixture has slightly lower currents than **CO2** equivalent

## Muon beam + gamma background



# HFO flammability tests

**Safety concerning HFO usage**

- R-1234yf classified as mildly flammable → Focus on R-1234ze

**R-1234ze + i-C4H10 + 40% RH flammability test conducted:**

ISO 1056 standard flammability test (detachement + flame propagation criteria) performed by external company

**Results**

- *Mixture with **1% i-C4H10** + R-1234ze **is flammable***
- Water vapour plays an important role

HFOs alone + i-C4H10 is flammable → Effects of the CO2 on the mixtures to be understood/checked

illustration of a flame detachment with flame propagation over a distance of at least 100 mm as criterion for flammability

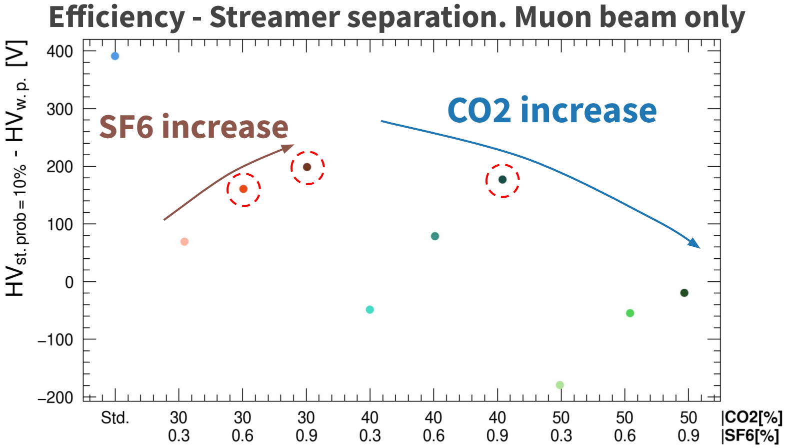
| test no. | Iso-butane fraction in test gas mixture in mol% | fraction of test gas mixture of iso-butane and HFO1234ze in mol% | fraction of air including 2.25 mol% water in mol% | reaction |
|---|---|---|---|---|
| **9** | **6.2** | **15.0** | **85.0** | + |
| 10 | 6.0 | 20.0 | 80.0 | - |
| **11** | **4.2** | **13.0** | **87.0** | + |
| **12** | **3.1** | **10.0** | **90.0** | + |
| **13** | **2.2** | **13.0** | **87.0** | + |
| 14 | 1.1 | 13.0 | 87.0 | - |
| **15** | **1.0** | **10.0** | **90.0** | + |
| 16 | 0.0 | 12.0 | 88.0 | - |
| 17 | 0.0 | 11.0 | 89.0 | - |
| 18 | 0.0 | 10.0 | 90.0 | - |
| 19 | 0.0 | 9.0 | 91.0 | - |

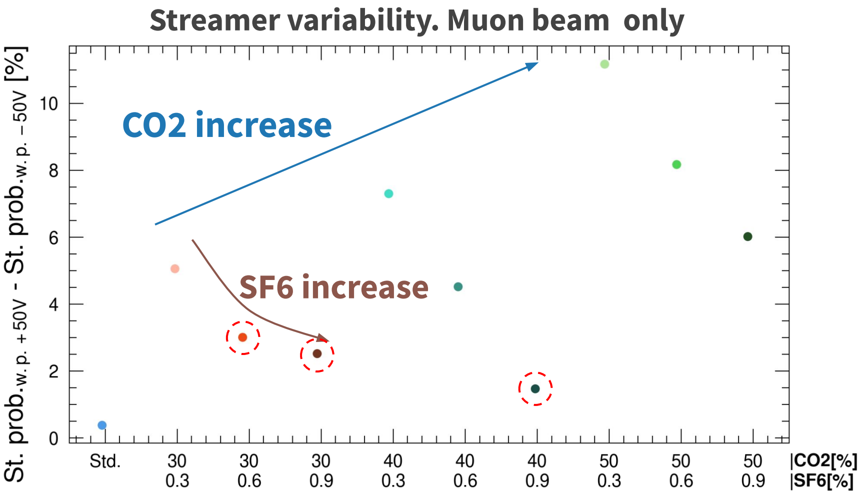
https://edms.cern.ch/document/2463340/1

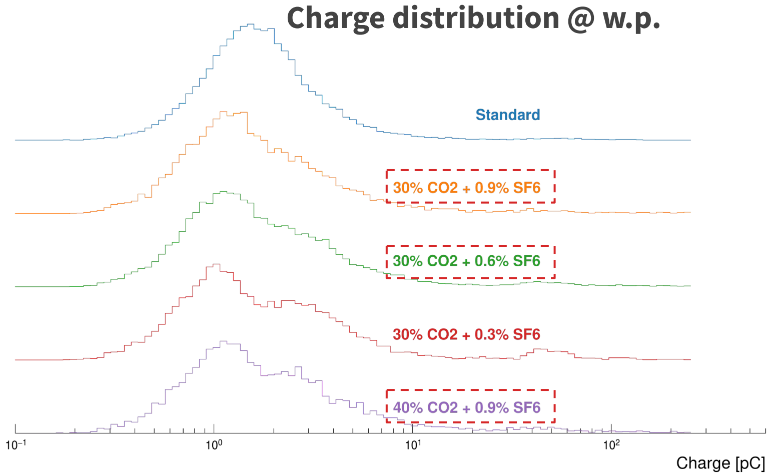
# SF6 adjustment in $CO_2$ + R-134a gas mixture

**Combination** (30%, 40%, 50%) **$CO_2$** x (0.3%, 0.6%, 0.9%) **SF6**

- Higher efficiency-streamer separation for 30%/40% $CO_2$ **+ 0.9% SF6** or 30% $CO_2$ **+ 0.6% SF6** → selected gas mixtures
- Lower variation of streamer probability for the same gas mixtures



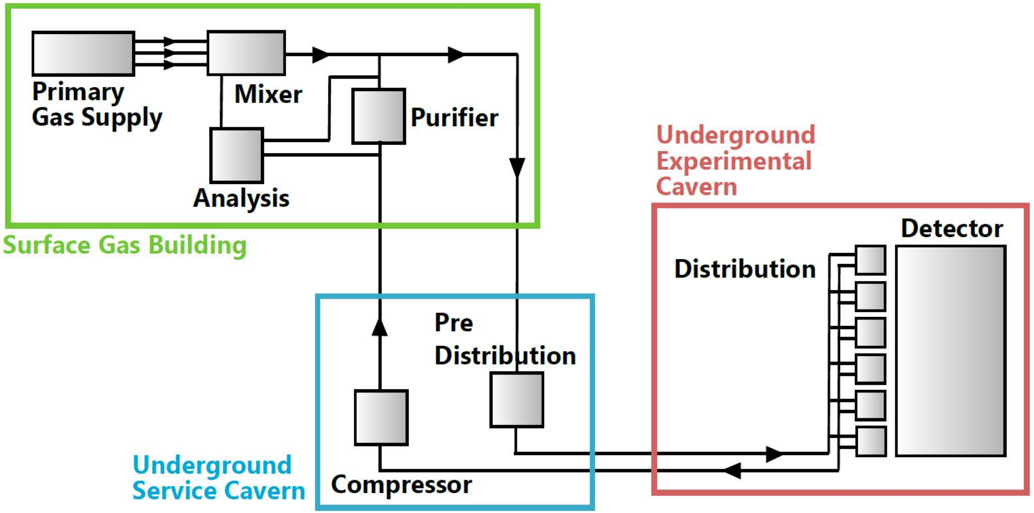



# Optimization of gas system technologies

## RPCs@LHC are operated with gas recirculation

RPC validated for 90% max. gas recirculation

Higher recirculation fractions leads to accumulation of impurities




## Optimization of gas systems

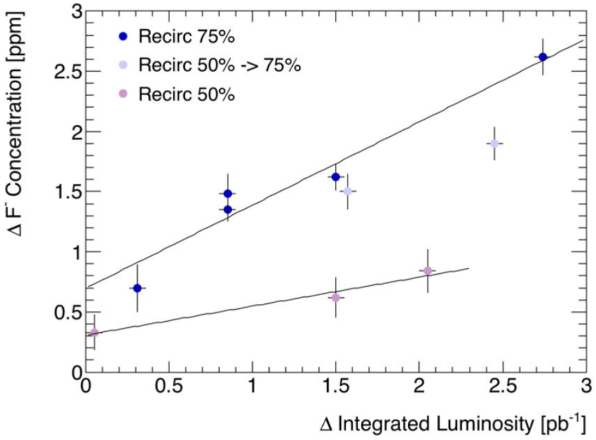
Finer granularity in gas distribution racks ⇒ ATLAS RPC, LS2

Control valves for pressure control ⇒ CMS RPC, LS2

Gas system modifications for 4 component gas mixtures ⇒ ATLAS RPC, Run 3

Recuperate remaining 10% of recirculated gas ⇒ CMS RPC, Run 3

**ALICE MID, Run 2 ISE measurement**

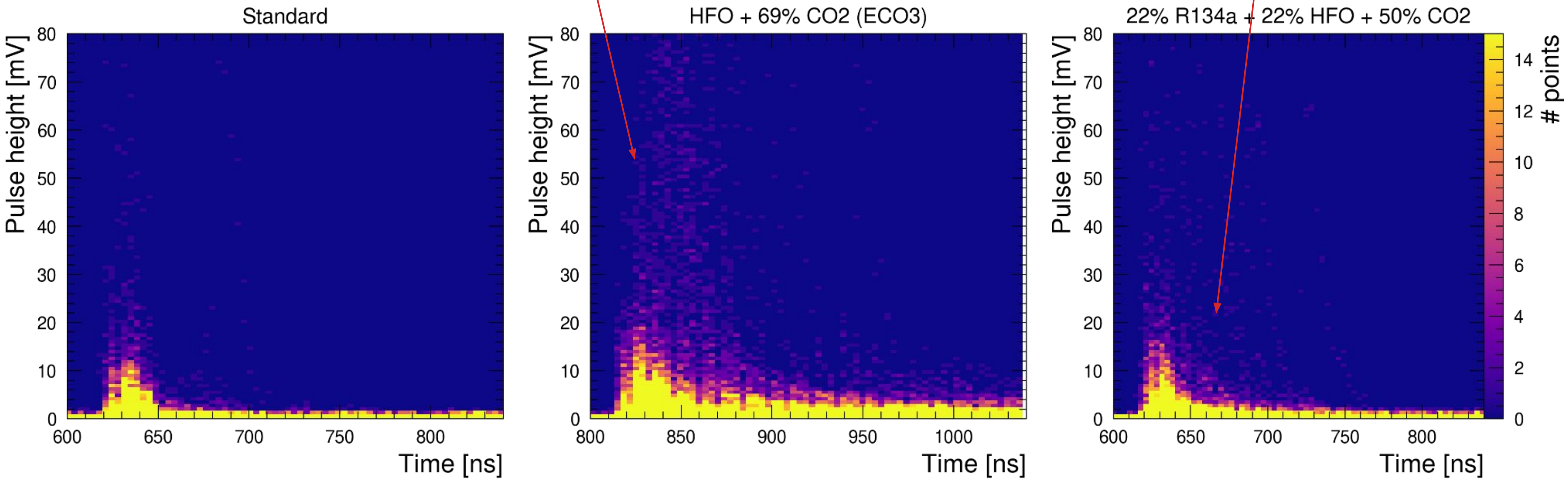


# Waveforms of Std vs. HFO vs. HFO + R134a gas mixtures

HFO only → higher charge content: bigger and longer signals

HFO + R-134a only: lower charge content and faster signals decay times

Waveforms with cosmics muons @ w.p.



# Reduction of R-134a: addition of non-fluorinated gas

**Reduction of R-134a in the standard gas mixture by addition of a 4th, non-fluorinated gas**

**$O_2$**: good performance but highly reactive → lower **flammability limit**, higher currents due to oxidation reactions

**Ne**: good performance but **no availability** on the market

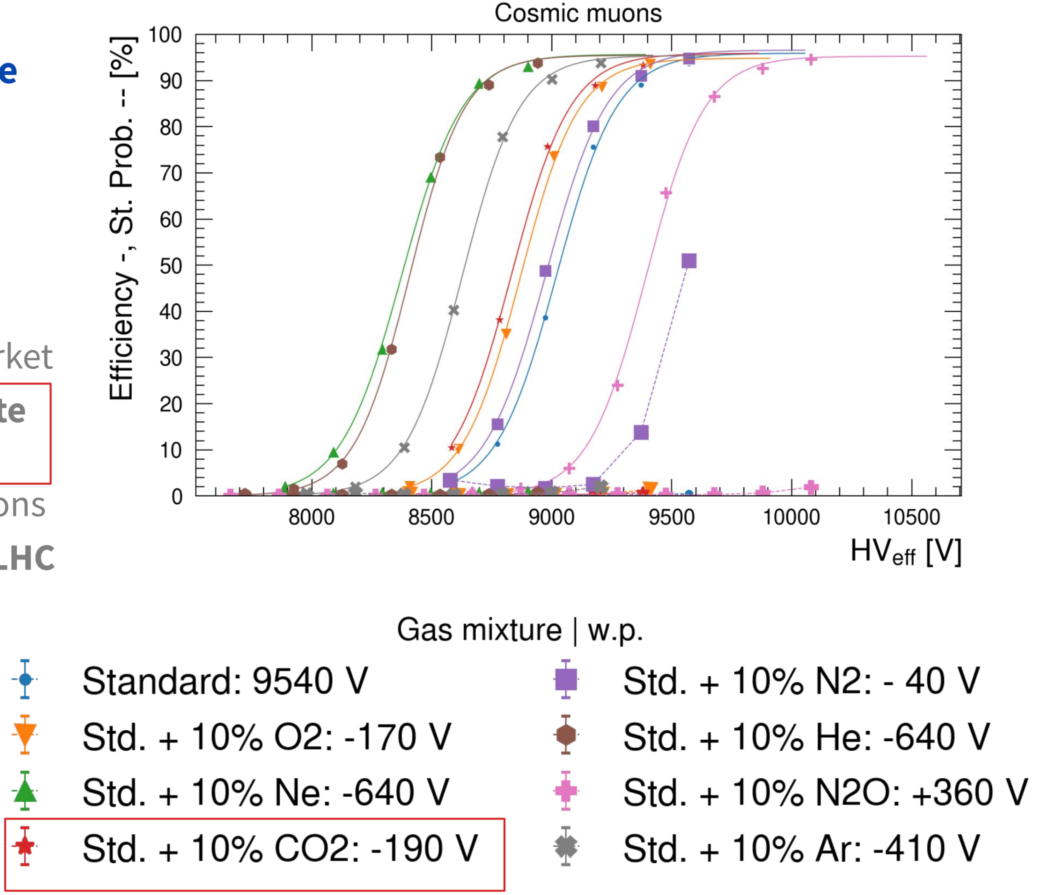
**$CO_2$**: good performance → **selected as main candidate** for GIF++ tests

**$N_2$**: **high streamer** contamination at low concentrations

**He**: good performance but **problematic for PMTs in LHC** caverns

**$N_2O$**: discrete performance but **increased working point** of ~ 300 V

**Ar**: slightly **high streamer probability**



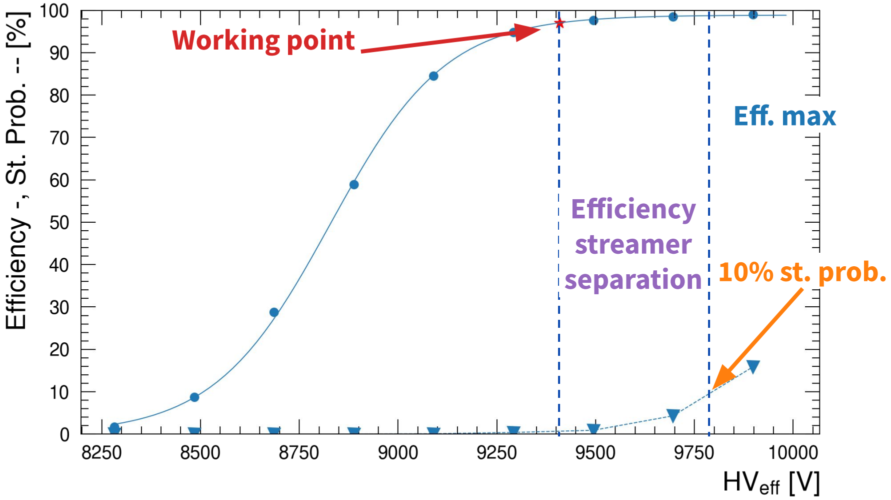
# Data acquisition and analysis

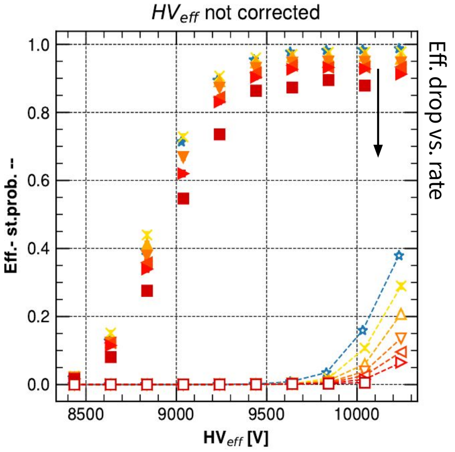
## Data acquisition

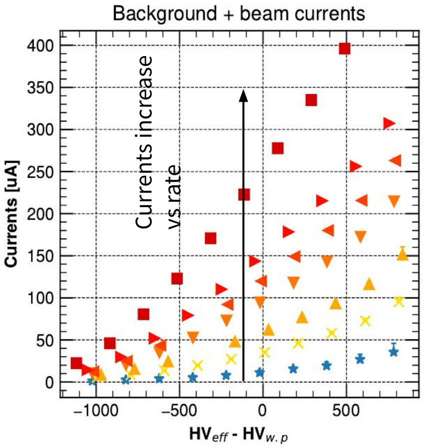
- **Raw waveform** digitizing: efficiency, charge, shape, time analysis of signals
- HV scans, ~$10^4$ trigger per HV point

## Data analysis

- When measuring MIP performance, efficiency fitted with sigmoid function
- Working point definition: **HV(95% of $\varepsilon_{max}$ ) + 150 V**
  - Used to compare different gas mixtures
- Streamers threshold @ $10^8$ $e^-$
- **Each gas mixture tested at different gamma background radiation (ABS filters)**
- Foremost parameters evaluated @ w.p. vs background rate



# Novec 4710 with R-134a/CO2 gas mixtures

**Novec 4710 + R-134a + 30% CO2 (+ 4.5% i-C4H10)**

**30% CO2 + 0.2% N4710** and **30% CO2 + 0.6% SF6** have similar performance (w.p., prompt charge, background currents)

**30% CO2 + 0.2% N4710**: lower gamma background currents

**30% CO2 + 0.6% N4710**: lower mean prompt charge but higher background currents → under investigation