Performance studies of RPC operated with alternatives to R-134a in the presence of LHC-like background radiation

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CERN | EP-DT Detector Technologies

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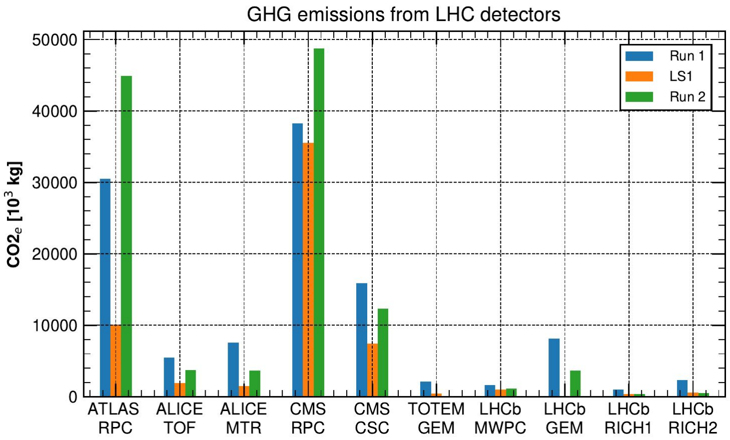
Outline

- RPCs at LHC
  - R-134a consumption
- Alternative gases to R-134a
  - R-1234ze as alternative to R-134a
  - Addition of alternative, non fluorinated components
- Addition of CO2 as a possible mitigation of R-134a consumption
  - Muon beam + Gamma background tests
- Conclusions

RPCs at LHC: R-134a consumption



RPCs at LHC are operated with 90-95% of *R-134a*

R-134 consumption during LHC Runs

Run 2: ~ **100 000 tCO2e**/year emitted from **R-134a** consumption

Early Run 3 estimates: ~ **90 000 tCO2e**/year of **R-134a**

Environmental + Economical factors

R-134a price increased of about **2.5 times** w.r.t to 2015

90 kT CO2e

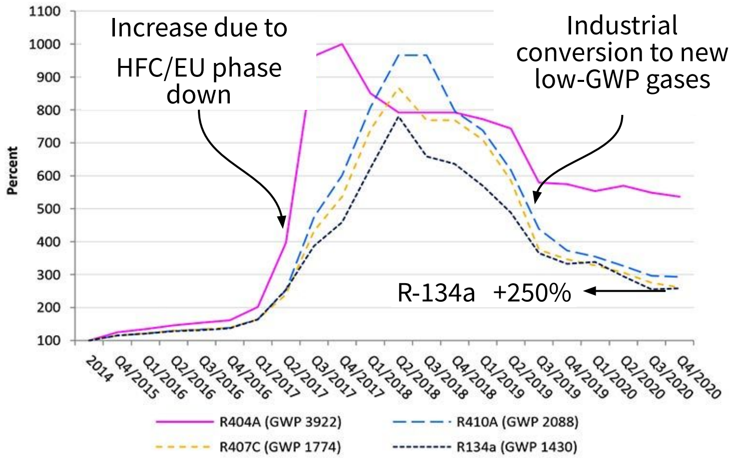
⇒ **3.5% of Geneva CO2e emissions (2019)**

⇒ **0.23% of Switzerland CO2e emissions (2018)**

19 400 cars/year

11 000 homes' energy use/year

https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator



Goal

Replace or reduce R-134a without changing the current RPC infrastructure (no change in FEB, HV, Gas system)

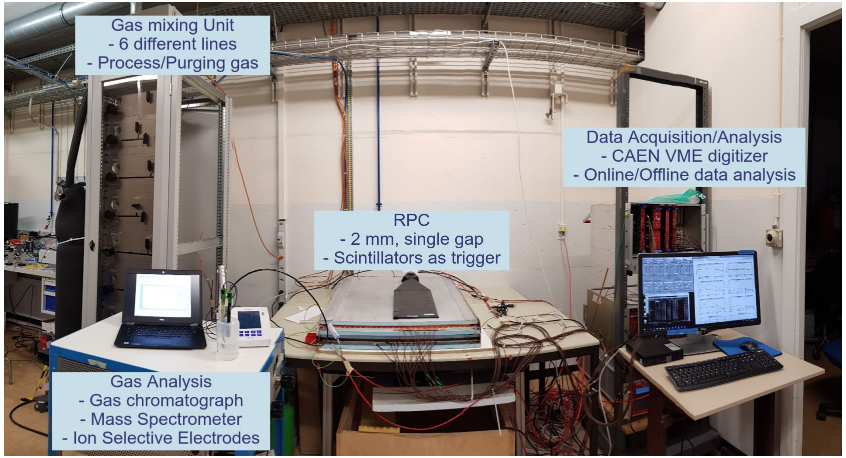
Experimental setup

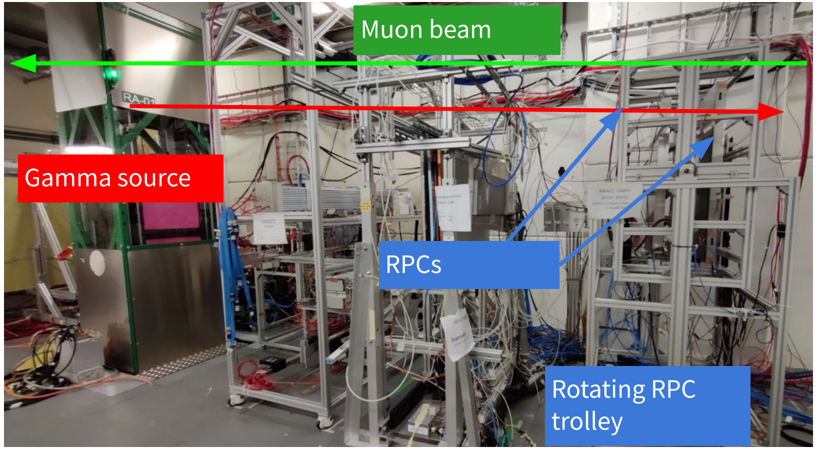
Laboratory setup

- Single gap, 2 mm electrodes + 2 mm 80x100 cm^2 gap HPL
- Tests of new gases
- Gas mixtures fine tuning: up to 6 components, 0.01% precision
- Low rates, cosmic muons
- Raw waveform analysis: efficiency, st. prob., cluster size, time resolution, prompt charge

GIF++ setup

- Muon beam + ^{137}Cs gamma source
- Gas mixtures validation:
  - Muon beam at different background rates (ABS filters)
  - Long term studies: currents stability
  - Cosmic muons measurements

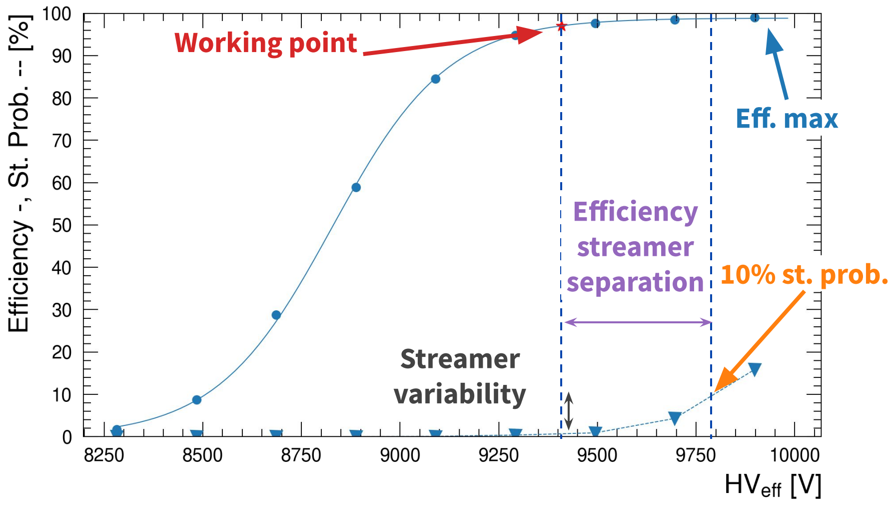




Data acquisition and analysis

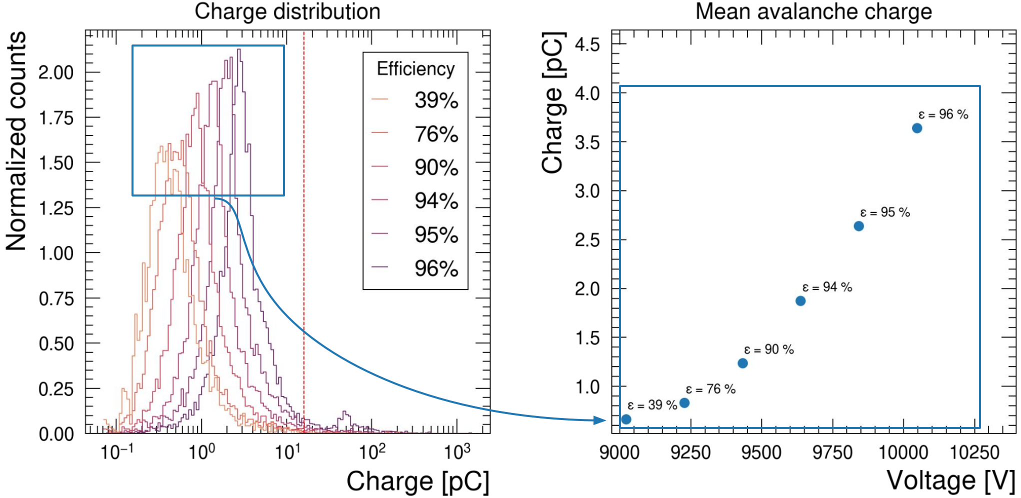
Data acquisition

- **Raw waveform** digitizing: efficiency, charge, shape, time analysis of signals
- 7 strips readout / RPC
- 2-3 RPC for **result consistency**
- HV scans: ~ 10 HV points, 10^4 waveforms for each HV point → **O(10^5-10^6)** waveforms analyzed per run



Data analysis

- Efficiency fitting with sigmoid function
- Working point definition: **HV(95% of ε_{max}) + 150 V**
- Avalanche / Streamer threshold: **10^8 electrons** ~ 16 pC
- **Efficiency-streamer separation**: $\Delta V_{w.p} - \Delta V_{10\%\ st.prob.}$, **streamer variability:** (w.p. ± 50V)
- **GIF++ tests**: foremost parameters evaluated at working point **for each ABS filter**
  - Tested up to 500-600 Hz/cm²



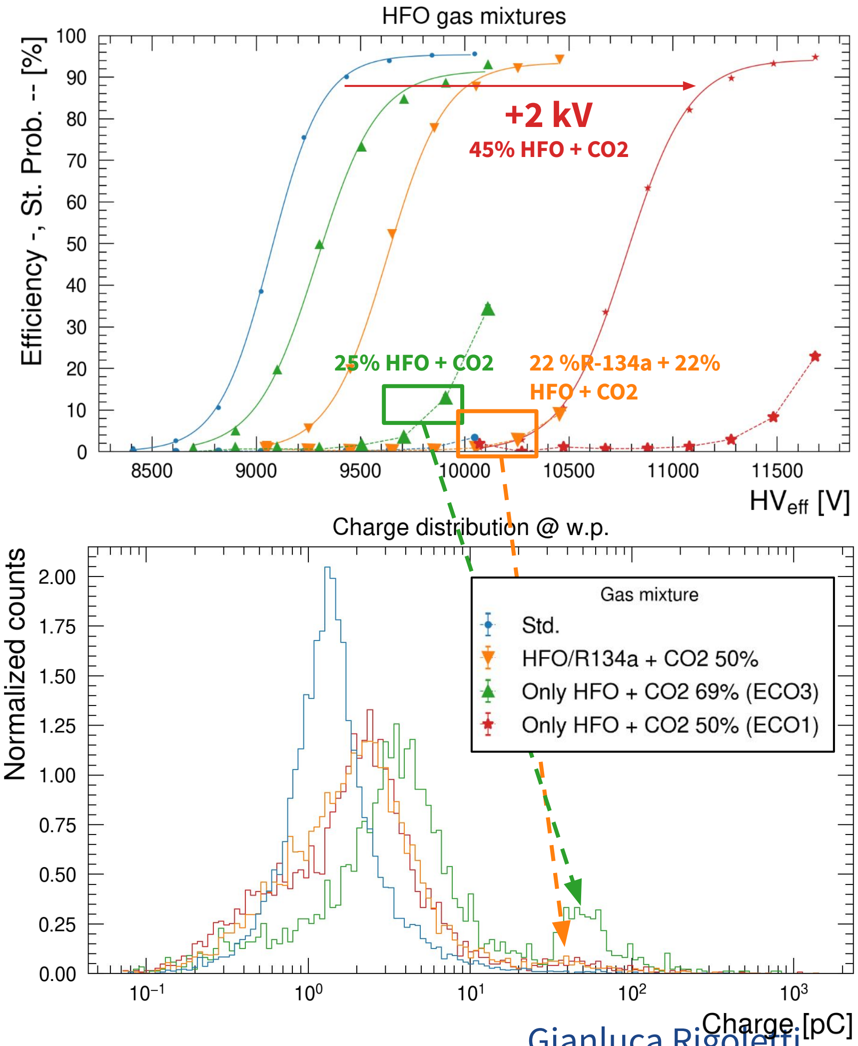
Alternative gases: R-1234ze

R-1234ze identified as possible replacement to R-134a

- Extremely **low GWP (~ 7)**
- Increasingly **wider adoption** in refrigerant industry
- However, **market price and availability** not yet comparable to R-134a → *Honeywell patented*
- **Cannot replace 1:1 R-134a** → w.p. too high → CO2/He required to lower w.p.
- **Long term effects** still under investigation

R-1234ze performance with CO2 (+ R-134a) with cosmic muons

- **45% HFO + CO2 (ECO1) ⇒** w.p. too high (~11.6 kV)
- **25% HFO + CO2 (ECO3) ⇒** low GWP, high charge content → higher currents. Currently being tested by *RPC ECOGAS collaboration*
- **22% HFO + 22% R-134a + CO2 ⇒** higher GWP, lower charge content than HFO only. **Possible compromise** between performance and environment

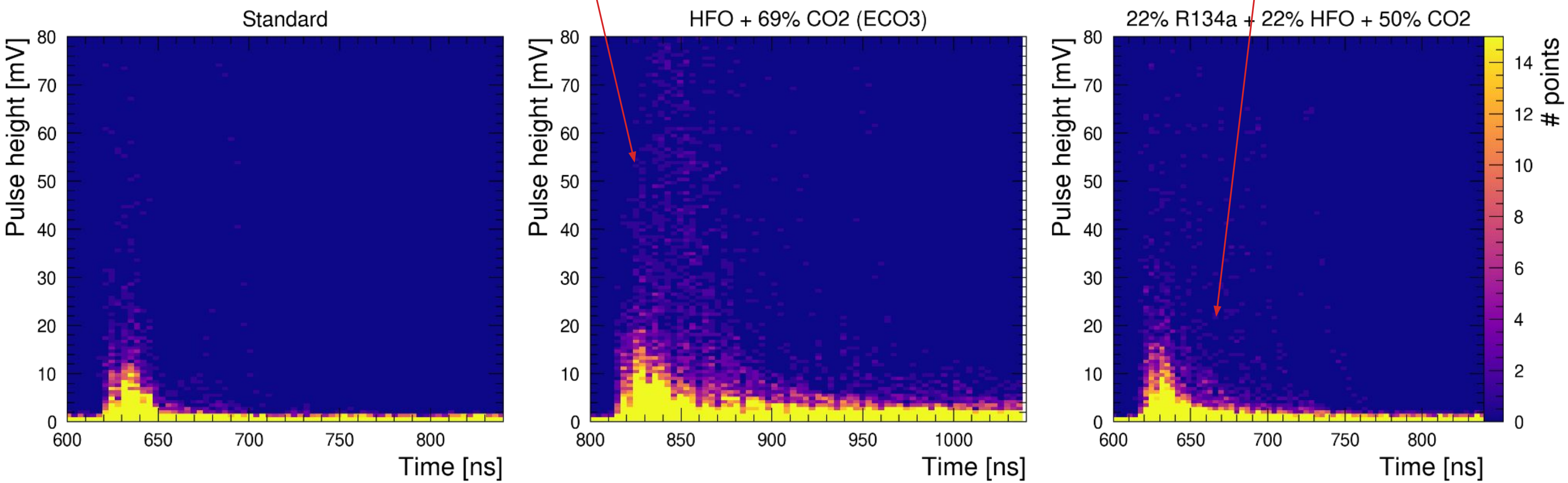


Waveforms of Std vs. HFO vs. HFO + R134a gas mixtures

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.



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

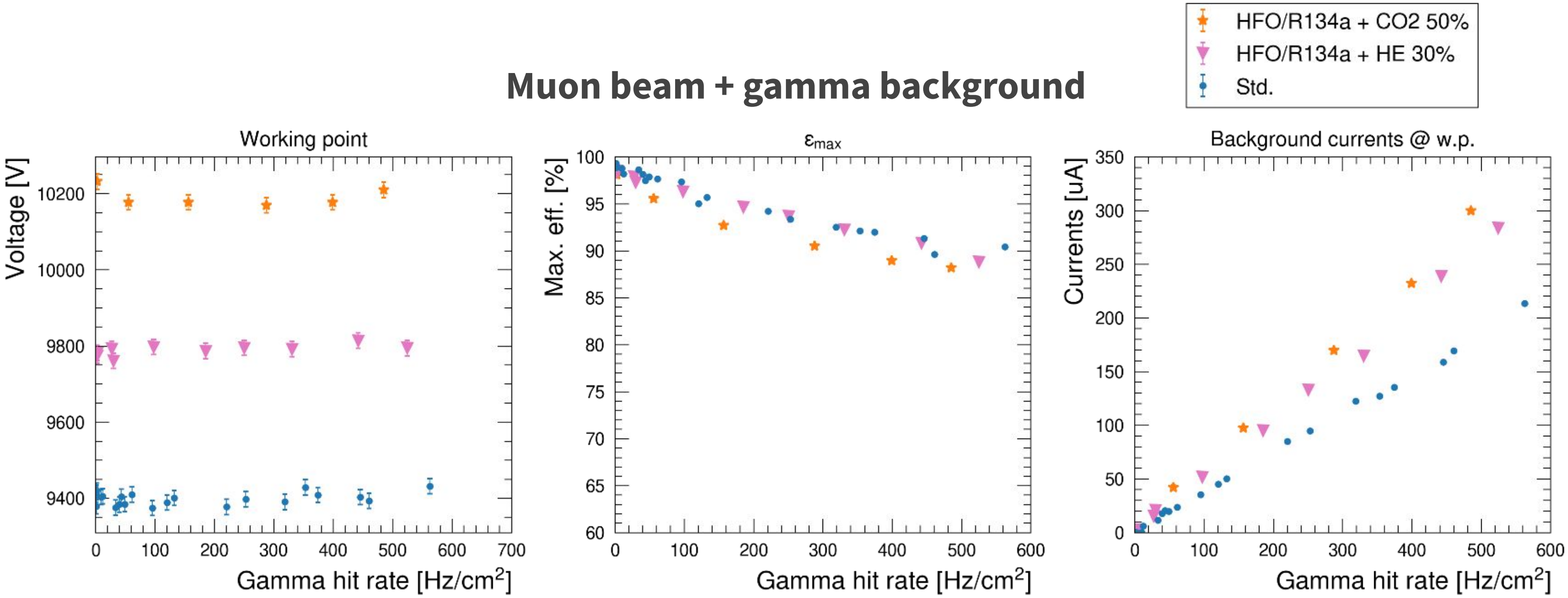
R-134a + R-1234ze: two gas mixtures at high rates (1 **CO2 50%**, 1 **He 30%**):

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

Alternative gases: reduction of R-134a consumption

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

O2: good performance but highly reactive → lower **flammability limit**, higher currents due to oxidation reactions

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

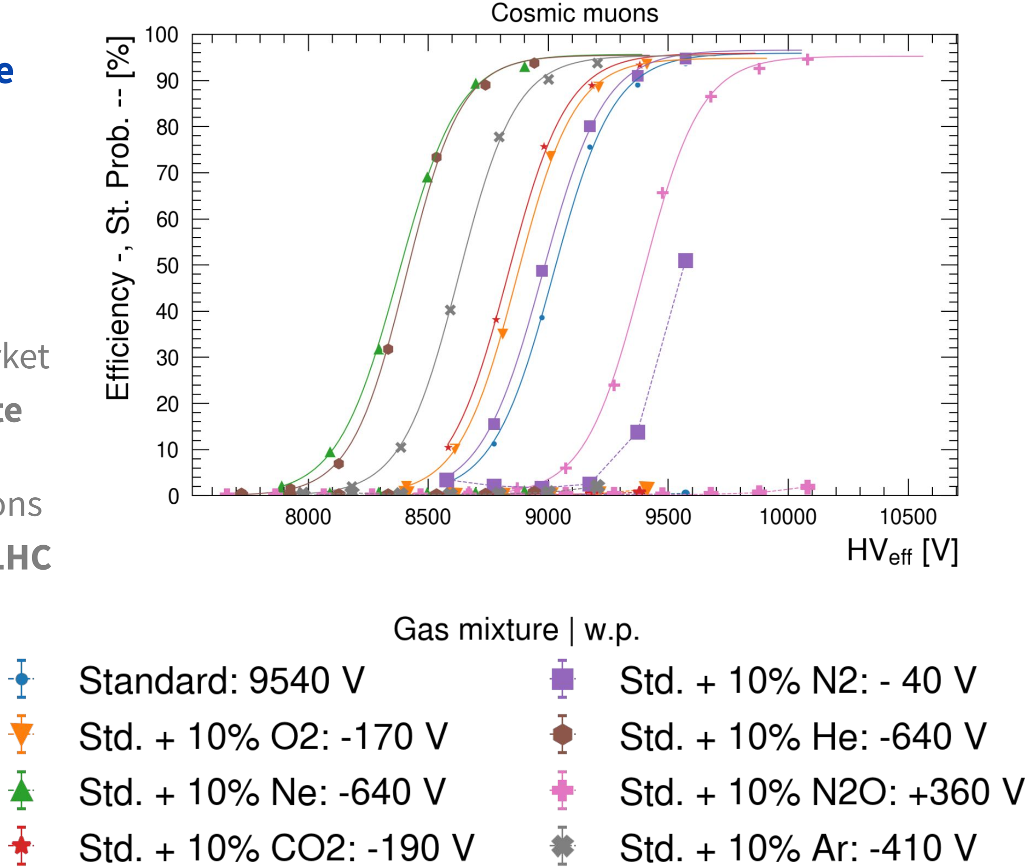
CO2: good performance → **selected as main candidate** for GIF++ tests

N2: **high streamer** contamination at low concentrations

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

N2O: discrete performance but **increased working point** of ~ 300 V

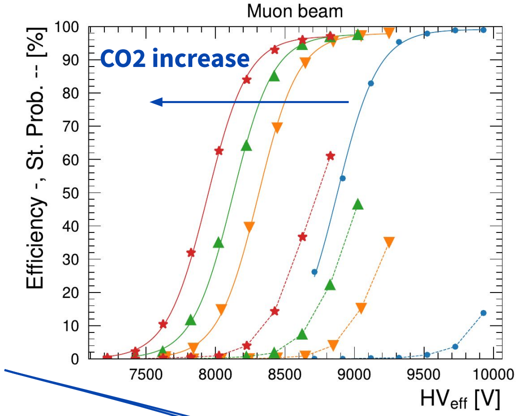
Ar: slightly **high streamer probability**

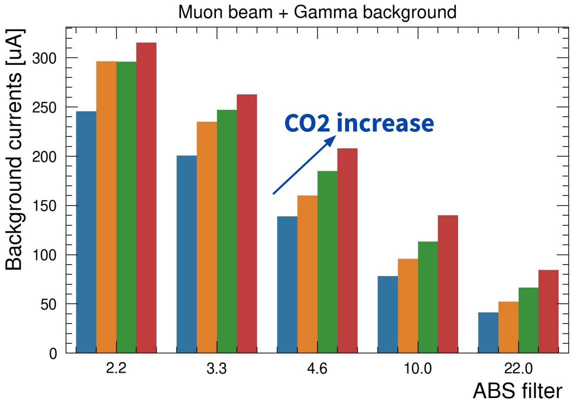


Mid-term solution to mitigate R-134a consumption

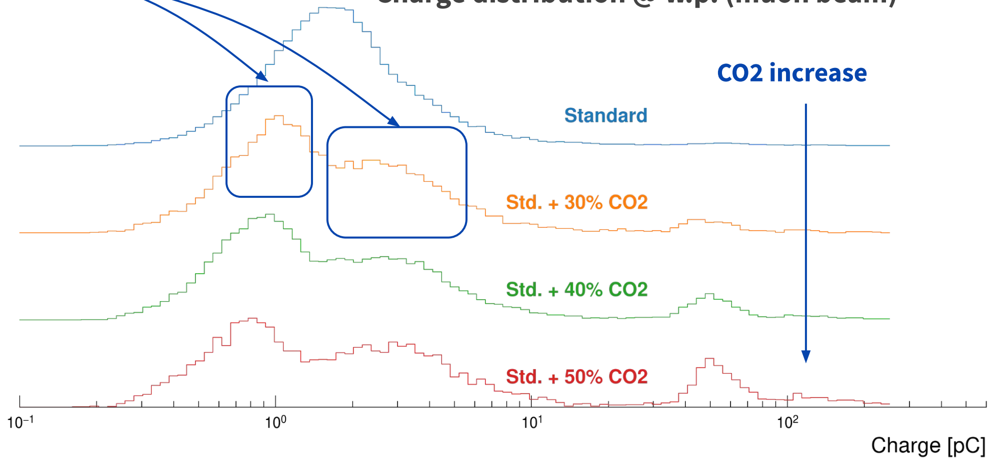
Studies on CO_2 impact when added to the standard gas mixture: 30%, 40%, 50%

- Tests performed with **muon beam** and **gamma background**
- w.p. decreases of **~ 190 V / 10% CO2**
- **GWP** reduction of **30-50%**
- **Current** increase of **+10-15%** @ 500 Hz/cm2
- **Streamer** fraction **increases**
- **Two** avalanche **populations** when using CO2 and R-134a → under investigation





Charge distribution @ w.p. (muon beam)



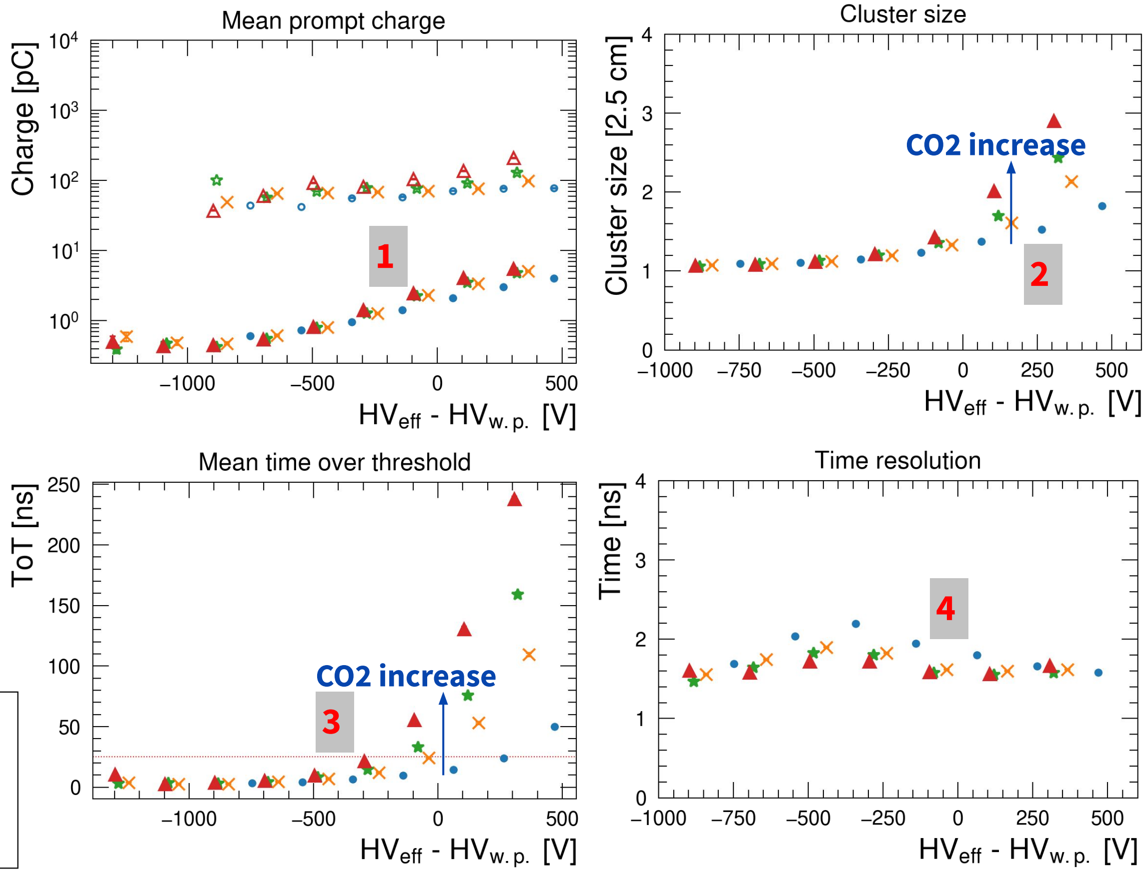
✳	Standard
▲	Std. + 30% CO2
■	Std. + 40% CO2
✸	Std. + 50% CO2

Addition of CO2 to the standard gas mixture

Addition of 30%, 40%, 50% of CO2 gas mixture as mid-term solution to mitigate R-134a. Muon beam studies

1. Average prompt charge slightly increasing (+10-15%)
2. Cluster size increases with CO2 amount
3. Average signal times over threshold increase with CO2
4. Time resolution of CO2 gas mixtures is lower than std. one

Adjustment of **SF6** needed to further suppress **streamers**

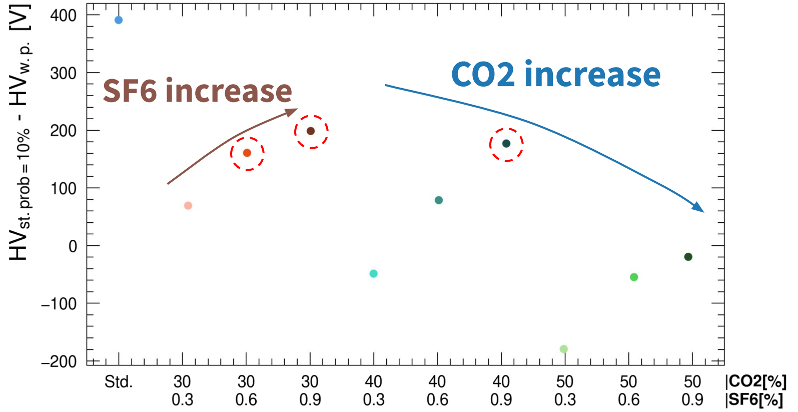


SF6 adjustment in CO2 + R-134a gas mixture

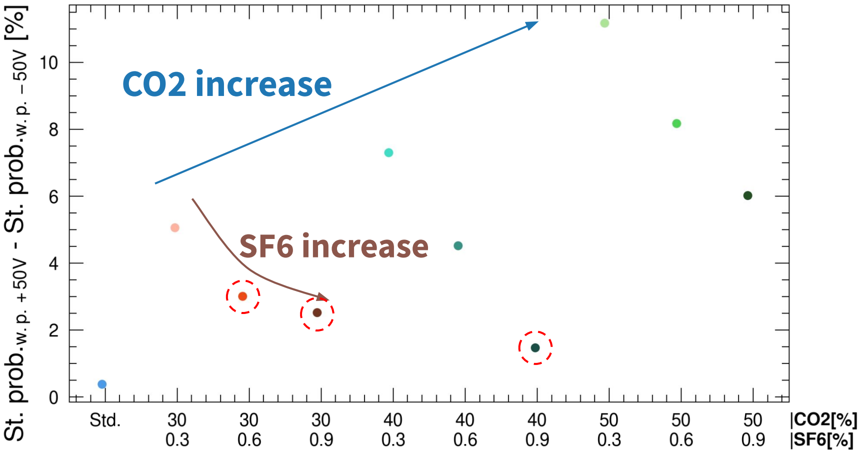
Combination (30%, 40%, 50%) **CO2** x (0.3%, 0.6%, 0.9%) **SF6**

- Higher efficiency-streamer separation for 30%/40% CO2 **+ 0.9% SF6** or 30% CO2 **+ 0.6% SF6** → selected gas mixtures
- Lower variation of streamer probability for the same gas mixtures

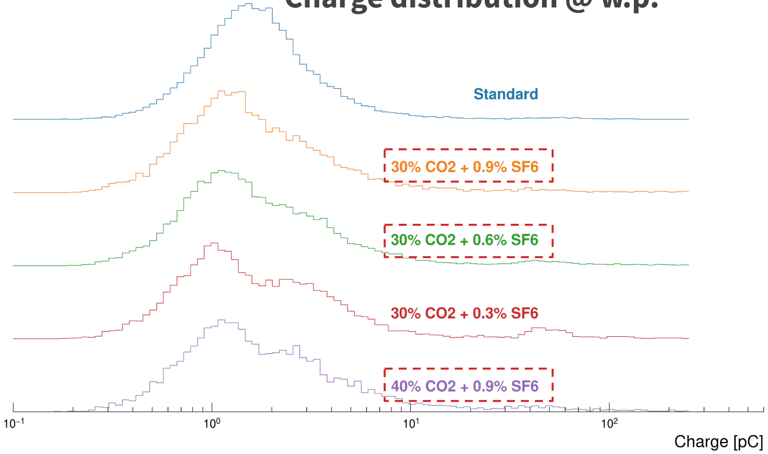
Efficiency - Streamer separation. Muon beam only



Streamer variability. Muon beam only



Charge distribution @ w.p.



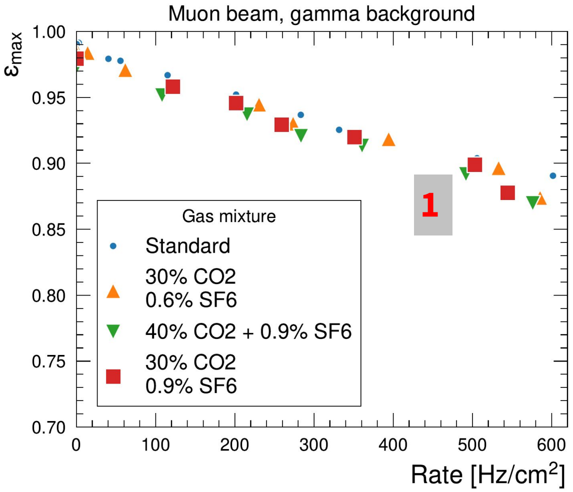
Selected CO2-based gas mixtures

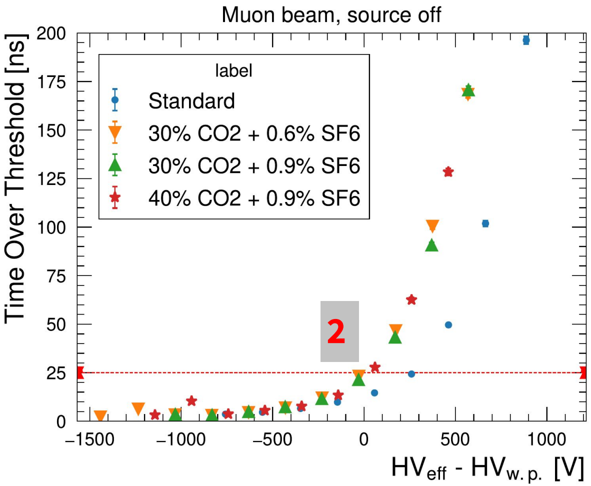
Selected CO2/SF6 gas mixtures

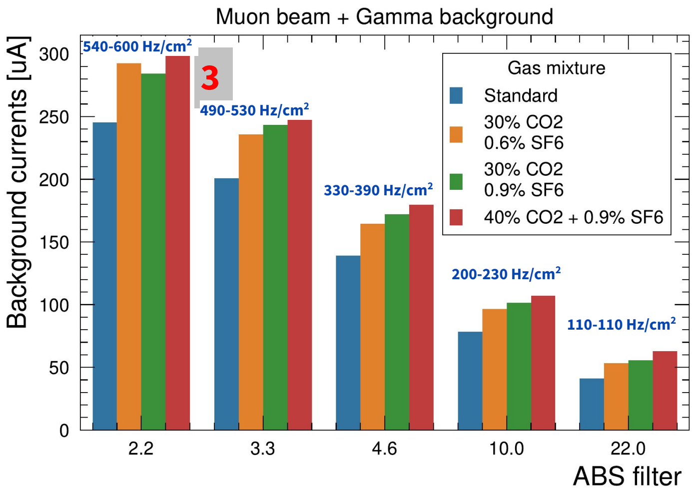
- **30% CO2 + 0.6% SF6**: overall good performance
- **30% CO2 + 0.9% SF6**: best performance but higher SF6 consumption
- **40% CO2 + 0.9%**: slightly worse performance (cluster size, ToT) but higher R-134a reduction

Observed performance

1. Efficiency drop similar to std. gas mixture up to 500 Hz/cm^2
2. Mean time over threshold below 25 ns for 30% CO2 gas mixtures
3. Currents at fixed ABS around 15-20% higher







Conclusions

Alternatives to R-134a

R-1234ze current main fluorinated alternative

- Needs to be used with a **4th gas** to keep "low" working point
- **SF6** concentration needs to be increased to ~ 1%
- **Market availability** and **price** still a matter of concern
- Still requires understanding of its **effects** on **long term operation** of RPC

Non fluorinated alternatives

- Several gas tested: N2, N2O, O2, Ne, He, CO2, Ar
- They cannot replace R-134a but **mitigate** its **consumption**
- **CO2 selected**: availability, price, good performance, known effects on other detectors

Addition of CO2 to mitigate R-134a consumption

- 30%, 40%, 50% of CO2 added to the standard gas mixture: **good performance** but **SF6** concentration needs to be **increased**
- 0.3%, 0.6%, 0.9% of SF6 tested for each CO2 concentration: few combinations selected
- **Foremost parameters** of selected CO2 + SF6 gas mixture **similar** to **standard gas mixture**
  - Only background currents found to be **15-20% higher** probably due to **avalanche mean prompt charge**

30-40% CO2 + 0.6%-0.9% SF6 are promising short to mid-term gas mixtures for RPC @ LHC experiments

Thank you

Backup

GWP calculation

GWP for a single gas is well defined: it is a measure of how much energy the emissions of **1 ton** of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO2)

Gas mixture is expressed in fractions of normal volume → proportional to number of moles → molecular weight

GWP of gas mixture: $(\Sigma GWP_i * M_i * f_i) / M_{CO2}$, where M is molecular mass and f the amount of the gas in the mixture

Example:

Suppose RPCs are operated with 1000 ln/h of CO2. After one year the tons of CO2 are:

1000 ln/h * 8760 h / 22.4 l/mol * 44 g/mol = **17.2 tons**

Suppose RPCs are operated with 70% R-134a and 30% CO2. If we simply do the proportion we would get: 1430 * 0.7 + 1* 0.3 = **1001** of GWP → *wrong estimation*

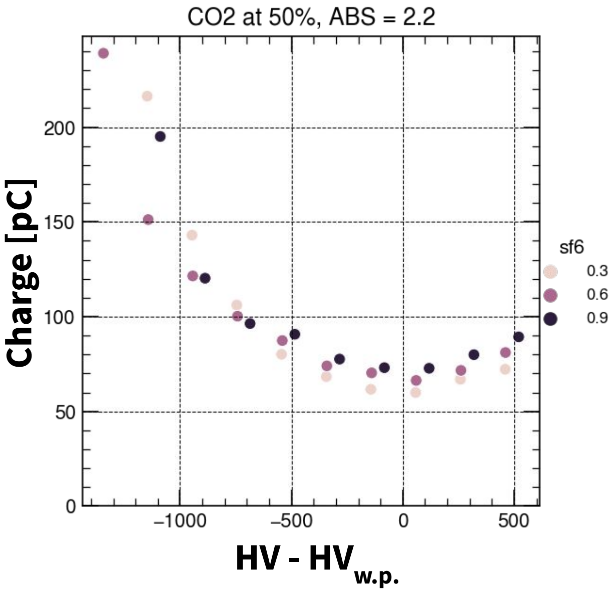
After one year the equivalent tCO2e are:

- **CO2**: 300 ln/h * 8760 h / 22.4 l/mol * 44 g/mol = 5.2 tons
- **R-134a**: 300 ln/h * 8760 h / 22.4 l/mol * 102 g/mol * 1430 = **39.9 kTons**

⇒ 39.9 ktCO2e ⇒ GWP_e = 39.9 ktons / 17.2 tons = **2320 GWP_e**

This results are because detectors and gas systems are operated using **normal volume units** and not mass of the gases

Gamma charge per count



Gas coefficients