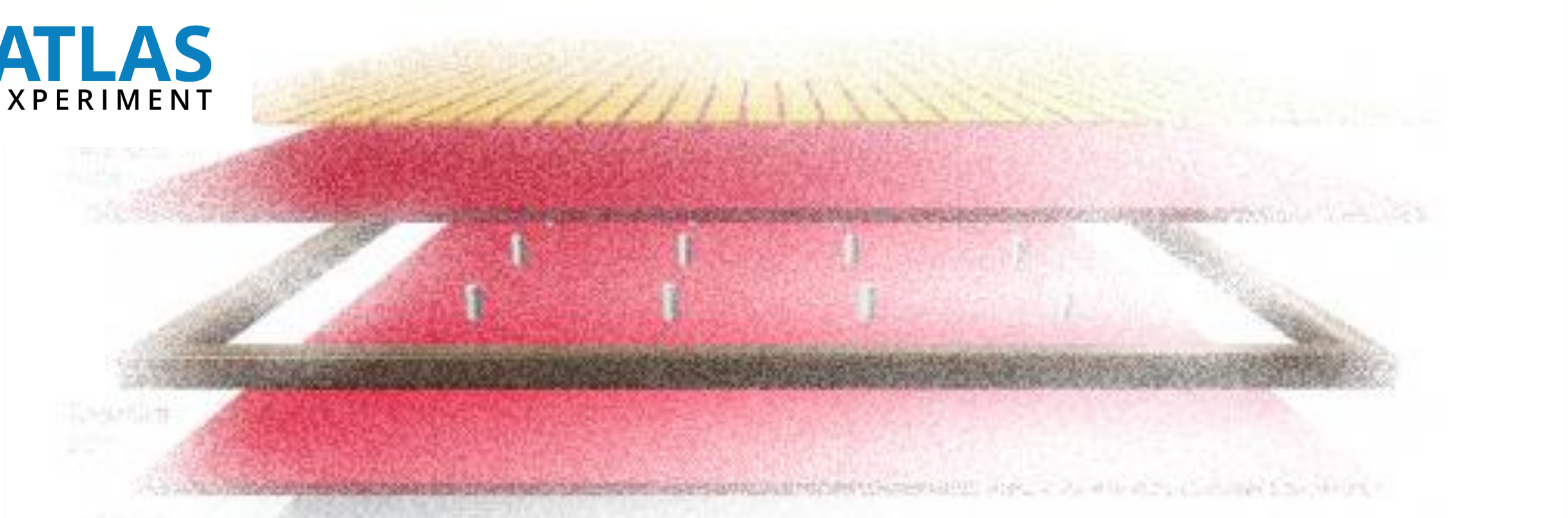


Matching sustainability and detector longevity for ATLAS RPCs in HL-LHC runs

Sinem Simsek on behalf of the ATLAS Muon Community

SustainableHEP
08 – 10 July 2026

RPC Standard Gas Mixture

RPCs are gaseous detectors used for muon triggering in several LHC experiments.

RPC

Experiment	Gas Mixture Components & Approximate Fractions
ATLAS	~94.7 % R-134a, 5.0 % i-C_4H_{10}, 0.3 % SF_6
CMS	~95.2 % R-134a, 4.5 % i-C_4H_{10}, 0.3 % SF_6
ALICE	~89.7 % R-134a, 10 % i-C_4H_{10}, ~0.3 % SF_6

Gas selection for stable detector performance:

- High efficiency
- Avalanche stability
- Low dark current
- Prevention against ageing effects

for 10 years of LHC operation

R-134a and SF_6 have high global-warming potentials (GWPs) and regulations/operational costs motivate replacements.

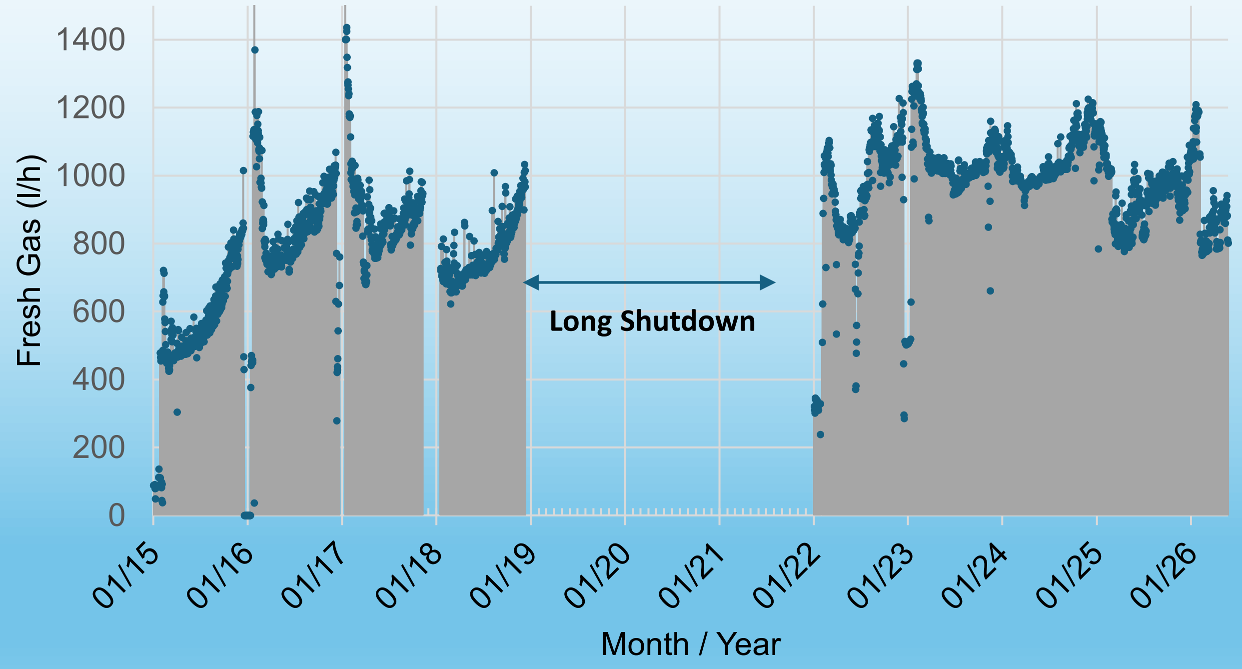
	Fraction (vol. %)	Role in the RPC Mixture	GWP (100 yr, IPCC AR6)
	R134a ($C_2H_2F_4$)	Main ionizing gas with high electron density	1,430
	iC_4H_{10}	Photon absorber (prevents discharge propagation)	3
	SF_6	Electron absorber (prevent streamers)	24,300

GWP of the Mixture ~ 1426

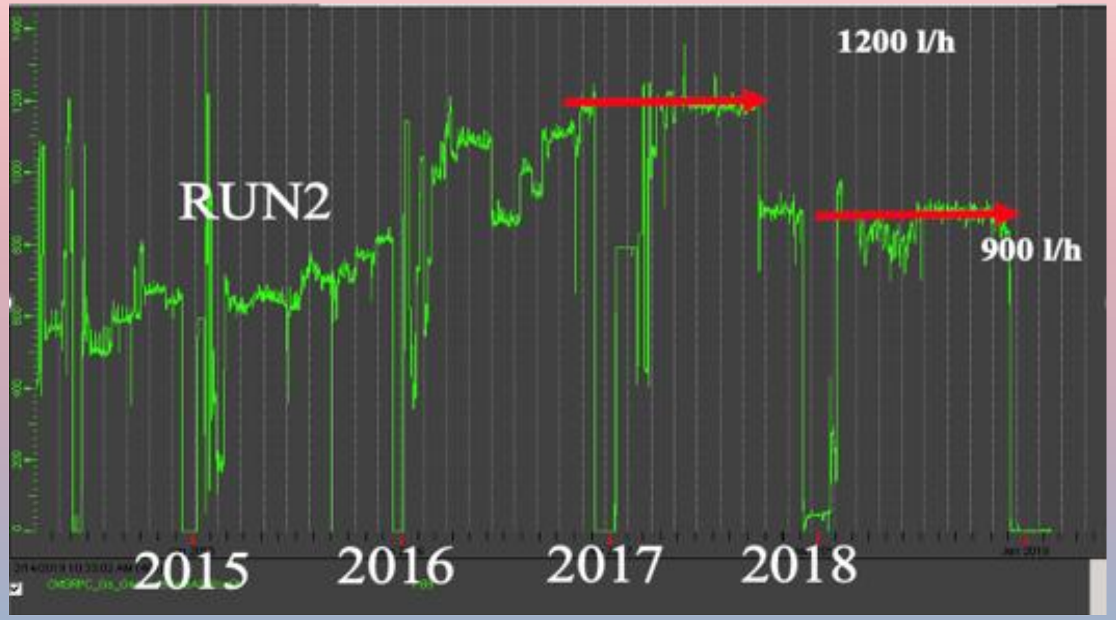
ATLAS & CMS Gas Consumption

- ATLAS and CMS RPC systems are among the largest greenhouse-gas contributors in detector operations, mainly affected by **gas leak** due to **intrinsic fragility of the gas inlets.**

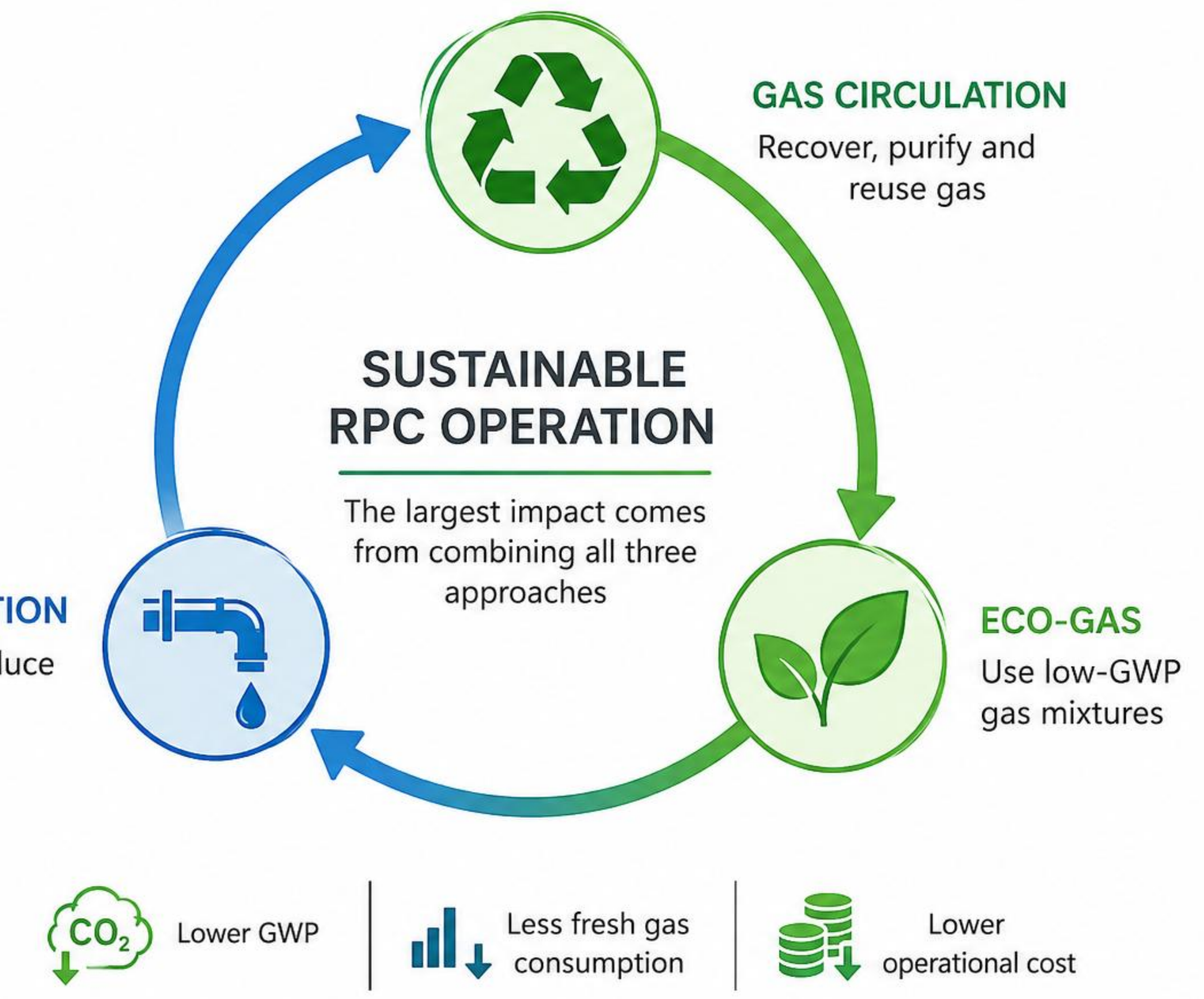
ATLAS RPC leak rate is 500-1400 l/h depending of the period of the year



CMS RPC leak rate was from ~ 600 L/h to 1200 L/h during Run 2.



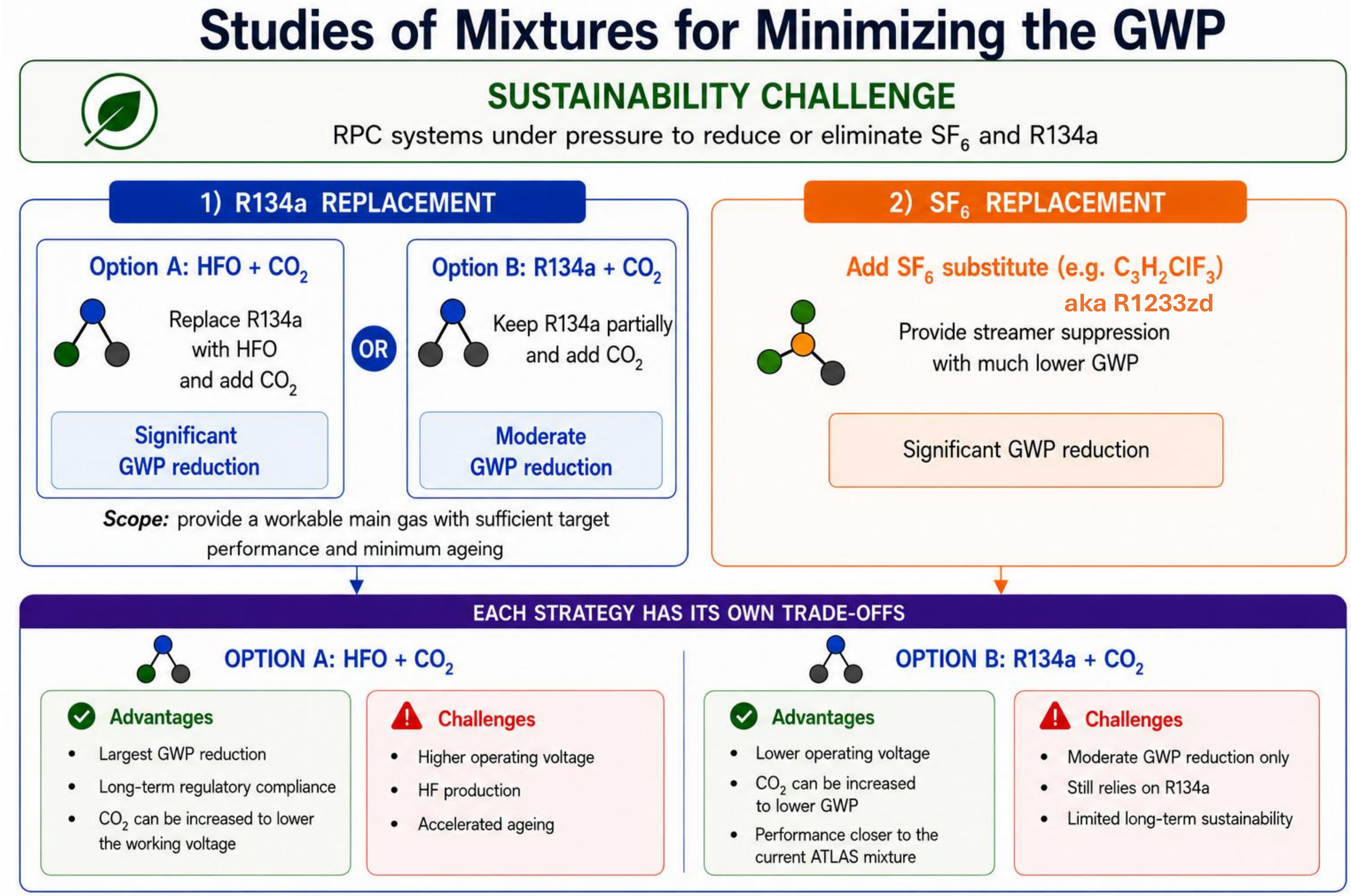
*G. Pugliese, "DRD1 Greenhouse Gas Task", 1st DRD1 Collaboration Meeting, CERN (2025)



Environmental Impact = Gas Consumption x GWP

- The solution can be achieved either by drastically reducing one of these factors or by significantly reducing both.
- Our current strategy addresses both factors to reduce the risk of not being able to fully achieve either one.

There is no universal solution. The optimal strategy depends on the detector technology and on the desired balance between environmental benefit and detector performance.



New Gas Mixtures for the Existing RPC System

ATLAS RPC gas search strategy: balancing detector performance and environmental compliance while controlling ageing effects

- Replace a fraction of **R134a** (GWP: 1,430) with CO_2 (GWP: 1)
- Reduce the **SF_6** (GWP: 24,300) fraction as much as possible by replacing it with **R1233zd** ($C_3H_2ClF_3$, GWP: ~4)

with 50 cm x 50 cm ATLAS-like RPC detector →(2 mm gas gaps, same Front-End technology, same faraday cage)

Aug 2023 – February 2025 the ATLAS RPCs were operated with a new gas mixture:
- **Mixture**: 64 % R134a - 30% **CO_2** - 5% iC_4H_{10} - 1% **SF_6** **(GWP ~ 1159)**

Environmental impact was reduced by ~ 19%

Since January 2025 the ATLAS RPCs are operated with a new gas mixture:
- **Mixture**: 64.5% R134a - 30% **CO_2** - 5% iC_4H_{10} - 0.5% **SF_6** **(GWP ~ 1044)**

Environmental impact is reduced by ~ 27%

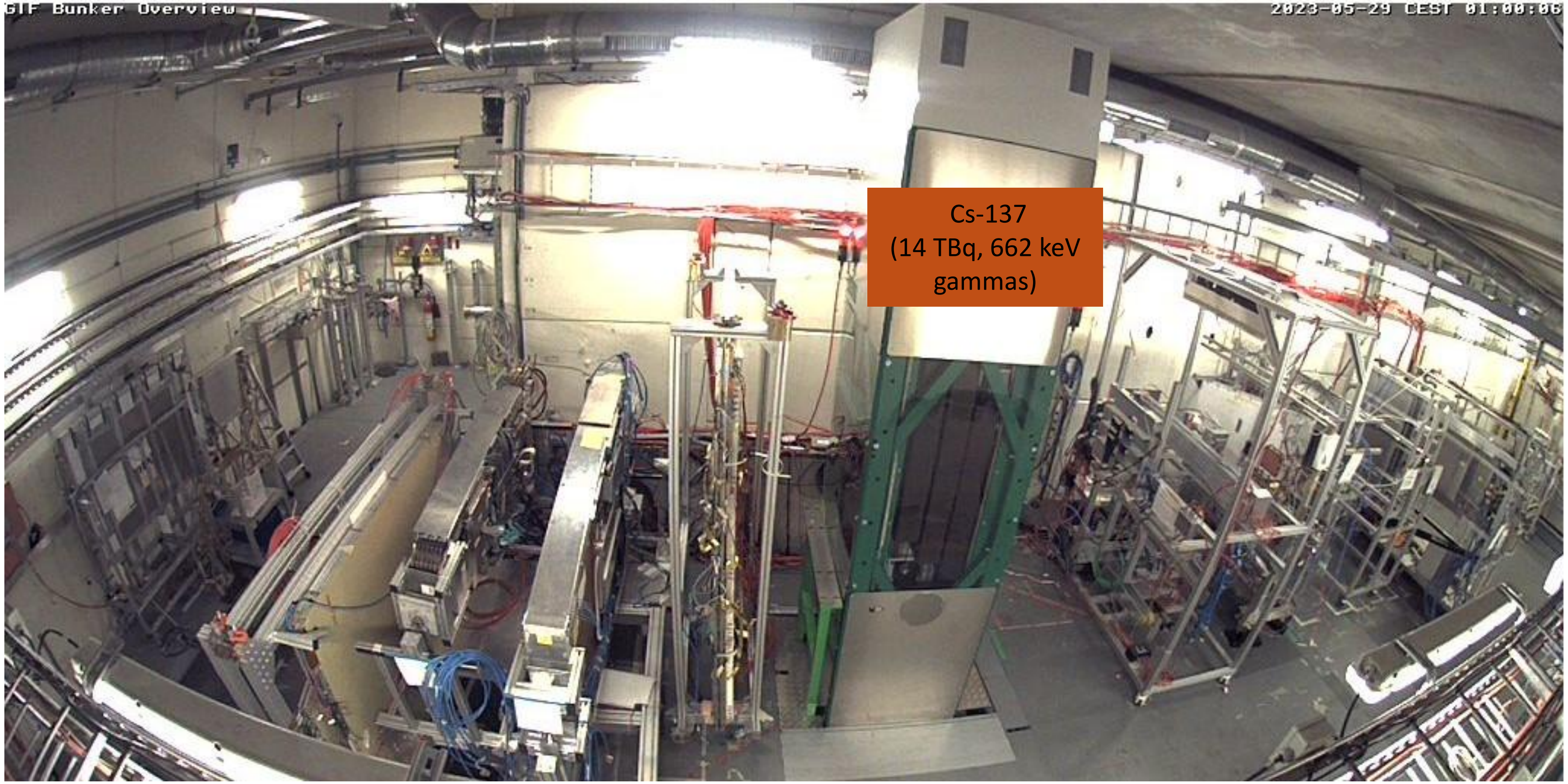
The candidate gas mixture for Run-4:
- **Mixture**: 63% R134a - 30% **CO_2** - 5% iC_4H_{10} - 2% **R1233zd** **(GWP ~ 901)**

Environmental impact is reduced by ~ 37%

Future Challenge:
- **Mixture**: 52% R134a - 40% **CO_2** - 5% iC_4H_{10} - 3% **R1233zd** **(GWP ~ 744)**

Environmental impact is reduced by ~ 48%

Test Area: CERN Gamma Irradiation Facility (GIF++)



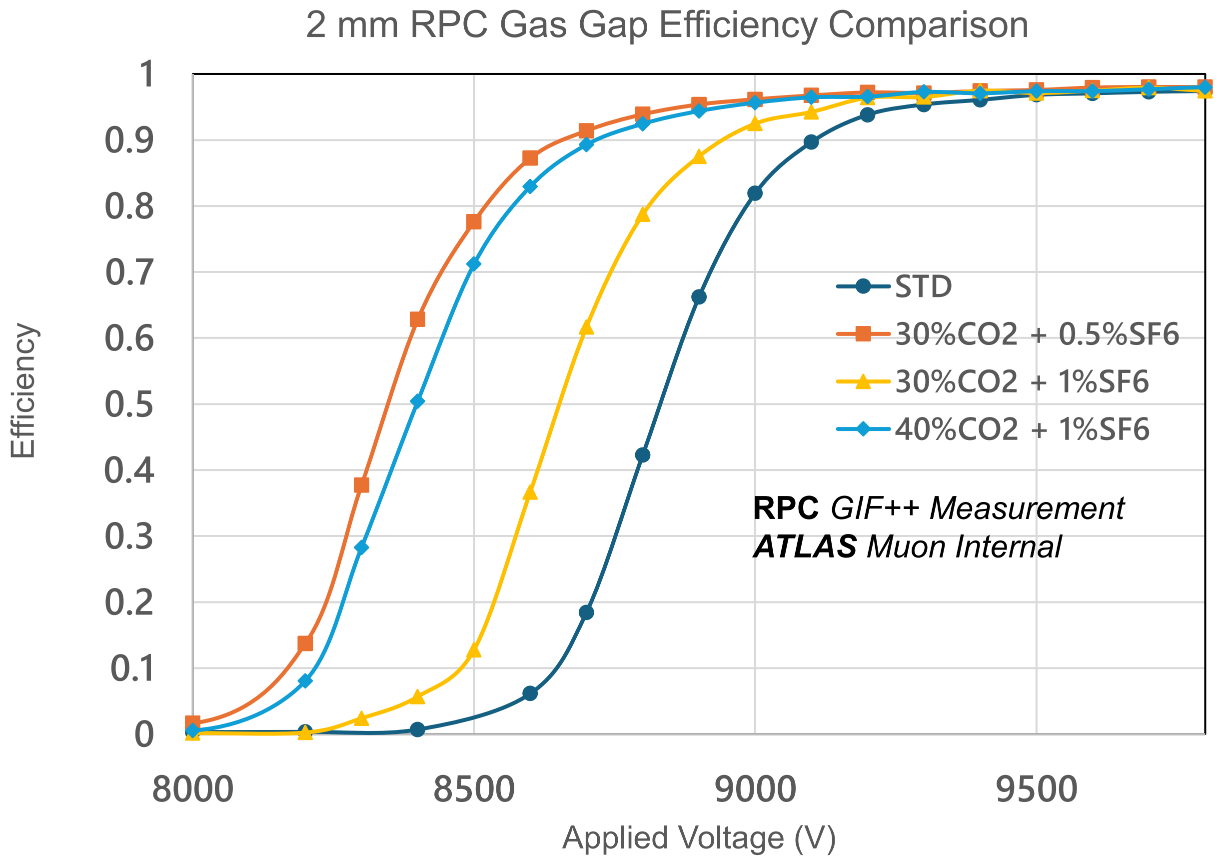
ATLAS RPC Setup

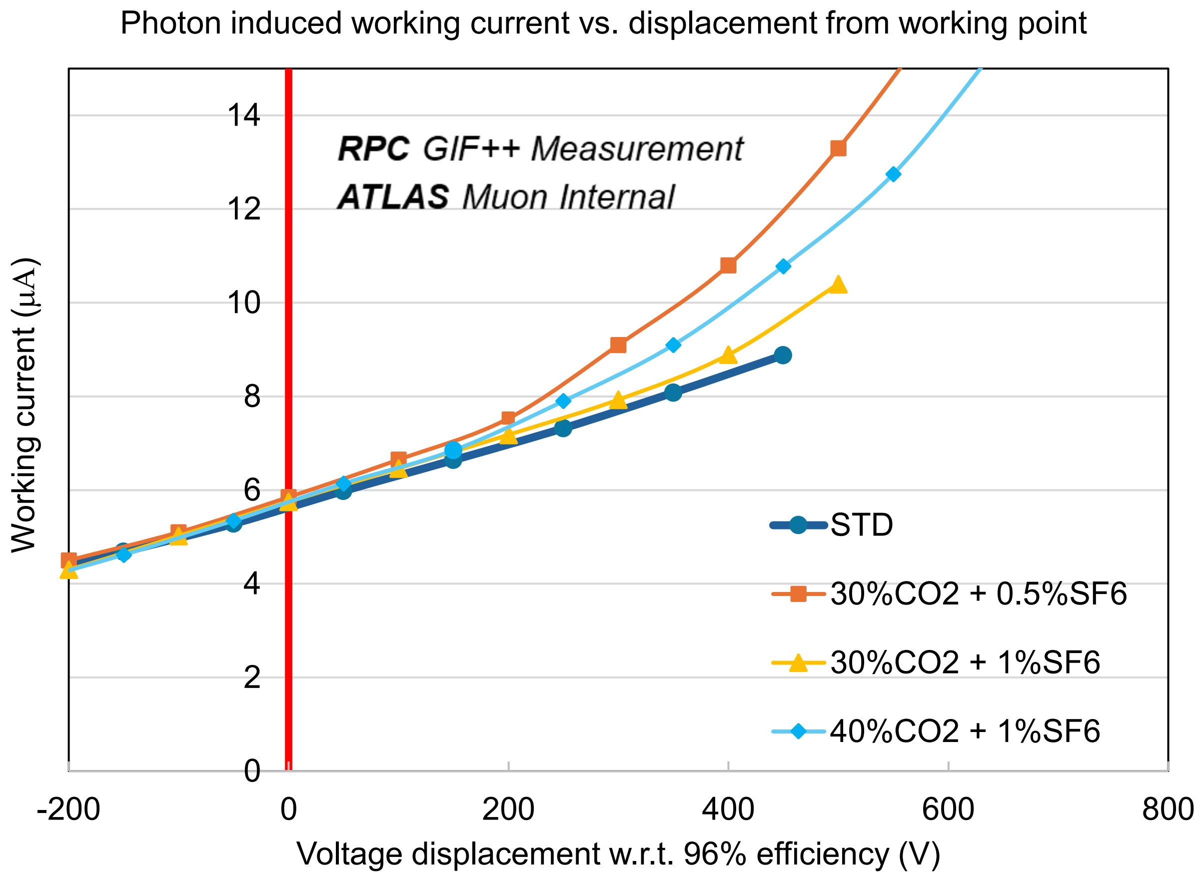
A coordinated irradiation + beam-test programme was established at CERN GIF++ facility to evaluate Eco-gas mixtures.
The program includes:

(i) Controlled gamma irradiation tests: accumulation of integrated charge and measurement of ageing effects (dark current and efficiency evolution).

(ii) Muon beam tests: measurement of efficiency, dark current, timing performance, and signal properties for the same gas mixture under irradiated and non-irradiated conditions.

Efficiency & Streamer Comparison





All mixtures reach the same efficiency plateau (~ 97%), with working voltages shifted by 200–500 V depending on the CO_2 and SF_6 content.

- Increasing CO_2 shifts the working voltage to lower values.
- Increasing SF_6 shifts the working voltage to higher values.

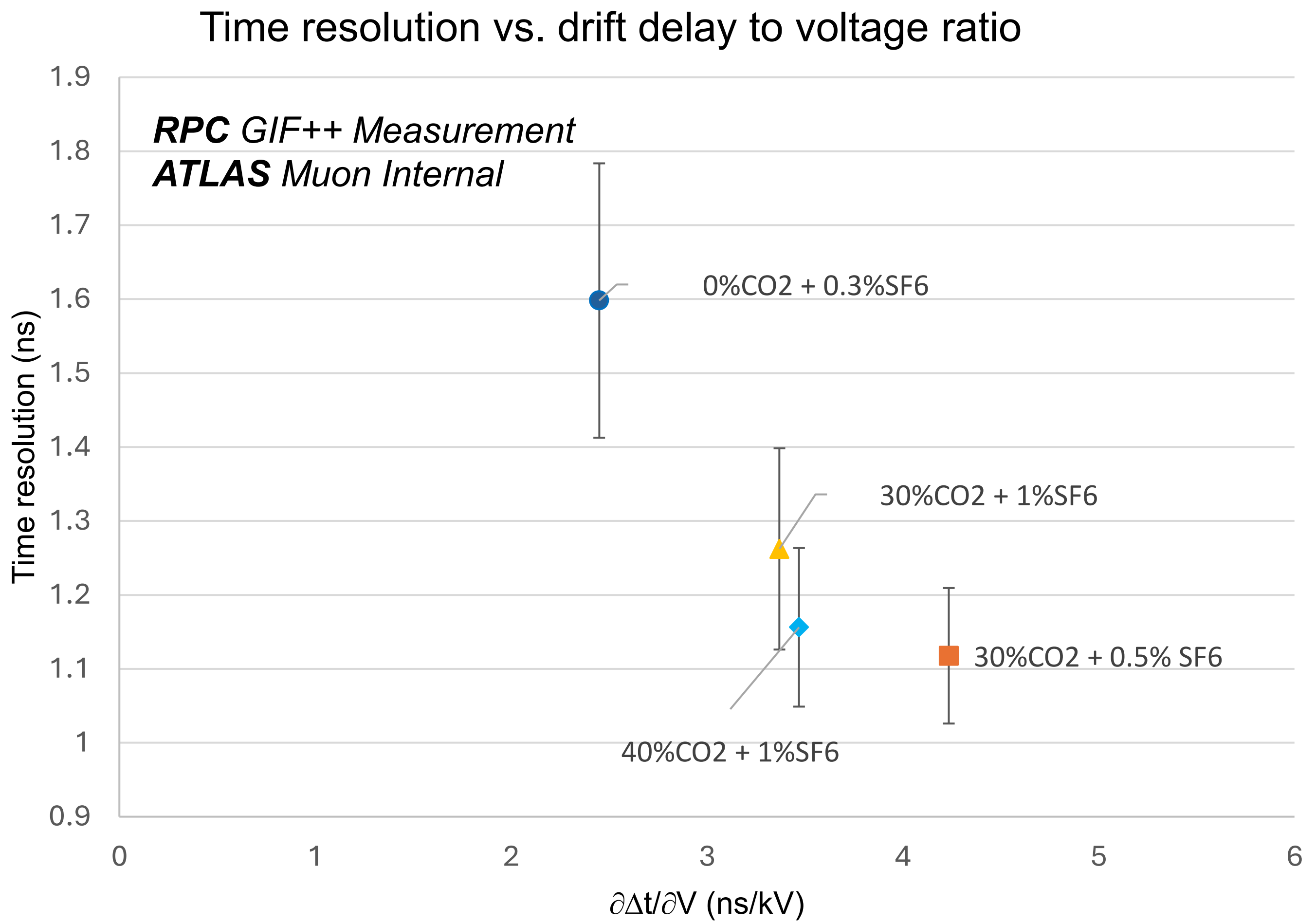
Same efficiency, different operating voltage.

Saturated Avalanche Model: deviation from linearity → streamer

The selected eco-gas mixtures preserve a streamer margin comparable to the standard gas, (200V–400V) while higher CO_2 and lower SF_6 increase non-linear currents.

ATLAS RPC working voltage (~9.0 kV) remains below the streamer region.

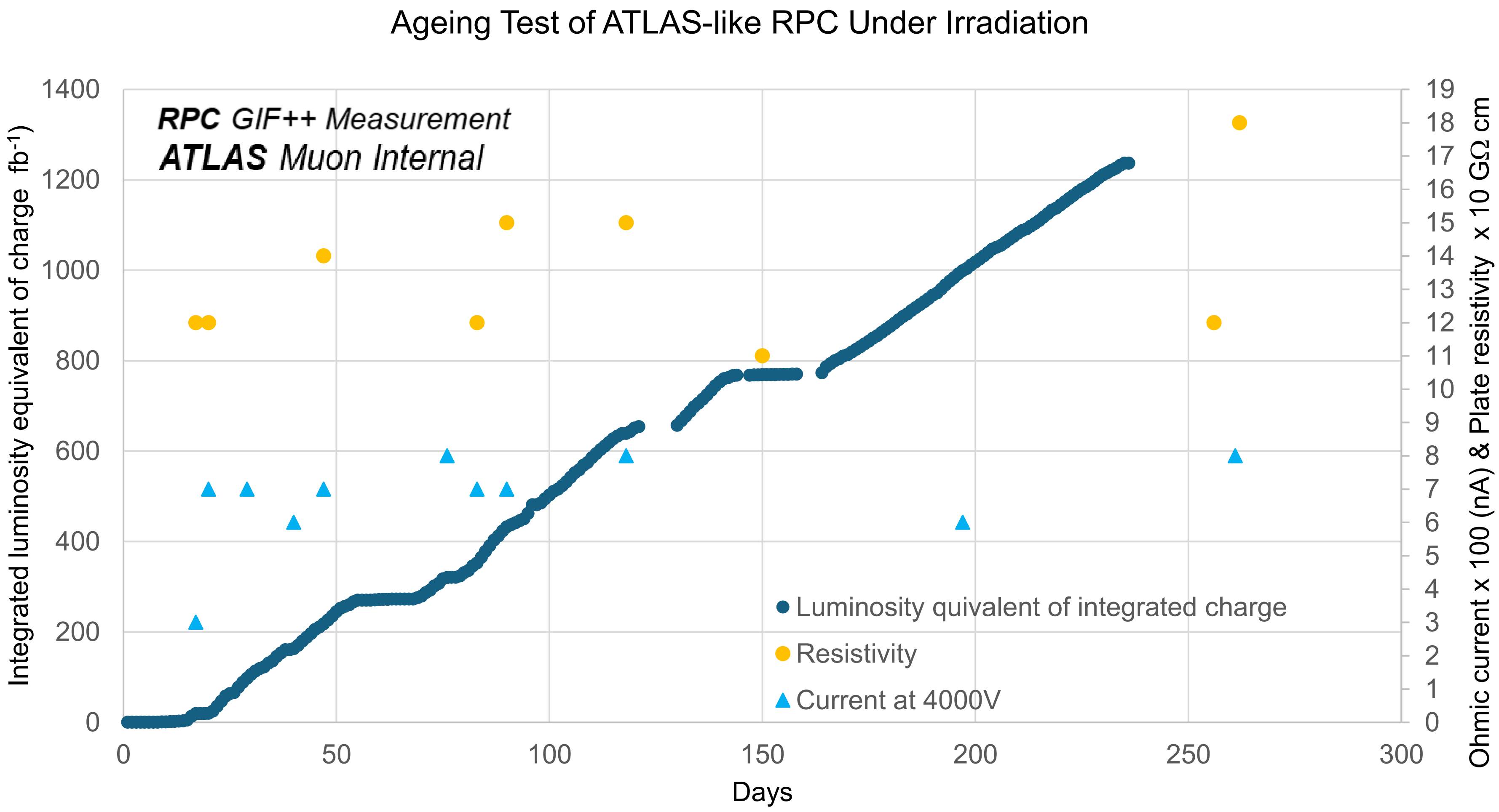
RPC Intrinsic Time Resolution



The derivative of drift delay with respect to voltage (∂Δt/∂V) indicates how faster an avalanche is growing with respect to given increments of electric field.

- Strong correlation with avalanche growth rate (∂Δt/∂V)
- **By increasing CO_2 and lowering SF_6, the RPC intrinsic time resolution is improved by up to ~ 30%.**

Ageing Test with 30% CO_2 + 0.5 % SF6



- Target →Full HL-LHC program corresponds to ~ 3000 fb^{-1}
- Approximately 42% of this target has been reached, corresponding to about 1250 fb^{-1}

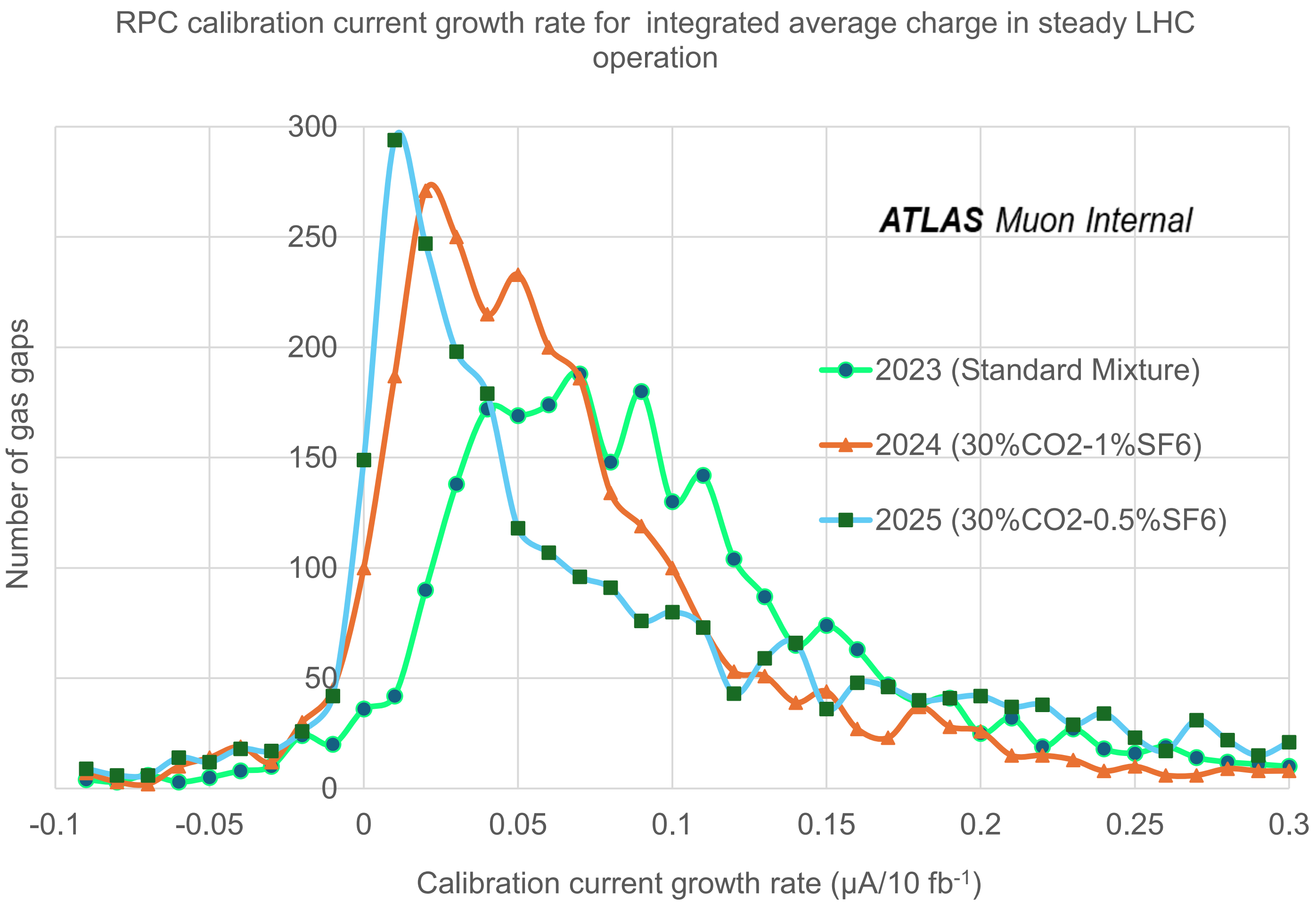
Results:

- ▲ The ohmic current remains excellent and stable over time.
- ● The electrode resistance was initially high, then increased by approximately 25% after the first exposure to radiation, and has remained stable since.

Comparison of STD & New RPC Gas Mixtures in ATLAS Cavern

Calibration current (I_{calib}): Current measured at the operating voltage without beam-induced background. For a stable detector, it should remain constant with accumulated charge; therefore;

I_{calib} growth rate ≈ 0 → **no current increase with accumulated charge**



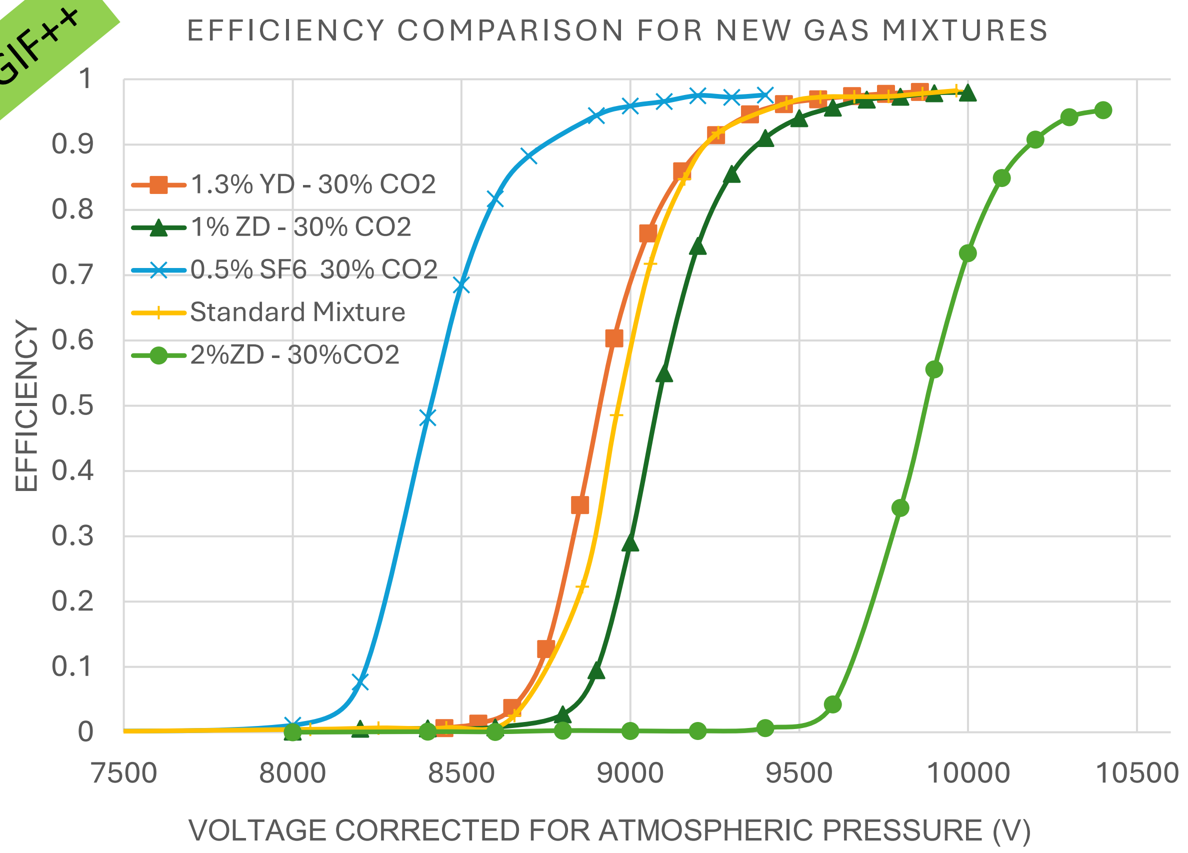
Results:

- The mixtures with reduced fluorinated-gas content show distributions more concentrated around zero
  → **smaller increase in the rate of I_{calib}.**
- Halving the SF_6 fraction further reduces I_{calib}, due to **lower dark-current contribution**.

The luminosity delivery rate in the selected periods:
in 2023 was 0.31 fb^{-1}/week
in 2024 and 2025 were 0.54 fb^{-1}/week

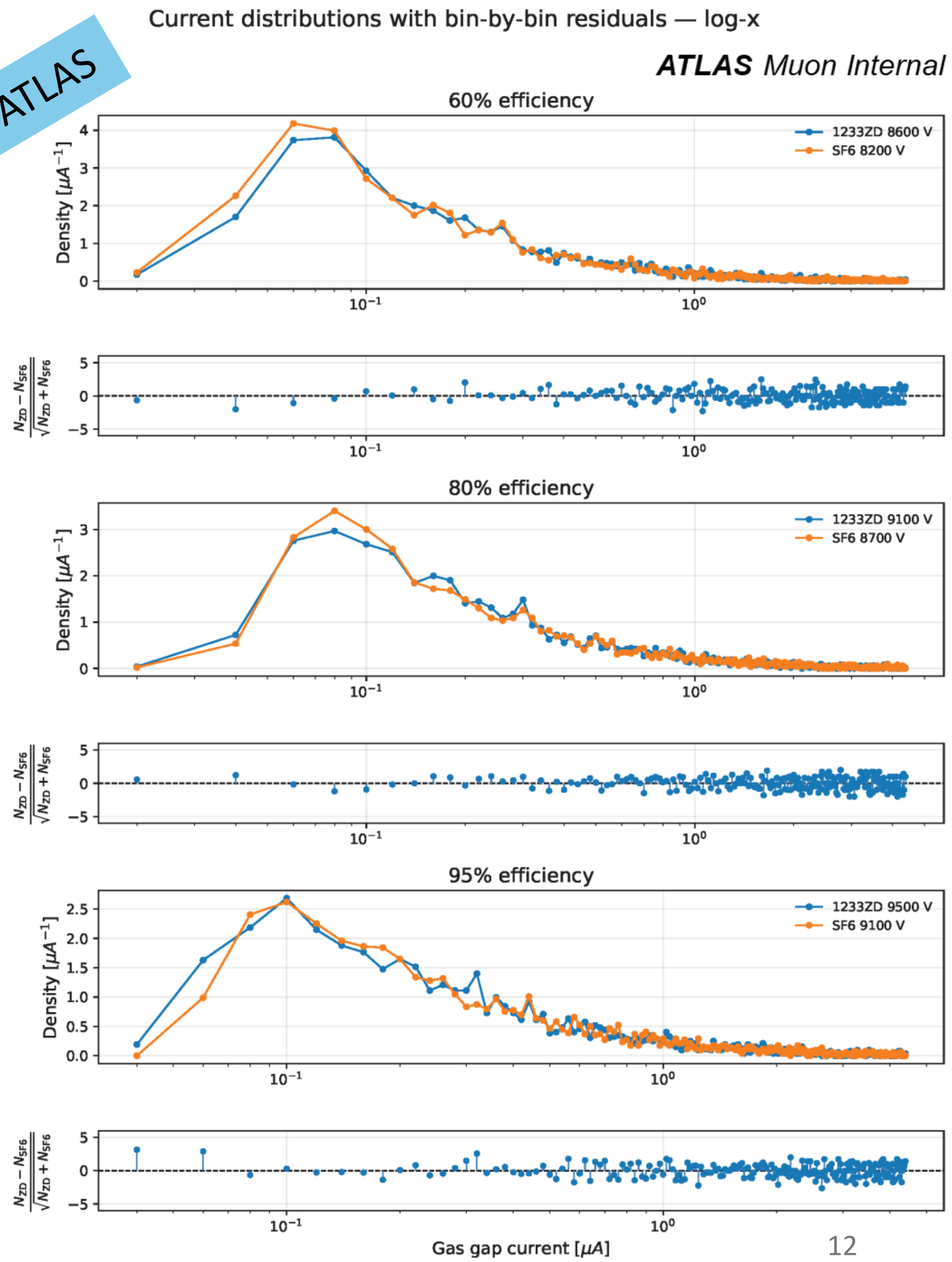
New candidate: R1233 as SF6 replacement

GIF++



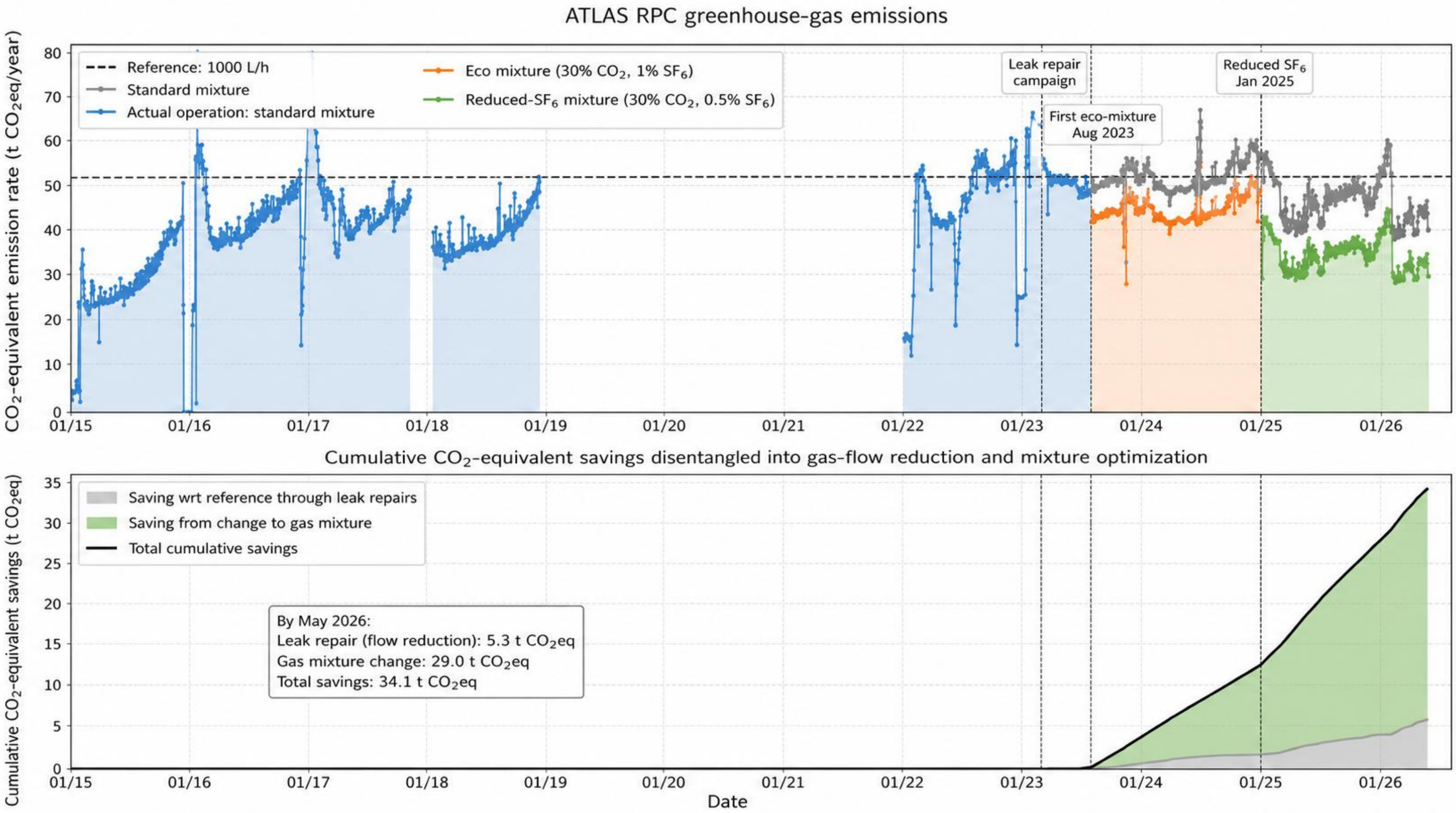
SF$_6$ replacement with R1233yd and R1233zd results in similar maximum efficiencies (~97%) but shifted working voltages, with the 0.5% SF$_6$ mixture reaching the efficiency plateau at the lowest voltage and the 2% R1233zd mixture requiring the highest operating voltage.

ATLAS



The ATLAS current results indicate that, for gas gaps exhibiting spontaneous currents (i.e. currents generated internally in the gas gap in the absence of particle-induced signals), the overall current behaviour remains very similar for the two gas mixtures, irrespectively to the quality of the gas gap.

CONCLUSIONS: Environmental Impact = Gas Consumption × Gas GWP



Beyond the environmental benefit (**−35 t CO_2eq/year**), the new gas mixture also reduces R134a consumption by **~34.5 t/year**, corresponding to an estimated annual saving **of ~0.35 MCHF** for ATLAS.

CONCLUSIONS

- The RPC system plays a critical role in muon detection, and its performance must be maintained while addressing challenges related to gas leaks, environmental impact, and long-term stability.

- ATLAS chose the conservative strategy because it could be implemented immediately on an operating detector while still providing a significant environmental benefit.
  - **Key achievement : 27% reduction in gas-mixture GWP achieved in ATLAS RPC operation.**
  - It is the **first concrete example** of sustainability-driven detector operation at the LHC.

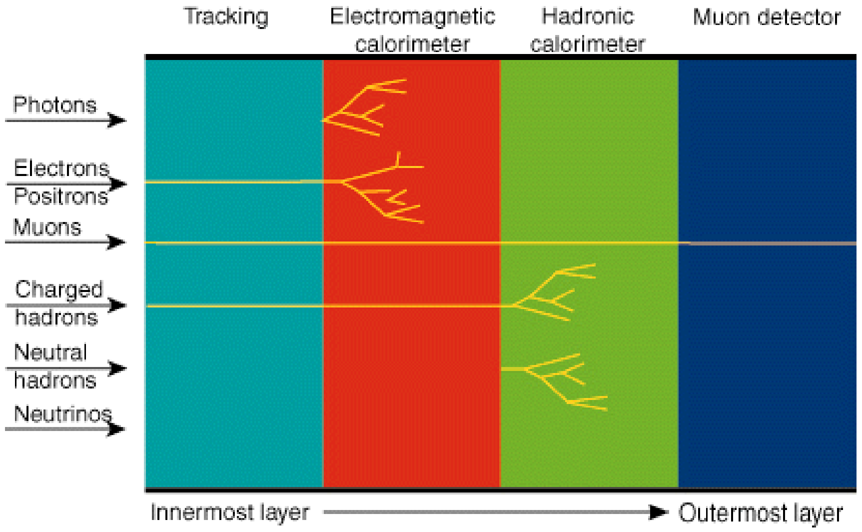
- **We obtained this result without affecting the overall detector functionality and coverage, but instead improving its performance.**

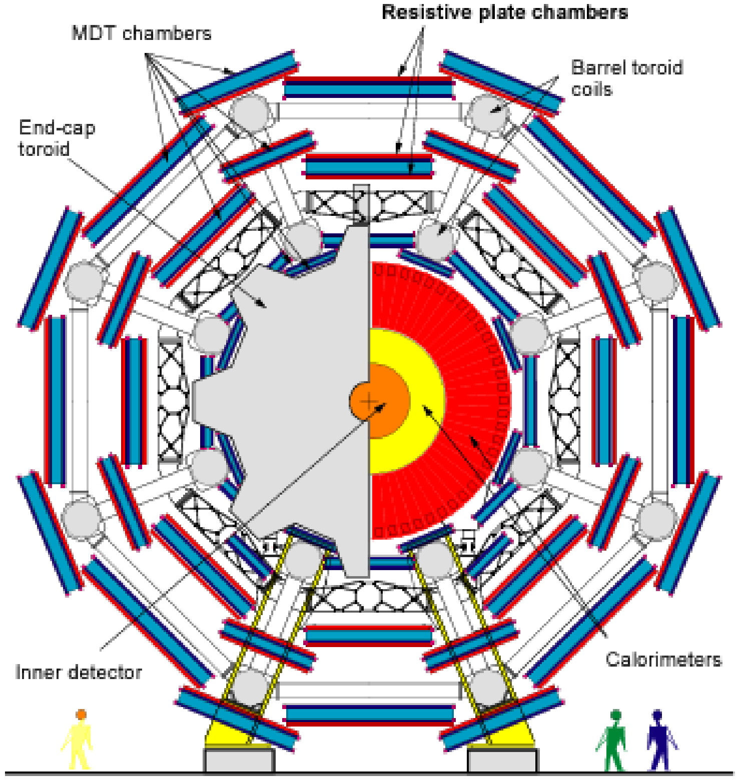
- Next step will be fully validating the new mixtures in the ageing test to establish the best possible mixture for the LHC Run-4.

THANK YOU

BackUp: Resistive Plate Chambers (RPCs)

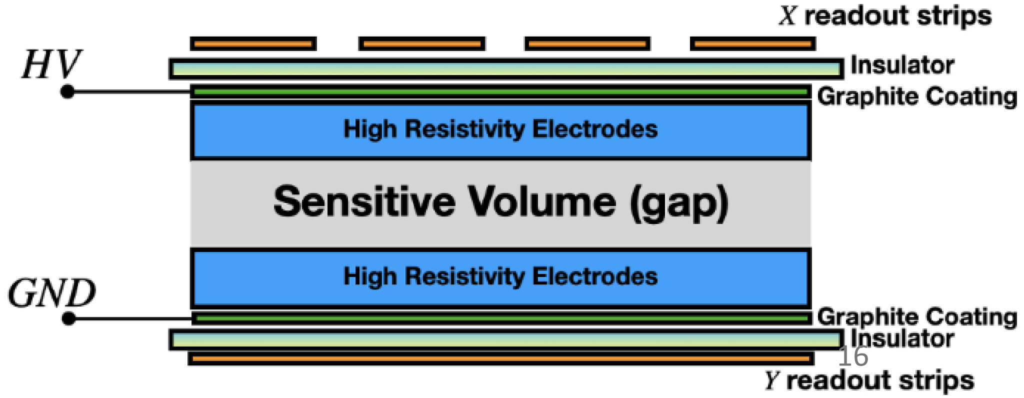
- RPC is a sub-detector of a muon system which is whatever comes after the hadronic calorimeter, wrapping all the other detectors.





- Each RPC detector chamber consists of 2 detector layers, each with readout panels which is sandwiching a gas volumes.

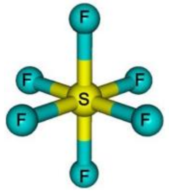
    - RPC gas volumes are made of two parallel resistive (bakelite) plates separated by 2 mm gas gap with insulating spacers.
    - Ionizing particles crossing the gas create avalanches of electrons/ions → fast electrical signal collected on readout strips.
    - Readout is organized by orthogonal strips (eta and phi) with eta strips measuring muon curvature.



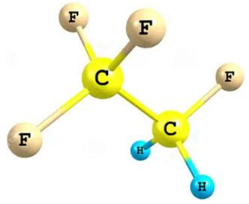
ECO-GAS Studies for RPCs

- Since ~2019, the LHC RPC community—through the RPC-ECOgas collaboration and the experiment groups as ATLAS / CMS has been actively testing low-GWP alternatives to the standard R-134a/SF_6 gas mixtures.

- **Conservative** solutions are R-134a/CO_2-based mixtures combined with SF_6 at different ratios.
  - Significant reduction of GWP (1430 → 1100)
  - Conserving the known RPC ageing features of the standard mixture.
  - Replacing just SF6 with C3H2ClF3 would further improve the GWP (900)

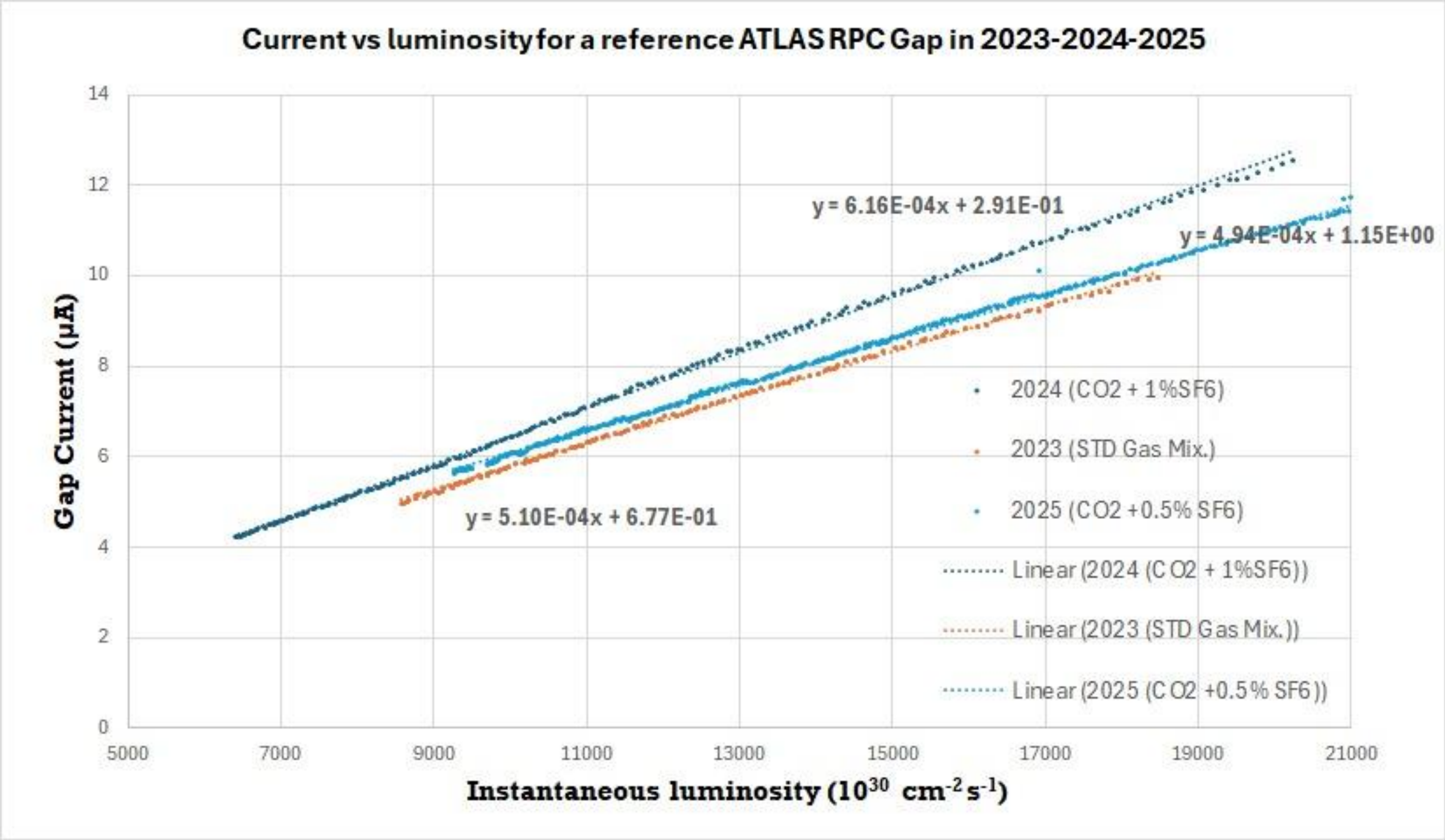


- **Radical** solutions are HFO-1234ze (tetrafluoropropene) and HFO/CO_2-based mixtures, sometimes combined with substitutes for SF_6 such as Chlorotrifluoropropene (C3H2ClF3 GWP ~ 1).
  - very low GWP (from 200 to 10 (without SF6) but representing a risk for the RPC performance and ageing.



ATLAS RPC IN CAVERN: COMPARISON OF THE CURRENT AFTER THE GAS MIXTURE CHANGE

This analysis considering the most radiation-exposed chambers in ATLAS, BML6A.09.CO as a reference chamber.



The plot confirms that the current vs. HV measured at GIF for the various gases shows that the mixture with 1% SF_6 has a current approximately 17% higher than the STD mix, while the one with 0.5% SF_6 shows a very similar current to the STD mix.