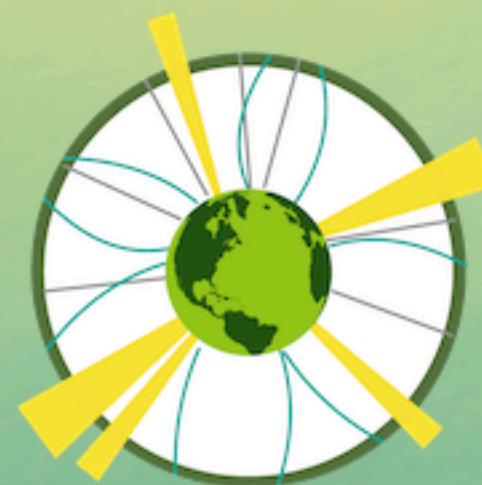




# From Discovery to Sustainability:

## The Green (r)Evolution of Gaseous Detectors in High Energy Physics



Sustainable HEP 2026 — 5th Edition

ULB  
UNIVERSITÉ  
LIBRE  
DE BRUXELLES



July 8th, 2026

Archana Sharma

(CERN Univ Libre de Bruxelles Belgium LifeLab Foundation)

Reduce • Recover • Replace • Redesign





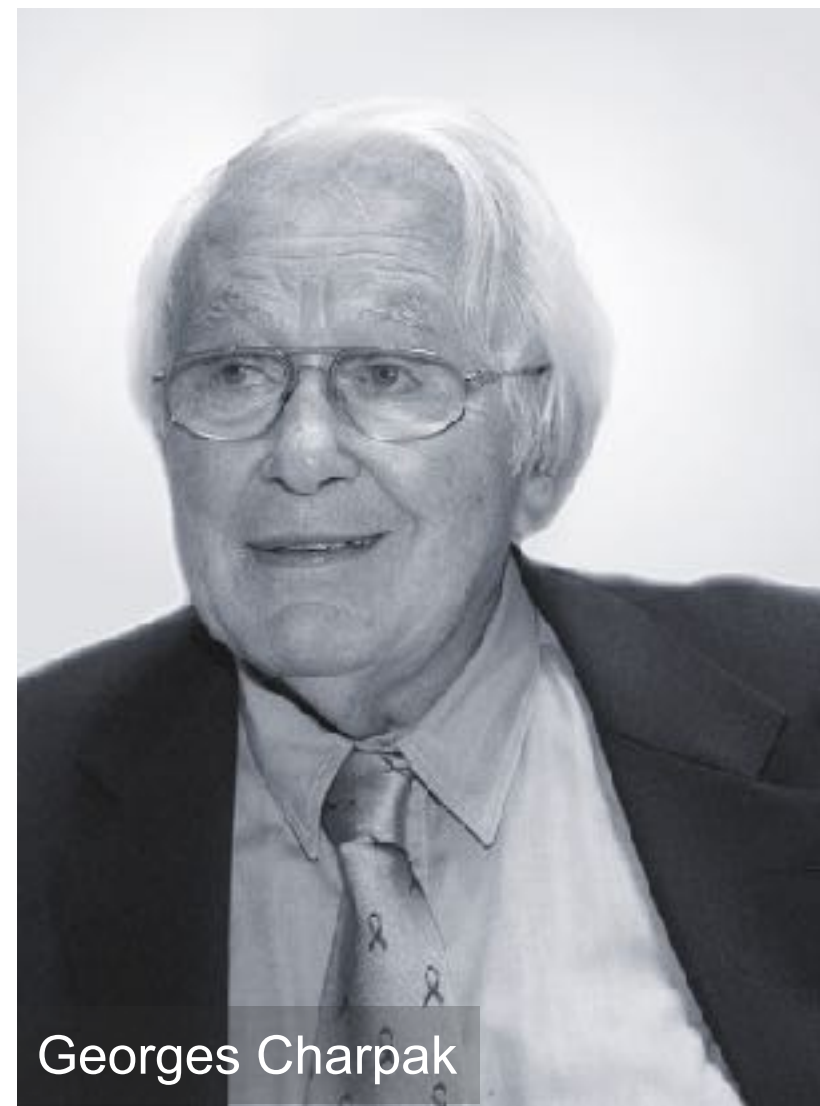
# At CERN we help to answer these questions



Carlo Rubbia



Simon Van der Meer



Georges Charpak

Several CERN scientists have received Nobel Prizes for key discoveries in particle physics.

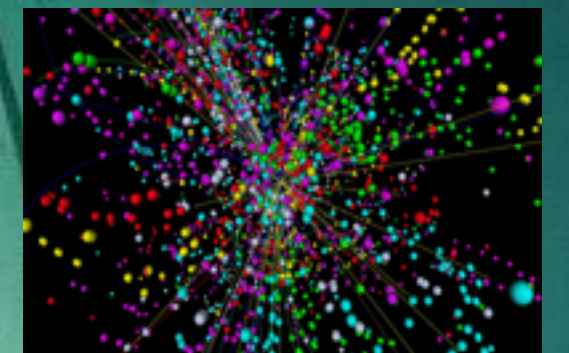
The Higgs boson was discovered in 2012; without it fundamental particles would be massless and atoms could not form.



François Englert and Peter Higgs



Temperatures more than *a billion times those in the heart of the Sun!*



“Store” beams for  $\sim 10$  hours. Protons travel  $\sim 10$  billion km around the LHC ring  $\sim$  round trip to Pluto  $\rightarrow$  need a good vacuum

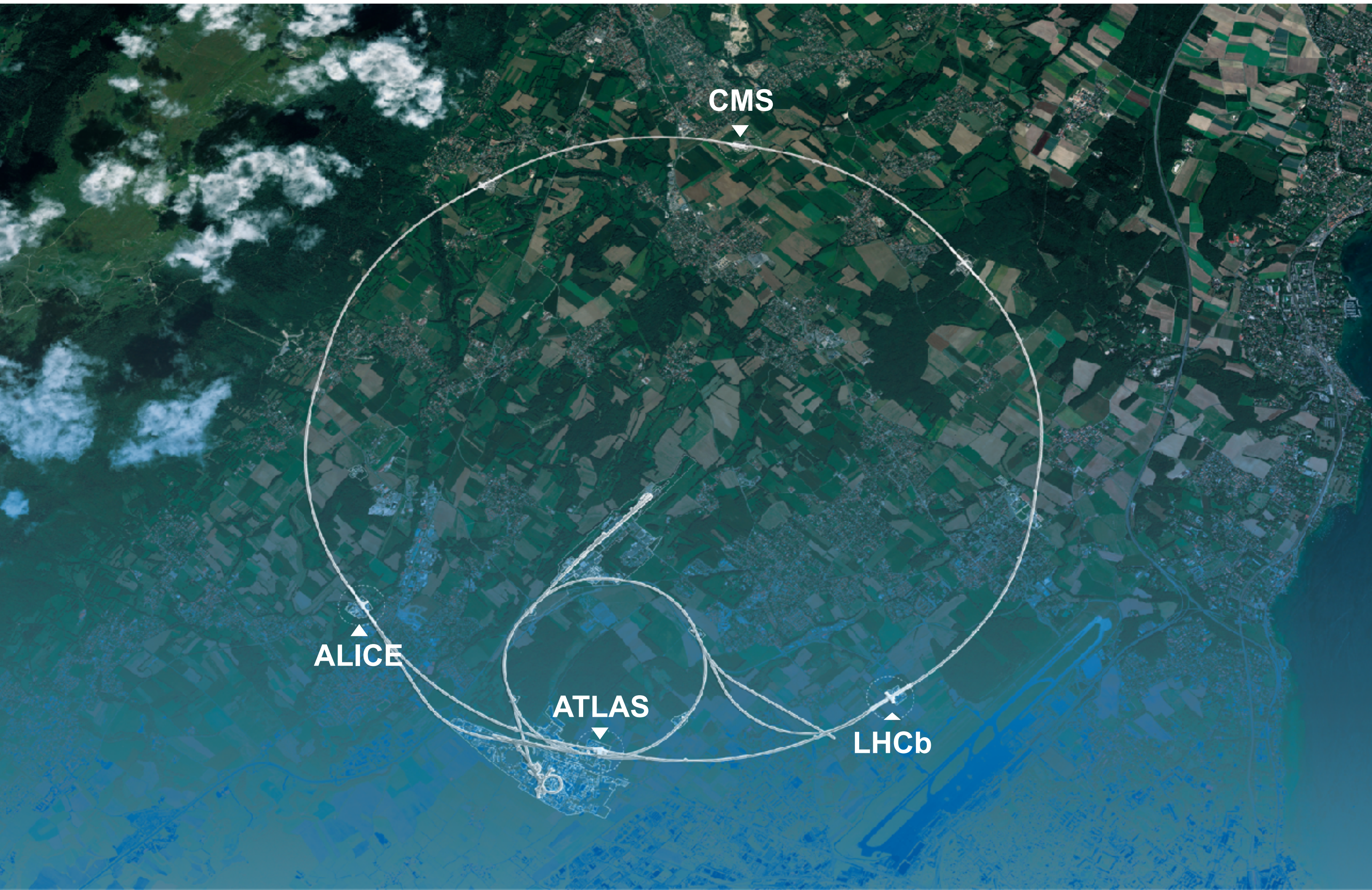
The LHC needs

Liquid Helium 1.9 degrees Kelvin - *colder than outer space!*

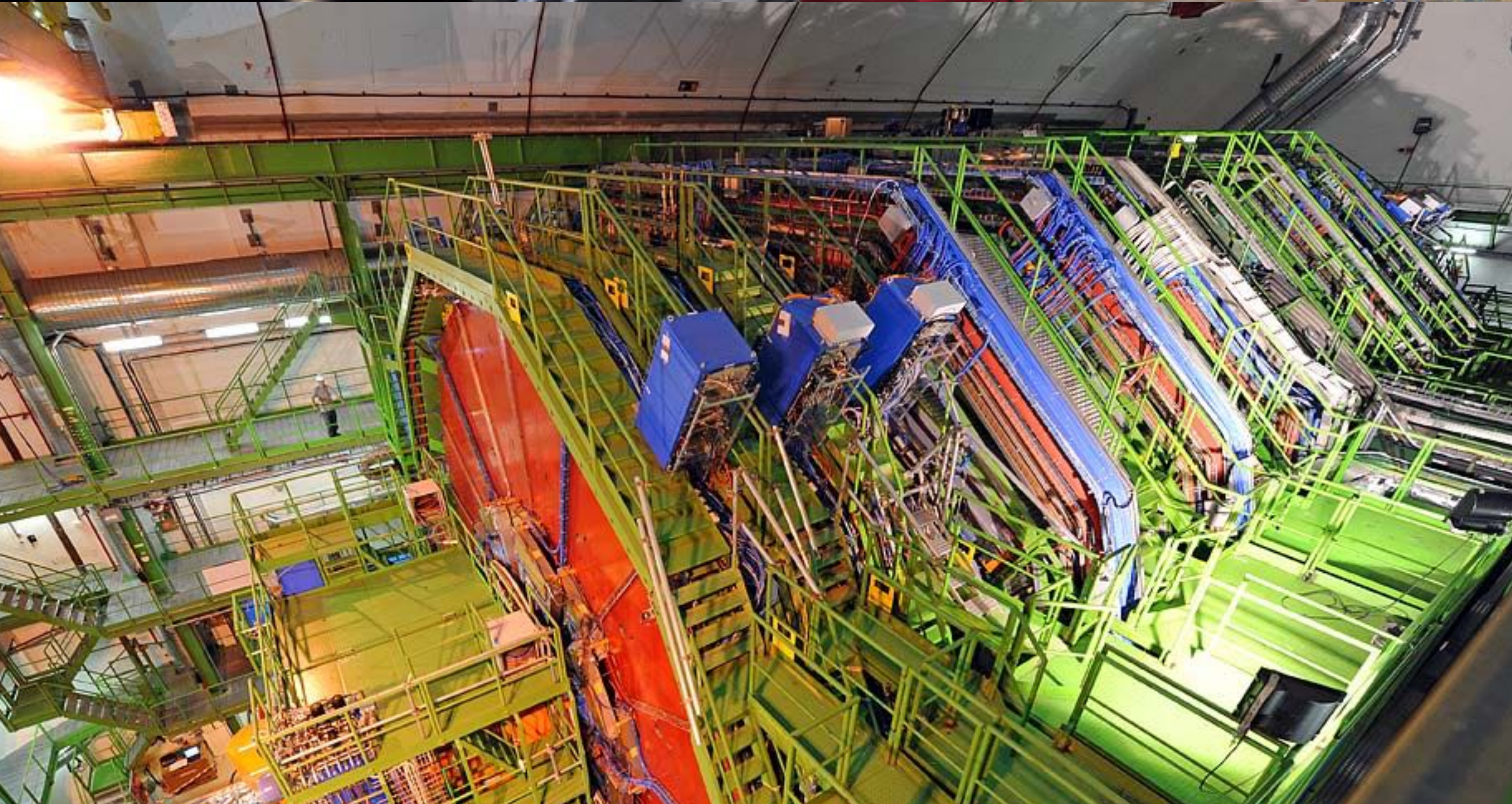
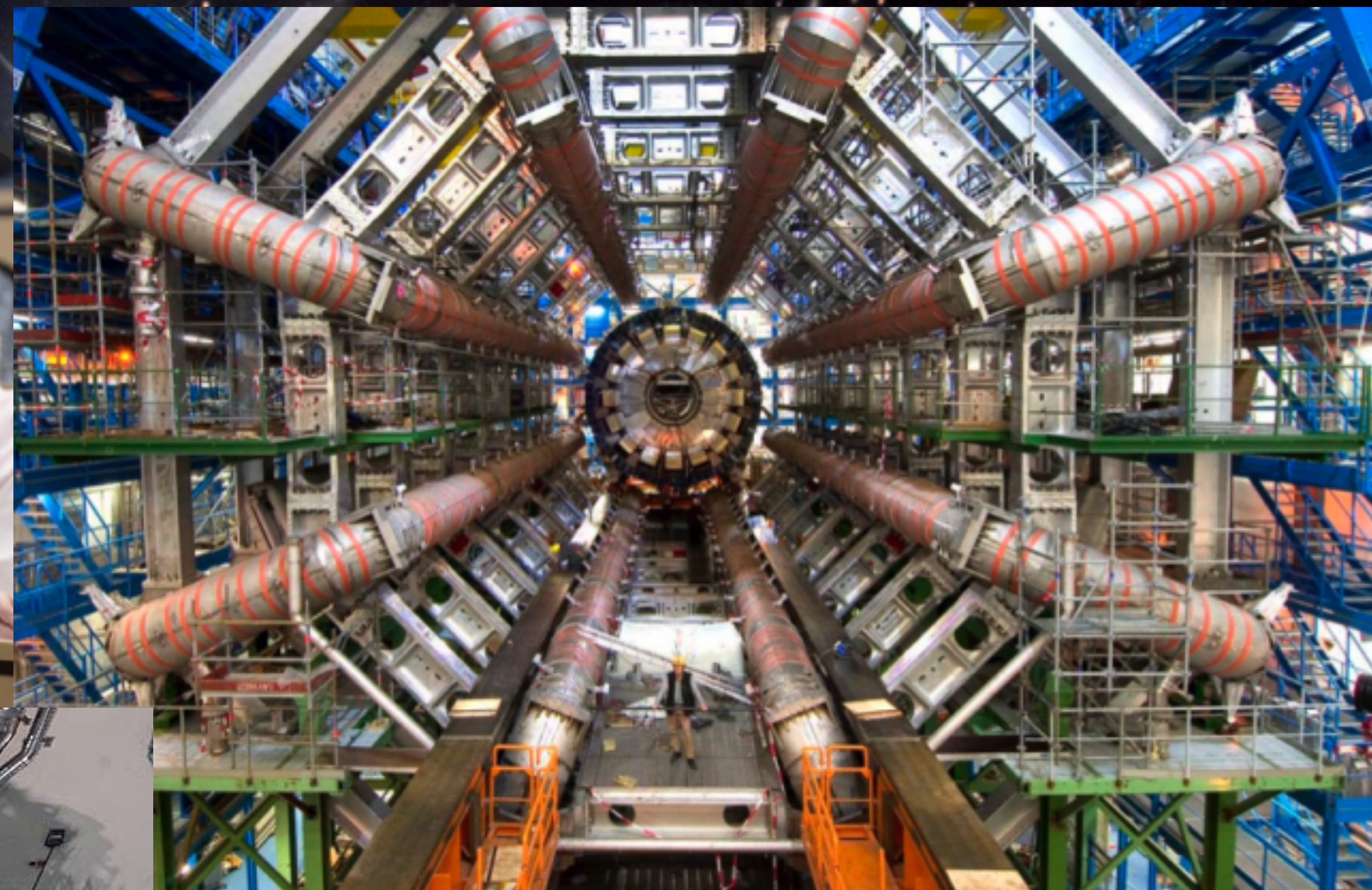
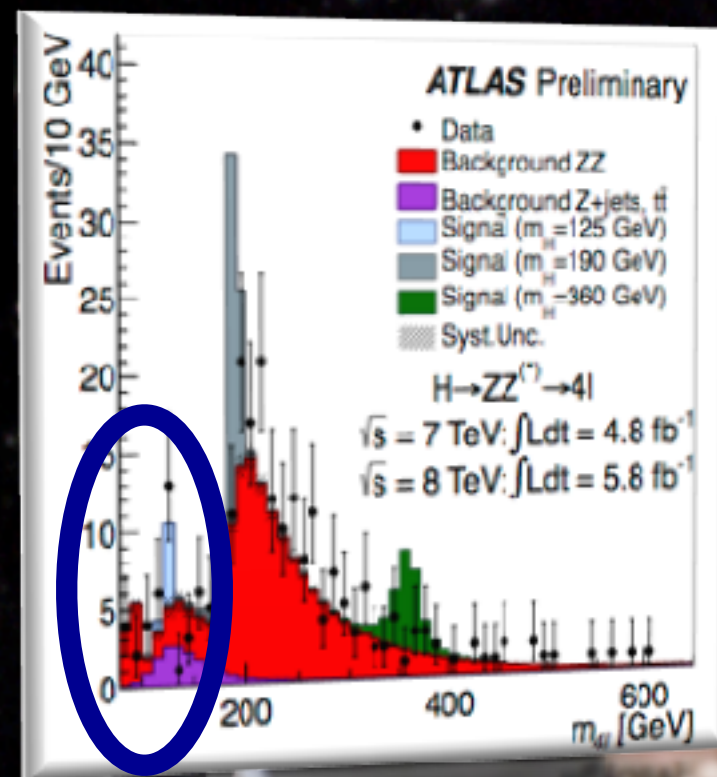




# Giant detectors record the particles formed at the four collision points









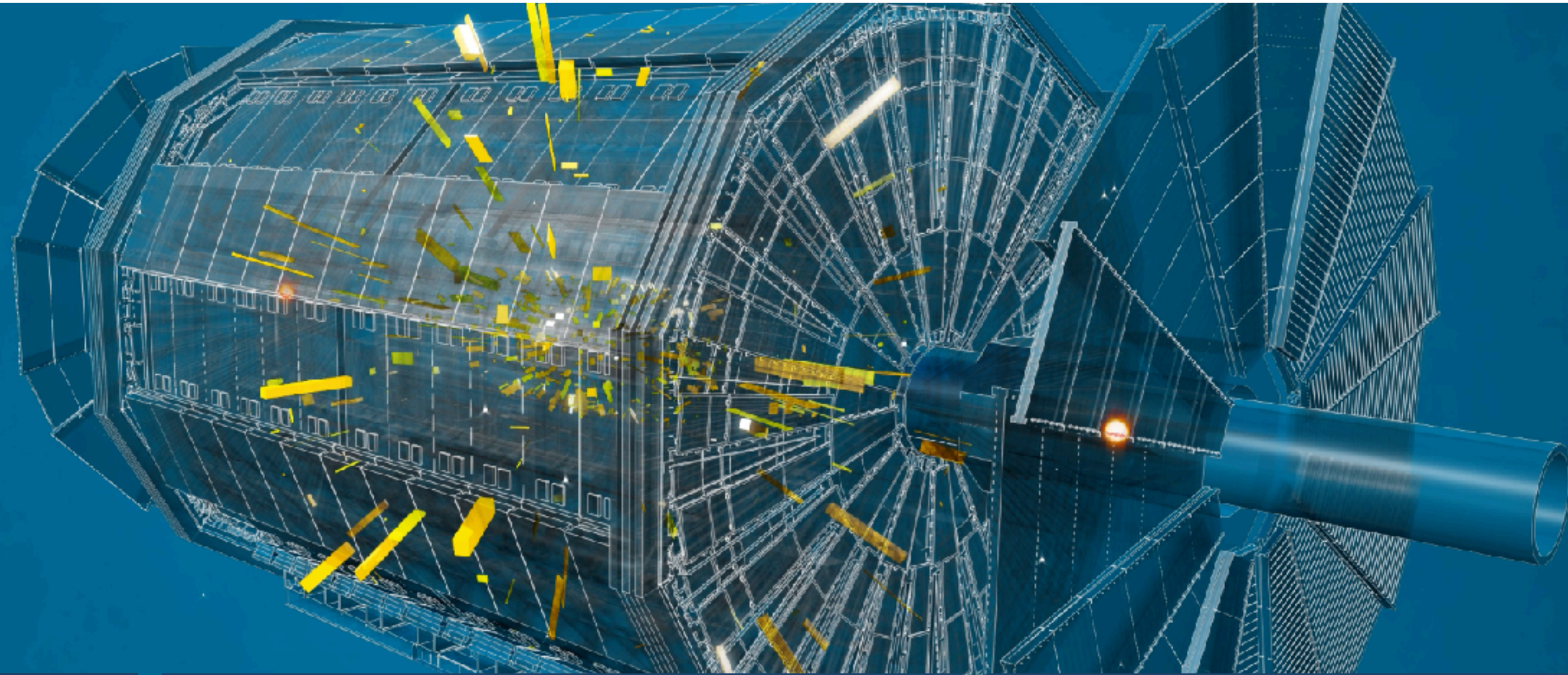


# Tuesday 8 October 2013 Nobel Prize





# The LHC detectors are analogous to 3D cameras



The detectors measure the energy, direction and charge of new particles formed.

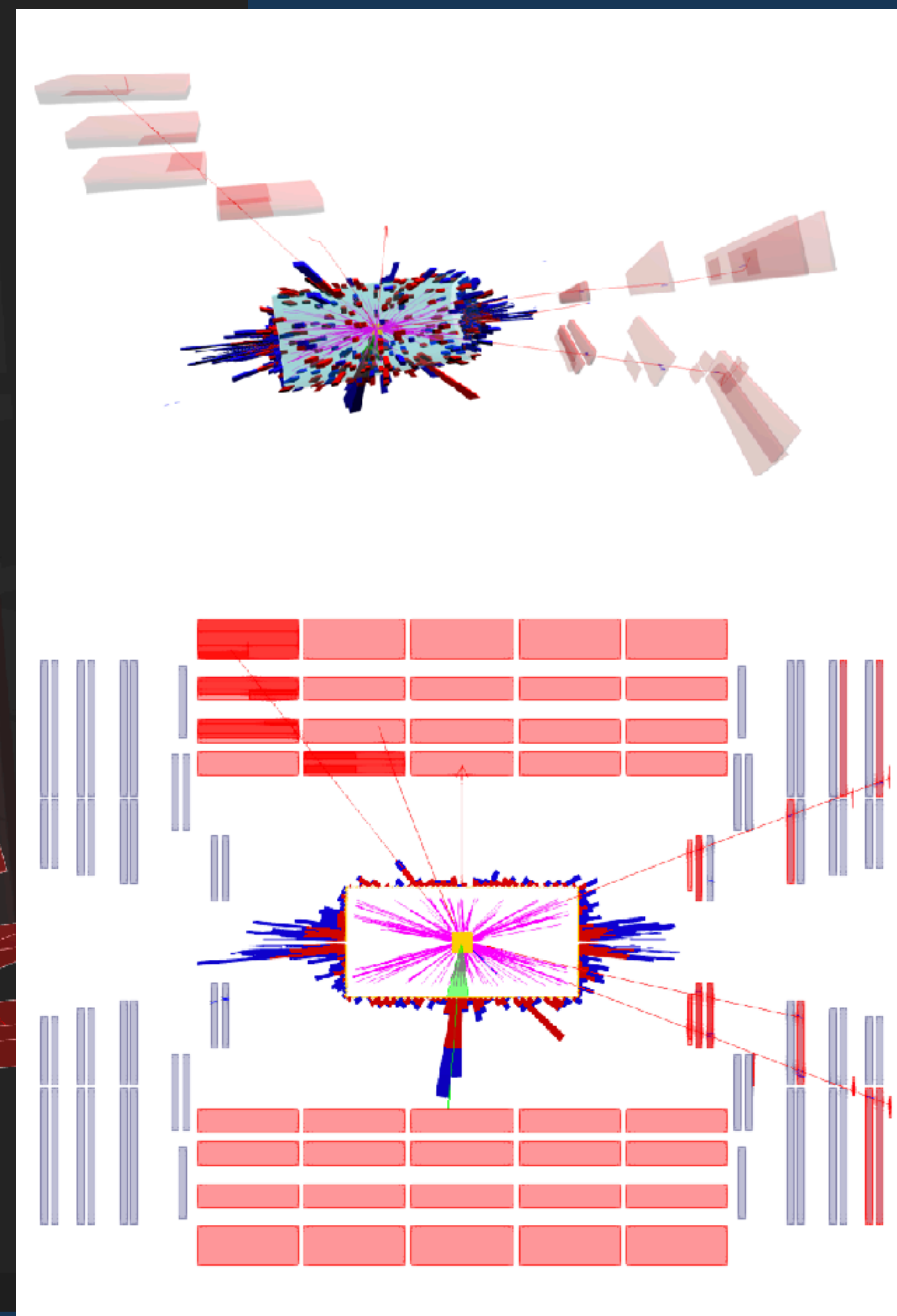
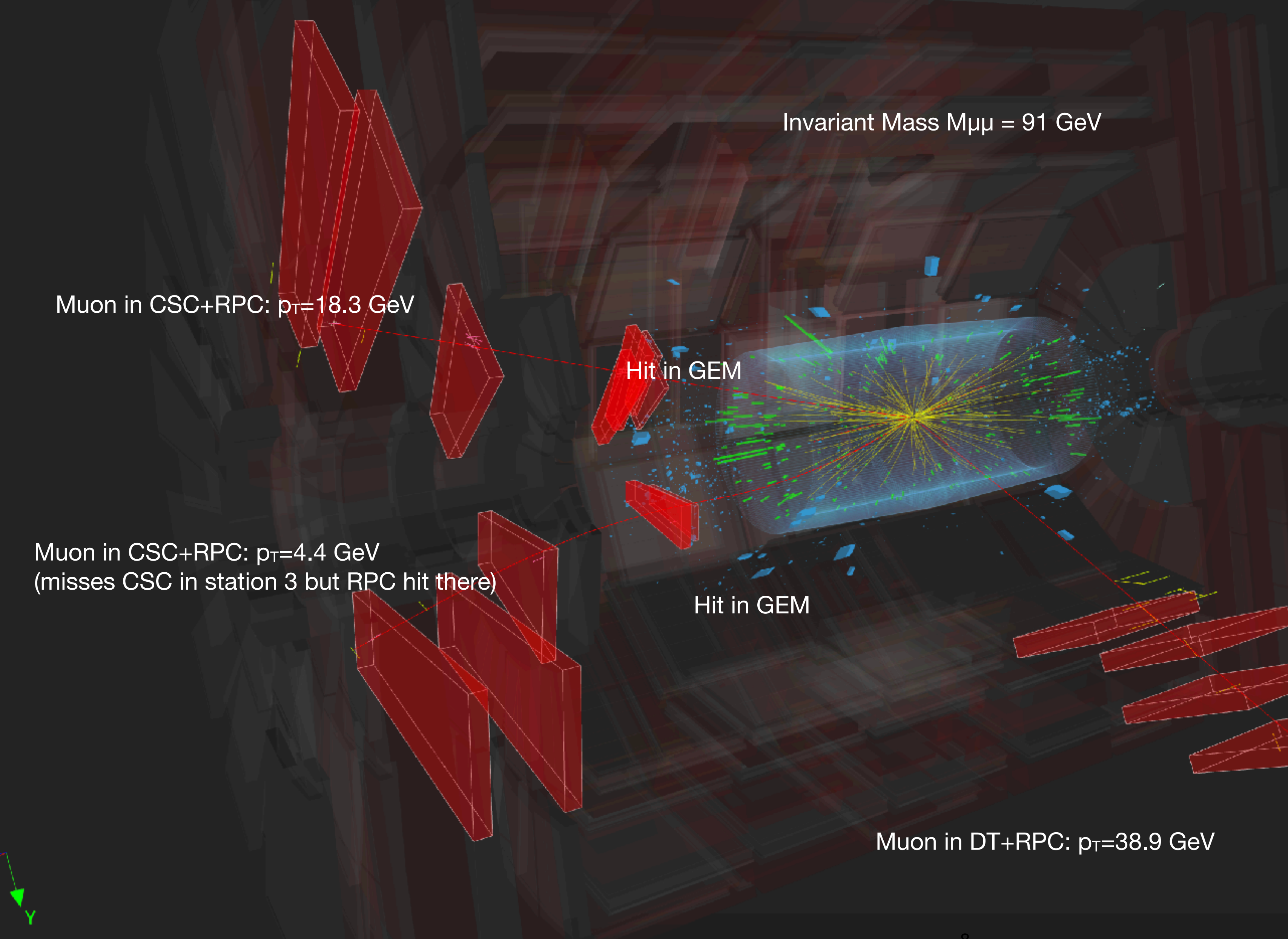


They take 40 million pictures a second. Only 1000 are recorded and stored.



The LHC detectors have been built by international collaborations covering all regions of the Globe.



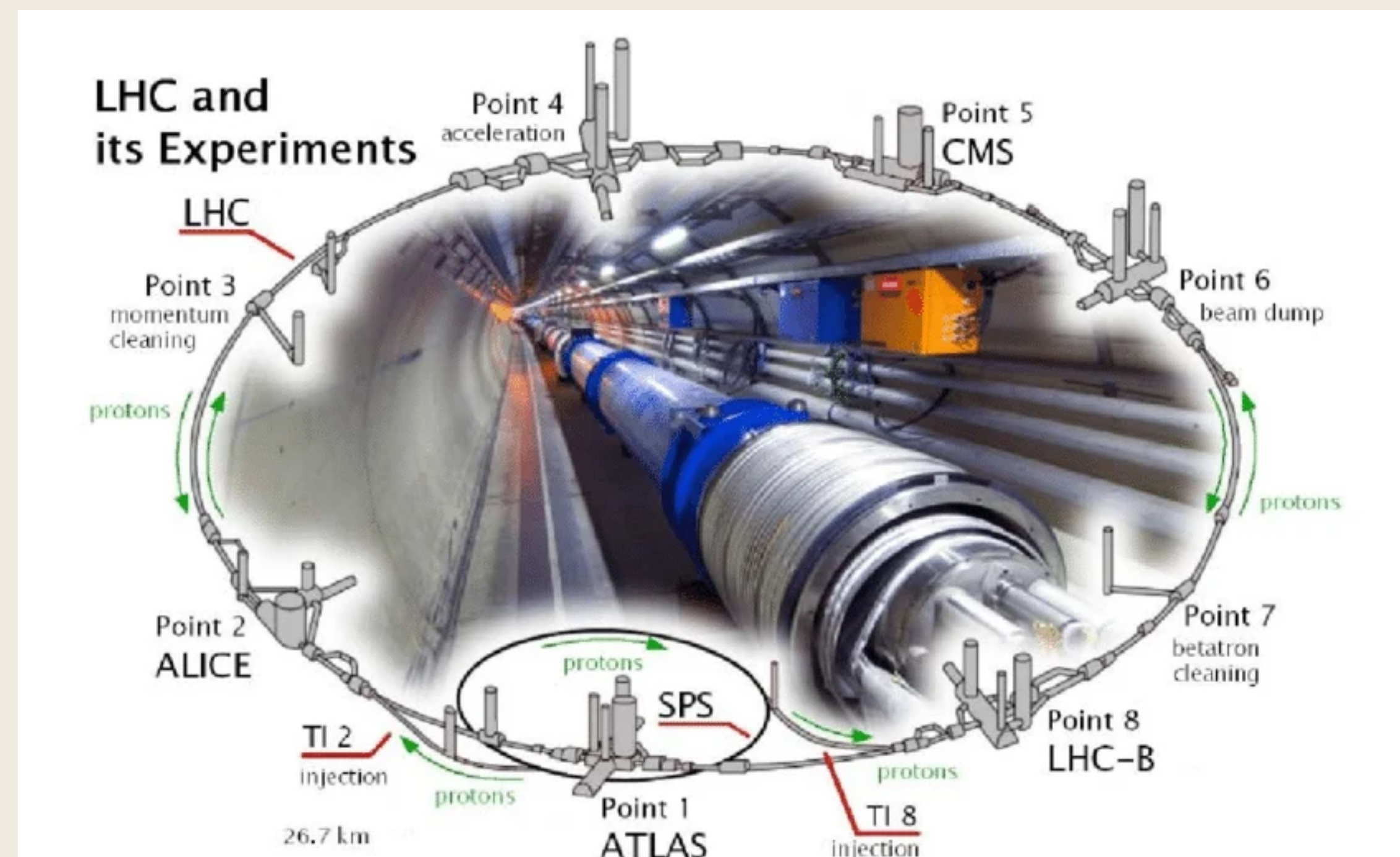




## Why This Topic Matters Now

# Climate responsibility is entering scientific infrastructure

- Gas detectors remain essential because they are scalable, robust, adaptable and cost-effective.
- The central message is not to reduce performance, but to redesign the environmental footprint.
- Sustainability is becoming a detector-design principle, not an afterthought.
- The presentation follows the four-sections: legacy, engineering response, design roadmap and a possible future playbook.



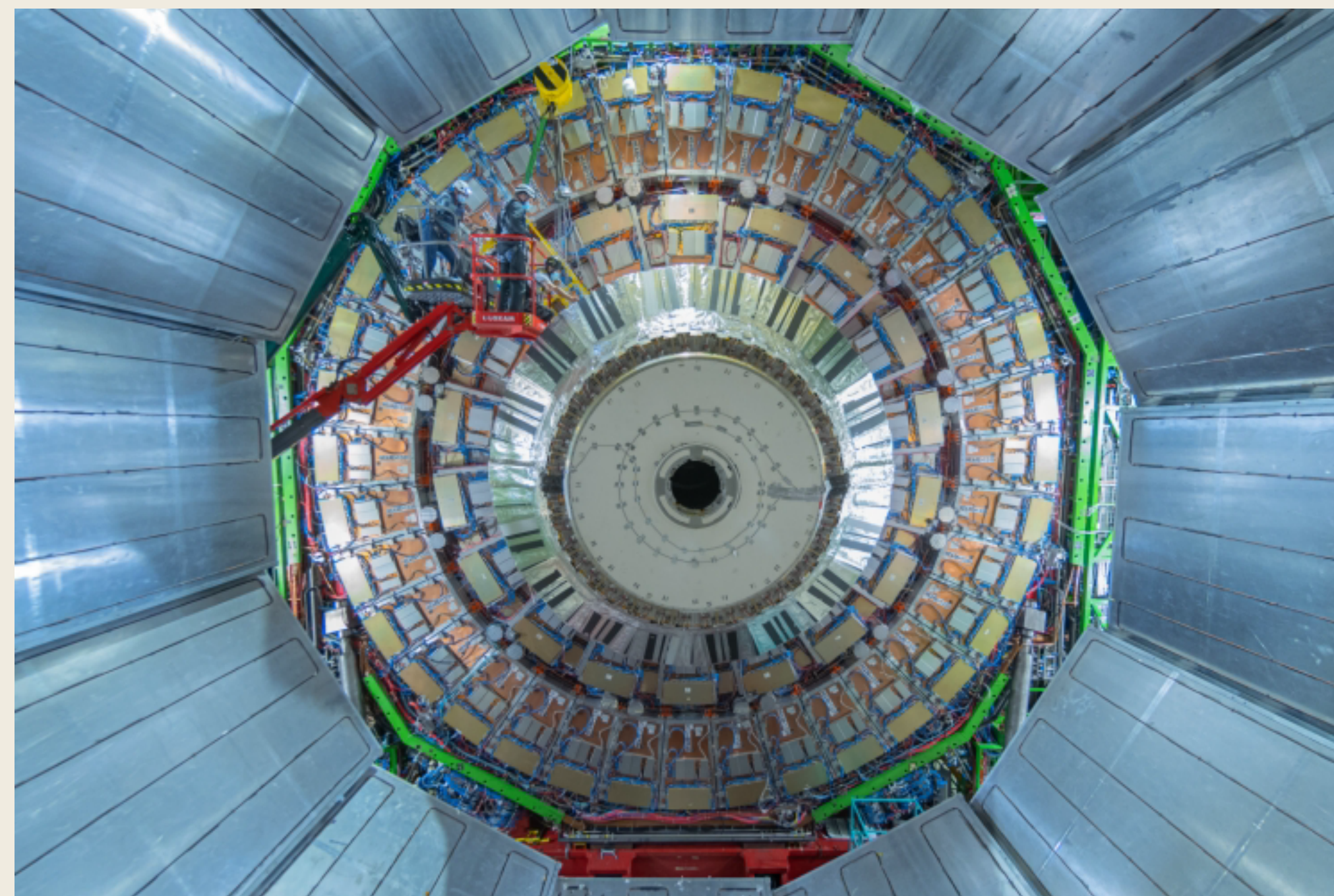
Across the four major LHC experiments, gaseous detectors (such as RPCs, MDTs, CSCs, and TPCs) cover a staggering total surface area of **thousands of square meters** (exceeding 10,000 m<sup>2</sup> combined) and encompass a total active internal gas volume of **several hundred cubic meters** (typically between 500m<sup>3</sup> and 800m<sup>3</sup>)



## Why This Topic Matters Now

# Climate responsibility is entering scientific infrastructure

- Particle physics has always pushed technology to extremes.
- Detectors were designed to answer impossible questions.
- Today, we face a new question: can we pursue discovery responsibly?
- Large experiments have long operational lifetimes.
- Gas systems, energy use, materials and maintenance all matter.
- Sustainability is becoming part of scientific excellence.
- Rethinking detector design, operation and culture.
- From performance-first to responsibility-integrated detector development.





- Efficiency.
- Resolution.
- Rate capability.
- Timing.
- Radiation tolerance.
- Stability.
- Ageing.





- They provide large-area detection where solid-state technologies are often impractical or too costly.
- They serve tracking, triggering, muon detection, timing and particle-identification roles.
- Their flexibility has allowed them to evolve across many generations of experiments.
- Their widespread success is precisely why their environmental impact now matters.
- The larger the detector system, the more important gas choice, flow and leakage become.

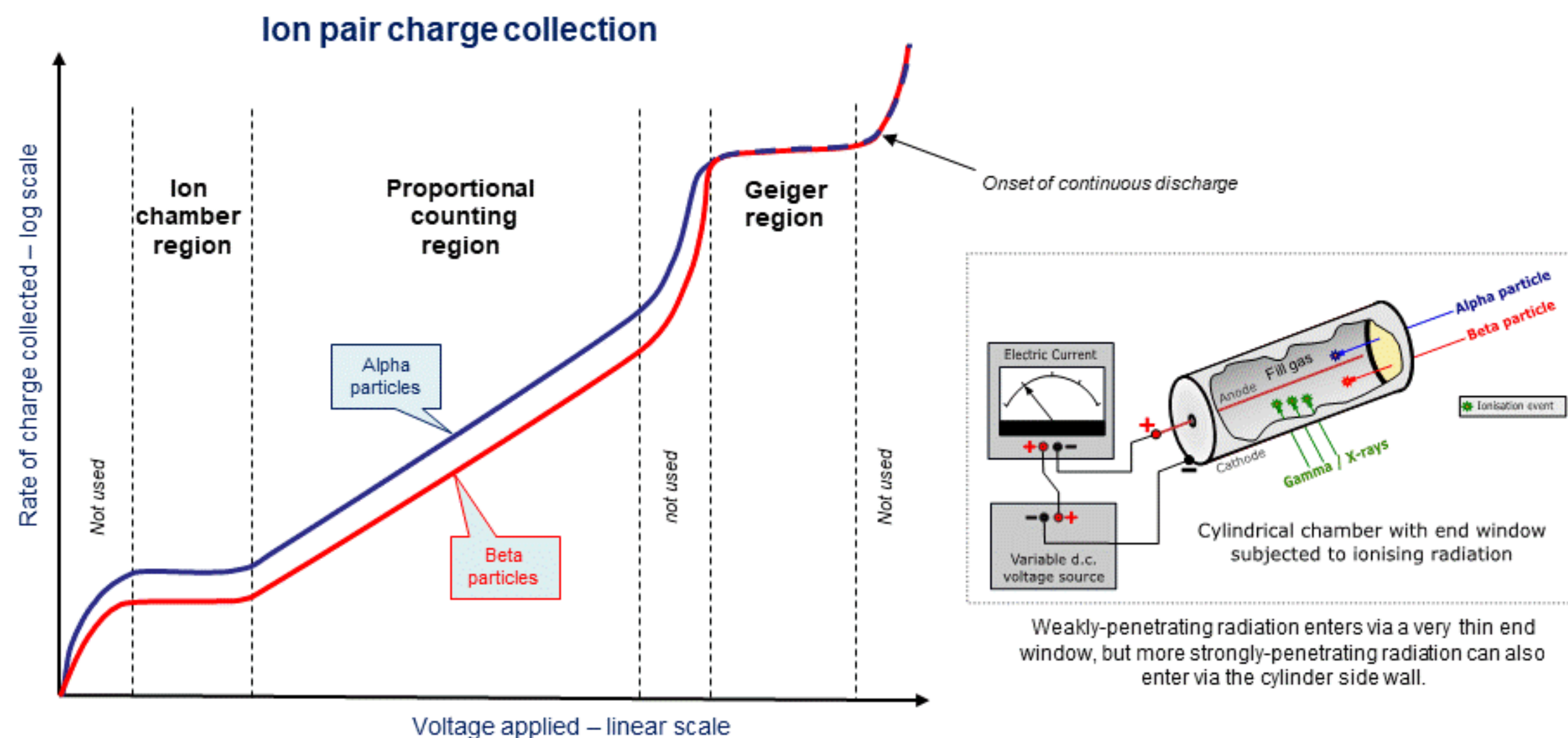




# Seeing the Invisible with Gaseous Detectors

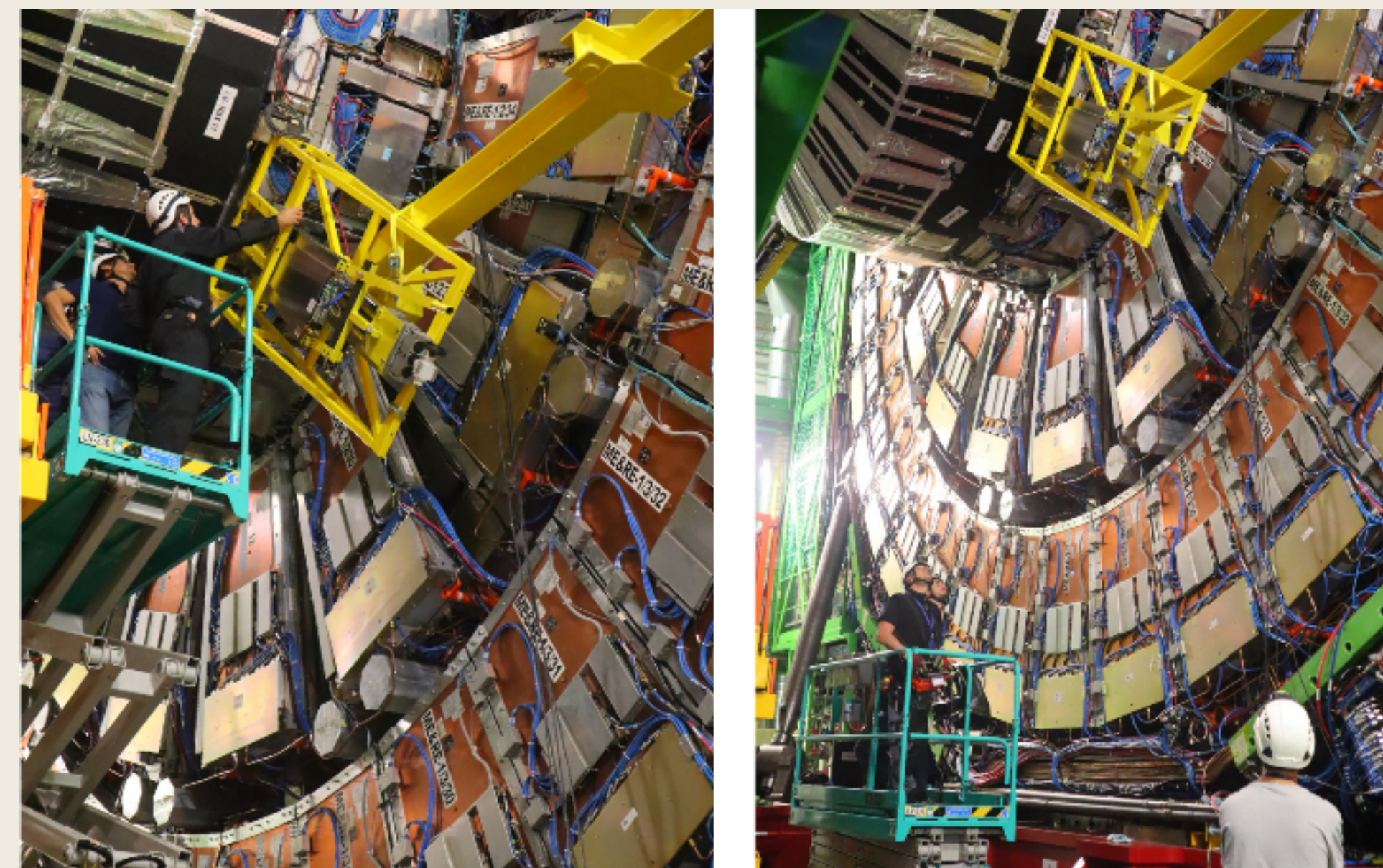
## Practical Gaseous Ionisation Detector Regions

This shows an idealised plot of the three gaseous detection regions, using the concept of applying a variable voltage to a cylindrical chamber which is subjected to constant ionising radiation. Alpha and beta particles are separately plotted to demonstrate the effect of different radiation energies, but the same principles apply to all forms of ionising radiation.



In the ion chamber region gas ionisation is direct and results in a current flow proportional to overall ionisation. At higher field strengths gas multiplication effects can be used, allowing output of individual ionisation events as measurable pulses.

In the proportional region, pulse sizes are proportional to the energy of each ionisation event. In the Geiger region a fill gas at reduced pressure ( $1/10^{\text{th}}$  atmosphere) allows greater multiplication but produces a uniform pulse for each ionising event regardless of its energy.



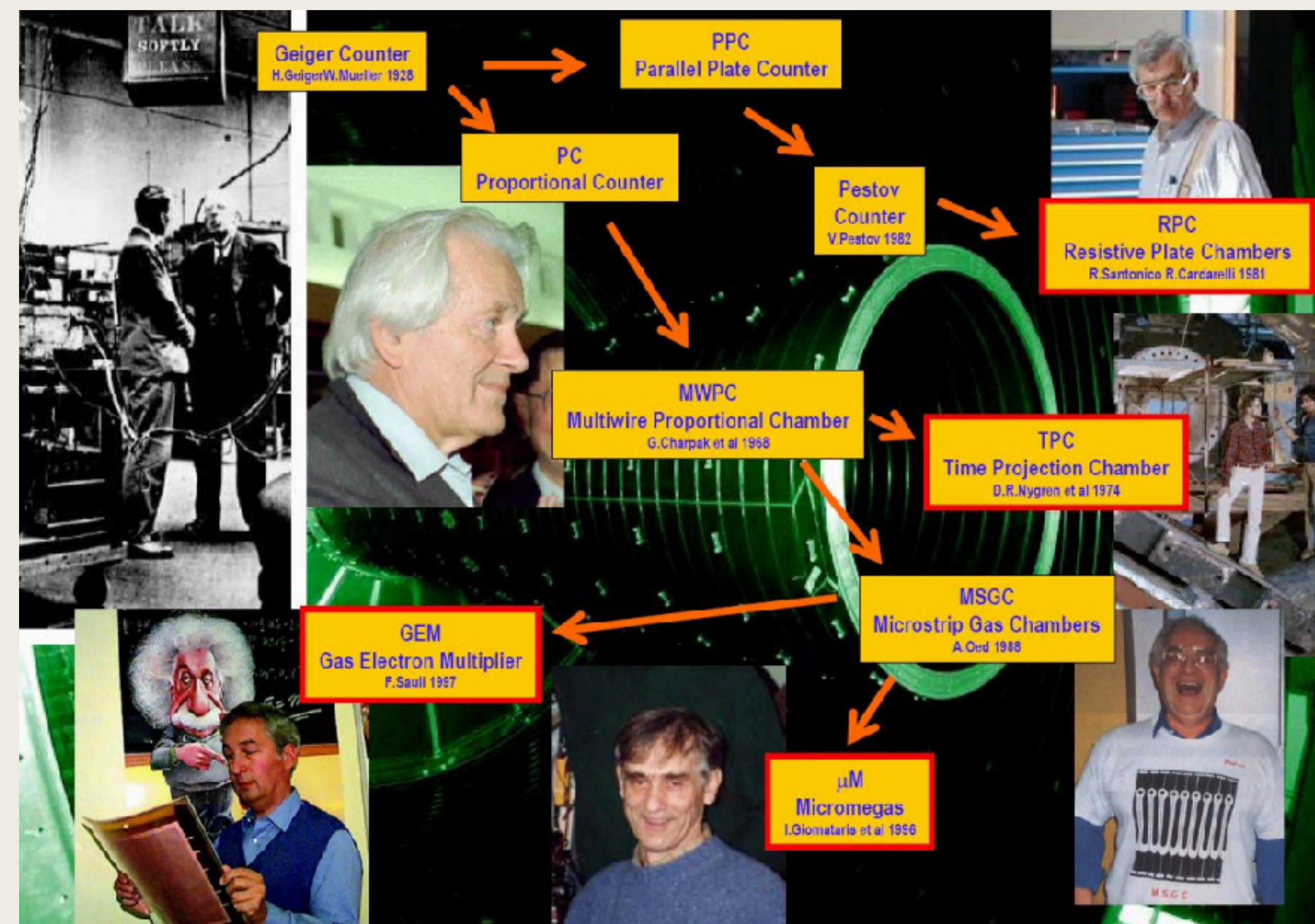
- A charged particle crosses the detector gas and creates ion-electron pairs.
- Electrons drift under an electric field toward the amplification region.
- Gas multiplication converts a tiny ionisation trail into an observable signal.
- Readout electronics transform this signal into data for reconstruction.
- The gas is therefore part of the detector physics, not a passive consumable.



# The Evolution of Detector Design Philosophy

- 1970s: Can we detect particles reliably?
- 1980s: Can we improve precision?
- 1990s: Can we build larger systems?
- 2000s: Can they survive the LHC?
- 2010s: Can they survive HL-LHC?
- Today: Can they survive without harming the planet?

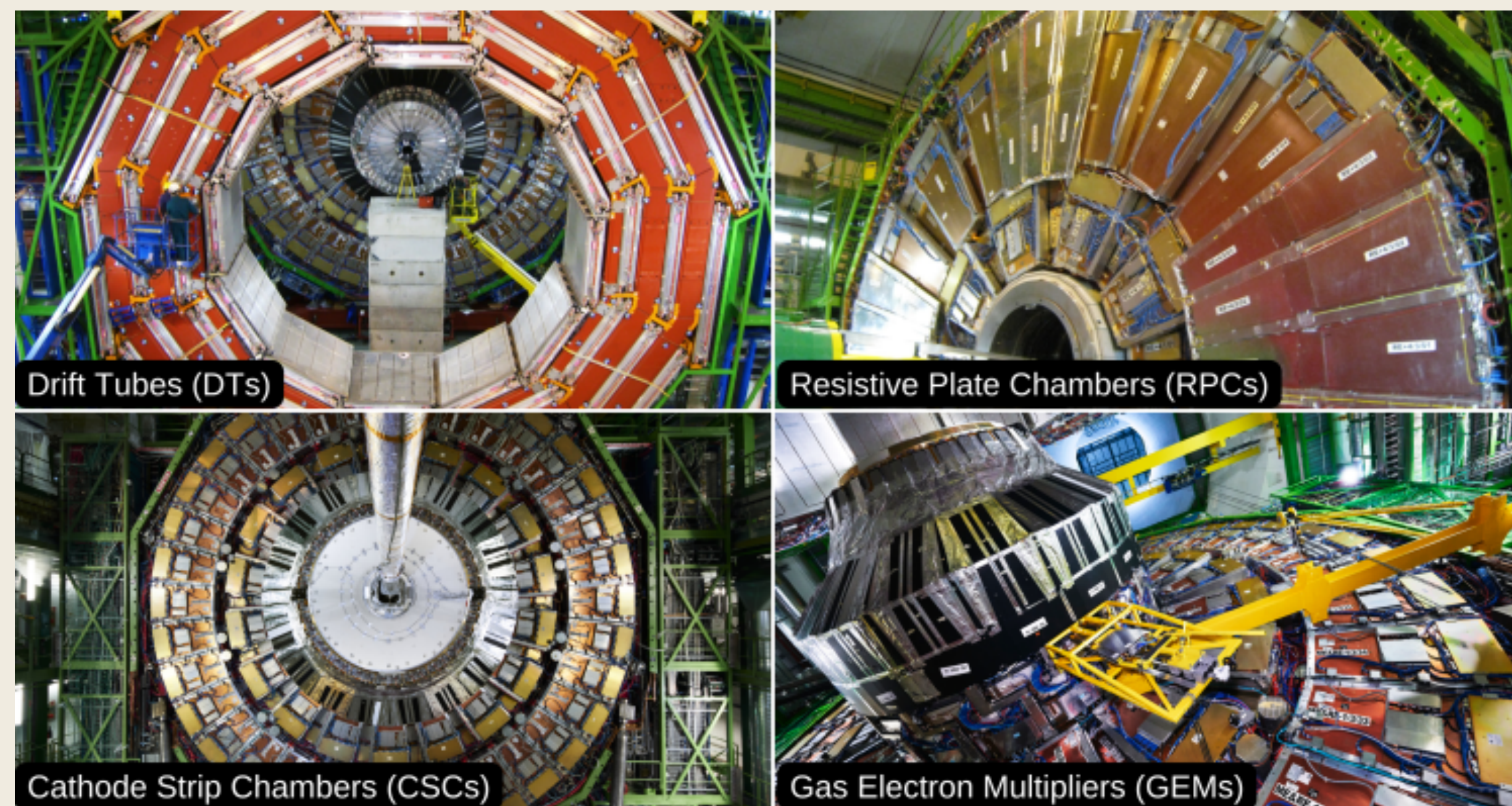
- Ionisation chambers and Geiger counters established the basic principles of radiation detection.
- Proportional counters introduced controlled gas amplification.
- Multi-wire proportional chambers transformed particle physics through electronic tracking.
- Drift chambers and TPCs enabled large-volume precision reconstruction.
- RPCs, Micromegas and GEMs show how gaseous detectors repeatedly adapt to new scientific needs.





# Why Gases Became Indispensable

- Gases offer large sensitive volumes with relatively low material budget.
- They allow high gain without excessive mechanical complexity.
- They are affordable for very large detector surfaces.
- They can be tuned through gas composition, pressure, flow and electric field.
- The challenge is that some historically excellent gases have high climate impact





## \*CMS as a Living Laboratory

### CMS:

#### From Construction to Responsibility

- Building detectors.
- Operating detectors.
- Optimising systems.
- Extending lifetime.
- Reducing environmental impact.

### What CMS Teaches Us

- Large systems expose real operational constraints.
- Small inefficiencies become large at scale.
- Long-term operation changes the meaning of design quality.



\*Could be any large experiment!





# Gas use in LHC detector systems

A compact map for explaining why mitigation is detector-specific



| System     | Typical gas role             | Examples          | Main climate driver                                     | Mitigation lever             | Talk message       |
|------------|------------------------------|-------------------|---------------------------------------------------------|------------------------------|--------------------|
| RPC        | avalanche streamer control   | ATLAS/CMS/ALICE   | R-134a + SF <sub>6</sub>                                | eco-mixtures + recovery      | hardest transition |
| CSC/Muon   | tracking gas gain            | CMS CSC           | CF <sub>4</sub>                                         | CF <sub>4</sub> recuperation | recover first      |
| RICH       | Cherenkov radiator           | LHCb RICH-2       | CF <sub>4</sub> /C <sub>4</sub> F <sub>10</sub> history | recuperation / redesign      | gas value high     |
| TPC        | drift volume                 | ALICE TPC         | large volume gas                                        | recirculation                | near-closed loop   |
| GEM/MPGD   | amplification in micro-holes | CMS GEM           | Ar/CO <sub>2</sub> baseline                             | flow optimisation            | greener baseline   |
| Labs/tests | prototype operation          | GIF++, test beams | small leaks add up                                      | portable recirculation       | culture shift      |

## THE HIDDEN FOURTH REQUIREMENT

TRADITIONAL OPTIMISATION BALANCED EFFICIENCY, STABILITY AND SAFETY.

SUSTAINABILITY NOW BECOMES THE FOURTH ESSENTIAL REQUIREMENT.

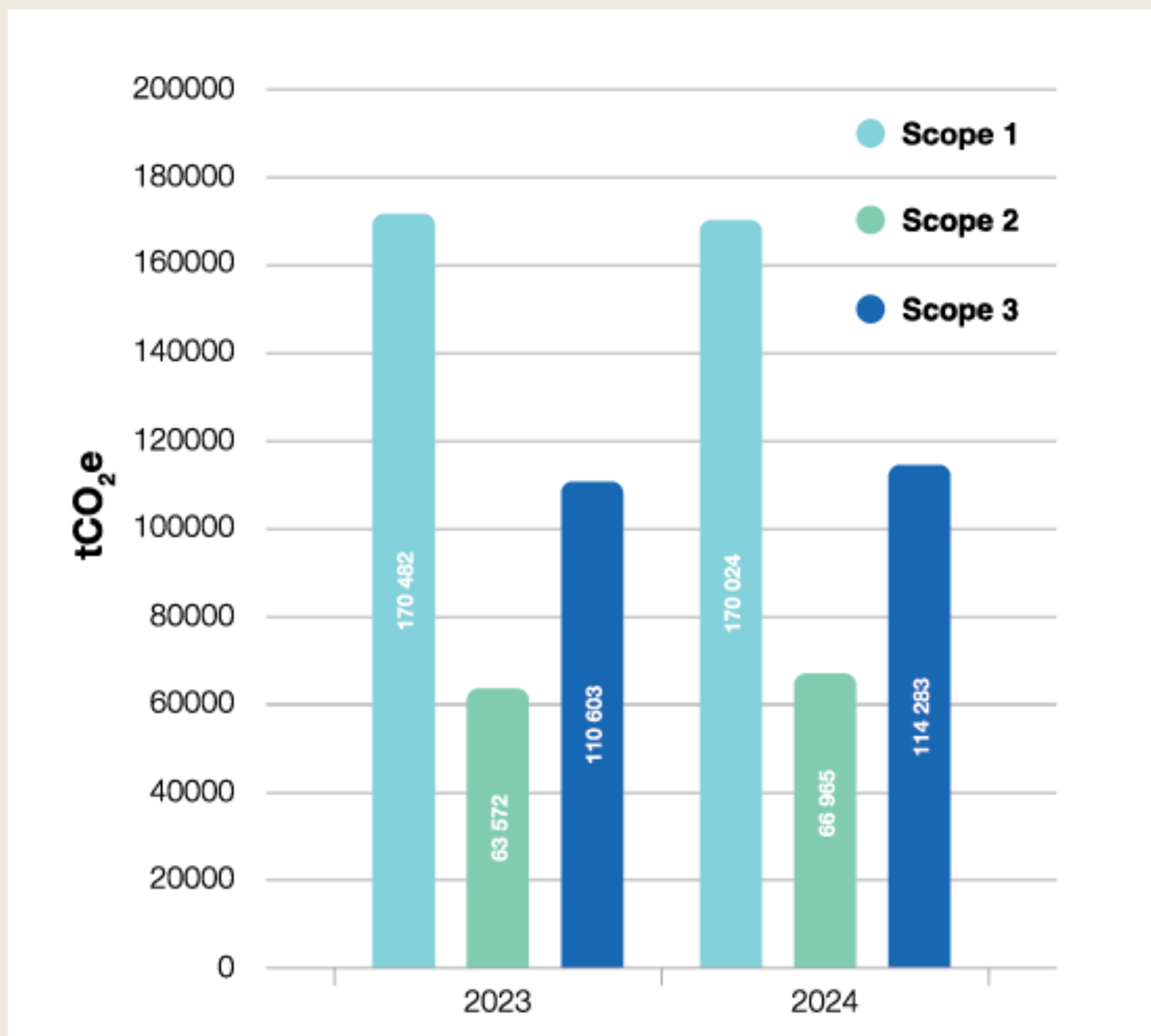
THIS INCLUDES GWP, CONSUMPTION, LEAKAGE, RECOVERY AND END-OF-LIFE HANDLING.

IT DOES NOT REPLACE DETECTOR-PERFORMANCE CRITERIA.

IT EXPANDS THE DETECTOR-DESIGN SPACE TO INCLUDE ENVIRONMENTAL RESPONSIBILITY.



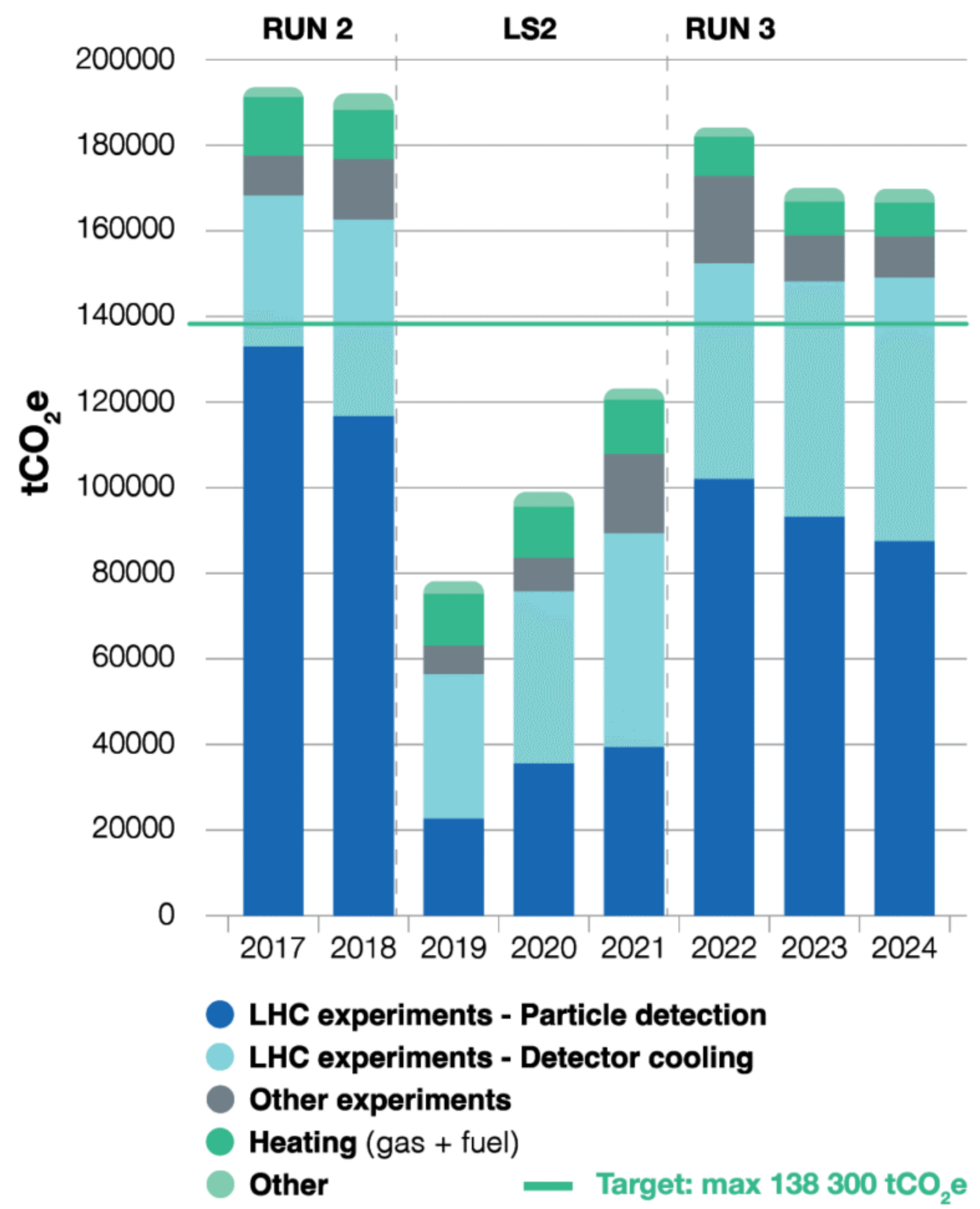
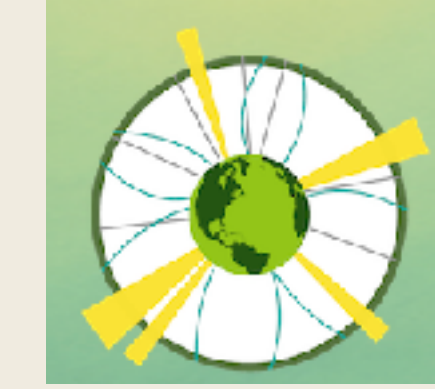
# CERN Emissions Context



- Detector gases now belong to institutional environmental accounting.
- Direct greenhouse-gas emissions are measured and reported.
- F-gases used in detection and cooling are visible contributors.
- The goal is to move from concern to engineering control.
- If emissions can be measured, they can be reduced.

For gaseous detectors, sustainability mainly enters CERN's carbon accounting through Scope 1: every leak or vented high-GWP detector gas becomes a direct emission. Scope 2 is dominated by energy use, while Scope 3 captures the broader life-cycle footprint of equipment, materials, travel and procurement.





Not to overstate one subsystem, but to show that direct greenhouse-gas emissions are visible, measured and now governed.

This makes gas systems part of CERN-wide environmental accountability.

Detector gases are now part of institutional environmental strategy.

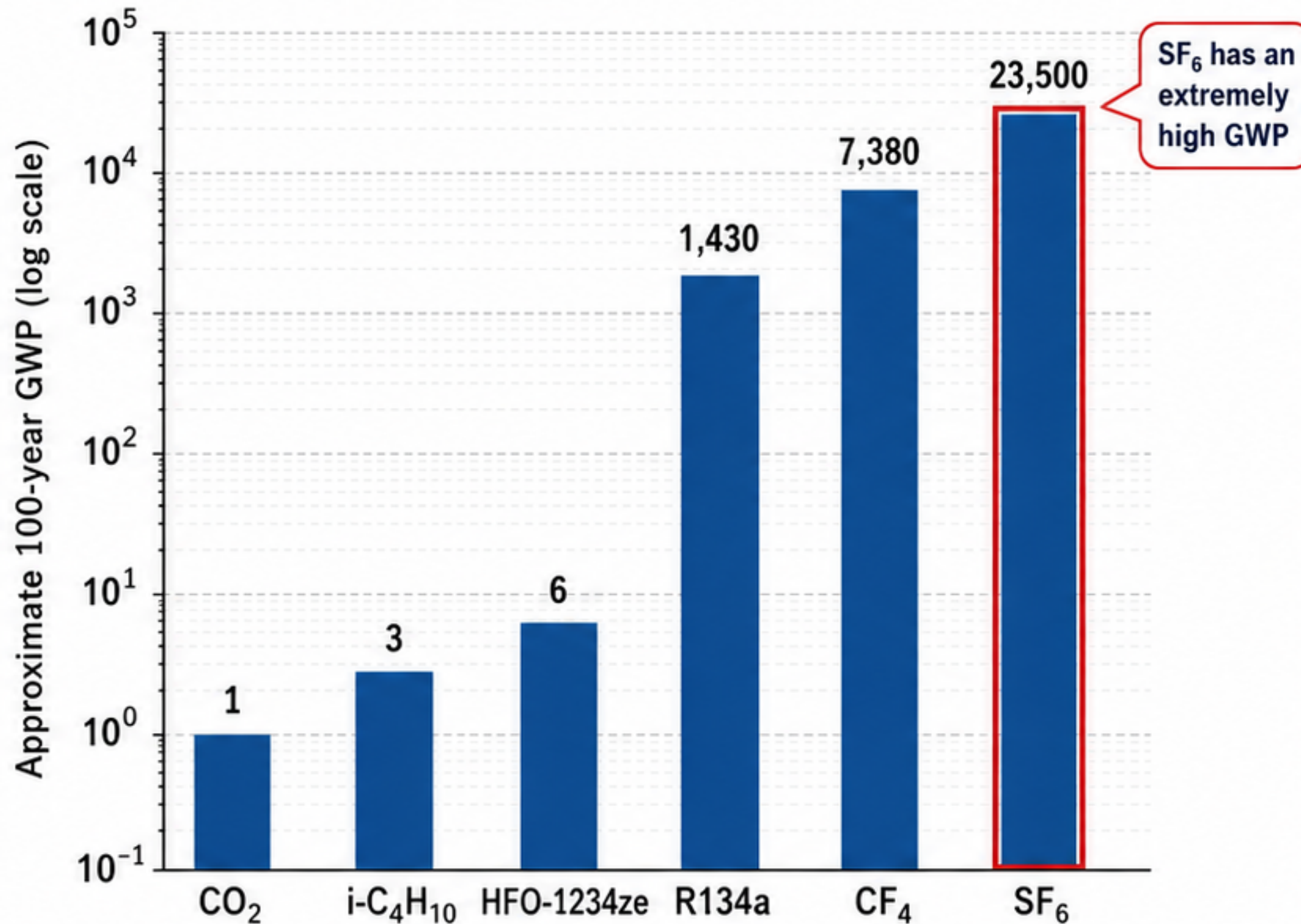
**Reference:** CERN Environment Report 2023-2024.



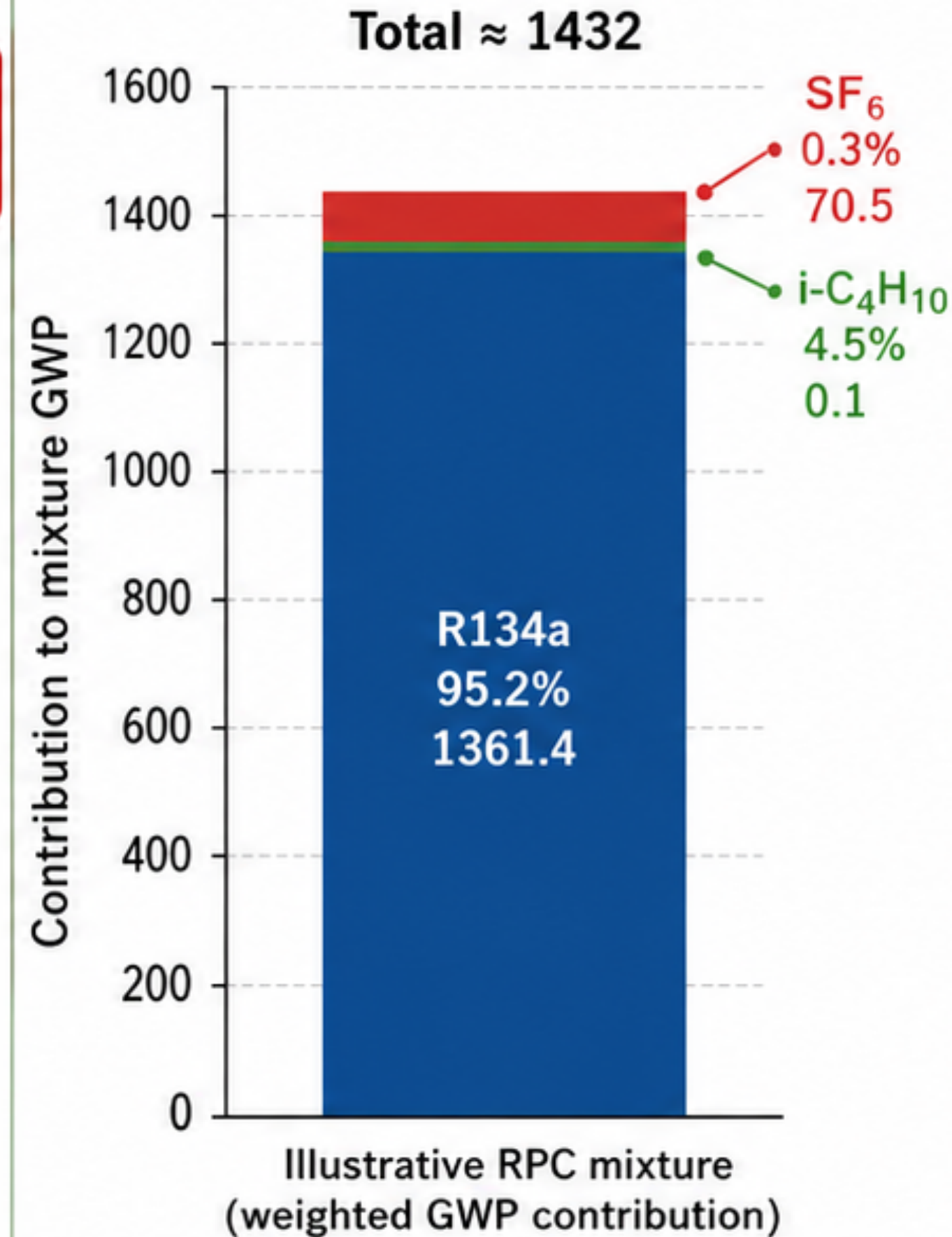
# Why even small amounts of SF<sub>6</sub> are detrimental

*Candidate gases for gaseous detectors and the disproportionate climate impact of trace SF<sub>6</sub>*

## Candidate gases span orders of magnitude in climate impact



## Tiny SF<sub>6</sub> fractions still matter



Illustrative RPC mixture by volume:  
95.2% R134a  
4.5% i-C<sub>4</sub>H<sub>10</sub>  
0.3% SF<sub>6</sub>

SF<sub>6</sub> share by volume: 0.3%  
SF<sub>6</sub> share of mixture GWP: 4.9%



Despite only 0.3% by volume, SF<sub>6</sub> adds ~70 GWP-units here — far more than the much larger i-C<sub>4</sub>H<sub>10</sub> fraction.



**Takeaway:** trace amounts of SF<sub>6</sub> can add a disproportionate climate burden, so eliminating or replacing it remains a high-value sustainability target.



# Why F-Gases Matter ?

| GROUP                     | GASES                                                                                                                                                                                     | tCO <sub>2</sub> e 2023 | tCO <sub>2</sub> e 2024 |
|---------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|-------------------------|
| Perfluorocarbons (PFCs)   | CF <sub>4</sub> , C <sub>2</sub> F <sub>6</sub> , C <sub>3</sub> F <sub>8</sub> , C <sub>4</sub> F <sub>10</sub> , C <sub>6</sub> F <sub>14</sub>                                         | 65 223                  | 75 177                  |
| Hydrofluorocarbons (HFCs) | HFC-23 (CHF <sub>3</sub> ),<br>HFC-32 (CH <sub>2</sub> F <sub>2</sub> ),<br>HFC-134a (C <sub>2</sub> H <sub>2</sub> F <sub>4</sub> ),<br>HFC-404a, HFC-407c,<br>HFC-410a, HFC-507,<br>HFC | 80 988                  | 64 092                  |
| Other F-gases             | SF <sub>6</sub> , NF <sub>3</sub>                                                                                                                                                         | 14 906                  | 21 567                  |
| Hydrofluoroolefins (HFOs) | R-449, R-1234ze,<br>NOVEC 649, R-1233ef                                                                                                                                                   | 145                     | 1                       |
|                           | CO <sub>2</sub>                                                                                                                                                                           | 9 220                   | 9 187                   |
| <b>Total Scope 1</b>      |                                                                                                                                                                                           | <b>170 482</b>          | <b>170 024</b>          |

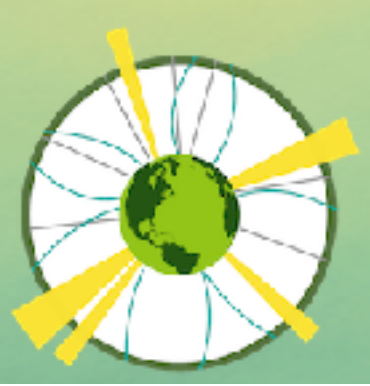
- Not all gases have the same climate impact.
- A small fraction of a very high-GWP gas can dominate the footprint.
- SF<sub>6</sub>, CF<sub>4</sub>, R134a and related fluorinated gases require special attention.
- Their long atmospheric lifetimes make losses especially consequential.
- Sustainability depends on gas chemistry, quantity, leakage and lifetime.

**Reference:** CERN Environment Report; EU F-gas regulation background.



# From open flow to closed-loop recirculation

The first operational lever is to reduce fresh gas demand



## Open-flow operation

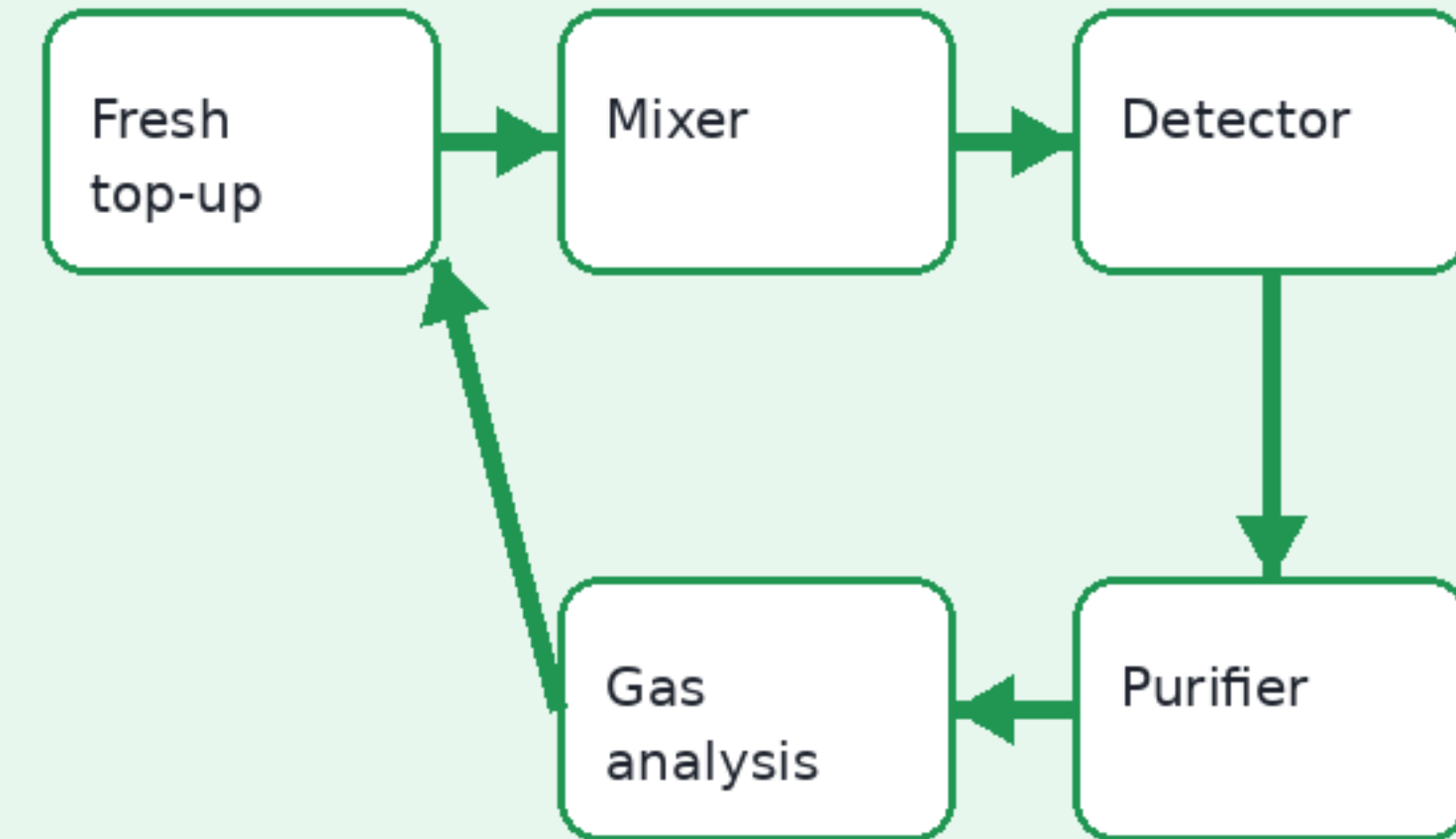


High fresh-gas use

All unused gas is emitted

Simple, but environmentally costly

## Closed-loop recirculation



## THE REGULATORY TURNING POINT

Environmental regulation around fluorinated gases is becoming stricter.

Scientific research must anticipate availability, cost and reporting constraints.

Future gas choices will face stronger scrutiny.

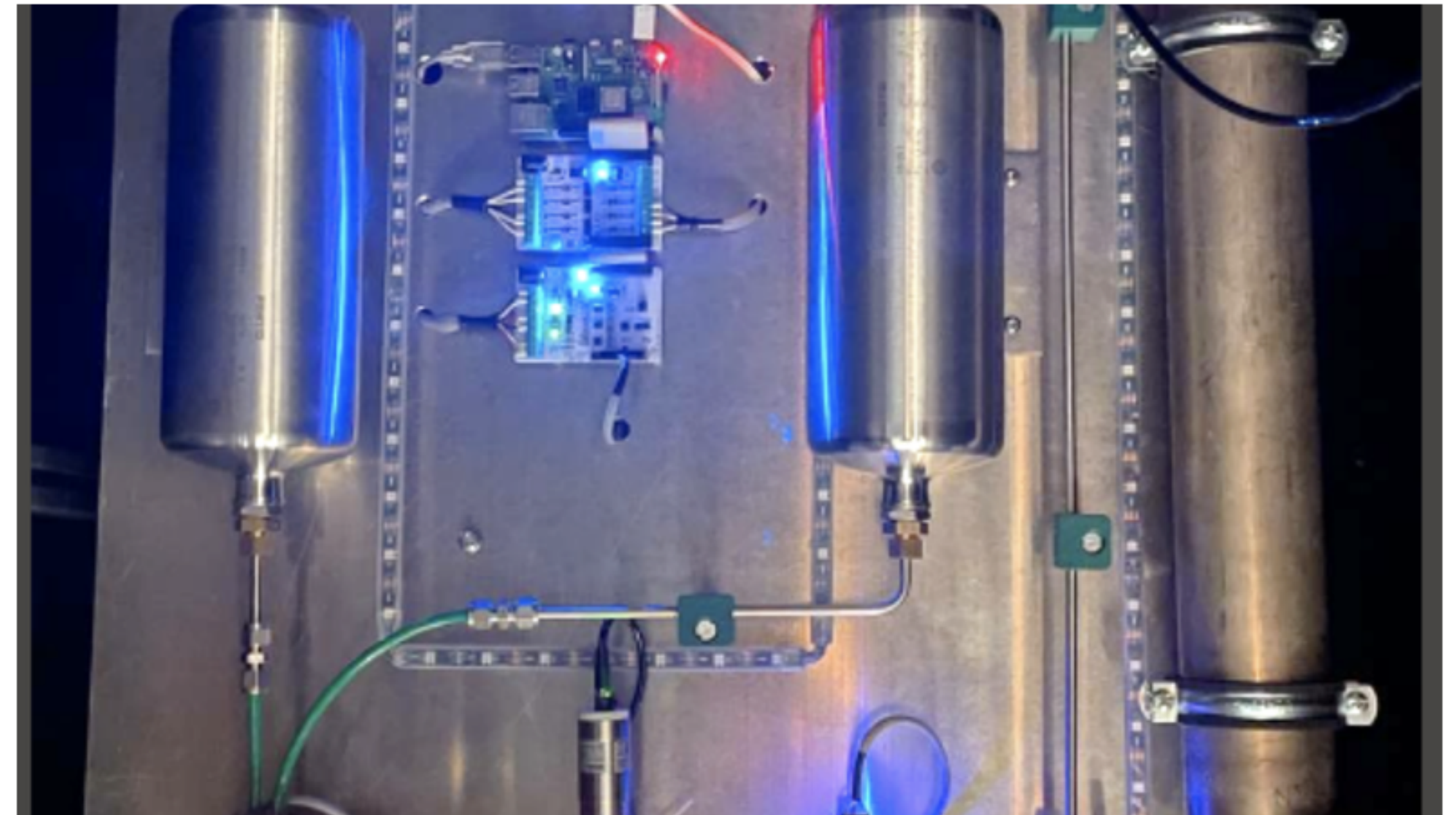
Detector projects should not wait until regulations force change.

Responsible planning protects both the science programme and institutional credibility.



# Recirculation is becoming modular

From LHC-scale systems to laboratory and test-beam units



RPCs often use mixtures with high-GWP components such as R134a and SF<sub>6</sub>.

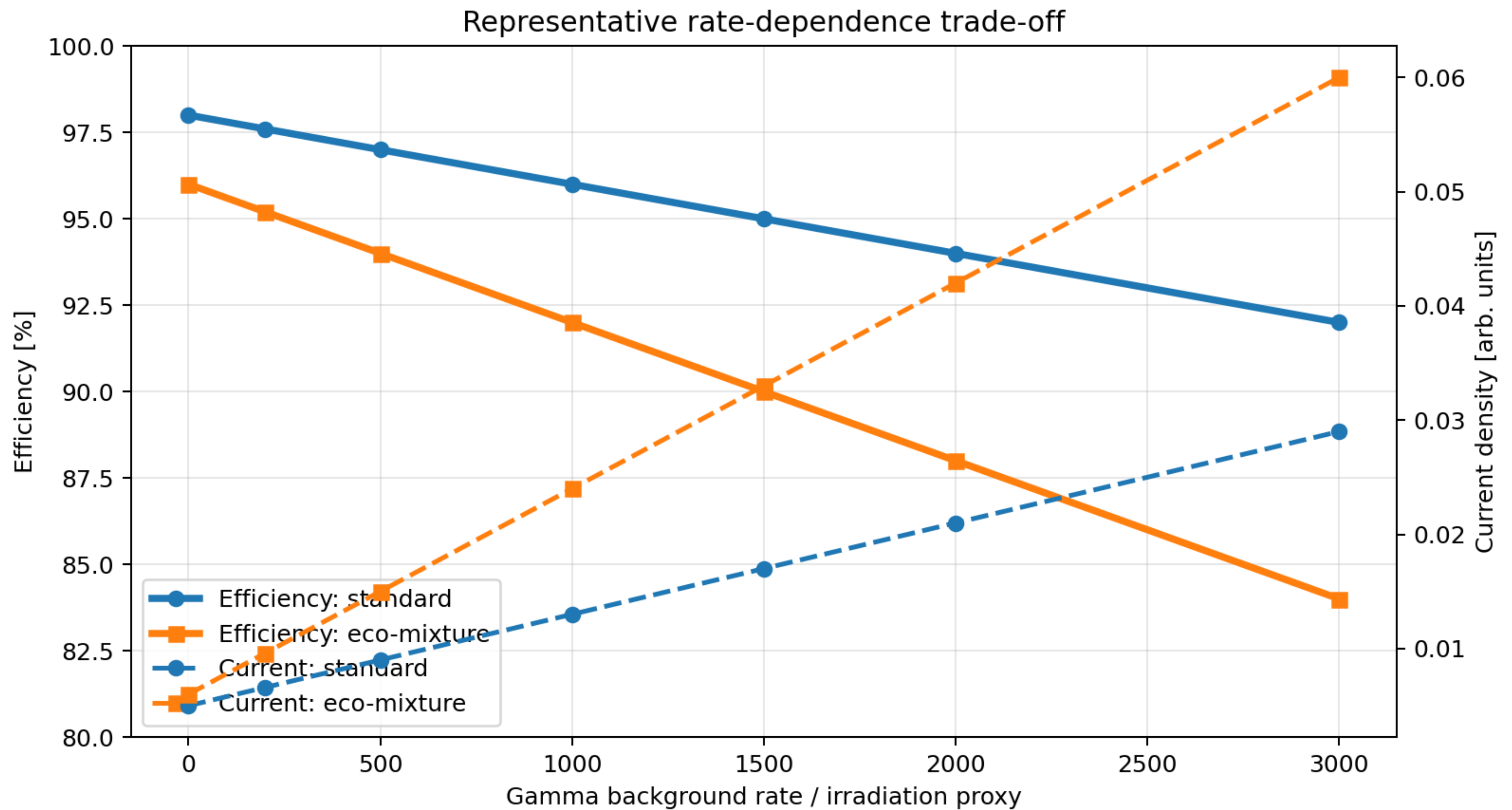
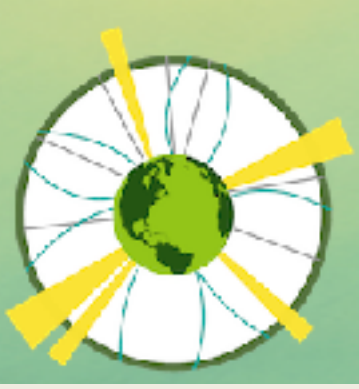
GEMs often operate with Ar/CO<sub>2</sub> mixtures in major applications.

Micromegas systems can also use comparatively lower-impact Ar/CO<sub>2</sub> mixtures.

TPCs may avoid high-GWP gases but involve large volumes and purity demands.

RICH systems may require specialised fluorocarbon radiators that are difficult to replace.





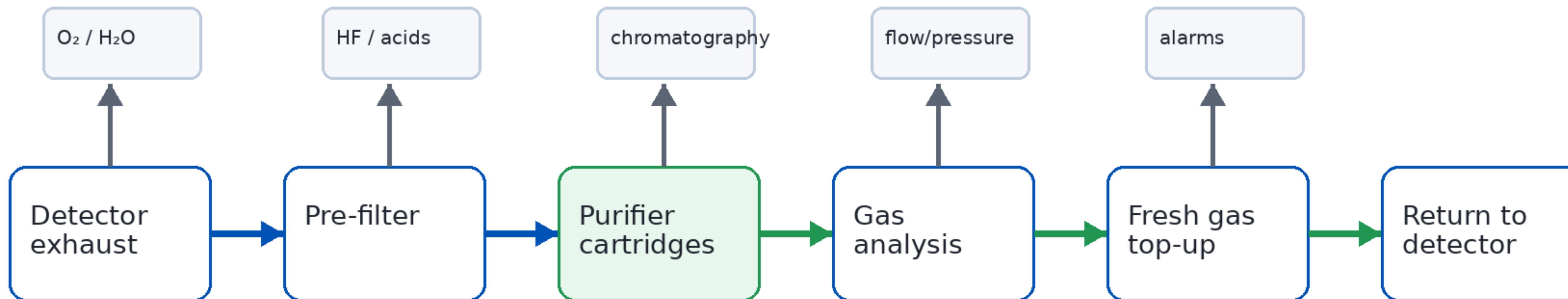
PRESENT GAS-MIXTURE LANDSCAPE

RPCS OFTEN USE MIXTURES WITH HIGH-GWP COMPONENTS SUCH AS R134A AND SF<sub>6</sub>.  
GEMS OFTEN OPERATE WITH AR/CO<sub>2</sub> MIXTURES IN MAJOR APPLICATIONS.  
MICROMEGAS SYSTEMS CAN ALSO USE COMPARATIVELY LOWER-IMPACT AR/CO<sub>2</sub> MIXTURES.  
TPCS MAY AVOID HIGH-GWP GASES BUT INVOLVE LARGE VOLUMES AND PURITY DEMANDS.  
RICH SYSTEMS MAY REQUIRE SPECIALISED FLUOROCARBON RADIATORS THAT ARE DIFFICULT TO REPLACE.



# Purification and monitoring make recirculation safe

Closed-loop operation needs chemistry, sensors and operational discipline



## RPCS: THE URGENT CASE

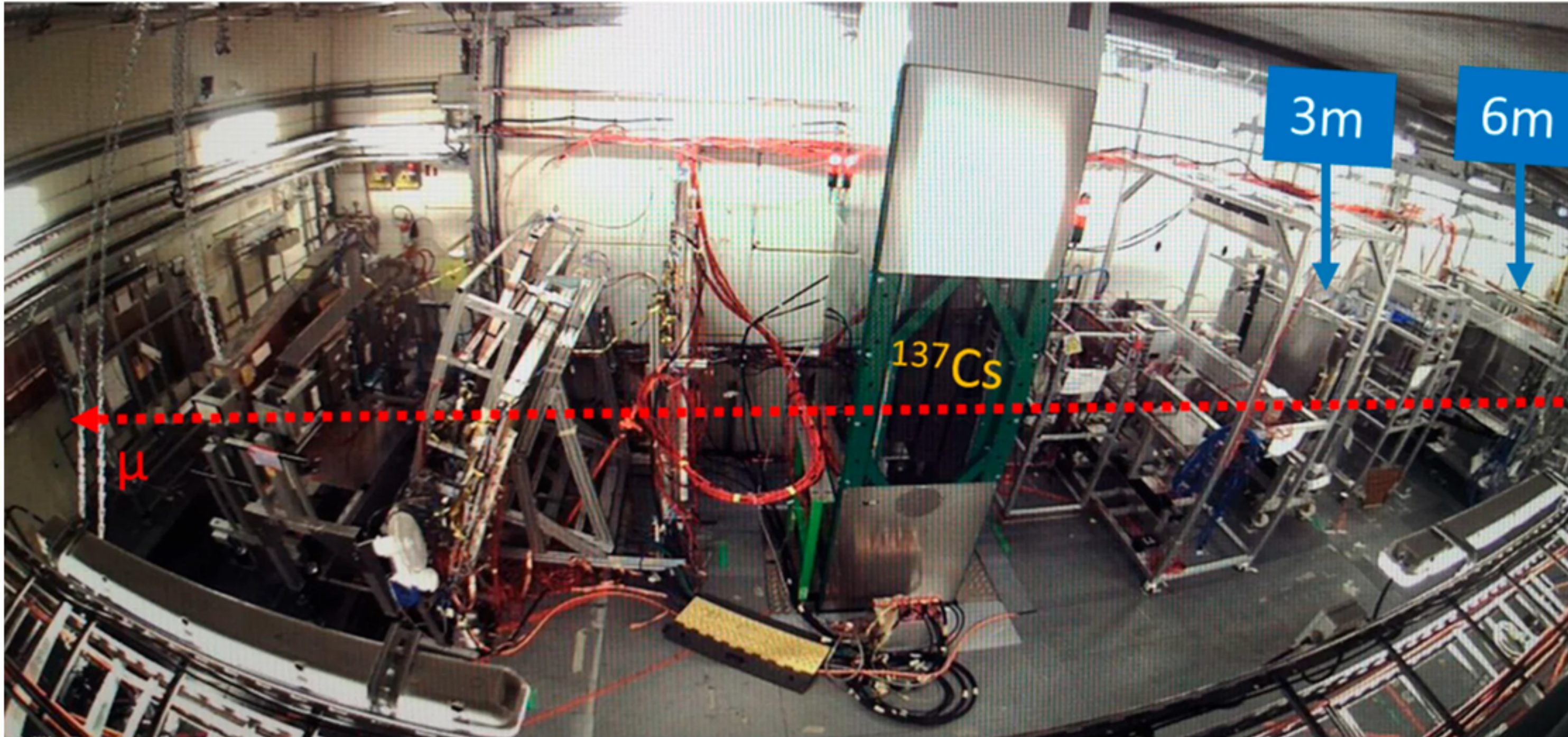
RPCS ARE EXTREMELY VALUABLE FOR FAST TIMING AND LARGE-AREA TRIGGERING. THEIR TRADITIONAL GAS MIXTURES HAVE EXCELLENT DETECTOR PROPERTIES. THE SAME MIXTURES RAISE ENVIRONMENTAL CONCERNS BECAUSE OF HIGH-GWP COMPONENTS.

REPLACING THE GAS AFFECTS VOLTAGE, EFFICIENCY, TIMING, CURRENTS AND AGEING. RPC ECO-GAS WORK IS THEREFORE SERIOUS DETECTOR R&D, NOT A SIMPLE SUBSTITUTION.



# GIF++ eco-gas test environment

Performance must be validated under irradiation, not only in quiet laboratory conditions



## What GIF++ enables

**$^{137}\text{Cs}$   $\gamma$  source**  
controlled background

**Muon beam**  
efficiency scans

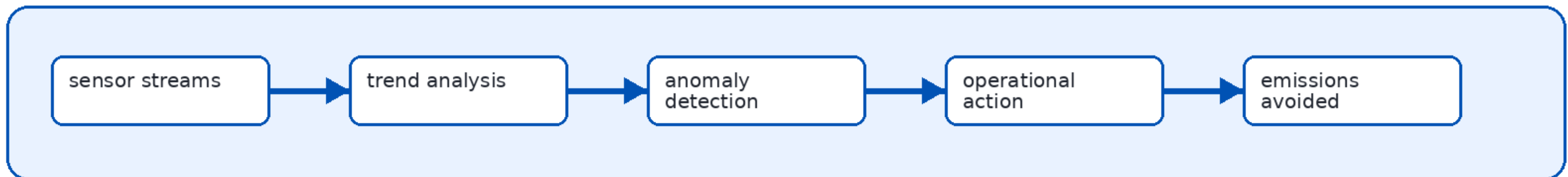
**RPC stack**  
multiple experiments

**Aging campaign**  
long-term validation



# Gas quality monitoring: from diagnostics to prevention

A detector gas system should be treated as a sensor network





# Recuperation: recover what cannot yet be replaced

Essential for R-134a, CF<sub>4</sub> and other high-value/high-GWP gases



## Why difficult?

Gas mixtures may form azeotropes or contain components with similar separation behaviour.

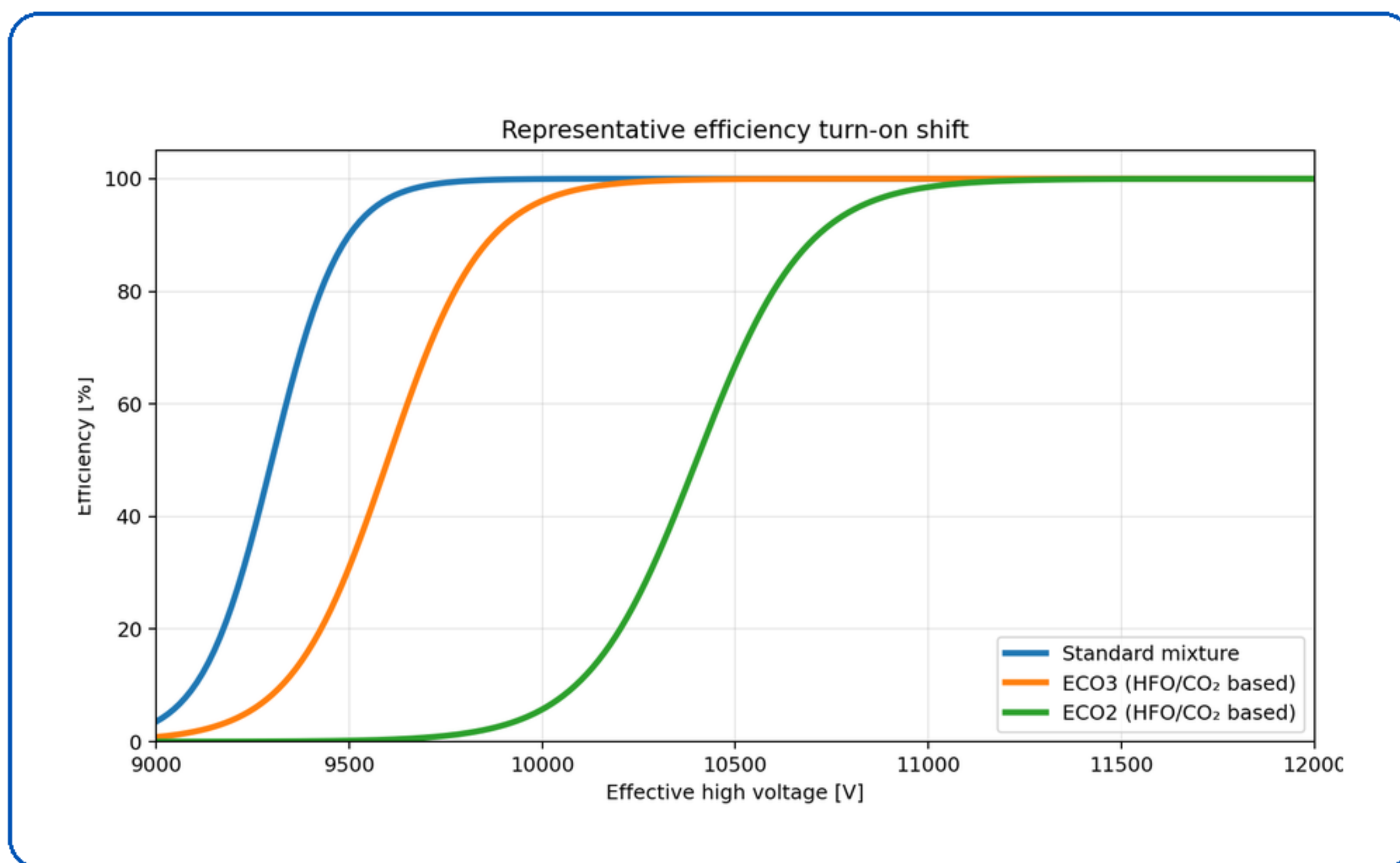
## Why powerful?

Recovery reduces purchase, disposal and direct emission of gases that are expensive, regulated or high-GWP.



# HFO-based mixtures: promising, but shifted operating point

Eco-RPC gases can reach efficiency, but often at higher voltage



## Positive result

Efficiencies above 95% are reachable in tested eco-mixtures.

## Trade-off

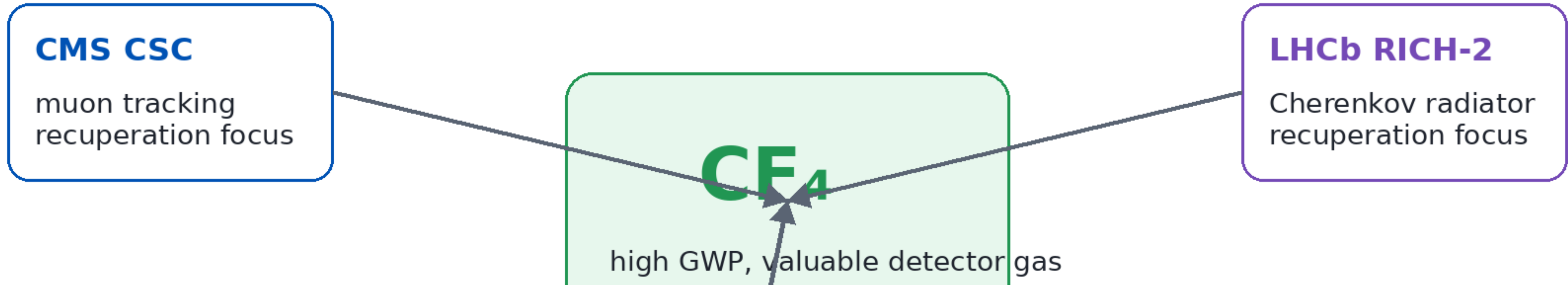
Higher operating voltage and current behaviour must be validated.

Eco-gas adoption is performance engineering



# CF<sub>4</sub> recovery: a useful bridge technology

For gases with no immediate drop-in substitute, recovery protects both physics and climate



## CF<sub>4</sub> Recovery as Bridge Technology

- CF<sub>4</sub> remains useful in some detector systems.
- Its environmental impact makes uncontrolled release unacceptable.
- Buy time for long-term replacement or redesign.

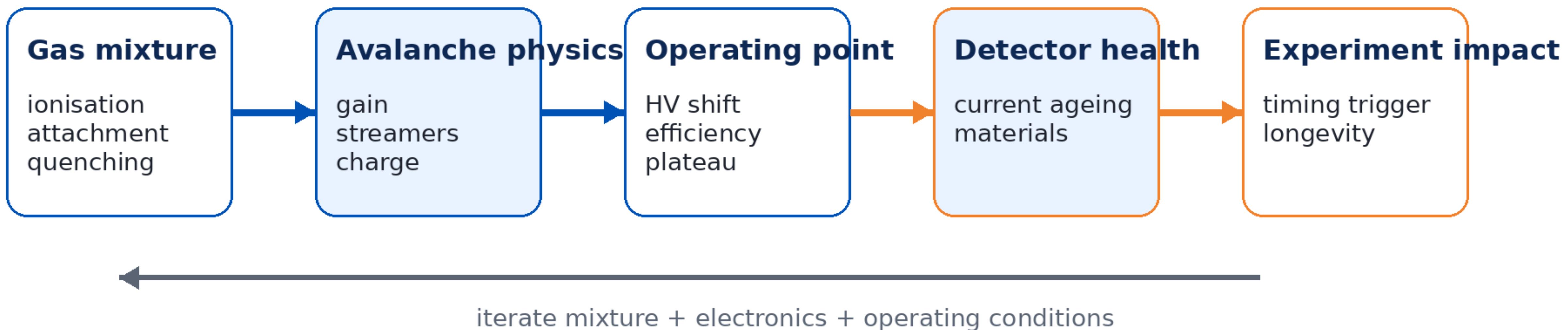
**Future systems**  
design recovery  
from day zero

Slide message: recovery is not a retreat from green design; it is the responsible bridge while alternatives are validated for physics performance.



# Why gas replacement is not a drop-in exercise

Changing the molecule changes the detector



**ECO-GASES ARE A DETECTOR R&D  
PROGRAM NOT A PROCUREMENT SUBSTITUTION**





# RPC case study: simple geometry, demanding gas chemistry

High timing performance depends critically on avalanche control

Traditional mix: R-134a + i-C<sub>4</sub>H<sub>10</sub> + SF<sub>6</sub>

readout strips

insulator

resistive plate

gas gap 1



central electrode

gas gap 2



resistive plate

insulator

readout strips

RPCS ARE MATURE AND POWERFUL, BUT THEIR GAS CHEMISTRY IS THE CENTRE OF TODAY'S SUSTAINABILITY CHALLENGE



# Ageing campaign: sustainability must survive time

A gas is only acceptable if detector performance remains stable over accumulated charge



## Dark current

watch for slow increases



## Resistivity

temperature-correct and trend



## Efficiency shift

validate working point after dose



AN ECO-MIXTURE MUST BE PROVEN OVER THE DETECTOR LIFETIME  
NOT ONLY AT THE FIRST EFFICIENCY PLATEAU





# RECOVER WHAT WE CANNOT REPLACE

Some high-GWP gases cannot be eliminated immediately because the detector performance and ageing case is still being studied. For those gases, recuperation is a responsible bridge technology. It gives time for R&D while reducing waste and emissions.

Recovery is the bridge between today's detector and tomorrow's gas mixture.

**Reference:** CERN EP News; Arena et al. 2024; gas recuperation studies.





# From open flow to closed-loop recirculation

The first operational lever is to reduce fresh gas demand

## Open-flow operation

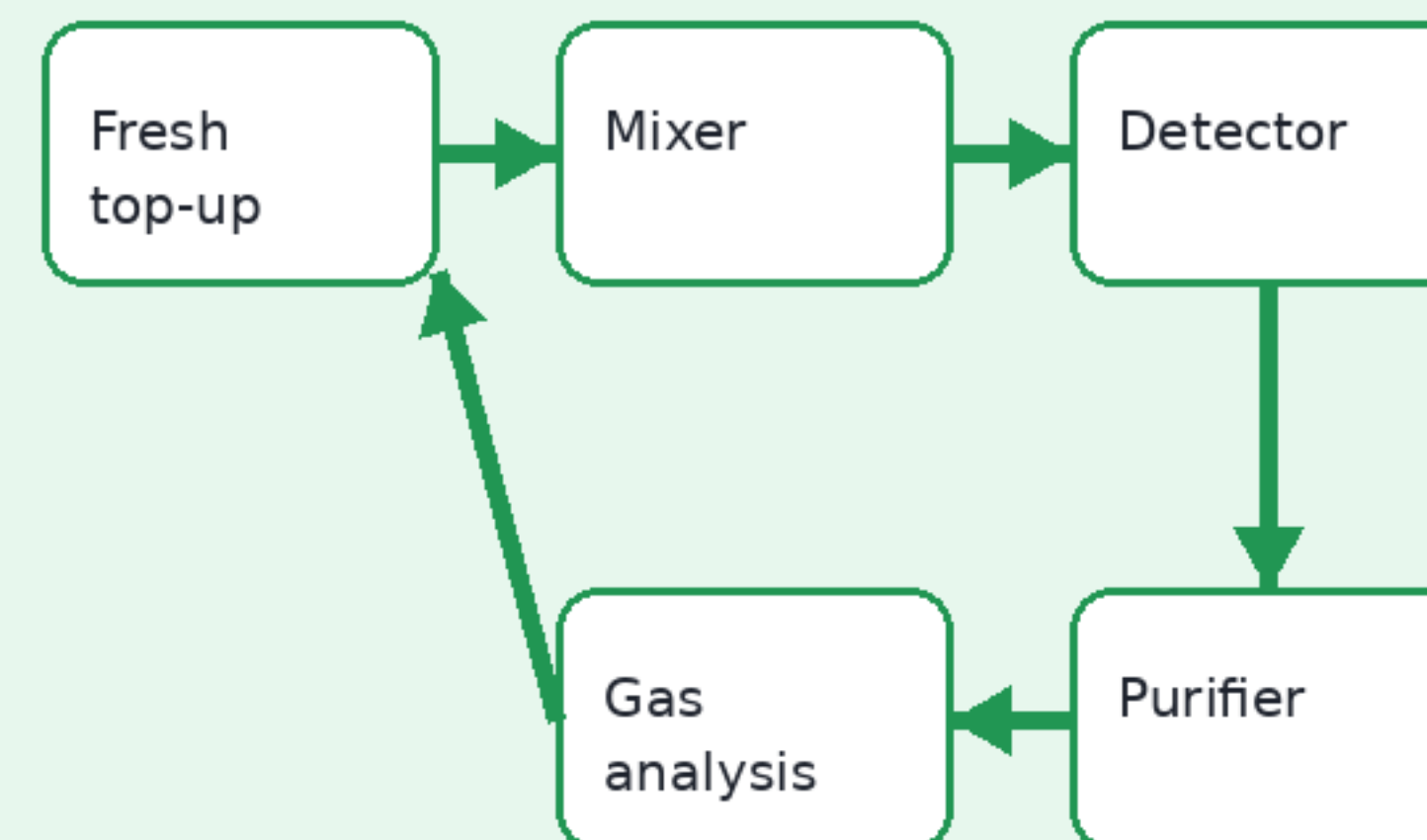


High fresh-gas use

All unused gas is emitted

Simple, but environmentally costly

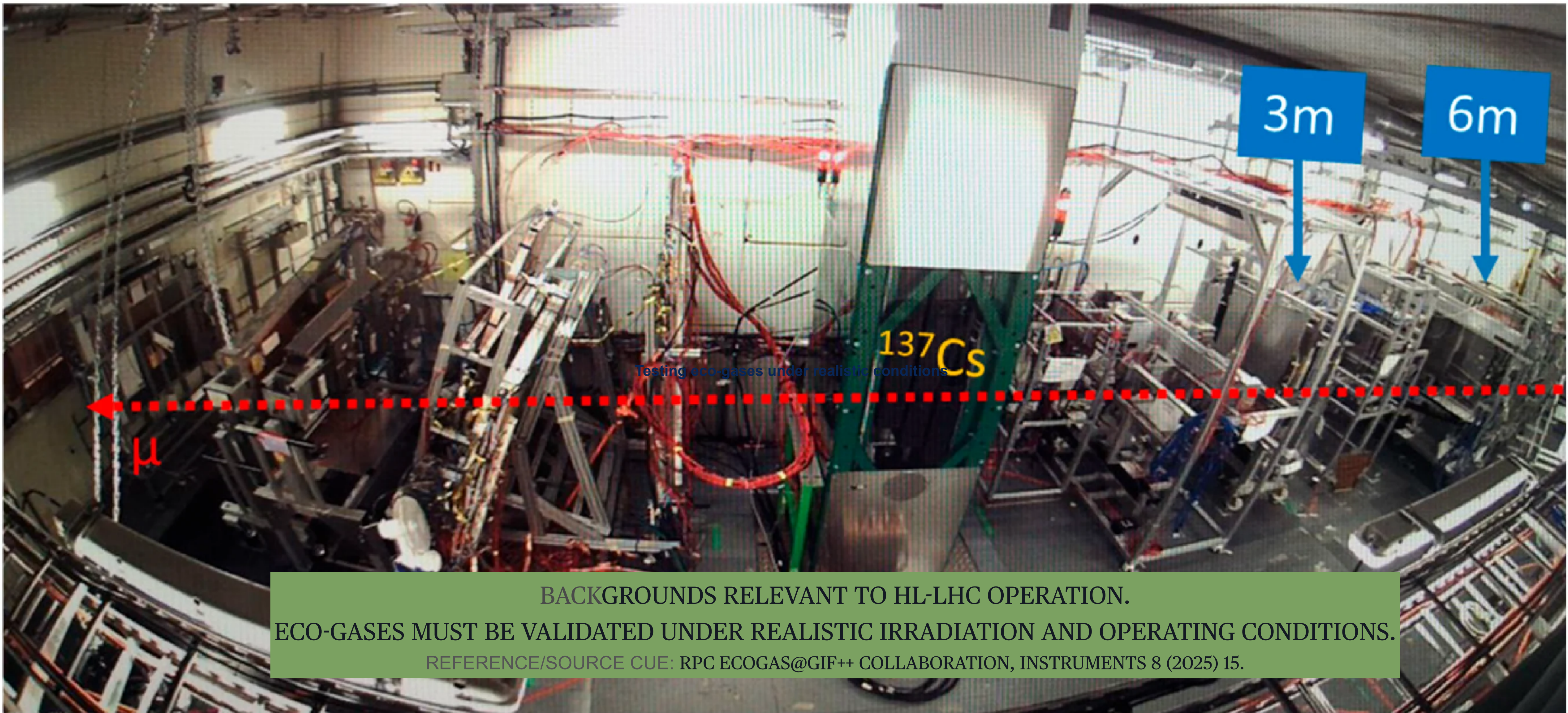
## Closed-loop recirculation



**AN ECO-MIXTURE MUST BE PROVEN OVER THE DETECTOR LIFETIME  
NOT ONLY AT THE FIRST EFFICIENCY PLATEAU**

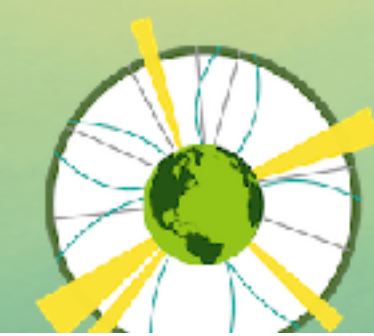


# TESTING ECO-GASES UNDER REALISTIC CONDITIONS

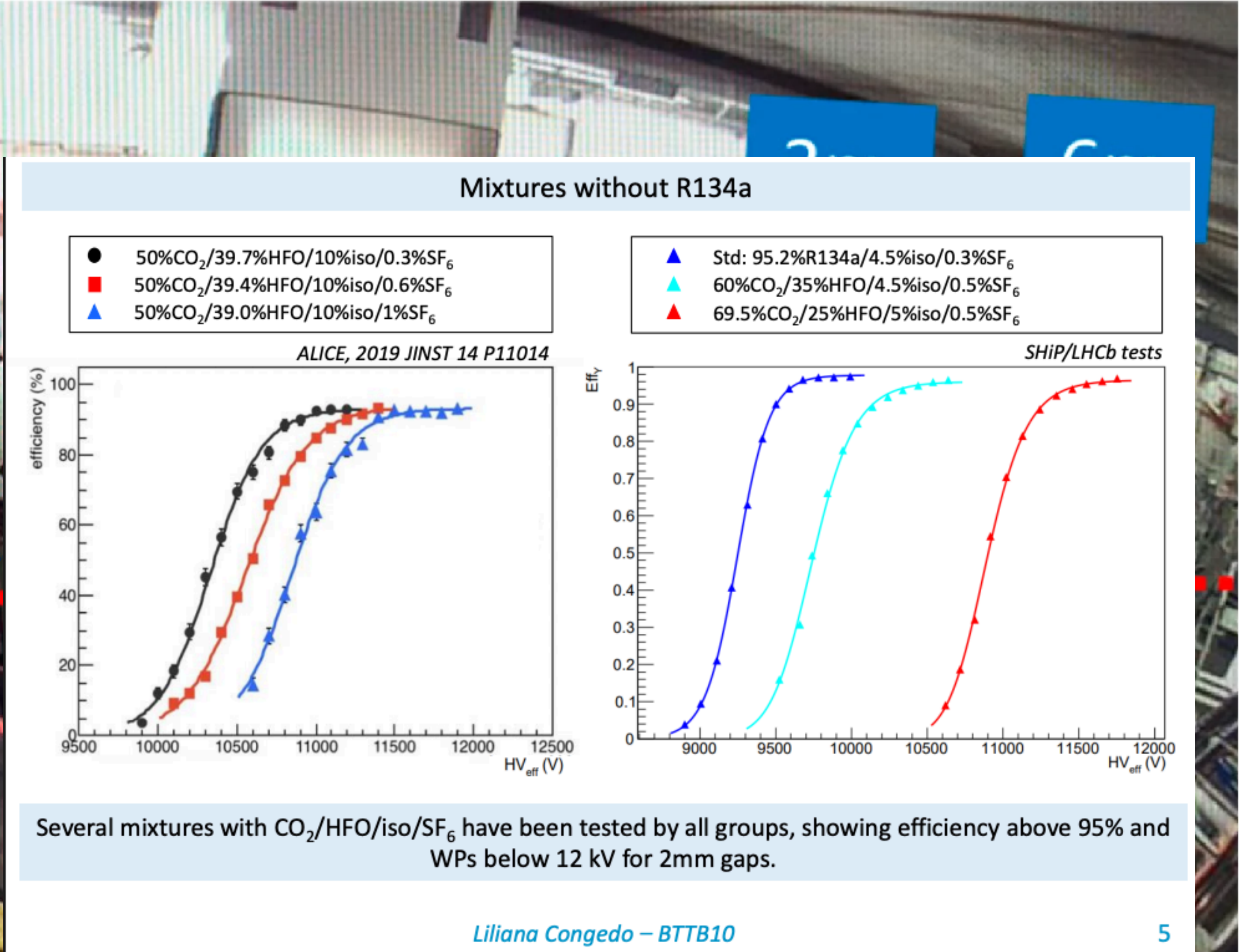


BACKGROUNDS RELEVANT TO HL-LHC OPERATION.  
ECO-GASES MUST BE VALIDATED UNDER REALISTIC IRRADIATION AND OPERATING CONDITIONS.  
REFERENCE/SOURCE CUE: RPC ECOGAS@GIF++ COLLABORATION, INSTRUMENTS 8 (2025) 15.





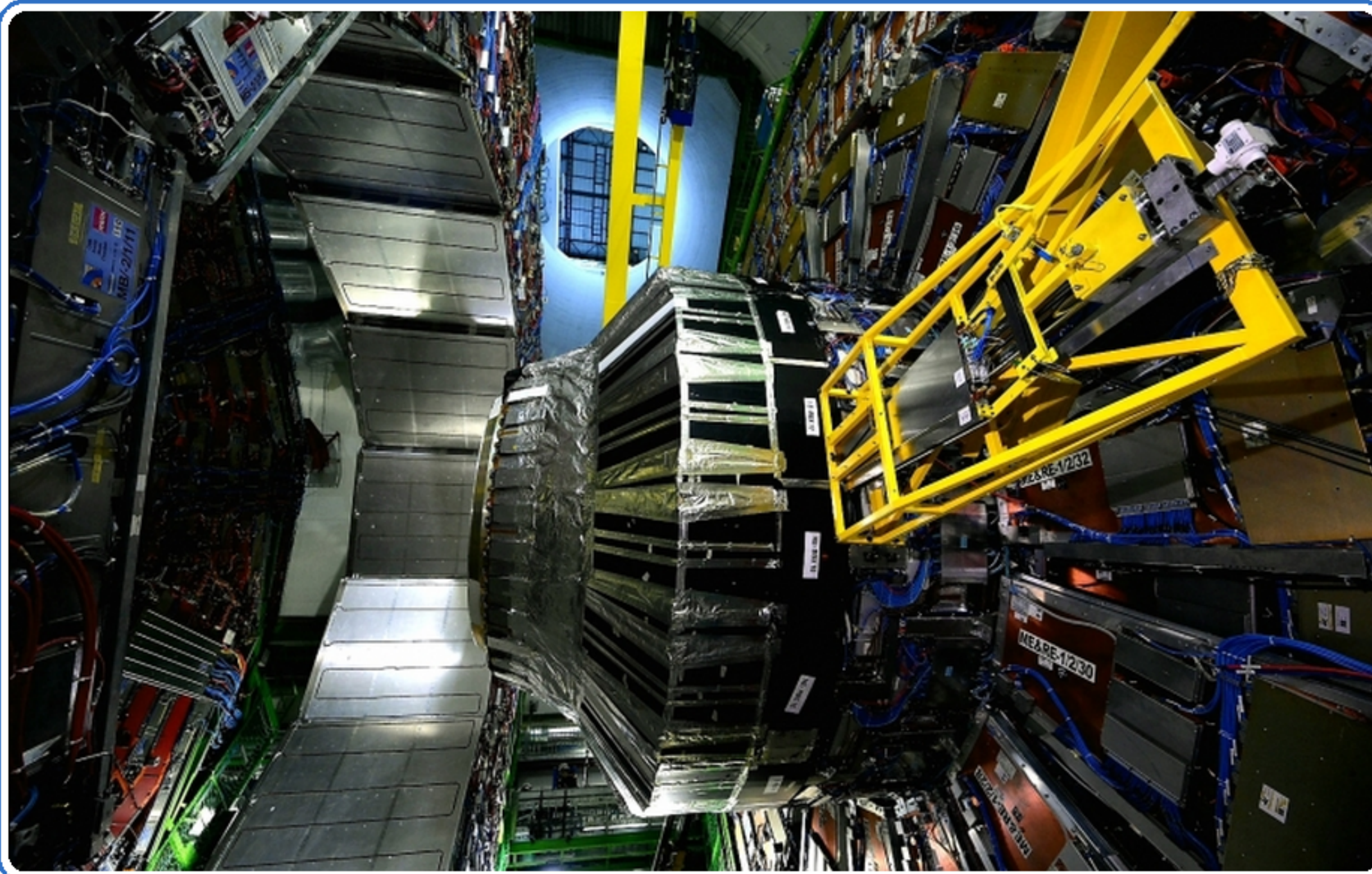
| Metric / Property                   | Standard Mixture                                                           | ECO1                                                     | ECO2                                                     | ECO3                                                     |
|-------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Global Warming Potential (100y GWP) | ~1485                                                                      | ~230                                                     | ~475                                                     | ~527                                                     |
| Chemical Composition                | 95.2% R134a / 4.5% i-C <sub>4</sub> H <sub>10</sub> / 0.3% SF <sub>6</sub> | 45% HFO / 50% CO <sub>2</sub>                            | 35% HFO / 60% CO <sub>2</sub>                            | 25% HFO / 69% CO <sub>2</sub>                            |
| Fixed Components                    | Baseline Standard                                                          | 4% i-C <sub>4</sub> H <sub>10</sub> / 1% SF <sub>6</sub> | 4% i-C <sub>4</sub> H <sub>10</sub> / 1% SF <sub>6</sub> | 5% i-C <sub>4</sub> H <sub>10</sub> / 1% SF <sub>6</sub> |
| Operating Voltage Shift             | Baseline (~9.5 kV)                                                         | Moderate increase                                        | Highest shift (~11.0 kV)                                 | Higher shift (~9.7 kV)                                   |
| Ageing Campaign Status              | Baseline legacy gas                                                        | Discarded after a few weeks                              | Active (under test since 2021)                           | Active (under test since 2021)                           |
| Integrated Charge Survival          | Proven high stability                                                      | Failed at ≈ 10--20 mC/cm <sup>2</sup>                    | Stable at ≈ 100 mC/cm <sup>2</sup> +                     | Stable at ≈ 100 mC/cm <sup>2</sup> +                     |
| Observed Stability Issues           | High greenhouse footprint                                                  | Rapid dark current increase                              | Moderate current density surge                           | Mildest current density surge                            |





# CMS GEM experience: a mature green platform

From R&D to installed detector systems — sustainability can ride on proven technology



CMS GE1/1 GEM installation — mature large-area GEM technology.

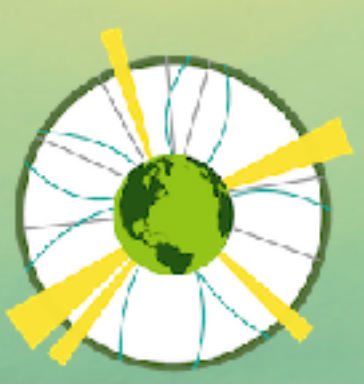


## • Strong Candidates

- MPGDs/GEMs already use low-GWP Ar/CO<sub>2</sub> operating mixtures in many applications.
- The sustainability focus shifts from emergency gas replacement to system optimisation.
- Large-area GEM systems show that industrialisation, QA and environmental responsibility can be developed together.

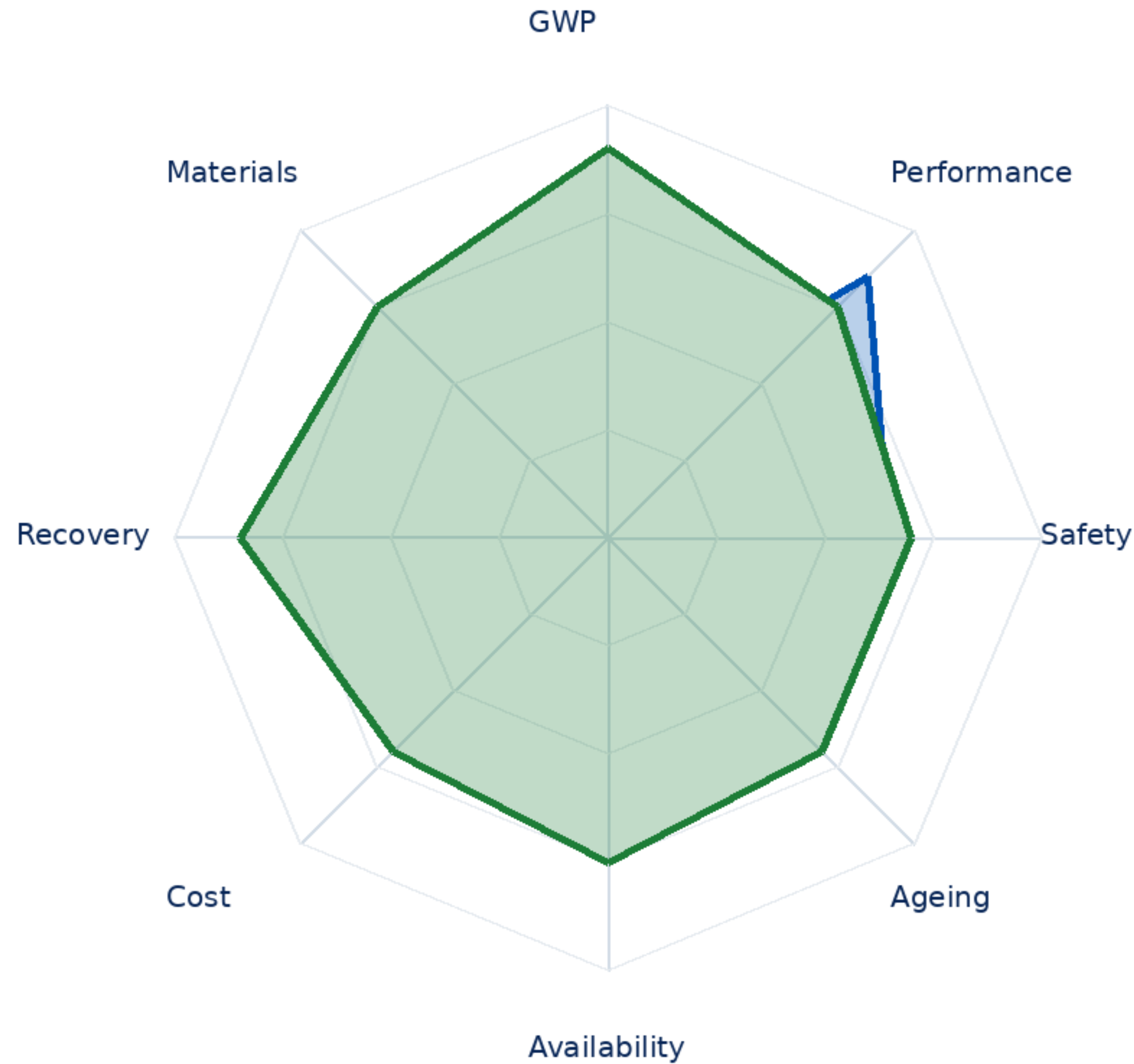
- GEMs use micro-pattern amplification inside small holes in a thin foil.
- They provide high rate capability, fine granularity and flexible readout.
- Many GEM systems can operate with Ar/CO<sub>2</sub> mixtures.
- This avoids the most problematic RPC-style fluorinated baseline gases





# Gas choice as a design principle

A sustainable mixture is selected by a multi-constraint detector design matrix



## Gas mixture design checklist

- Detector gain, efficiency and timing
- Ageing under irradiation
- Compatibility with materials and purifiers
- Safety: flammability, toxicity, pressure
- GWP, regulation and procurement risk
- Recirculation / recovery feasibility
- Operational robustness over decades

■ Legacy optimisation ■ Sustainable optimisation

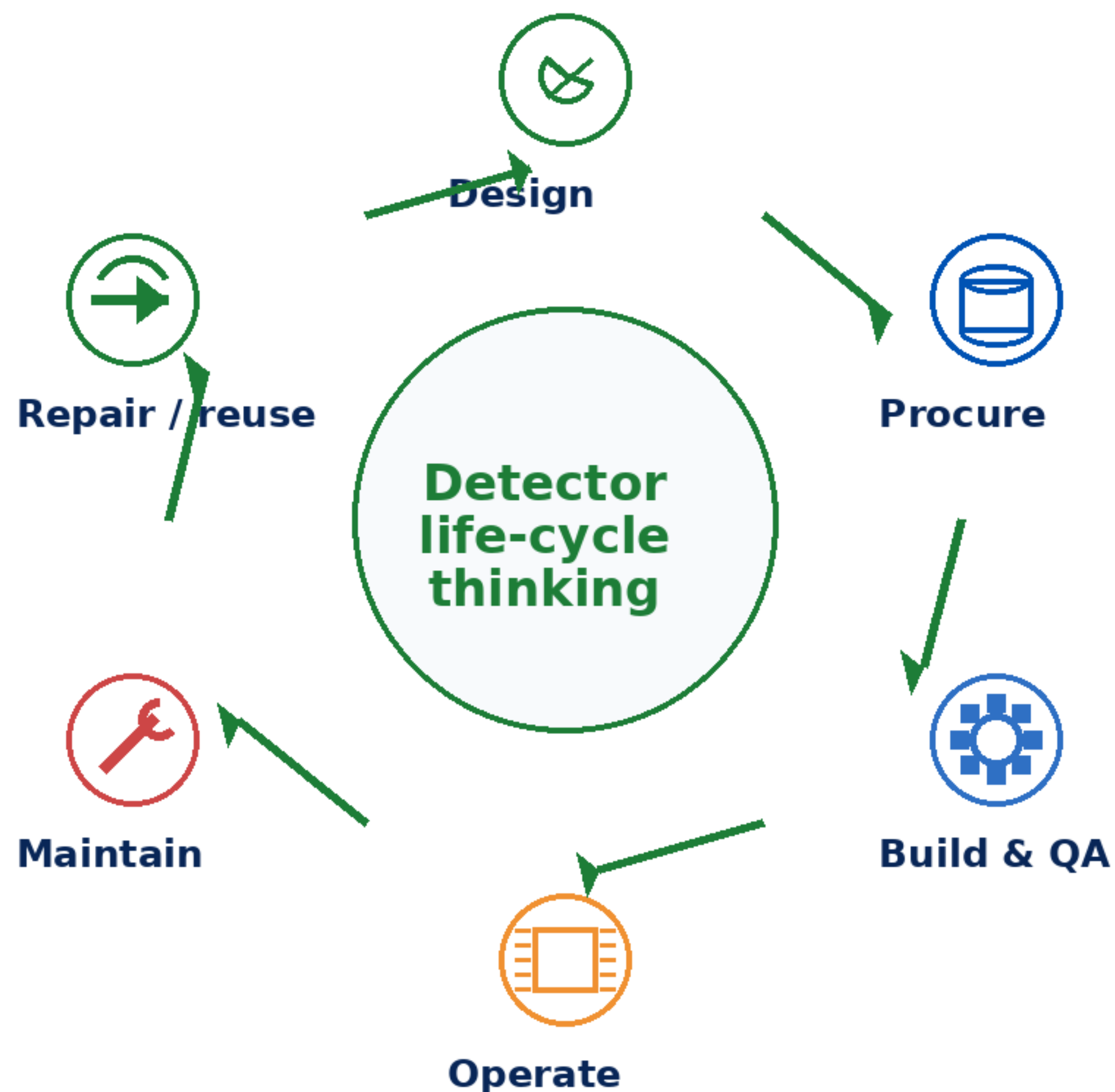


# Materials, production and maintenance

A sustainable detector has a life cycle — not only an operating gas

## What to track

- materials inventory
- supply-chain risk
- cleaning/chemicals
- spares strategy
- end-of-life plan



## What improves

- longer lifetime
- less downtime
- fewer replacements
- lower waste
- better reproducibility





Gent, Belgium



Chandigarh, India



CERN, Switzerland



Delhi, India



Bari, Italy



NCP Pakistan



BARC, India



Aachen, Germany



SINP, Kolkata



Frascati, Italy



Florida, USA

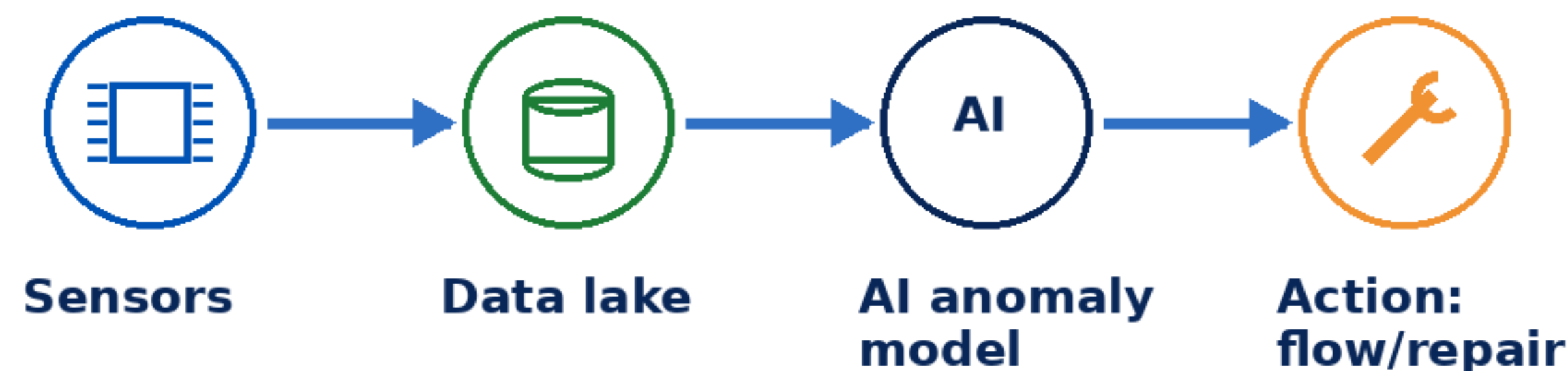
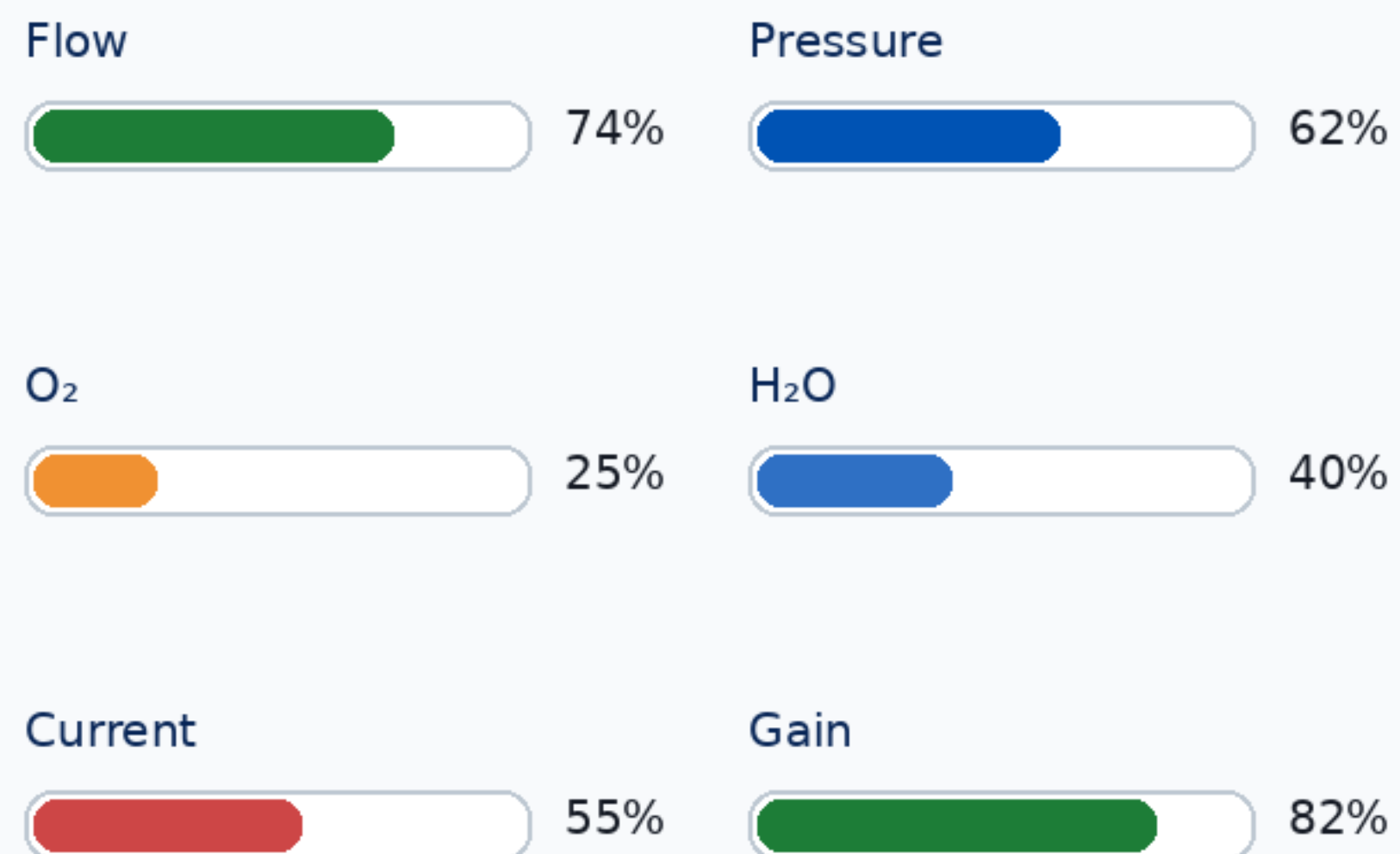




# Smart monitoring and AI-assisted gas systems

The future gas system is instrumented, predictive and self-documenting

## Gas-system dashboard



## Micromegas, TPCs and RICH Systems

- Micromegas detectors offer high-rate precision tracking with relatively simple mixtures.
- TPCs provide large-volume 3D tracking and particle identification.
- Their sustainability challenge often lies in volume, purity and recirculation.
- RICH detectors may depend on gases chosen for optical performance.
- Each detector family requires its own sustainability pathway.

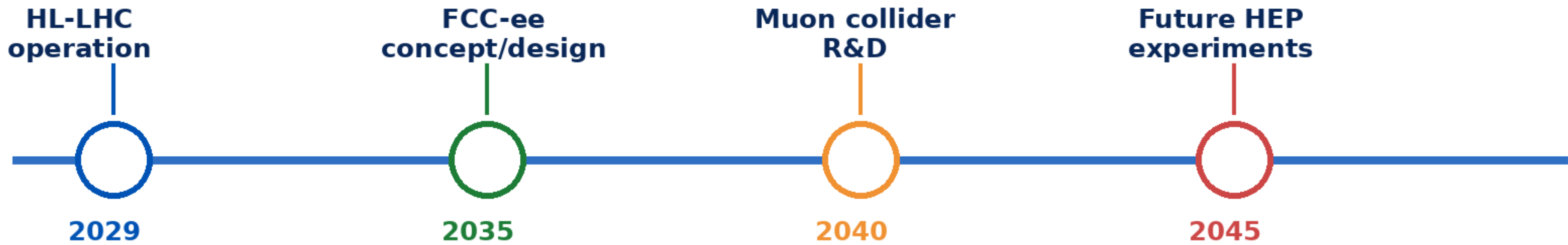
### Predictive operations:

- detect slow leaks before alarms
- correlate current, humidity and gas quality
- reduce fresh-gas flow without risking detector stability



# Future facilities: sustainable by design

HL-LHC, FCC, muon-collider and EIC-style programmes must include gas sustainability from day zero



FUTURE DETECTORS SHOULD BE LOW-GWP BY ARCHITECTURE  
NOT BY RETROFIT

t.





# Common standards and open databases

The field needs comparable data: gas properties, detector performance, ageing and safety in one place

## Sustainable gaseous detector database — proposed fields

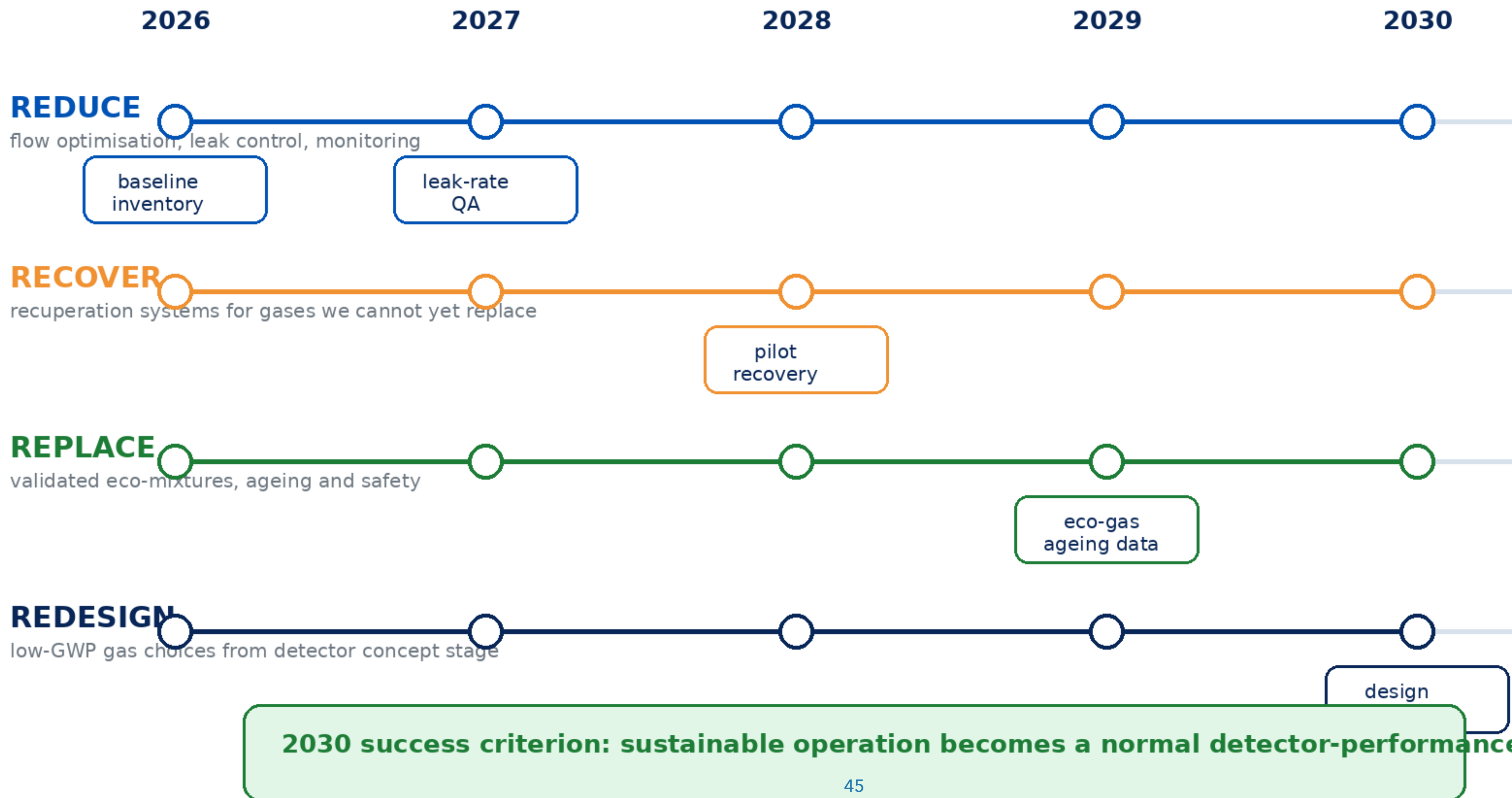
| Mixture                                               | GWP  | Detector | Working point | Efficiency | Ageing    | Safety | Recovery |
|-------------------------------------------------------|------|----------|---------------|------------|-----------|--------|----------|
| Ar/CO <sub>2</sub> 70:30                              | low  | GEM      | gain/HV       | ✓          | ✓         | ✓      | ✓        |
| HFO/CO <sub>2</sub> /i-C <sub>4</sub> H <sub>10</sub> | low  | RPC      | HV shift      | test       | long-term | check  | possible |
| R-134a mix                                            | high | RPC      | known         | ✓          | ✓         | ✓      | recover  |
| CF <sub>4</sub> mix                                   | high | RICH/CSC | known         | ✓          | ✓         | ✓      | recover  |

MINIMUM REPORTING STANDARD: OPERATING POINT  
ENVIRONMENTAL METRIC  
AGEING DOSE SAFETY NOTES RECOVERY STATUS



# Roadmap for sustainable gaseous detectors

A 2030 agenda: reduce consumption, recover valuable gases, replace high-GWP mixtures and redesign systems





# Lessons from the field

What the first wave of sustainability work in gaseous detectors is already teaching us

## 1. There is no single silver bullet

Reduce, recover, replace and redesign must be pursued together.

## 2. Eco-gas replacement is scientific R&D

Performance, ageing and safety must be validated under realistic conditions.

## 3. Engineering details matter

Leaks, connectors, purifiers and monitoring can dominate the real footprint.

## 4. Culture matters as much as technology

Collaborations need shared responsibility, common standards and training.

**DRD1@CERN**

DRD1 is the platform where gaseous detector R&D is redefined for the next generation: not only higher rate, better timing, finer granularity and larger area, but also lower-GWP gases, reduced fresh-gas consumption, recovery of unavoidable greenhouse gases, smart monitoring, robust ageing validation and shared standards. In this sense, DRD1 is not simply an R&D collaboration; it is a mechanism for making sustainability part of the scientific design culture of future particle physics.



# GEM gases vs RPC gases: why the transition is easier for GEMs



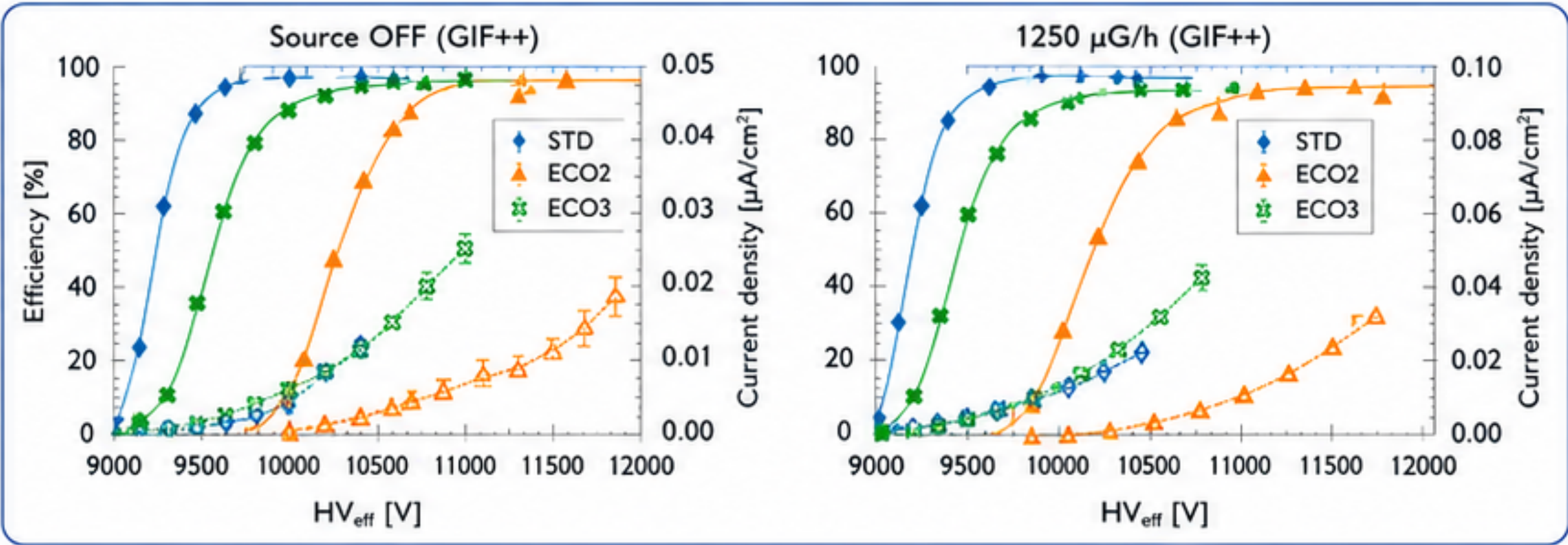
 **GEMs already operate from a much greener baseline, while RPCs still require a difficult transition away from fluorinated gases.**

- RPCs traditionally use fluorinated mixtures: R-134a as the main component, plus a small fraction of SF<sub>6</sub> to suppress streamers.
- These mixtures have high climate impact, so eco-RPC options based on HFO-1234ze / CO<sub>2</sub> / i-C<sub>4</sub>H<sub>10</sub> are being intensively studied.
- However, eco-RPC mixtures typically require higher operating voltage and careful optimisation of efficiency, current, timing and ageing under irradiation.
- GEMs commonly run with non-fluorinated mixtures such as Ar/CO<sub>2</sub> (for CMS GEM commissioning, Ar/CO<sub>2</sub> 70:30), so the sustainability improvement path is much simpler.



Representative CMS GE1/1 GEM installation.

|                            | RPC                                                         | GEM                                                             |
|----------------------------|-------------------------------------------------------------|-----------------------------------------------------------------|
| Typical baseline gas       | R-134a + i-C <sub>4</sub> H <sub>10</sub> + SF <sub>6</sub> | Ar/CO <sub>2</sub> (± small additives depending on application) |
| Main GWP burden            | High (R-134a, SF <sub>6</sub> )                             | Low when using Ar/CO <sub>2</sub>                               |
| Current R&D focus          | Eco-mixtures + ageing validation                            | Flow optimisation + recirculation                               |
| Net sustainability outlook | Improving, but challenging                                  | Already favourable                                              |



Representative eco-RPC efficiency/current curves from GIF++ studies.



**Takeaway:** GEMs start from a lower-GWP operating point; RPCs need deeper gas-mixture innovation.



# Why GEMs are the greenest option for future gaseous detectors

For many future applications, GEMs combine high physics performance with the most sustainable gas strategy.



*CMS GEM technology as a mature large-area detector platform.*



**1. Low-GWP baseline:**  
standard operation can be fluorine-free with Ar/CO<sub>2</sub> mixtures.



**2. Lower regulatory risk:**  
no routine dependence on R-134a or SF<sub>6</sub> in the baseline mixture.



**3. Closed-loop friendly:**  
recirculation can further reduce fresh-gas demand and emissions.



**4. Excellent detector performance:**  
high rate capability, fine segmentation, robustness and scalability.



**5. Future-ready:**  
strong match to HL-LHC upgrades and next-generation collider needs.



**Still needed:** minimise leaks, optimise flow, validate long-term ageing, and design sustainable gas systems.



*Recirculation and gas-management systems further improve the environmental footprint.*



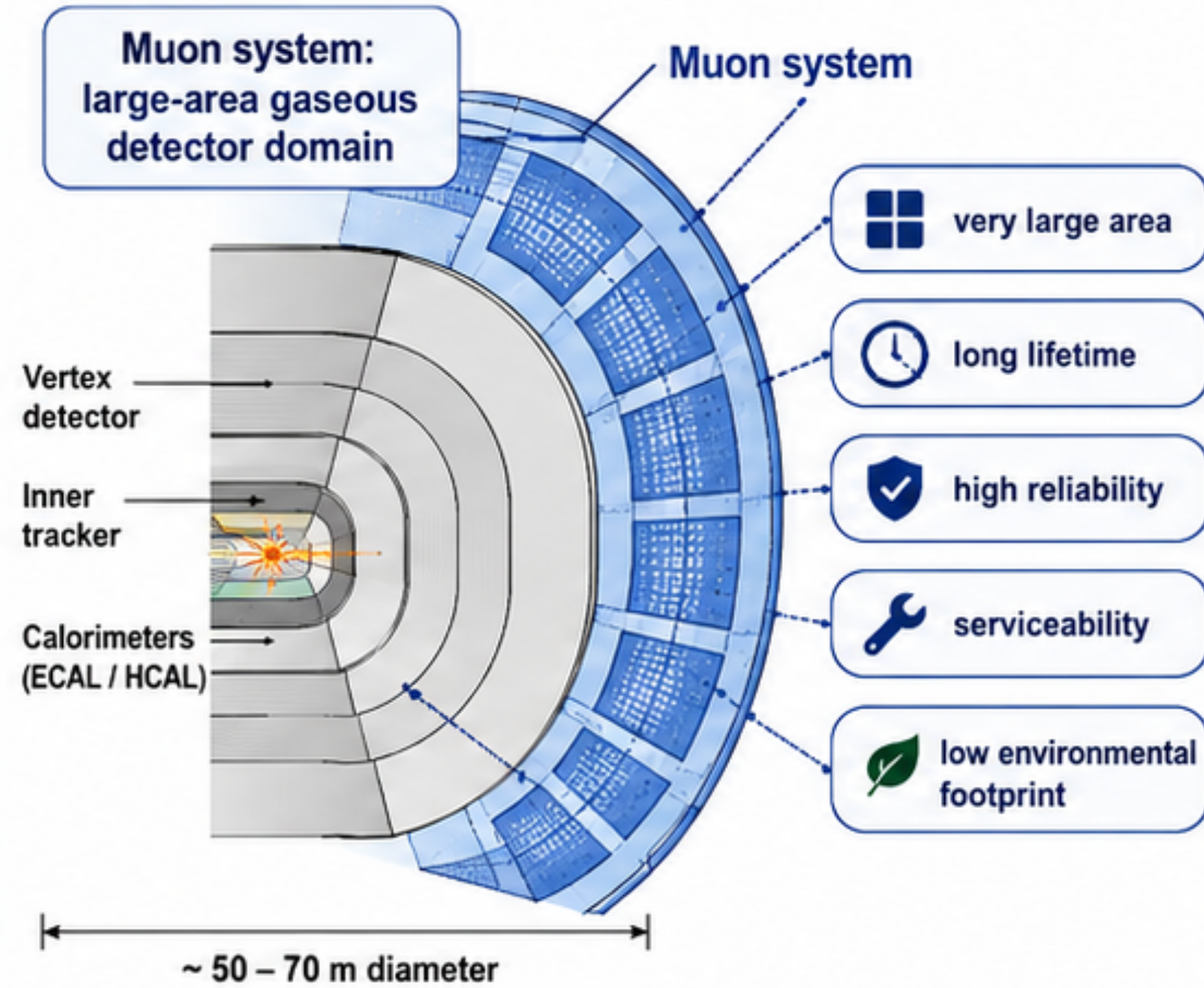
**Bottom line:** GEMs are not automatically zero-impact, but they already offer the clearest path to high performance with low-GWP operation.



# Possible FCC muon system gas optimisation

*Illustrative concept for a future low-GWP, large-area muon detector system*

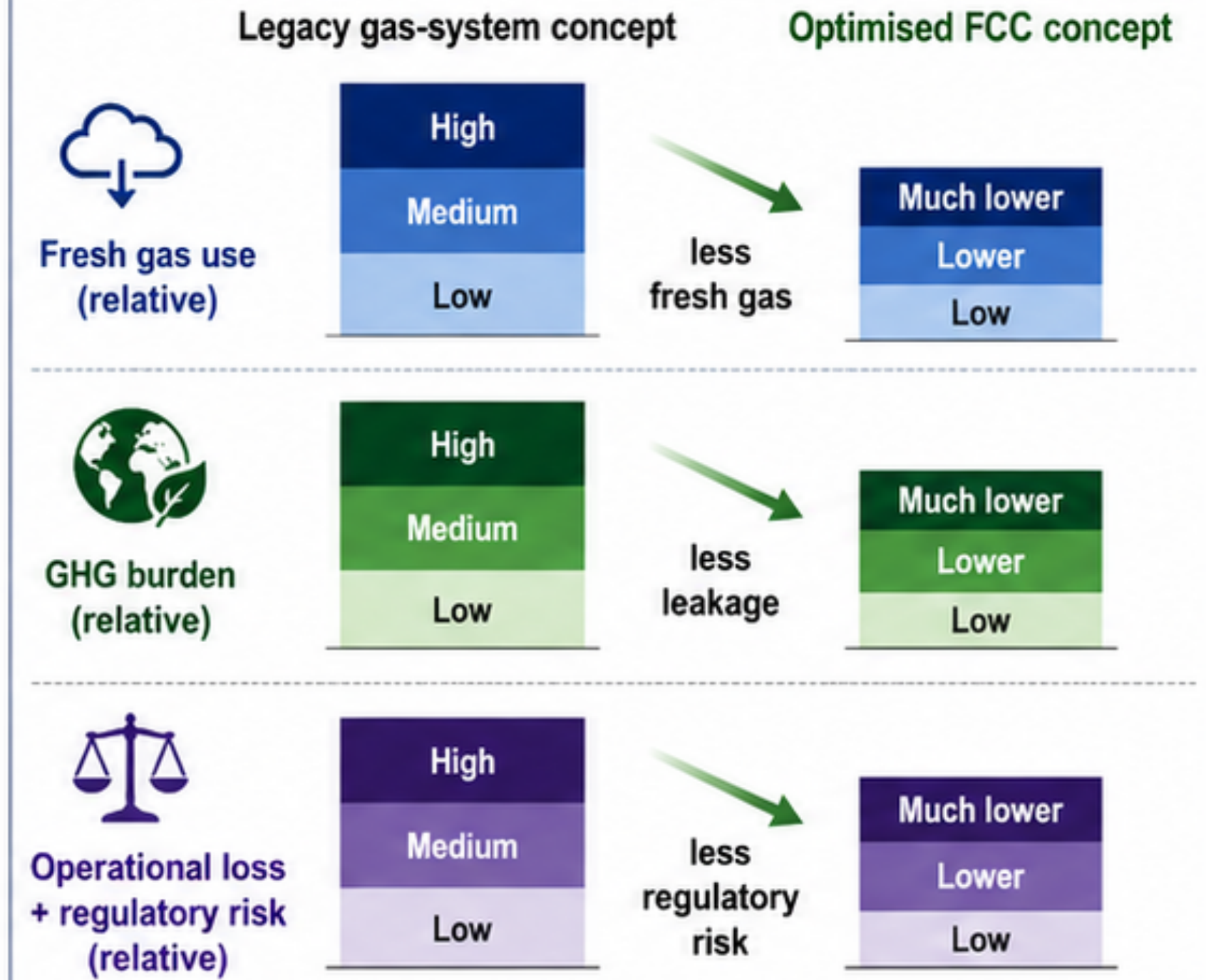
## 1. Future FCC detector concept (simplified)



## 2. Optimisation framework – five key levers

- 1 Low-GWP baseline gas**  
Prefer fluorine-free or minimal-fluorine mixtures wherever performance allows.
- 2 Closed-loop recirculation**  
Reduce fresh-gas demand through high recirculation fractions.
- 3 Leak-tight architecture**  
Segmented lines, qualified connectors, accessible maintenance.
- 4 Smart flow zoning**  
Adapt flow to detector region, rate and occupancy.
- 5 Monitoring + recovery**  
Continuous gas-quality diagnostics and recovery for any residual high-GWP components.

## 3. Pathway to a more sustainable gas system (conceptual)



### Possible detector technology choices

- GEM / MPGD-like layers for low-GWP operation
- Eco-optimised RPC-like solutions where timing is needed
- Detector-specific mixture tuning by region

### Design principle

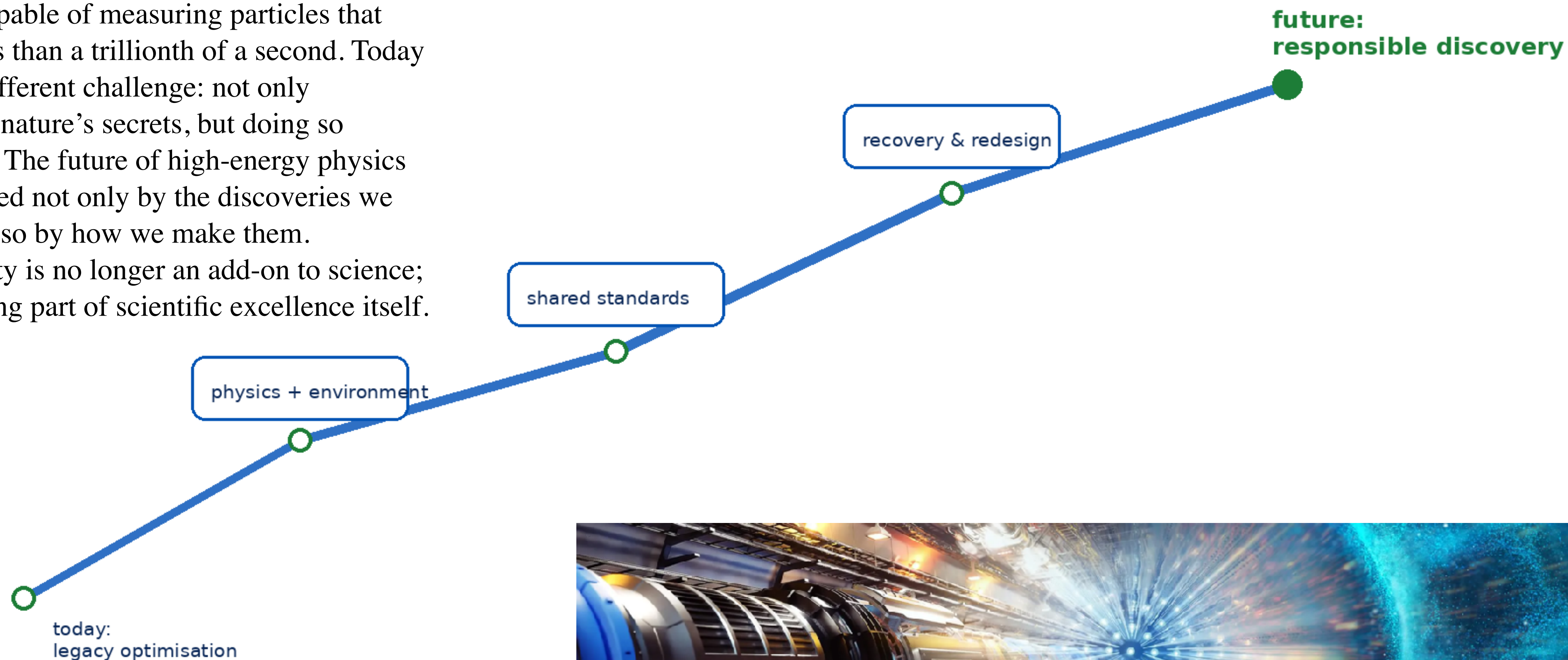
For FCC-scale muon systems, sustainability must be built in from day zero, not retrofitted later.

**Bottom line:** FCC muon-system gas optimisation means choosing the detector, gas, infrastructure and monitoring together as one integrated low-GWP design problem.



# An aspirational vision for the future

Our community has always solved problems that once seemed impossible. We learned to build detectors capable of measuring particles that exist for less than a trillionth of a second. Today we face a different challenge: not only discovering nature's secrets, but doing so responsibly. The future of high-energy physics will be judged not only by the discoveries we make, but also by how we make them. Sustainability is no longer an add-on to science; it is becoming part of scientific excellence itself.







## AND ..... A LOT OF REFERENCES NOT MENTIONED HERE



### 1. CERN Environment Report 2023–2024, “Emissions” section

Essential for the CERN-wide sustainability frame: F-gas emissions, Scope 1 context, leaks, recirculation, recovery and alternative gases.

### 2. CERN HSE, “Cutting emissions, powering science”, 2026

Useful for the policy slide: CERN adopted its first F-Gas Policy in July 2024, and F-gases account for about 90% of CERN’s direct Scope 1 emissions.

### 3. European Commission, F-gas legislation — Regulation (EU) 2024/573

Best regulatory reference for explaining why availability, cost, procurement and long-term detector planning are changing.

### 4. M.C. Arena et al., “Towards more eco-friendly gaseous detectors,” NIM A 1068, 169784, 2024

Probably the single best modern overview paper for your keynote. It frames the three pillars: recirculation, recuperation, and eco-friendly gas mixtures.

### 5. R. Guida et al., “Reducing the Greenhouse Gas Usage from Particle Detection Systems: Status and Perspectives,” 2025

Excellent up-to-date review of CERN’s strategy: why F-gases are used, why replacement is difficult, and what mitigation paths are realistic.

### 6. G. Rigoletti et al., “Overview of CERN strategies for the reduction of greenhouse gas emissions from particle detectors,” PoS ICHEP2024, published 2025

Very good for a concise technical strategy slide: recirculation, GHG recovery systems, and the search for eco-gases.

### 7. M. Capeans, R. Guida, B. Mandelli, “Strategies for reducing the environmental impact of gaseous detector operation at the CERN LHC experiments,” NIM A 845, 253–256, 2017

A foundational CERN paper on the subject; good for showing that this effort started well before the current policy pressure.

### 8. R. Guida, M. Capeans, F. Hahn, S. Haider, B. Mandelli, “The gas systems for the LHC experiments,” IEEE NSS/MIC, 2013

Useful background for explaining why LHC gas systems are complex, large, stable, safety-critical infrastructures rather than simple gas bottles.

### 9. R. Guida, B. Mandelli, G. Rigoletti, “Studies on alternative eco-friendly gas mixtures and development of gas recuperation plant for RPC detectors,” NIM A 1039, 167045, 2022

Important because it connects two themes: alternative RPC mixtures and recuperation technology.

### 10. M.C. Arena et al., “Recuperation systems for fluorinated gases at the CERN LHC Experiments,” NIM A 1068, 169789, 2024

Best dedicated reference on fluorinated-gas recovery/recuperation at CERN. Very useful for a slide on “recover what we cannot yet replace.”

### 11. R. Guida, M. Busato, B. Mandelli, G. Rigoletti, “Optimization strategies for the greenhouse gas consumption of the RPC detectors at the CERN LHC experiments,” NIM A 1055, 168444, 2023

Strong reference for mitigation before full gas replacement: dilution, optimization, leak management, operational strategies.

### 12. G. Rigoletti, R. Guida, B. Mandelli, “Gas recirculation systems for RPC detectors: From LHC experiments to laboratory set-ups,” NIM A 1049, 168095, 2023

Good for showing that recirculation is not only a large-experiment solution but can be scaled down to laboratory R&D.

### 13. RPC ECOGas@GIF++ Collaboration / L. Quaglia et al., “Exploring Eco-Friendly Gas Mixtures for Resistive Plate Chambers: A Comprehensive Study on Performance and Aging,” NIM A 1068, 169747, 2024

Key technical reference for eco-gas performance and ageing under realistic irradiation conditions.

### 14. R. Guida, B. Mandelli, G. Rigoletti, “Performance studies of RPC detectors with new environmentally friendly gas mixtures in presence of LHC-like radiation background,” NIM A 958, 162073, 2020

Useful for explaining why eco-gases must be tested under background rates relevant to HL-LHC, not only in benign laboratory conditions.

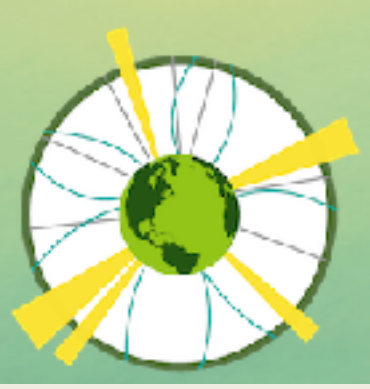
### 15. G. Proto, O. Kortner, H. Kroha, “Replacing SF<sub>6</sub> in resistive plate chamber detectors for HL-LHC experiments and beyond,” JINST 20, P06031, 2025

Important latest reference because SF<sub>6</sub> has extremely high GWP and its replacement is one of the hardest RPC-gas problems.

### 16. Benussi et al., “Properties of potential eco-friendly gas replacements for particle detectors in high-energy physics,” 2015

### 17. Bianchi et al., “Environment-friendly gas mixtures for RPCs: an experimental and simulation study,” 2020, for simulation-plus-test methodology.





# Thank you!