# Going Green at CERN

## Machine Learning for Eco-Friendly Gas Mixtures in RPC Detectors

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End-of-Year Seminar, 1st year PhD

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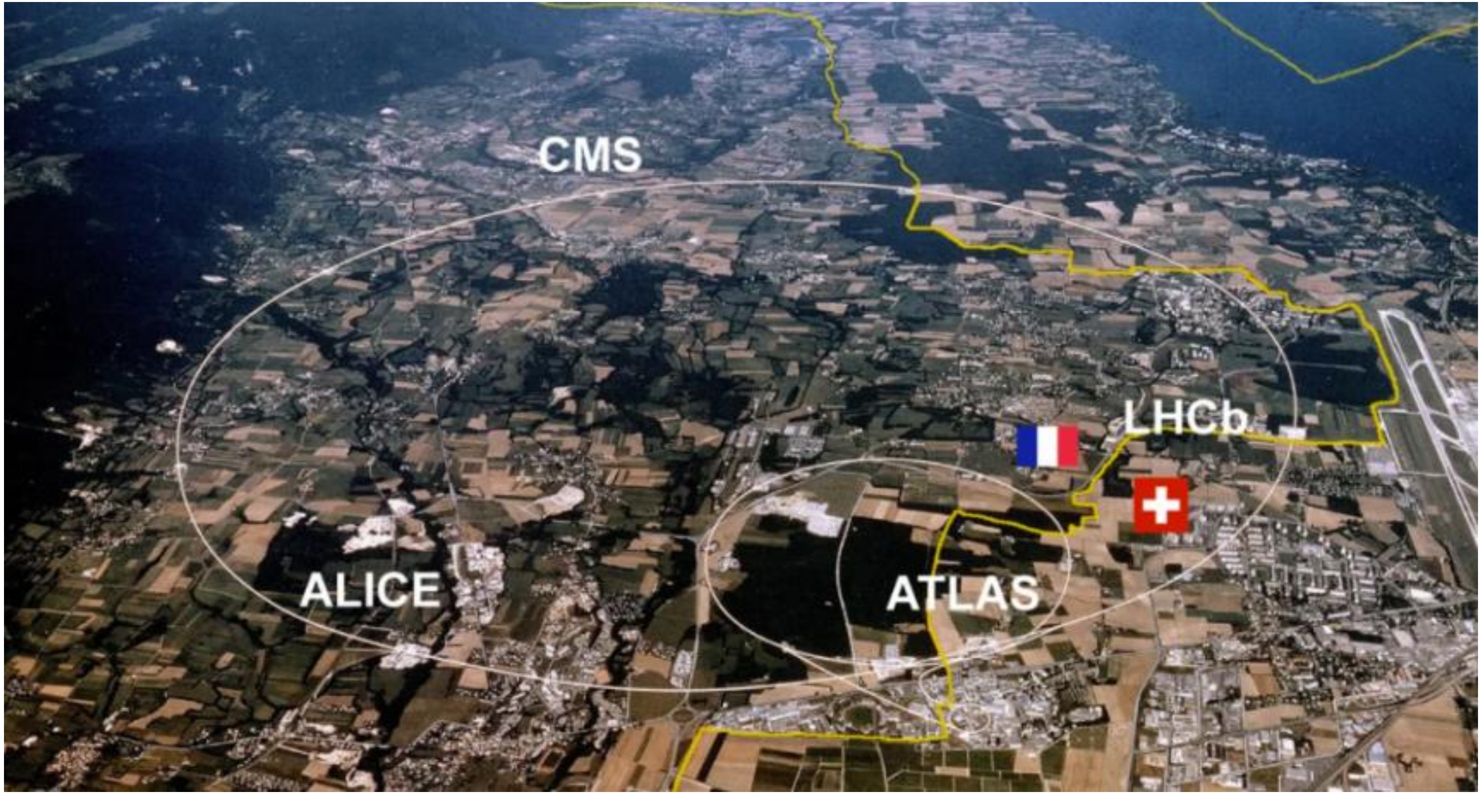
UNIVERSITÀ DI PAVIA

INFN Istituto Nazionale di Fisica Nucleare

CMS

# Particle Physics Relies on Detectors



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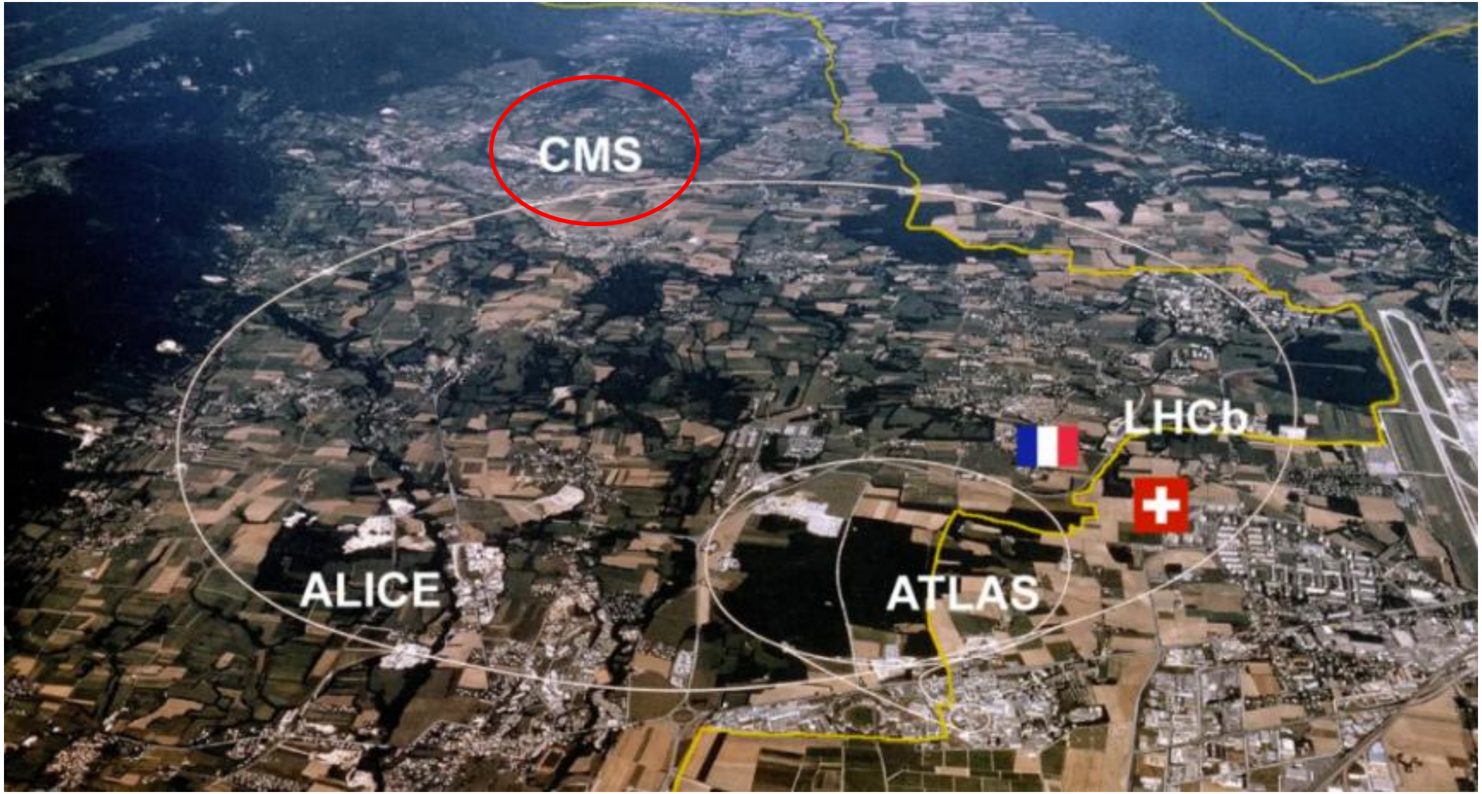
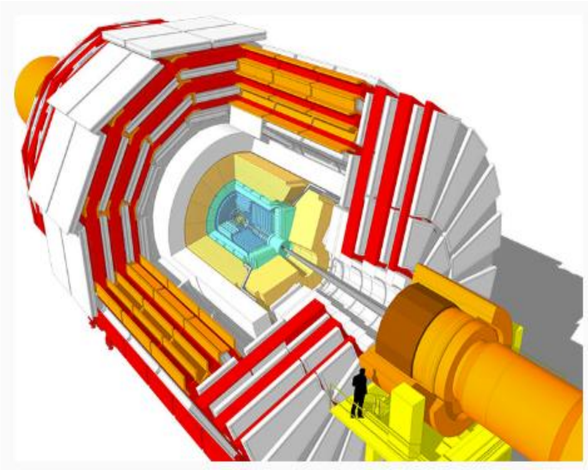


# The Compact Muon Solenoid (CMS) experiment



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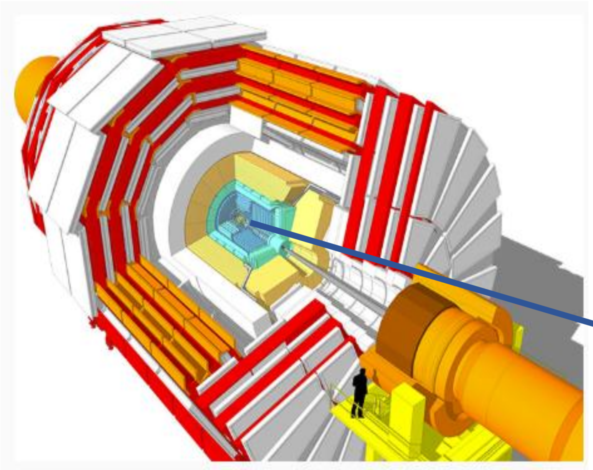

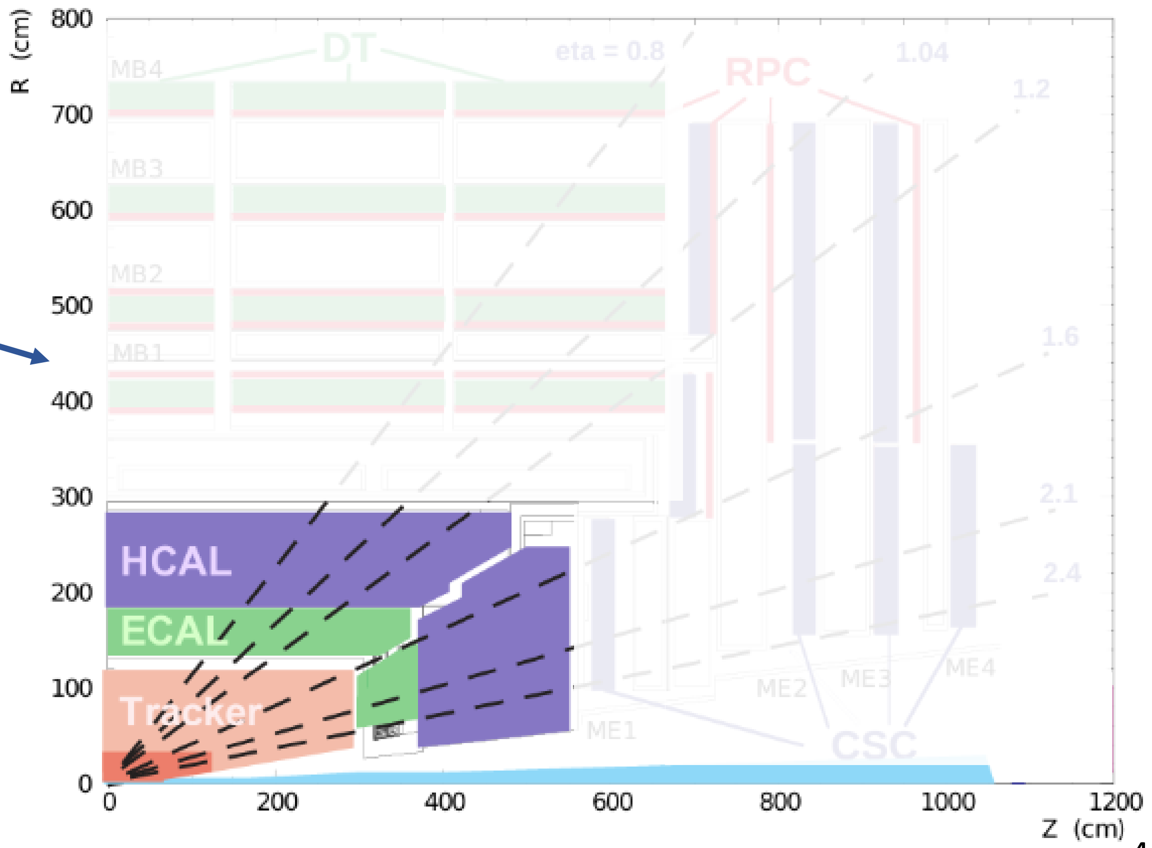

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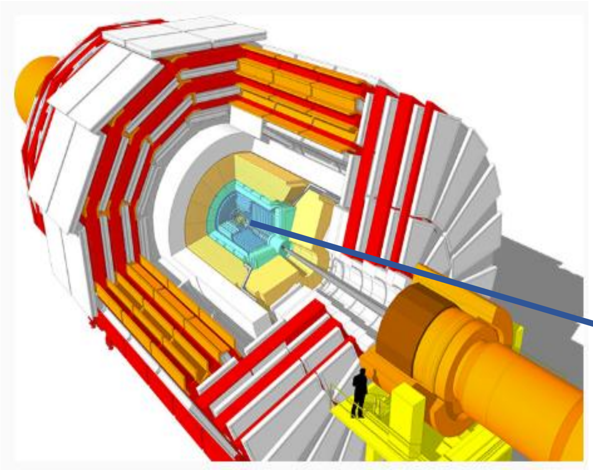

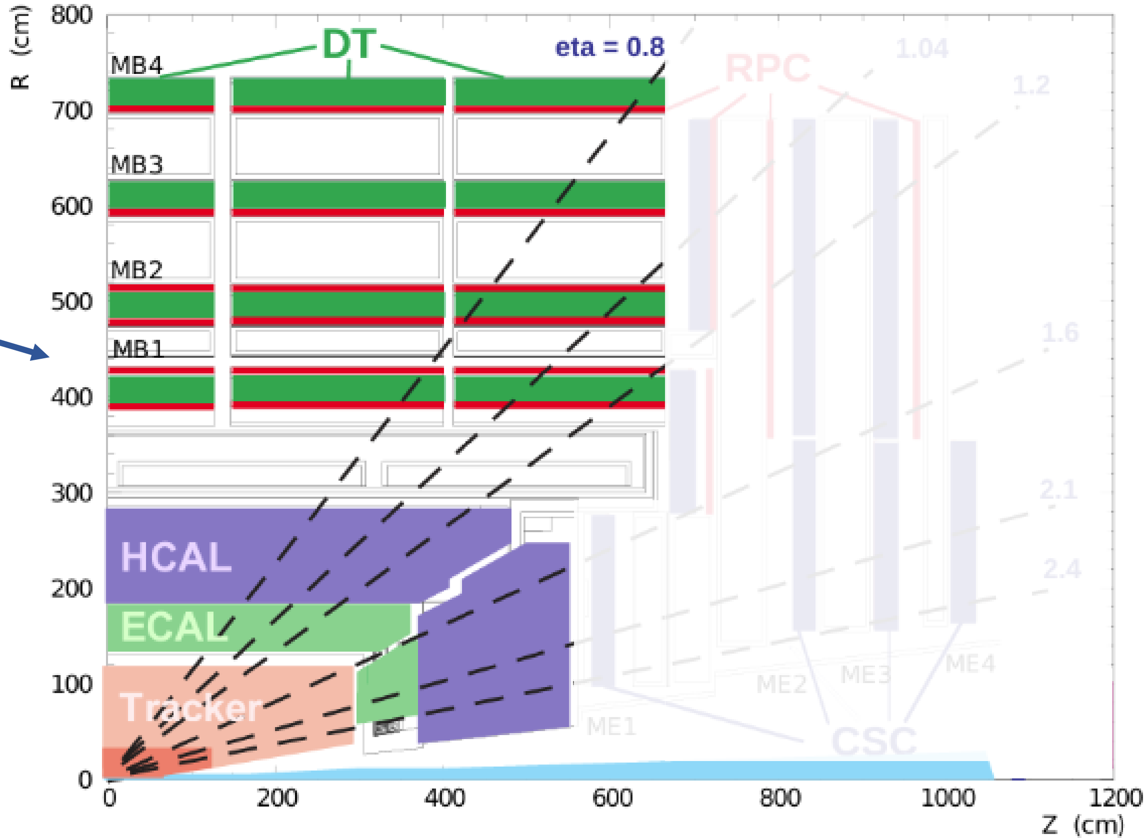

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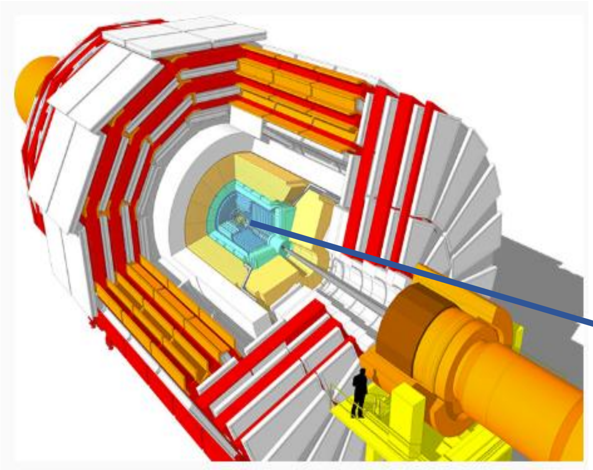
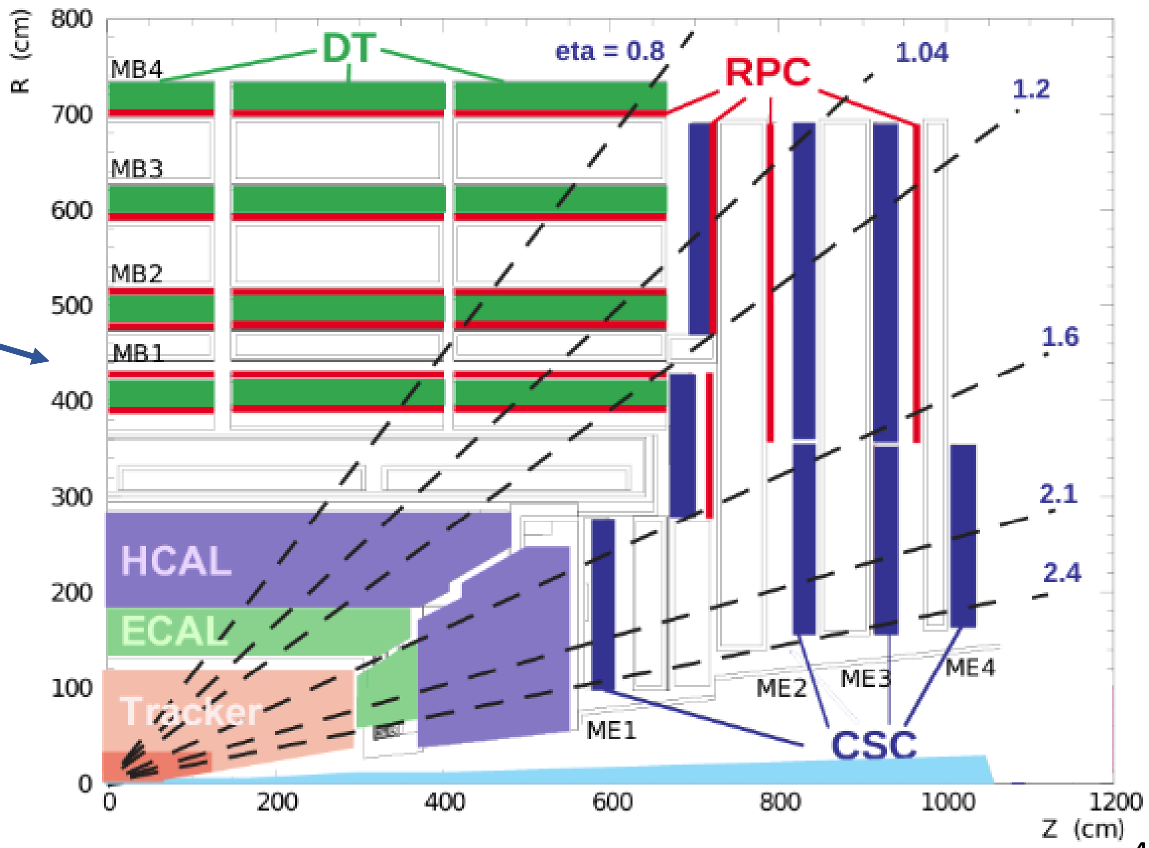
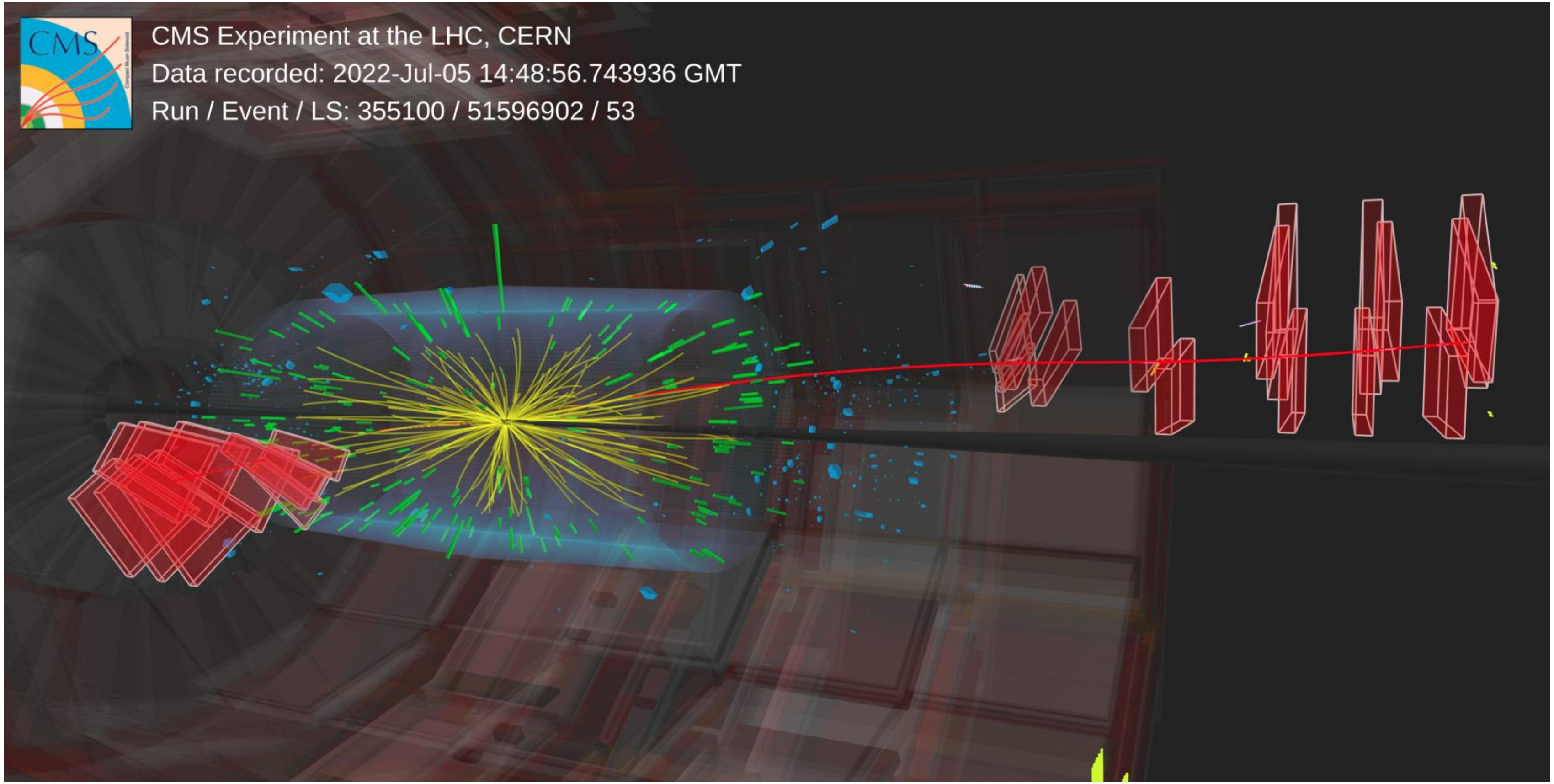
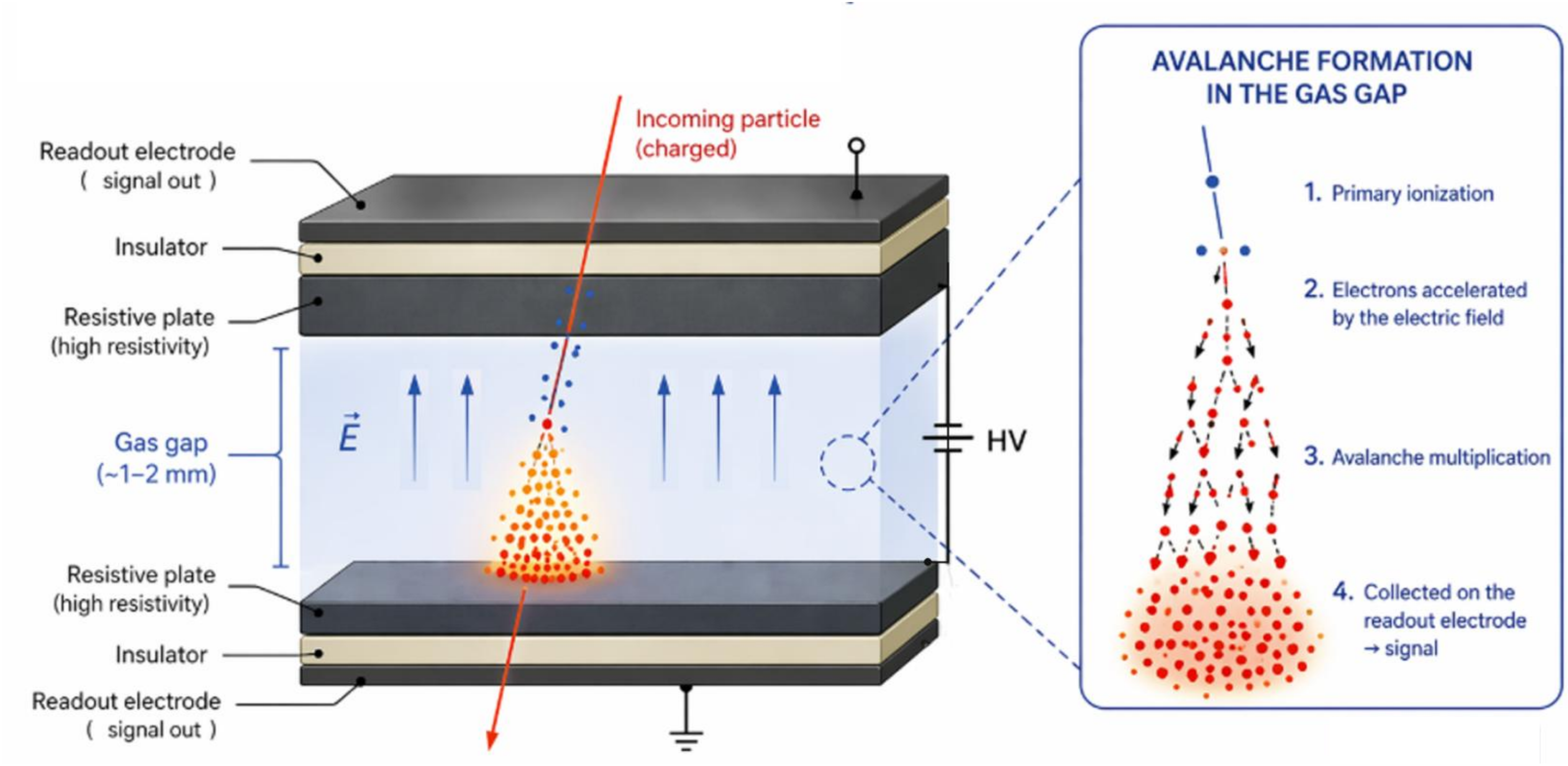




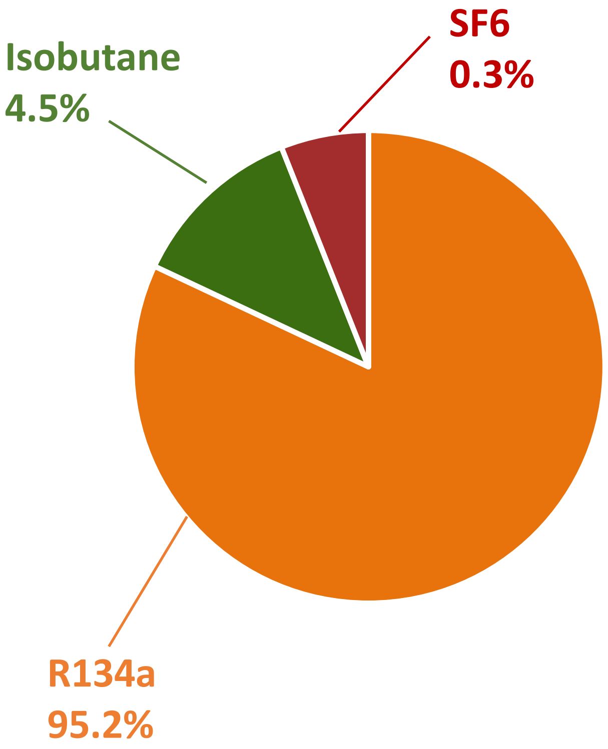
# The role of RPC in the CMS muon system



# Resistive Plate Chamber (RPC) Detectors



# The Standard RPC Gas Mixture




**Tetrafluoroethane (R134a)**

$C_2H_2F_4$

**Isobutane**

$i\text{-}C_4H_{10}$

**Sulfur hexafluoride**

$SF_6$

Used in ATLAS (until 2023), CMS, and (similarly) ALICE.

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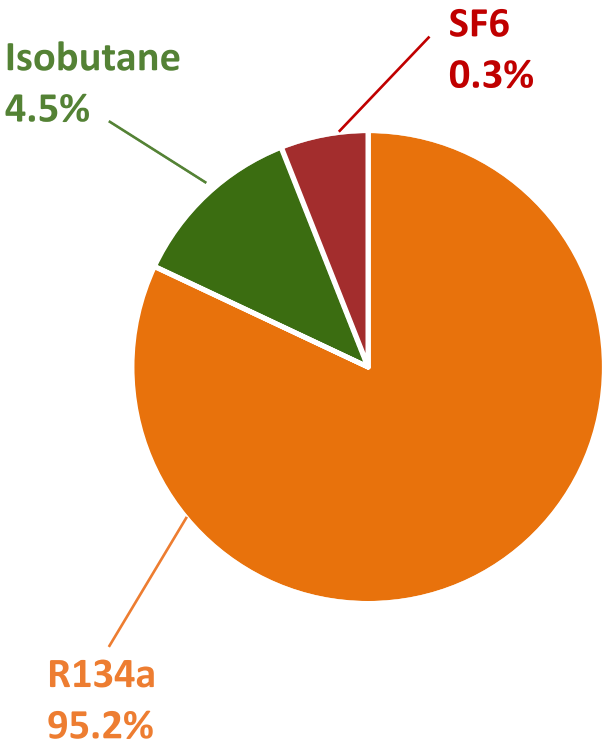
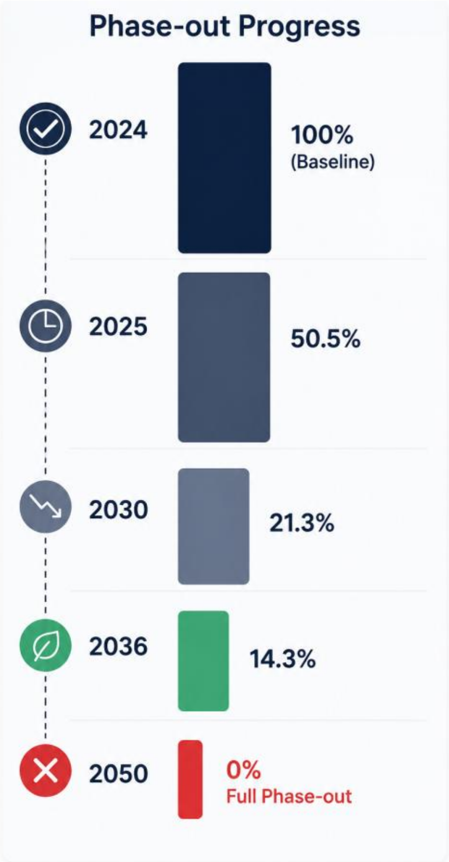



| | | GWP<br>*$CO_2$ = 1* |
|---|---|---|
| ~~Tetrafluoroethane (R134a)~~ | ~~$C_2H_2F_4$~~ | 1430 |
| **Isobutane** | $i\text{-}C_4H_{10}$ | 3.3 |
| ~~Sulfur hexafluoride~~ | ~~$SF_6$~~ | 22800 |

**GWP** (Global Warming Potential): factor that expresses how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide ($CO_2$), on a mass basis and over a defined period, usually 100 years

# RPC emissions & EU HFC Phase Out




Regulation (EU) 2024/573

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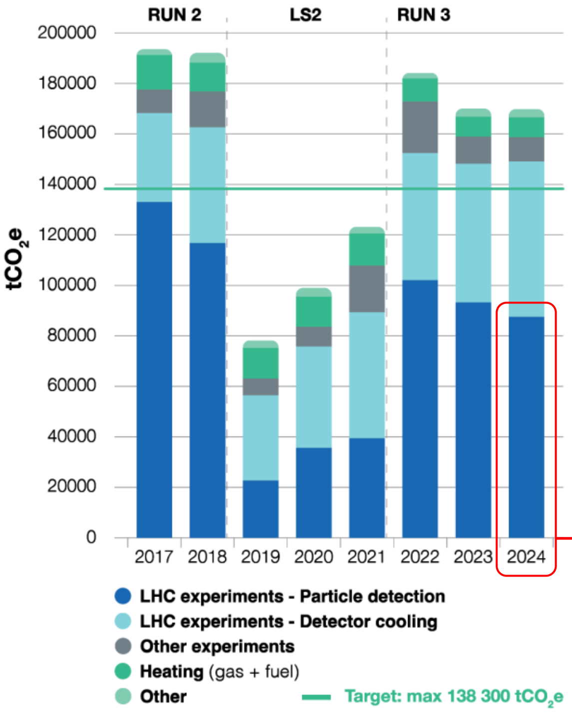
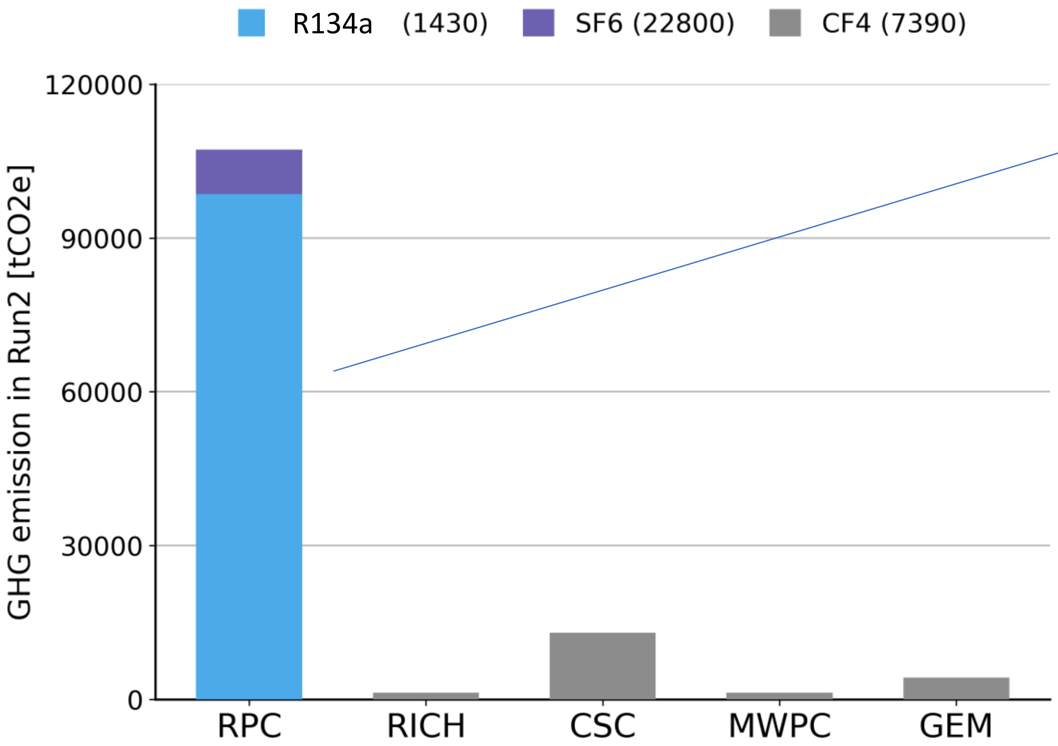



CERN 4th Environment Report (2023-2024)

*During 2024 about 50% of detector - related emissions originated from RPC systems.*

# RPCs Are the Main Emitter Among CMS Gas Detectors




Leaks at detector level
→ **critical** because a recuperation system is in place

Repair campaign during $LS_2$

# Three Complementary Strategies

### Gas Recuperation

Recover and reuse gas to minimize losses

### Gas Recirculation

Recirculate gas in closed-loop systems

### Alternative Gases

Replace high-GWP gases with low-GWP options

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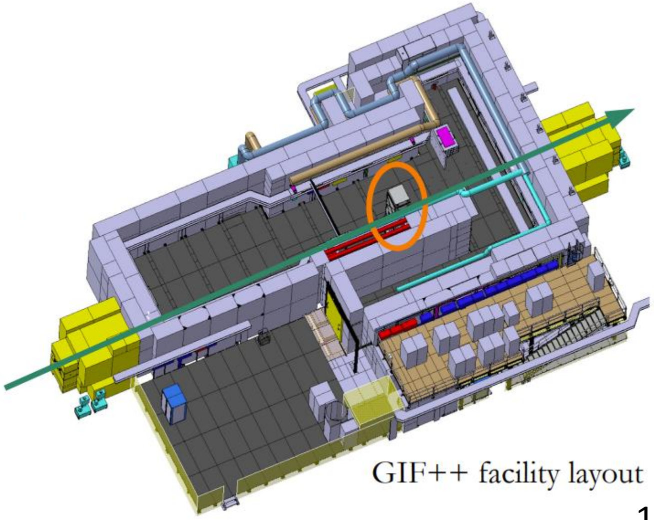
# A Field-Wide Effort: RPC EcoGas@GIF++

A shared R&D collaboration testing alternative gas which I belong to

| CERN Gas Team | ALICE | ATLAS | CMS | LHCb |
|---|---|---|---|---|

Studies conducted at the Cern Gamma Irradiation Facility GIF++

- Simulate HL-LHC gamma background: 12.5 TBq $^{137}Cs$ source
- Multiple gamma attenuators factors (ABS) available
- Trigger: 100 GeV μ beam from SPS



GIF++ facility layout

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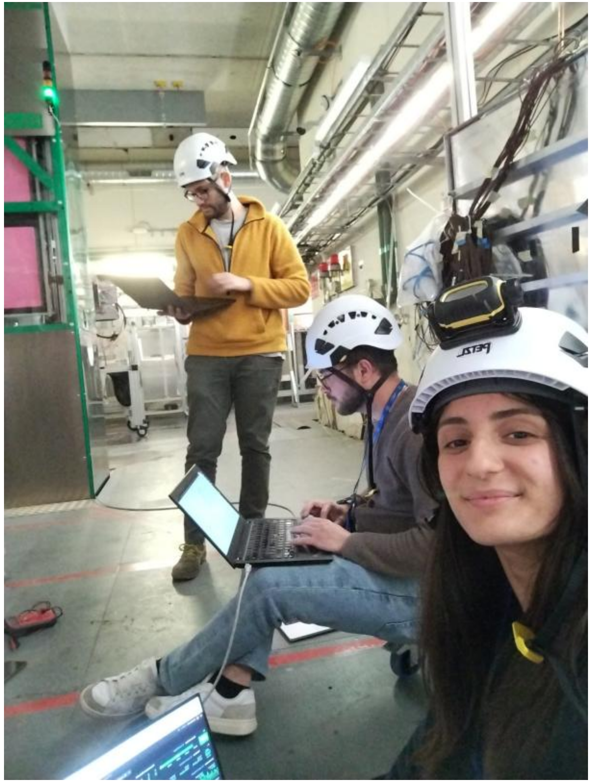
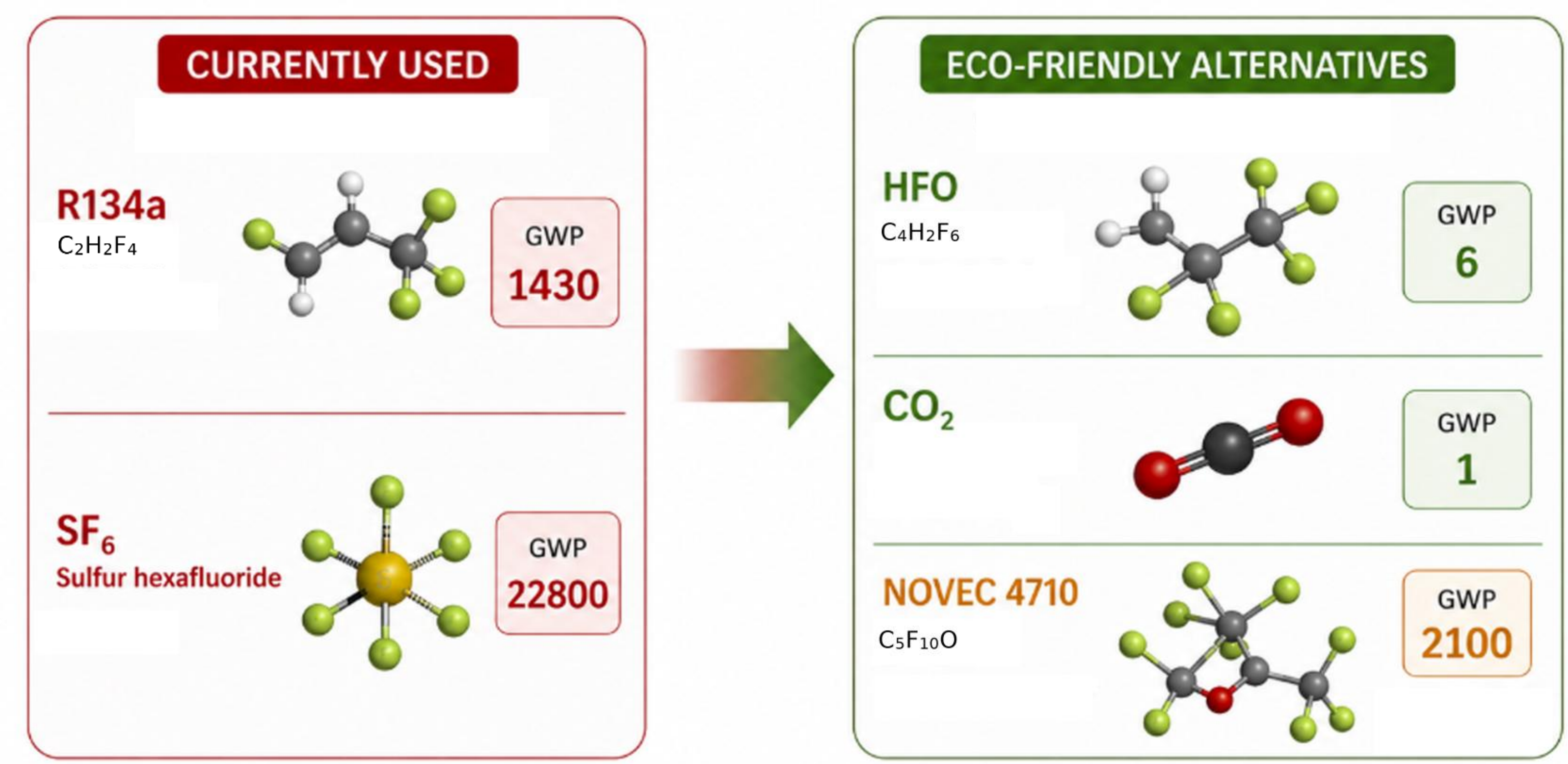
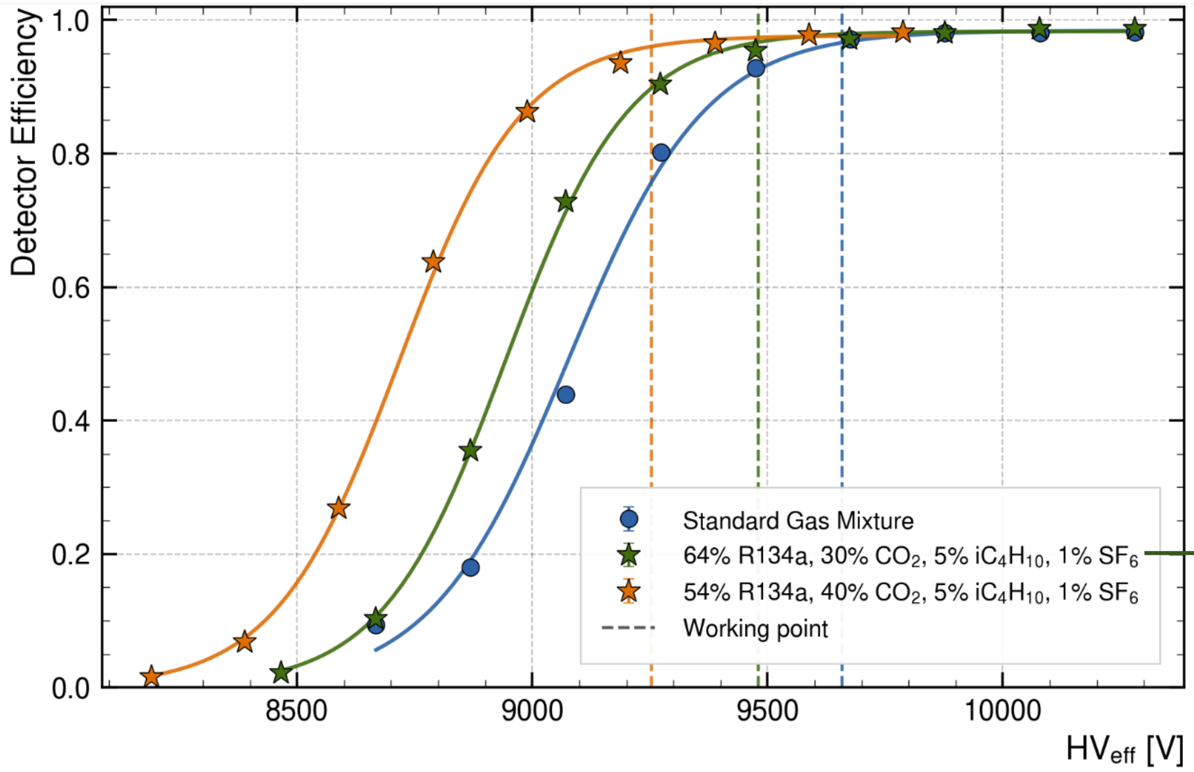


# From High-GWP Gases to Eco-Friendly Alternatives



# Case Study: $CO_2$-based gas mixtures




adopted by ATLAS for its RPC system since August 2023

# Open Problem: Why Not Directly in CMS?

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| **Recuperation, not replacement** | CMS already recovers ~80% of R134a → switching to $CO_2$ doesn't cut emissions once recuperation is factored in |

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R134a and $SF_6$ may be phased out of the market regardless of these trade-offs. CMS needs a validated, low-impact alternative ready.

# My PhD Project

Finding low-GWP gas mixtures for RPC detectors using machine learning

**Reduce**

Environmental impact of RPC operation

**Speed up**

The discovery process via ML

**Build & Test**

RPC test facility setup and measurements in Pavia

# My ML Approach: The Goal

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**Gas mixture composition** → **Dense Neural Network** → **Predicted efficiency curve**

**Why:** A model that predicts the efficiency curve from composition alone can prioritize which mixtures are worth testing

# My ML Approach: Representing Gas Composition

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**Missing gas** → energy set to 0 eV: no physical meaning and indistinguishable from "very low energy"

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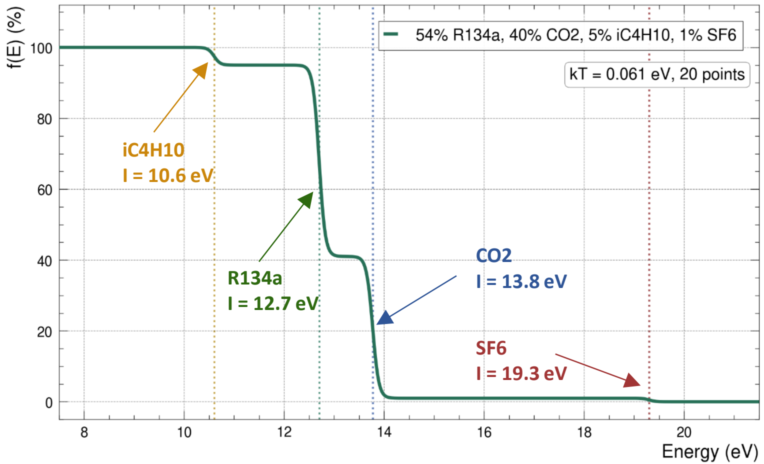
## Scalar representation

**Input:** gas % and ionization energy, listed as separate numbers for each component

**Missing gas** → energy set to 0 eV: no physical meaning and indistinguishable from "very low energy"

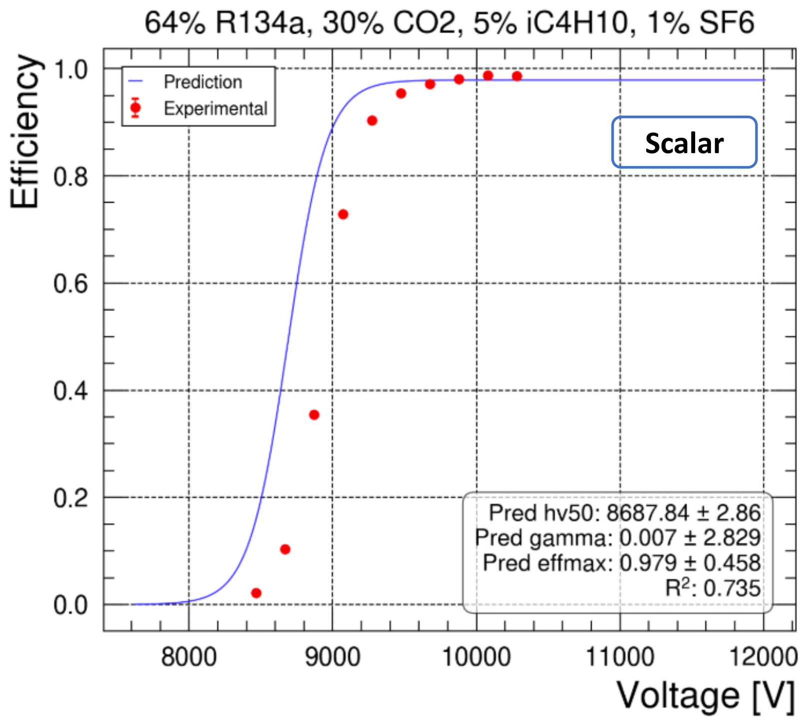
## Fermi-like representation

**Input:** one smooth curve f(E), a weighted step at each gas's ionization energy




**Missing gas** → simply contributes nothing

# My ML Approach: Representing Gas Composition



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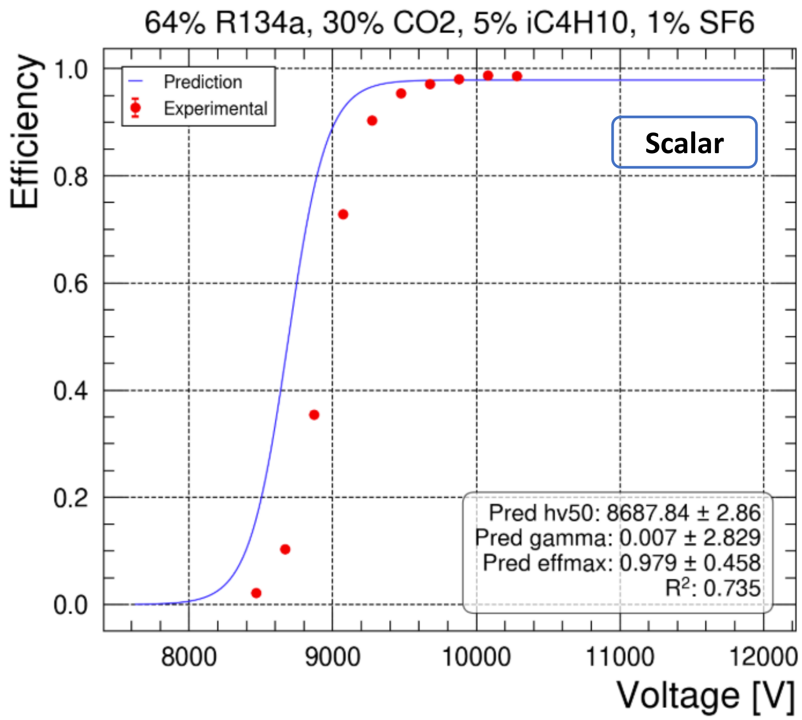


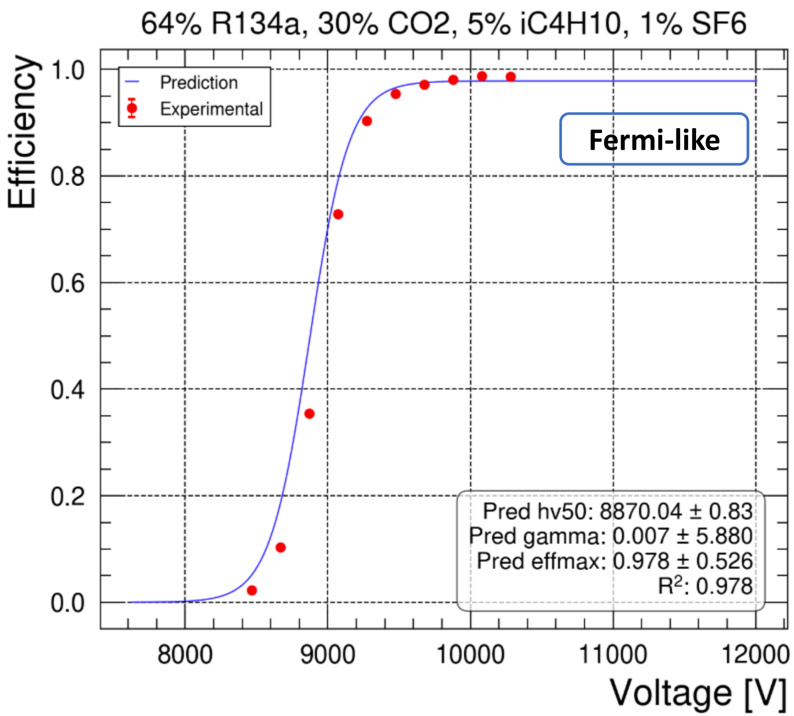

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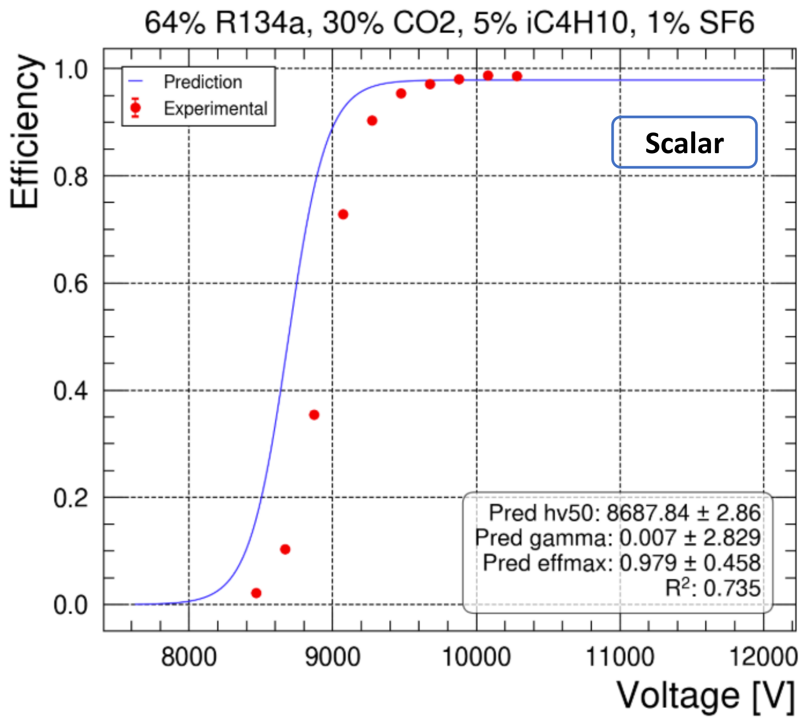


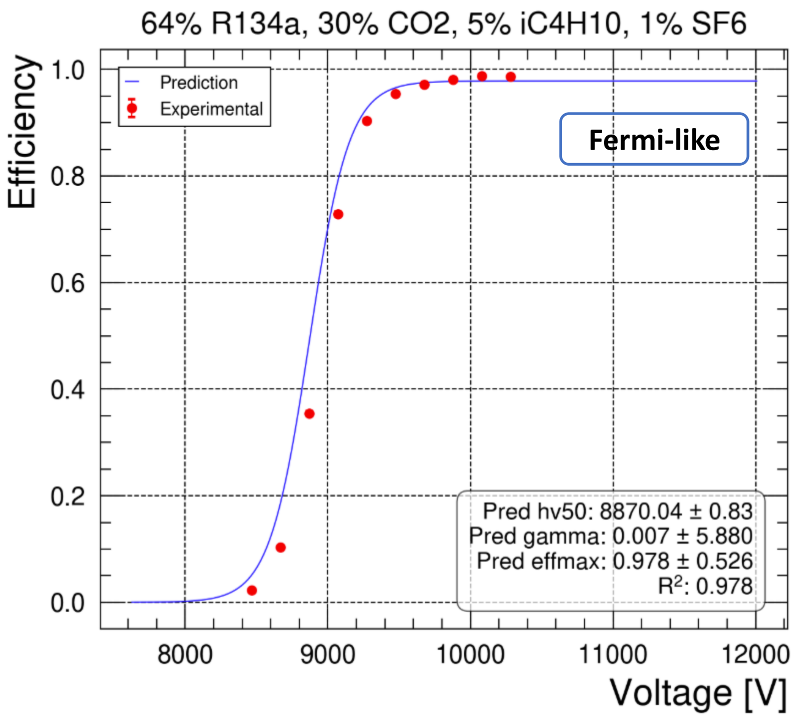


Across 16 tested mixtures Fermi-like model is more accurate and robust: $R^2$ median rises from **0.80 to 0.92**.

# Building a Test Facility in Pavia

| | |
|---|---|
| **Why** | LHC is in Long Shutdown 3 for the HL-LHC upgrade → GIF++ test-beam campaigns are unavailable during this period |

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| **What** | Setting up a complete RPC test facility at the Pavia CMS laboratory |

# Building a Test Facility in Pavia

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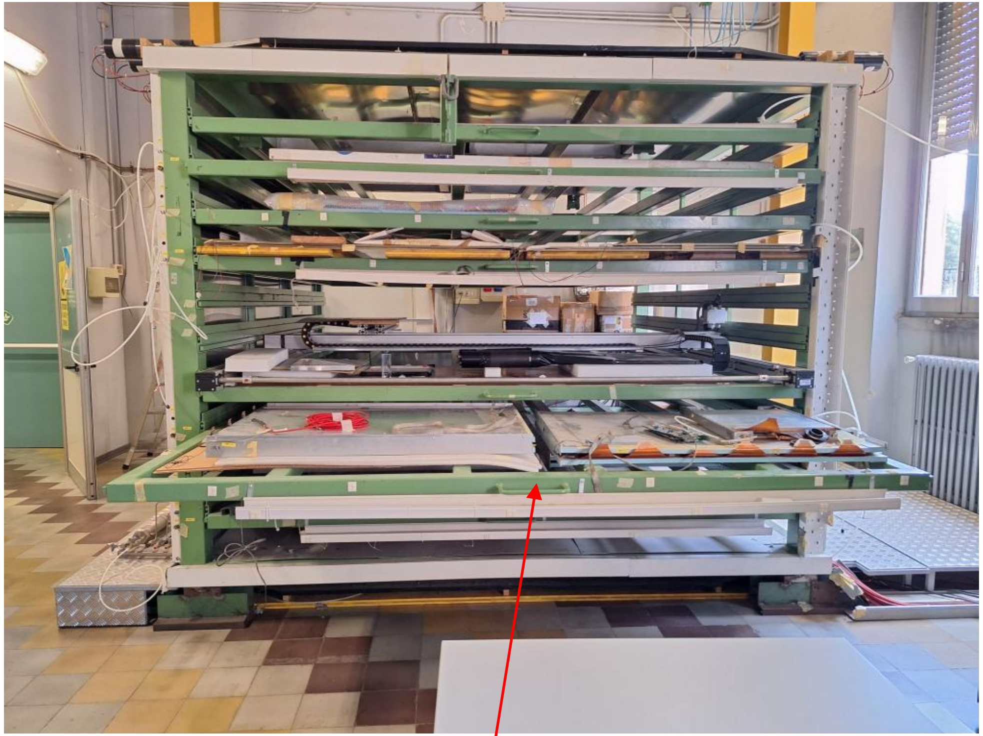
|---|---|
| **Why** | LHC is in Long Shutdown 3 for the HL-LHC upgrade → GIF++ test-beam campaigns are unavailable during this period |
| **What** | Setting up a complete RPC test facility at the Pavia CMS laboratory |
| **Status** | Gas system, high-voltage and detector are ready<br><br>Next: Full system testing and DAQ commissioning |

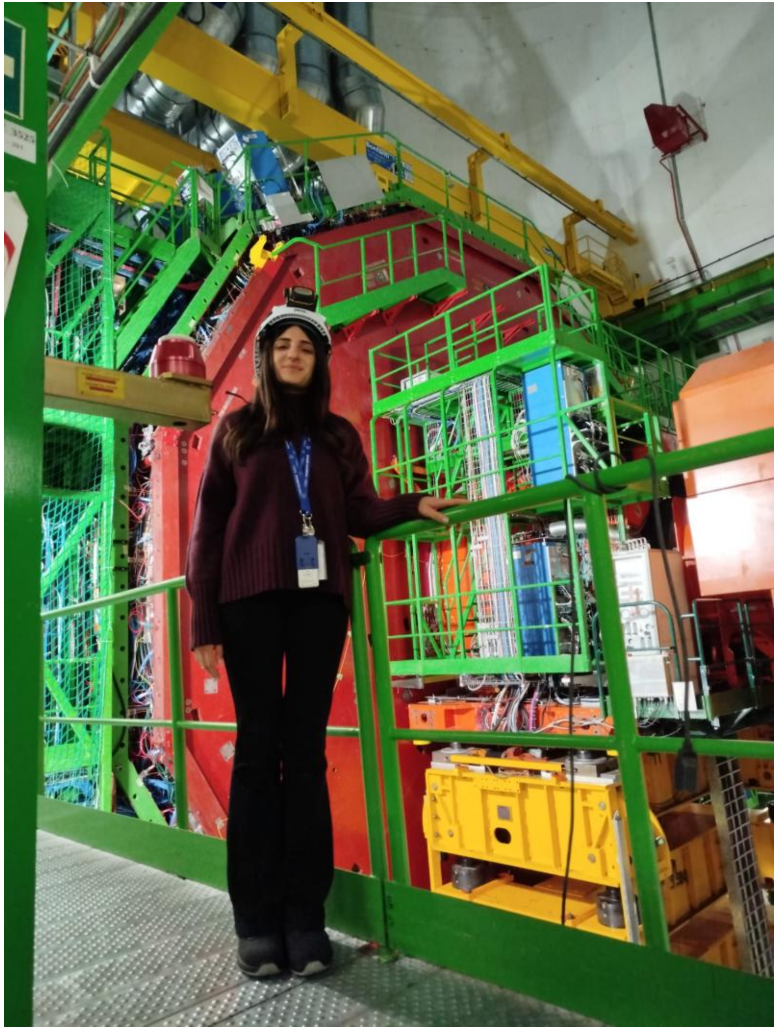
# Building a Test Facility in Pavia



RPC detectors

# Going Green at CERN

RPC detectors in CMS need to move to low-environmental-impact gas mixtures without losing performance and machine learning can speed up the search for the right combination.



# Backup: $R^2$ — Coefficient of Determination

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

$y$ measured (experimental) value

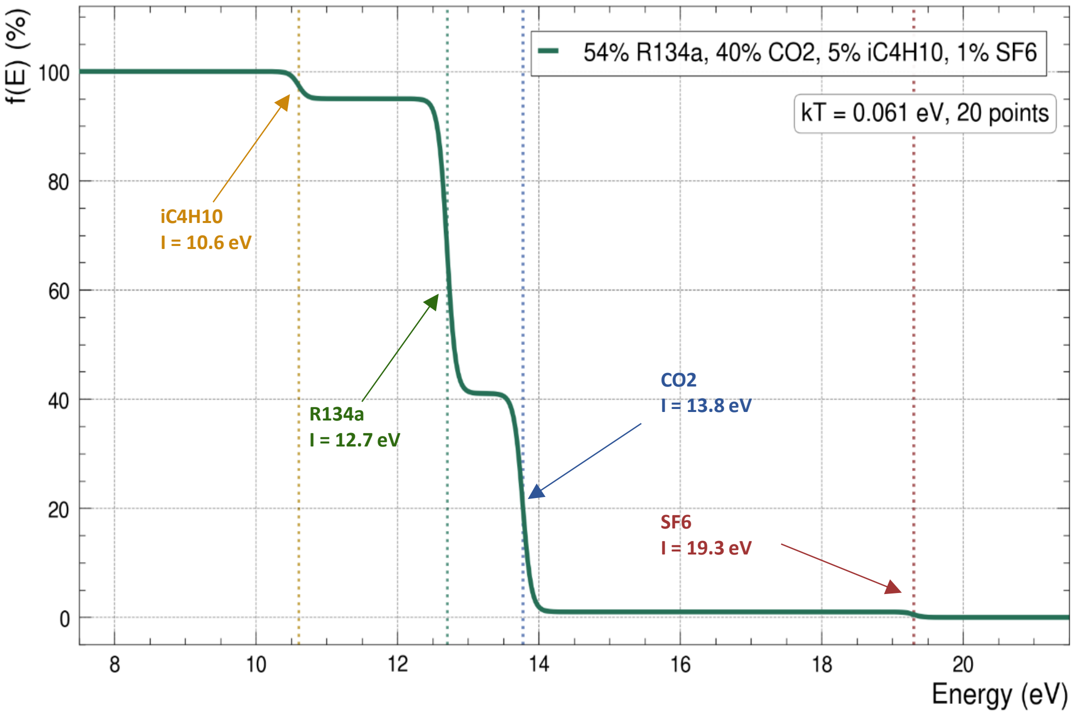
$\hat{y}$ predicted value from the model

$\bar{y}$ mean of the measured values

**$R^2 = 1$** → perfect fit · **$R^2 = 0$** → no better than predicting the mean · **$R^2 < 0$** → worse than the mean

# Backup: The Fermi-like Represtation

$$f(E) = \sum_i \frac{m_i}{1 + e^{\left(\frac{E - ie_i}{kT}\right)}}$$




| | |
|---|---|
| $m_i$ | fraction of gas i in the mixture (e.g. 0.40 for 40% $CO_2$) |
| $IE_i$ | first ionization energy of gas i (eV, tabulated) |
| $kT$ | smoothing width of the step — a shape hyperparameter, not a physical temperature |