5 November 2026

Instrumentation R&D and BHEP applications

IIHE Annual Meeting 2026

Dora Geeraerts

On behalf of the IIHE instrumentation group



Drinks at pilar

PILAR




Drinks at pilar
PILAR


Drinks at pilar
PILAR
Listening to a 20-minute presentation about instrumentation R&D and BHEP applications

Overview

IIHE involvement in DRD collaborations CERN

DRD1

Gaseous detectors

VUB+ULB

- Ecogas studies
- High-timing (multi-gap) RPCs development
- Calorimetry with timing RPCs
- Gaseous detectors for muography
- Electronics for gaseous detectors
- Management:
  - D. Jannsens as WG4 (simulations) Co-Coordinator
  - M. Tytgat in Management Board, Scientific Board and WG1 (Technologies) Co-Coordinator

DRD6

Calorimeters

VUB

- 5D (3D space + energy + time) calorimetry with timing-RPCs (T-SDHCAL project)
- Management: M. Tytgat as WP1 (sandwich calorimeters) Steering Board member

DRD3

Solid state sensors

- Under consideration for ULB+VUB

Overview

Four themes of instrumentation

1

Silicon timing sensors

LGAD space-charge gain suppression
Djunes Janssens

TI-LGAD characterisation
Mathias Beghuin

2

CMS muon system

GE1/1 GEM refurbishment
Emma Croisez Ventura & Aya Beshr

ME0 Level-1 track finder
Aya Beshr & Isabelle De Bruyn

RPC EcoGas study
Donya Ahmadi

iRPC hit reconstruction
Juhee Song

3

Muography

Portable Muoscope
Donya Ahmadi

THGEM prototyping
Adithyan Rajan, Yanwen Hong

MURAVES experiment
Adithyan Rajan, Yanwen Hong & Dora Geeraerts

SCIDEP experiment
Adithyan Rajan, Dora Geeraerts

4

Medical physics

Dose monitoring in proton therapy
Pierre Gérard Ortega

Overview

Four themes of instrumentation

1

Silicon timing sensors

LGAD space-charge gain suppression
Djunes Janssens

TI-LGAD characterisation
Mathias Beghuin


Gilles De Lentdecker


Pascal Vanlaer


Steven Lowette


Djunes Janssens


Mathias Beghuin

Overview

Four themes of instrumentation



Gilles De Lentdecker



Michael Tytgat

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CMS muon system

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Yanwen Hong



Donya Ahmadi

Overview

Four themes of instrumentation



Donya Ahmadi



Dora Geeraerts



Adithyan Rajan



Yanwen Hong

3

Muography

Portable Muoscope
Donya Ahmadi

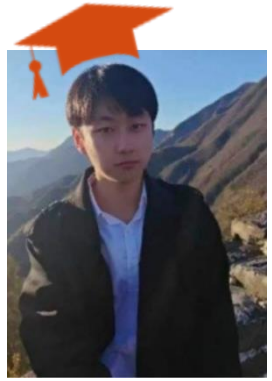
THGEM prototyping
Adithyan Rajan, Yanwen Hong

MURAVES experiment
Adithyan Rajan, Yanwen Hong & Dora Geeraerts

SCIDEP experiment
Adithyan Rajan, Dora Geeraerts, Zhe Wang



Michael Tytgat



Zhe Wang (Kevin)

Overview

Four themes of instrumentation



Gilles De Lentdecker



Pierre Gérard Ortega

4

Medical physics

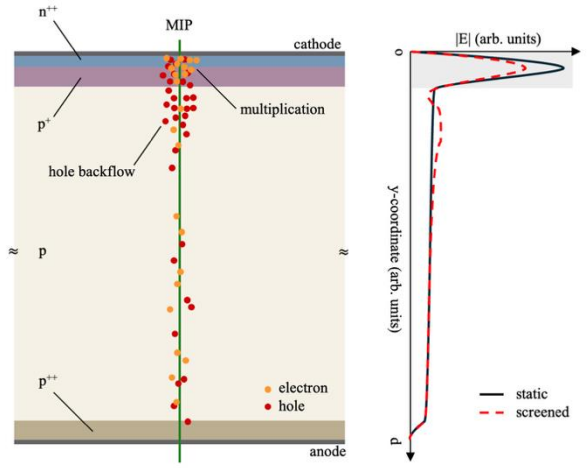
Dose monitoring in proton therapy
Pierre Gérard Ortega

LGADs: space-charge gain suppression improves timing

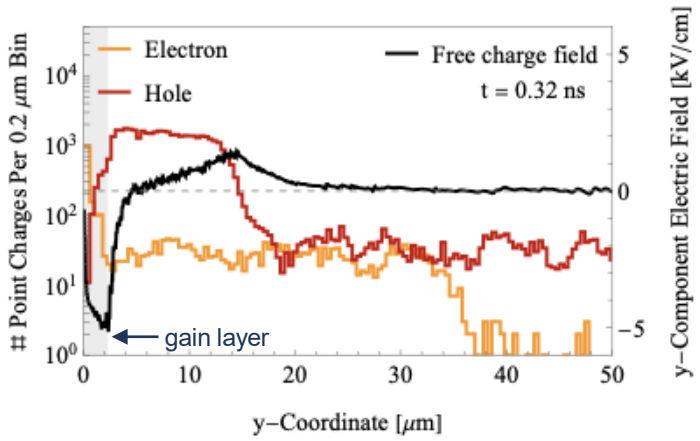
Low Gain Avalanche Detectors (LGADs) are thin silicon sensors with internal gain, built for 30–50 ps timing at the HL-LHC (CMS ETL, ATLAS HGTD).

We added the field of the avalanche's own charge to **Garfield++**: dense ionisation lowers the local gain, evening out signals and sharpening the timing.

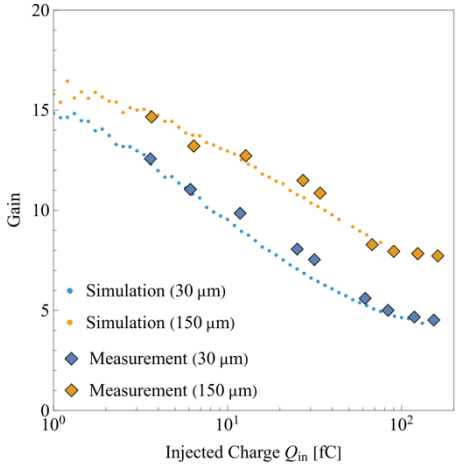
1 A dense track screens the gain layer



2 Add space-charge field to simulation



3 Model matches TPA laser data



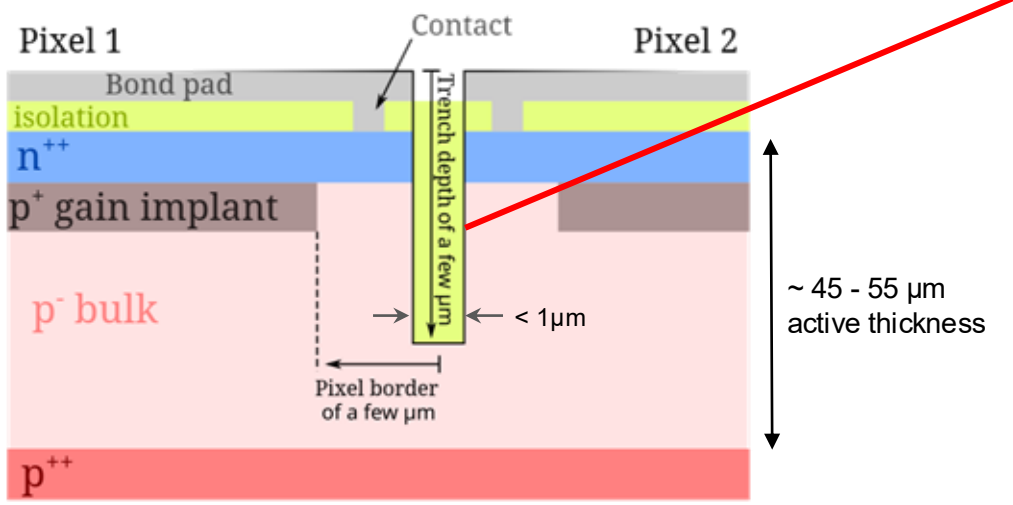
Intrinsic time resolution, 180 GeV/c pions: 53.9 ps → 44.5 ps (≈ 17 % better than with a static field)

D. Janssens, M. Moll, H. Schindler, arXiv:2609.08666 (2026).
TPA data: S. Pape et al., Sensors 24 (2024) 8032.

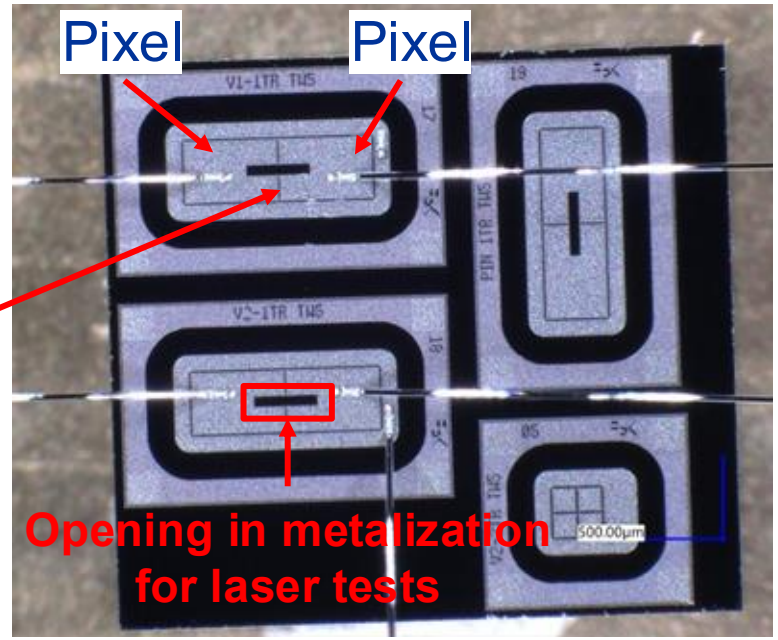
Trench-Isolated LGAD characterisation

Low Gain Avalanche Diodes (LGAD) for **4D tracking** need to achieve simultaneously:

- spatial resolution ~ 10 µm
- time resolution < 30 ps
- excellent uniformity
- radiation tolerance > 10^{16} 1-MeV n_{eq}/cm^2

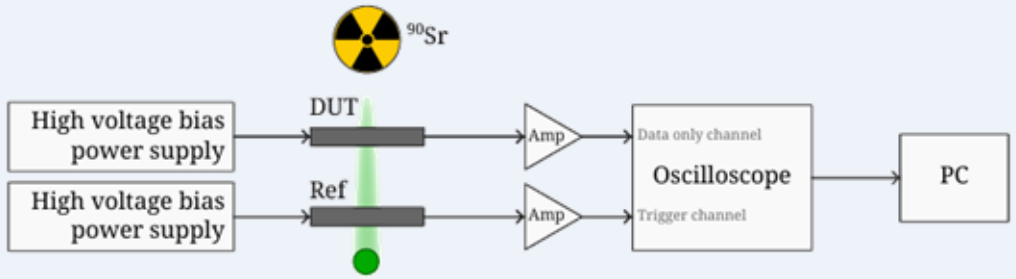


Transversal slice of a TI-LGAD,
from [Senger, M. (2024)]

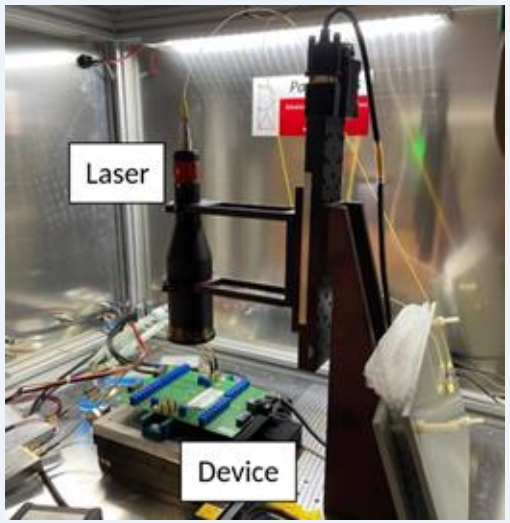


Trench-Isolated LGAD
test structures

Plan for an IIHE test facility



Beta source setup, from [Senger, M. (2024)]



TCT setup at University of Zürich, Nov.-Dec. 2025



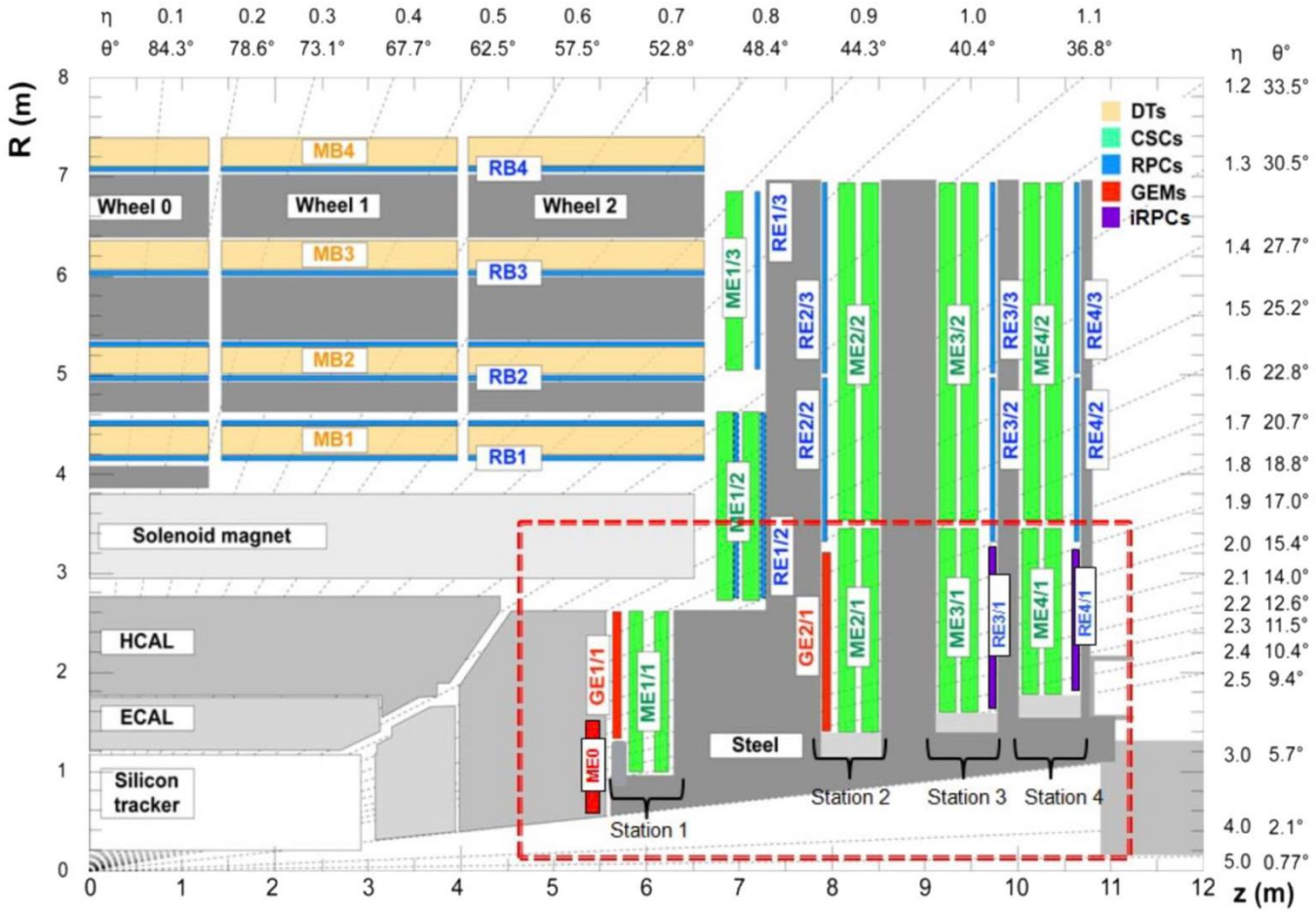
Oct. 2025 test beam at CERN

To deploy at IIHE

	Beta-source setup	Laser TCT setup	Test-beam setup
Time resolution	yes	approximate	yes
Spatial resolution	no	yes	yes
Parameters vs position	no	yes	yes
Collected charge	yes	no	yes
Gain	yes	approximate	yes
Detection efficiency	no	no	yes

Table from Senger, M. (2024)

Gas Electron Multiplier (GEM): motivations



- The GEM stations will improve muon detection in forward regions (|η| > 1.6) and increase redundancy
- Prepare CMS for higher luminosity and radiation rates, with effective detection until 2040

The 3 generations of CMS GEM detectors

- **GE1/1:** initial installation of triple-GEM detectors in the first endcap station, in operation since 2021
- **GE2/1:** partially installed in late 2024 (20 modules)
- **ME0:** extends the muon coverage beyond |η| = 2.4, to be installed in 2027 behind the HGCAL

Working on GEM:
Aya, Emma, Isabelle & Yanwen

GE1/1 refurbishment

- GE1/1: 4 years of operation in CMS → a lot of results to identify possible weaknesses
- Opportunity to refurbish the already installed CMS GE1/1 during LS3
- Refurbishment study done in collaboration with **IIHE**

GE1/1 now extracted and ready for improvements!



Assembly of the 1st refurbished GE1/1 prototype

Fast Track Finder for the ME0 Level-1 Trigger

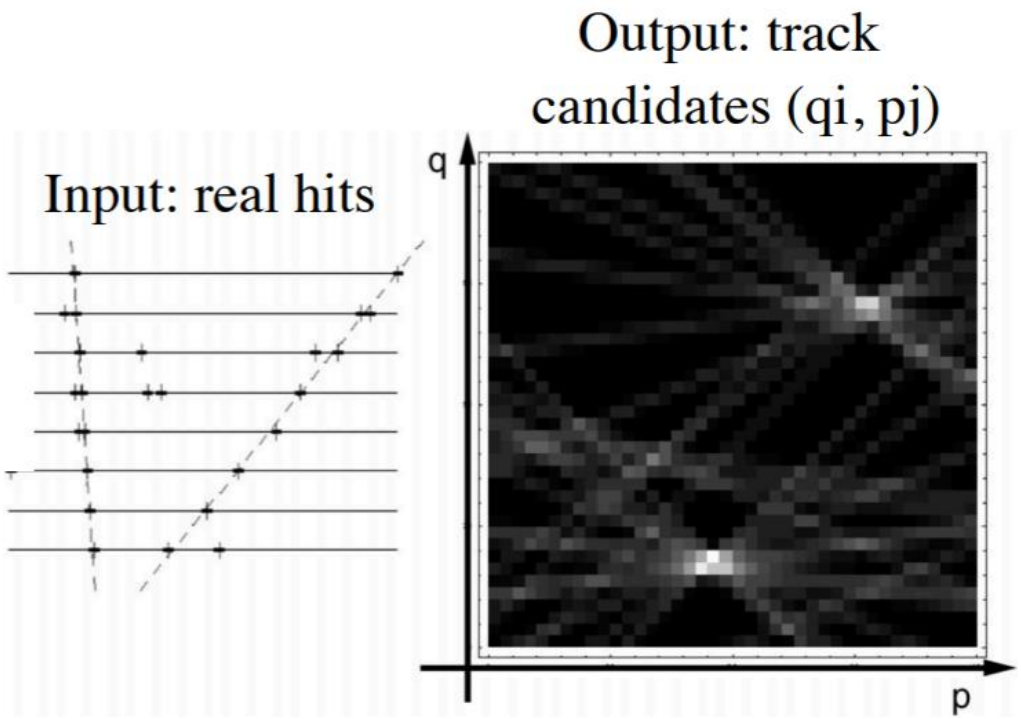
Tracking algorithm for ME0

- Reconstruct standalone muon tracks
- Trigger based on estimated muon momentum

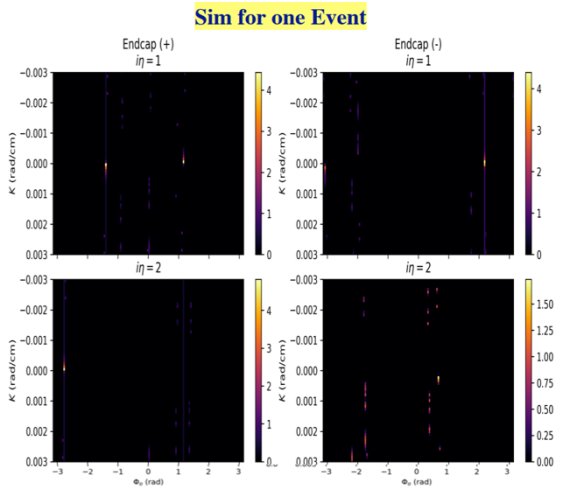
Artificial Retina

- Pattern recognition algorithm inspired by the biological visual mechanism
- Each track is defined by 2 parameters (p, q); the intersection of the track with the k^{th} detector layer is $y_k(p, q)$
- Compare real hits $x_r^{(k)}$ to predicted hits ①
- Calculate the grid response ② and find local maxima in the (p, q) grid

① $s_{ijkr} = x_r^{(k)} - y_k(p_i, q_j)$ ② $R_{ij} = \sum_{k,r} \exp\left(-\frac{s_{ijkr}^2}{2\sigma^2} \right)$



Fast Track Finder: Retina grid and workflow



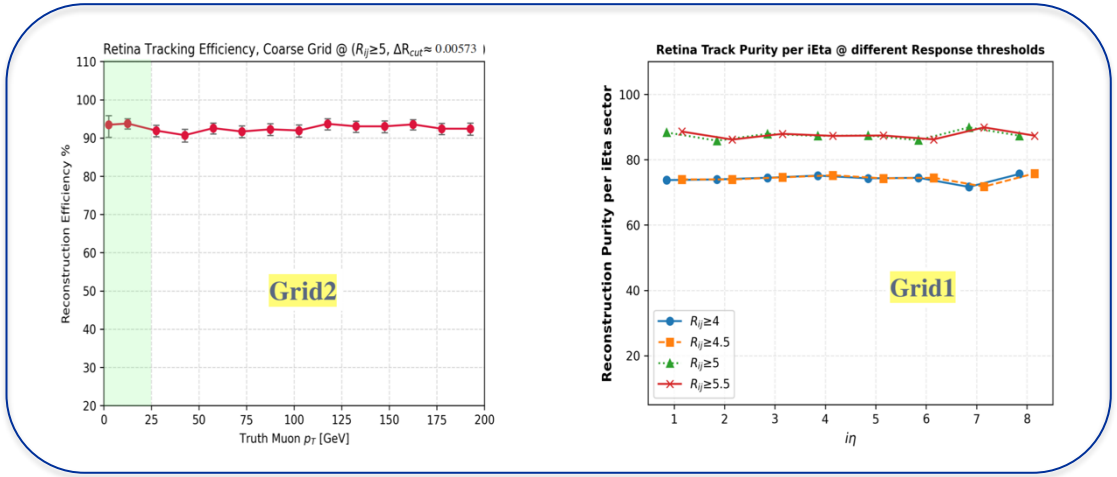
Using a 2D Retina grid with

- Initial track direction in ME0 at the first layer (close to the interaction point): φ_1
- Track slope in ME0: $k = \frac{\Delta\Phi_{bending}}{\Delta z_{layers}} = \frac{\Phi_6 - \Phi_1}{z_6 - z_1}$

Using linear model: $\varphi_i = \varphi_1 + k(z_i - z_1)$ for the Retina grid

Workflow

1. Find local maxima
2. Apply threshold on grid response
3. Remove duplicate peaks
4. Match reconstructed tracks to simulated tracks
5. Calculate efficiency & purity for different grid layouts
6. Estimate muon momentum (non-uniform B field)



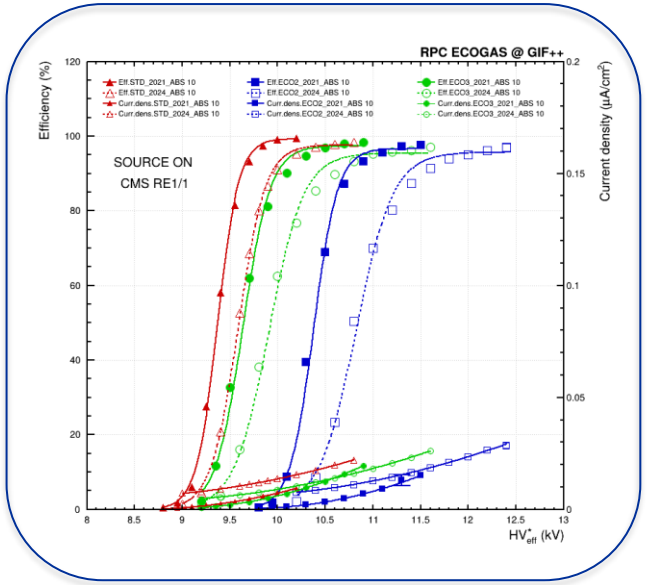
Currently working on improving the Retina grid: finer φ binning, interpolation, variable k binning, …

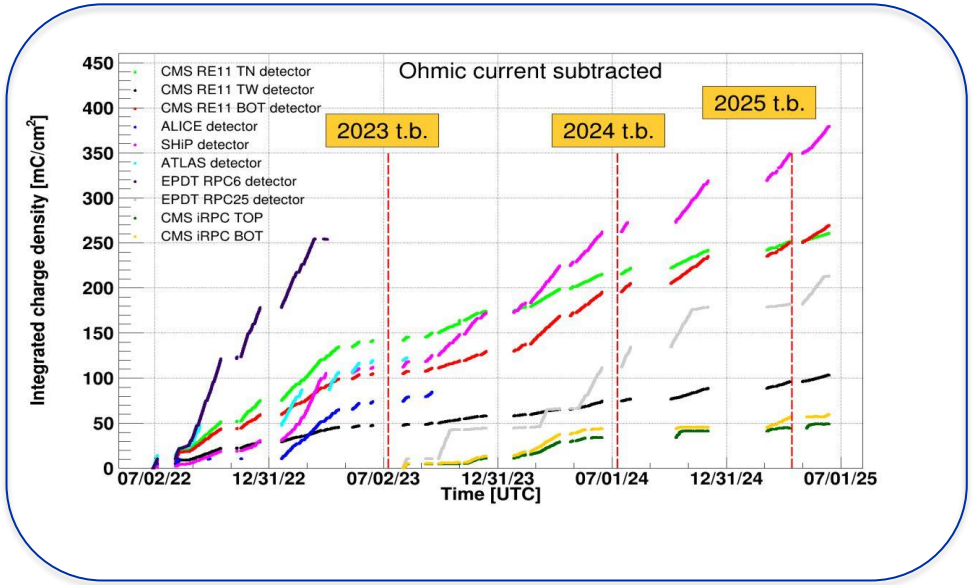
CMS-RPC EcoGas Study

- Standard RPC gas mixture contains fluorinated greenhouse gases (R134a and SF6) with very high GWP (Global Warming Potential): R134a ≈ 1430, SF_6 ≈ 22,800, while CO_2 = 1.
- Rising costs and reduced availability in Europe, combined with CERN's commitment to cutting direct greenhouse gas (GHG) emissions.
- Search for alternative low-GWP, low-toxicity, non-flammable gases that keep RPC performance and are compatible with current electronics and HV → EcoGas study with **HFO/CO_2-based mixtures**.

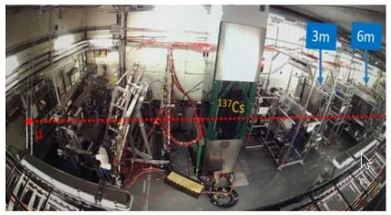
Study under CERN Gamma Irradiation Facility GIF++ (12.5 TBq ^{137}Cs source + 150 GeV/c muon beam)

- Long-term performance: 2021 vs 2024 (CMS RE1/1, source on)
- Integrated charge of all chambers measured for aging studies
- R1233zd (GWP ≈ 1) tested as SF_6 replacement





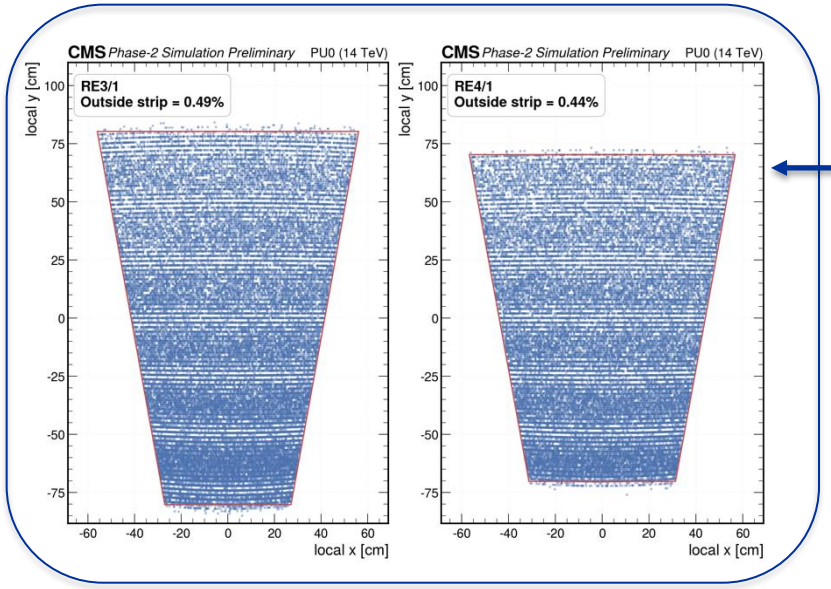
Mixture	R134a (%)	HFO-1234ze (%)	CO_2 (%)	iC_4H_{10} (%)	SF_6 (%)	GWP	CO_2e (g/l)
STD	95.2	–	–	4.5	0.3	1485	6824
ECO_2	–	35	60	4	1	476	1522
ECO_3	–	25	69	5	1	527	1519



First simulation study of iRPC two-end hit reconstruction

Improved RPC (iRPC)

- One iRPC chamber consists of 96 strips
- iRPCs have a better time resolution than existing RPCs and extend coverage to forward regions
- Two-end readout plus timing information is crucial → a reconstructed hit gives **(time, x, y)**



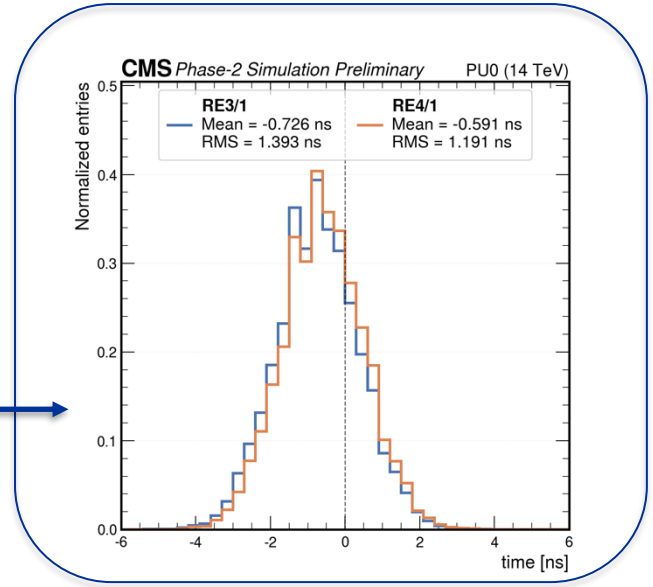
Reconstructed iRPC hit: time, x and y

Local positions of reconstructed hits in RE3/1 and RE4/1

- Reconstructed hit positions fill the chambers as expected
- The y banding is from discrete TDC time steps
- Less than 0.5% of hits reconstructed beyond the strip ends, since y is from Δt

Normalized hit-time distributions

- The RMS is consistent with the time smearing (~1 ns)



Performance in Phase-2 simulation

- Matching: pair a true muon hit with a reconstructed hit in the same chamber
- **Efficiency** of the hit reconstruction: fraction of true muon hits that produce a reconstructed hit

$$E = \frac{N_{true\ muon\ with\ reco.\ hit}}{N_{true\ muon}} \approx 93.4\%$$

The loss is in the digitization step: once a signal exists, almost all become reconstructed hits (~99.8%)

Muon radiography

= imaging technique that uses naturally occurring cosmic-ray muons to probe the internal structure of large-scale objects

Absorption / transmission muography measures the attenuation of the muon flux after it passes through an object.

- sensitive to density
- applicable to very large targets
- 2D image
- relies on knowledge of the incident muon flux

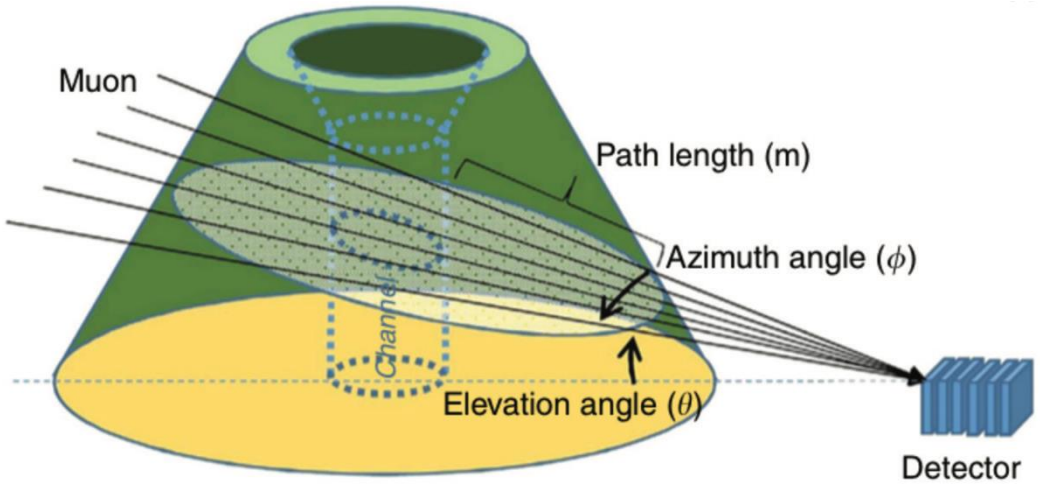


Image from Despina Hatzifotiadou, 19th IPPOG Meeting (2020)

Common detector technologies for muography

Plastic scintillators · Nuclear emulsions · Gaseous detectors (MWPC, MicroMegas, RPC …)

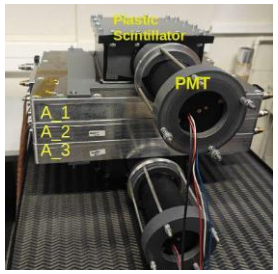
Portable Muoscope Project

Aim: R&D of a general-purpose, portable gaseous-detector-based muon telescope for muography applications in confined/remote environments, e.g. geology, archaeology, civil engineering and industrial safety.

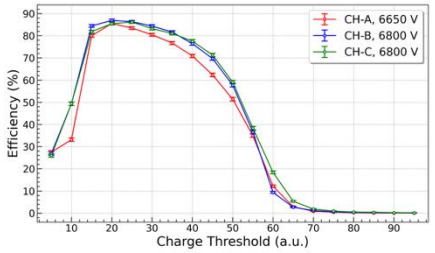
Portable Muoscope

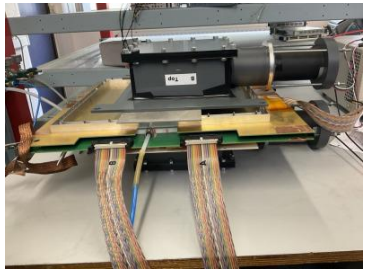
- single/double-gap glass-RPC based muon telescope
- compact, portable, robust, autonomous, low power & gas consumption, modular geometry

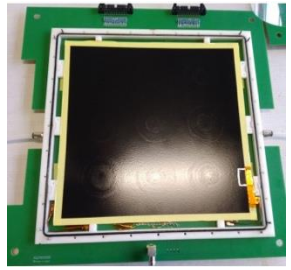
Collaboration **VUB & UCLouvain**

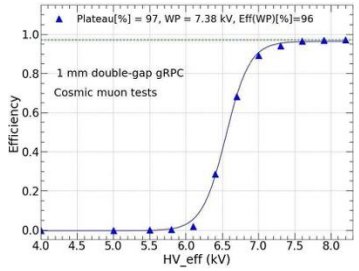










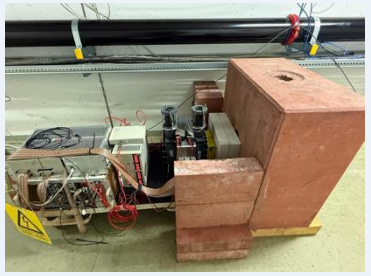


Initial deployments: DESY-II & ELI

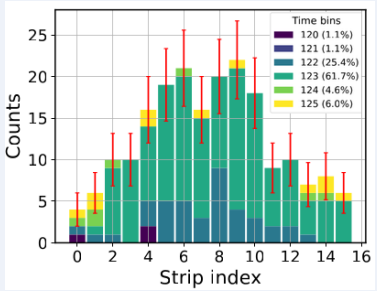
- Aug. 2026: 3 chambers operating in sealed mode for a week @ DESY-II synchrotron, Hamburg
  - 4 GeV electron beam; bunches of 1.9×10^9 electrons; 4 µs pulse duration; 160 ms bunch spacing
- Sep. 2026: two weeks @ ELBA ELI Beamlines, Czech Republic
  - Electron beam driven by laser wakefield acceleration
- Muon telescope placed behind tungsten target and concrete beam dump



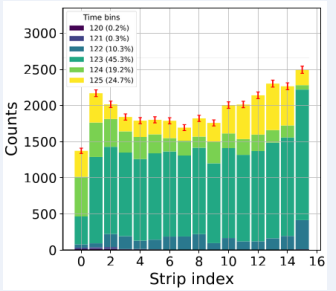




Cosmic data

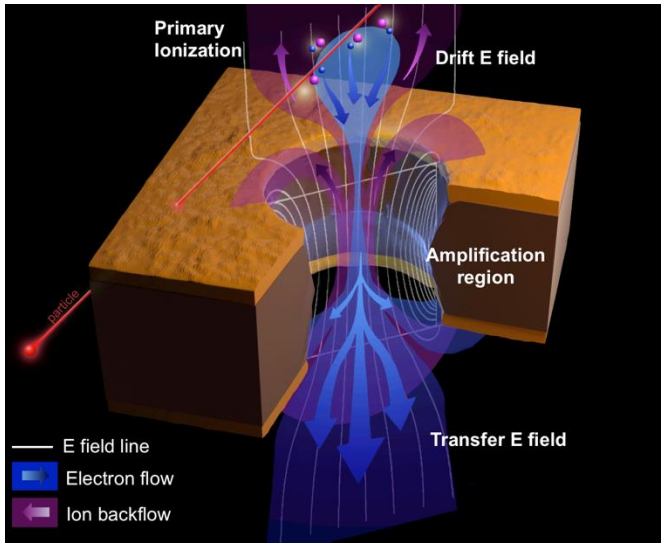


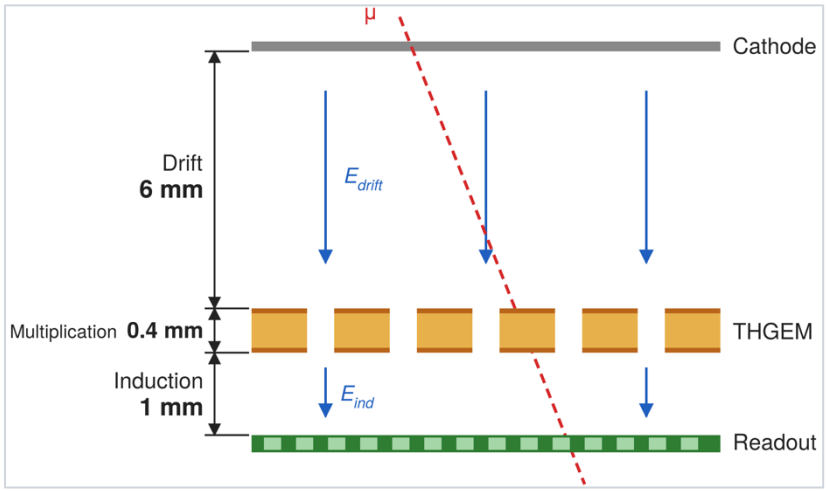
Beam data

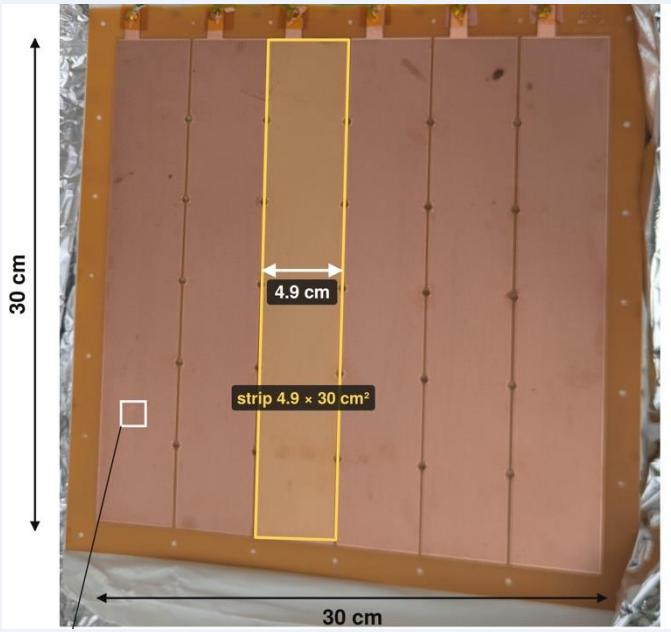


THGEM prototyping: motivation and application

- Develop a compact, portable muon telescope for muography using **THGEM**.
- Explore the potential for improved spatial resolution in muon tracking
- Can run with single/dual component mixtues: simpler logistics + no issues with ecogas
- Prototype and characterize the detector towards an integrated, enclosed system.



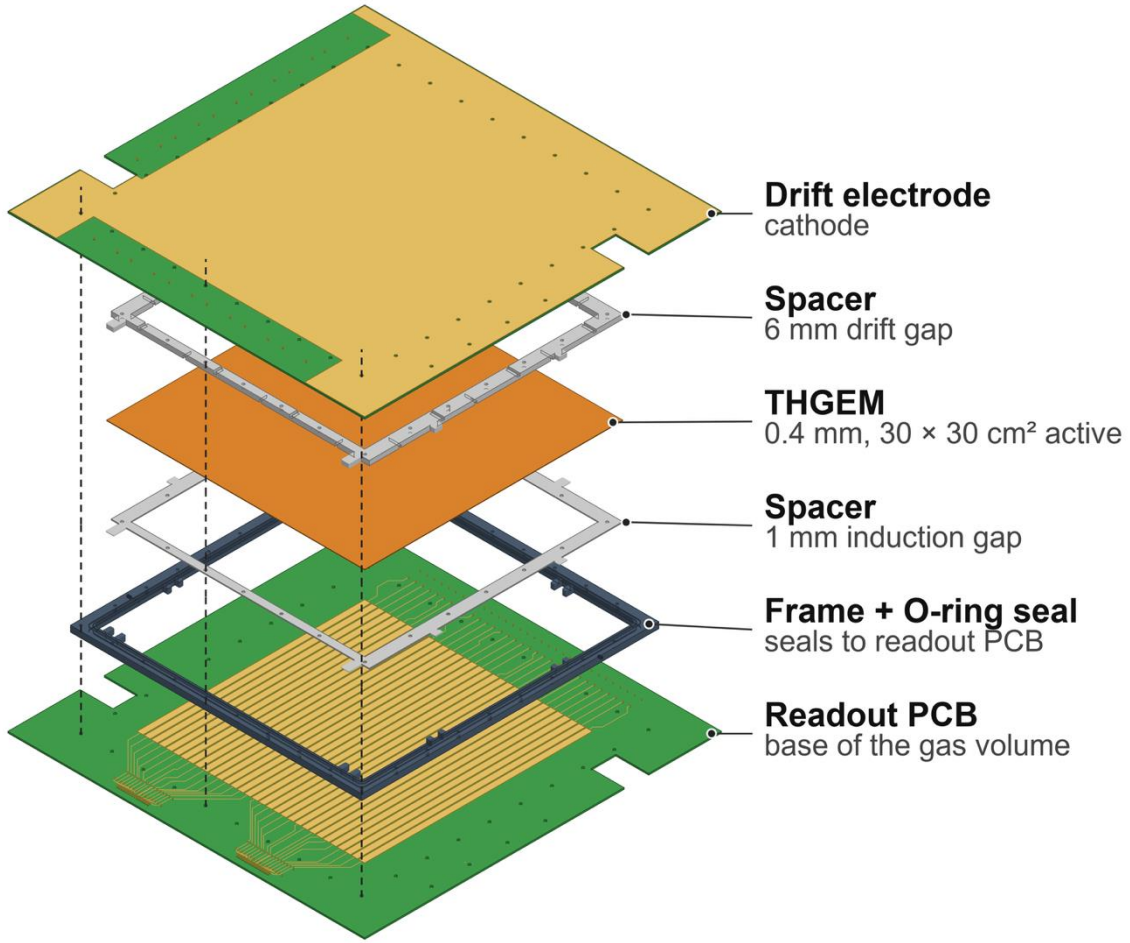




Integrating the THGEM into a gas-tight chamber

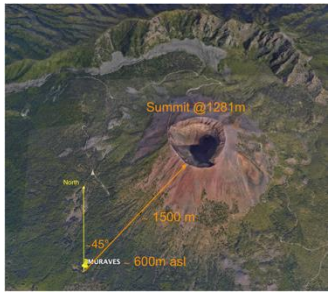
- Integrate the THGEM into a compact, self-contained, gas-tight chamber.
- Small gas volume, lightweight, and modular for stacking into a multi-layer tracker.
- The readout PCB and the frame form the gas volume, sealed with an O-ring, so no external vessel is needed.
- Integrated HV feedthroughs and readout connections.

Status: design complete; fabrication, leak testing and first HV tests next



MURAVES Experiment at Mt. Vesuvius

- MUon RAdiography of Mt. VESuvius
- Collaboration between Italy (INGV, INFN Naples & Florence) and Belgium (UCLouvain & VUB)
- Study rock density distribution of summit cone of Mount Vesuvius
- Three detectors: 1500 m from the volcano crater and ~600 m a.s.l.
- Each muon tracker: 2x4 planes made of 64 triangular scintillator bars

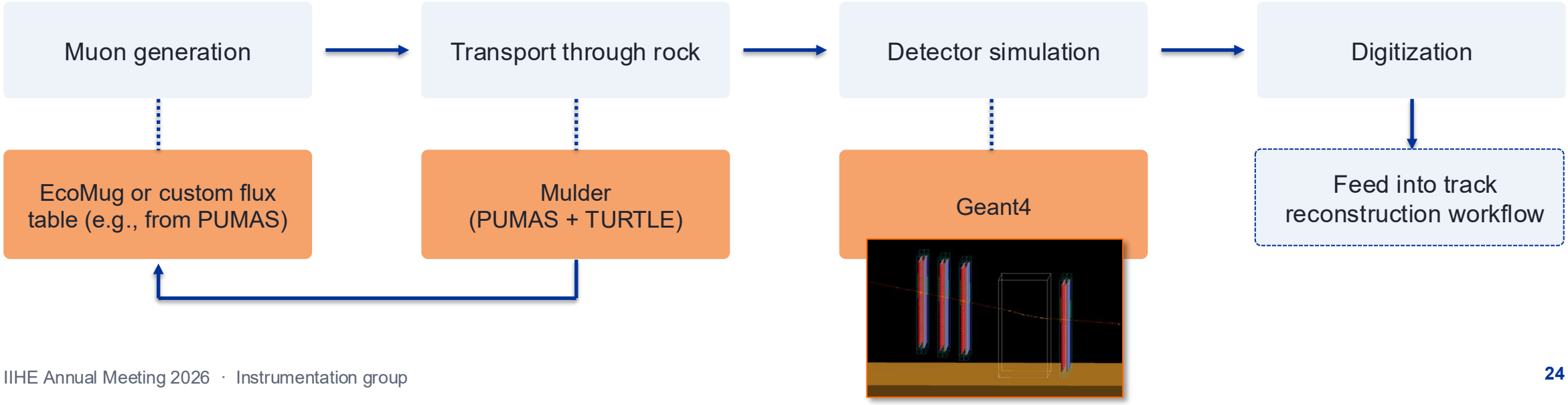






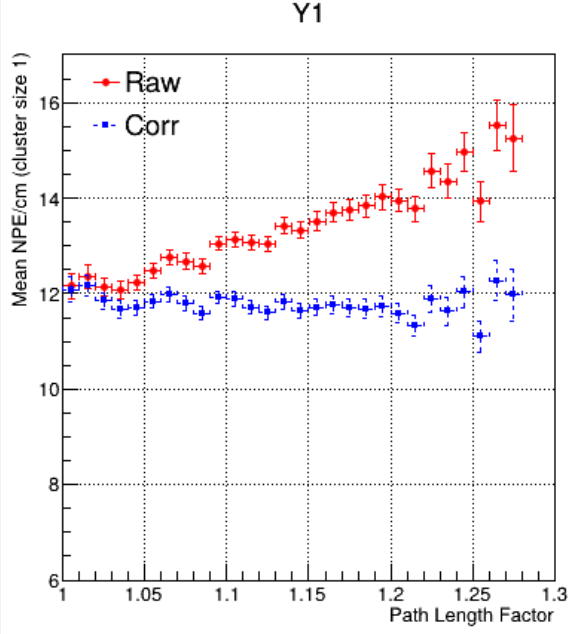
End-to-end simulation pipeline

Goal: run simulated data through the existing MURAVES track reconstruction workflow to compare measured data to MC

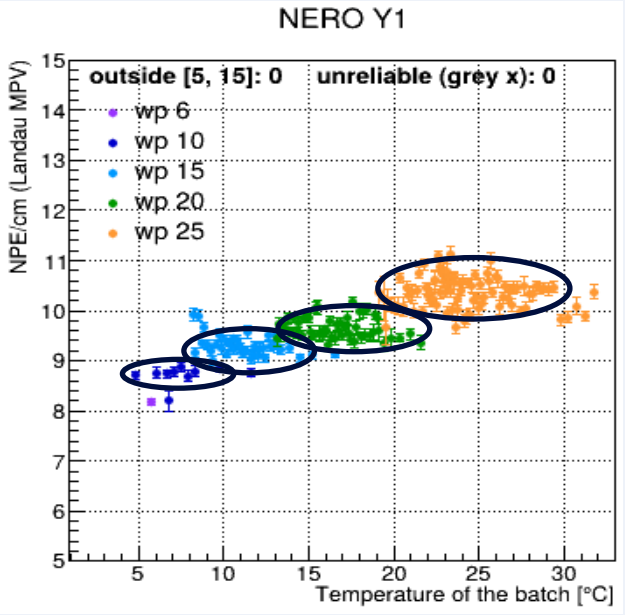


Digitization: path length to NPE

- Cluster energy in data is normalised using the reconstructed track path length to obtain a path-length-independent response.
- Corrected response (blue) remains relatively stable with the path-length factor, unlike the increasing raw response (red).



- The calibrated light yield is expressed in **NPE/cm** and used to convert simulated particle path lengths into NPE.
- Different conversion factors are applied for different data-taking periods to account for variations in SiPM response and overvoltage settings (working point).



Density evaluation strategy for Mt. Vesuvius

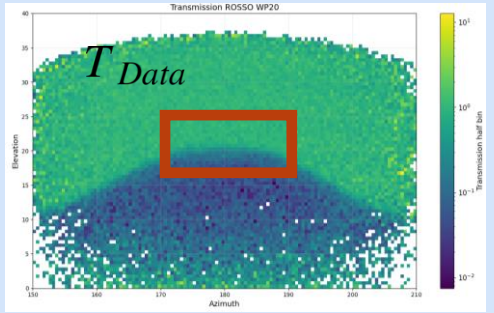
Refining data analysis

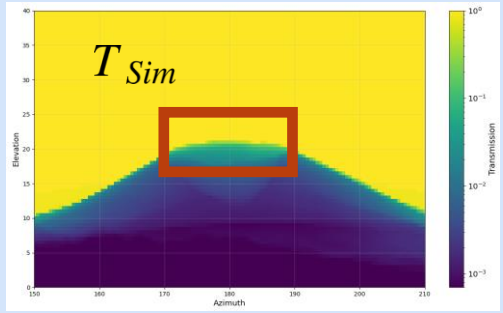
- ~400 h more data organised and added to the analysis
- χ^2-based criteria for track quality selection
- Working on alignment study before χ^2 distribution morphing

Simulation of muon transport through Mt. Vesuvius

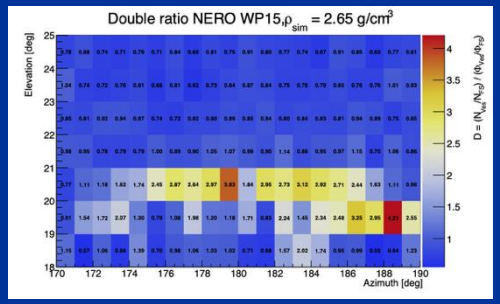
- **TURTLE:** utilities for the long-range transport of Monte-Carlo particles through a topography.
- **PUMAS:** library to transport muons in matter by forward or backward Monte Carlo

Transmission:

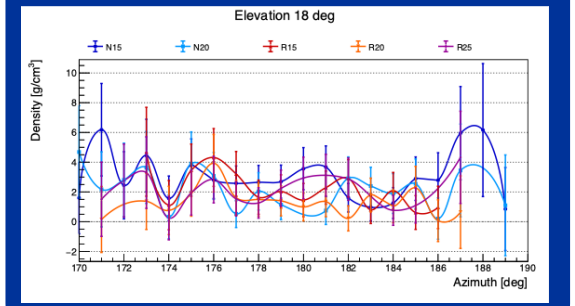




Relative Transmission:



$$\mathscr{D} = \frac{T_{Data}}{T_{Sim}(\rho_0)}$$



Muography of the Egyptian Pyramids

- ScIDEP = Scintillator Imaging Detector for Egyptian Pyramids
- Collaboration VUB, USA, Romania, Egypt
- 2 scintillator-based detectors under development

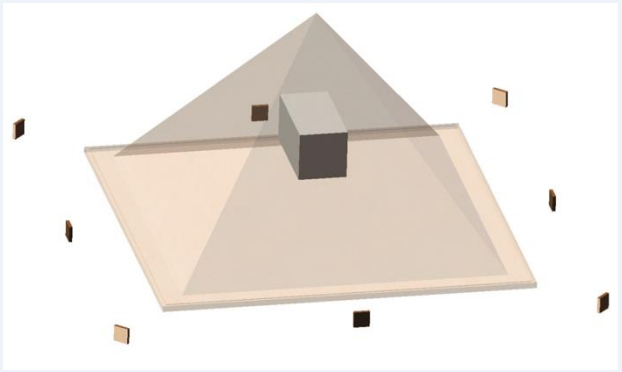
Pyramid simulation in Geant4

- Back-sampling approach
- Quantitative analysis of void discriminability / detectability
- SART 3D image reconstruction

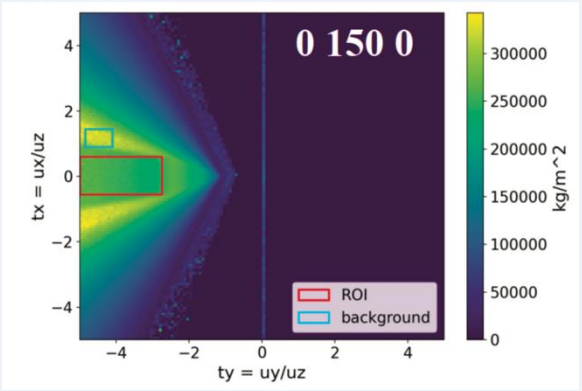
Focusing on new target location

- Field trip conducted
- Feasibility study ongoing



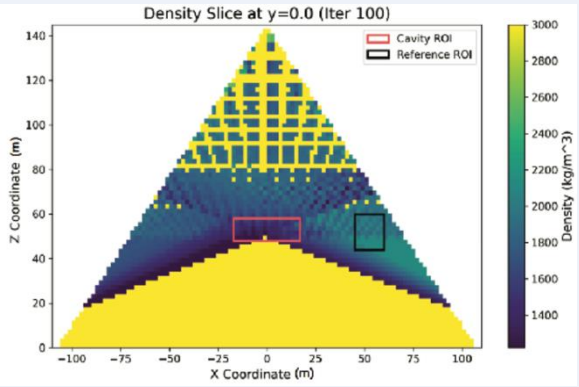


2D opacity map



CNR = 4.59 ; Z_{ROI} = 31.12 ; C_{rel} = 0.2199

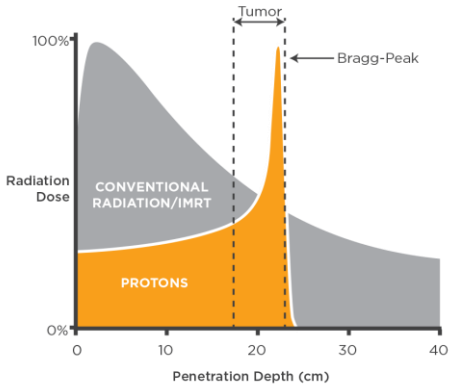
Slice of 3D density map

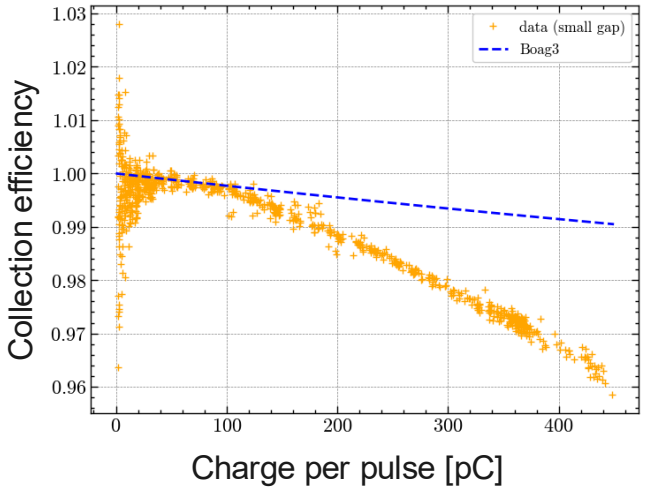


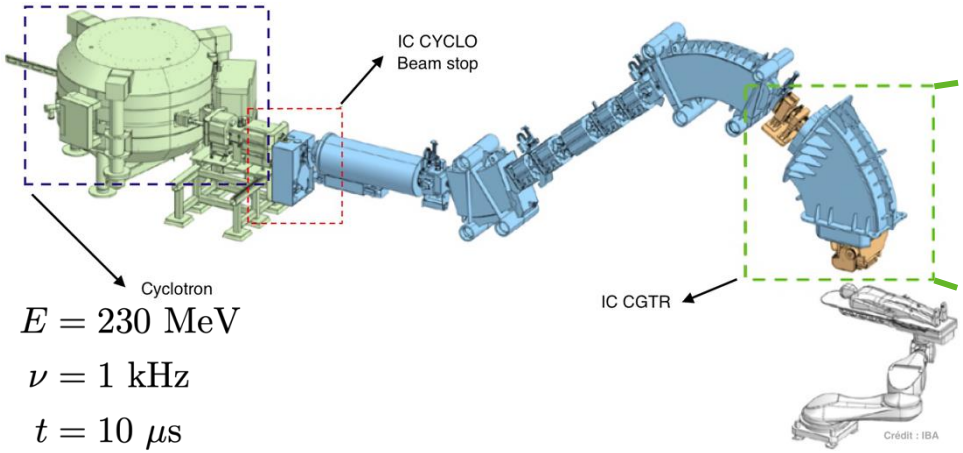
CNR = 2.37 ; Z_{ROI} = 21.76 ; C_{rel} = 0.271

Recap: dose monitoring in proton therapy

- Motivated by the Bragg peak
- Dose measured by air-vented ionisation chambers (gap ~1 mm)
- Attachment to O_2 → free-electron fraction $p = f(\eta, d)$
- Ion–ion recombination
- Boag's model corrects in real time: CE = $f(p, d, Q, E)$, through FPGA
- FLASH: differential effects on normal vs. tumoral tissues
- **At UHDR (≥ 40 Gy/s): Boag fails above ~100 pC per pulse**



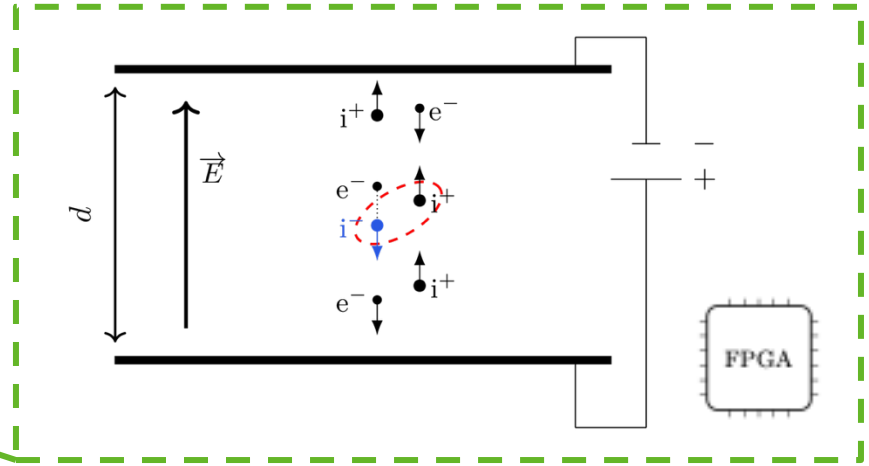




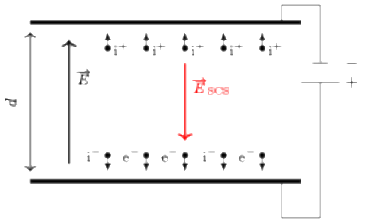
$E = 230$ MeV

$\nu = 1$ kHz

$t = 10$ μs



Two additions to Garfield++



Built on Garfield++ (CERN): Monte Carlo software to simulate the drift of charged particles

New

1 Ion–ion recombination

Negative and positive ions recombine, from the local ion densities

$$dn_{\pm}/dt = -\alpha\, n_{+}\, n_{-}$$

Computed on voxels (3D discretisation of space)

New

2 3D space-charge field

The field induced by the particles is recomputed from the charge densities

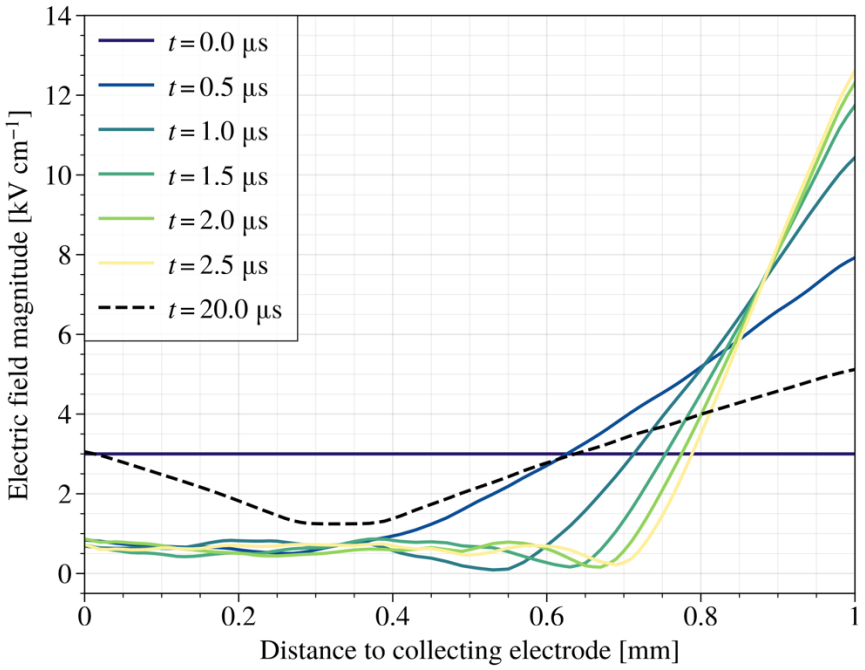
$$\nabla^2\varphi = -\rho/\varepsilon_0$$

Poisson equation solved iteratively (Gauss-Seidel)

Both in the official Garfield++ release (June 2026) · (arXiv:2606.24384)

Key result: free electrons drive the loss

Electric field in the gap (2 Gy pulse)



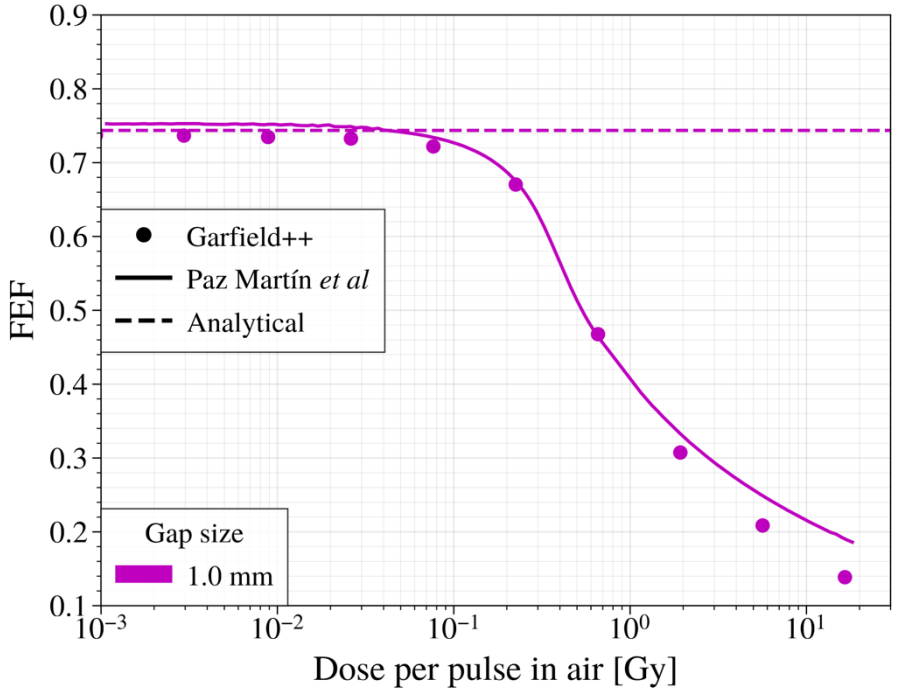
SIMULATION

Gap
1 mm

Voltage
300 V

Pulse duration
2.5 µs

Free-electron fraction (FEF)



Space charge lowers the field → more attachment → FEF drops → CCE loss

Acknowledgements

Funding

FWO-Weave UCLouvain-VUB on muography	**Dora & Adithyan**
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CMS IRI (base funding CMS)	**Yanwen (past) & Mathias**
FNRS Fellowships	**Isabelle & Djunes**
Chinese Scholarship Council	**Kevin (past)**
CMS Muon M&O	**Aya**
ProtherWal	**Pierre**
ULB funding	**Emma**

General:

- Horizon 2020 projects (staff exchange) for muography
- ProtherWal for proton therapy

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CMS

weave
Research funding without borders

fwo

fnrs

Horizon 2020
European Union Funding
for Research & Innovation

- The IIHE has a vibrant R&D program
- Very promising for the future
- It is vital for our lab to maintain a significant R&D activity

Thank you for you attention!

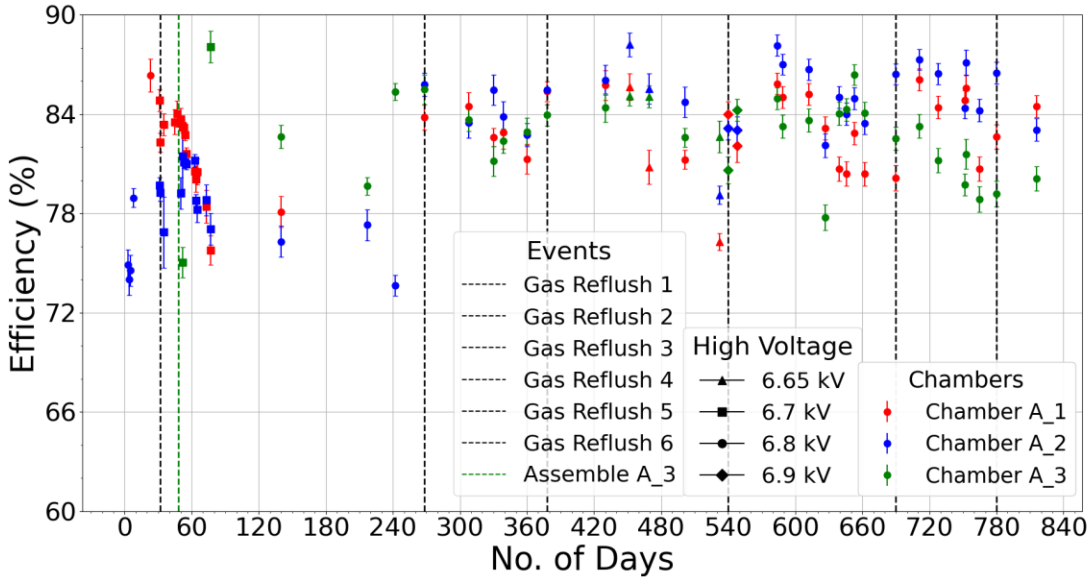
Questions?

The contributors will be happy to answer ☺

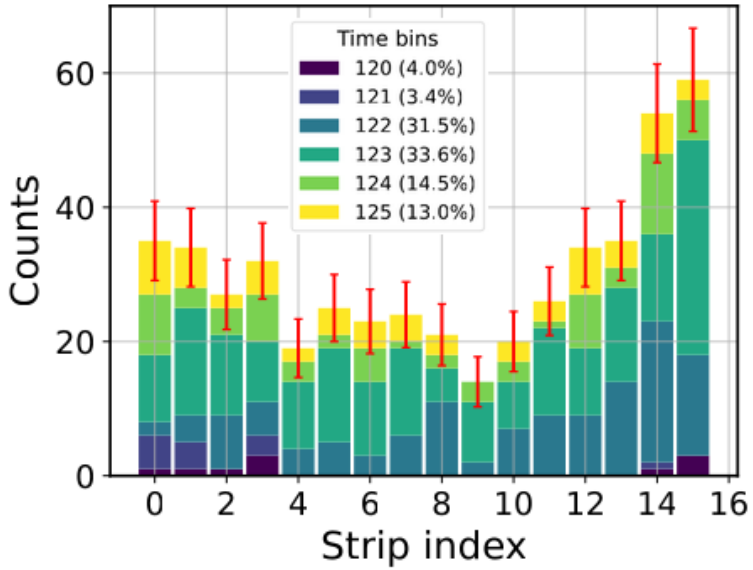


Backup: Muoscope stability and shielding

Detection efficiency of the three chambers as a function of time, over less than three years. Vertical lines indicate the gas refills of chamber A3; marker shapes indicate the applied high voltage.



Occupancy of one of the chambers after adding shielding around the detector and placing the chambers furthest away from the beam dump.



References

A. Samalan, Muon Detector Development for the CMS Phase-2 Upgrade and Muon Radiography Applications, PhD thesis, Ghent University, Ghent, Belgium, Mar. 2024
S. Ikram et al., “Development and performance analysis of glass-based gas-tight RPCs for muography applications”, J. Appl. Phys. 138 (2025) 174502
S. Ikram et al., “RPC Telescope Tests for Muon Detection at Laser-Plasma Accelerators”, Appl. Sci. 16 (2026) 9946