Instrumentation R&D

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IIHE Annual Meeting, 10th Nov. 2025

CMS Phase-2 R&D Activities

CMS – Muon-GEM

I. Activities on the Three Stations of GEMs

II. Fast Track Finder for ME0 Level1-Trigger

III. CMS-GEM Detector Control System (DCS)

CMS – Muon-RPC

IV. iRPC Hit Reconstruction

V. CMS-RPC EcoGas Studies

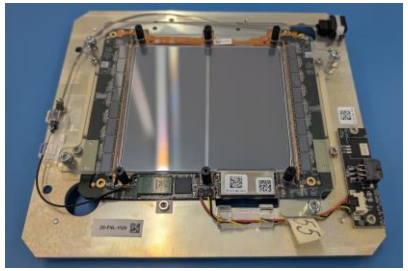
CMS - Tracker

VI. Pixel digi morphing

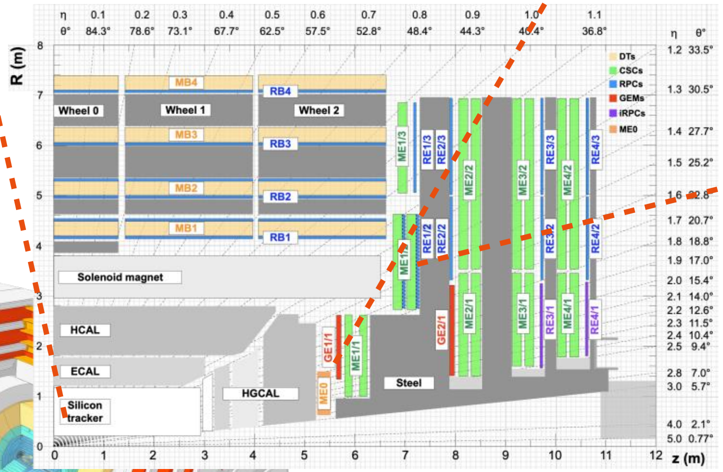
CMS Phase-2 involvement of IIHE

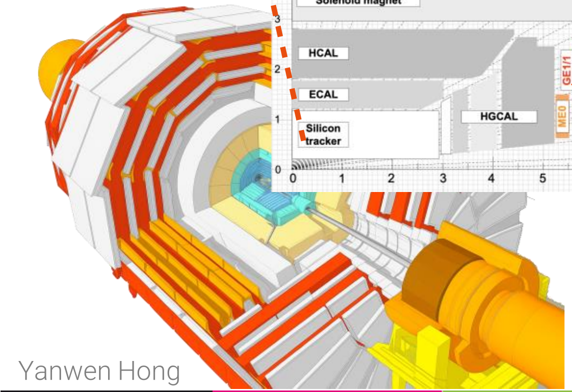
- Tracker (pixels + strips)

  See talk Aloke

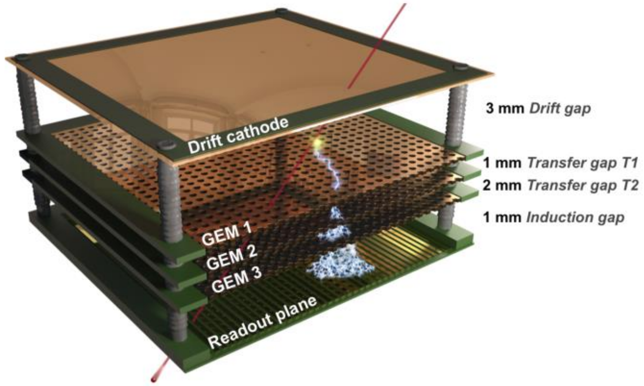


- Coverage closer to the beam, up to η~4; more precise momentum and impact parameter ; radiation tolerant ; low material budget
- OT 2S sensor module assembly at IIHE



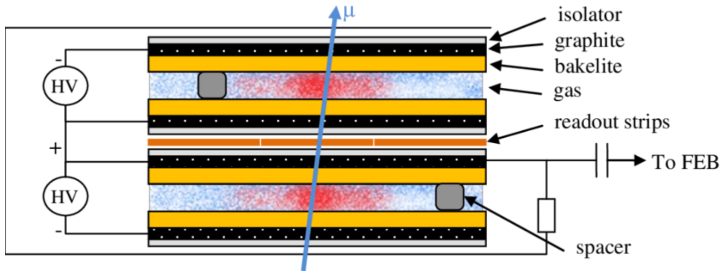


- Gas Electron Multiplier (GEM)



- To enhance muon tracking and triggering capabilities in the high-background environment of the forward spectrometer, providing high spatial resolution.
- GE1/1: Initial installation of triple-GEM detectors in the first endcap station.
- GE2/1 & ME0: to be installed; ME0 extends the muon coverage beyond $|\eta| = 2.4$.

- Resistive Plate Chamber (RPC)



- To provide robust, fast muon triggering with excellent time resolution for both the barrel and endcap regions.
- RE3/1 and RE4/1:
  Improve trigger efficiency and redundancy in the forward region;
  Introduce iPRC (Improved RPCs) with finer segmentation and advanced electronics.

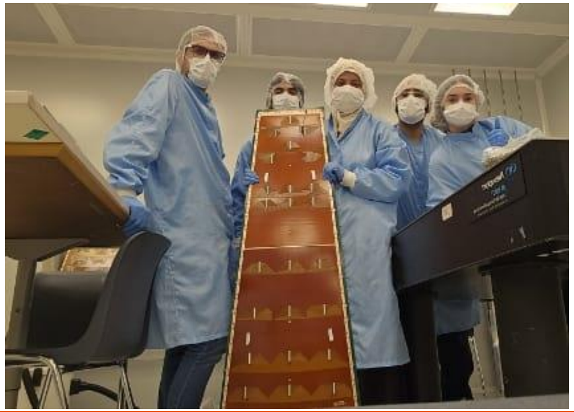
Activities on the Three Stations of GEMs

Aya Beshr

Yanwen Hong

GE1/1 R&D for Improved Timing

- New PCB design:
  • additional 4 central pillars.
  -> improves PCBs planarity by conserving the gap distances.
- New GEM foils design:
  • Double azimuthal segmentation;
  -> mitigate discharge propagation & improve gain uniformity.
  • Addition of hospital holes.
  -> helps in access foils for fixing short circuits.



Assembly of the 1st refurbished GE11 Prototype

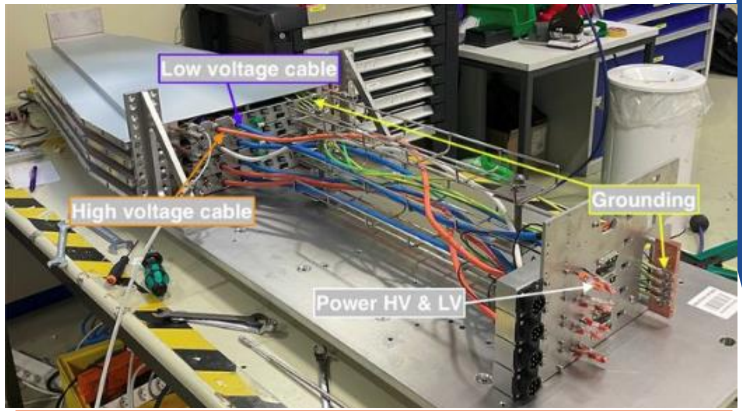
GE2/1 Detector Production & QC

- GE2/1 foil stack preparation (3-layer modules) and module assembly.
- Module QCs setup in production site Ghent and operations, on Gas Tightness & High Voltage Circuit Tests.
- Refurbish problematic modules, e.g. bad GEM foils stretching, short circuits,….etc.

Assembly of the first GE2/1 in Ghent clean room

ME0 Detector Production & QC

- ME0 foil QCs & stack preparation.
- ME0 module assembly.
- Module QC on Gas Tightness & High Voltage Circuit Tests.
- Refurbish problematic modules, e.g. bad GEM foils stretching, short circuits,….etc.
- 6-layer ME0 stack modules preparation assistance.



6-layer ME0 stack preparation in b904 CERN

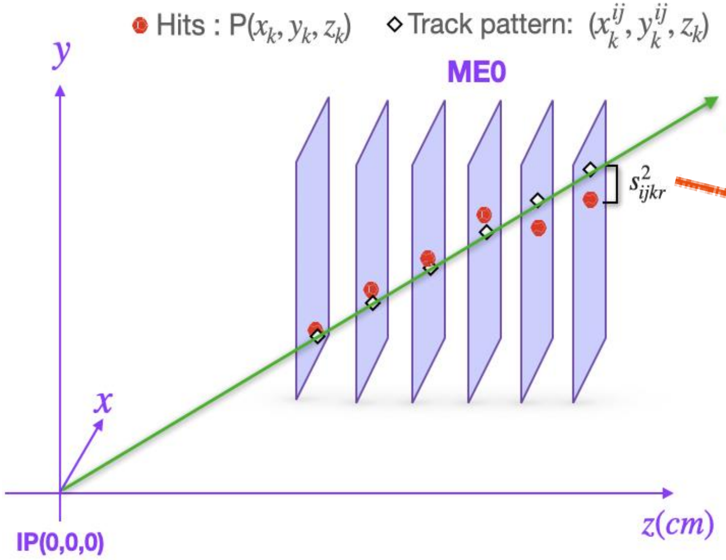
Fast Track Finder for ME0 Level1-Trigger

- A dedicated **Fast Track Finder (FTF)** algorithm "*Artificial Retina*" is being developed for the CMS ME0 Level-1 trigger, 6 layers of triple-GEM chambers, to maintain efficient triggering at the HL-LHC, implemented for the first time in CMS.

Aya Beshr
Isabelle De Bruyn

Retina algorithm for track reconstruction:

- pattern recognition algorithm inspirited by biological visual mechanism.
- each track is identified by two parameters (p, q) & the coordinates of the intersections of the track with the detector layers are $y_k(p, q)$, where k = detector layer.



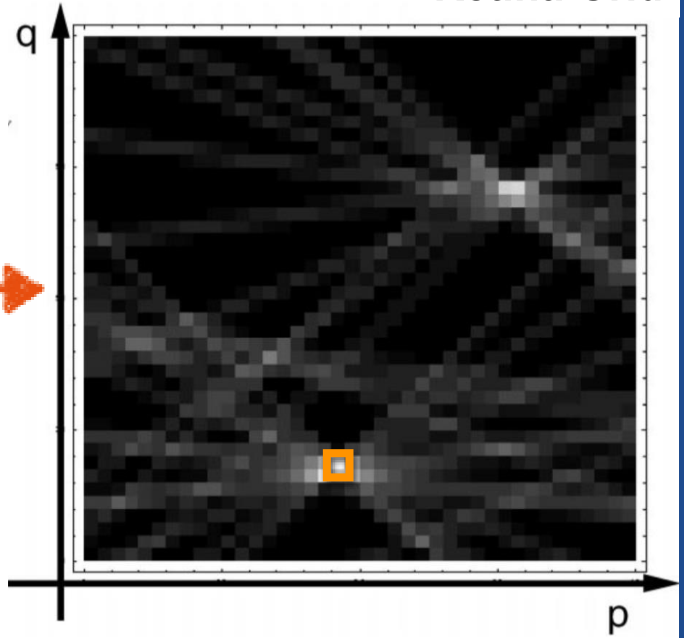
For each event, following quantities are computed:

$$R_{ij} = \sum_{k,r} exp(-\frac{s_{ijkr}^2}{2\sigma^2}),$$

where $s_{ijkr} = x_r^{(k)} - y_k(p_i, q_j)$

meaning the intensity of the response.

Retina Grid



Fast Track Finder for ME0 Level1-Trigger

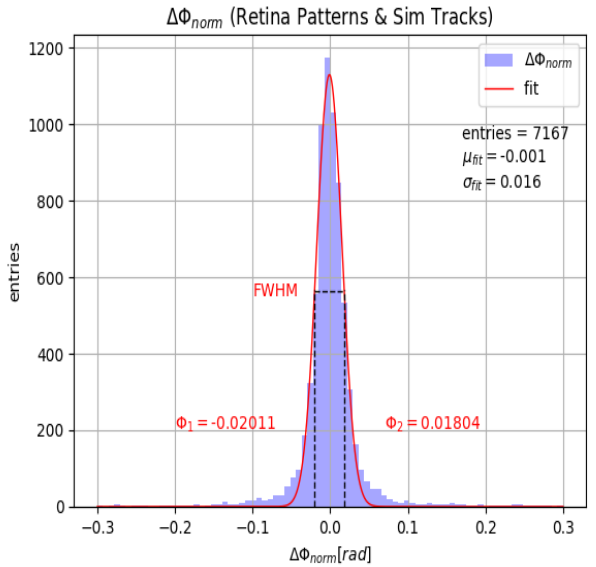
Aya Beshr
Isabelle De Bruyn

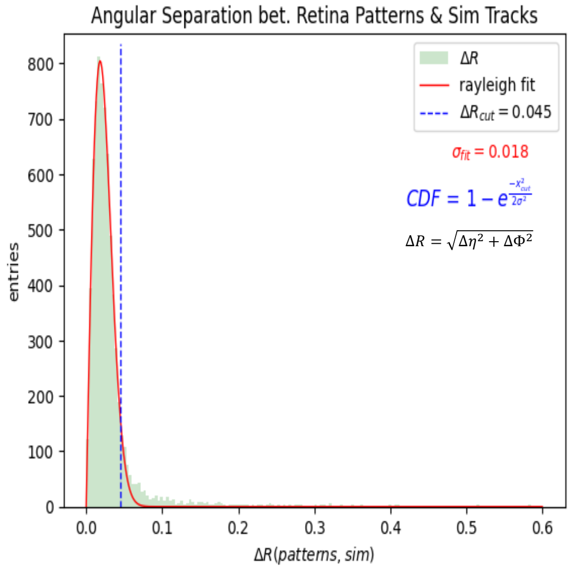
- **Retina grid** built up by CMS Simulated Muons tracks for ME0 samples, total number of cells = 8,192.
- Workflow:

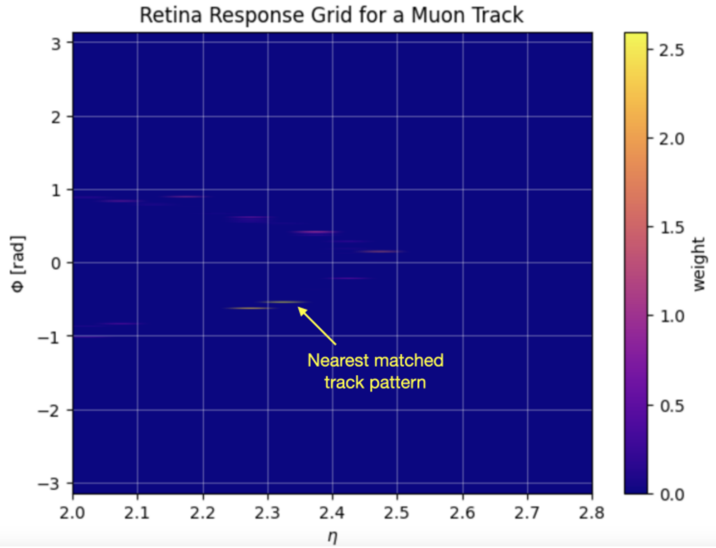
Using different Sim Muons Sample with 8 muons/Event → Find Total nSimTracks with 4-6 Hits → Pass corresponding SimHits to Retina Algo & find best matchingTrack Pattern (weight at global maxima) → Match Track Pattern & Sim Track wrt ΔR (Better resolution in ϕ) → Calculate Retina Efficiency

- Retina Efficiency:

$$\epsilon_{retina} = \frac{Number of Matched Patterns}{Total Number of Sim Tracks} = \frac{6154}{7167} \times 100 \approx 85\% \text{ (preliminary)}$$





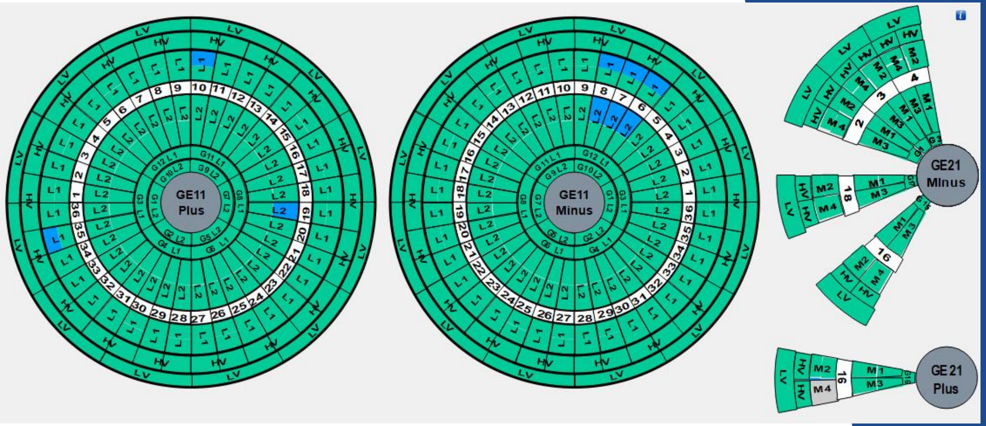


CMS-GEM Detector Control System

Isabelle De Bruyn
Yanwen Hong

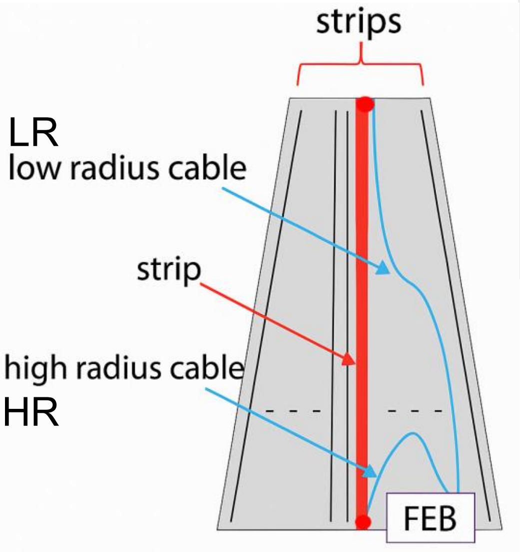
- Detector Control System (DCS): a distributed control system that monitors and controls the various operational parameters and services of each detector part.
- An automation technology, WinCC OA (SIMATIC WinCC Open Architecture), a SCADA (Supervisory Control and Data Acquisition) framework, is used in the DCS development.

1. **Maintenance of current GEM DCS:**
   debugging, patching, operational support.
2. **Extend DCS covering newly installed GE2/1 chamberslast winter:**
   update components UI (User Interface), Gas, CAEN, FSM, and Detector Protection.
3. **Development of a new GEM DCS project:**
   a scratch-built, feature-rich, more efficient platform capable of controlling GE1/1, GE2/1, and ME0, targeted for production testing at CMS in 2026.
4. **Expert-on-call shift:**
   real-time operations support with immediate response to alerts and phone calls, through CERN Phone Mobile application.



CERNphone mobile

CMS - iRPC Hit Reconstruction



- New CMS iRPCs give a better spatial and time resolution. By measuring the time difference between the signals at both ends of the readout strips, this helps in resolving ambiguities in the endcap trigger for multiple tracks.
- Two readout strip end: low radius (**LR**) and high radius (**HR**).
- Clustering is needed to reconstruct a muon from multiple hits.

Juhee Song

iRPC Digi

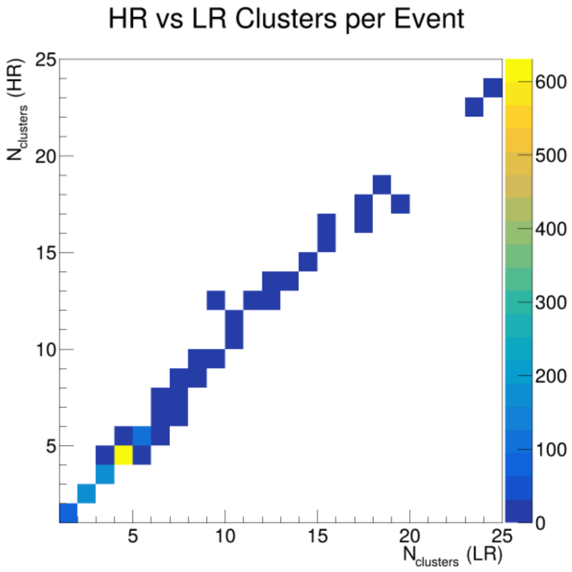
Single muon simulation sample (5000 events), iRPC hits' time are registered.

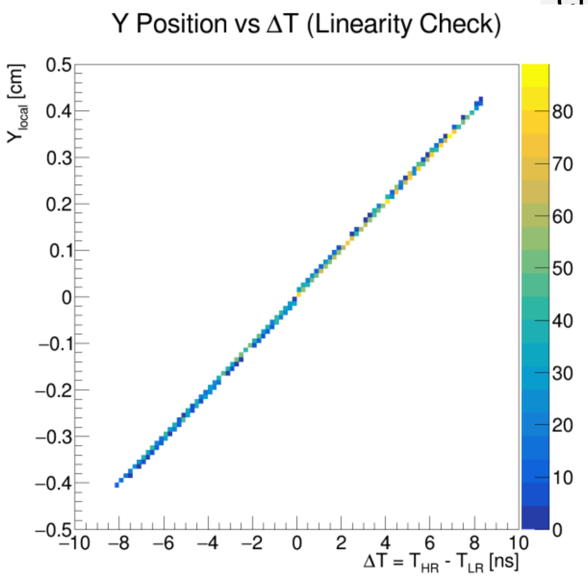
iRPC Cluster

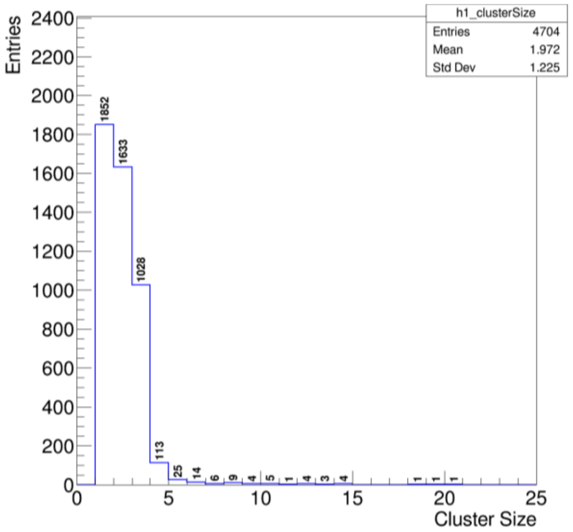
One-side cluster: cluster HR/LR separately, combine strips if $|\Delta T\_strips| < 3$ ns.
Final cluster: merge one-side HR+LR clusters when $|\Delta Strip|<0.9$ to finalize.

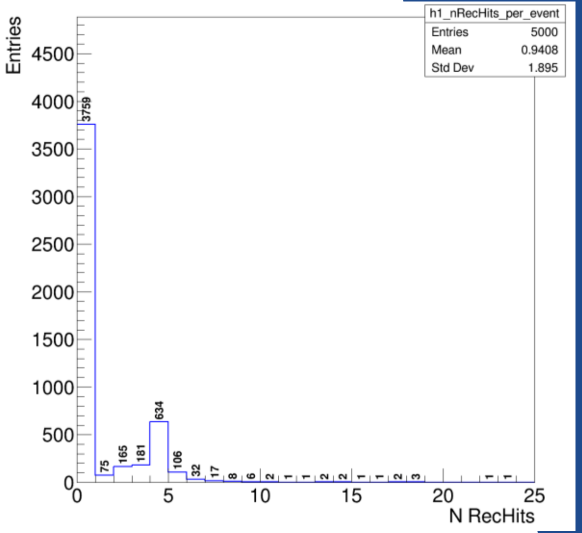
iRPC RecHit

Produce iRPC RecHits from the time and position of the final iRPC Clusters.









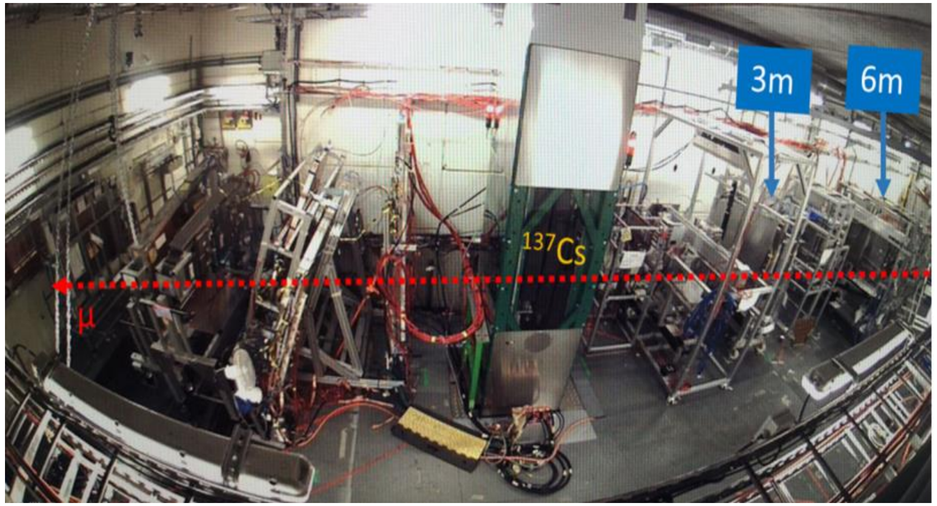
CMS-RPC EcoGas Study

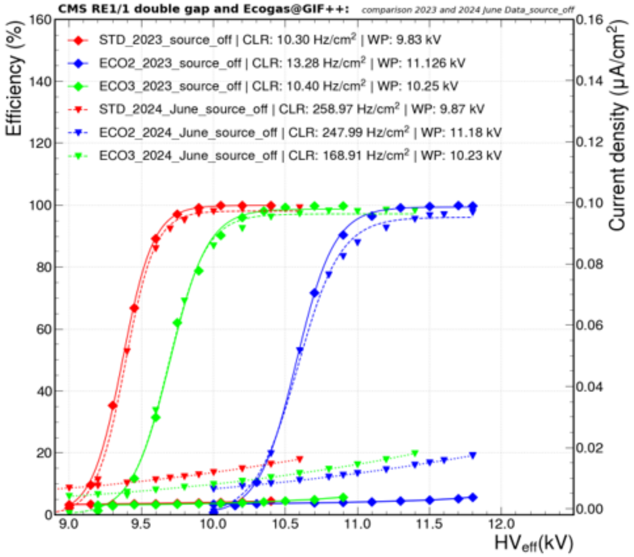
Donya Ahmadi

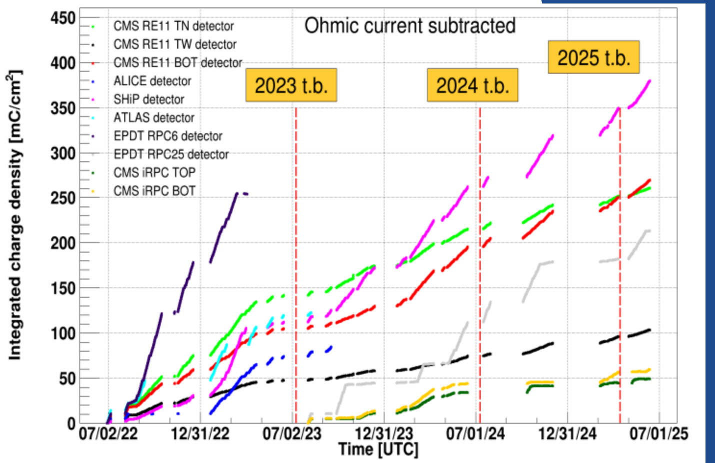
- The standard RPC gas mixture contains fluorinated greenhouse gases, R134a and SF_6 ,with very high GWP (Global Warming Potential). R134a ≈ 1430, SF_6 ≈ 22,800, while CO_2 = 1.
- Rising costs and reduced availability in Europe, combined with CERN's commitment to cutting direct greenhouse gas (GHG) emissions.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

	R134a (%)	HFO-1234ze (%)	CO_2 (%)	IC_4H_{10} (%)	SF_6 (%)	GWP	CO_2e (g/l)
STD	95.2	-	-	4.5	0.3	1485	6824
ECO2	-	35	60	4	1	476	1522
ECO3	-	25	69	5	1	527	1519

- Study under CERN Gamma Irradiation Facility GIF++ (12.5 TBq ^{137}Cs source + 150 GeV/c muon beam).
  - Performance comparison between 2023/24 data and ECO.
  - Integrated charge of all chambers measured for aging studies.





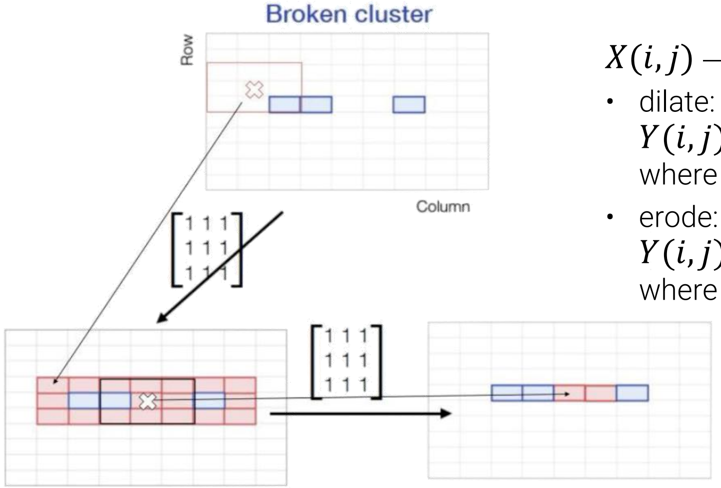


CMS Tracker: Digi-morphing for HLT

Chirayu Gupta
Saranya Nandakumar

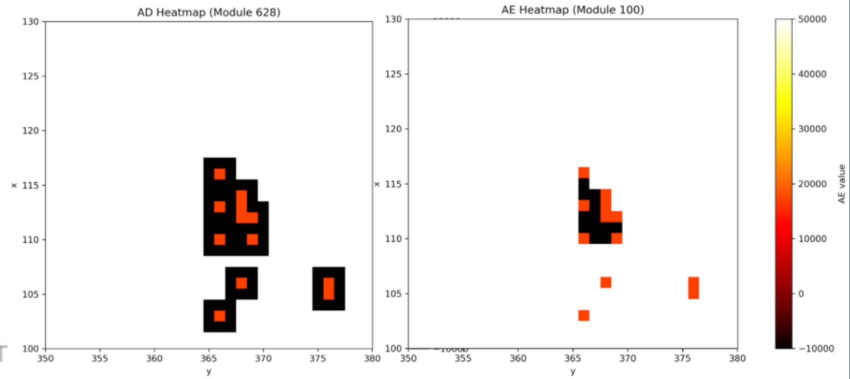
- Significant radiation damage is expected in the remainder of Run 3 for silicon sensors in the CMS pixel detector.
- Loss of pixels -> decrease of charge collection efficiency:
  - Pixels missing inside clusters → split or broken clusters
  - Pixels missing at end of clusters → shorter clusters
- Consequence: off-track clusters, fake/duplicate tracks, reduced resolution, and large hit position bias.

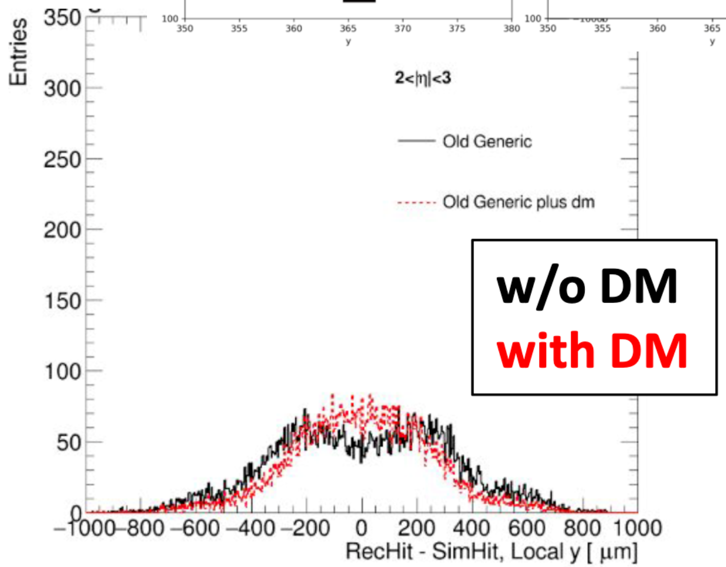
- Solution: An image morphing-based **"closing" technique to reconnect fragmented clusters**.
  - Algorithm operates directly at pixel (Digi) level; offline and High-Level Trigger (HLT) versions (GPU).
  - Employ convolution operations using **dilate + erode** kernels to insert "extra pixels" into broken pixel clusters.



$X(i,j) \rightarrow Y(i,j)$

- dilate:
  $Y(i,j) = maxX(i+k, j+l)$ for all (k,l)
  where $M(k,l) != 0$ in a kernel M
- erode:
  $Y(i,j) = minX(i+k, j+l)$ for all (k,l)
  where $M(k,l) != 0$ in a kernel M

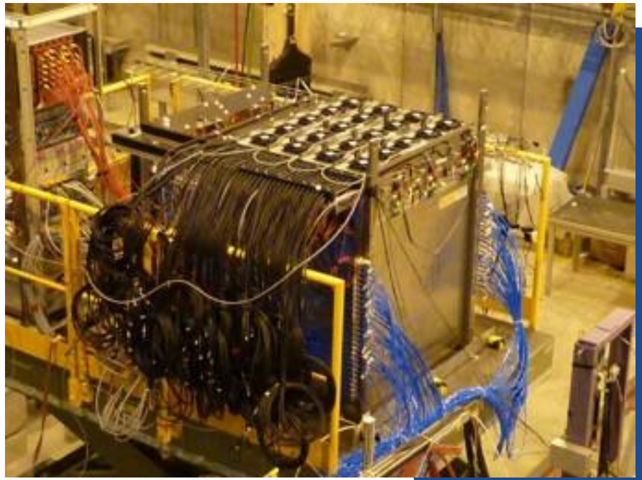


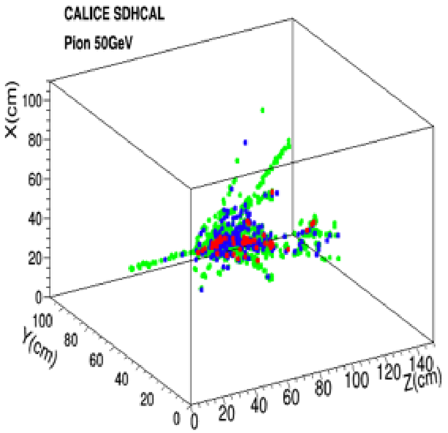


From CMS to Future Colliders

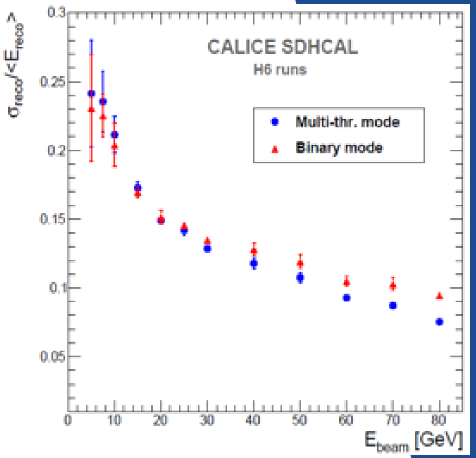
RPC-based Calorimeter

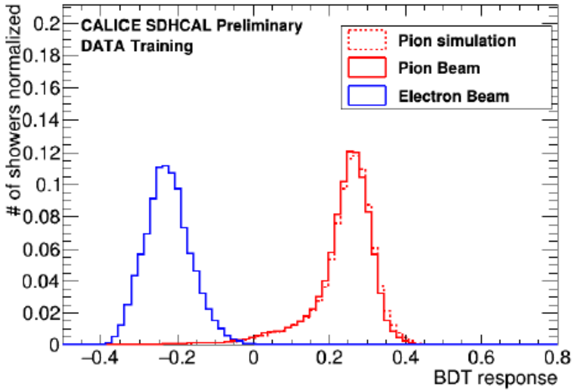
- Semi-Digital HCAL (SDHCAL) is
  - a gaseous detector-based (glass-RPCs), highly-granular option for an HCAL based on PFA.
  - part of the International Large Detector (ILD) baseline detector option, originally proposed for ILC/CEPC, and now also proposed for FCCee.





- SDHCAL was originally developed inside CALICE Collaboration:
  - sampling calorimeter, i.e. stainless steel absorber alternated with single-gap glass resistive plate chambers.
  - 48-50 layers (-6λI); ~1.3m3 prototype.
  - 1 cm x 1 cm readout granularity with pads; ~450k channels (more than full CMS calorimeter system already …).
  - 3-threshold readout with 64-ch HARDROC ASICs.
  - Triggerless DAQ system using power-pulsing scheme tailored to ILC (to be modified for FCCee).
  - Self-supporting mechanical structure made with stainless steel plates.
  - Collaborators mainly from France, Spain, Belgium, Korea, China.





VII

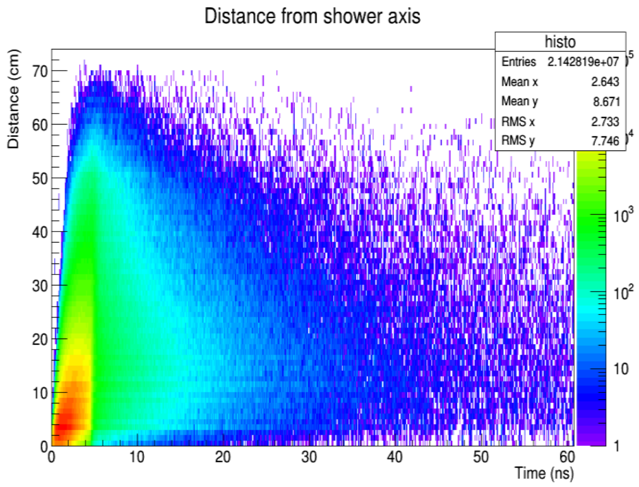
RPC-based Calorimeter

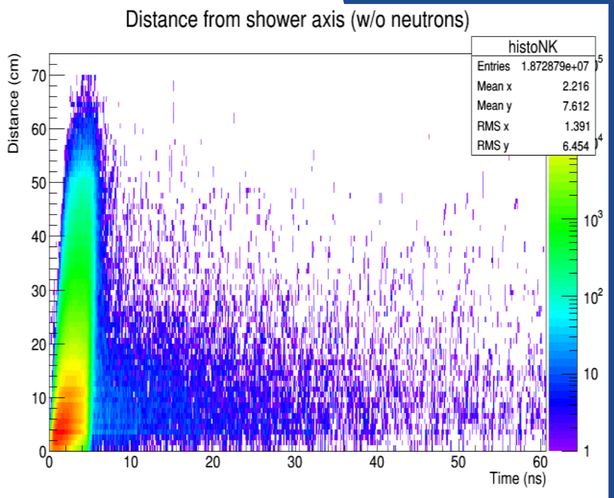
New (wo)manpower needed

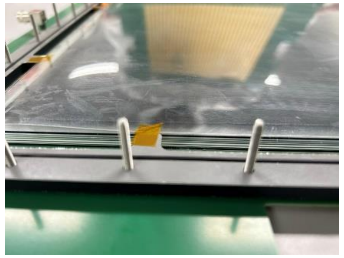
- Next step: Timing-SDHCAL (5D calorimetry) i.e. timing capabilities of calorimeter systems open up new possibilities for TOF, LLP, shower reconstruction ...; hadronic showers show a complex time structure, with late components connected to neutron-induced processes; e.g. 100ps timing precision could aid in shower energy reconstruction and shower separation.
  - → replace single-gap RPCs in SDHCAL with **advanced 100ps multi-gap RPCs**; R&D on:
- **large-area detectors** for ILD-like concept
- **optimization of timing precision**, rate capability (new materials ?)
- **new front-end electronics**, i.e. high time precision + continuous readout for circular colliders
  - → baseline: **Petiroc ASIC**
  - future: **LIROC ASIC + PicoTDC**
- **new detector cooling system**

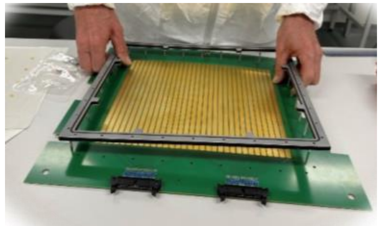
Reference: M. Tytgat et al., *Towards the T-SDHCAL hadronic calorimeter for a future Higgs factory*, NIM-A 1077 (2025) 170520

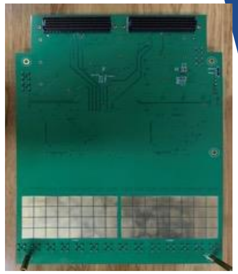
Separate delayed neutrons for better energy reconstruction











Embedded in DRD1/6 and ILD Detector Concept collaborations

Other R&D Projects and Applications

Instrumentation Topics

Medical Applications

VIII. Dosimetry for FLASH Proton Therapy

Muography Detector R&D and Applications

IX. THick-GEM

X. Portable Muoscope

XI. Scintillator Telescope

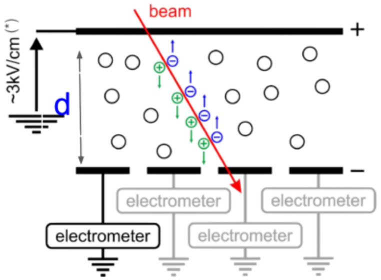
XII. ScIDEP Project at Egyptian Pyramid of Khafre

XIII. MURAVES Experiment at Mt. Vesuvius

Dosimetry for FLASH Proton Therapy

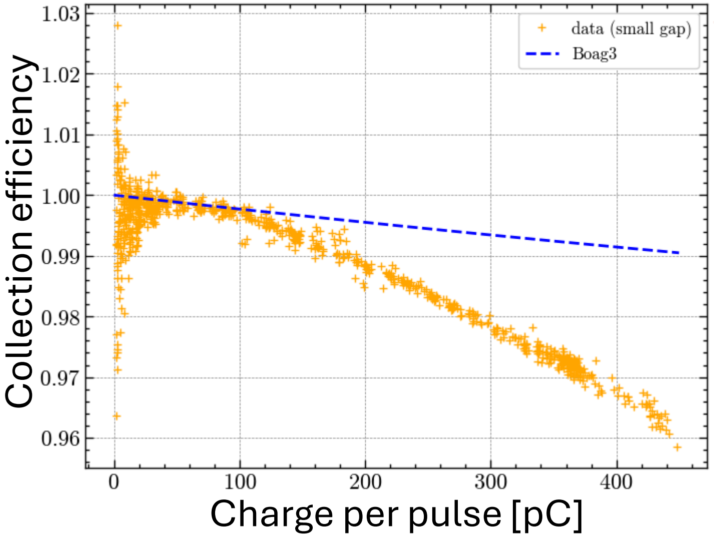
Pierre Gérard Ortega
Indrani Jayam

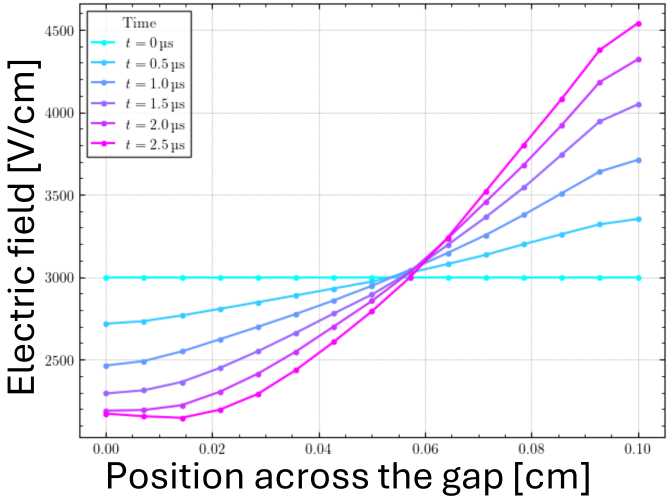
- FLASH Proton Therapy: 10x higher doses (> 40 Gy/s) compare to conventional, with less effect on healthy tissues.
- Real-time dose measurement with high precision is challenging:
  high charge density -> ion recombinations -> Ionization Chambers (IC) collection efficiency loss -> dose underestimation.

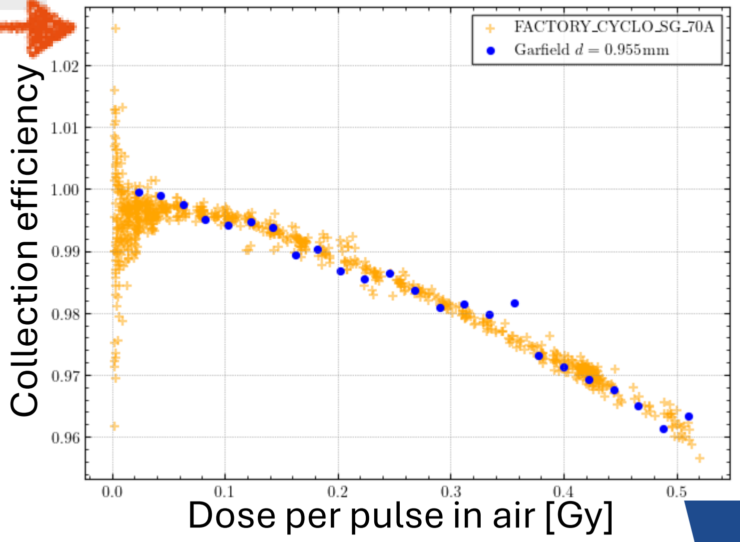


- Theoretical Boag Model works well at low doses per pulse not anymore at ultra-high dose per pulse (UHDR).

- Using Garfield++ feature Magboltz for computing:
  - effect of the **space charges** and the distortion of the field inside the chamber.
  - free electron fraction



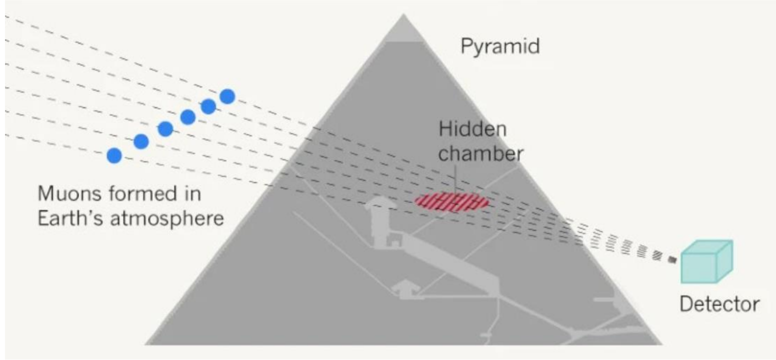




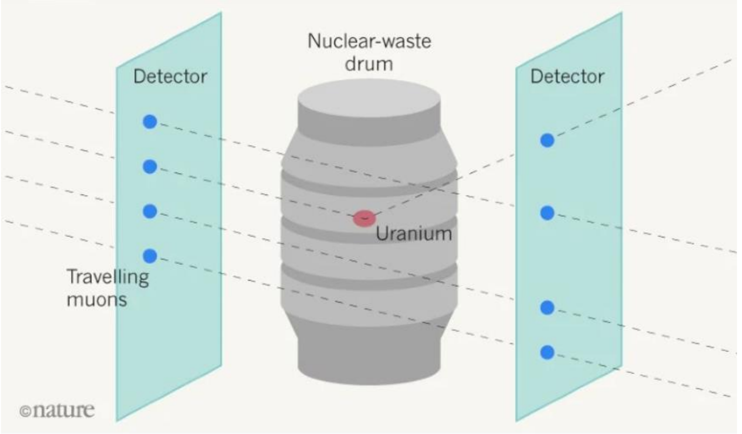
Muon Radiography

- Muon Radiography (Muography) is an 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 incident muon flux



- Scattering muography measures the angular deflection of muons caused by interactions with atomic nuclei in the matter.
  - sensitive to atomic number
  - small to medium size targets
  - 3D image.
  - high position resolution, large area detectors

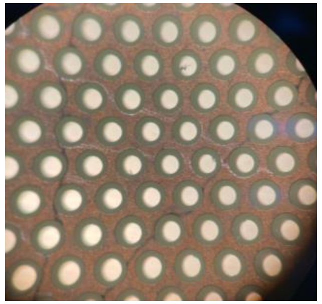


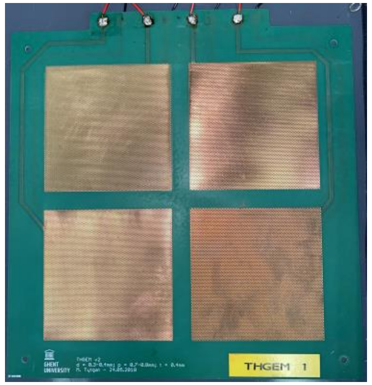
- Common detector technologies for muography:
  - Plastic scintillators
  - Nuclear emulsions.
  - Gaseous detectors (MWPC, MicroMegas, RPC …)

THick - GEM

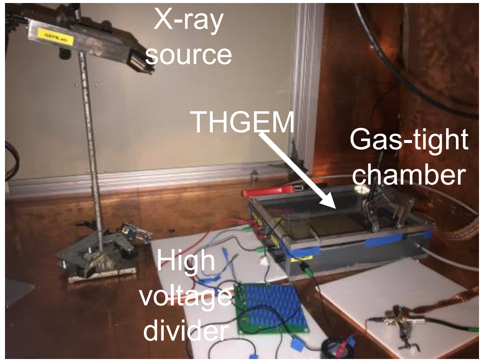
Yanwen Hong

- Like standard GEMs, THick GEM (**THGEM**) use an internal hole-based gas avalanche multiplication mechanism.
- particularly interesting for muography applications:
  - mm-size amplification hole structure by mechanical drilling in regular Printed Circuit Boards.
  - spatial resolution: 100 μm
  - operated at moderate HV with simpler gas mixtures or even mono-gases.
  - robust and economical.



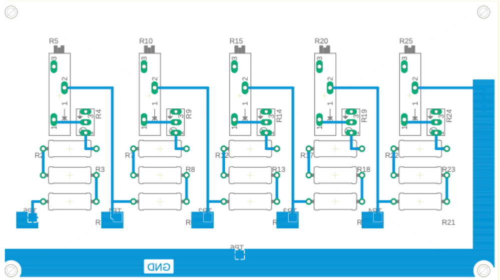


- Preliminary detection of the X-ray signal



- Cosmic Muon detection setup in VUB lab, with 2 PMTs as triggers.
- Ongoing R&D:

- Fabrication a low-mass entrance window for the detector enclosure.
- Selection of readout strip line termination R_T

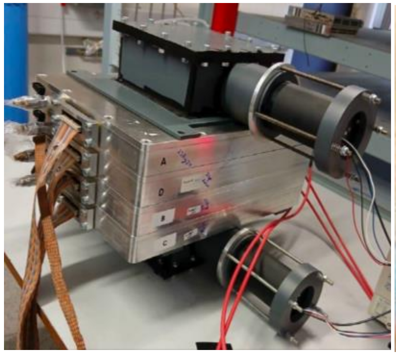


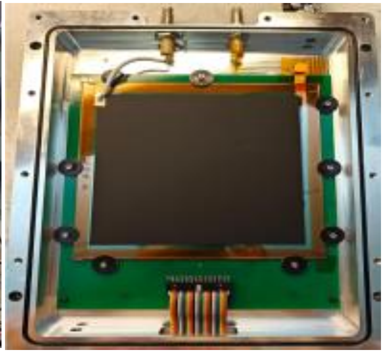
- Cleaning of oxidation of PCBs
- Optimisation of Voltage divider

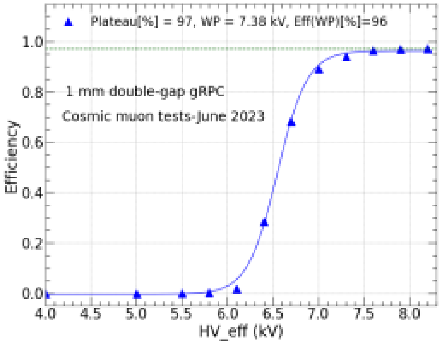
Portable Muoscope Project

- **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.
- Collaboration VUB-UCLouvain

- Portable Muoscope:
  - single/double-gap glass-RPC based muon telescope.
  - design featured by compactness, portability, robustness, autonomous operation, low power & gas consumption, modular geometry.



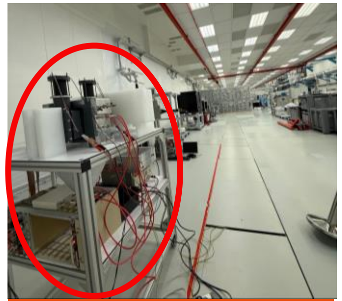




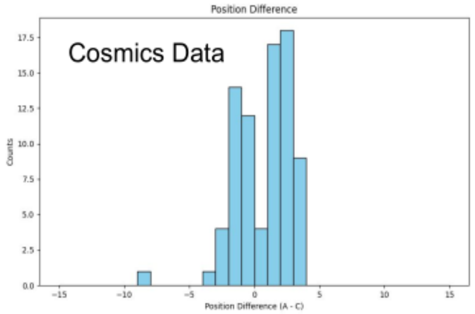
Donya Ahmadi

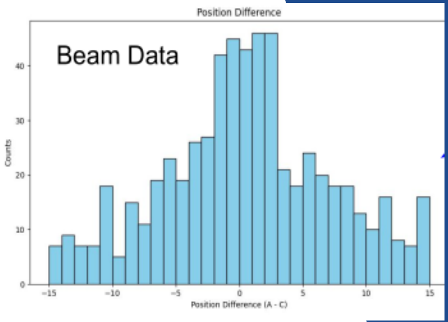
- Test Beam @ELI:
- ELI Laser-Driven Muon Source: Compact (<100m2) GeV muon production driven by laser electron acceleration at ELI (Extreme Light Infrastructure) Beamlines laser centre (near Prague, Czech Republic).

- First muon source users at ELI. Data taking in April-May and August 2025; data analysis ongoing.



Experimental Set-up





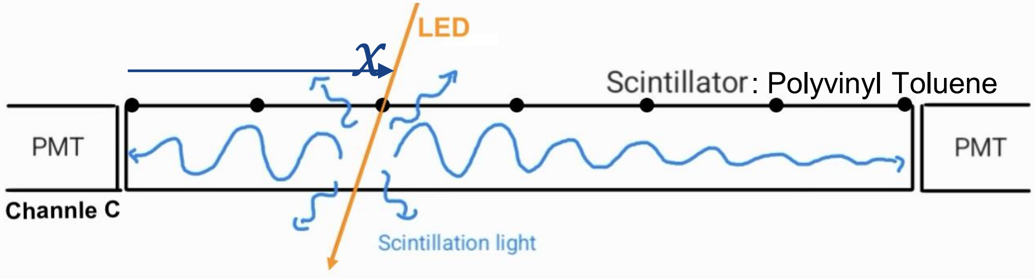
Construction new Scintillator Telescope

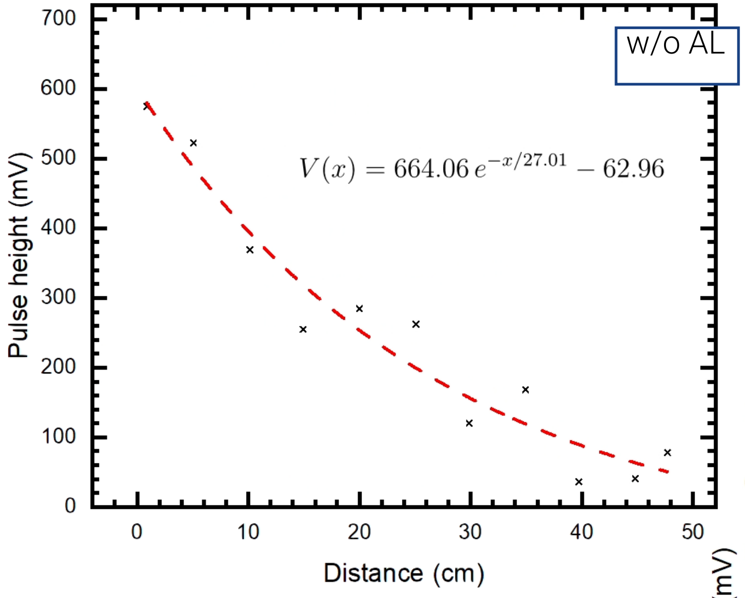
Zhe Wang

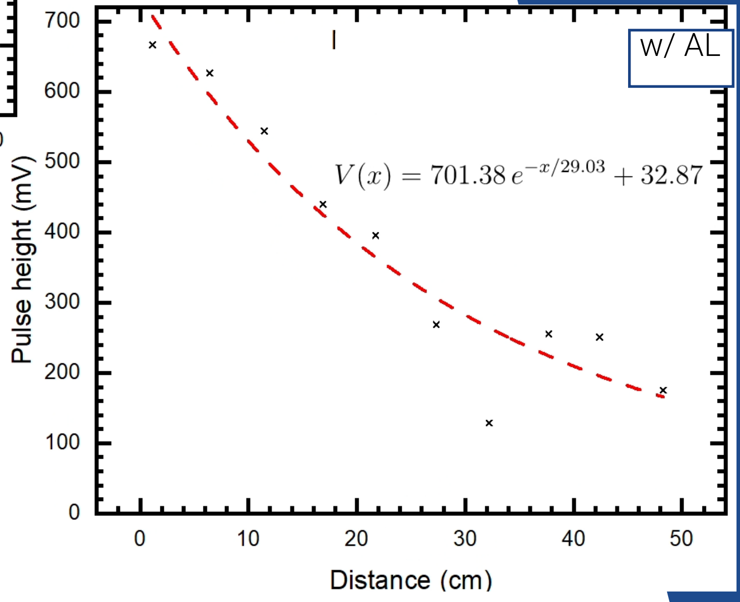
- Scintillator light attenuation in scintillator material: The number of photons decreases exponentially as they travel along the bar due to absorption and scattering:

$$N(x) = N_0 e^{-x/\lambda}$$

- A reflective wrap, e.g. Aluminum foil, helps to redirect photons, reduce photon loss and improve the light collection efficiency at the PMTs.
- Reflective Wrap: Aluminum foil (5 nm).
- LED light is injected into the scintillator bar at equidistant holes.







- The reflective wrap **aluminum foil provides improvement** in light loss throughout the scintillator bar.

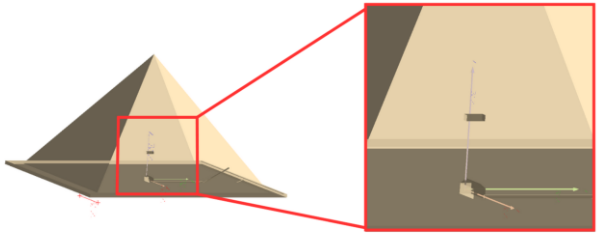
ScIDEP Project at Egyptian Pyramid of Khafre

- ScIDEP = Scintillator Imaging Detector for Egyptian Pyramids (Collaboration VUB, USA, Romania, Egypt)
- In this study, develop a simulation pipeline to assess the detection of hidden voids in Pyramid of Khafre.

Zhe Wang
Dora Geeraerts

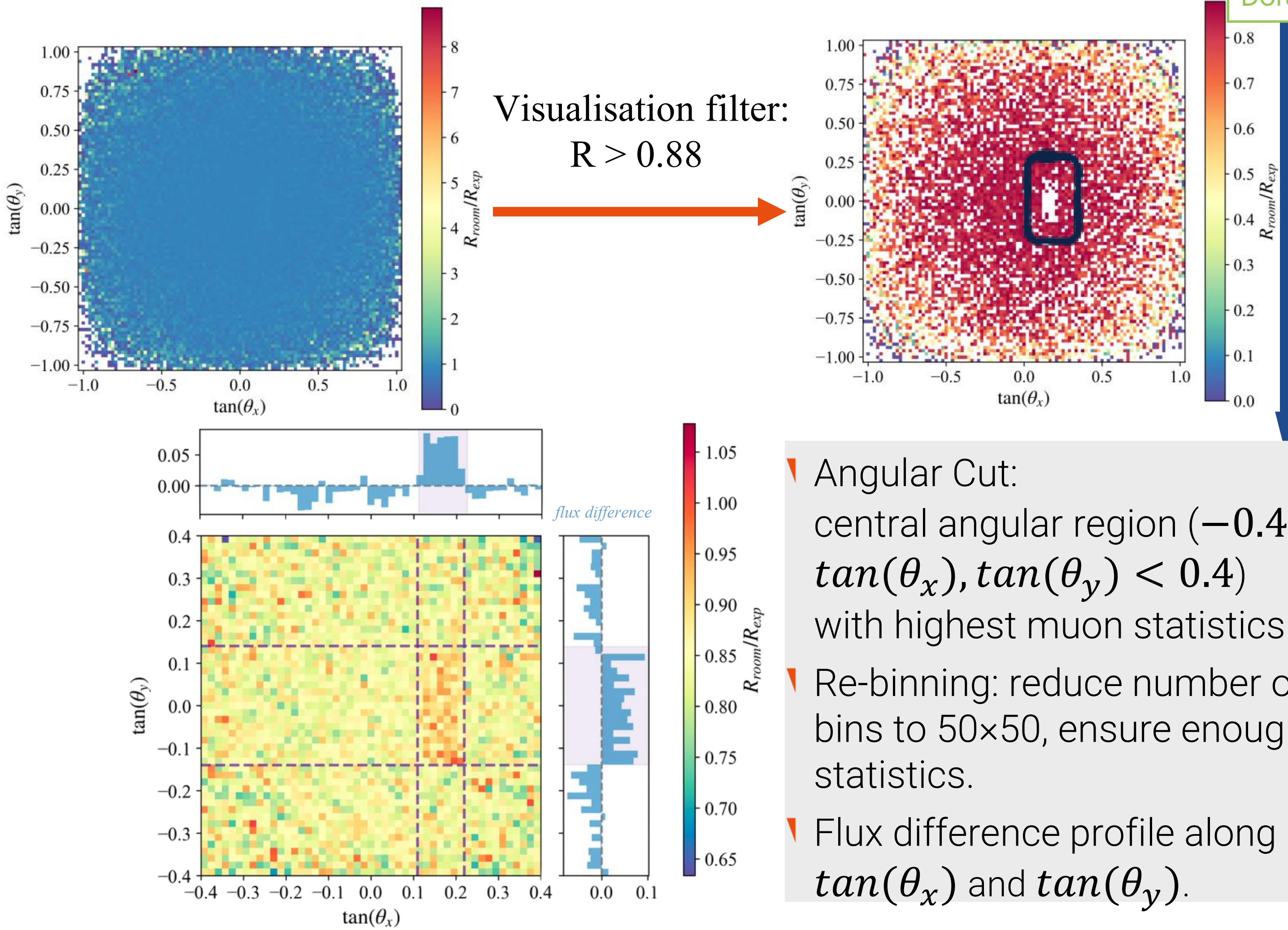
Methodology:

- Simulation framework:
  - Cosmic Muon Generator: **EcoMug**
  - Pyramid & Detector Model: **Geant4** a detailed 3D model of the pyramid, including a known internal chamber and a hypothetical hidden void.



- Track Reconstruction: a novel track reconstruction algorithm based on **Hough Transform** and **DBSCAN clustering**. High efficiency (>99.8%).
- Relative transmission map:

$$R(\theta, \phi) = \frac{T_{withchamber}}{T_{withoutchamber}}$$

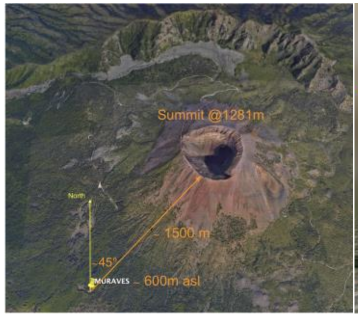


- Angular Cut: central angular region ($-0.4 < tan(\theta_x), tan(\theta_y) < 0.4$) with highest muon statistics.
- Re-binning: reduce number of bins to 50×50, ensure enough statistics.
- Flux difference profile along $tan(\theta_x)$ and $tan(\theta_y)$.

MURAVES Experiment at Mt. Vesuvius

Yanwen Hong

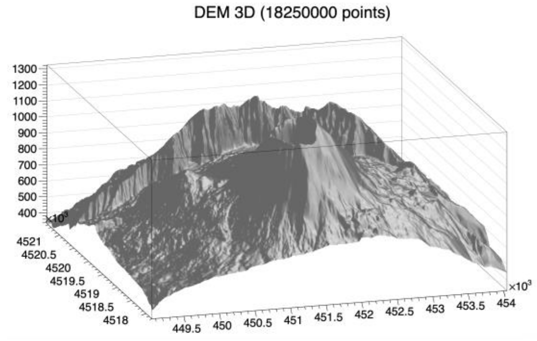
- The **MURAVES** (MUon RAdiography of Mt. VESuvius) experiment aims to apply muon radiography to the summit of the Vesuvius; collaboration VUB, UCLouvain, INFN
- The detectors are located 1500m away from the volcano crater and ~ 600m asl.
- Each muon tackers has 4 planes of 1m^2 active area, a 60cm of lead block in between two downstream planes. Each layer composed of 64 triangular adjacent scintillator bars.

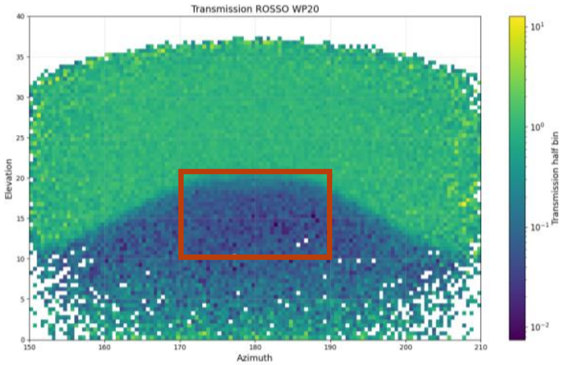


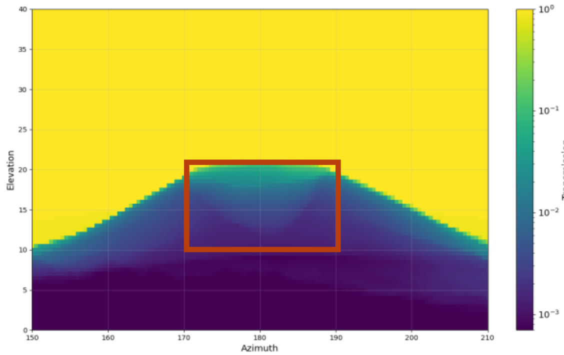
- Refining data analysis:
  - ~ 400 h more data are being organised and added to the analysis.
  - χ^2 - based criteria for Golden track selection.
  - Unit conversion between steradian and deg^2

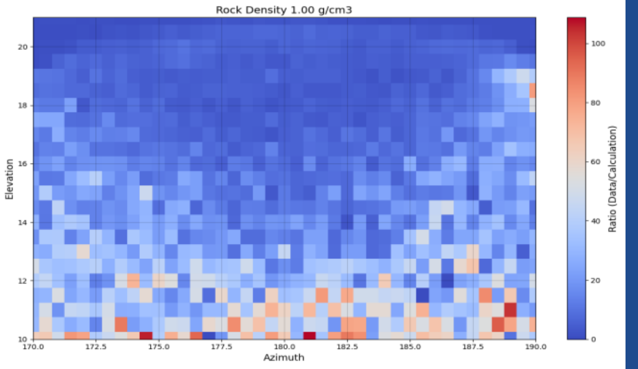
- Simulation of muon transport through Mt. Vesuvius:
  - TURTLE: utilities for the long range transport of Monte-Carlo particles through a topography.
  - PUMAS library: transport muon or tau leptons in matter by forward or backward Monte Carlo.

- Transmission: $$T(\theta,\phi) = \frac{N_\mu^v(\theta,\phi)/\Delta t^v}{N_\mu^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^v \cdot S_{eff}(\theta,\phi)\int_{E_{min(\rho)}}^{\infty}\Phi(\theta,\phi;E)dE}{\epsilon^{fs}\cdot S_{eff}(\theta,\phi)\int_{E_0}^{\infty}\Phi(\theta,\phi;E)dE}$$
- Relative Transmission: $T_{relative} = \frac{T_{Data}}{T_{Simulation}}$ for density extraction









Funding

- Current funding for detector R&D projects remains relatively limited; the past few years mainly yielded:
- Muography (Muraves)
  - 1 European H2020 network project -> travel money
  - 1 FNRS-FWO Weave project (UCLouvain-VUB) -> 2 PhD students, Dora and Adithyan, starting Jan. 1, 2026

- Medical applications:
  - support from ProtherWal

- Future Colliders (FCC):
  - 1 SNSF-FWO Weave project (UZurich-VUB) -> 2 PhD students, Eduardo and Kunal

- Equipment:
  - Small amounts from FNRS/FWO/university funds

- More applications in the pipeline …

Thank You for your Attention!