Gas-Tight RPCs for Portable Muography: Development, Performance, and Application

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Muography

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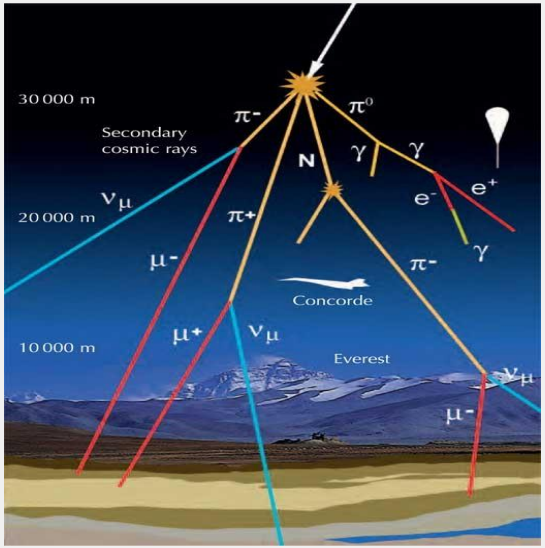
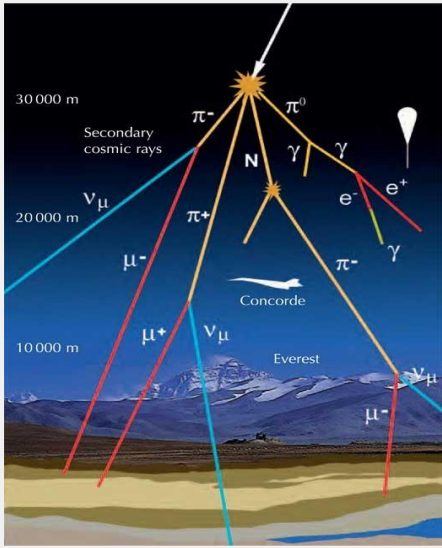
  - Most penetrating part of the cosmic shower
  - At sea-level, cosmic muons have an average energy of roughly 4 GeV and their flux is around 1 muon sr^{-1} cm^{-2} min^{-1}.



Source: Alberto Izquierdo; courtesy of Francisco Barradas Solas, Science in School)

Muography

An imaging technique that utilizes naturally occurring cosmic-ray muons to probe the internal structure of large-scale objects.



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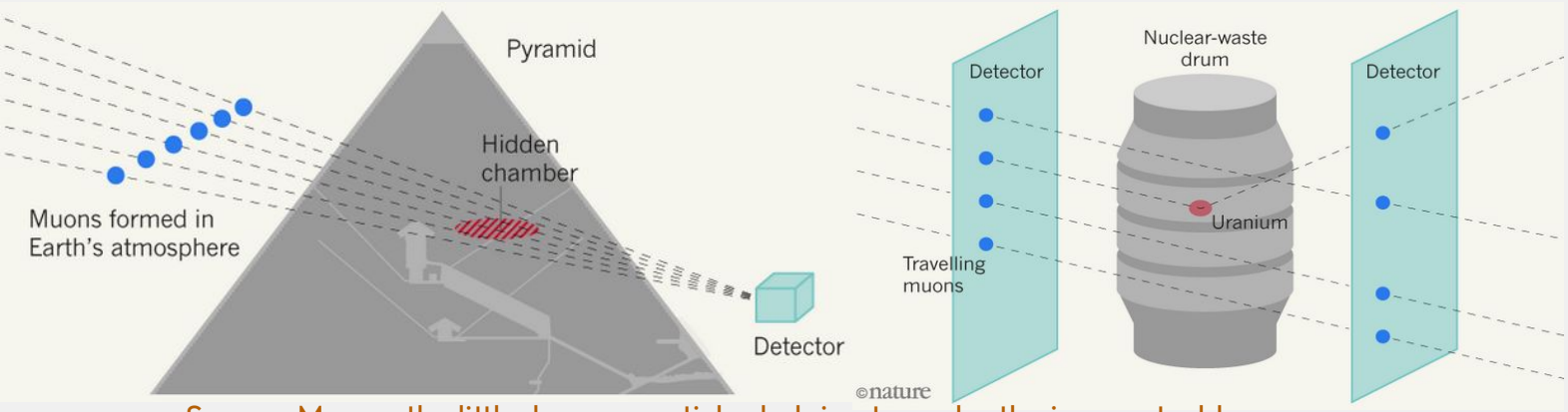


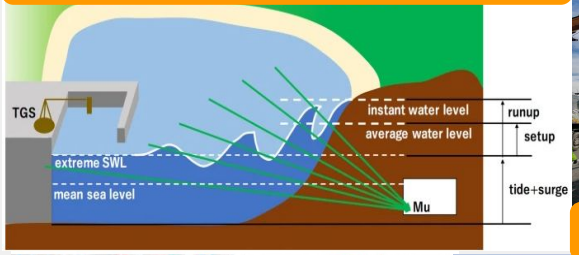
Source: Muons: the little-known particles helping to probe the impenetrable

Applications

Muography has found various applications in different fields, such as:

- Volcanology,
- Archeology,
- Mining explorations,
- Civil infrastructure integrity checks,
- Cultural heritage studies,
- Industrial safety,
- Cargo Inspection

Conceptual view of muography for tide monitoring.



Silent Border Tomograph

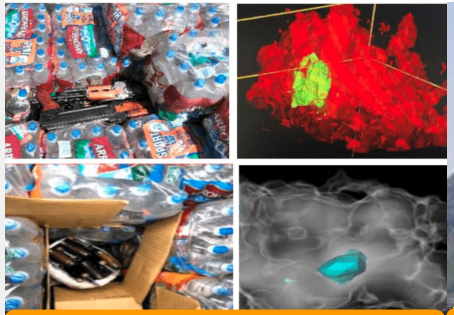
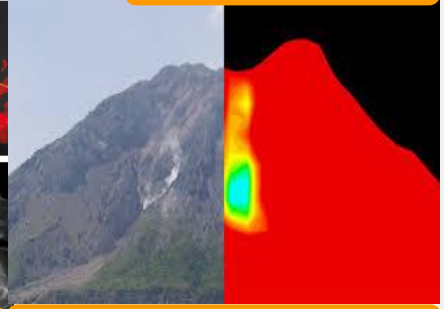
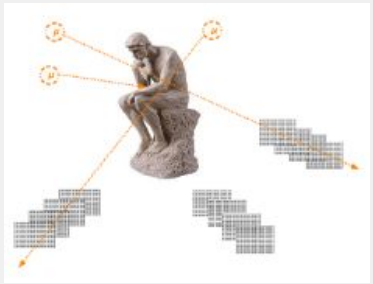


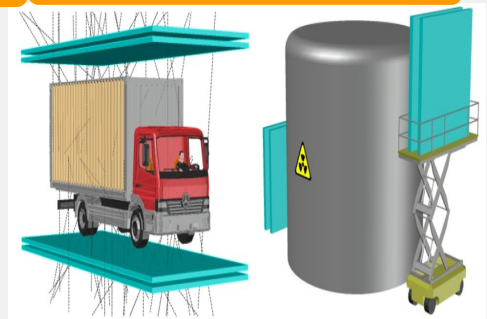
Image of weapons using Discovery Scanning system



Muon Radiography of Mount Asama

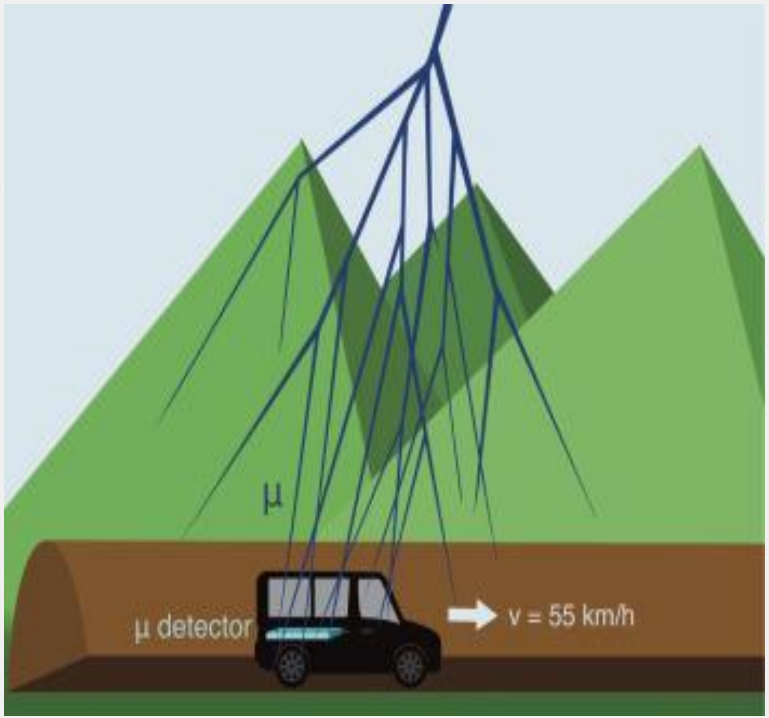


Cultural Heritage Imaging



Left: Cargo Inspection, right: Nuclear Storage inspection.

Development of a portable particle detector



Credit: Real-time portable muography with Hankuk Atmospheric-muon Wide Landscaping : HAWL

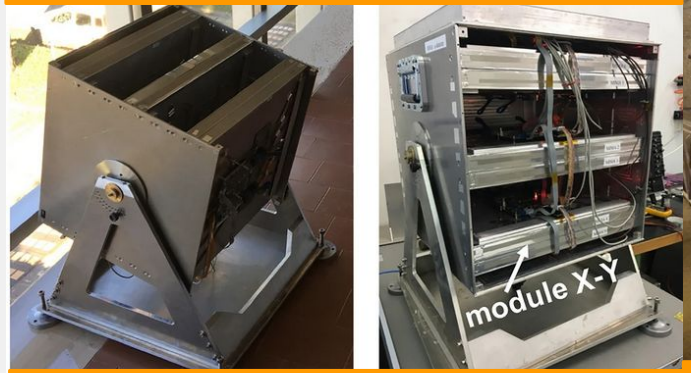
Motivation

Portable muon telescopes are mainly used for experiments conducted in confined or restricted environments.

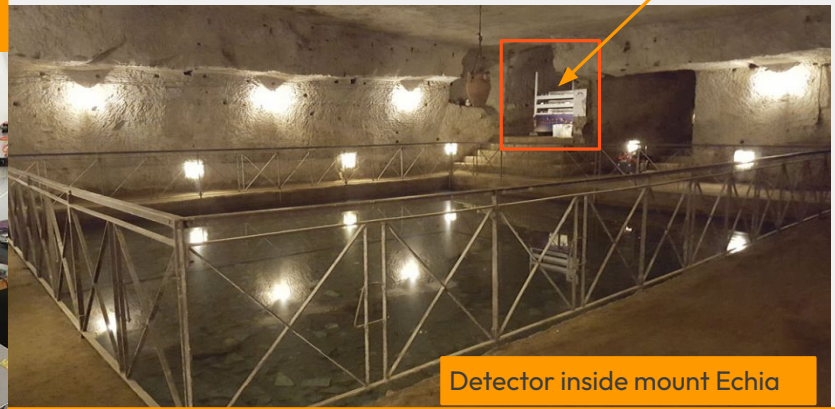
The design goal of the detector includes:

- ➔ Portability
- ➔ Autonomous Operation
- ➔ Gas Tightness (In gaseous Detectors)
- ➔ Robustness
- ➔ Modular Geometry
- ➔ Safe and Cheap

The MIMA muon tracker employed for the muon radiography measurements in the Temperino mine.

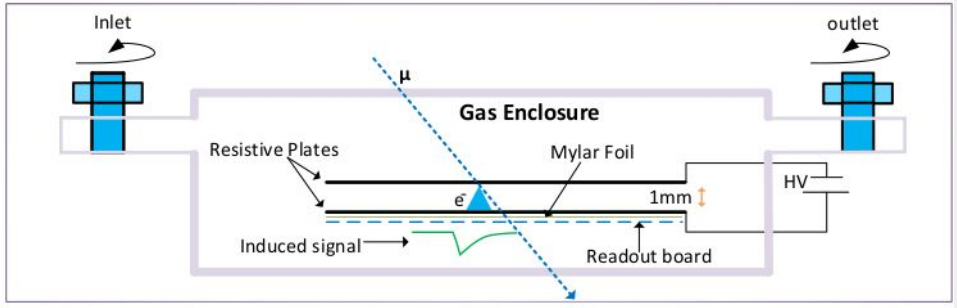


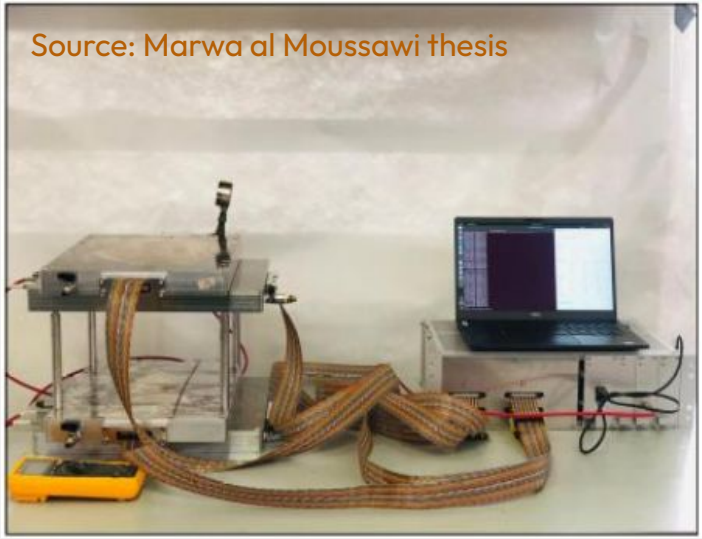
Three-dimensional muon imaging of cavities inside the Temperino mine (Italy): Scientific Reports 22329 (2022)



Saracino, G., et al. "Applications of muon absorption radiography to the fields of archaeology and civil engineering." Philosophical Transactions of the Royal Society A 377.2137 (2019): 20180057.

Resistive Plate Chambers




Source: Marwa al Moussawi thesis

An ionizing particle passing through the gas gap and creating an electron avalanche towards the anode in RPC.

- **ADVANTAGES**
  - Large chamber sizes
    ➔ low price
    ➔ easily fabricated
    ➔ transported
  - Good intrinsic spatial resolution <100 μm.
  - Excellent timing resolution (<50 ps).
  - Already used in muography, but with large areas (e.g. volcanology)

The concept of a gas-tight RPC is relatively novel and introduces several challenges:

- Acceleration in polymerization on the detector surface
- Variations in the homogeneity of gas mixture over time.
- Increased discharge probability

- Stability in environmental parameters—including temperature, humidity, and pressure variations as well as in the high voltage (HV).

Glass Painting ,Chamber Assembly And Performance Analysis

Glass Painting

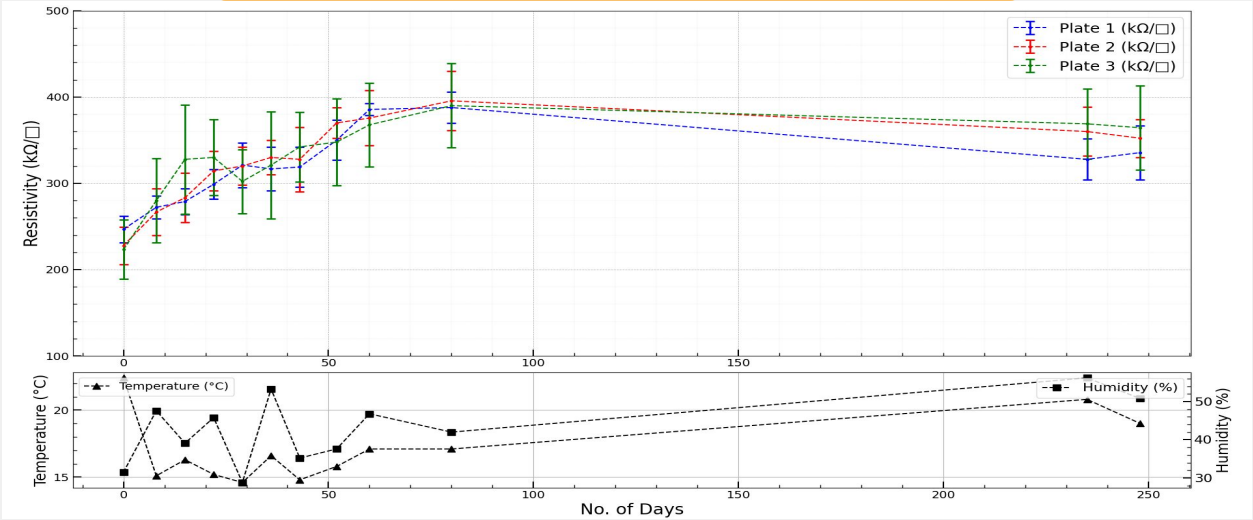
- The RPCs are constructed using glass plates of thickness 1.1 mm and an active area of 16 x 16 cm^2 coated with resistive paints with a surface resistivity ranging from 0.5 to 1.0 MΩ / □.

- To calculate Mass Ratio of resistive and conductive paint , relation: $r_c = \frac{m_r}{m_c + m_r}$

Screen Mesh used for coating

Glass Plate after coating

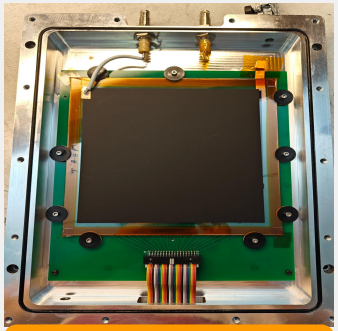
Temporal evolution : average surface resistivity and external measurements of temperature and humidity.



Performance Testing

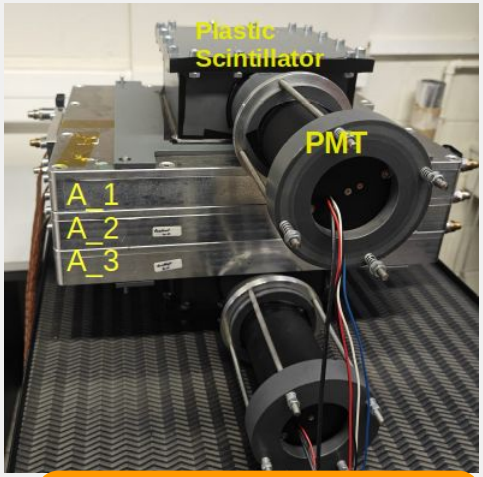
- After detector assembly, filling with gas, verify leak current and Optimizing High Voltage.

Active Detection Component
CMS Gas mixture (C2H2F4 – 95.2%, SF6 – 0.3% and i-C4H10 -4.5%)



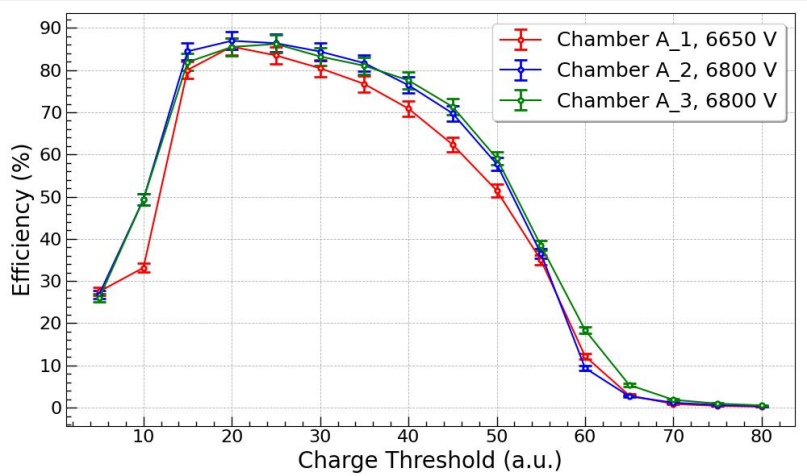
Assembled Chamber before gas filling

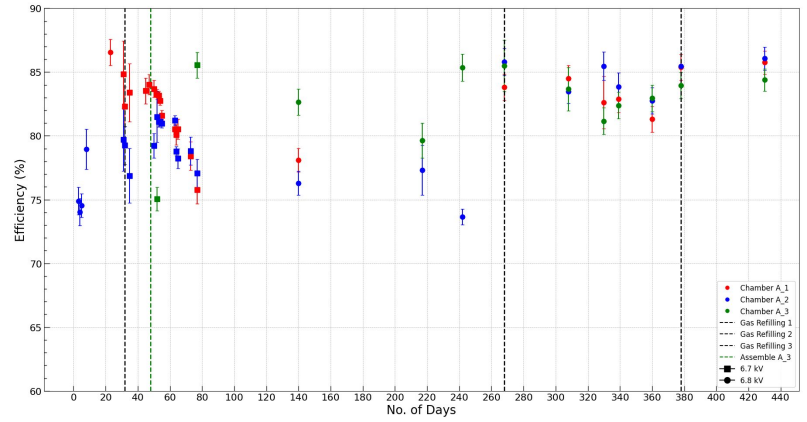
- To study detector's performance:
  - Plastic scintillator pads, having the same active area as the RPCs and coupled to PMTs, were used as external triggers.
  - RPC pre-trigger signals from the logical OR of all 16 strips are collected in parallel as the coincident scint. trigger signal.
  - DAQ uses old CMS RPC FEB consisting charge sensitive preamplifiers and discriminators that are processed by FPGA for data-collection.

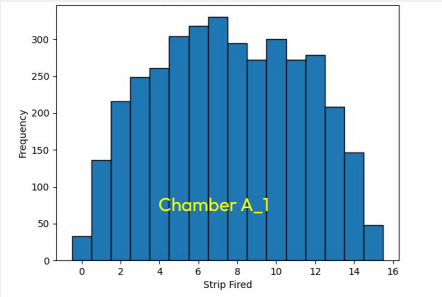


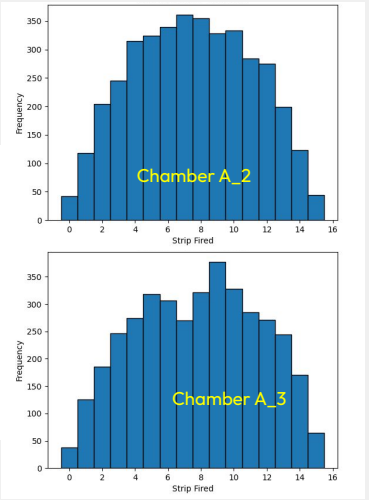
Experimental setup for efficiency measurement

Performance Testing: Occupancy and Efficiency









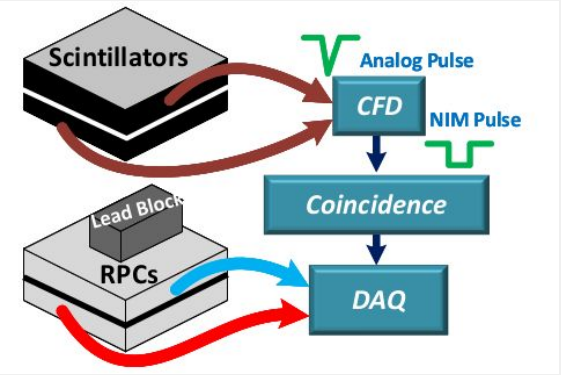
Efficiency Scan shows: Detectors are operating with **>85% efficiency**

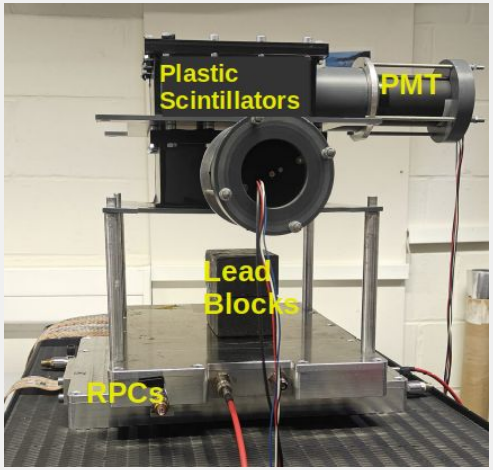
- **Occupancy for three identical chamber in the same orientation follows the same trend.**
- **Detectors have been operating with good efficiency for over a year.**

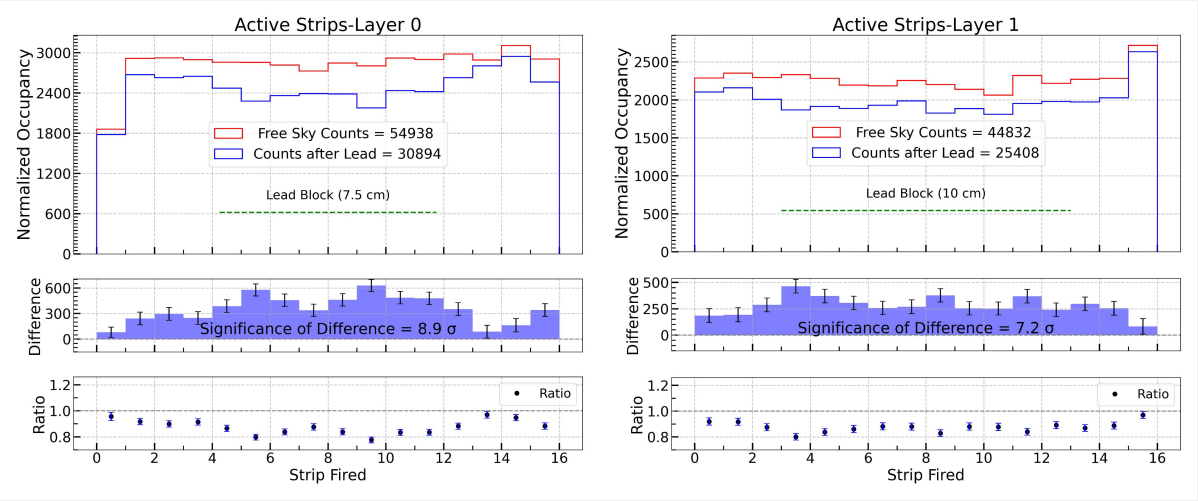
Absorption Muography

A small scale muon absorption feasibility study was carried in the lab:

- The experimental setup consists of two plastic scintillators on top and two orthogonally arranged RPCs (labeled "Layer 0" and "Layer 1") acqu data for bidimensional (XY) spatial information.
- Two Lead blocks (Length= 10cm, width = 7.5cm, height =4.5cm+4.5cm)in the region between the scintillators and RPCs

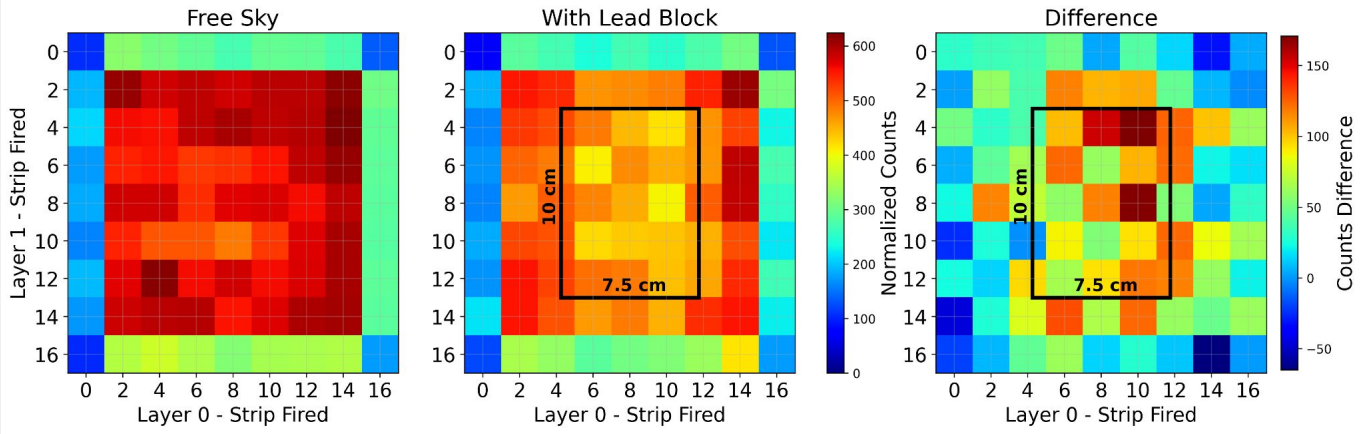






Absorption Muography

2D histograms for the same configuration

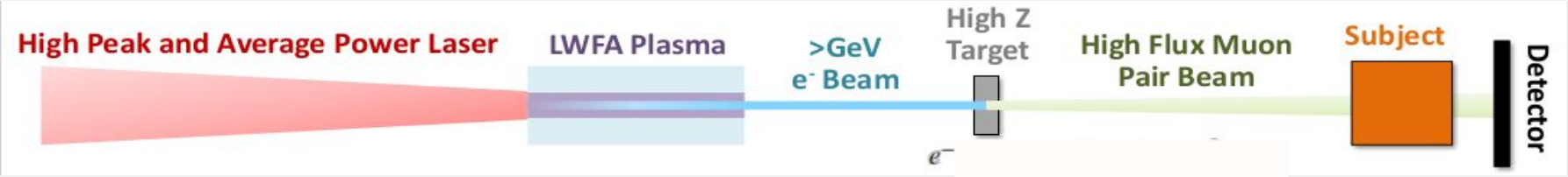


- These simplified muon absorption experiment provided valuable insights into the feasibility and performance of gas-tight RPCs from a practical application standpoint.
- By analyzing both the total muon counts and their spatial distribution, we fully characterize the shielding effect and muon attenuation.

Beam Test at ELI (Prague) (April-May, August and September 2025)

Muon Production via Laser Electrons

- Muons could be a game changing technology if there were a compact active source of muons available.



Conceptual layout of the muon source.

Image Source: “Reagan ELI-BL Muon Source Workshop”.

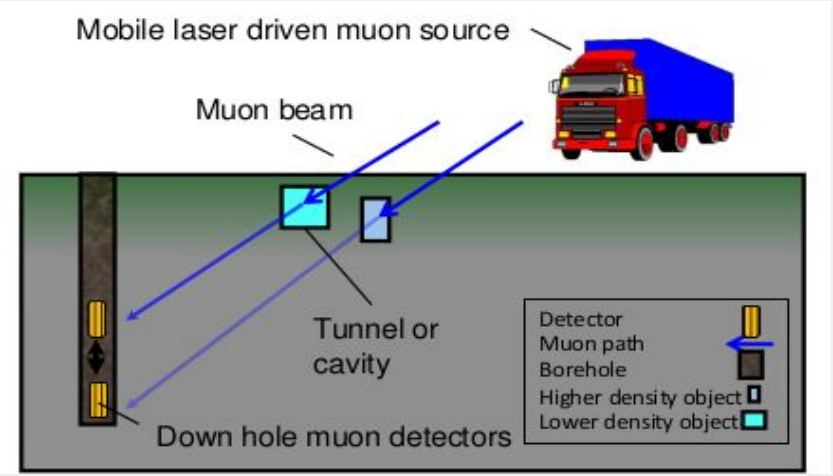
- Muons produced via photo-production or electro-production are characterized by their short pulse duration and high flux.

Potential Benefits of Artificial Muons

- **Higher Particle Flux:** The flux is significantly higher than that of cosmic muons.
- **Controllable Energy**: Unlike cosmic muons, whose energies vary unpredictably, beamline allows for control over the energy of the beam.
- **Known Directionality:**The beam direction is well defined, unlike cosmic muons which arrive from random directions.

➔ Muons are not hazardous to life forms or the environment, provided the flux is not extremely high.

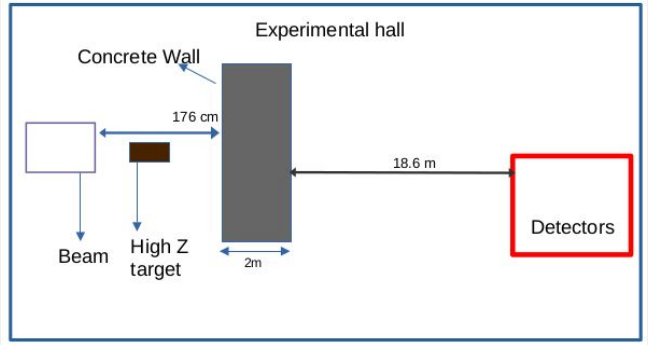
➔ Muons can be used to detect many different materials



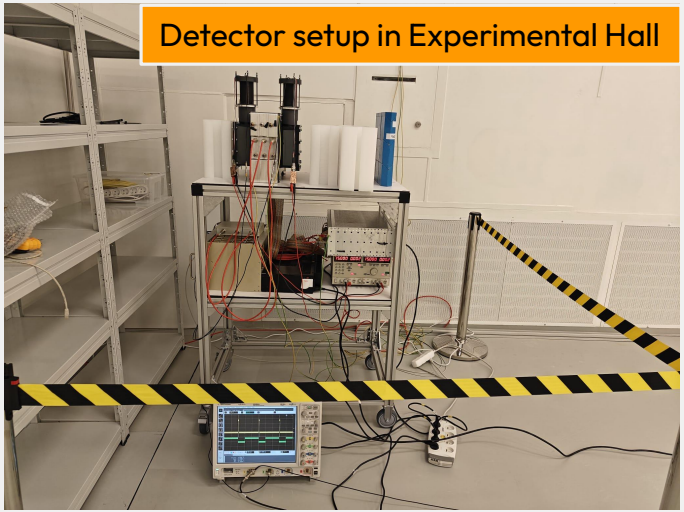
Source: Todd Ditmire “Laser Induced Muon Production for Detecting Special Nuclear Materials and WMD”

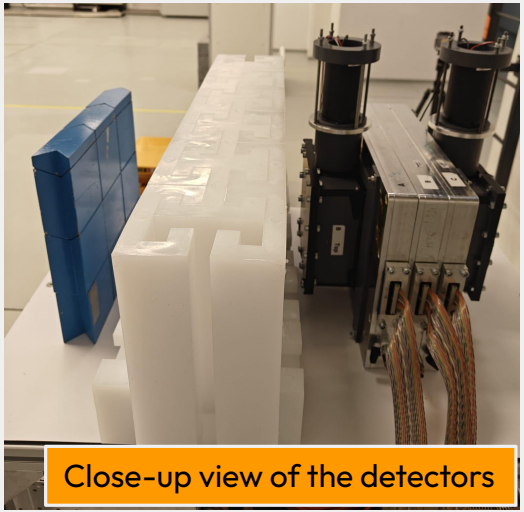
Portable System Validated

- ELI (The Extreme Light Infrastructure): The world's largest and most advanced high-power laser infrastructure and a global technology.




Detector Shipment


Detector setup in Experimental Hall

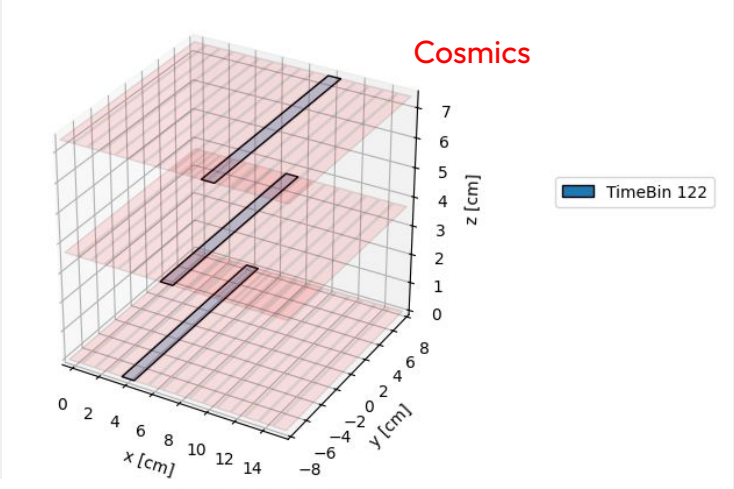

Close-up view of the detectors

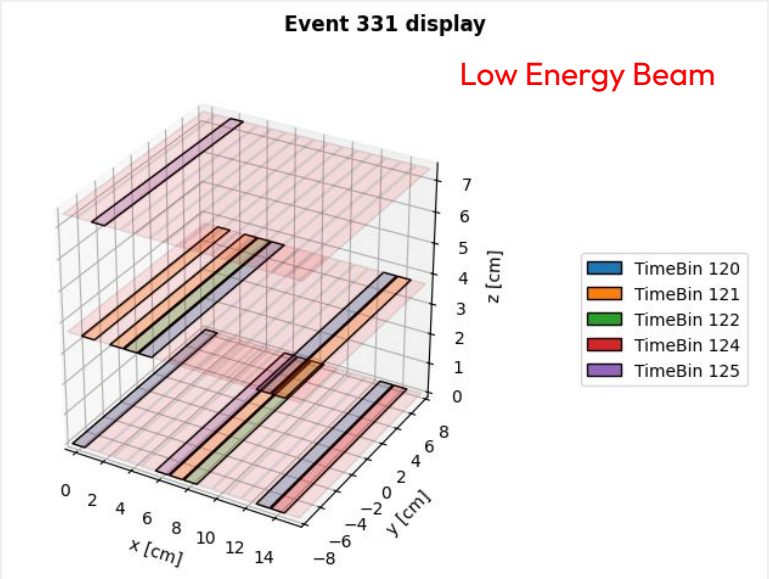
- We successfully transported and operated our detector to the test site (Prague) in April/May and then in August.

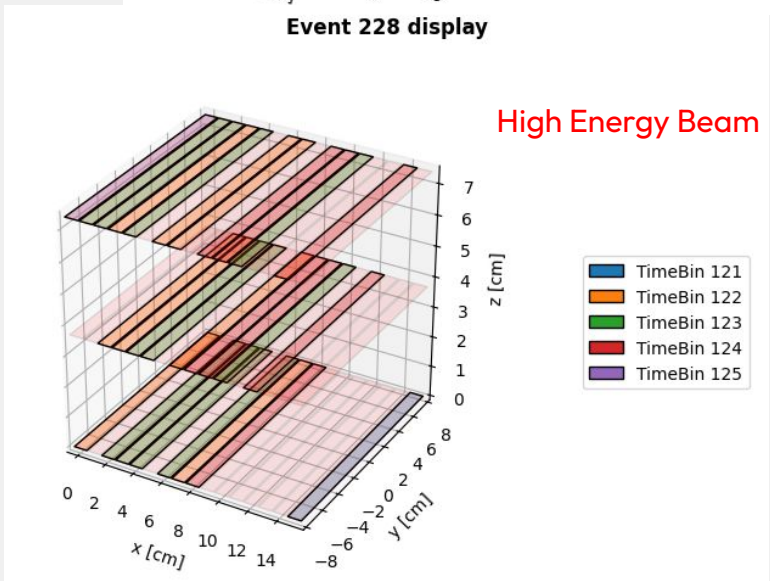
Event Display

Comparison across three datasets:

- ➔ **Cosmic Data** – baseline reference for detector performance
- ➔ **High-Energy Beam** – validation under intense particle flux
- ➔ **Low-Energy Beam** – study of detector response at lower energies







Data Filtering & Off line Analysis Steps

Applied selective cuts to refine the dataset.

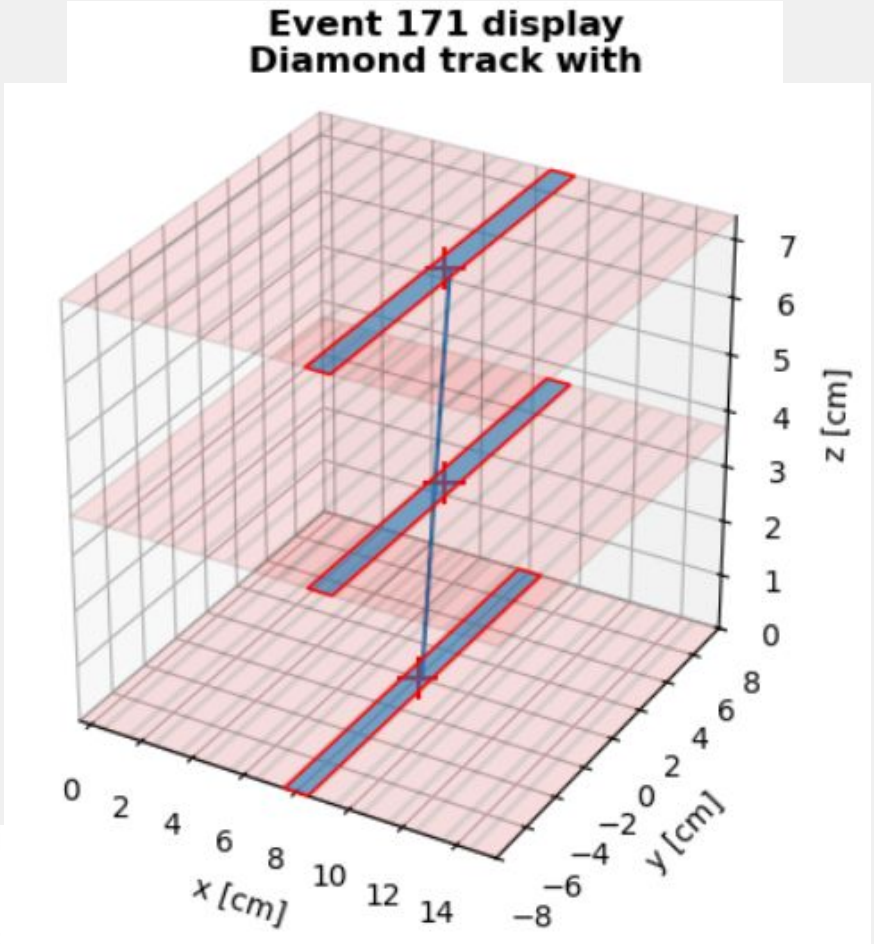
To perform tracking events are categorized based on:

- **Events per time bin** → focusing on relevant activity
- **Cluster size per detector layer** → enabling granular analysis

Cosmics Data:Tracking

Muon tracks are split into categories, based on the properties of the fired strip:

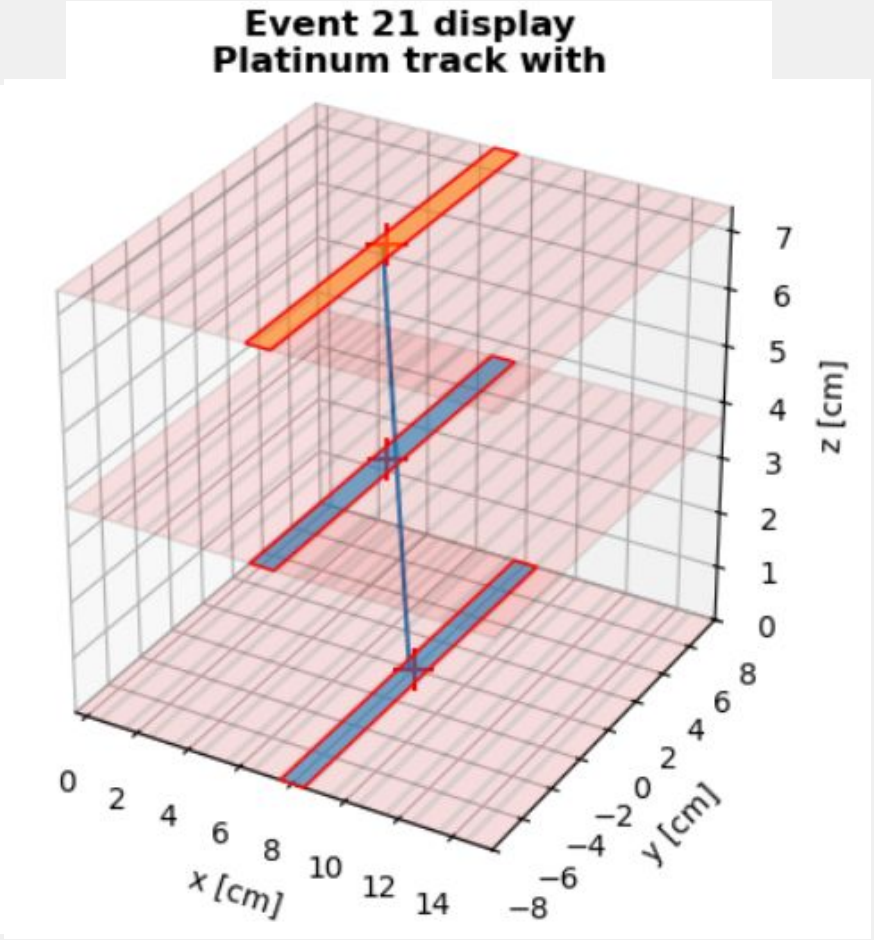
- **Diamond**: single strip fired per layer, same time bin. Fix units



Cosmics Data: Tracking

Muon tracks are split into categories, based on the properties of the fired strip:

- **Diamond**: single strip fired per layer, same time bin.
- **Platinum**: single strip fired per layer, multiple time bin.



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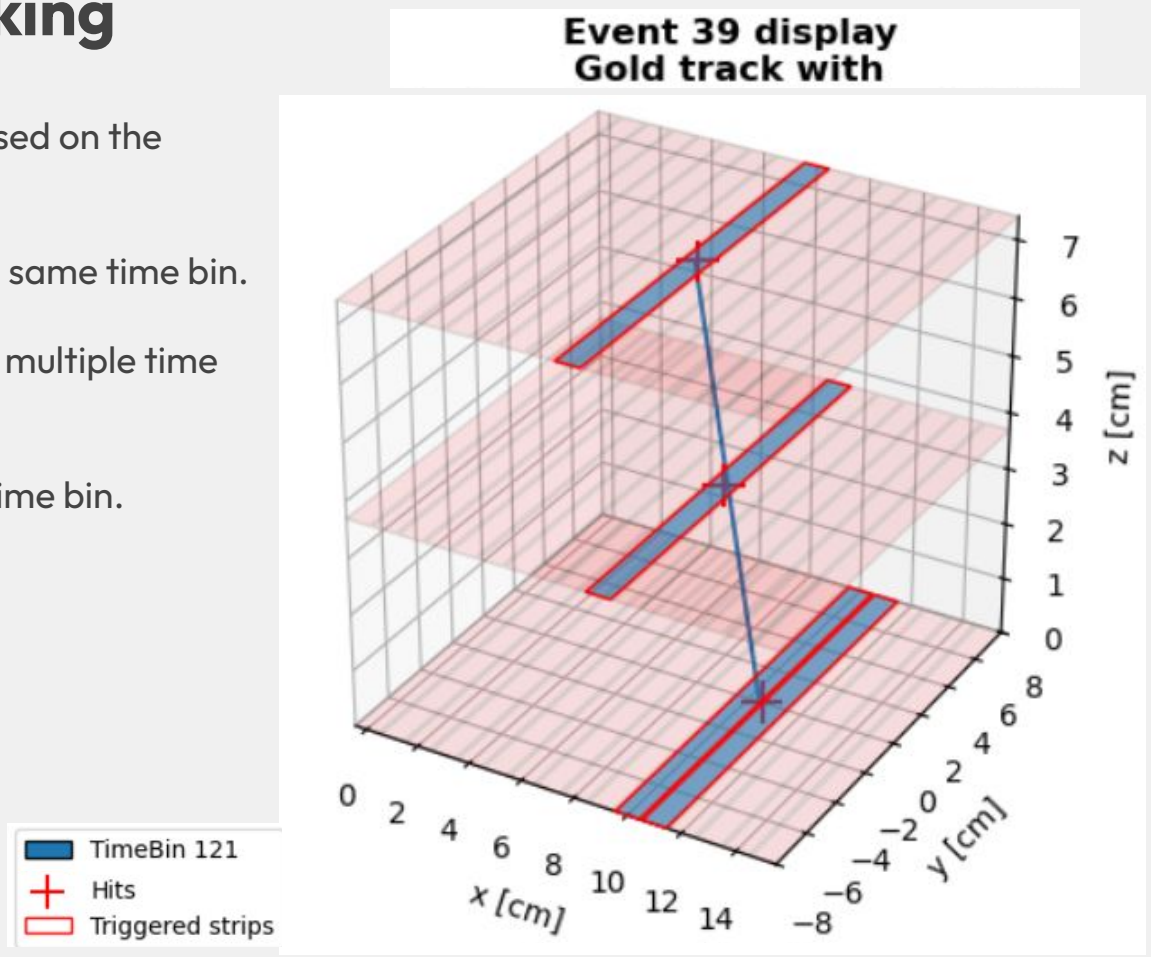
- **Gold**: single cluster per layer, same time bin.



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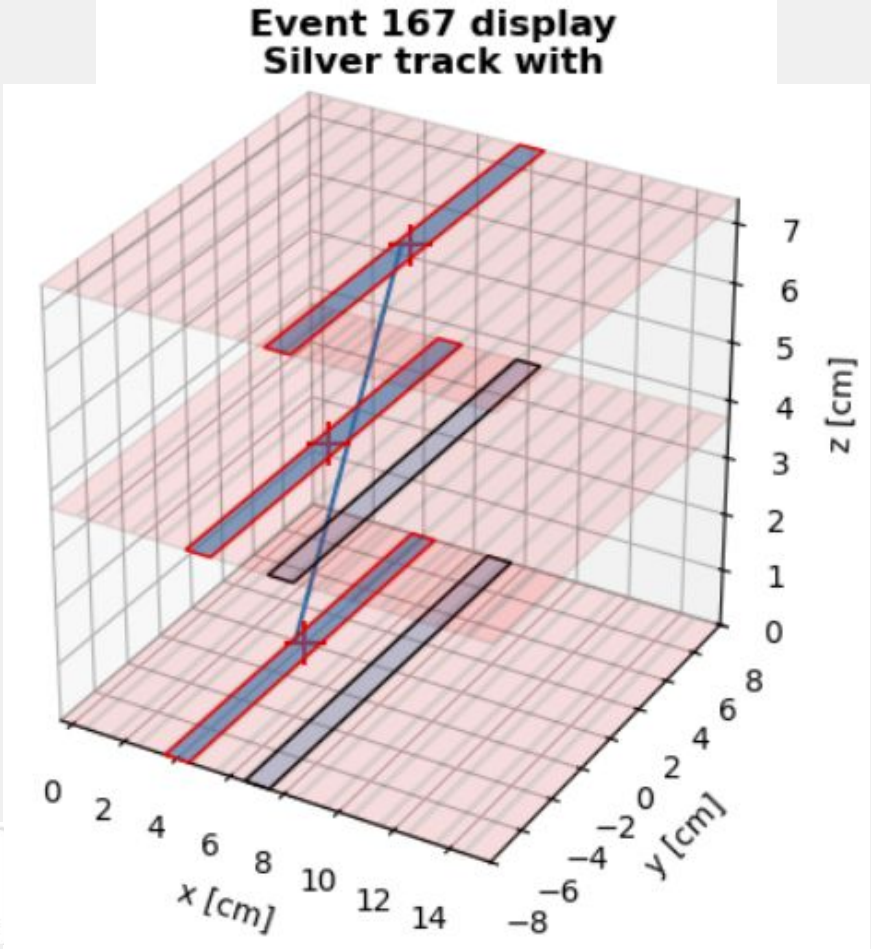

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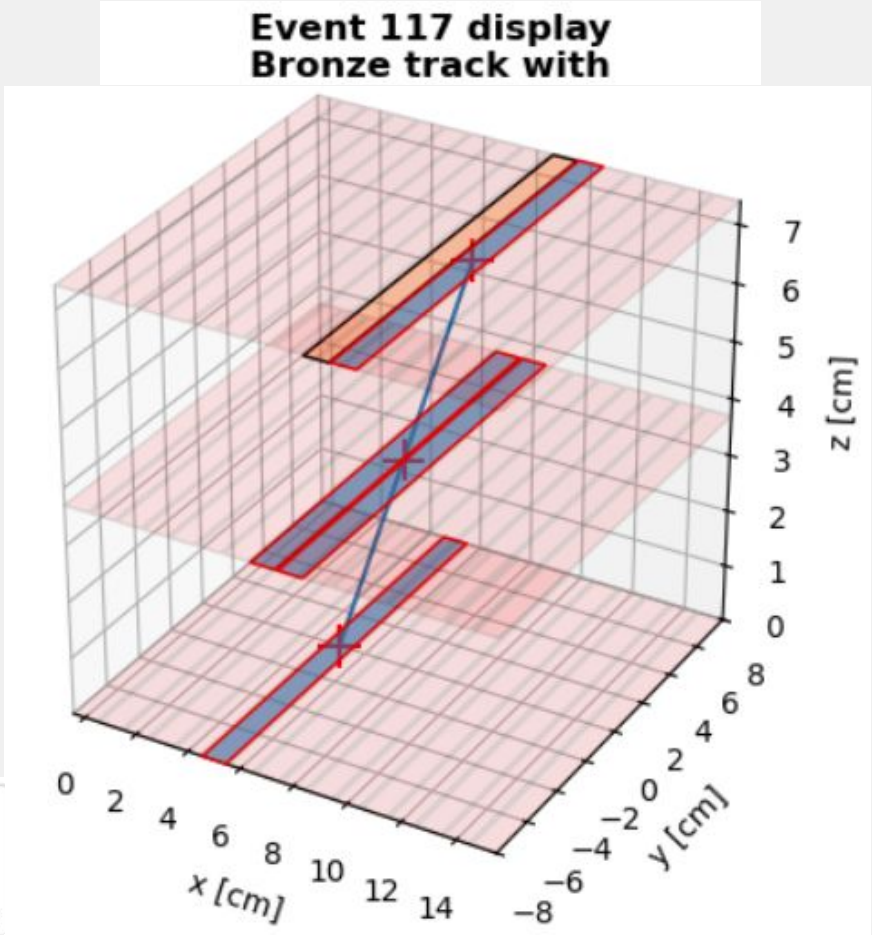
- **Gold**: single cluster per layer, same time bin.
- **Silver**: multiple cluster per layer (keep largest one), same time bin.
- **Bronze**: multiple cluster per layer (keep largest one), multiple time bin.



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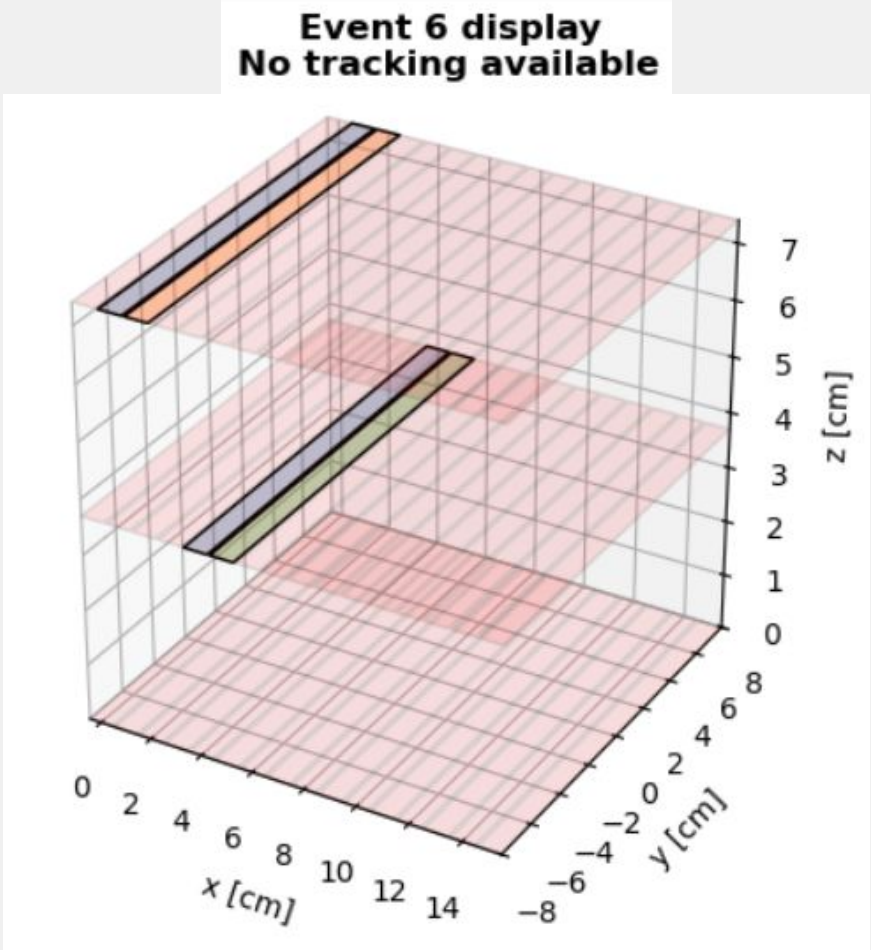
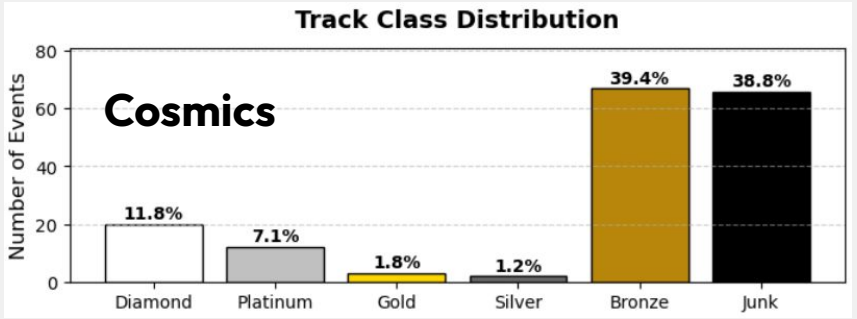
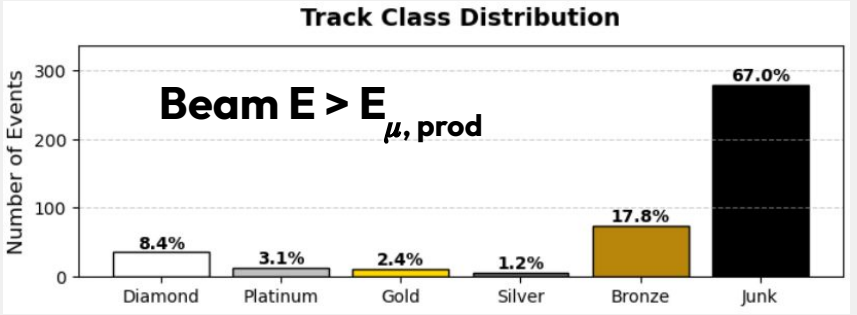
- **Silver**: multiple cluster per layer (keep largest one), same time bin.
- **Bronze**: multiple cluster per layer (keep largest one), multiple time bin.
- **Junk**: do not meet above requirements.

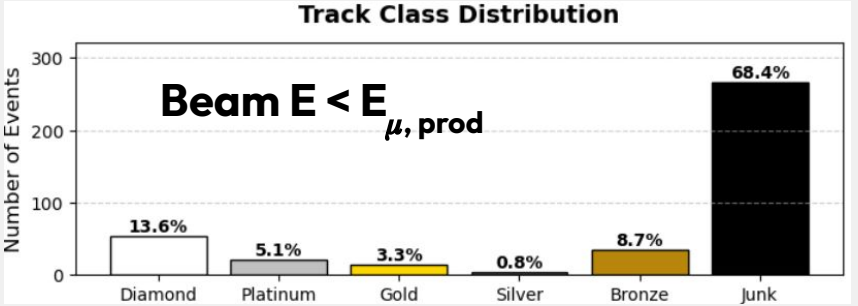


Different blends

- ➔ We are in the process of digesting the data taken in August, including optimization of the different track **category definitions.**
- ➔ Junk fraction is **40% in cosmics**, and **70% with beam** (any energy!), attributed to large background of secondaries (most likely neutrons)
- ➔ **Fraction of "bronze"** tracks is the one that changes the most with different beam conditions
- ➔ Overall, **statistics is too little for any firm conclusion**: 104 good events with cosmics, 137 with high energy, 123 with low energy, and we expect cosmics to be a large fraction of the good events in the beam runs
- ➔ We were operating "parasitically" so far; we are preparing a request for extended beam time as **main users in 2026**







Summary

➔ Stable and Uniform Glass Coating

Successfully coated glass plates with consistent surface resistivity and uniformity — a key step in detector Reliability.

➔ High Detector Efficiency

Developed detectors are operating with >85% efficiency.

➔ Small scale Muon Absorption Test

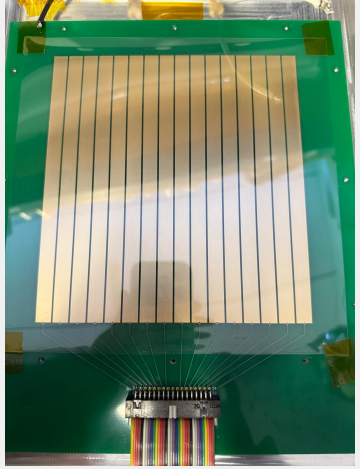
Muon absorption test was successfully conducted in the lab, demonstrating basic proof of concept.

➔ Detector Upgrade in Progress

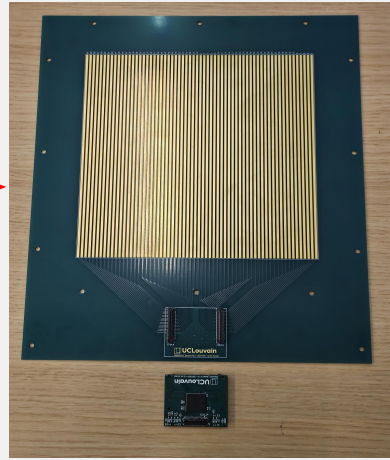
Current upgrades target lower gas consumption,improved modularity, and reduced casket dimensions.

➔ Successful Beam Test at ELI

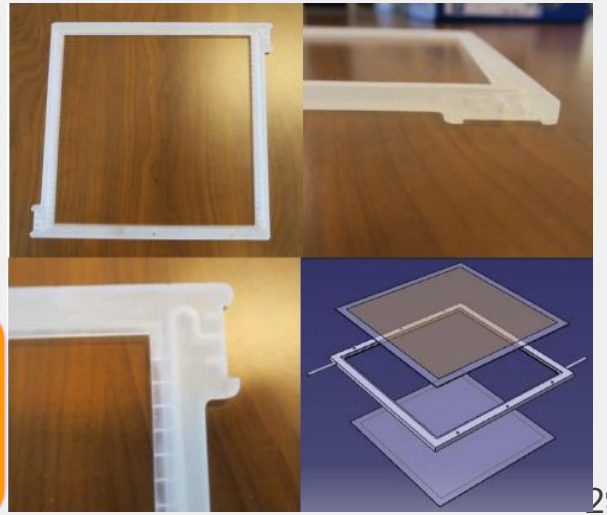
BeamTest at ELI validated the portability and robustness of the prototype in real operational conditions.



16-strips



64-strips

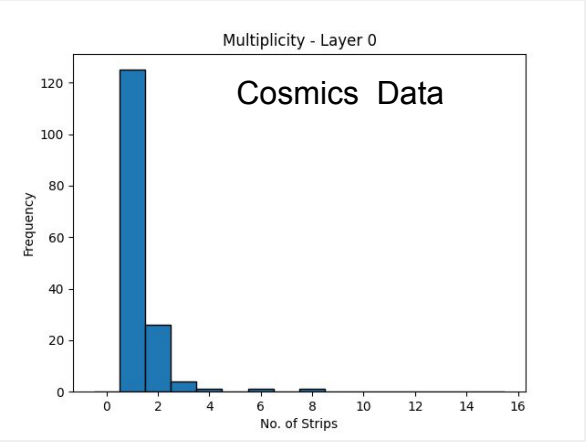


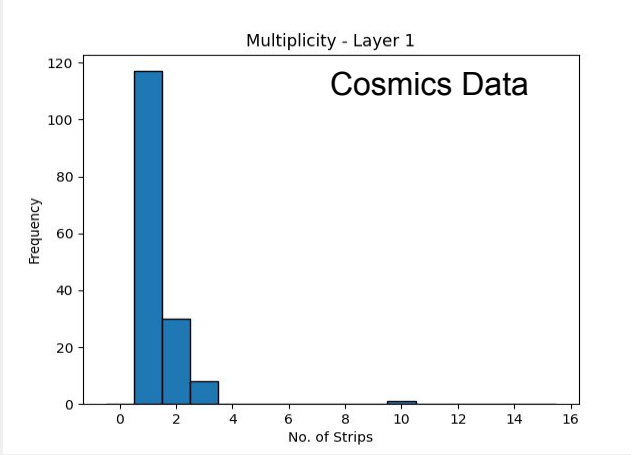
3D printed frame that requires lower gas volume only in the gas gap instead of the entire outer casing in the current version

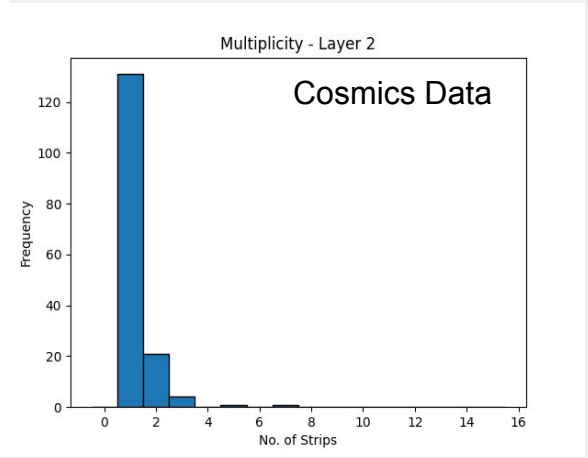
Thank you for your attention!

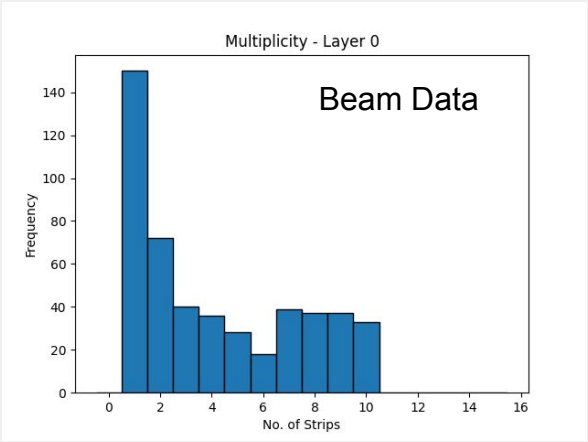
Backup Slides

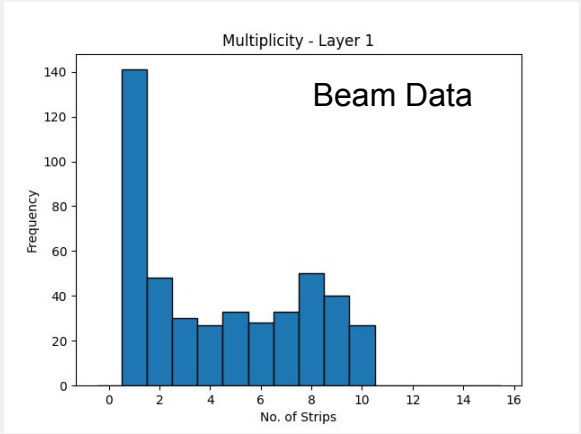
Multiplicity for Cosmics and Beam Data

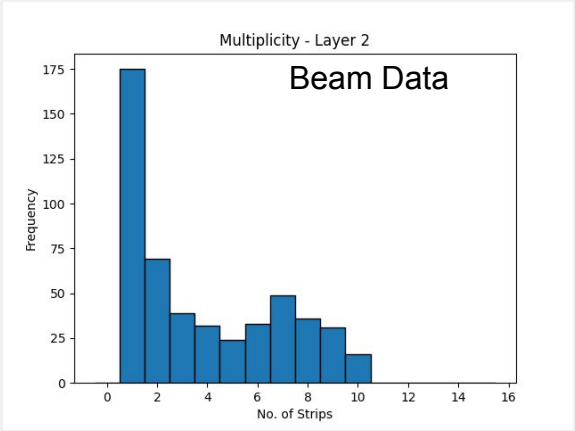






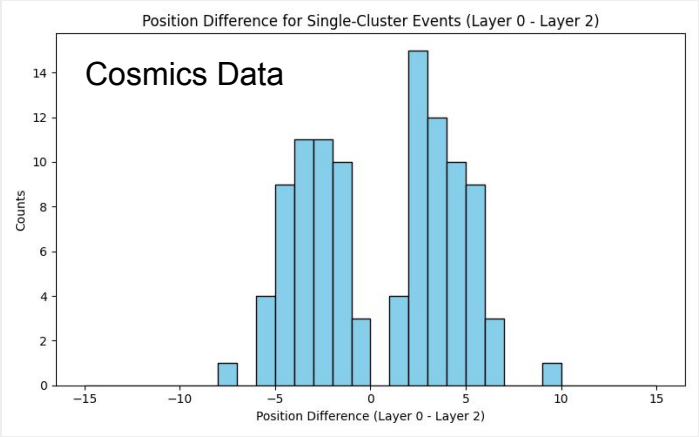


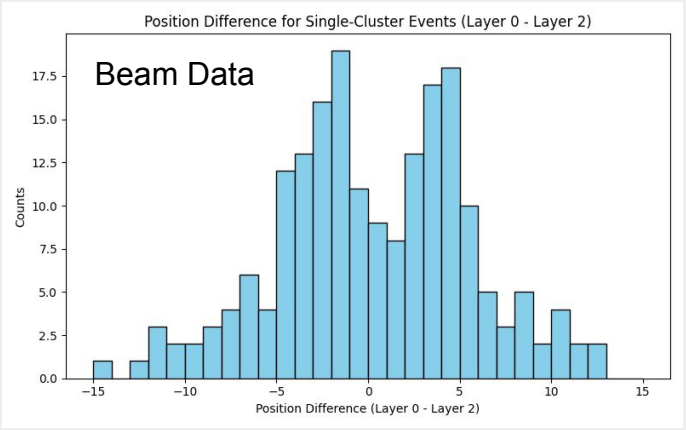




Summary For April/May Beamtest

- Events at $\Delta x \approx 0$ are consistent with energetic beam-produced charged particles.
- April/May data lacks discrimination power between muons/electrons.

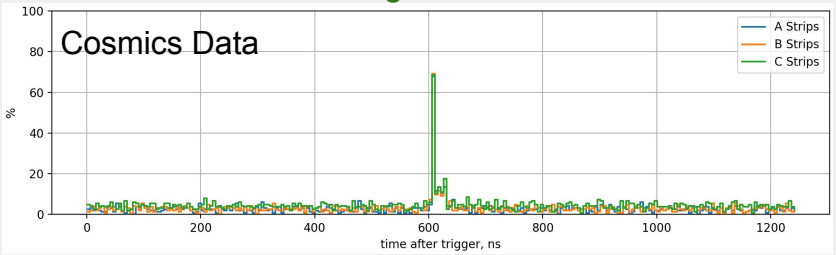


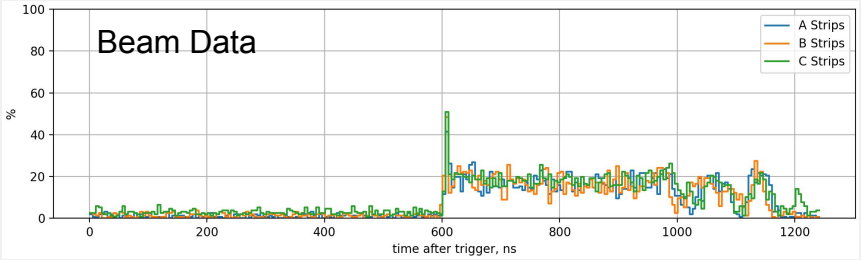


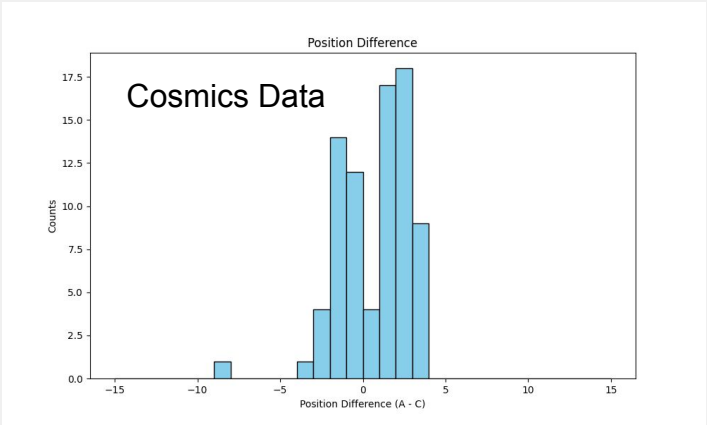
Preliminary Insights : August Data

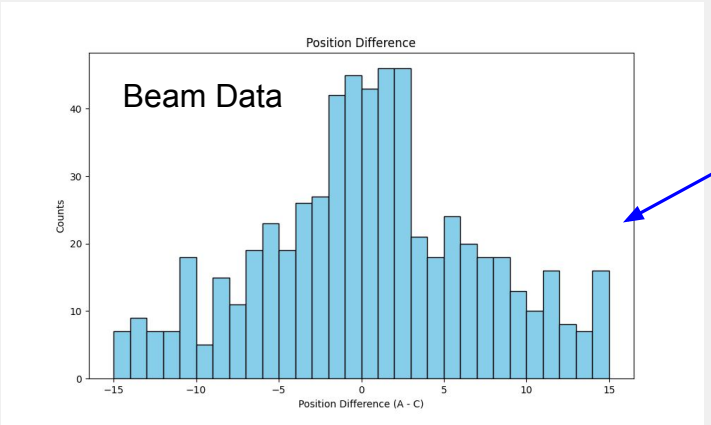
- New grounding wires
- New input for laser trigger signal
- The detector was positioned 18.6 m from the beam dump.

Timing Information of one of the dataset for cosmics and Beam data







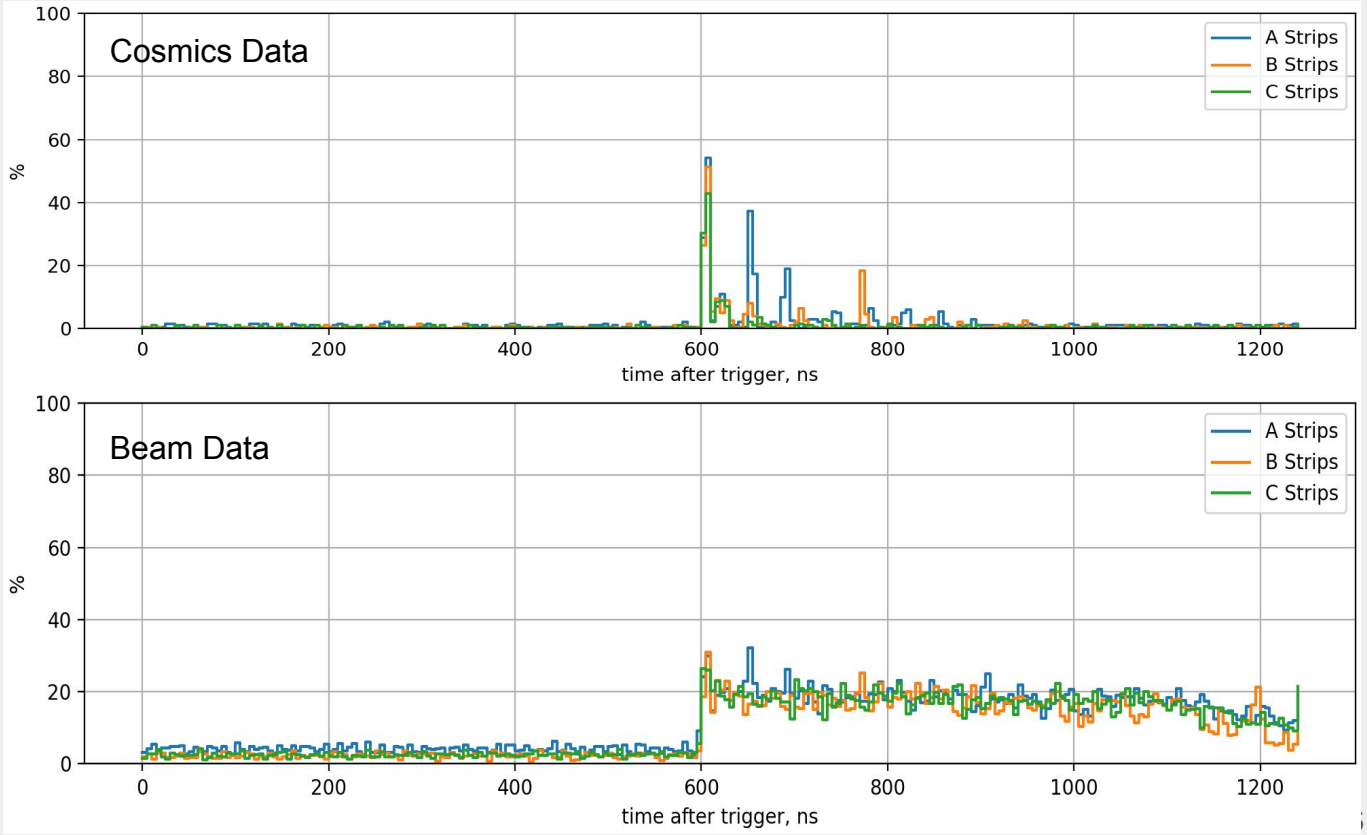


An event is selected if all three chambers contain at least one cluster.

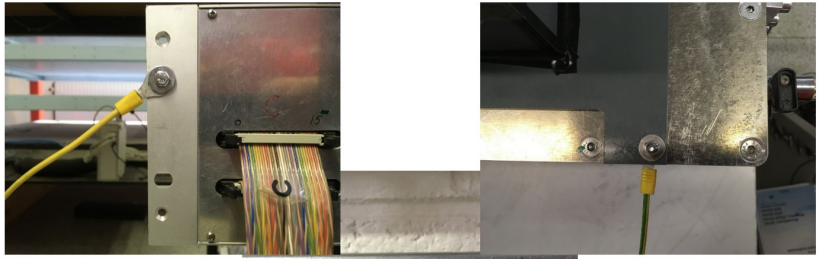
Position Difference for Cosmics and Beam Data

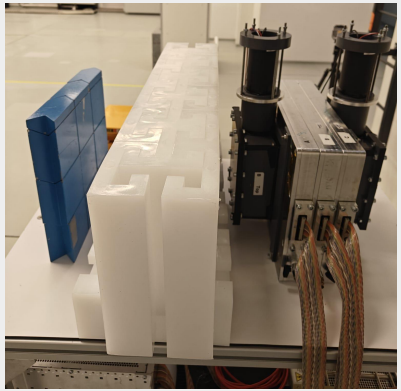
Timing information from April 2025 dataset

- 1 hr run time
- Threshold = 35
- HV= 7kV



Grounding Cables and Detector Position During August Beam Test

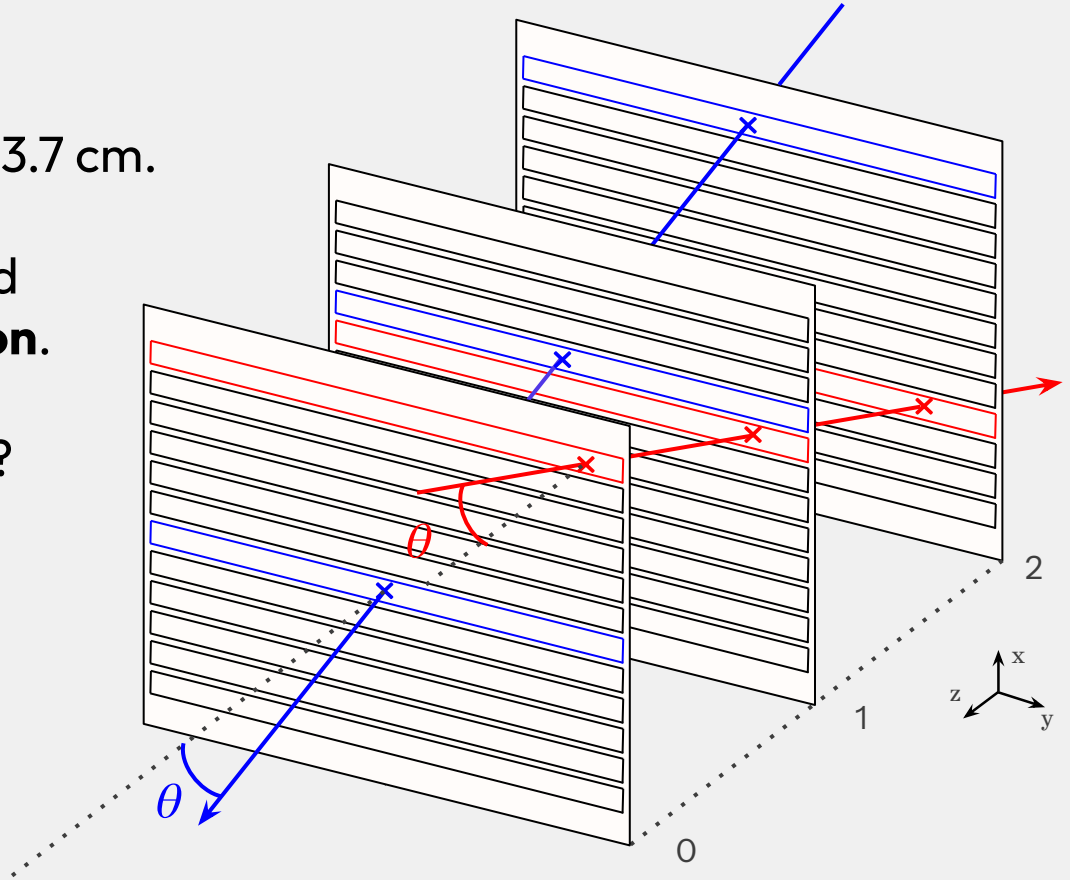




Credit: Pavel Demin (CP3)

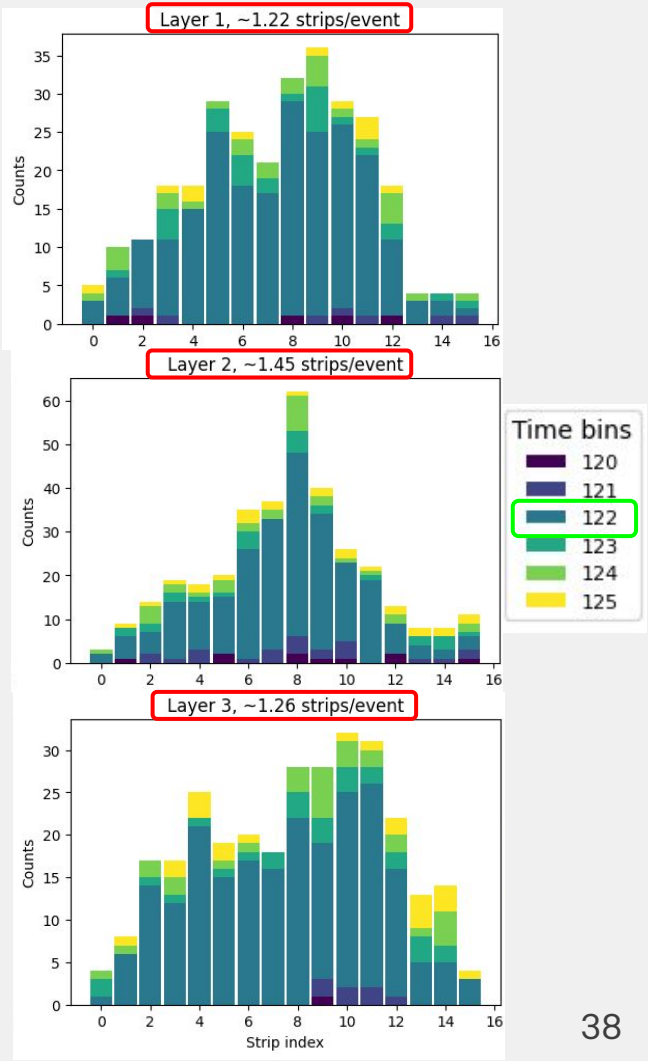
Cosmic data-taking: Detector setup

- Detector panels are separated by 3.7 cm.
- Strips are **placed horizontally**, and **aligned** along the **vertical direction**.
- What kind of events do we expect?
  - **Forward** muons in red: $\theta > 0$.
  - **Backward** muons: $\theta < 0$.



Cosmic data-taking: Strip occupancy

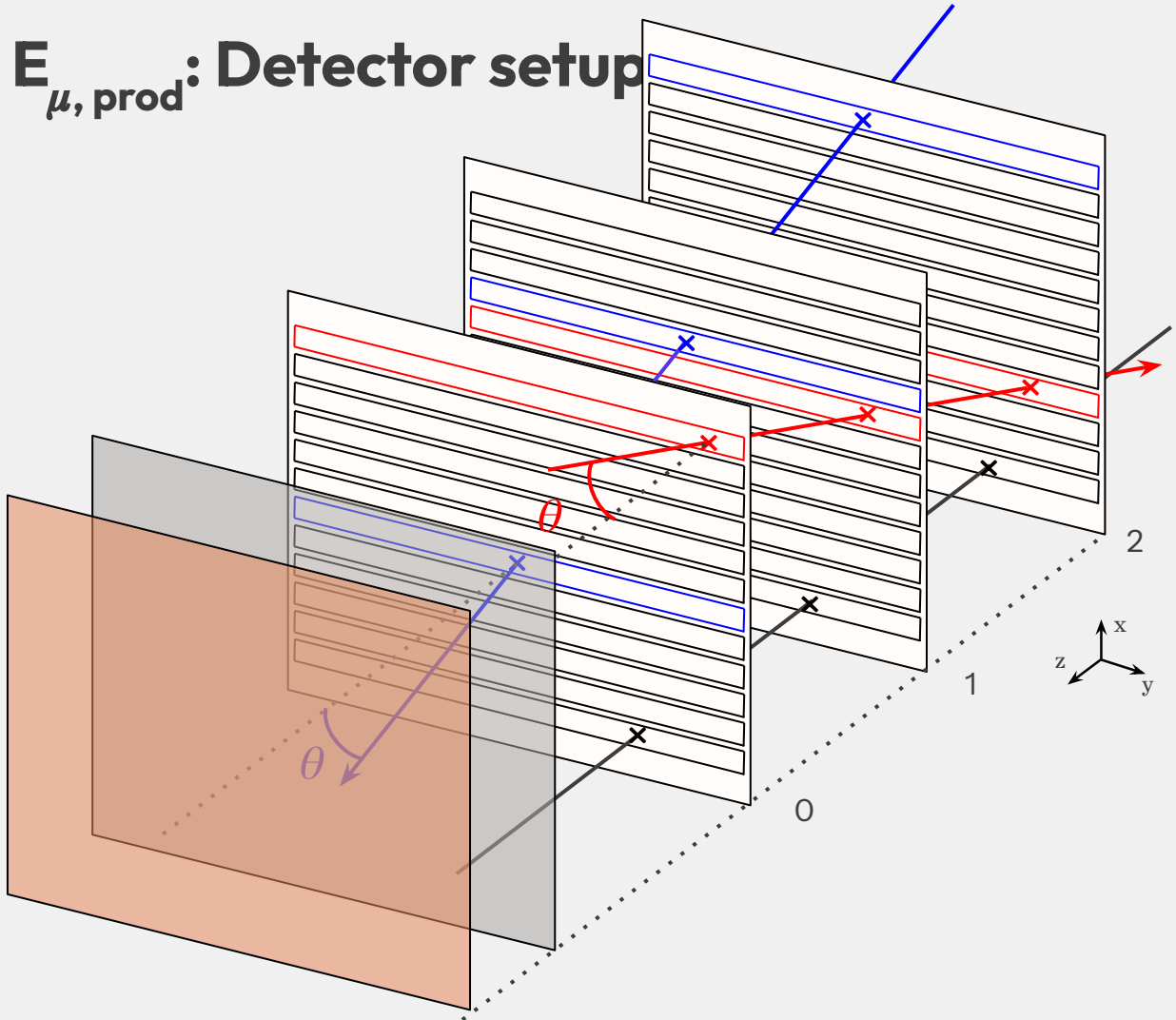
- For **each layer**, **average** number of **strips fired** per event ~ 1.
- Strips fired have **consistent timing** w.r.t. the **trigger signal** (time bin 122).
- **Excess** of events in **central strips** and **deficit** of events in **side strips:** consistent with **vertical muon flux**, and **absence** of **horizontal muons**.



Beam data-taking E > $E_{\mu,\,prod}$: Detector setup

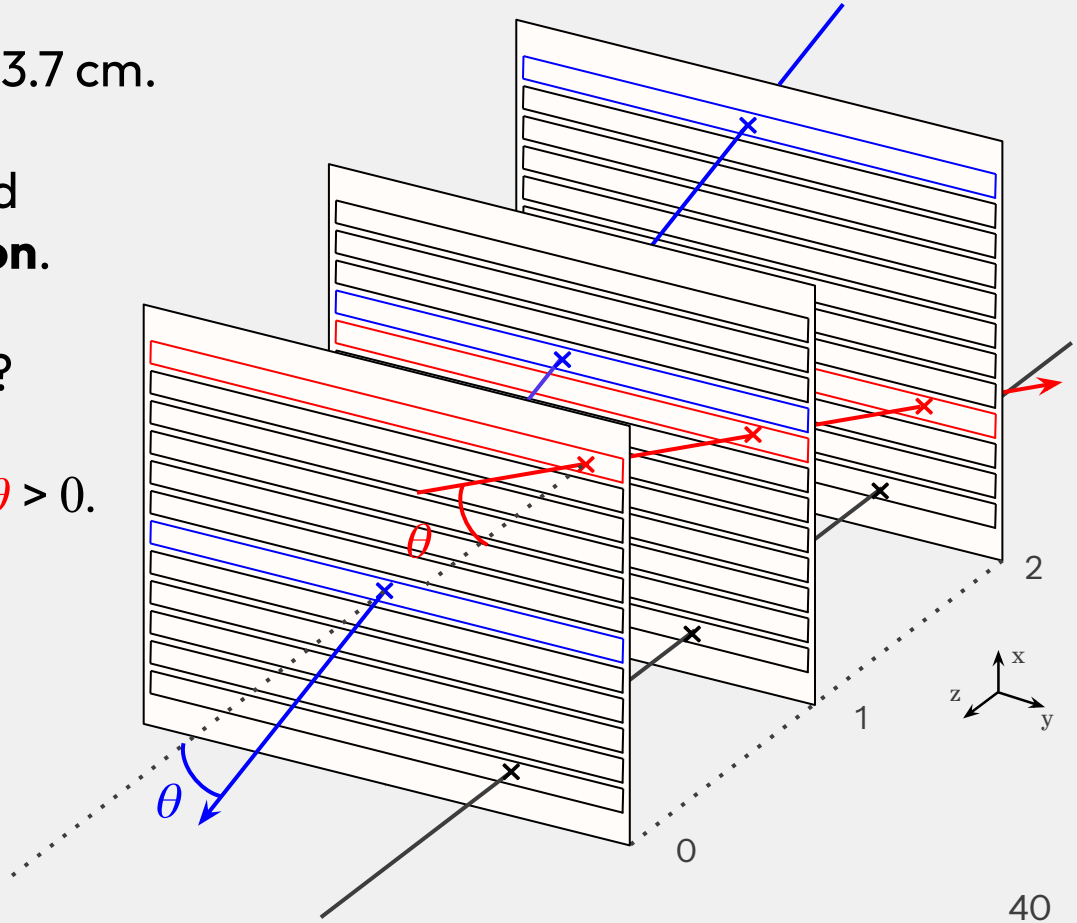
Polyethylene

Lead



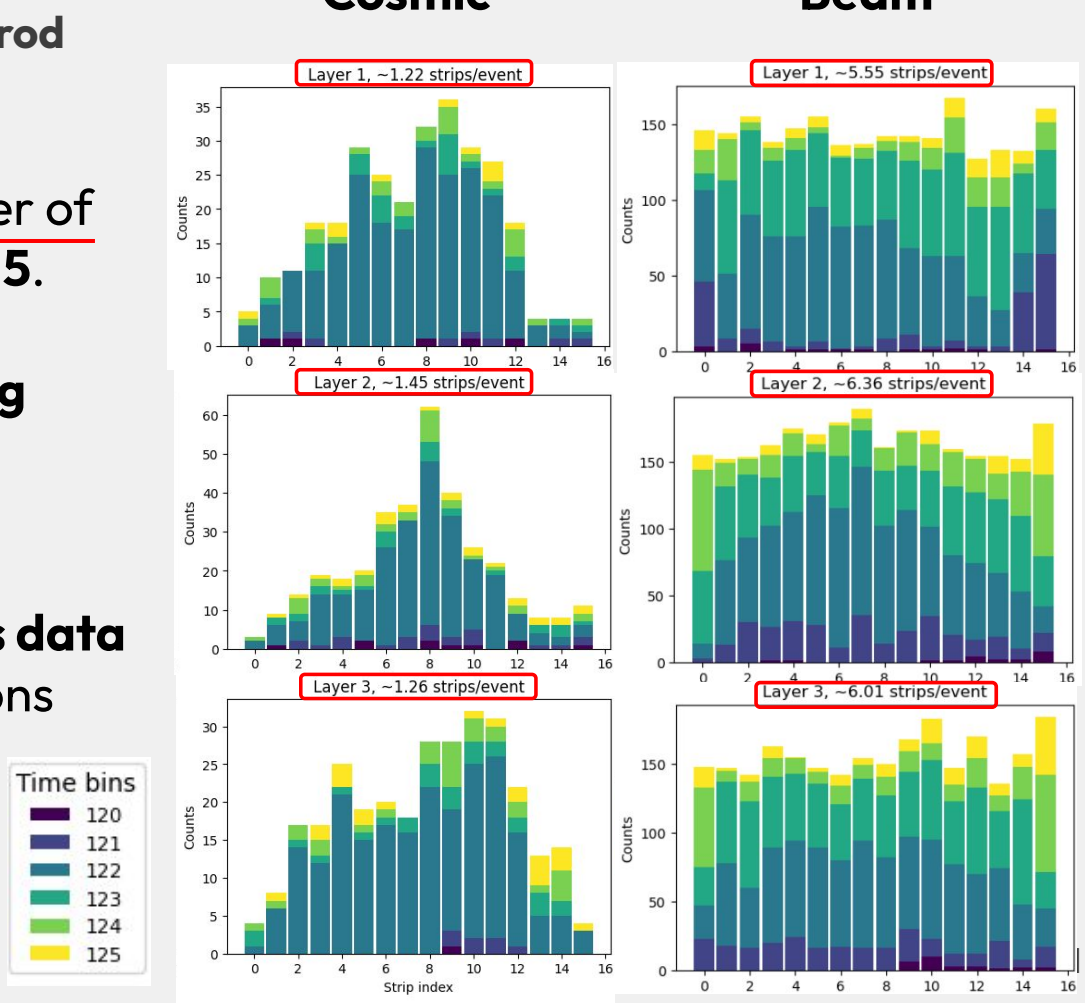
Beam data-taking E > $E_{\mu, prod}$: Detector setup

- Detector panels are separated by 3.7 cm.
- Strips are **placed horizontally**, and **aligned** along the **vertical direction**.
- What kind of events do we expect?
  - **Forward cosmic** muons in red: $\theta > 0$.
  - **Backward cosmic** muons: $\theta < 0$.
  - **Horizontal beam muons:** $\theta = 0$.



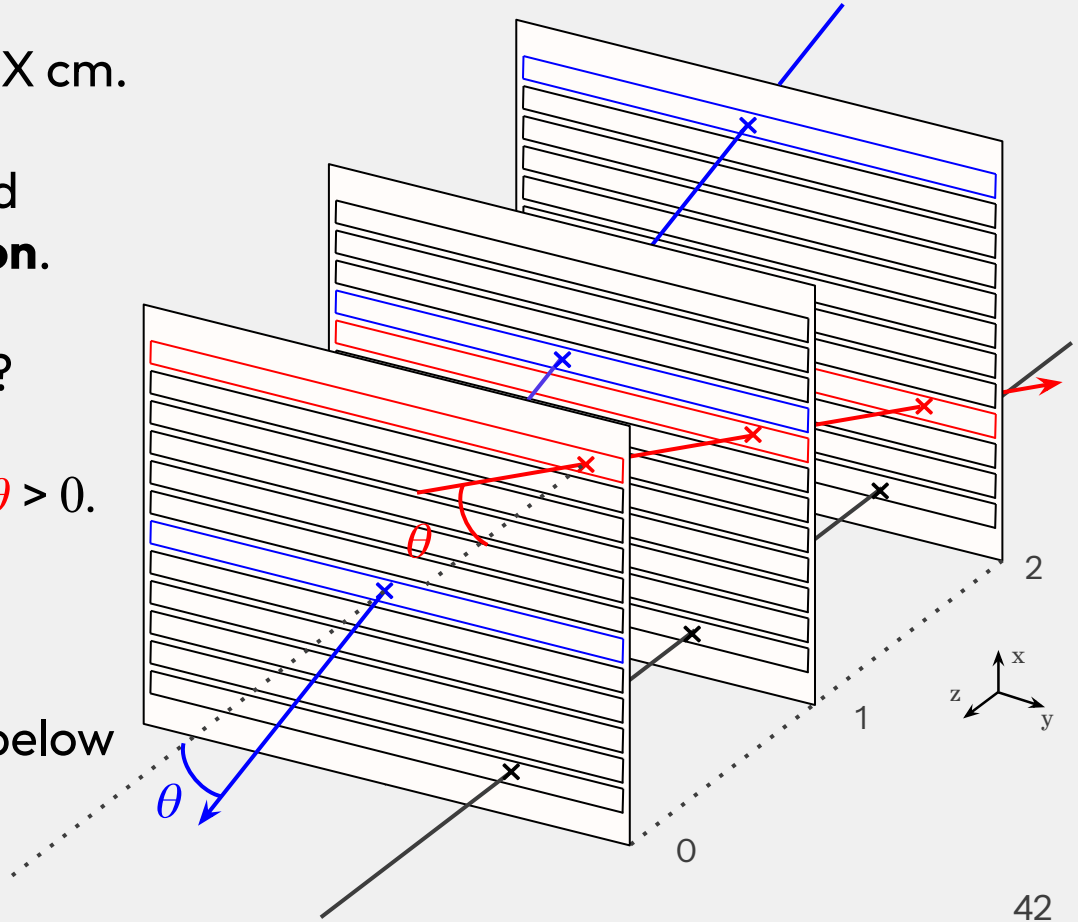
Beam data-taking $E > E_{\mu, prod}$

- For **each layer**, **average** number of **strips fired** per event is **large > 5**.
- Strips fired have **multiple timing** w.r.t. the **trigger signal**.
- **Uniform strip occupancy** inconsistent with **cosmic muons data** (**vertical** tracks) and beam muons data (**horizontal** tracks)**.**
- Possible explanation: too many secondaries.



Beam data-taking $E < E_{\mu, prod}$

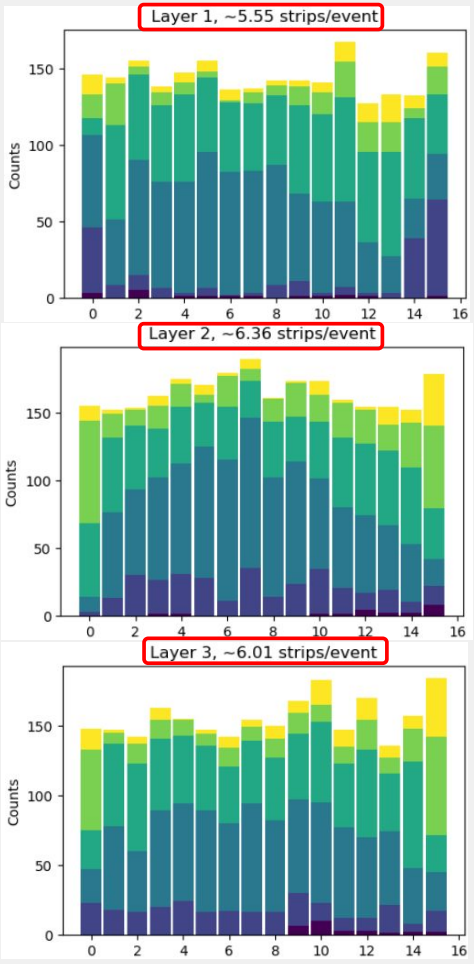
- Detector panels are separated by X cm.
- Strips are **placed horizontally**, and **aligned** along the **vertical direction**.
- What kind of events do we expect?
  - **Forward cosmic** muons in red: $\theta > 0$.
  - **Backward cosmic** muons: $\theta < 0$.
  - **No beam muons:** $\theta = 0$, we are below production threshold.



Beam data-taking E < $E_{\mu, prod}$

- For **each layer**, **average** number of **strips fired** per event is **large ~ 3**.
- Average number of **strips fired decreases** as we move further away from shielding material. 3.48 > 3.06 > 2.63.
- New time bin appears
- Strips fired have **multiple timing** w.r.t. the **trigger signal**.
- **Strip occupancy** inconsistent with **cosmic muons data** (**vertical** tracks) and beam muons data (**horizontal** tracks)**.**
- Possible explanation: **too many** secondaries, **but different mix** of secondaries.

Beam E > $E_{\mu, prod}$



Beam E < $E_{\mu, prod}$