The ENUBET Demonstrator: beamtest characterization across the years

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on behalf of the nuSCOPE Collaboration

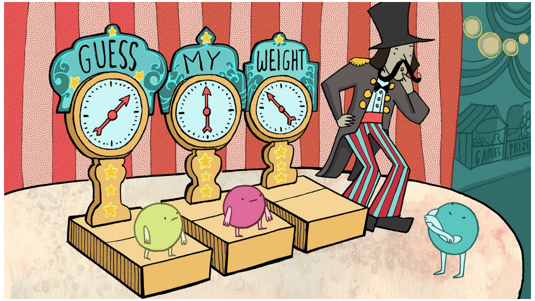
The systematic problems

The **main goals** of the current and future neutrino oscillation experiments are:

- the measurement of δ_{CP} in the CKM matrix
- the neutrino mass ordering
- a better determination of the oscillation parameters

But **several uncertainties** are involved:

- the neutrino flux
- the interaction cross section
- the detector efficiency



Process of interest: Charged Current (CC) interaction with nuclei
→ Perform an accurate measurement of the CC cross-section in the GeV range

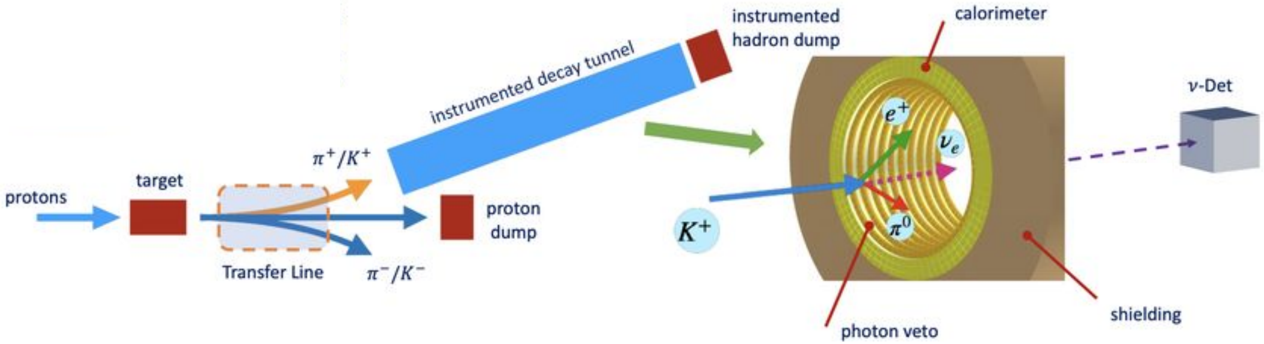
The ENUBET project (ERC-Consolidator Grant 2015)

ENUBET → Enhanced NeUtrino BEams from kaon Tagging

Provide a high-quality neutrino beam that will allow the measurement of the CC cross-section for ν_e (and possibly ν_μ) with a **1% precision** [1] [2] [3] [4]

Detect the large-angle leptons generated in the decay

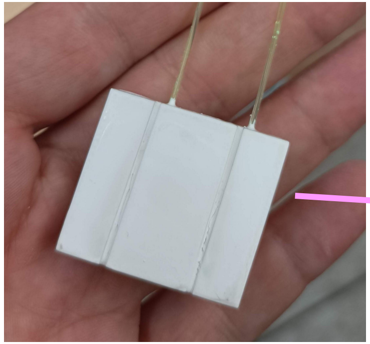
$$K_{e3}^{+} \rightarrow e^{+}\pi^{0}\nu_{e}$$

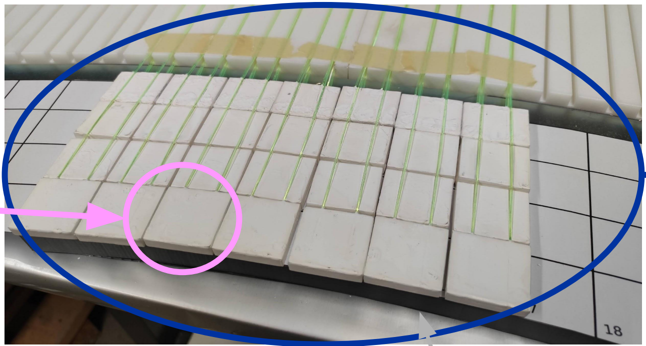


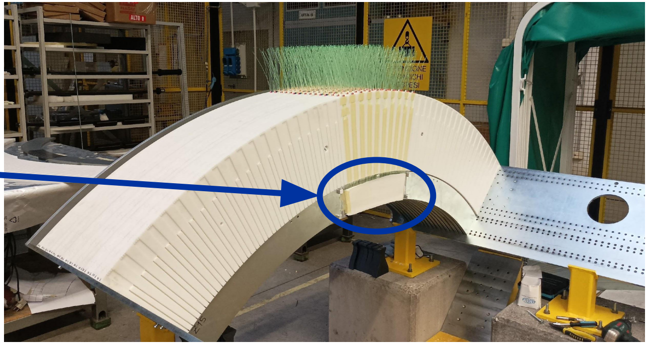
The ENUBET Demonstrator

Largest prototype of the ENUBET collaboration

- 2022 version → **400 channels** readout by 400 SiPMs
- 2023 version → **1200 channels** readout by 1200 SiPMs

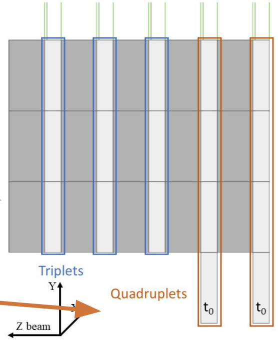






LCM composed of:
5 arches of **scintillator tiles**
and 5 arches of **iron**

Tile t_0 used as photon veto



The ENUBET detector: particle discrimination

Study of the energy deposit and event topology of the decay: $K^+_{e3} \to e^+ \pi^0 \nu_e$

e^+ (signal) topology

$\pi^0 \to \gamma\gamma$ (background) topology

$\mu^\pm$ (signal/background) topology

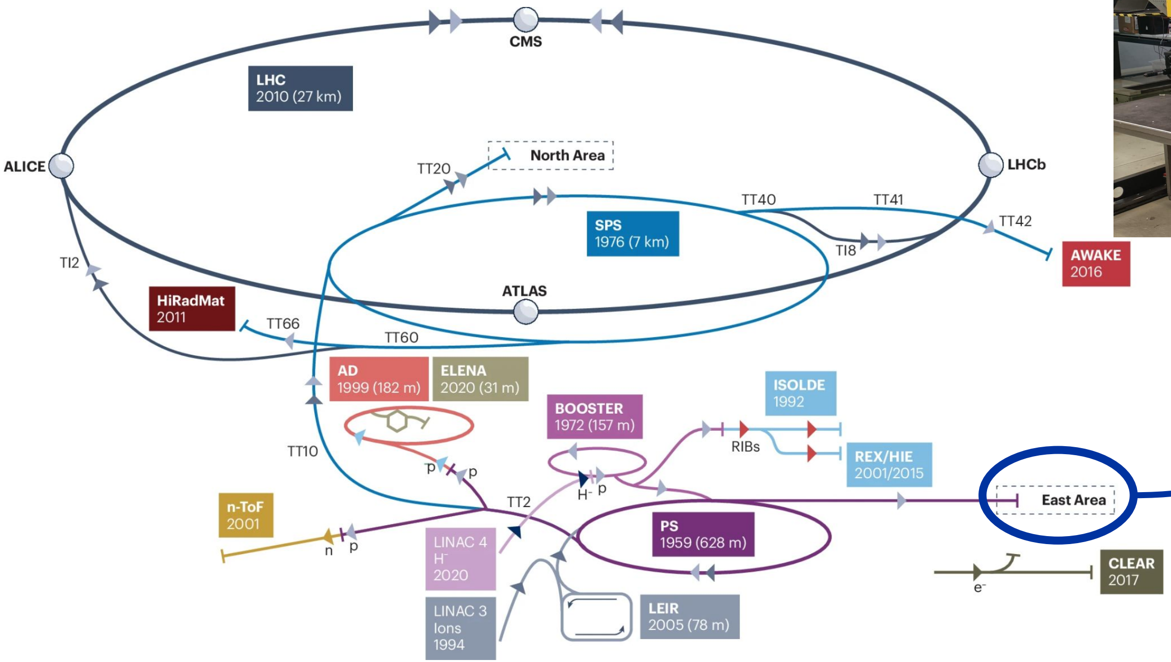
$\pi^\pm$ (background) topology

- Scintillating tiles
- Hit tiles → energy deposited by particles
- Hit t_0 tiles → photon veto tiles

Decay		BR (%)	Comment
$\pi^+ \to \mu^+\nu_\mu$		~ 100	Hadron dump
$K^+ \to \mu^+\nu_\mu$		63.56(11)	Background
$K^+ \to \pi^+\pi^+\pi^-$		5.58(2)	Background
$K^+ \to e^+\pi^0\nu_e$	called K^+_{e3}	5.07(4)	Signal
$K^+ \to \mu^+\pi^0\nu_\mu$	called $K^+_{\mu3}$	3.35(3)	Signal
$K^+ \to \pi^+\pi^0\pi^0$		1.76(2)	Background

The ENUBET beamtests @ CERN PS

In 2022, 2023 and 2024, beamtests have been done at the CERN PS **T9 extracted beamline**

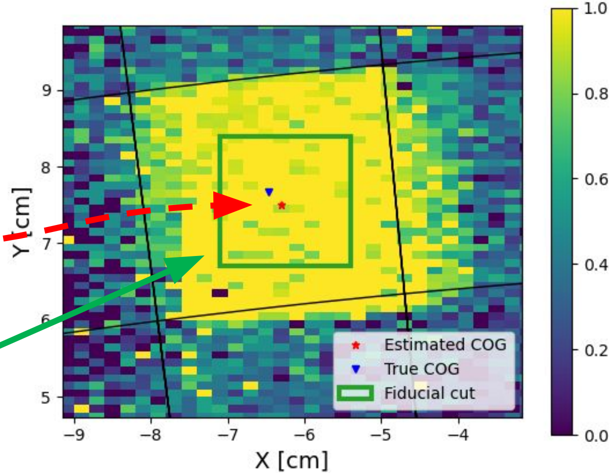


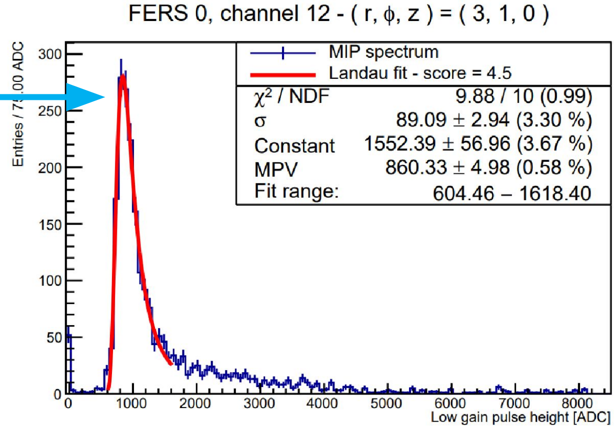
Equalization of the channels

Every SiPM, which performs the readout of one channel, could have a different response, so an equalization procedure of the 1200 SiPMs is needed:

- Estimate the **COG** with the efficiency map of each tile
- Select MIP particles impinging in the **fiducial cut** area
- Fit the MIP **peak** and equalize the channels:

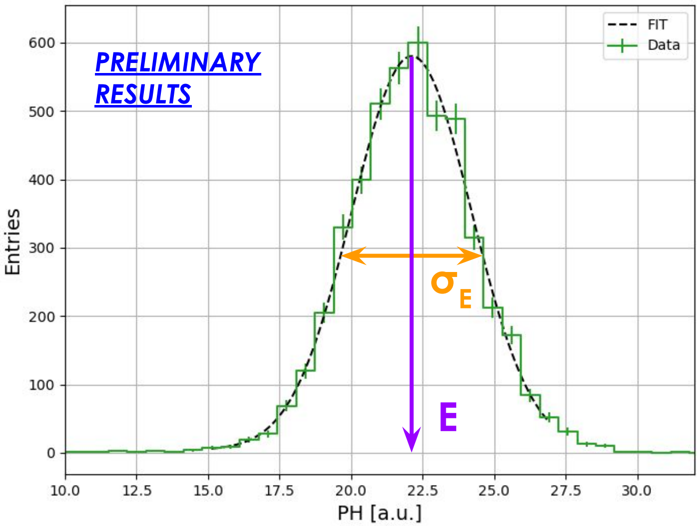
$$PH_{equ} = \frac{PH - baseline}{peak - baseline}$$



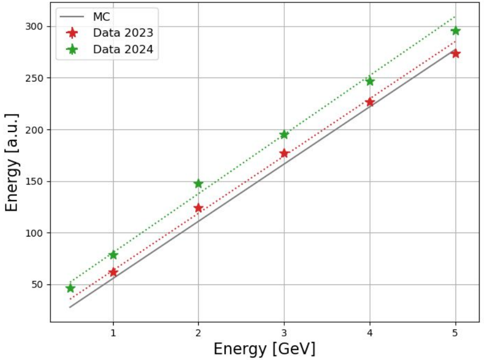


Calibration and energy resolution

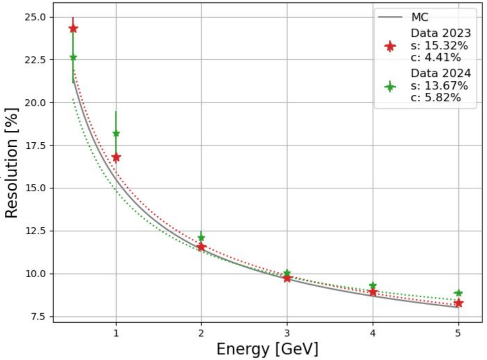
After the equalization, it is possible to sum the responses of the channels and measure the **energy deposited** by the incoming particles



Calibration



Energy resolution

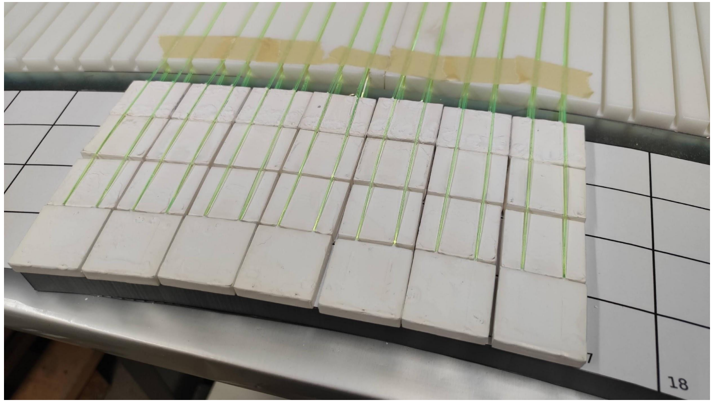


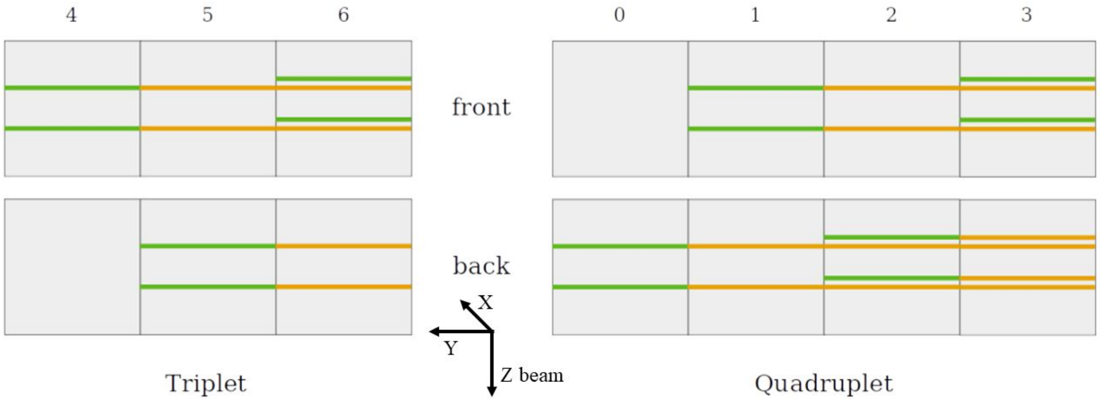
$$R = \frac{\sigma_E}{E} = \frac{s}{\sqrt{E}} \oplus c$$

→ **Linearity** and **energy resolution** values compatible with the ones from previous prototypes

Crosstalk analysis

- Crosstalk studied only for the first layer of the Demonstrator
- WLS fibers have to cross the upper tiles → some light could be lost





- **Readout fibers**
- **Transit fibers**

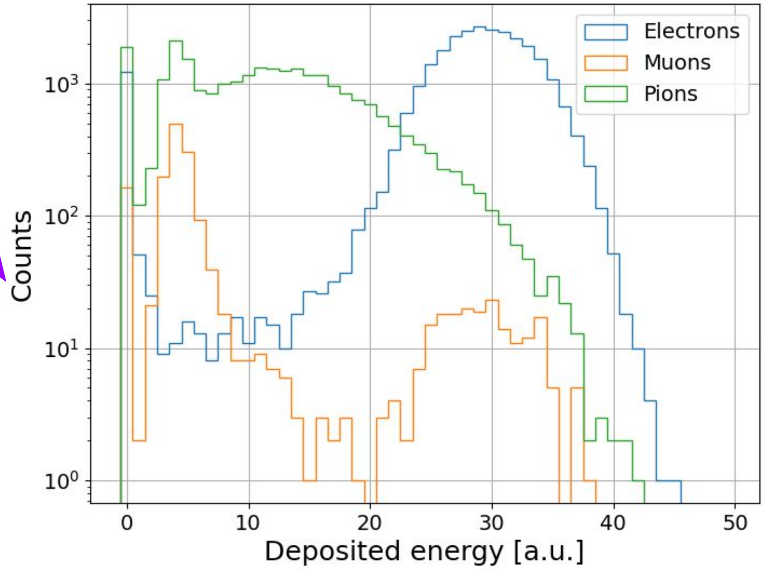
→ **Crosstalk < 5%** for all the tiles in the first layer through the years

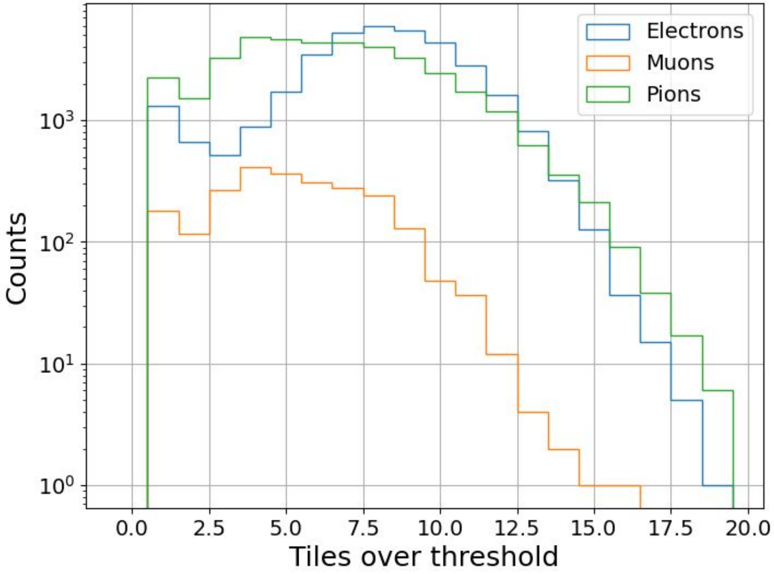
Particle IDentification test

Aim: discriminate electrons from other particles

For each event, two parameters were evaluated:

- ❖ Total number of **tiles over threshold**
- ❖ **Deposited energy** in the Demonstrator



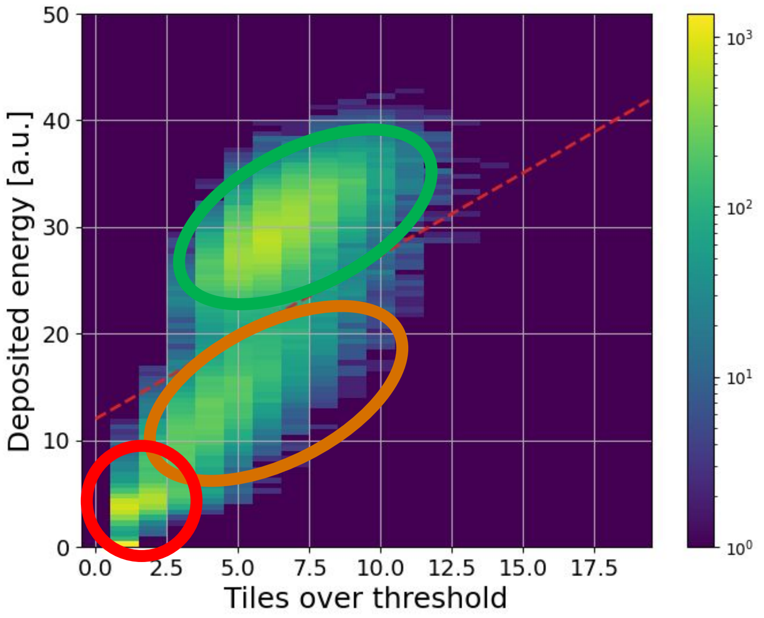


Predicted values:

- ❖ Events over threshold → **electrons**
- ❖ Events under threshold → **muons** and **hadrons**

True values obtained from the Cherenkov detectors:

- ❖ Signal in both detectors → **electrons**
- ❖ Only signal in the first detector → **muons**
- ❖ No signal in both detectors → **hadrons**



PRELIMINARY RESULTS

Accuracy → fraction of events correctly classified:

~ 78 % in classifying **electrons**

~ 76 % in classifying **muons** and **hadrons**

Precision → fraction of events correctly predicted:

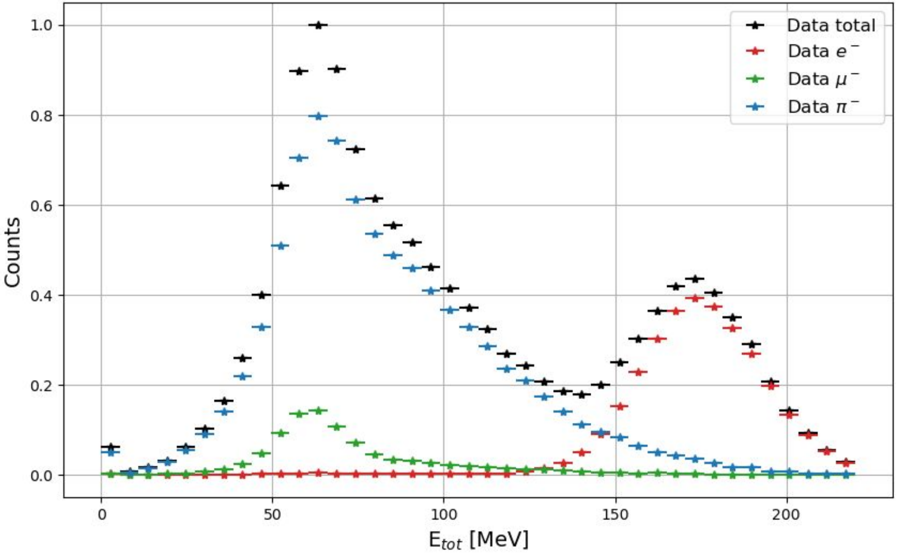
~ 73 % in classifying **electrons**

~ 87 % in classifying **muons** and **hadrons**

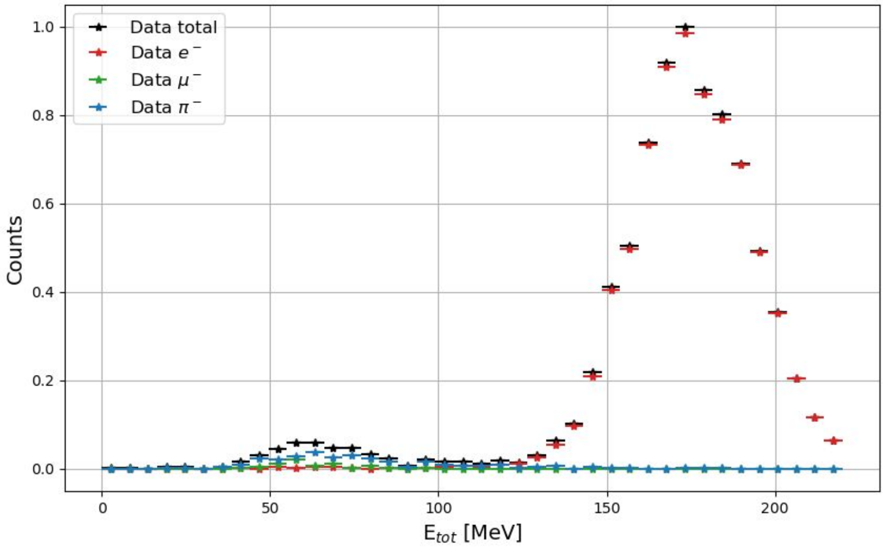
Deposited energy [1]

We have studied the particle energy deposit with different beams impinging on the Demonstrator in horizontal position

3 GeV hadron beam



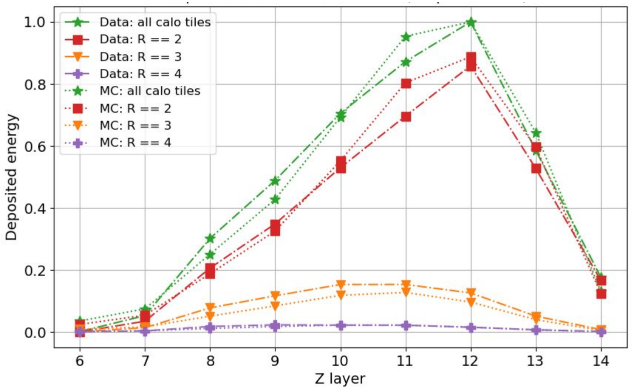
3 GeV electron beam



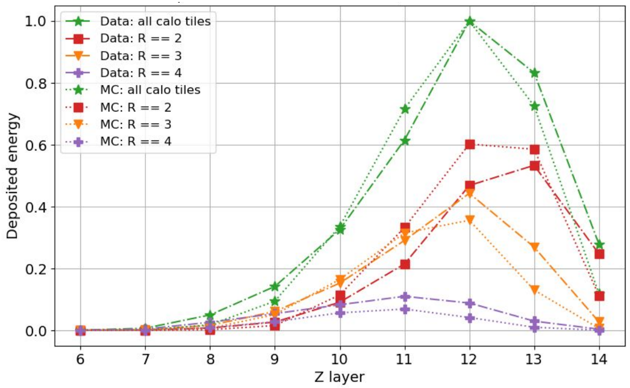
PRELIMINARY RESULTS

Deposited energy [2]

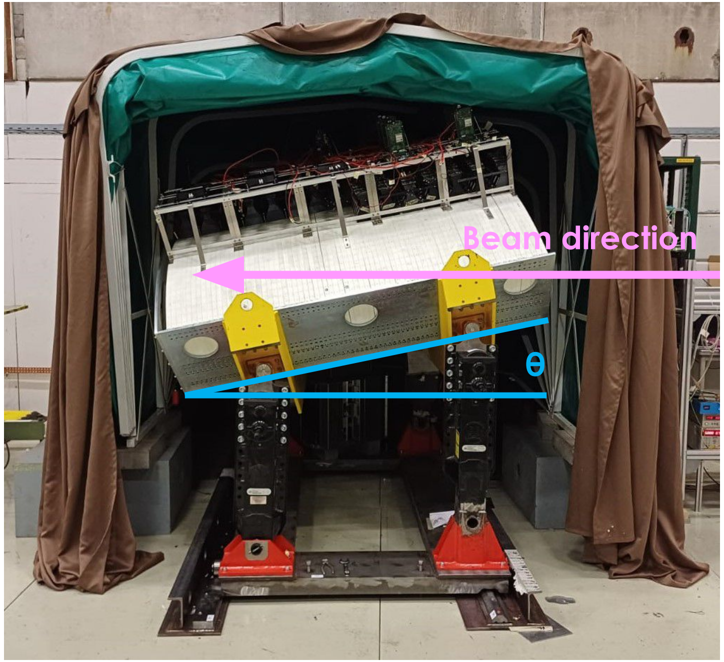
We have tilted the Demonstrator of 100 and 200 mrad to study the **energy deposit in the Z layers**



θ = 100 mrad



θ = 200 mrad



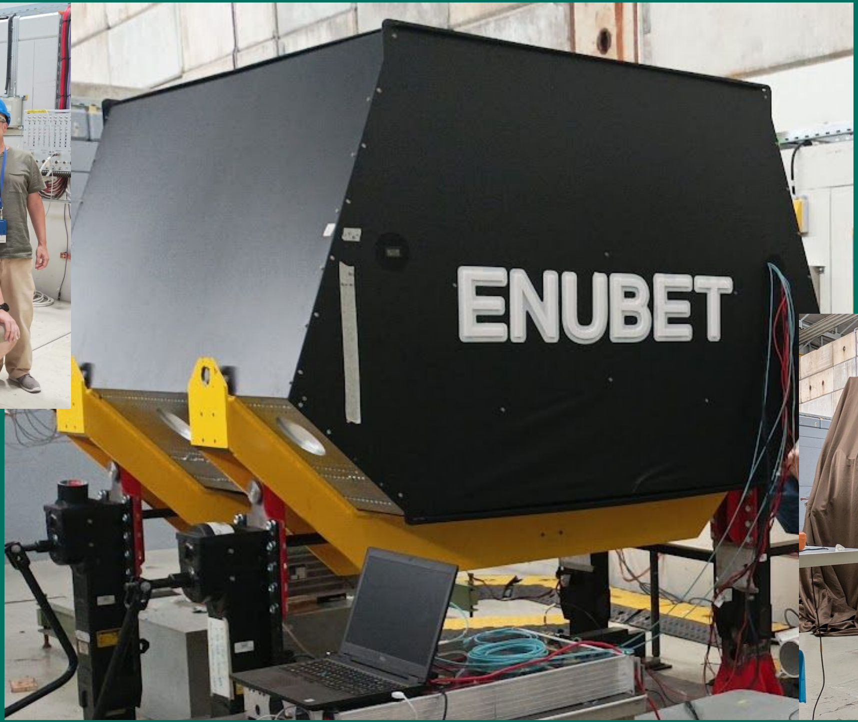
PRELIMINARY RESULTS

Conclusions

The preliminary results of the beamtests of the **ENUBET collaboration** showed:

- ✔ The **basic performance** of the Demonstrator
- ✔ Linearity and energy resolution values in agreement with previous smaller prototypes
- ✔ Crosstalk < 5 % for all the tiles of the first layer, which **validate the outward readout scheme** of the scintillating light
- ✔ **Good preliminary results in PID**
- ✔ **Good results in the study of the energy deposition**

Thanks for your attention!



References

[1] ESPP 2026 Update
[2] F. Terranova et al., arXiv (2025)
[3] A. Longhin et al., Eur. Phys. J. C (2015)
[4] G. Ballerini et al., JINST (2018)

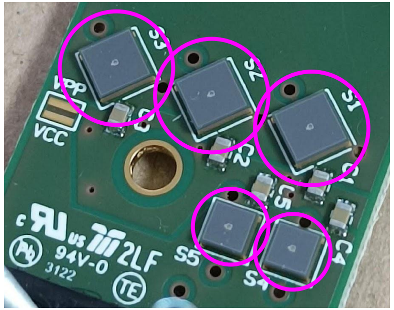
The ENUBET detector: detection principle

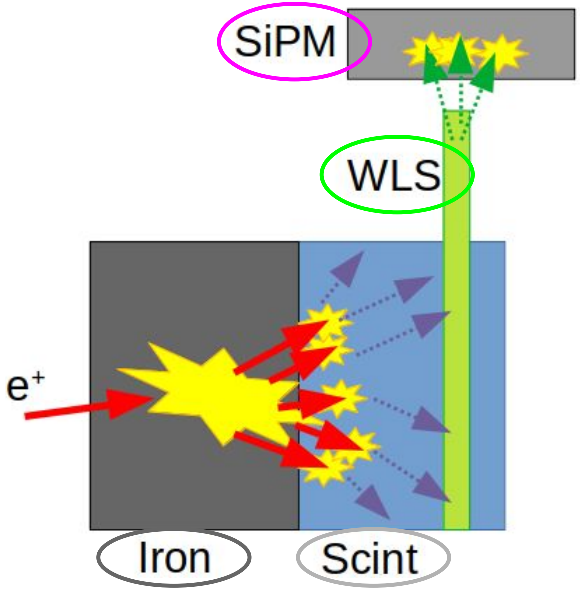
The ENUBET detector is a **segmented**, **inhomogeneous**, electromagnetic **calorimeter**

Plastic scintillator tiles interleaved with radiator material (Fe):

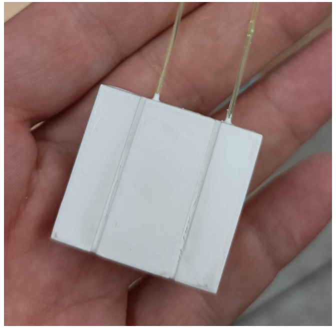
- an EM shower is produced in the **iron layers**
- charged products crossing the **scintillator tiles** cause scintillation (UV)
- scintillation light is shifted to green by **WLS** fibers and readout conveyed to a **SiPM**

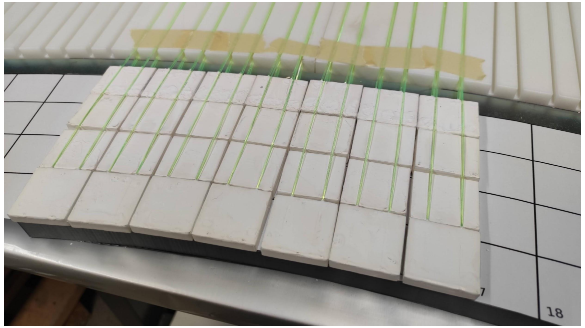
SiPM = array of Single-Photon Avalanche Diodes (SPAD), readout in parallel
→ signal proportional to # of incoming photons!

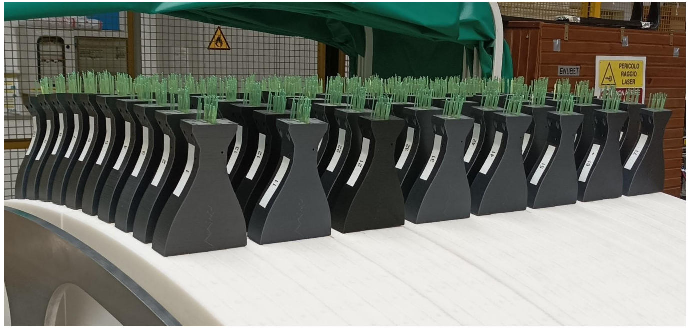


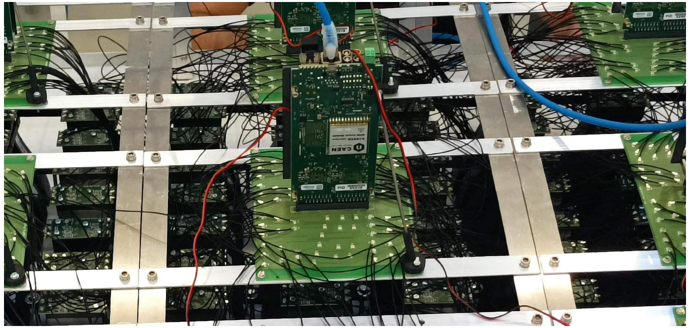


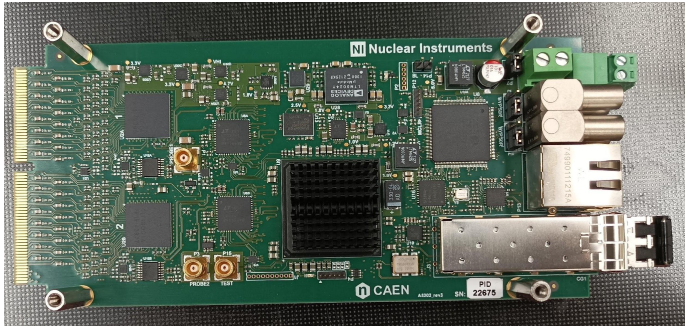
Construction

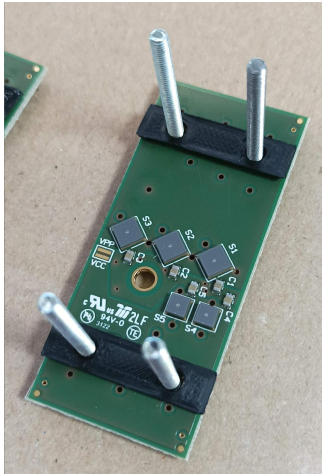












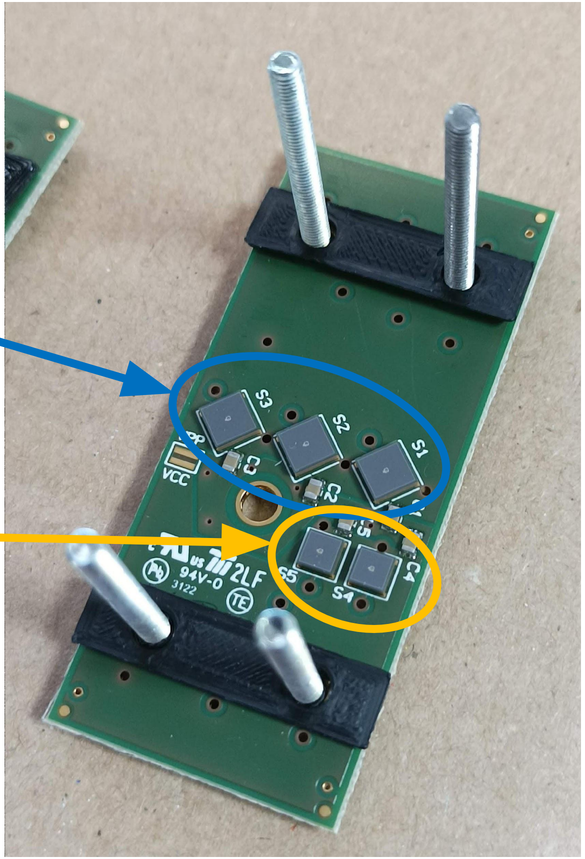
SiPMs information

Calorimetric tiles readout by Hamamatsu S14160-4050HS SiPMs:

- Active area 4 × 4 mm^2
- Pixel pitch: 50 μm

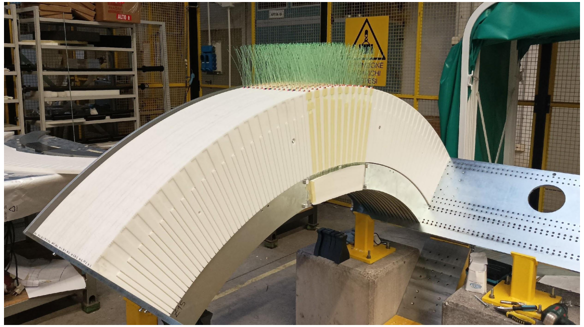
t_0 tiles readout by Hamamatsu S14160-3050HS SiPMs:

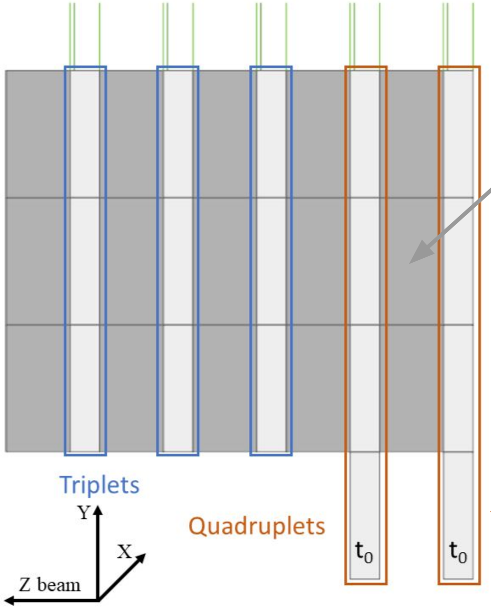
- Active area: 3 × 3 mm^2
- Pixel pitch: 50 μm



The ENUBET Demonstrator

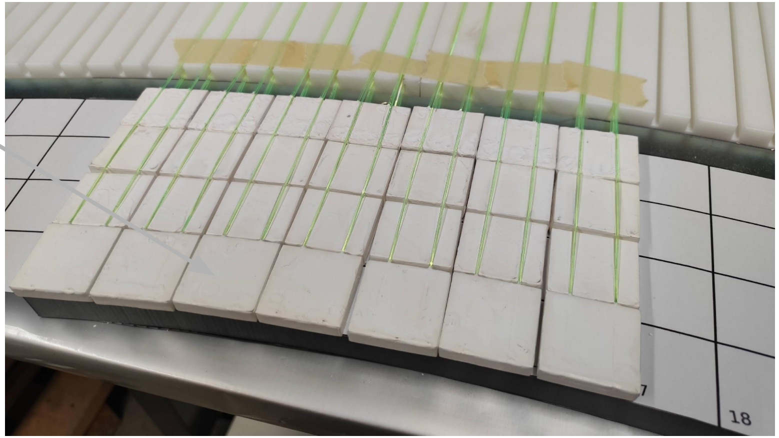
- **Largest prototype** of the ENUBET collaboration
- Composed of **75** alternated arches of iron and plastic scintillators spanning 45°:
  - 2022 version → **400 channels** readout by 400 SiPMs
  - 2023 version → **1200 channels** readout by 1200 SiPMs



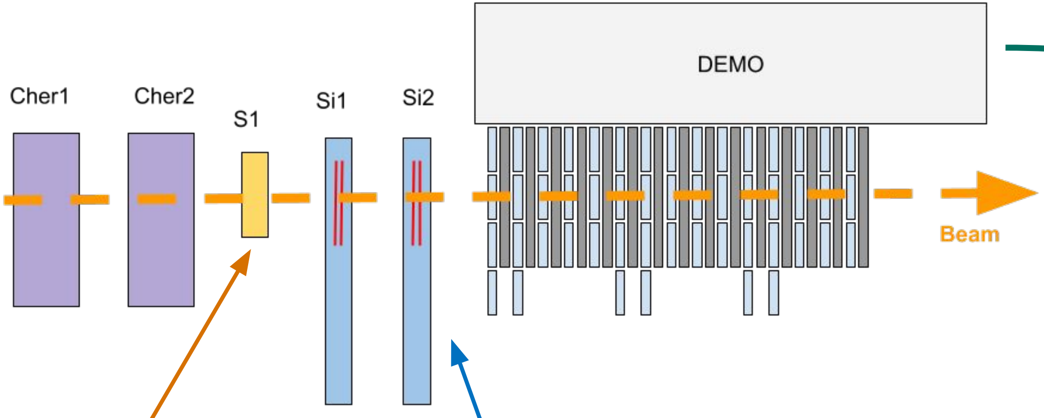


LCM composed of 5 arches of **iron** and 5 arches of **scintillator tiles** with an active area of 3 x 3 x 0.7 cm^3

Tile t_0 used as photon veto



The experimental setup

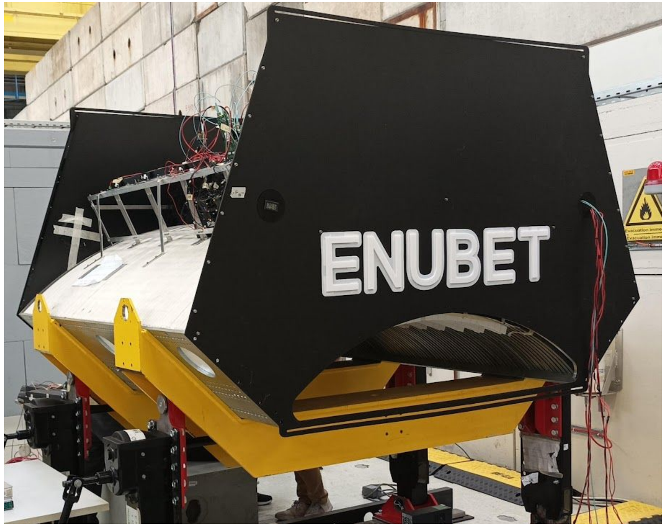


Trigger & Tracking system

Trackers:

- 2 single side microstrip detectors each
- Strip pitch: 242 μm
- Active area: 9.5 x 9.5 cm^2
- Spatial resolution: 30 μm

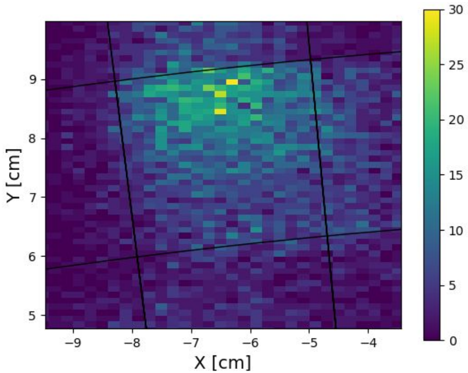
Demonstrator



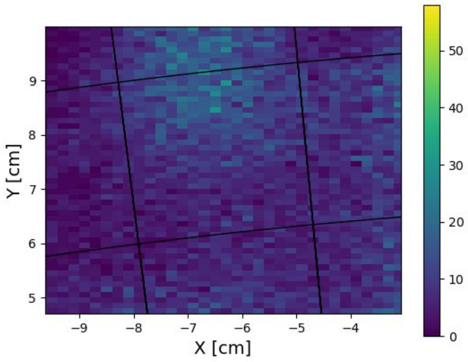
Efficiency map

Ratio of the number of **detected particles** over the number of **particles that hit** the tile

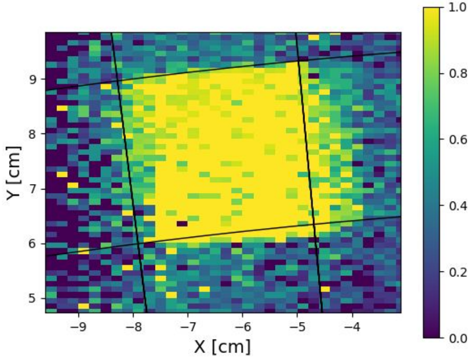
Detected particles



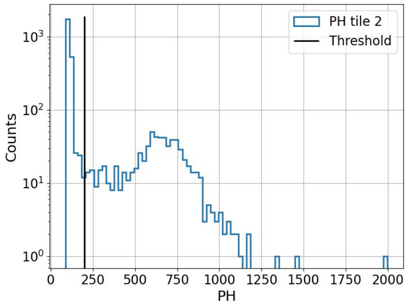
Hitting particles



Efficiency map

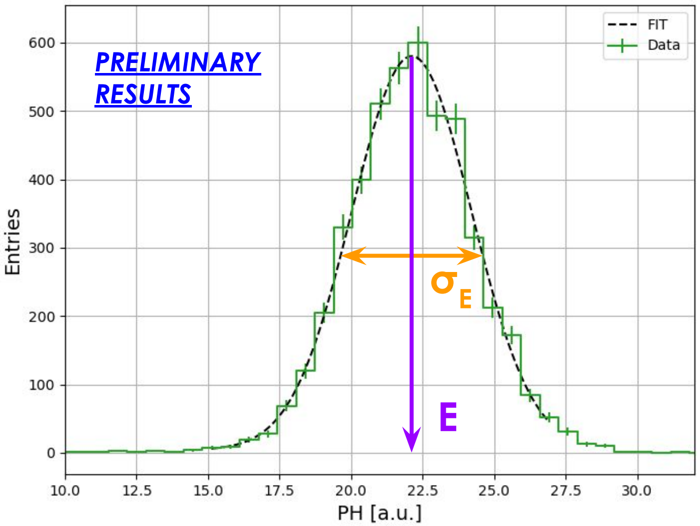


Particle selected with a PH threshold cut

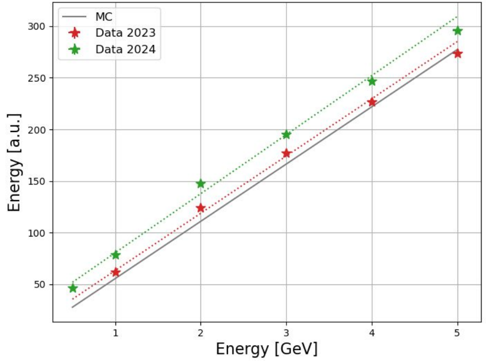


Calibration and energy resolution

After the equalization, it is possible to sum the responses of the channels and measure the **energy deposited** by the incoming particles

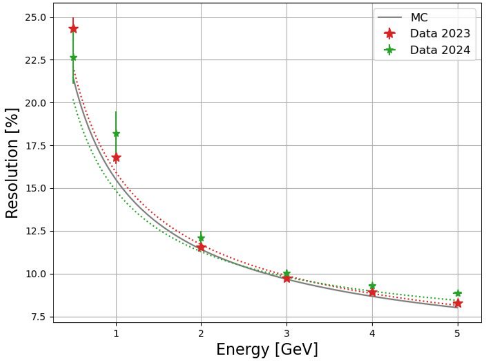


Calibration



Energy resolution

$$R = \frac{\sigma_E}{E} = \frac{s}{\sqrt{E}} \oplus c$$

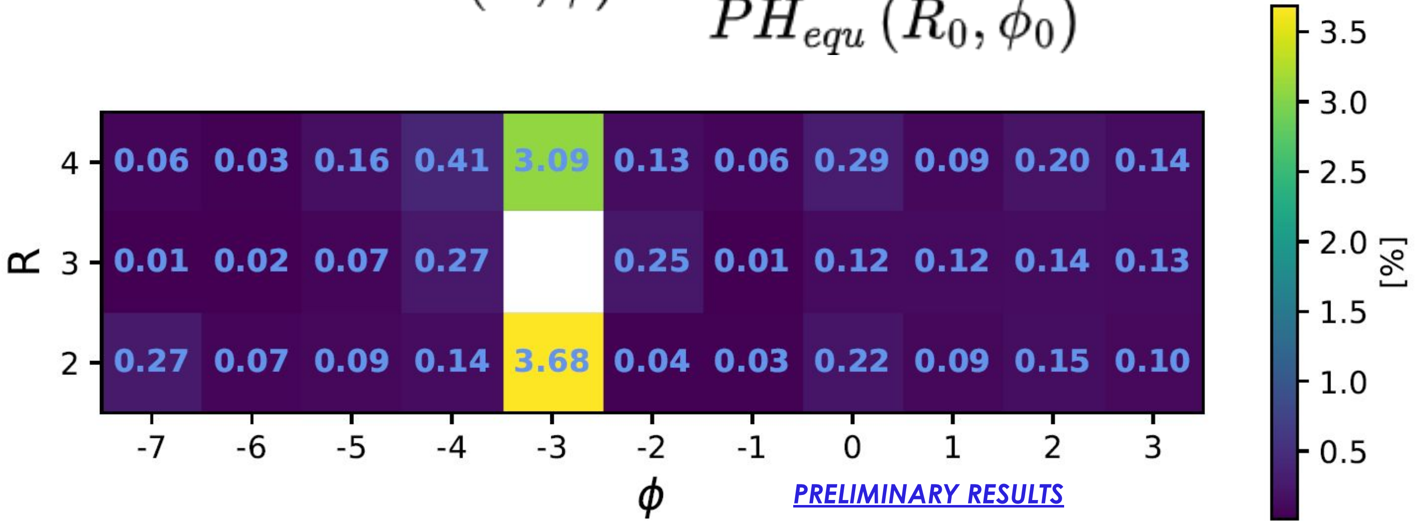


→ **Linearity** and **energy resolution** values compatible with the ones from previous prototypes

Crosstalk analysis

For each tile (R, Φ) of the first layer, the crosstalk has been computed as the ratio between the signal in neighbouring tiles and the signal in reference tile (R_0 , $Φ_0$):

$$ratio\,(R,\phi) = \frac{PH_{equ}\,(R,\phi)}{PH_{equ}\,(R_0,\phi_0)}$$



→ **Crosstalk < 5%** for all the tiles in the first layer for both the years

Accuracy and precision

❖ **Accuracy**: degree of closeness of the measured quantity to its true value, defined as:

(TP + TN) / (TP + TN + FP + FN)

❖ **Precision**: how close the measurements are to each other, defined as:

TP / (TP + FP)

Where:

- TP is true positive
- TN is true negative
- FP is false positive
- FN is false negative