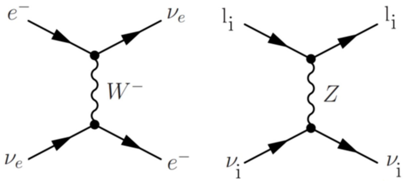
# Beamtest characterization of the ENUBET Demonstrator

Giosuè Saibene
PhD student at Università degli Studi dell'Insubria - DiSAT
Associate - INFN - sezione di Milano Bicocca

110° Congresso Nazionale
(Società Italiana di Fisica 2024)
Bologna, 09-13 settembre 2024
on behalf of the ENUBET Collaboration

# Neutrino physics

❖ Despite their abundance, their characteristics are not so well known




❖ They interact only by weak interaction

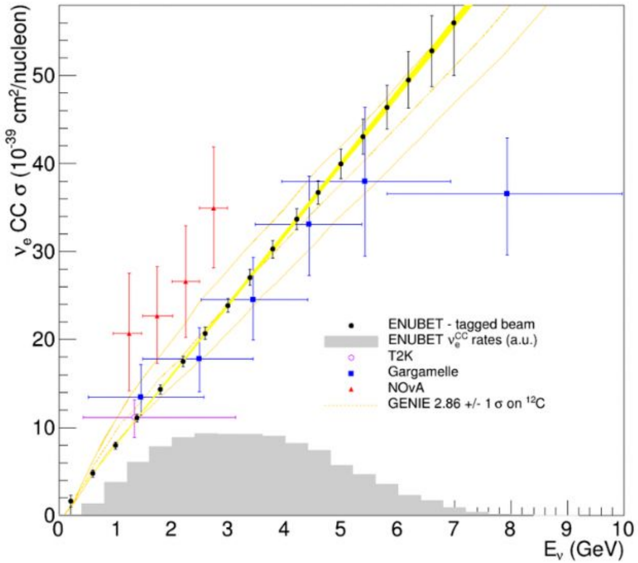
❖ Measurements of neutrino interaction event rates have some systematics:

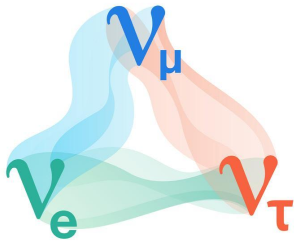
➢ the **neutrino flux**

➢ the **interaction cross section**

➢ the detector efficiency

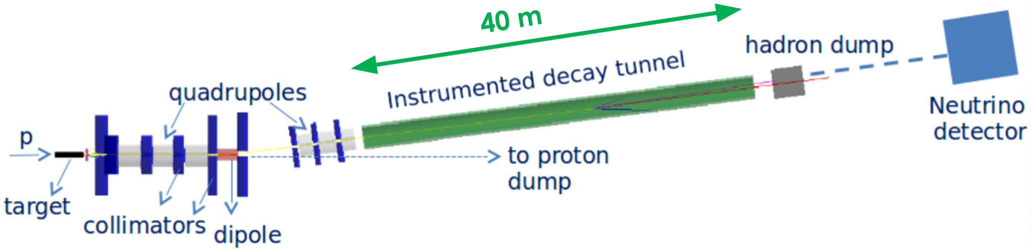
→ Need to reduce the systematics from 10 % to ~ 1 %

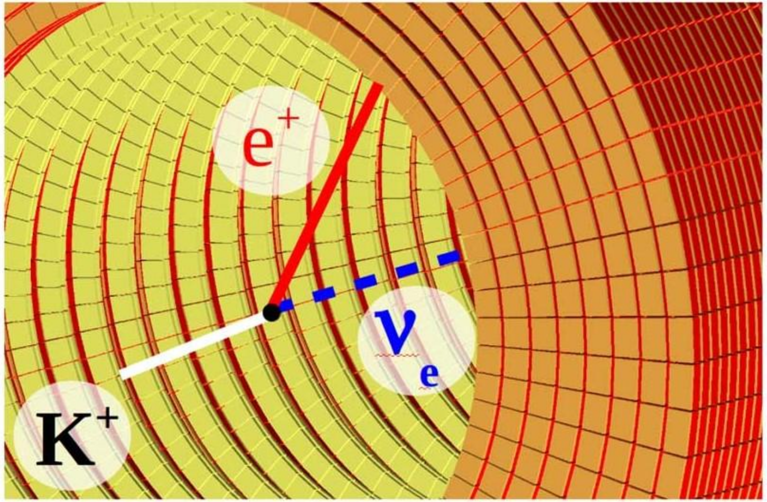


# The ENUBET project (ERC-Consolidator Grant 2015)

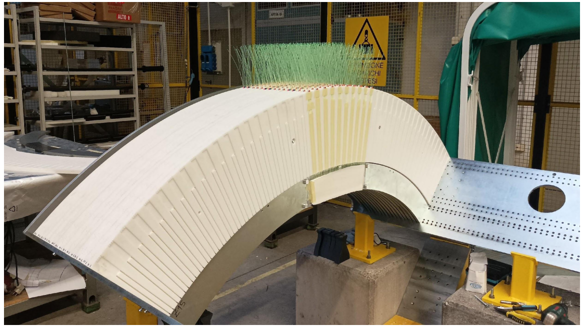
- Design a **pure** and **controlled** source of $\nu_e$
- Monitor the **neutrino flux** directly inside the **decay region**
- Detect the large-angle leptons generated in the decay: $K^+_{e3} \rightarrow e^+ \pi^0 \nu_e$

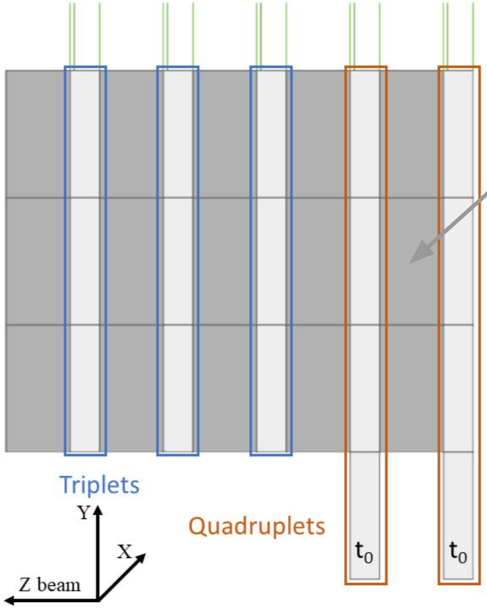


# The ENUBET Demonstrator

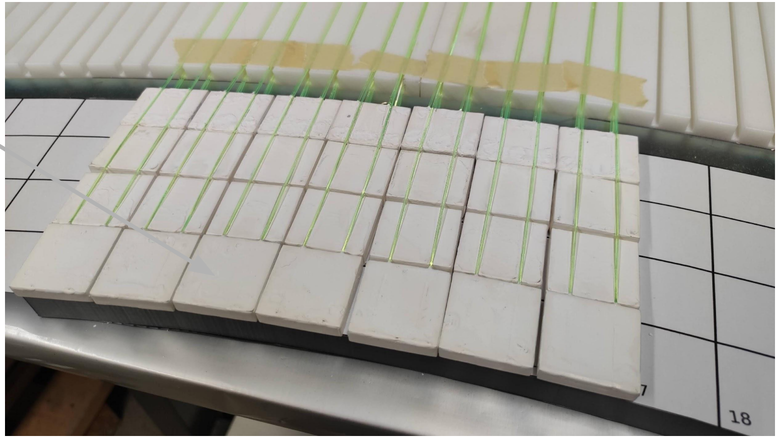
- **Largest prototype** of the ENUBET collaboration
- Composed of **75** alternated arches of iron and plastic scintillators spanning 45°:
  - 2022 version → **400 channels** readout by 400 SiPMs
  - 2023 version → **1200 channels** readout by 1200 SiPMs






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 ENUBET detector: particle discrimination

Study of the energy deposit and event topology → Particle discrimination

$e^+$ (signal) topology

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

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

$\pi^\pm$ (background) topology

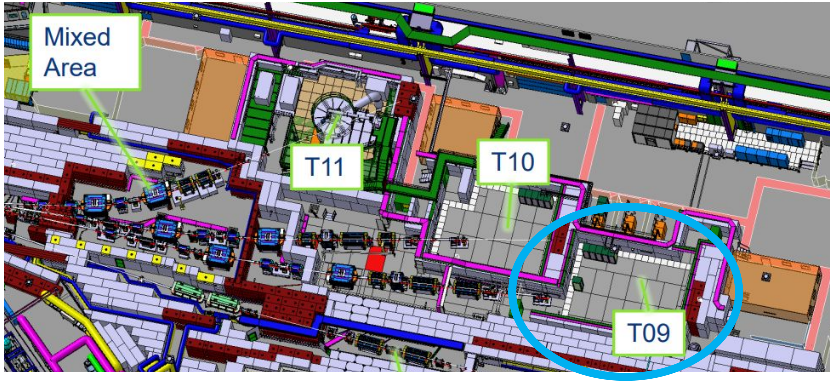
- Scintillating tiles
- Hit tiles → energy deposited by particles
- Hit $t_0$ tiles → photon veto tiles

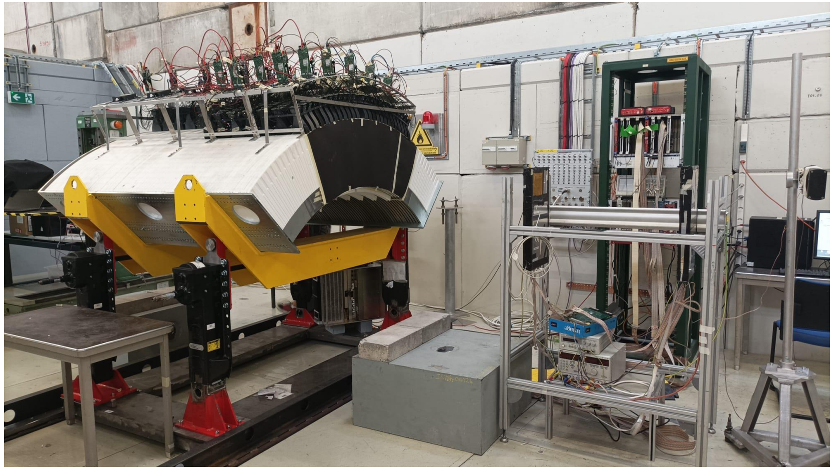
| Decay | | BR (%) | Comment |
|---|---|---|---|
| $\pi^+ \rightarrow \mu^+\nu_\mu$ | | $\sim 100$ | Hadron dump |
| $K^+ \rightarrow \mu^+\nu_\mu$ | | 63.56(11) | Background |
| $K^+ \rightarrow \pi^+\pi^+\pi^-$ | | 5.58(2) | Background |
| $K^+ \rightarrow e^+\pi^0\nu_e$ | called $K^+_{e3}$ | 5.07(4)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

# The ENUBET beamtests @ CERN PS

In 2022 and 2023, two beamtests have been done at the CERN PS **T9 extracted beamline**. Goals:

- ❑ Verify the feasibility and **basic performance** of the design
- ❑ Measure the **linearity** and **energy resolution** of the largest prototype of the collaboration, the **Demonstrator**
- ❑ Study the **crosstalk** of the scintillator planes
- ❑ Preliminary **Particle IDentification (PID)** test

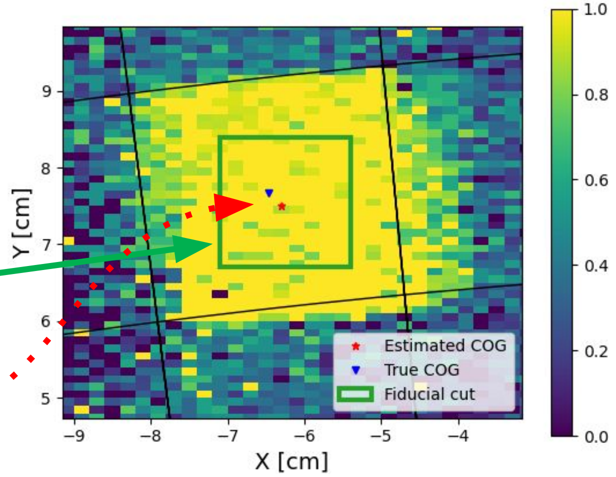


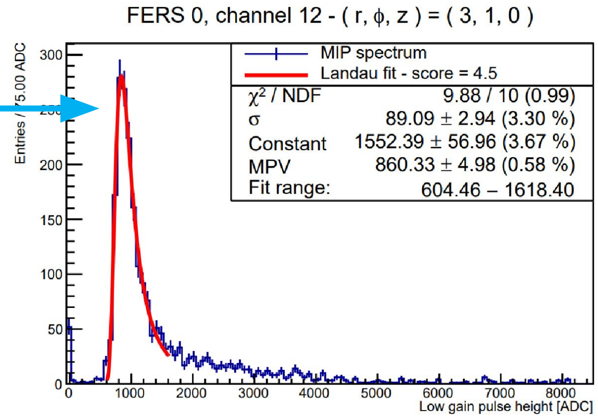



# Equalization of the channels

- The scintillating tiles of the Demonstrator are readout by SiPMs:
  - Calorimetric tiles are 2/3 of the total
  - $t_0$ veto tiles are 1/3 of the total
- Selecting MIP events with a trajectory falling in the **fiducial cut**
- The **COG** was estimated with the efficiency map of each tile
- Fit the MIP **peak** and equalize the channels:

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

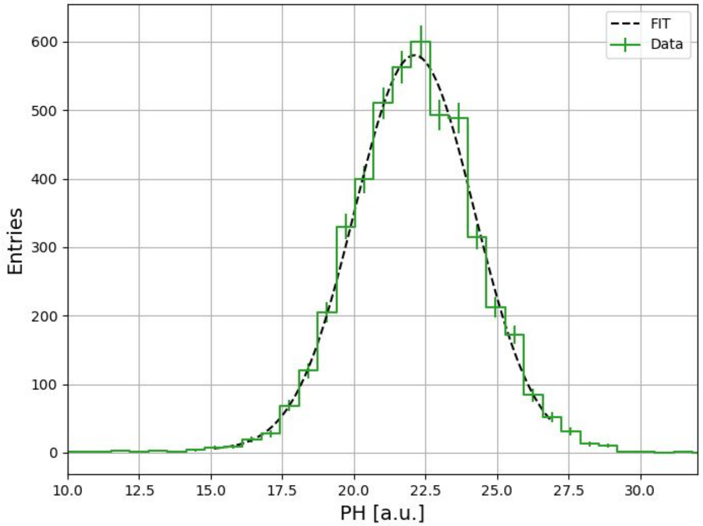


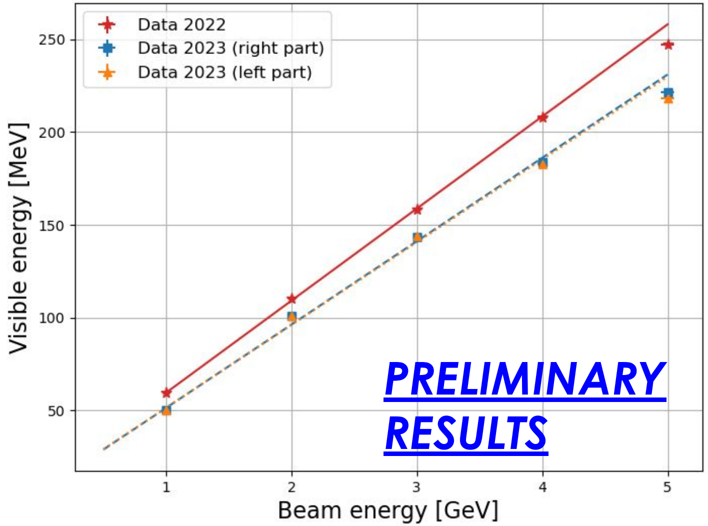
# Calibration and linearity

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

→ Find the correspondence between the PH (measured in arbitrary unit) and energy (in GeV) deposited by the incoming particles



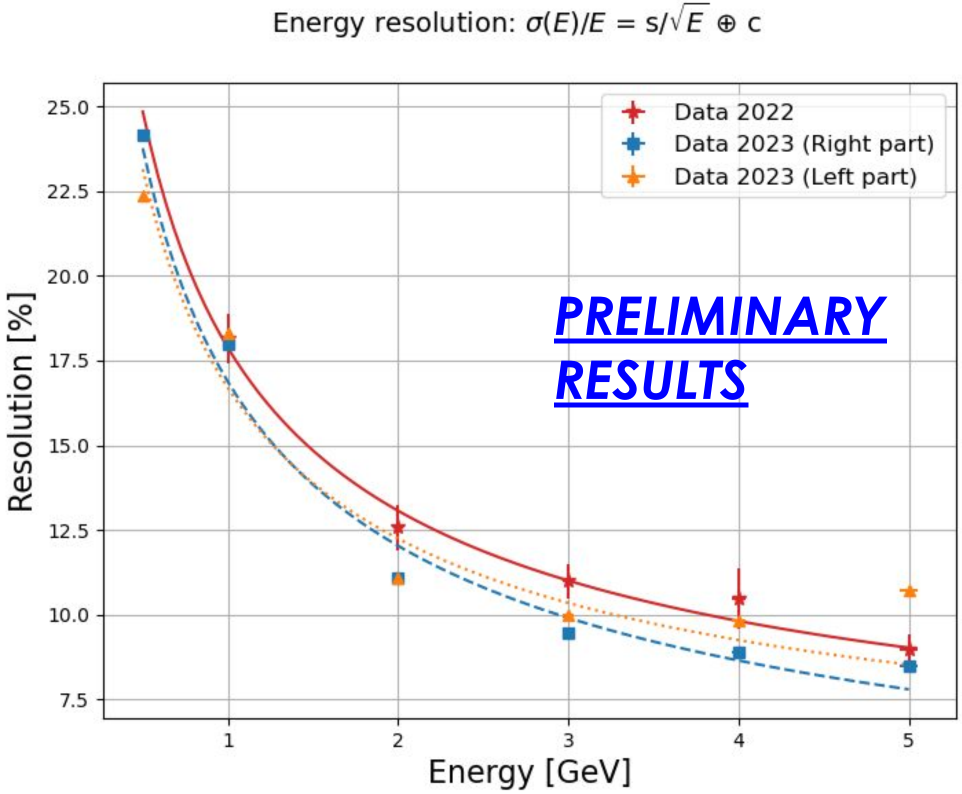

$E_{ADC}$ ----> $E_{GeV}$



# Energy resolution (2022 & 2023)

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

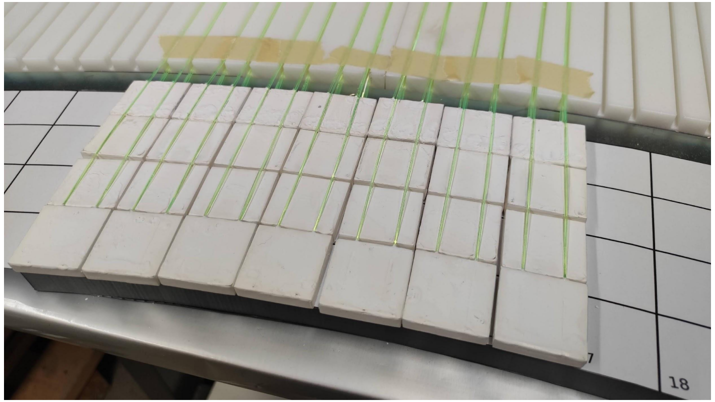
- **E**: calibrated energy in GeV
- **$\sigma_E$**: standard deviation of the energy fit
- **s**: stochastic term
- **c**: constant term

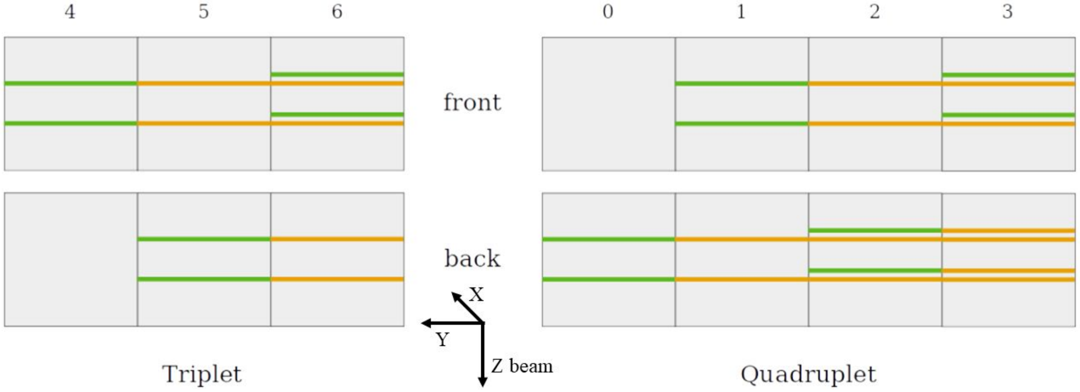



→ **Linearity** and **energy resolution** values compatible with the ones from previous prototypes

# Crosstalk analysis (2022 & 2023)

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

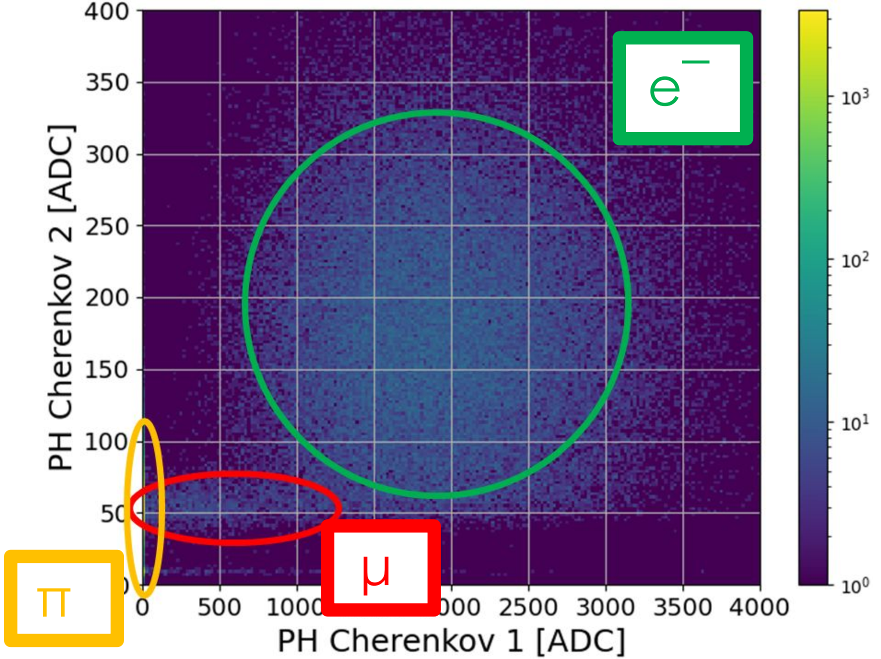


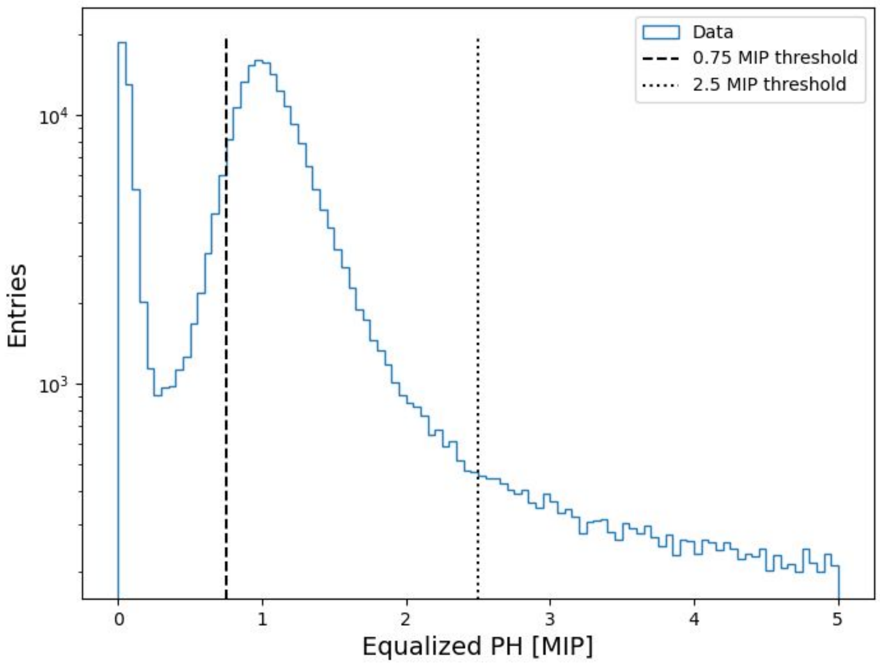



- Readout fibers
- Transit fibers

Selected MIP events using Cherenkov detectors:

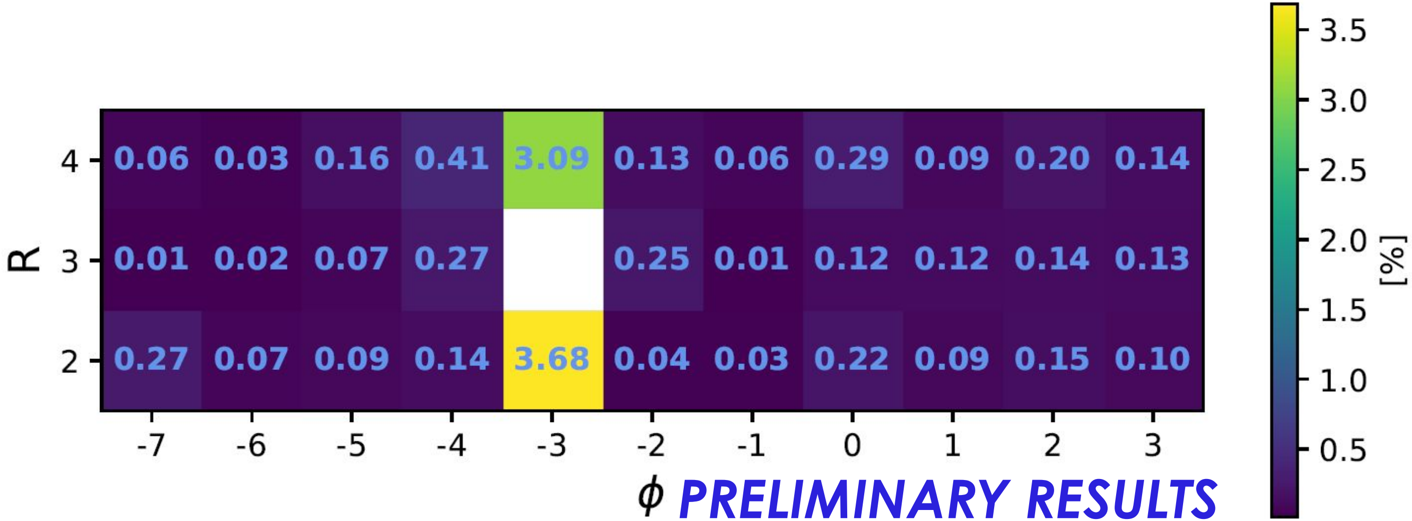
- **Muons**
- **Electrons** and **pions** with a $PH_{equ}$ ~ 1 MIP



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 ($R_0$, $Φ_0$):

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



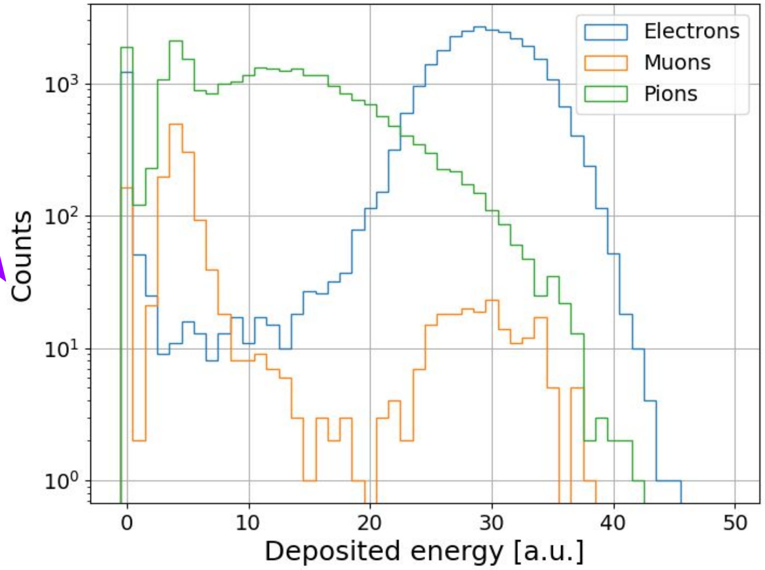

***PRELIMINARY RESULTS***

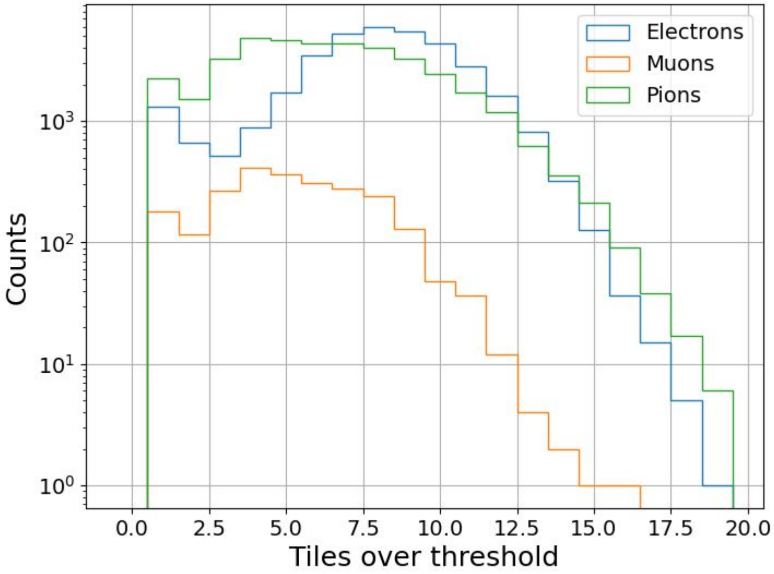
→ **Crosstalk < 5%** for all the tiles in the first layer for both the years

# Preliminary Particle IDentification test (2022)

Aim: discriminate electrons from other particles

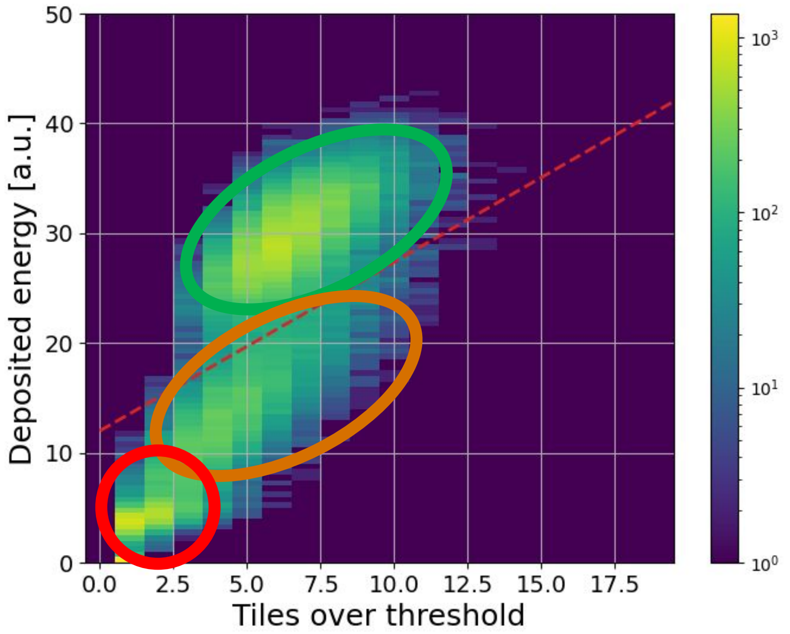
For each event, two parameters were evaluated:
- ❖ Total number of **tiles over threshold**
- ❖ **Deposited energy** in the Demonstrator



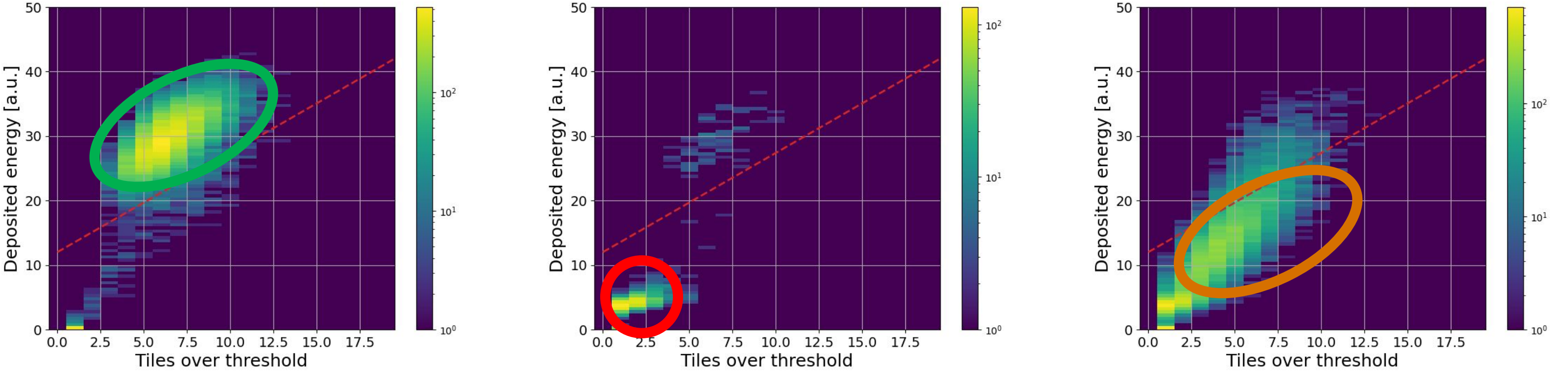
Predicted values:

- ❖ 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**




Accuracy → fraction of events correctly classified: (TP + TN) / (TP + TN + FP + FN)

~ 78 % in classifying **electrons**

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

Precision → fraction of events correctly predicted: TP / (TP + FP)

~ 73 % in classifying **electrons**

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

***PRELIMINARY RESULTS***

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

# Conclusions

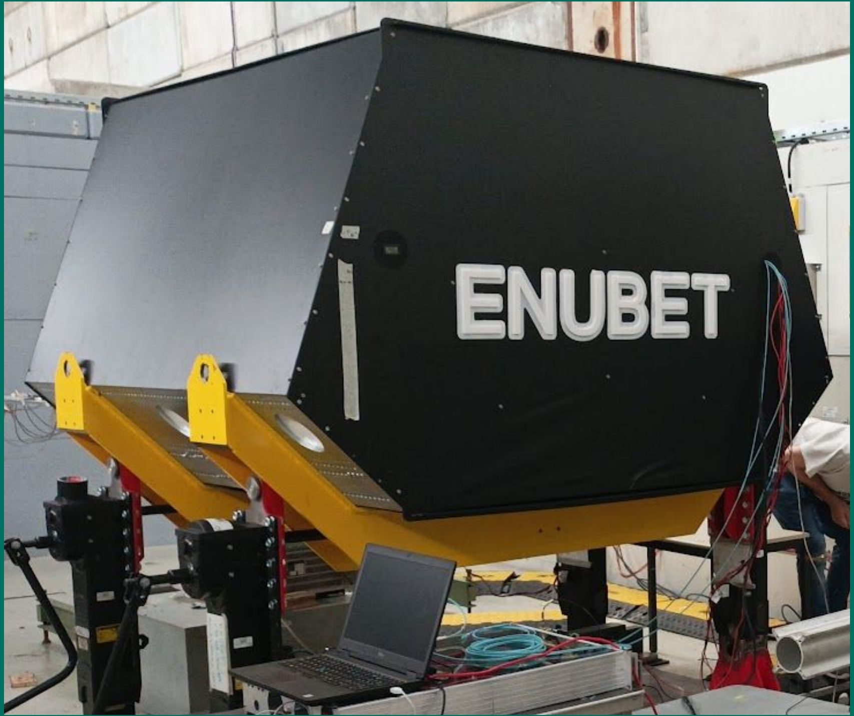
The preliminary results of the 2022 and 2023 beamtests of the **ENUBET collaboration** showed:

- ✔ 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** (2022)

Next steps:

- ❑ Improve the PID algorithm
- ❑ Analyze the 2024 beamtest data
- ❑ Verify the results with the simulations (Toolkit GEANT4)
- ❑ Publication of the 2022 and 2023 beamtest results
- ❑ Study of feasibility to implement the experiment at CERN

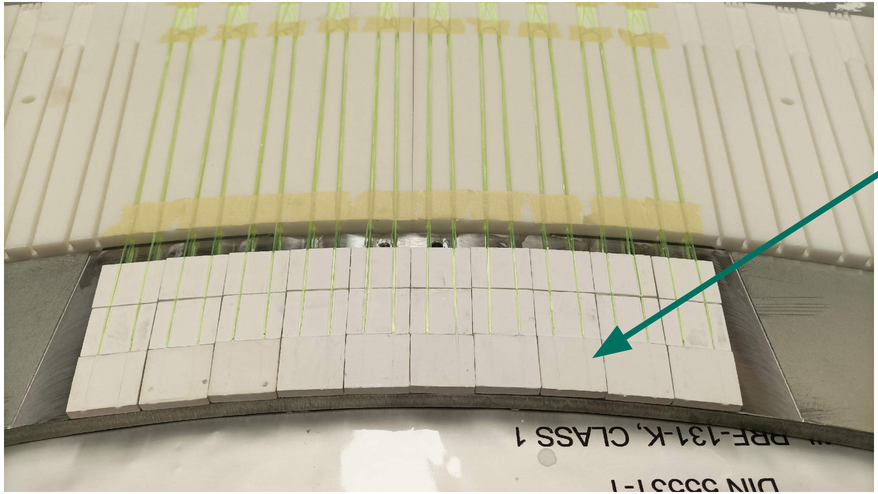
# Thanks for your attention!



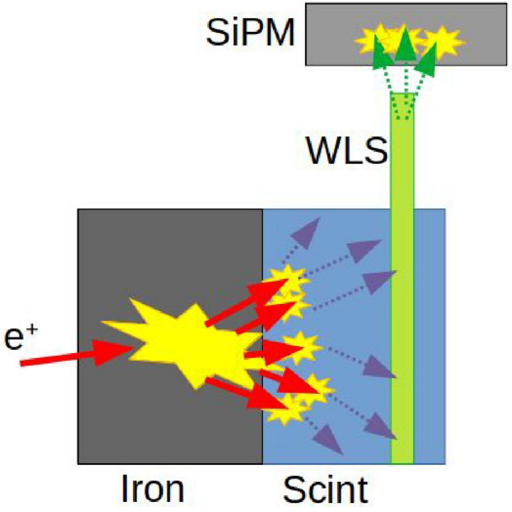

# The ENUBET detector: detection principle

**Plastic scintillator** tiles interleaved with **radiator material** (Fe):

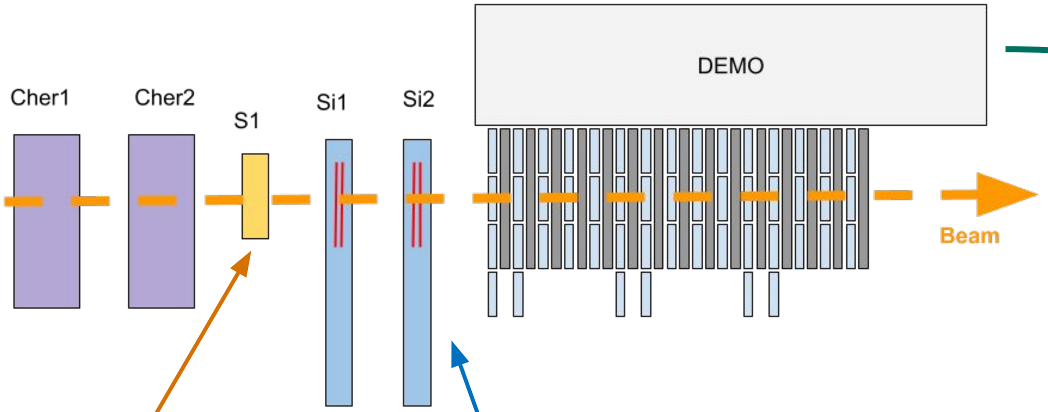
- An EM shower is produced in the iron layers
- Charged products crossing the scintillator tiles cause **scintillation** (UV)
- Scintillation light exit in the outward direction in **WLS fibers**
- Light readout by **SiPMs** → signal proportional to the number of incoming photons



Active area of a scintillating tile: $3 \times 3 \times 0.7\ \mathrm{cm}^3$



# The experimental setup (2022 & 2023)

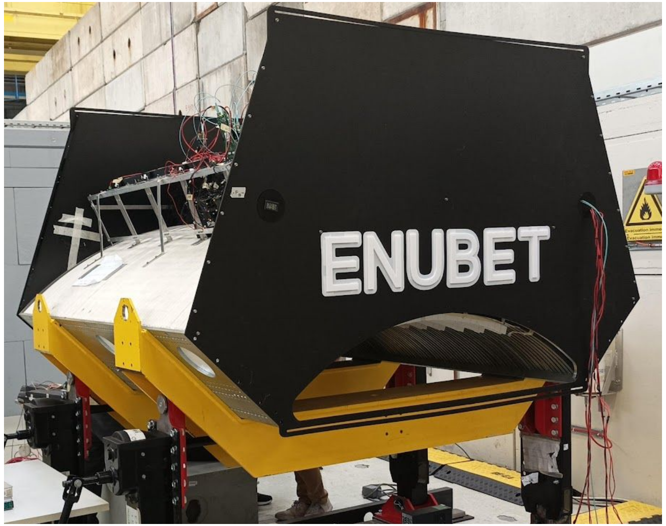



Trigger & Tracking system


Trackers:

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

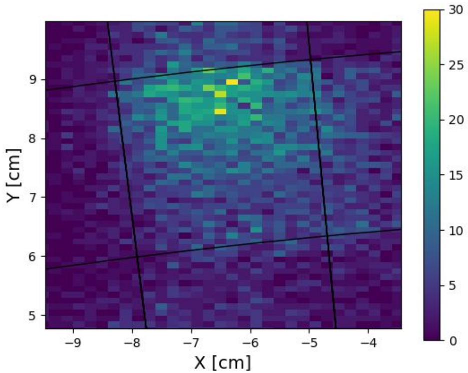
## Demonstrator



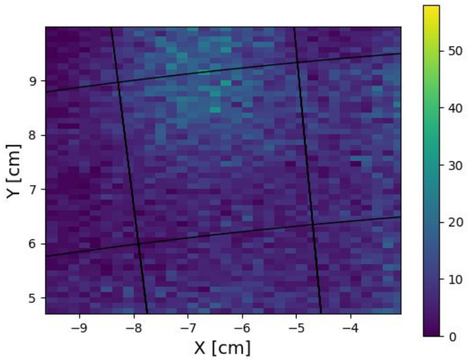
# Efficiency map

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

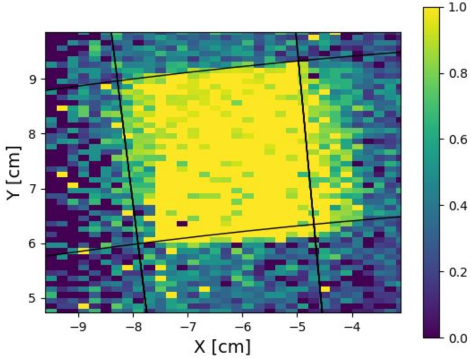
Detected particles



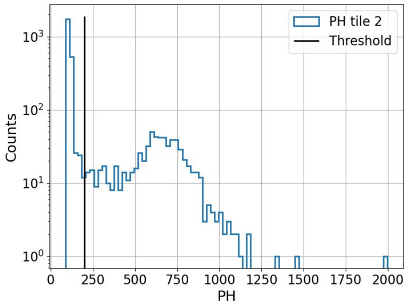

Hitting particles



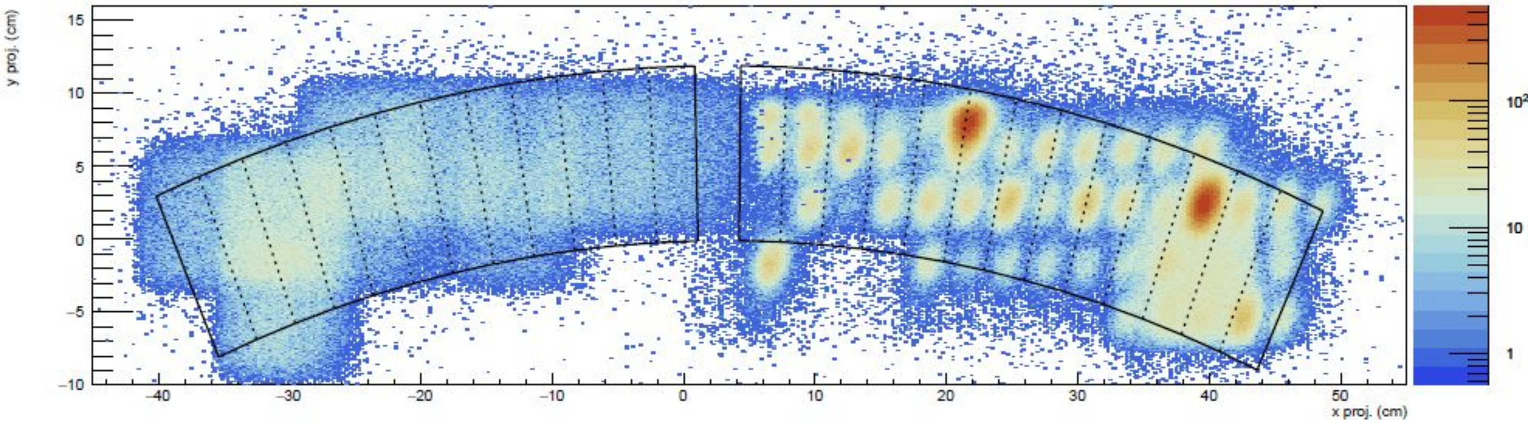

**Efficiency map**



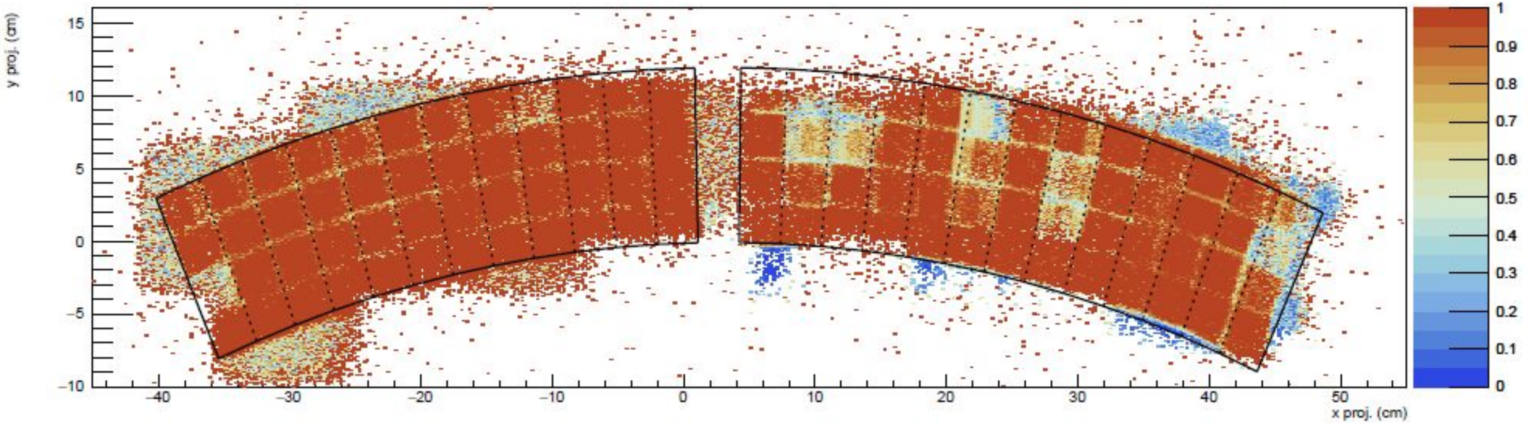

Particle selected with a PH threshold cut



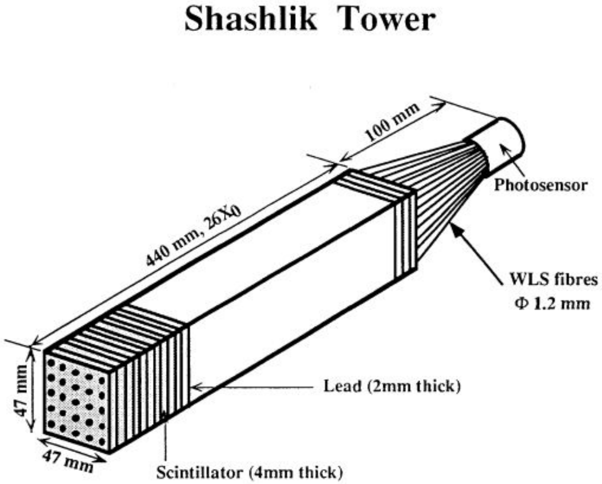
# Efficiency map 2023

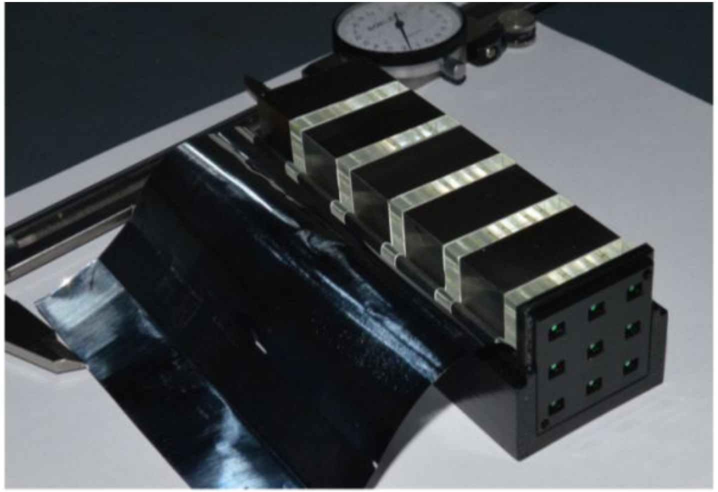


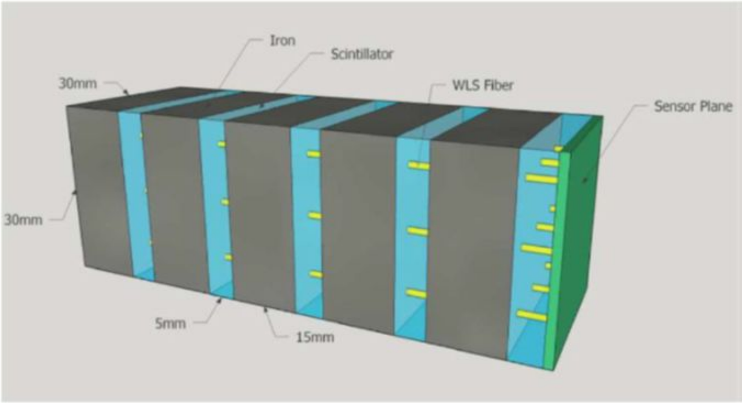

**PRELIMINARY RESULTS**



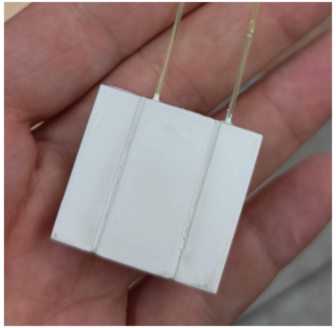
# Shashlik configuration

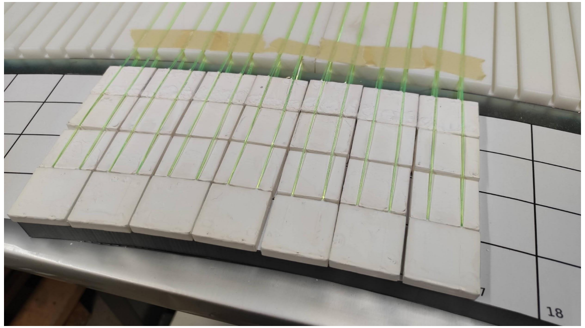


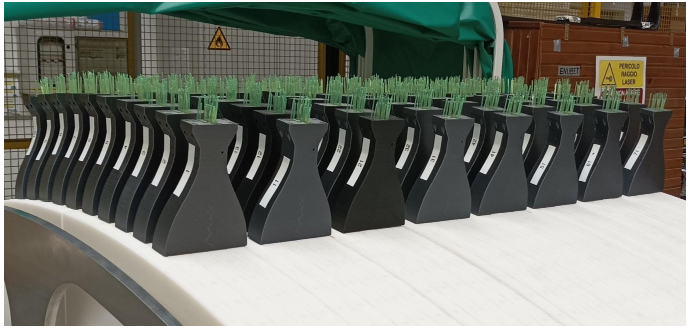



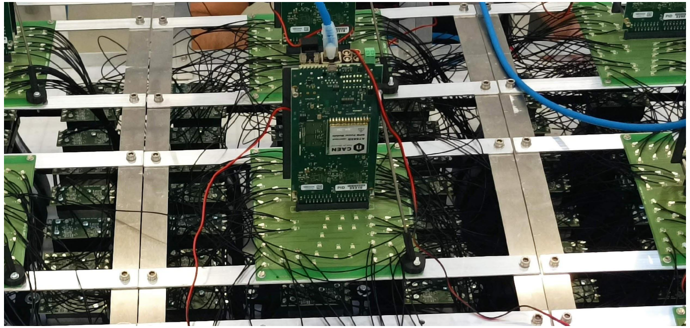


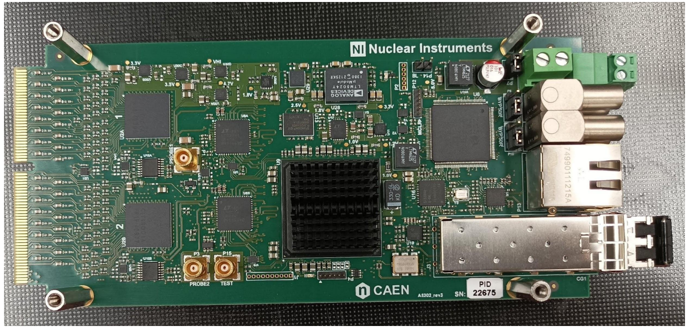
# Construction

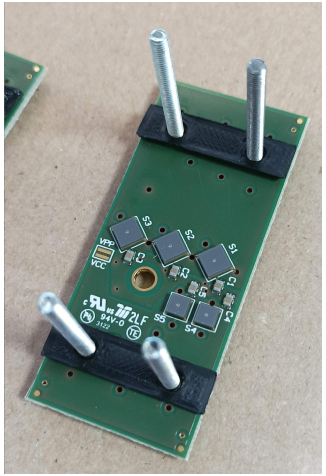




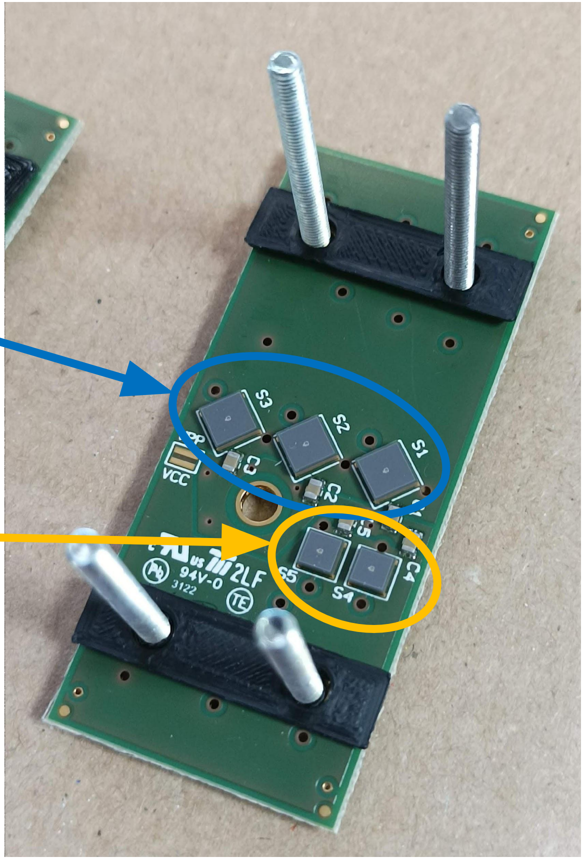




# SiPMs information



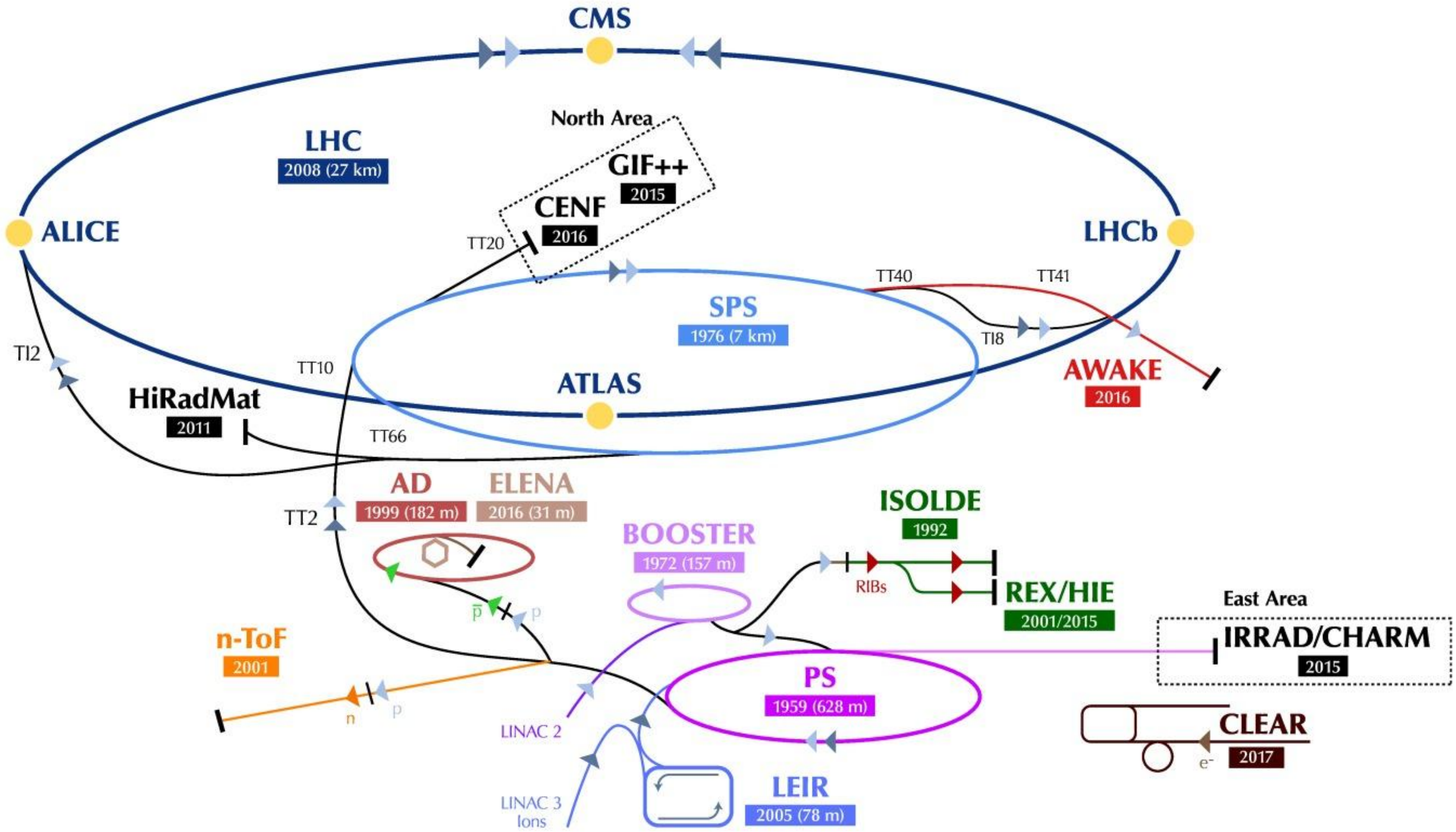

**Calorimetric tiles** readout by Hamamatsu S14160-4050HS SiPMs:

- 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

# CERN


CMS
North Area
LHC
2008 (27 km)
GIF++
2015
CENF
2016
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT66
AD
1999 (182 m)
ELENA
2016 (31 m)
ISOLDE
1992
TT2
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
East Area
IRRAD/CHARM
2015
n-ToF
2001
p̄
p
PS
1959 (628 m)
n
p
LINAC 2
CLEAR
2017
e⁻
LINAC 3
Ions
LEIR
2005 (78 m)

# Demonstrator 2023

**1st calibration run**
**Hadron run**

Conc. 154

Anode 25

Anode 26

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | | | | | | | | | 81 | 106 | 131 | 156 | 181 | 206 | 231 |
| 16 | | | | | | | | | 82 | 107 | 132 | 157 | 182 | 207 | 232 |
| 15 | | | | | | | | | 83 | 108 | 133 | 158 | 183 | 208 | 233 |
| 14 | | | | | | | | | 84 | 109 | 134 | 159 | 184 | 209 | 234 |
| 13 | | | | | | | | | 85 | 110 | 135 | 160 | 185 | 210 | 235 |
| 12 | | | | | | | | | 86 | 111 | 136 | 161 | 186 | 211 | 236 |
| 11 | | | | | | | | | 87 | 112 | 137 | 162 | 187 | 212 | 237 |
| 10 | | | | | | | | | 88 | 113 | 138 | 163 | 188 | 213 | 238 |
| 9 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 89 | 114 | 139 | 164 | 189 | 214 | 239 |
| 8 | 9 | 19 | 29 | 39 | 49 | 59 | 69 | 79 | 90 | 115 | 140 | 165 | 190 | 215 | 240 |
| 7 | 8 | 18 | 28 | 38 | 48 | 58 | 68 | 78 | 91 | 116 | 141 | 166 | 191 | 216 | 241 |
| 6 | 7 | 17 | 27 | 37 | 47 | 57 | 67 | 77 | 92 | 117 | 142 | 167 | 192 | 217 | 242 |
| 5 | 6 | 16 | 26 | 36 | 46 | 56 | 66 | 76 | 93 | 118 | 143 | 168 | 193 | 218 | 243 |
| 4 | 5 | 15 | 25 | 35 | 45 | 55 | 65 | 75 | | | | | | | |
| 3 | 4 | 14 | 24 | 34 | 44 | 54 | 64 | 74 | 94 | 119 | 144 | 169 | 194 | 219 | 244 |
| 2 | 3 | 13 | 23 | 33 | 43 | 53 | 63 | 73 | 95 | 120 | 145 | 170 | 195 | 220 | 245 |
| 1 | 2 | 12 | 22 | 32 | 42 | 52 | 62 | 72 | 96 | 121 | 146 | 171 | 196 | 221 | 246 |
| 0 | 1 | 11 | 21 | 31 | 41 | 51 | 61 | 71 | 97 | 122 | 147 | 172 | 197 | 222 | 247 |
| -1 | | | | | | | | | 98 | 123 | 148 | 173 | 198 | 223 | 248 |
| -2 | | | | | | | | | 99 | 124 | 149 | 174 | 199 | 224 | 249 |
| -3 | | | | | | | | | 100 | 125 | 150 | 175 | 200 | 225 | 250 |
| -4 | | | | | | | | | 101 | 126 | 151 | 176 | 201 | 226 | 251 |
| -5 | | | | | | | | | 102 | 127 | 152 | 177 | 202 | 227 | 252 |
| -6 | | | | | | | | | 103 | 128 | 153 | 178 | 203 | 228 | 253 |
| -7 | | | | | | | | | 104 | 129 | 154 | 179 | 204 | 229 | 254 |
| -8 | | | | | | | | | 105 | 130 | 155 | 180 | 205 | 230 | 255 |

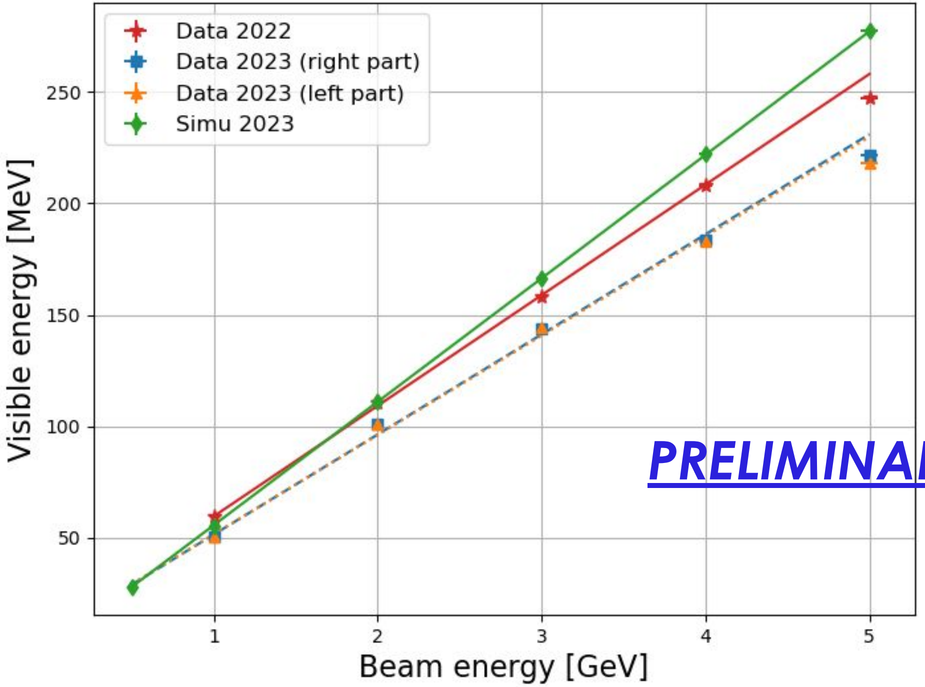
1st electron run

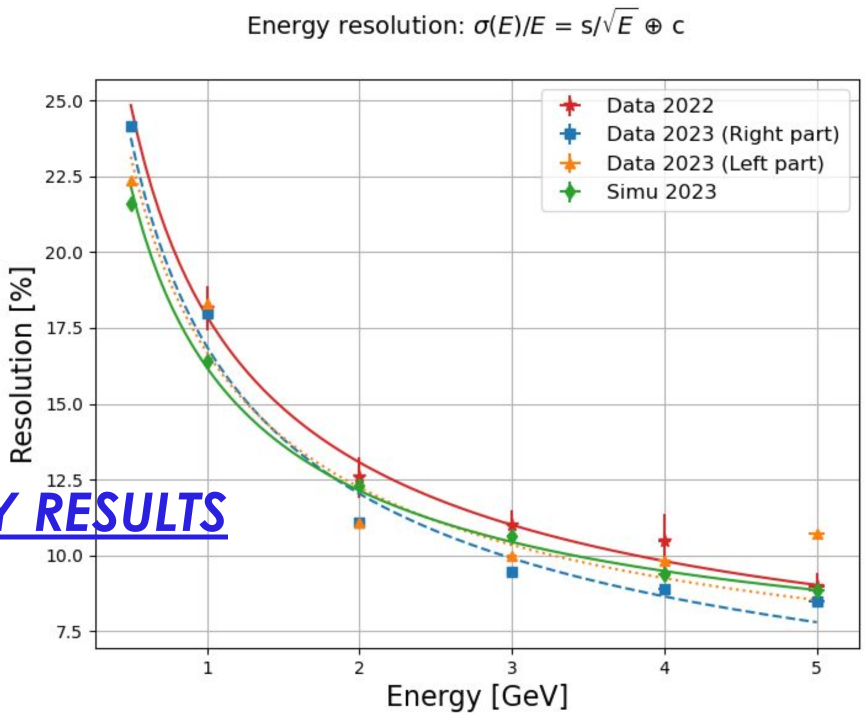
Beam direction

2nd electron run

**2nd calibration run**
**Muon run**

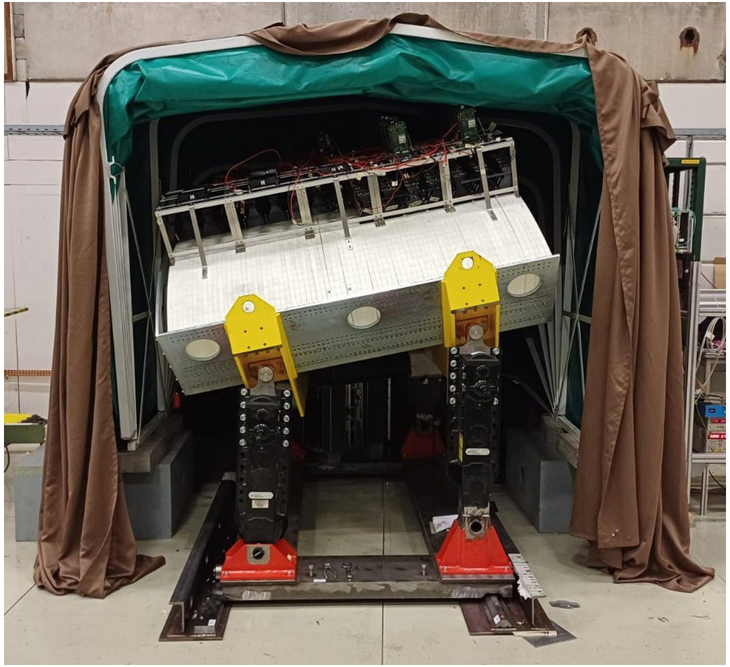
# Linearity & Energy resolution → Simulation

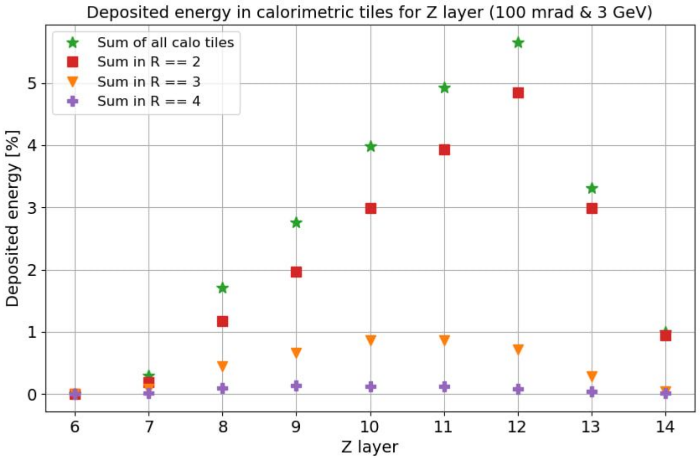


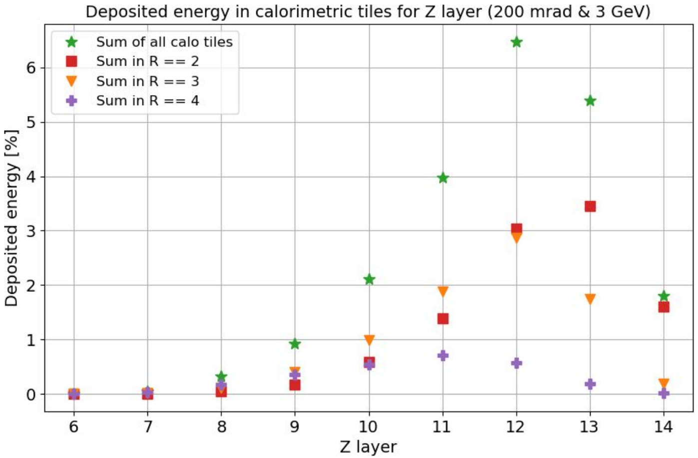




***PRELIMINARY RESULTS***

# Deposited energy with tilted Demonstrator






***PRELIMINARY RESULTS***

# 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