2025 CEPC International Workshop

Dual-Readout Fibre-Sampling Calorimetry:

R&D Status and Plans

Roberto Ferrari

8 November 2025

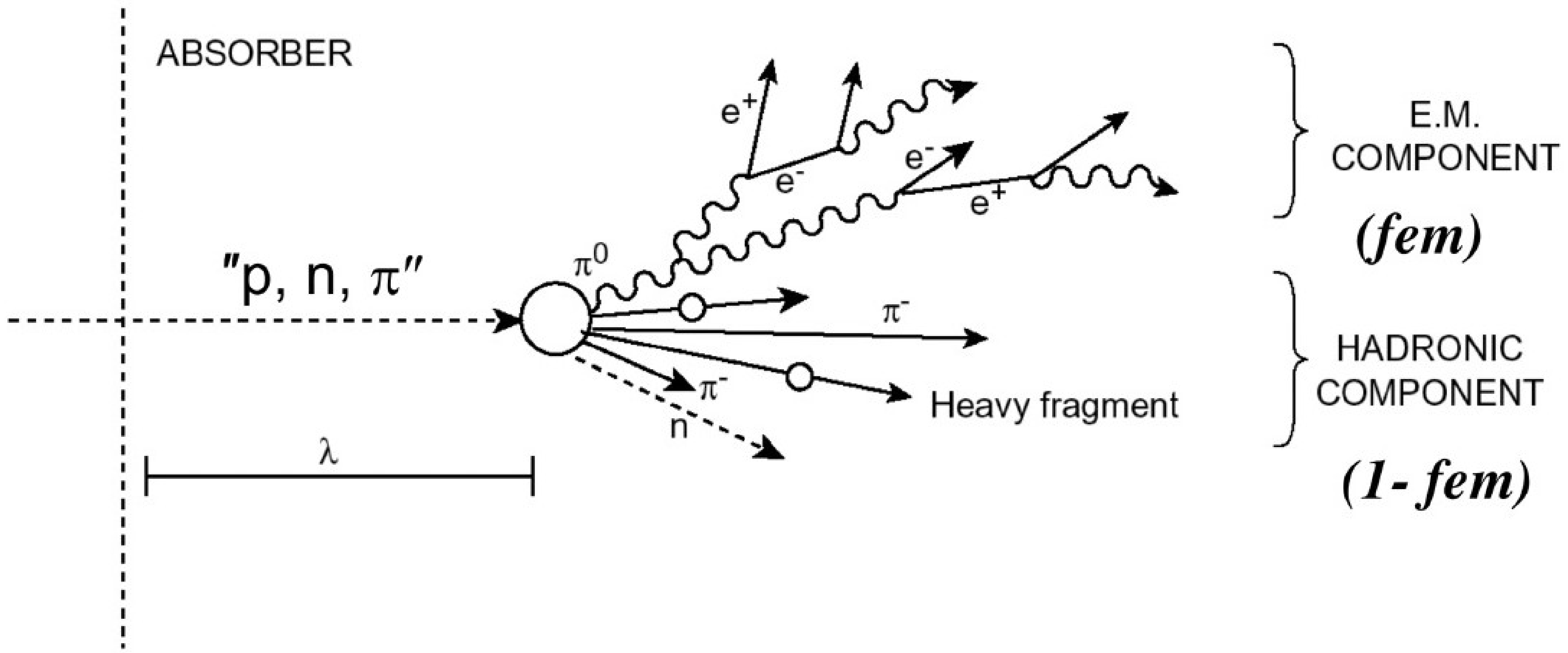
INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

1) EU prototype (HiDRa)

2) U.S. prototype (DREAM++)

Outline

Disentangle relativistic (i.e. electromagnetic) and non relativistic (i.e. nuclear) components of hadronic shower



both scintillation & Cherenkov light

almost only scintillation light

→ get (compensate for) f_{em} event by event

dual-readout algebra

$$S = E \times [\ f_{em} + s \times (1 - f_{em})\ ]$$

$$C = E \times [\ f_{em} + c \times (1 - f_{em})\ ]$$

f_{em} = electromagnetic shower fraction

$s = (h/e)_S$, $c = (h/e)_C$: detector-specific constants

by solving the system, both E and f_{em} can be reconstructed

E measured at em energy scale

more on dual-readout formulae …

$$E = \frac{S - \chi \cdot C}{1 - \chi}$$

$$1 - f_{em} = \frac{1}{1 - (\frac{h}{e})_C} \cdot \frac{S - C}{S - \chi \cdot C}$$

measurable if χ known

measurable event by event, if χ known

(1-f_{em}) can be reconstructed within (unknown) constant factor (>) O(1)

$$\chi = \frac{1 - (\frac{h}{e})_S}{1 - (\frac{h}{e})_C} = \frac{E - S}{E - C}$$

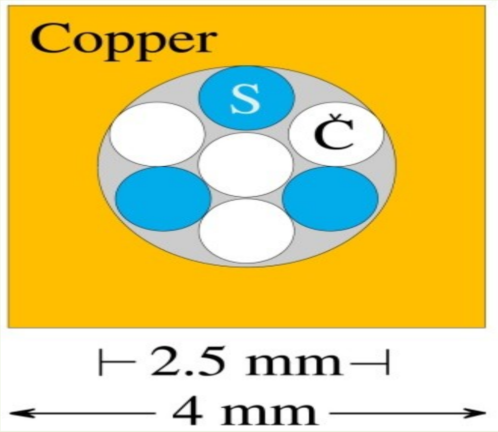
$$if \quad (\frac{h}{e})_S > (\frac{h}{e})_C \Rightarrow \chi < 1$$

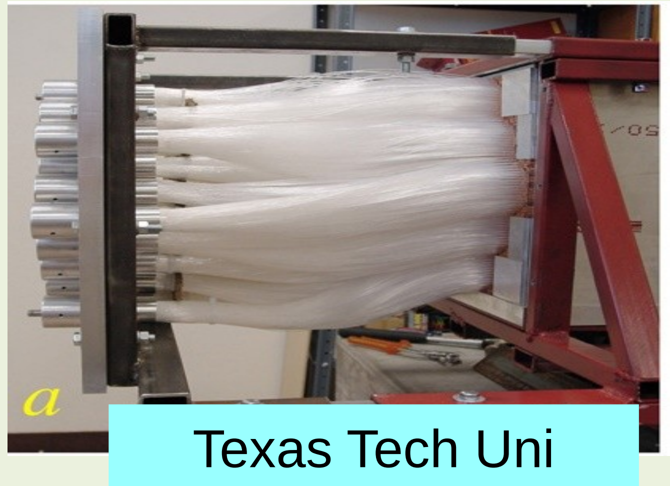
χ measurable if E known ⟶ **χ can be extracted from testbeam data**

DREAM/RD52 dual-readout "spaghetti" prototypes

2003
DREAM

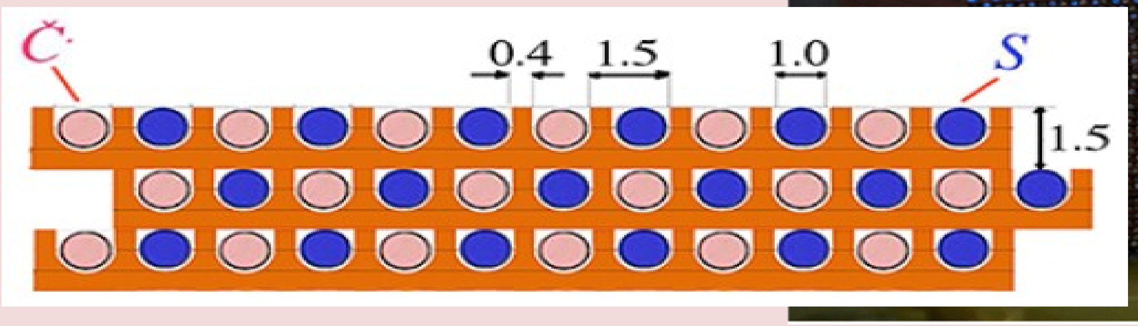
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}





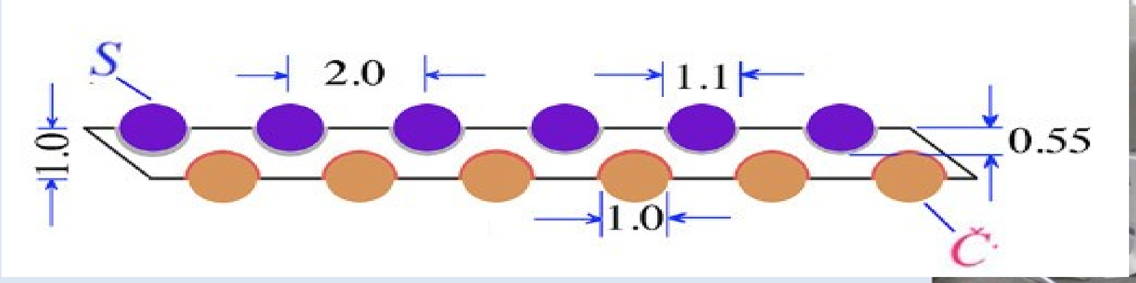
2012
RD52

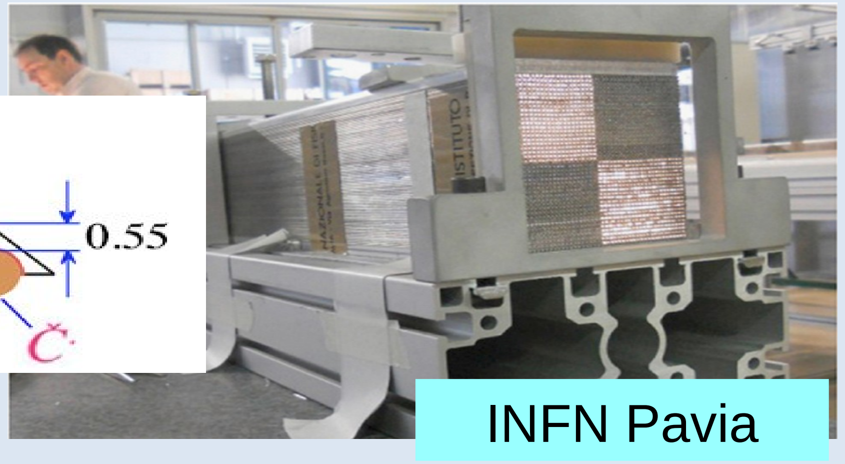
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

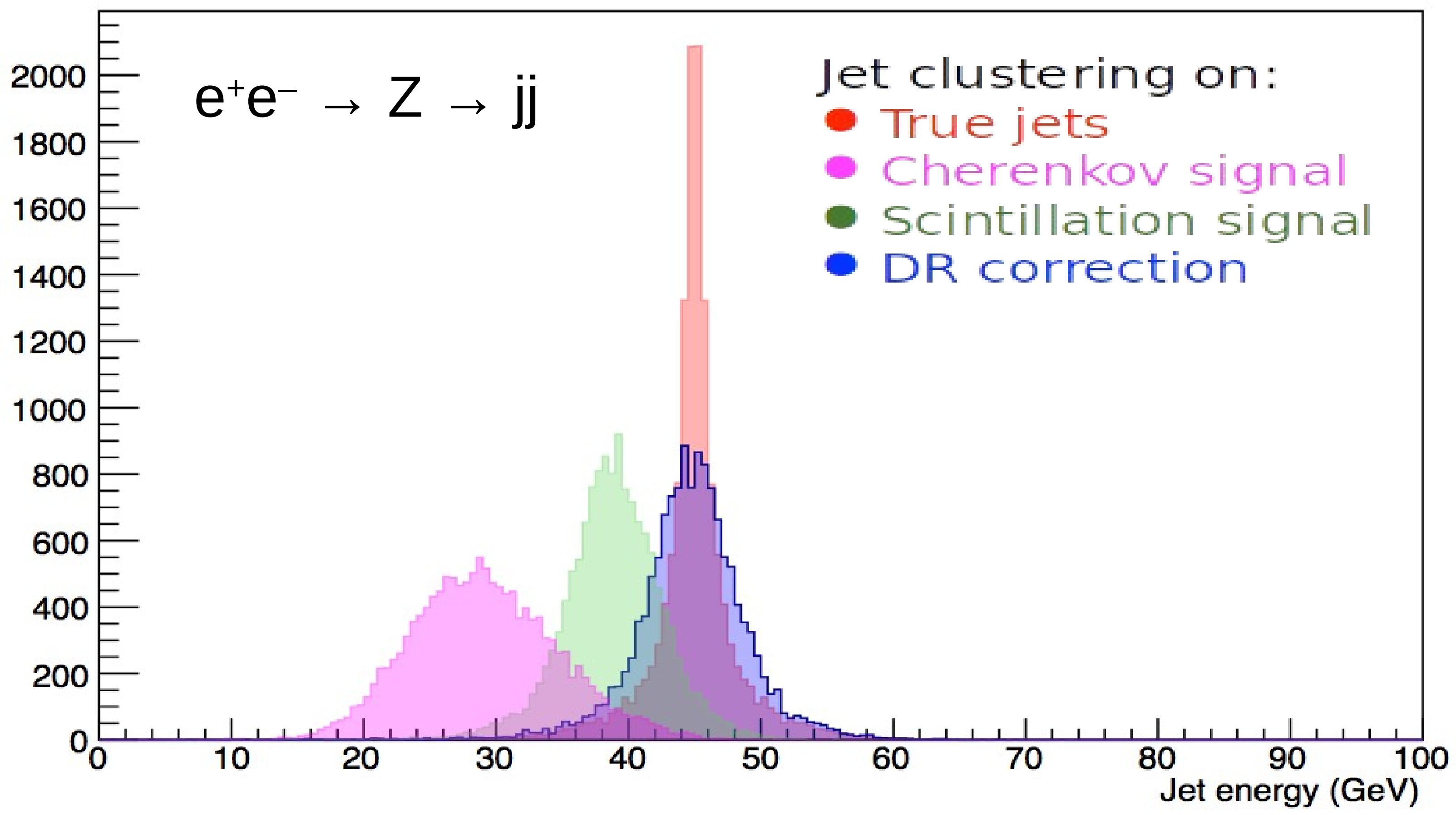




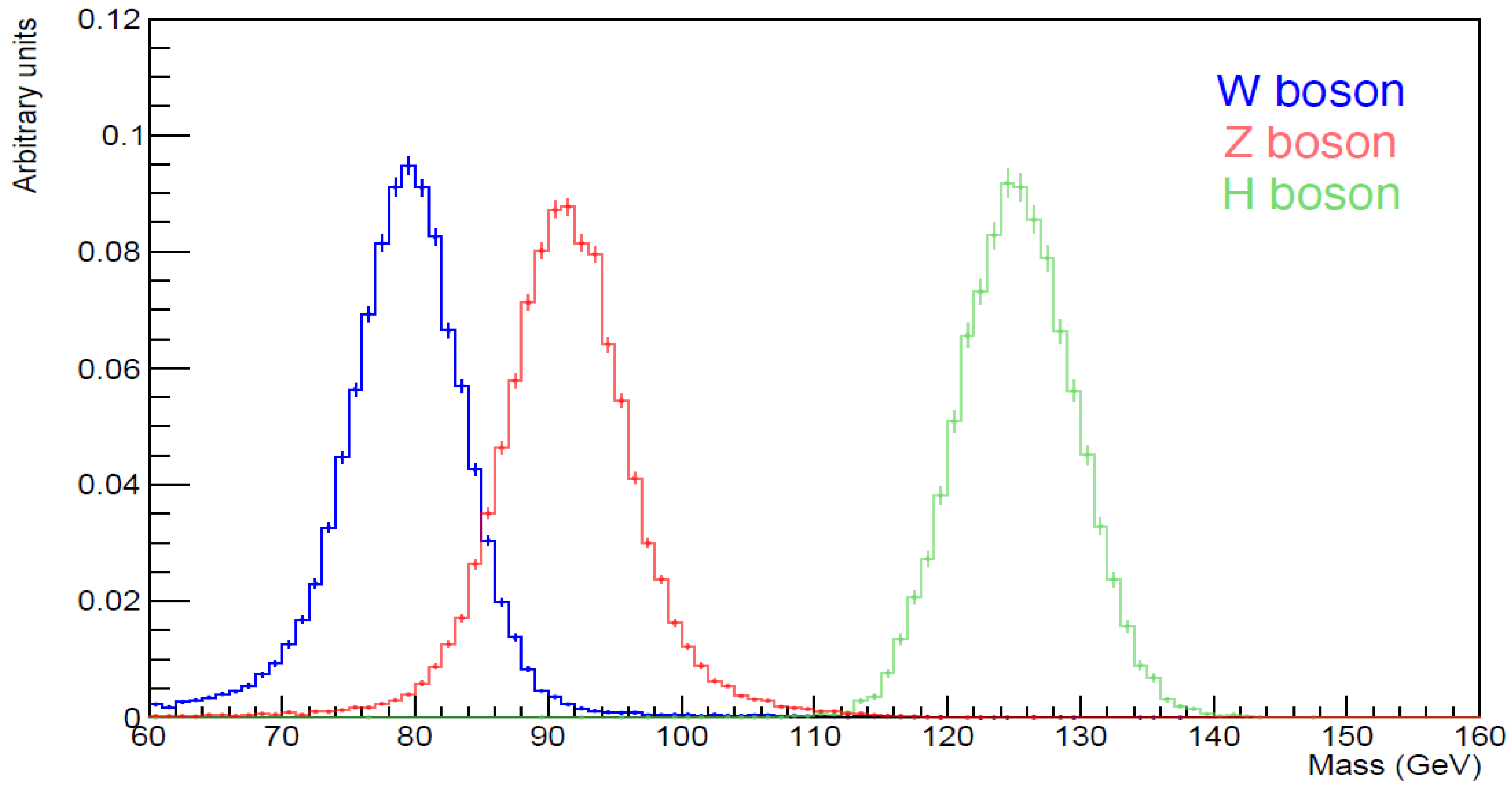
Geant4 simulations (fibre calorimeter)

- Gaussian resolution
- Adequate separation of W / Z / H

Single jet resolution @ 45 GeV



W/Z/H → jj invariant mass

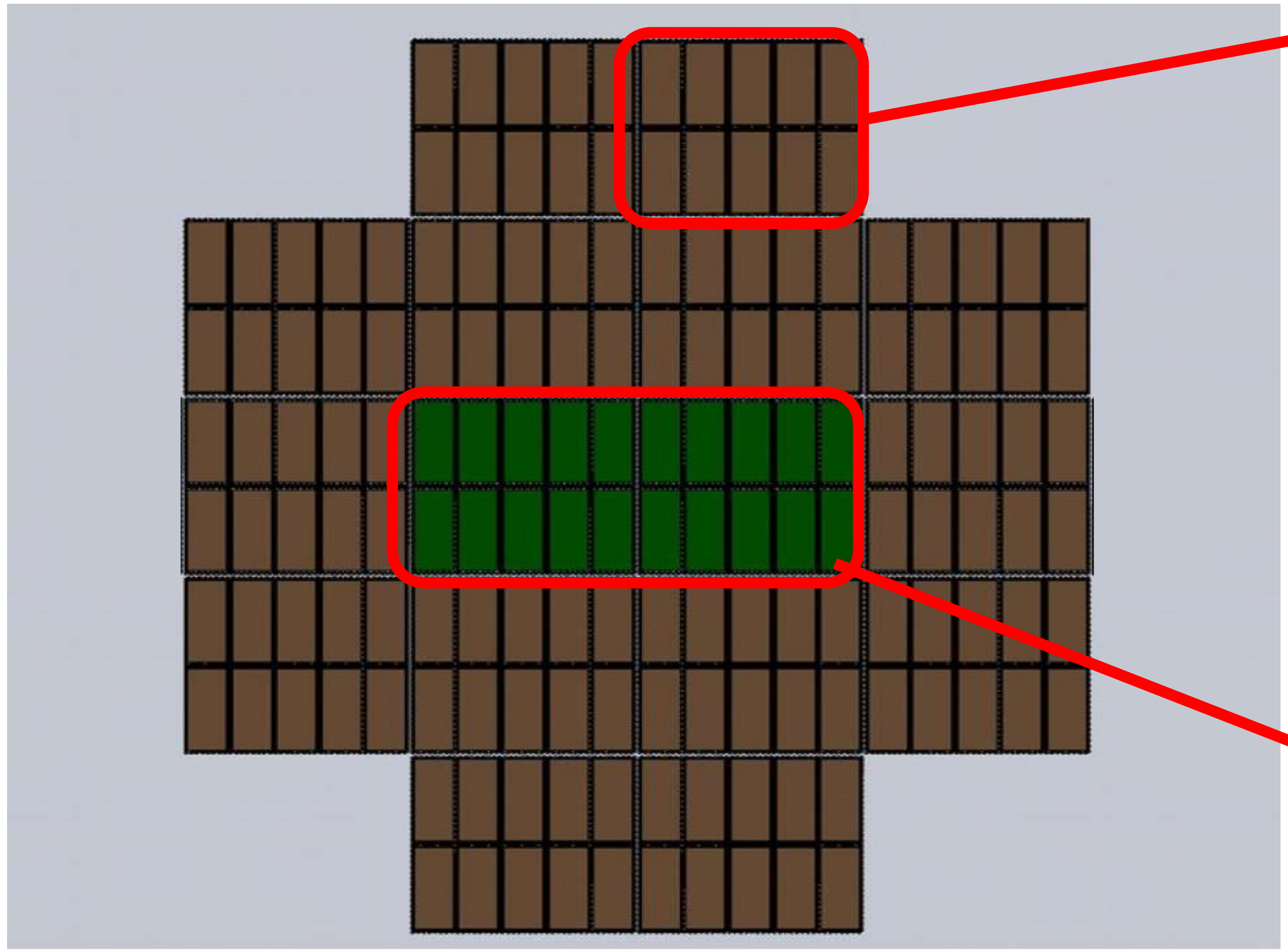


Next steps

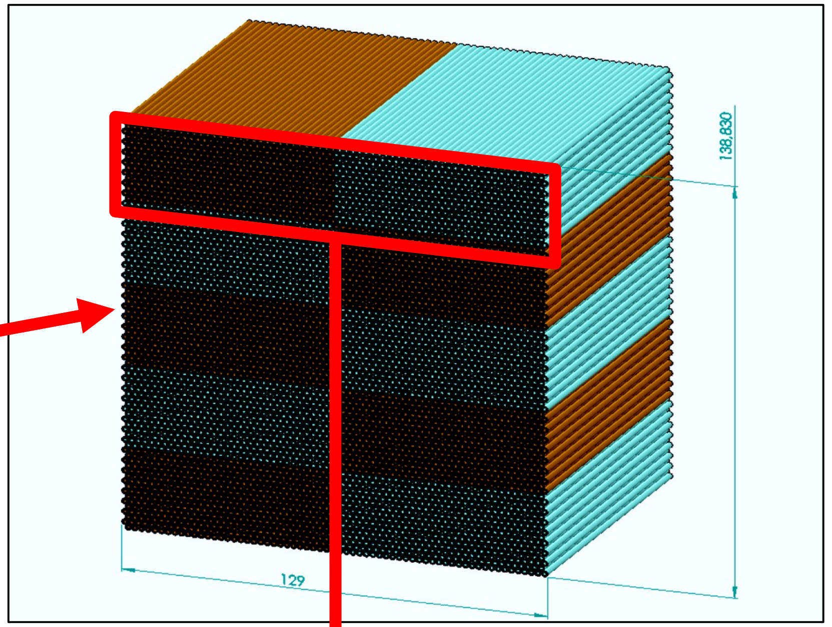
Exploit high granularity and timing (and PFA)

HiDRa – Highly granular Dual Readout demonstrator

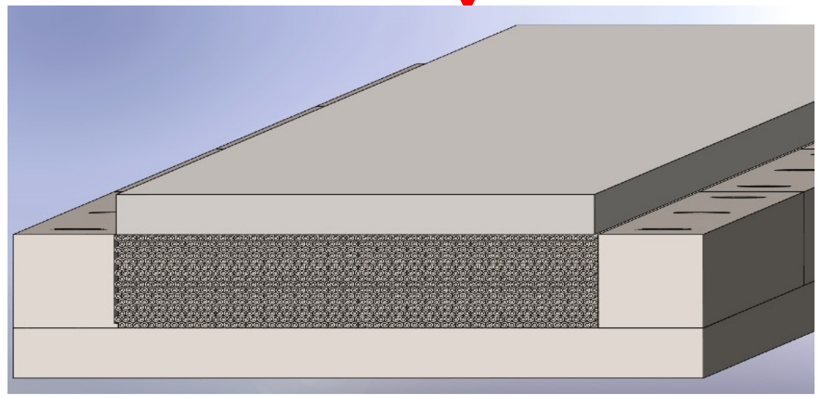
Hadronic-size prototype:
16 modules w/ highly granular core



~ 65 × 65 × 250 cm^3



1 Module: 5 MMs
~ 13 × 13 cm^2
5120 fibres

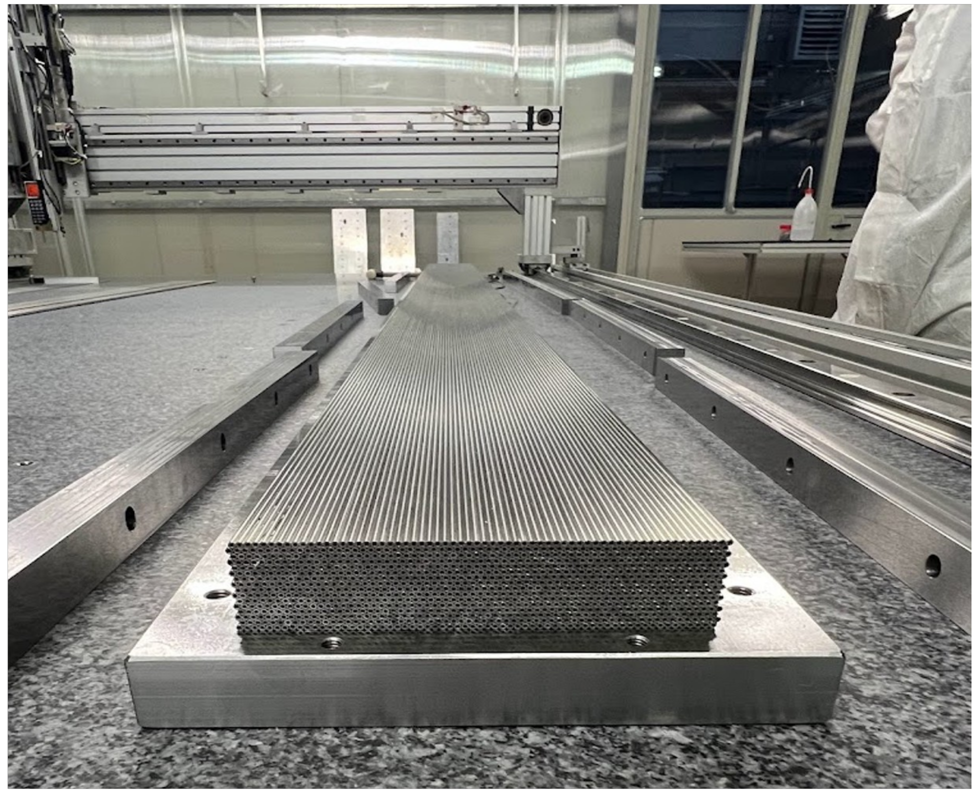


1 MiniModule:
64 × 16 = 1024 fibres in total
512 S + 512 C

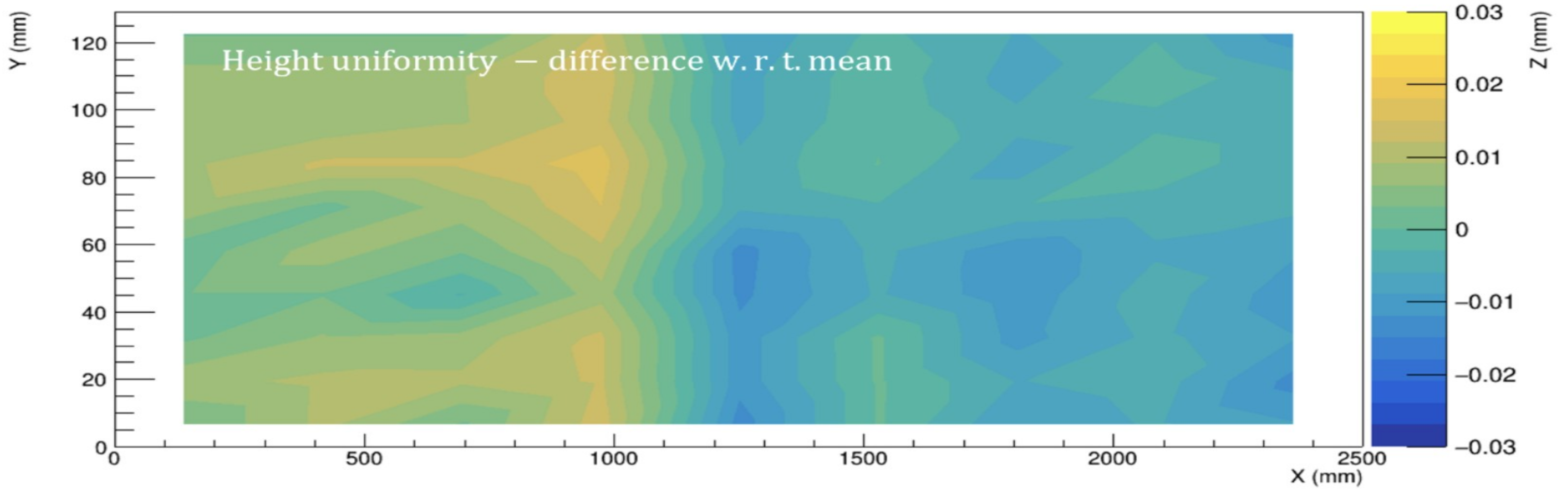
highly granular core:
10240 fibres to be read out with SiPMs

Construction technique and mechanical precision

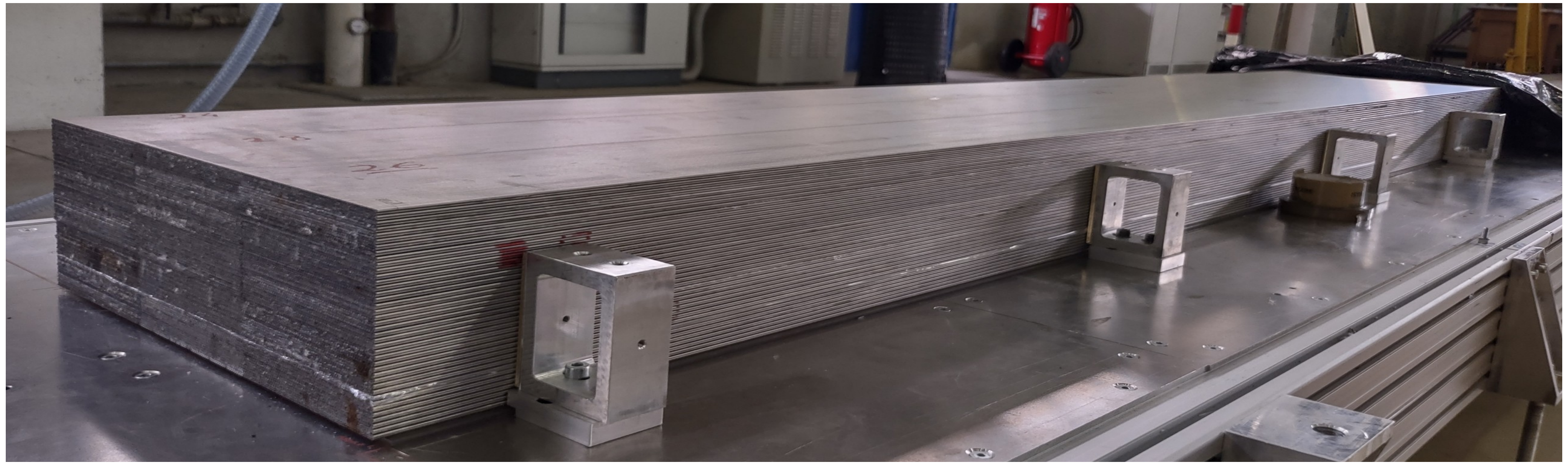
Semi-automatic system for planarity measurement: 90 measurements per minimodule

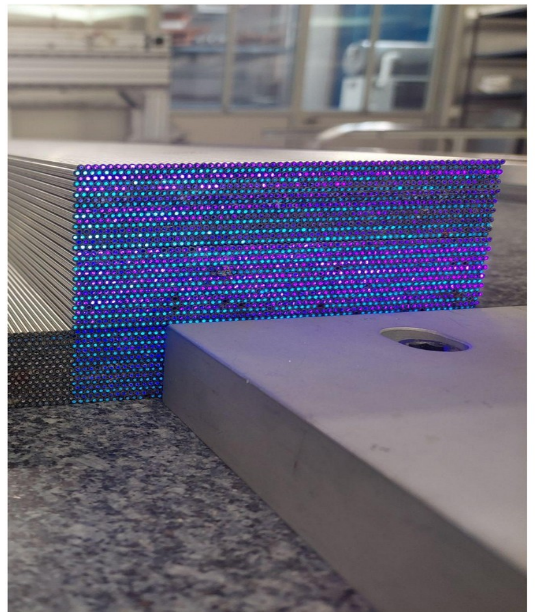


O(10 μm) precision on minimodule height (calor2024)

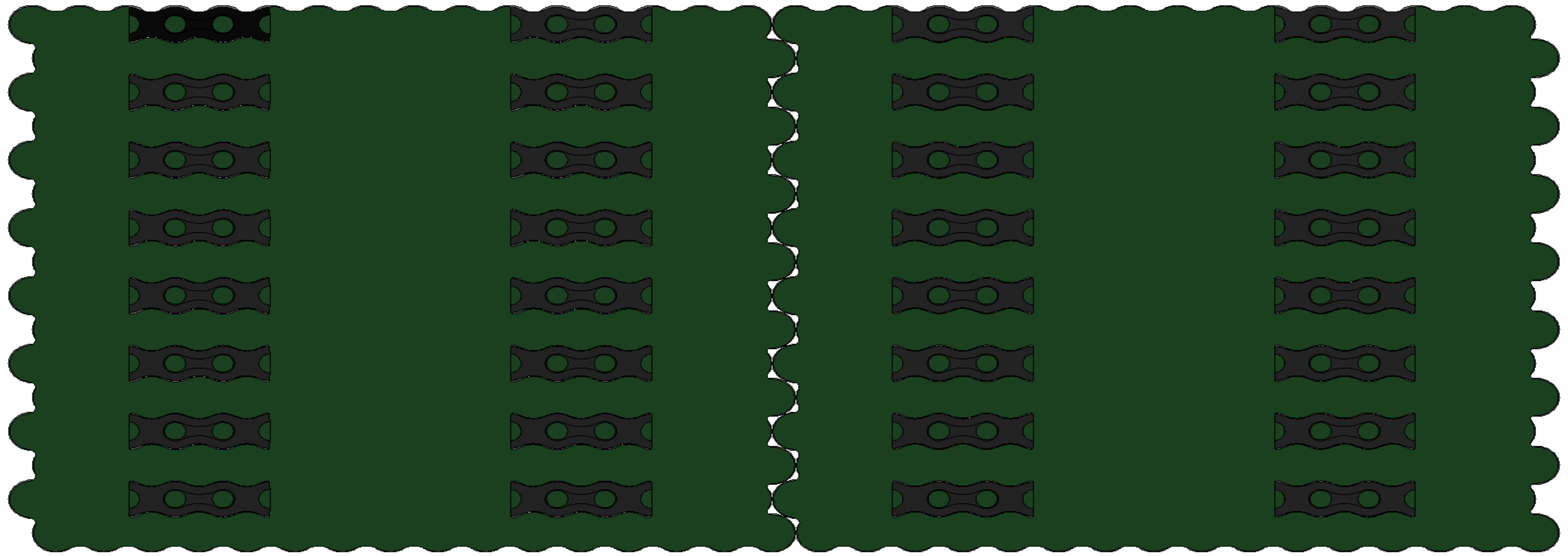


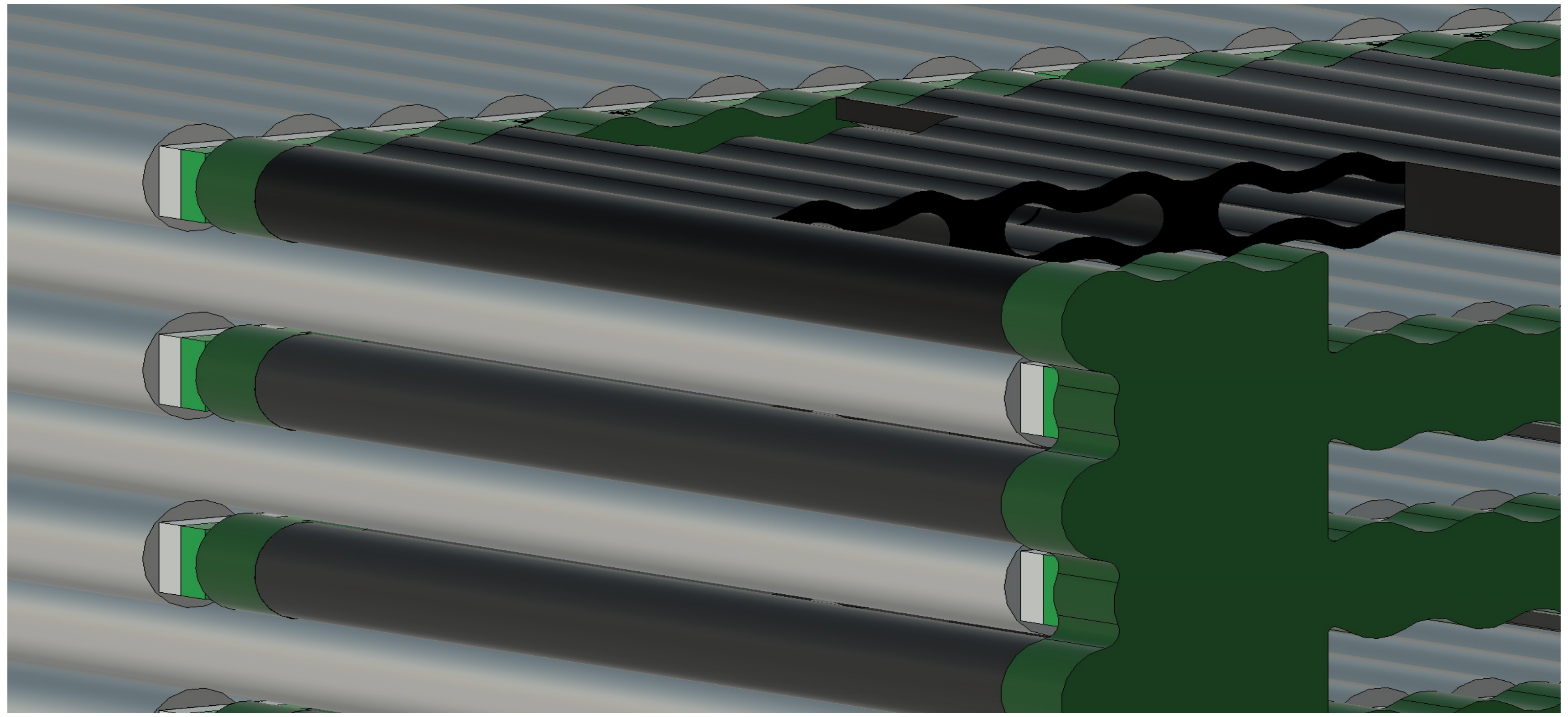
Production started in November 2023: 70/80 minimodules assembled
First test beam with 36 modules in August-September 2024 (PMT readout only)

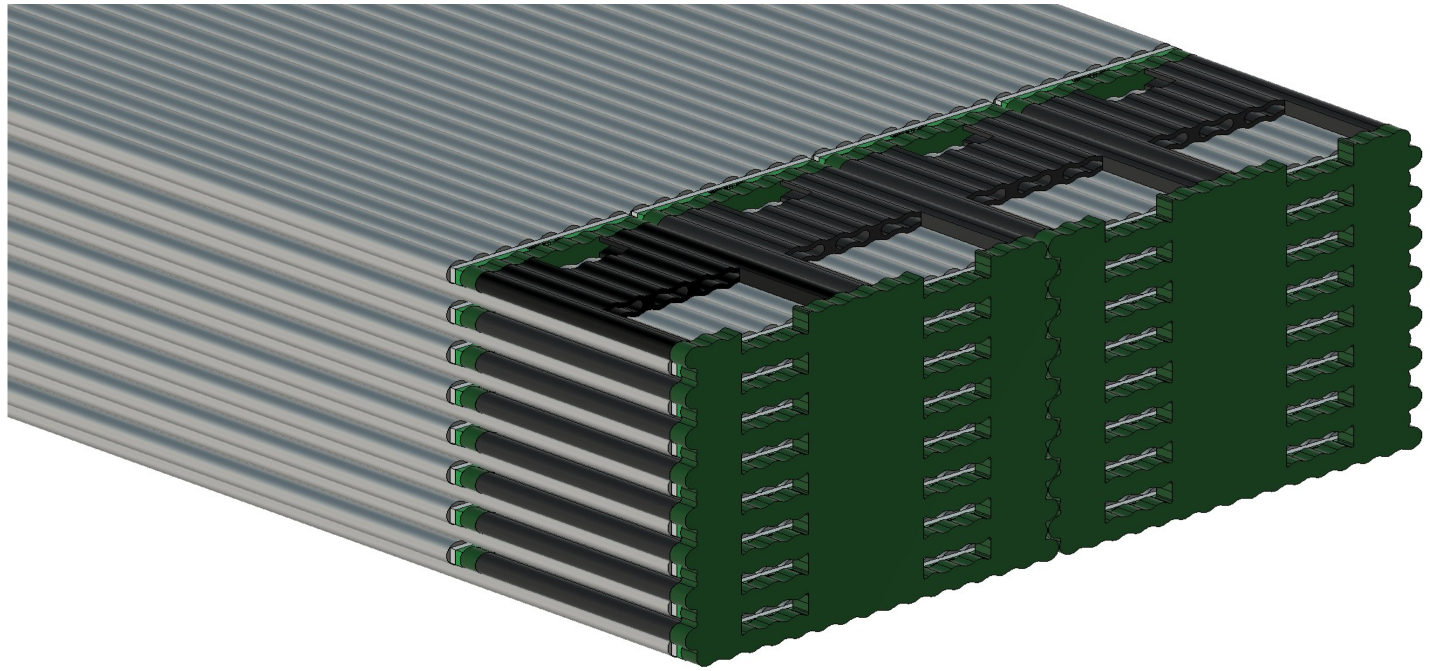


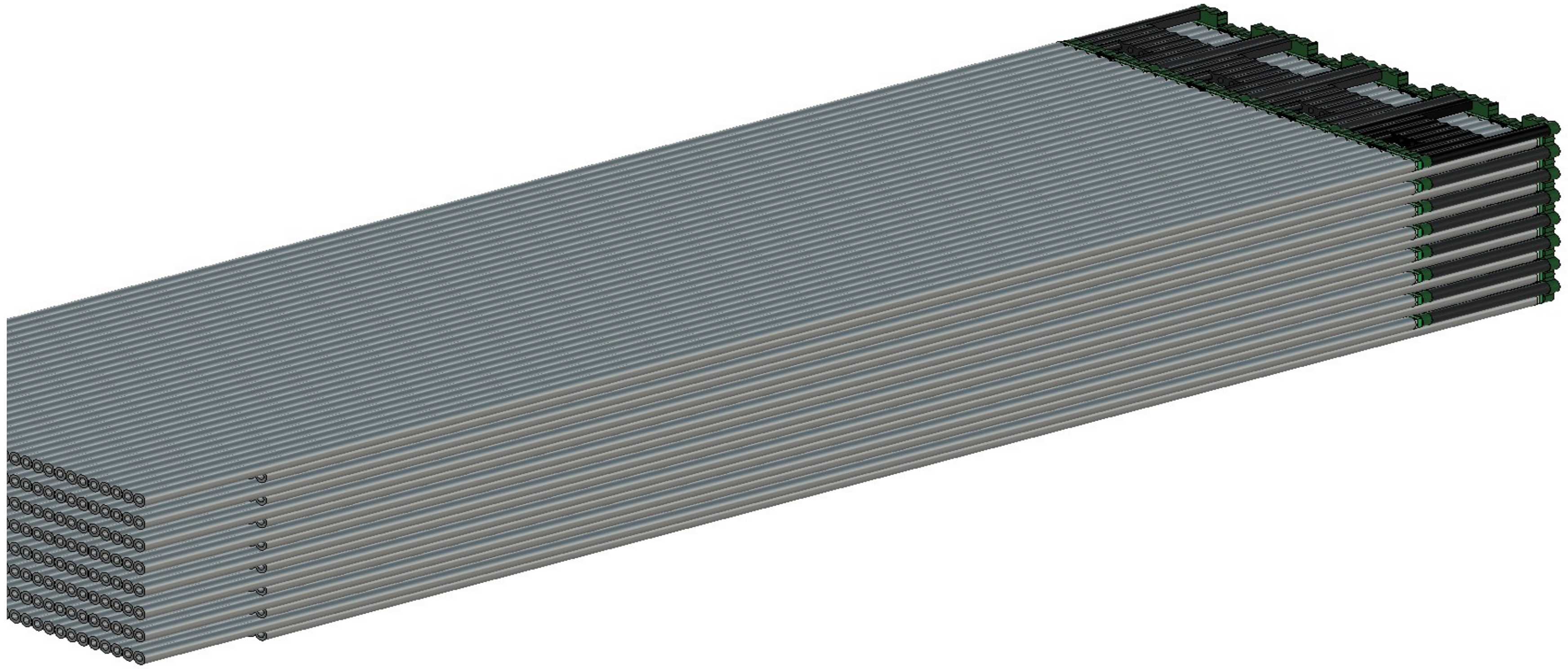


Integration of highly granular modules





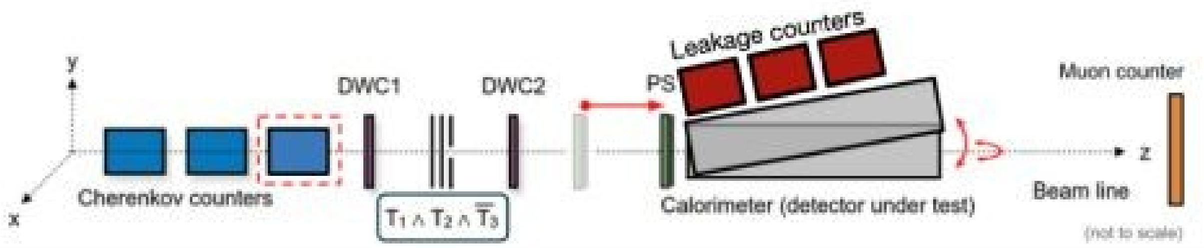




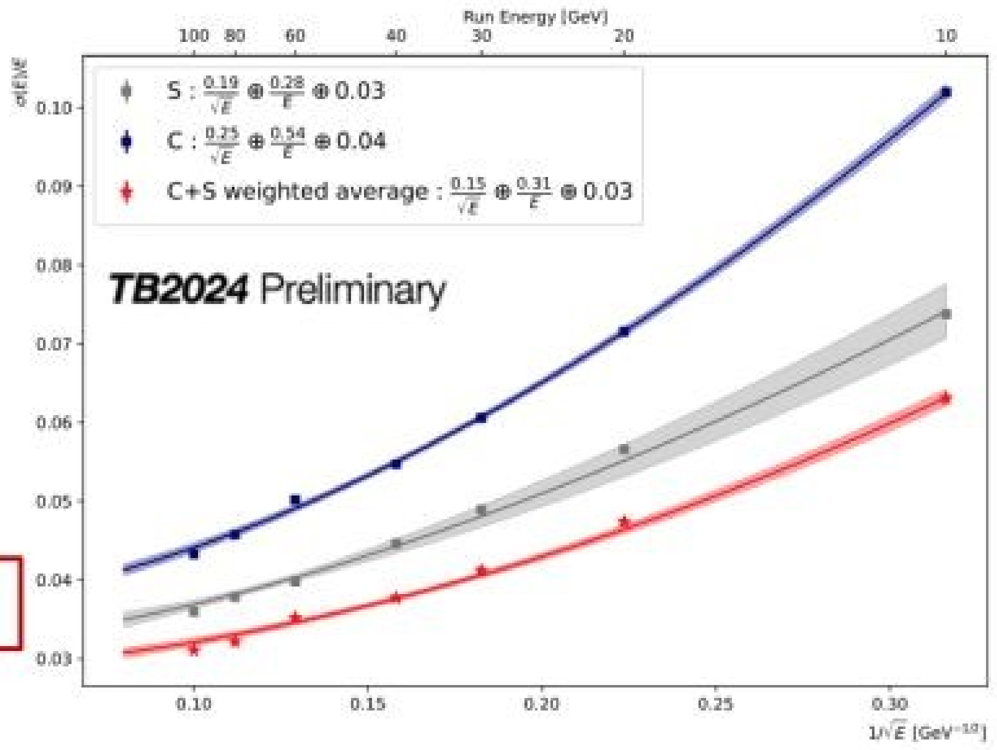
2024 beam test

Low-granular prototype qualification on beam:

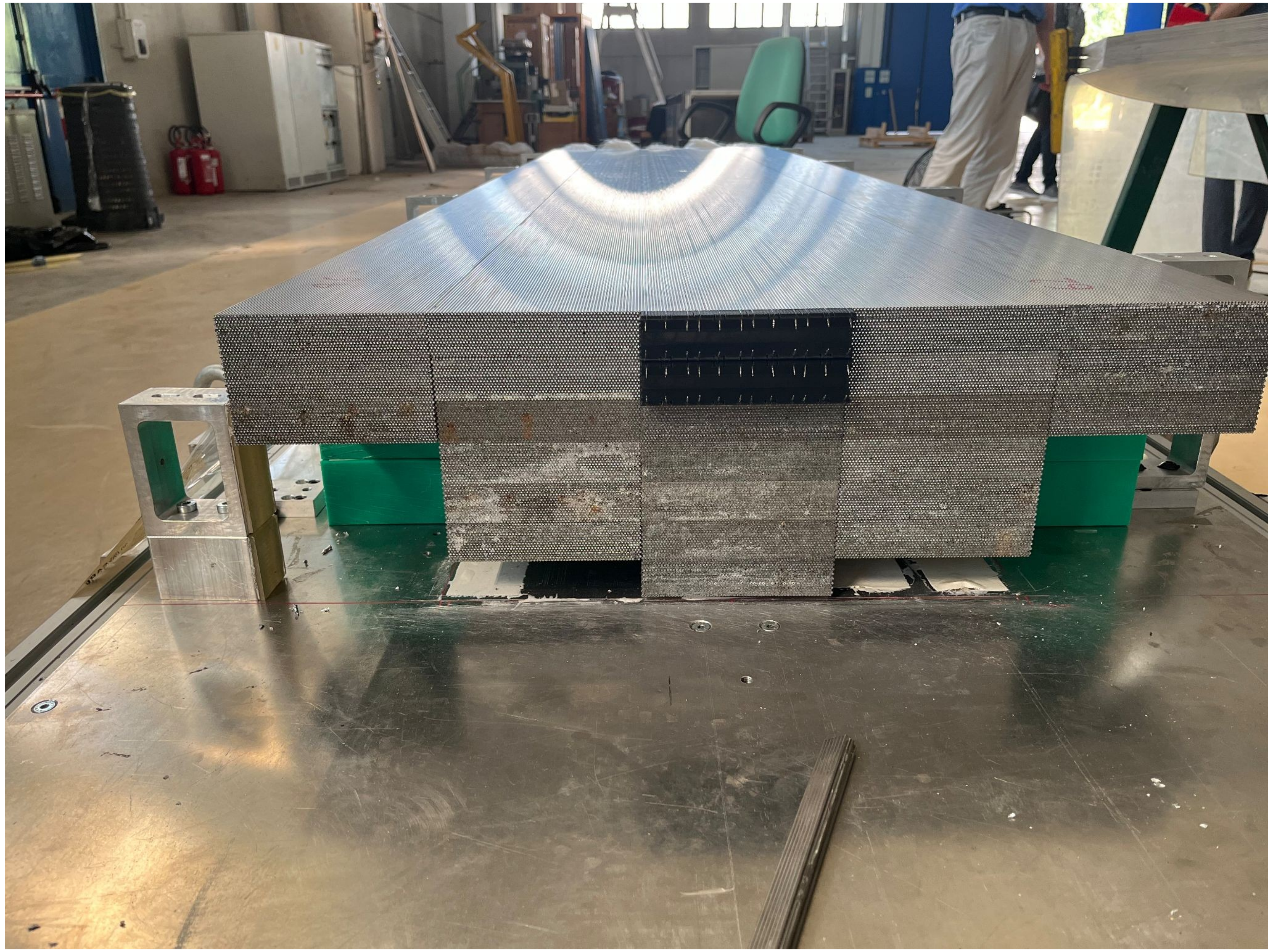
- 36 minimodules, 3 columns × 12 rows: ~ 39 × 39 × 250 cm^3
- Nominal angle of 2.5° between beam line and both X and Y axes
- PMT-readout only (36+36 PMTs)



L. Nasella @ VCI2025



2025 prototype – mechanical integration

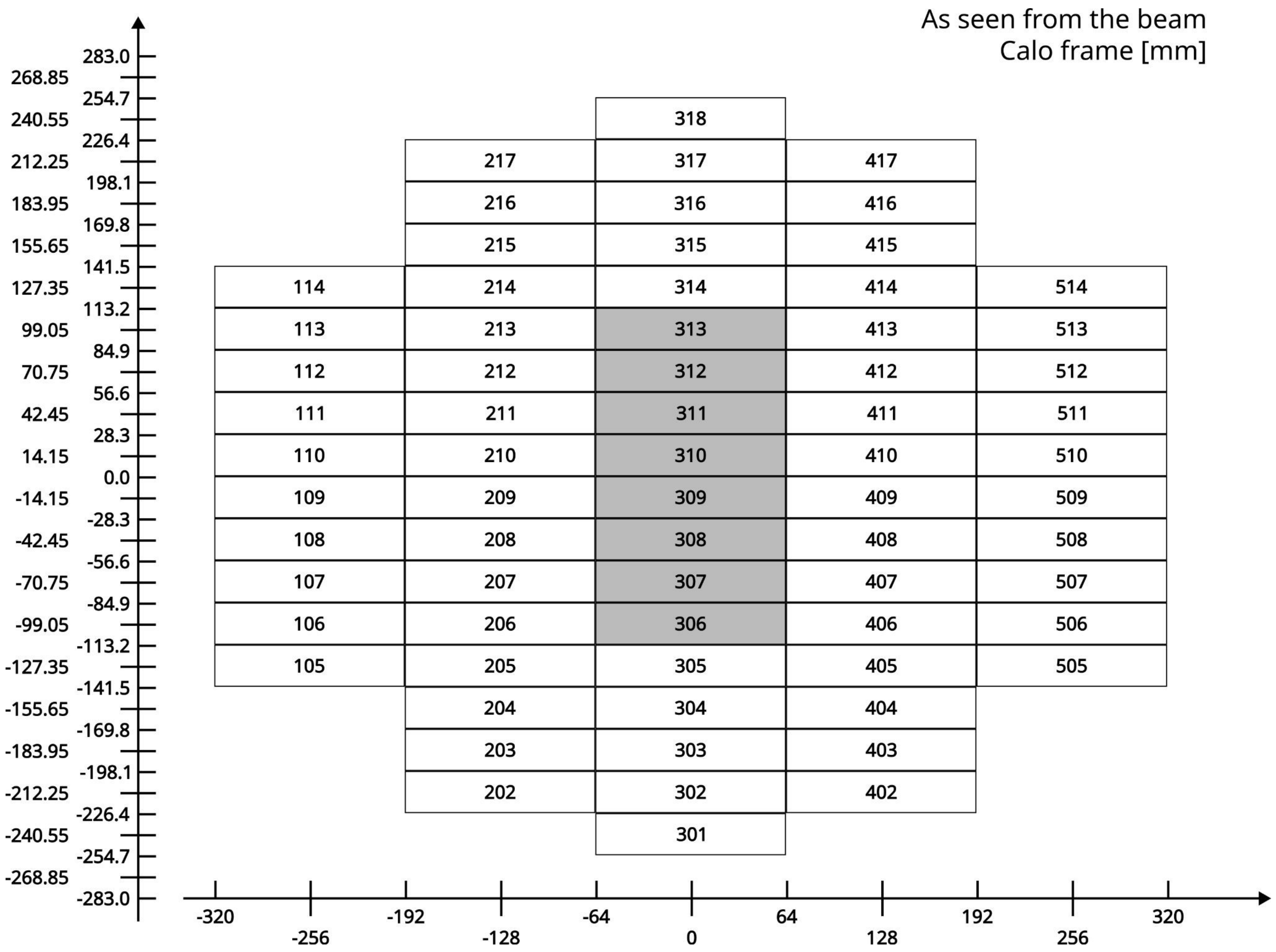


2025 beam test (October 2→8)

70 modules, 128 × 28 × 2500 mm^3

- **8 instrumented with SiPMs**: one SiPM / fibre + analog grouping of 8 fibres per readout channel
- **62 with PMTs**: each PMT reading bundle of 512 fibers of one kind

124 PMT + 1024 SiPM channels



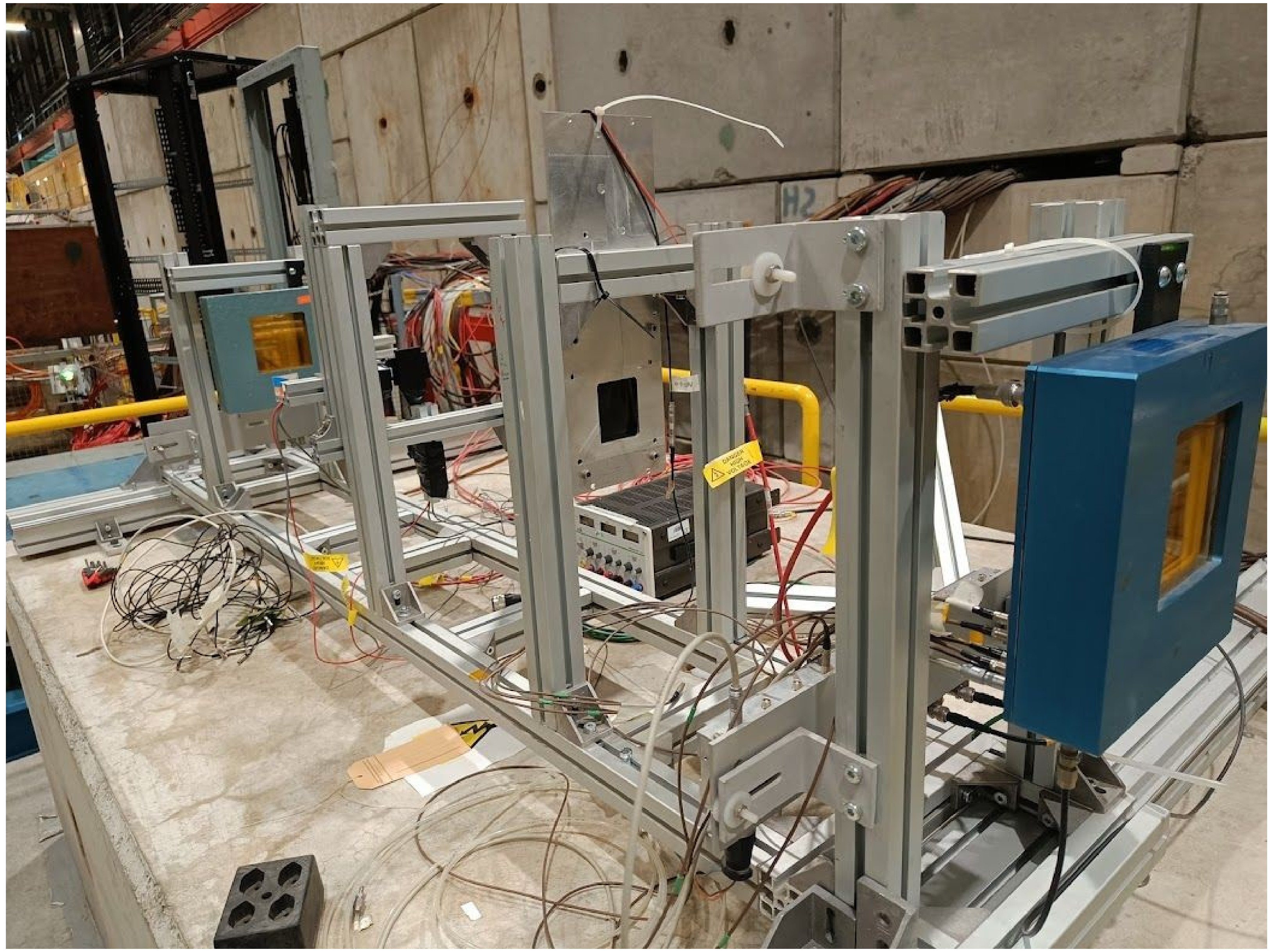
Detectors

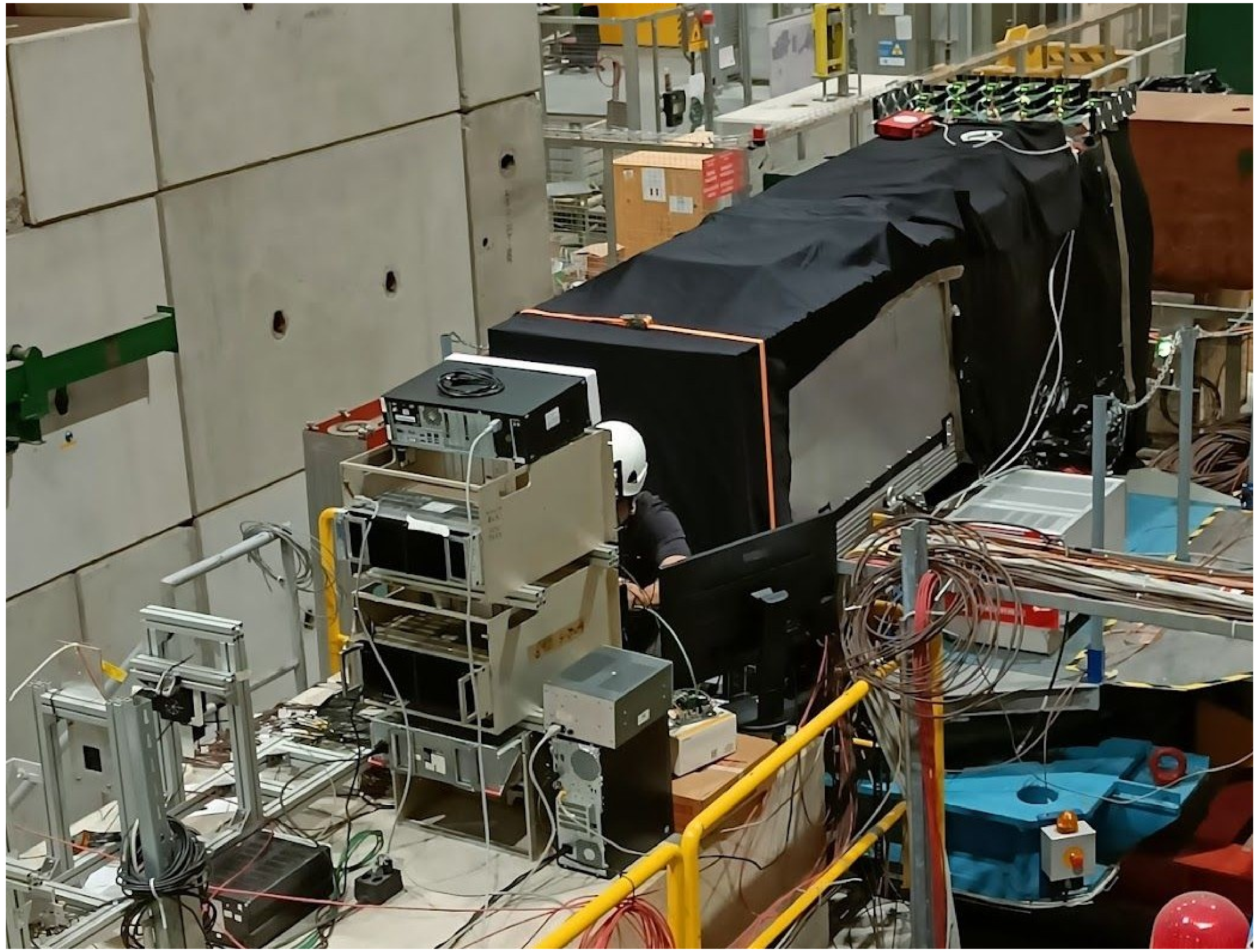
- 3 (Helium) Cherenkov counters → electron ID
- DWC # 1 → tracking
- VETO scintillator* → for beam halo cleaning
- Two (~4×4 cm^2) trigger scintillators
- DWC # 2 → tracking
- **Calorimeter → DUT**
- Tail catcher → energy containment
- Muon counter (after iron absorber) → muon ID

+ 6 leakage counters on top and bottom of the calorimeter → energy containment

*VETO acquired but NOT used for triggering

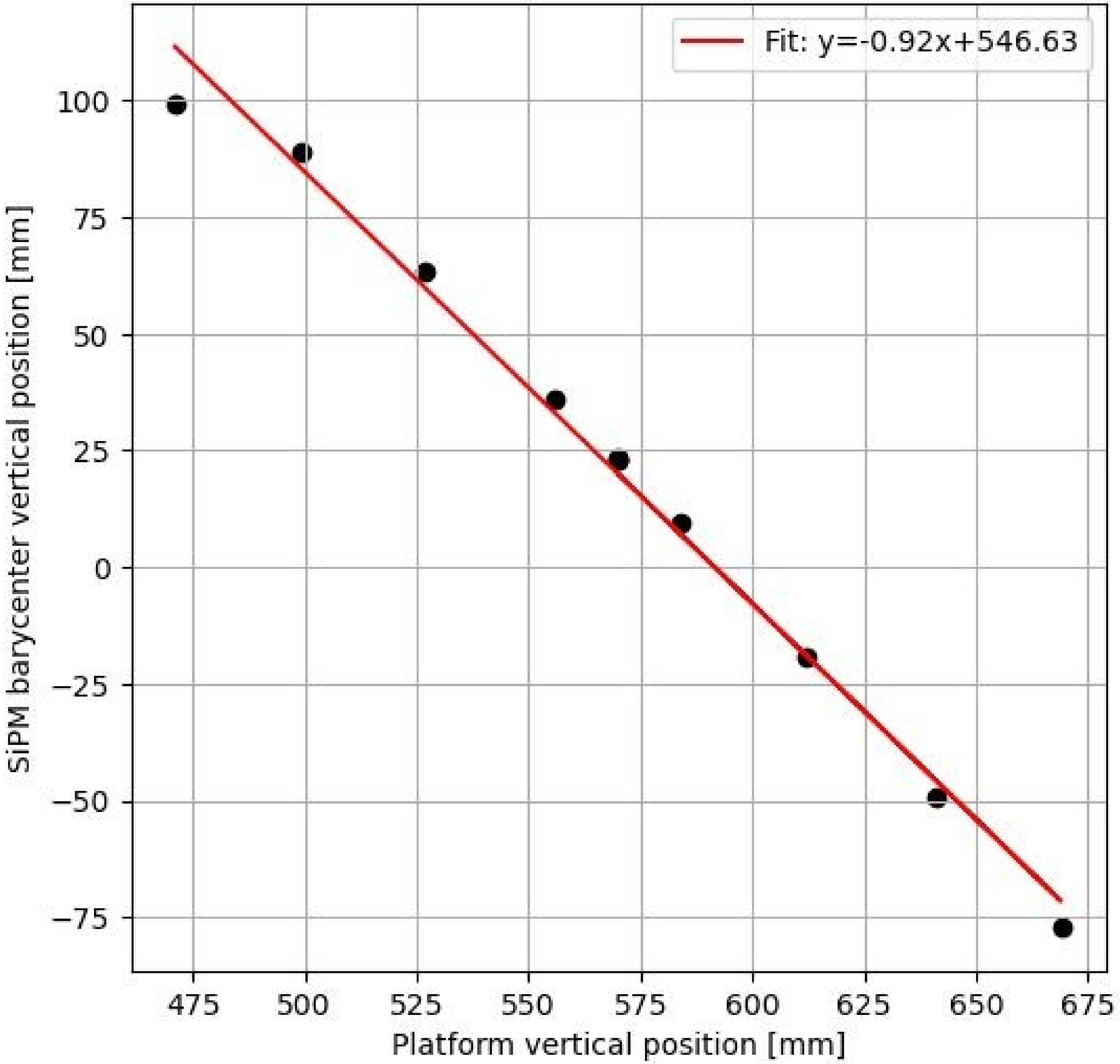
Setup – all trigger and readout elx in beam area





Vertical alignment w/ data

Vertical alignment with 20 GeV positron beam



Data taking

Very good beam availability (> 1000 runs, most of them with several k events)

DAQ rate @ 20 GeV e^+: 2 kEvt / spill → 5-6 kEvt / spill (last two days)

Calibration runs:

- SiPM pedestals
- Alignment with positron beam barycentre
- PMT equalisation (twice: lower → higher gain)
- SiPM position scan (for equalisation) w/ both e+ and μ beams
- Upper leakage-counters calibration

Data taking

Physics performance studies:

- e^+ energy scan up to 160 GeV * (including 100 GeV beam with low-energy-spread tune)
- e^+ energy scan at 0° (horizontally)
- π energy scan *
- Tower uniformity w/ e^+
- π shower profile, hit top modules to sample core and tail with SiPMs
- Short μ energy scan
- μ angular scan
- μ @ 7° and e^+ @ 60° **

* w/ both low and high PMT gain

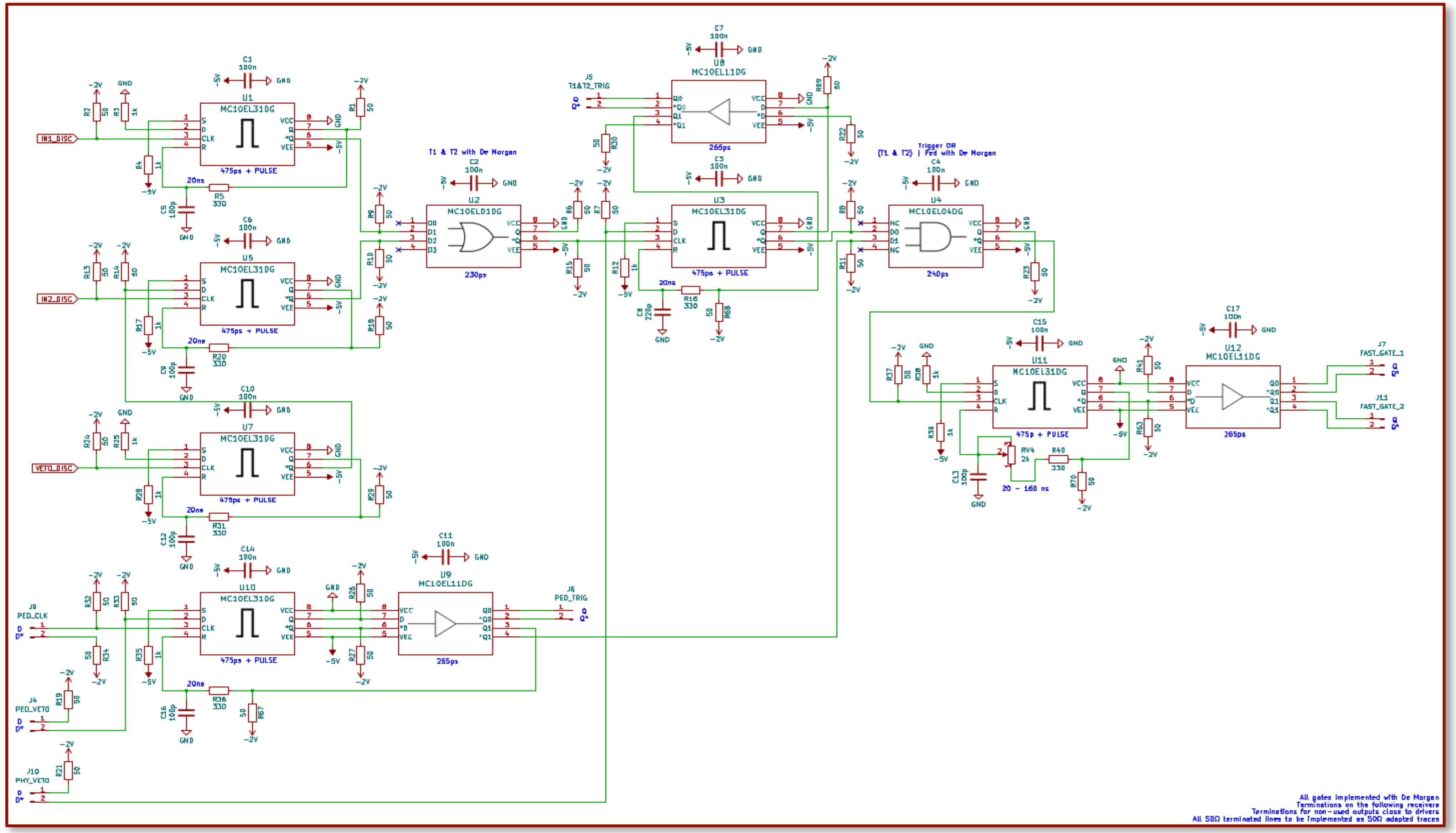
** angle limited by calo box dimensions

Low-latency custom trigger board

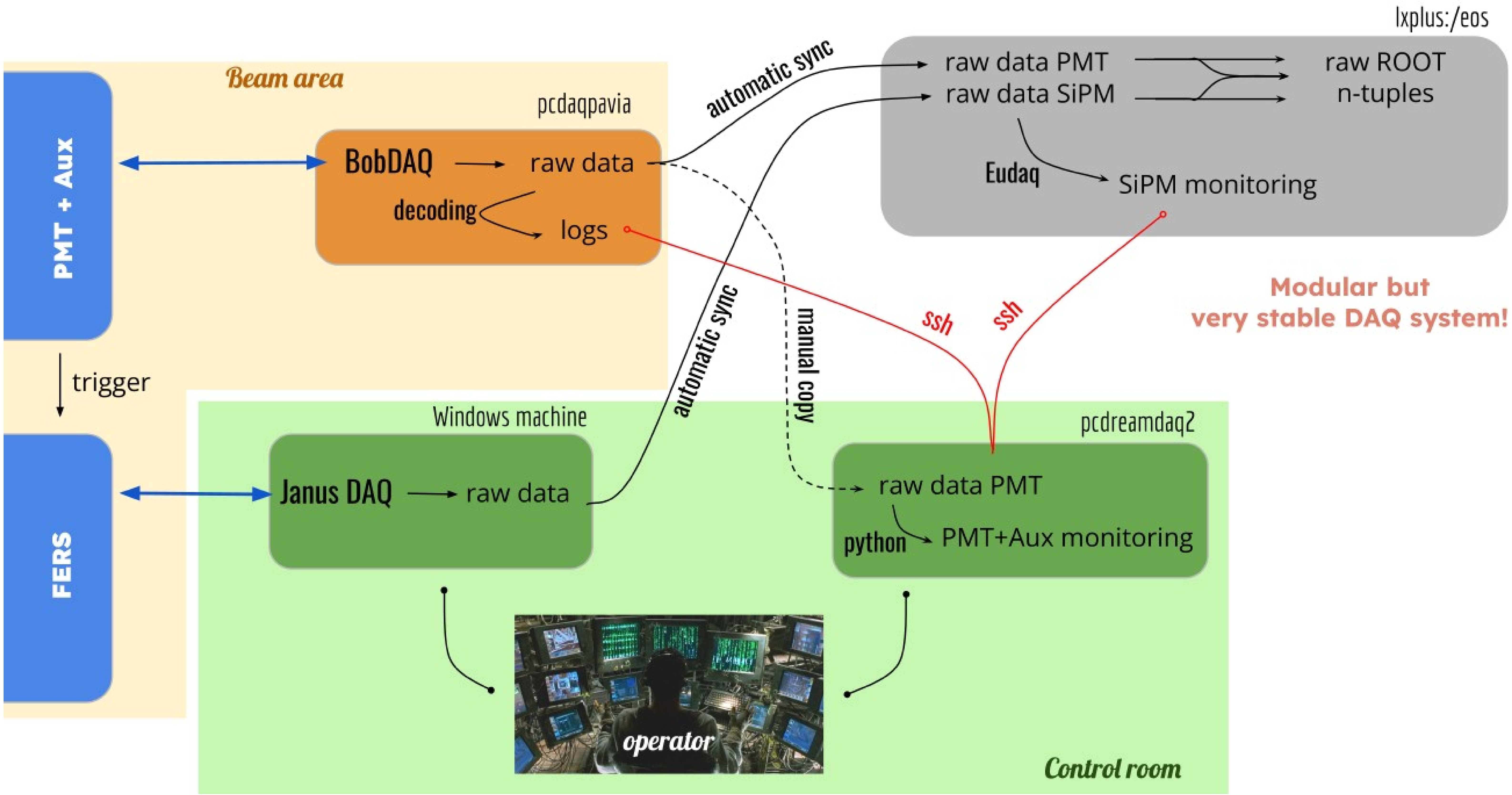
Low-latency trigger board (designed in Pavia)

- 3 analogue comparators with NECL logic output
- NECL devices (gates, buffers, D flip-flops)
- 3 analogue Inputs: 2 × trigger, 1 × veto
- 3 digital inputs: 2 × veto, 1 × pedestal clk
- 2 fast-gate outputs
- 2 trigger-latch outputs (physics / pedestal)

Total latency ~ 13 ns

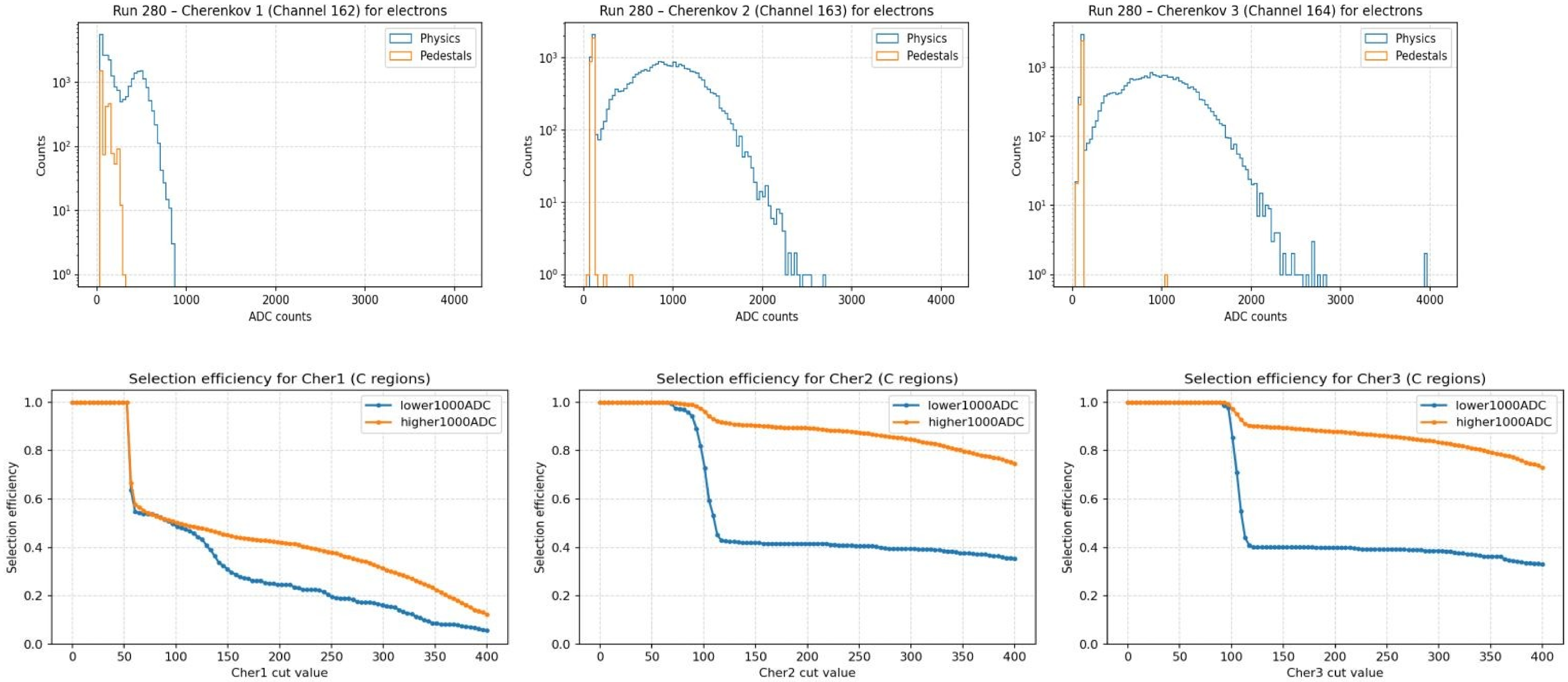


Dataflow and control



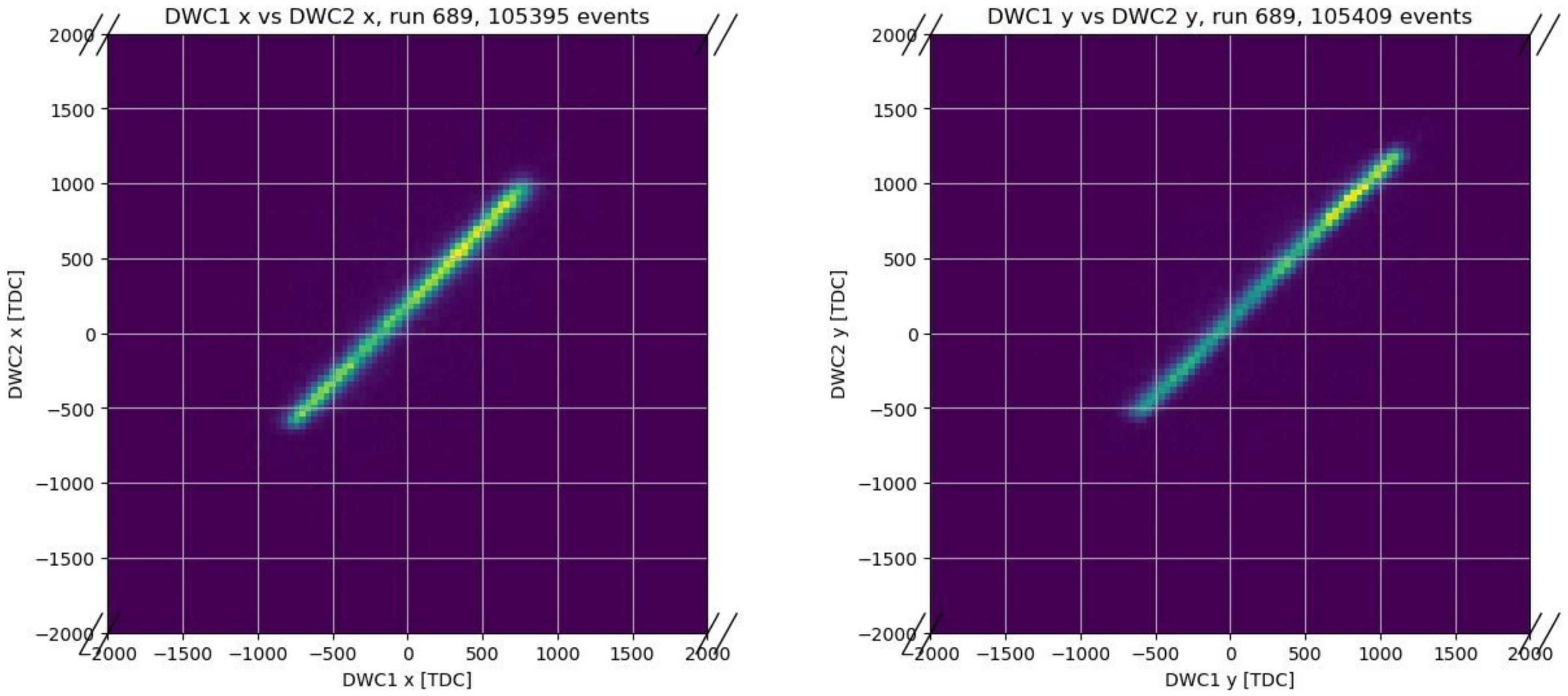
Performance: Cherenkov counters

Use PMT total signal to tag electrons (cut @ 10000 cts) → one counter (Cher 1) almost blind

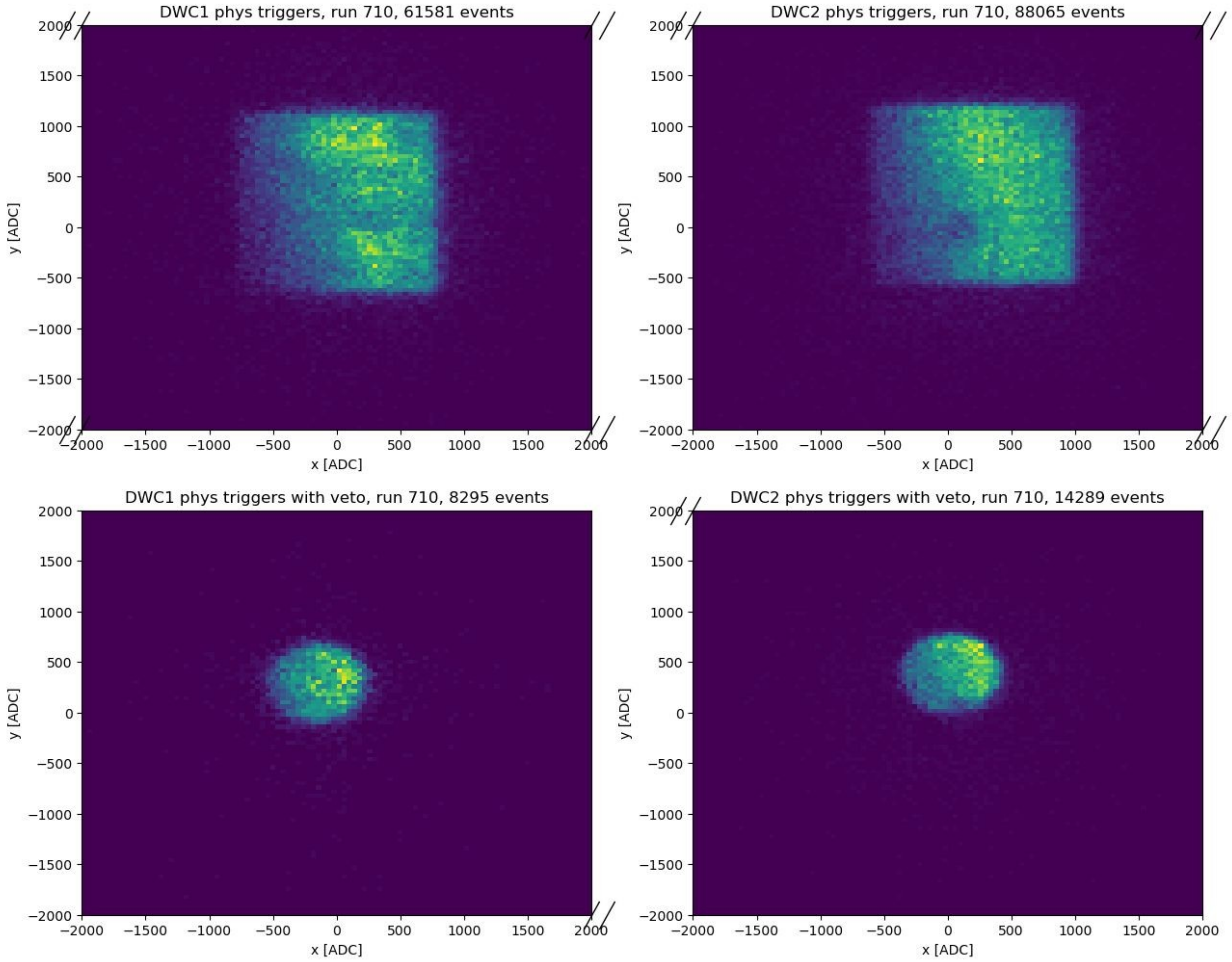


DWCs and beam spot

Chamber correlation

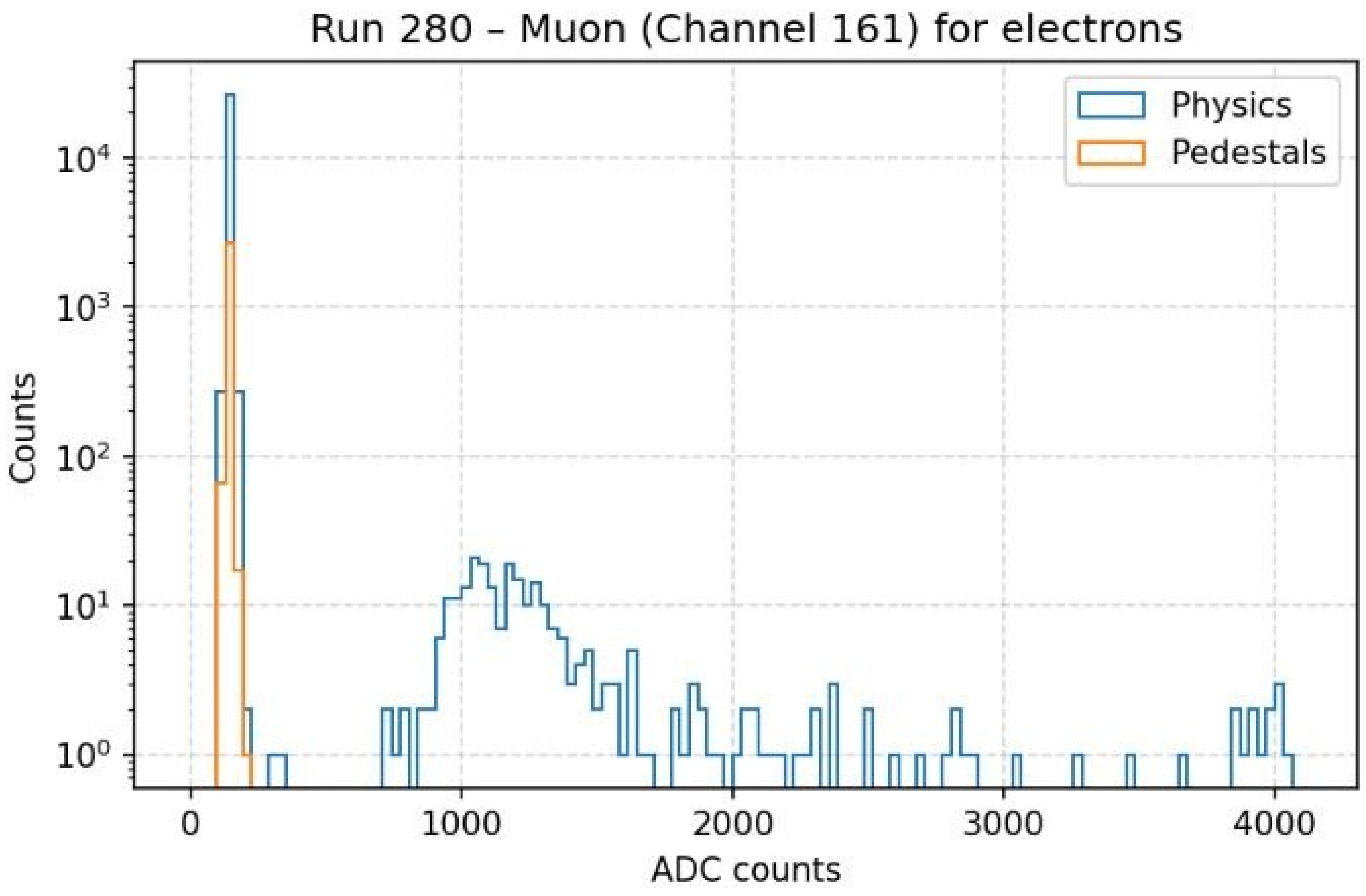


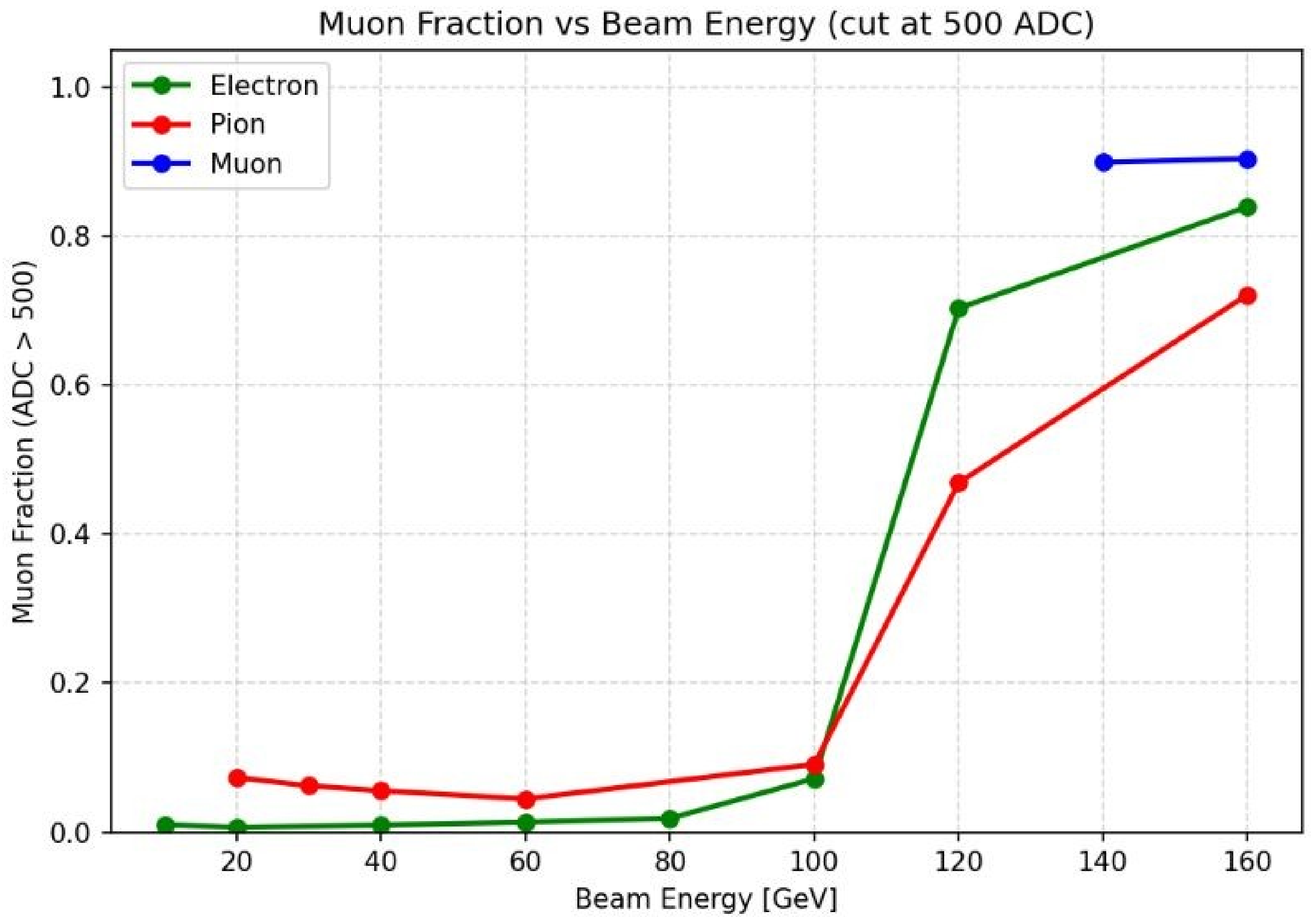
Offline VETO selection



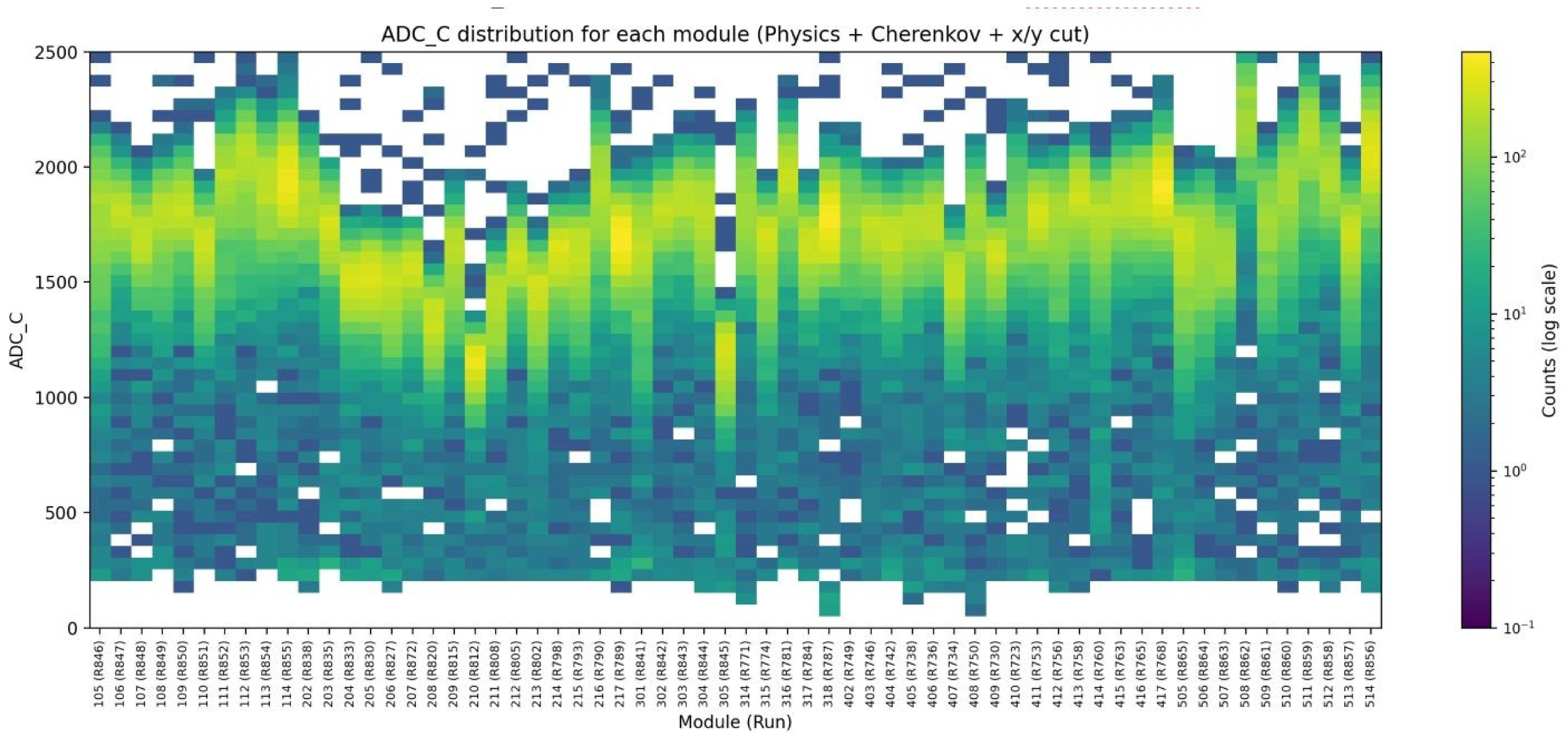
μ counter

Above 100 GeV, very high μ contamination



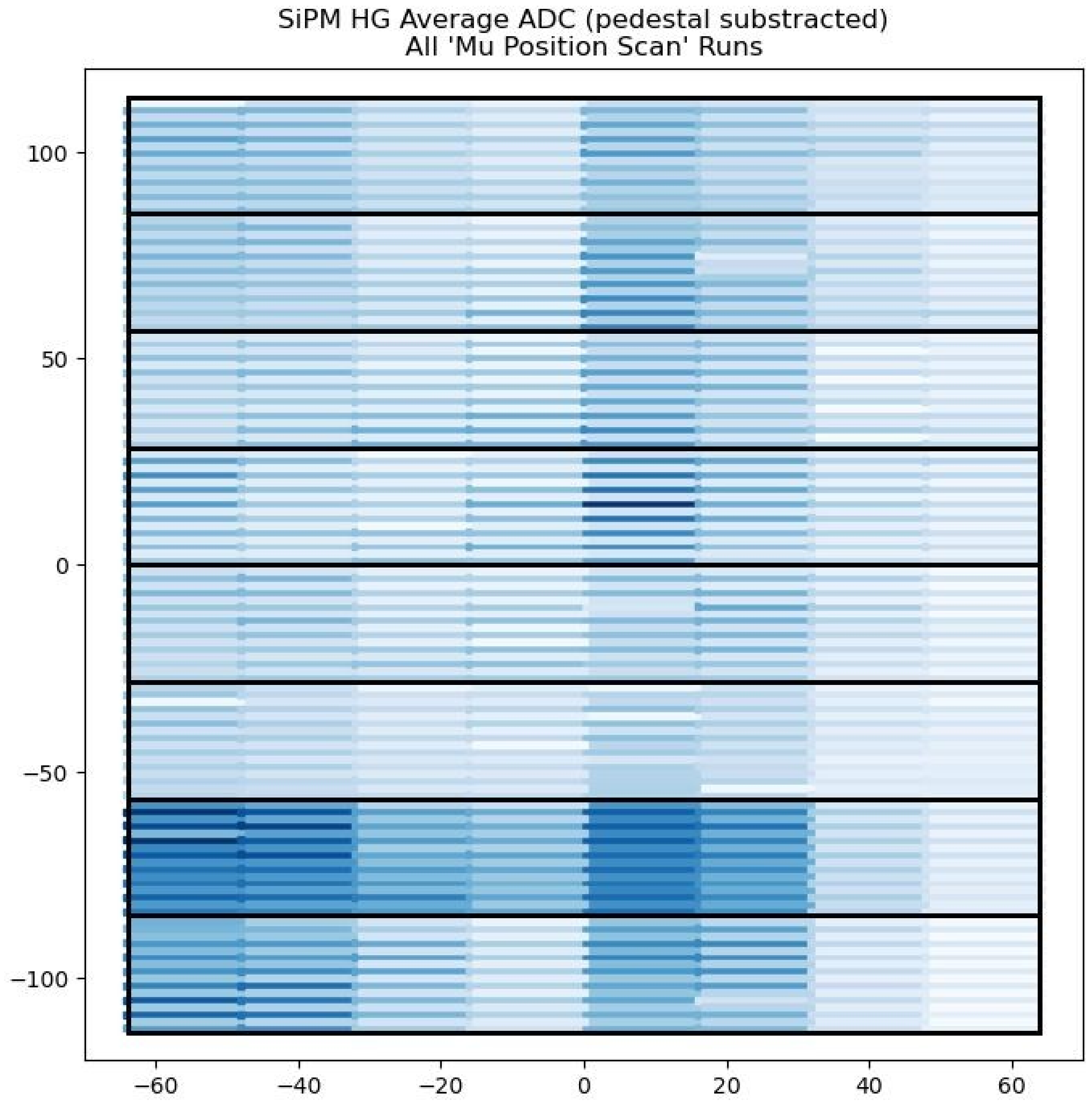


PMT response uniformity

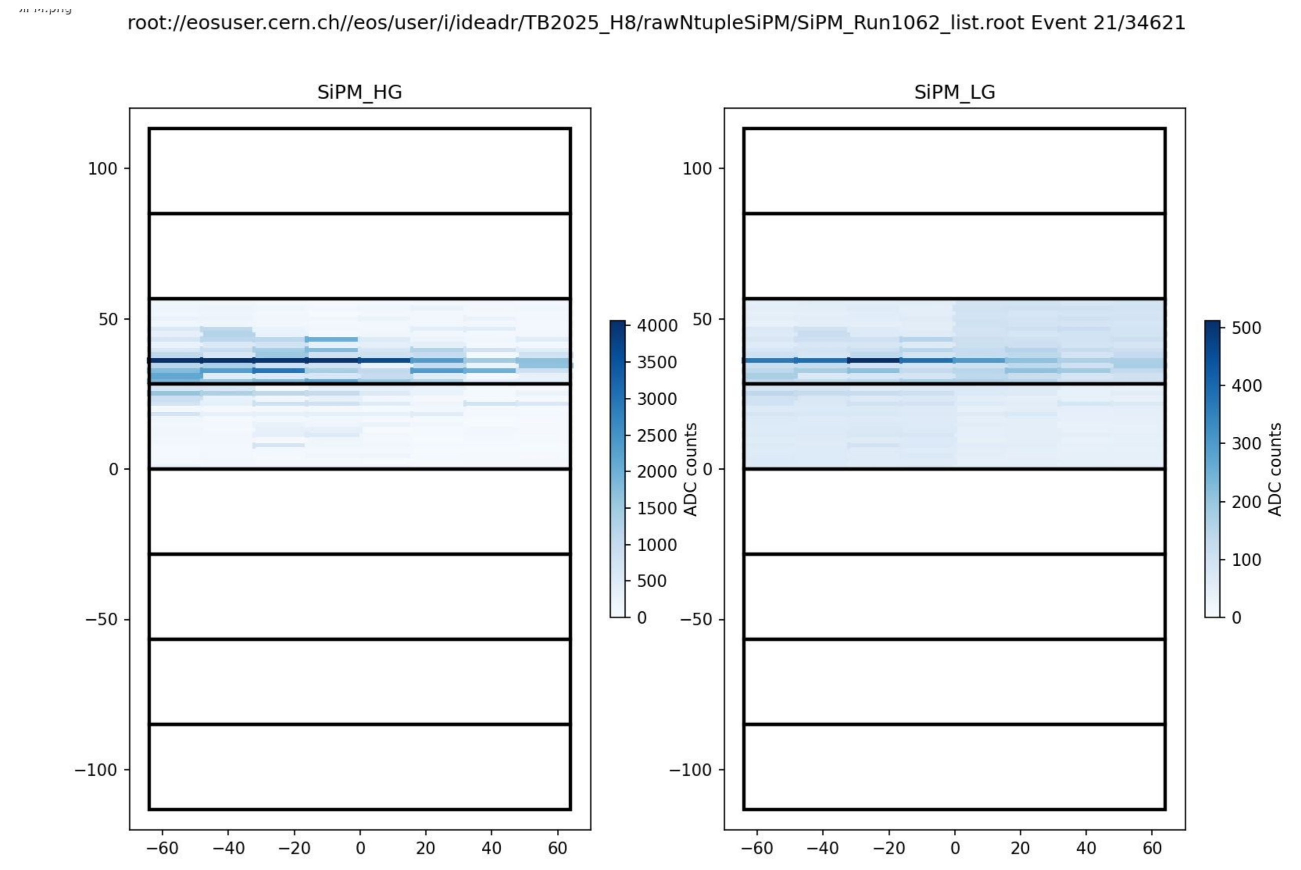


SiPM response

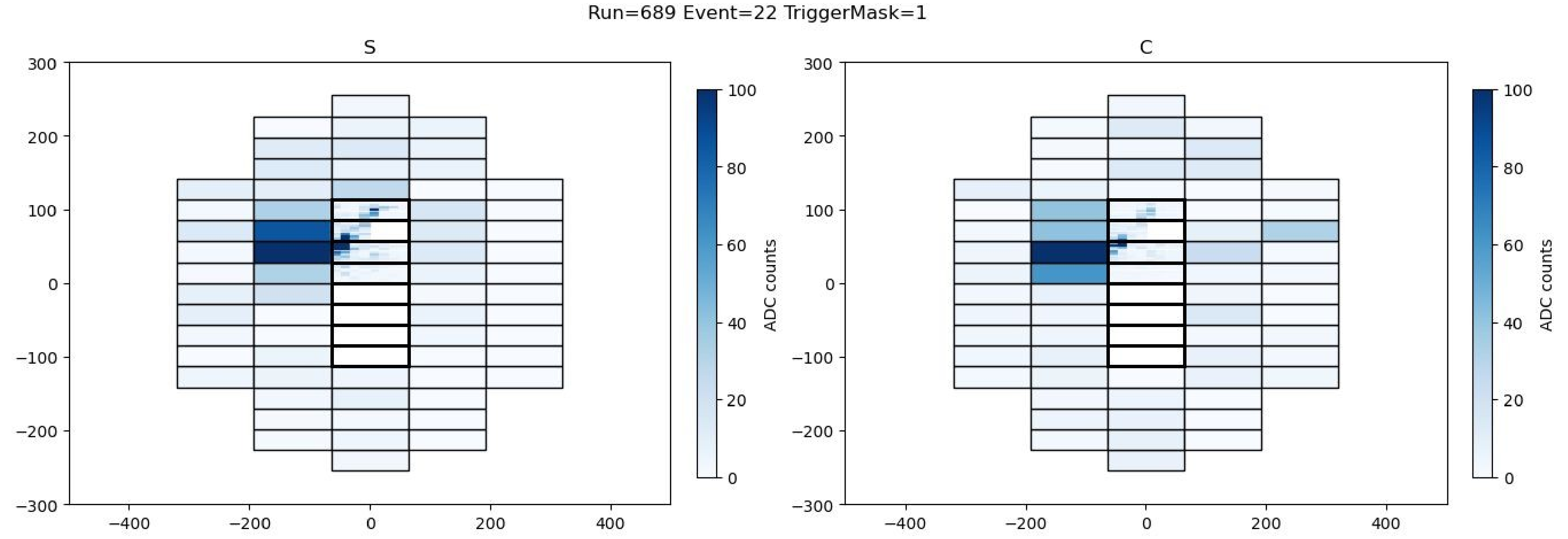
All μ position-scan data



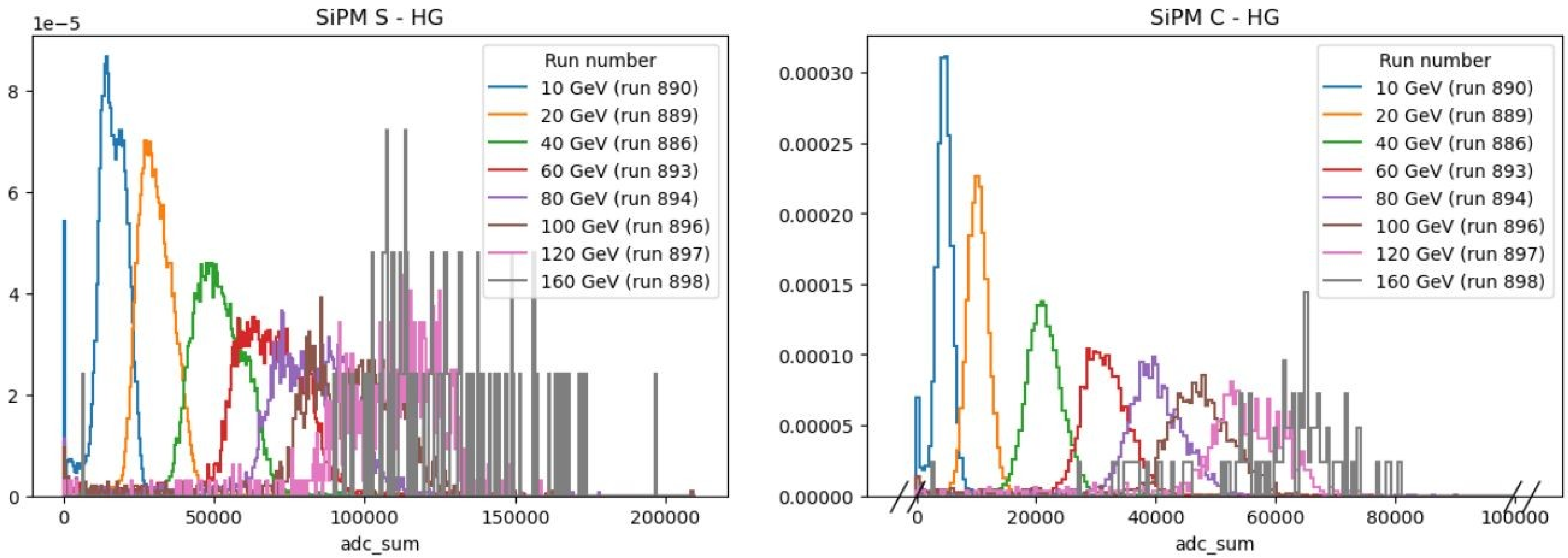
e⁺ @ 60°



60 GeV π



e^+ energy scan



Data analysis plan

Assess data quality of data (stability, beam purity, position alignment, ...)

Tune sample selections and check their stability

Equalisation:

a. PMTs with 20 GeV e^+ data
b. SiPMs: multiphoton spectra destroyed by noise → μ data (?)
c. Runs with beam both on SiPMs and PMTs

Assess position dependence of PMT response as function of x/y → identify “mitigation” strategies

Assess electron signal resolution and linearity

π studies: dual readout, leakage, lateral profile, comparison with simulation, … resolution

μ studies: unfold ionisation (MIP) and radiative contributes ↔ assess properties of S and C signals

Study fibre light-attenuation length (not trivial w/ 60° angle) → identify “mitigation” strategies

Timing studies in SiPM data

Next year(s)

Complete HiDRa prototype w/ all 80 minimodules

Assess equalisation and calibration procedure w/ electrons

Assess position dependence of electron response

Assess hadronic performance w/ pions and protons (χ factor)

Muons ?

em crystal calo in front → cross calibration, combined performance (PFA)

GEANT4 simulations:

Validate G4 simulations in particular concerning hadron shower modeling

Assess hadronic performance at all levels (single particles, jets, complex final states)

Fully exploit dual-readout potential for physics programme at FCC-ee

Hardware/detector open issues

*** NOT EXHAUSTIVE ***

- Fibre loading - by far - too time consuming → needs some automatisation
- Fibre attenuation length → to be understood and “recovered”
- Photocathode uniformity → exploit light mixers
- Timing information (ToA, ToT) → exploit new ASIC architectures
- Data reduction → exploit intelligence in front-end elx (?)
- Light sensors → exploit Digital SiPMs
- Trigger Board: fix cross-talk and noise issues, add digital control

Thought: Dual Readout + HighGranularity + Timing

How about we **combining the two approaches** and going beyond:

Start with Traditional Dual Readout

Excellent individual hadron energy resolution

Increase granularity in the XY plane

in the XY plane:

- Fine shower shape structure in the XY plane;
- resolve confusion matrix for particle-flow

Longitudinal segmentation from Precise Timing

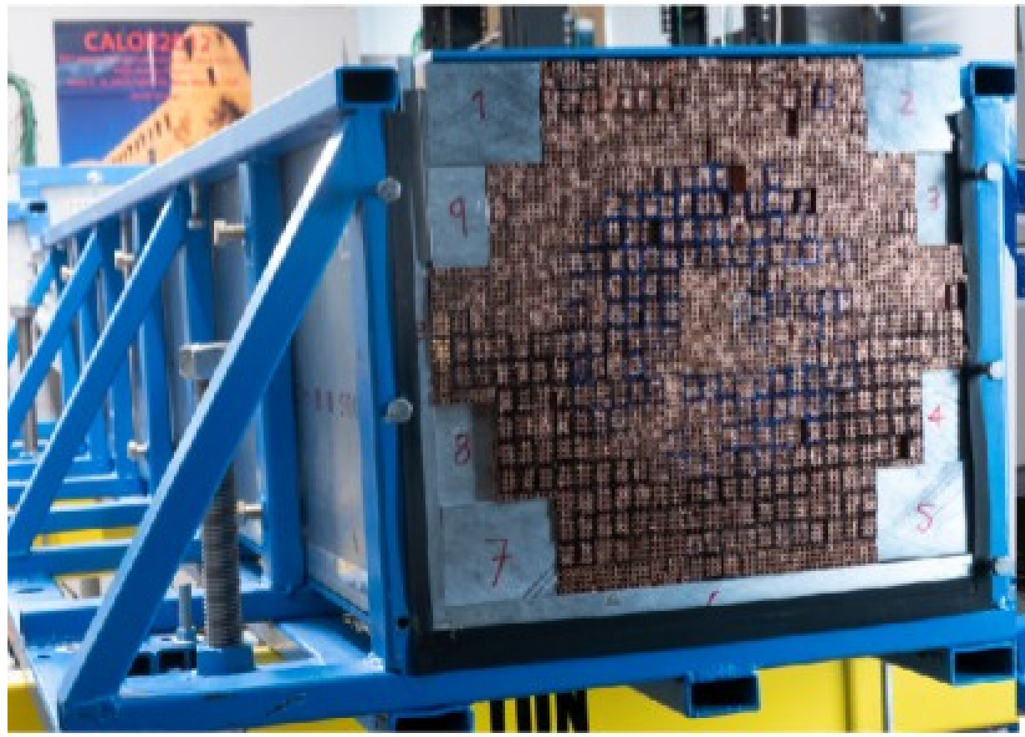
in the Z axis:

- Traditional fiber-based calorimeter did not utilize the timing information
- But thanks to developments on SiPM, electronics, and ML, we can possibly recover the lost timing (longitudinal) information

DREAM ++ (HG-DREAM)

Let us Build the prototype and Study!

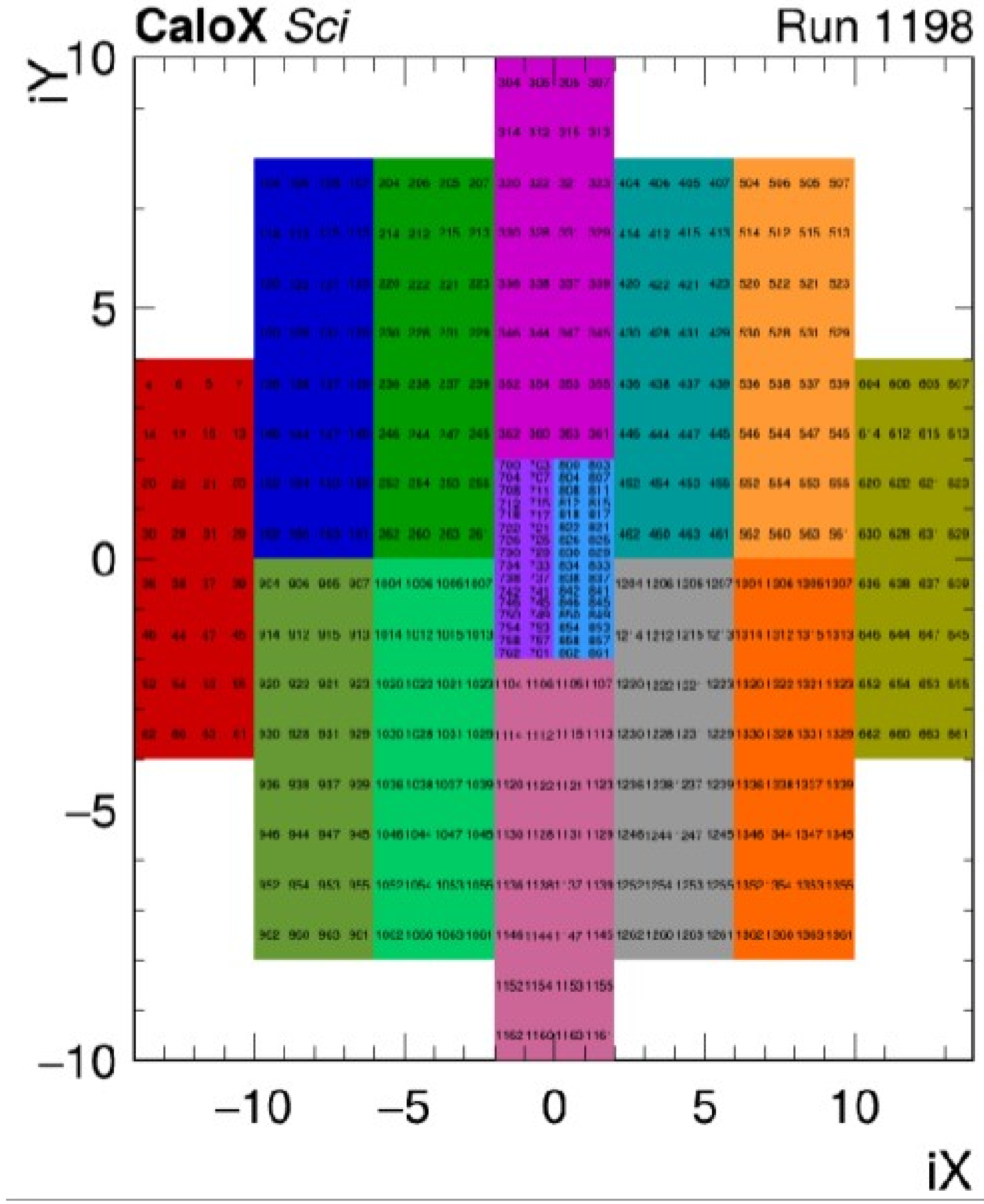
- High Granularity
- Fast readout with excellent time resolution:
  - SiPM
  - Advanced electronics for fast readout
  - advanced algorithms for both fast online processing and accurate offline reconstruction



9

Exploit SiPMs w/ fast (+ slow) output

Channels and Readout Electronics



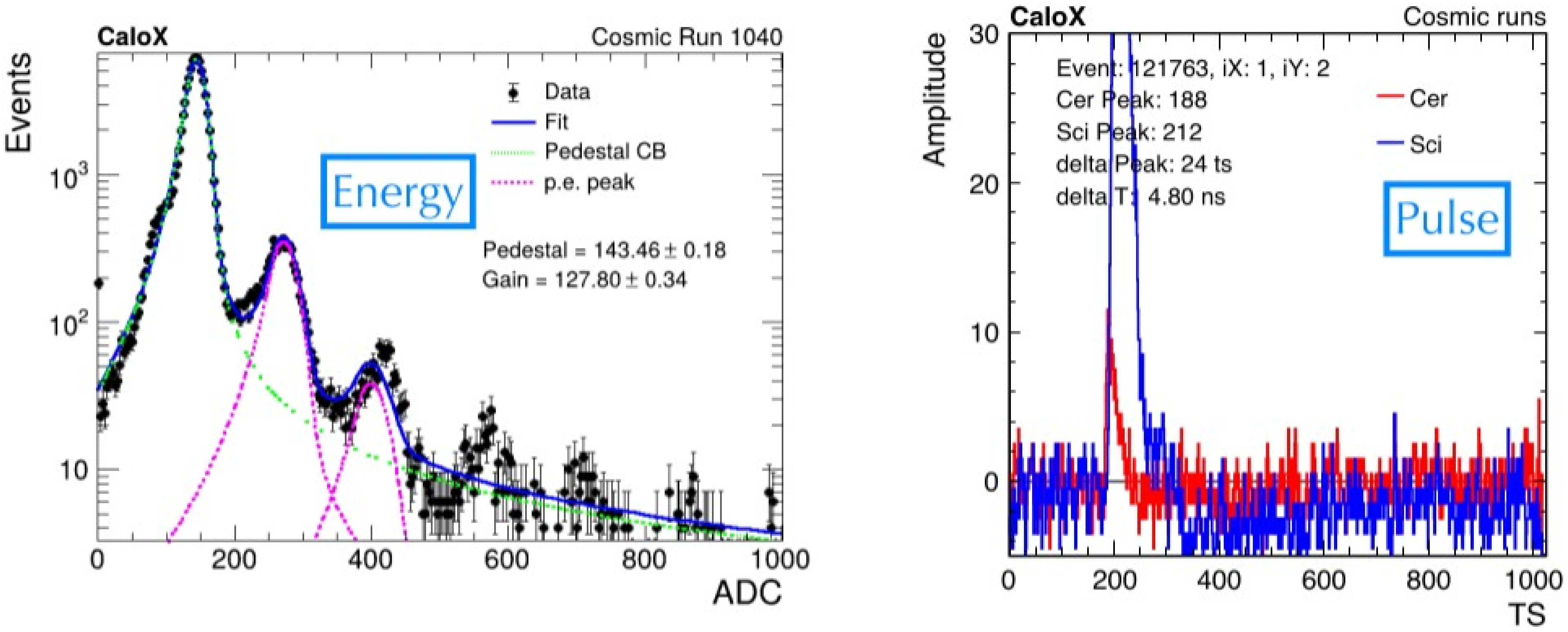
- 896 channels in FERS in total, split evenly between C and S channels, for the energy measurement
  - Central region: 3mm SiPM, each channel corresponds to a tower of 1.2cm x 0.4cm. "High Granularity"
  - Outer region: 6mm SiPM, each channel corresponds to a tower of 1.2cm x 1.6cm

- 224 channels in DRS in total, largely on Cherenkov, to study pulse shapes for timing and longitudinal information
  - 5GS sampling frequency; readout every 200ps

12

Energy (FERS) and time (DRS)

Channel Outputs

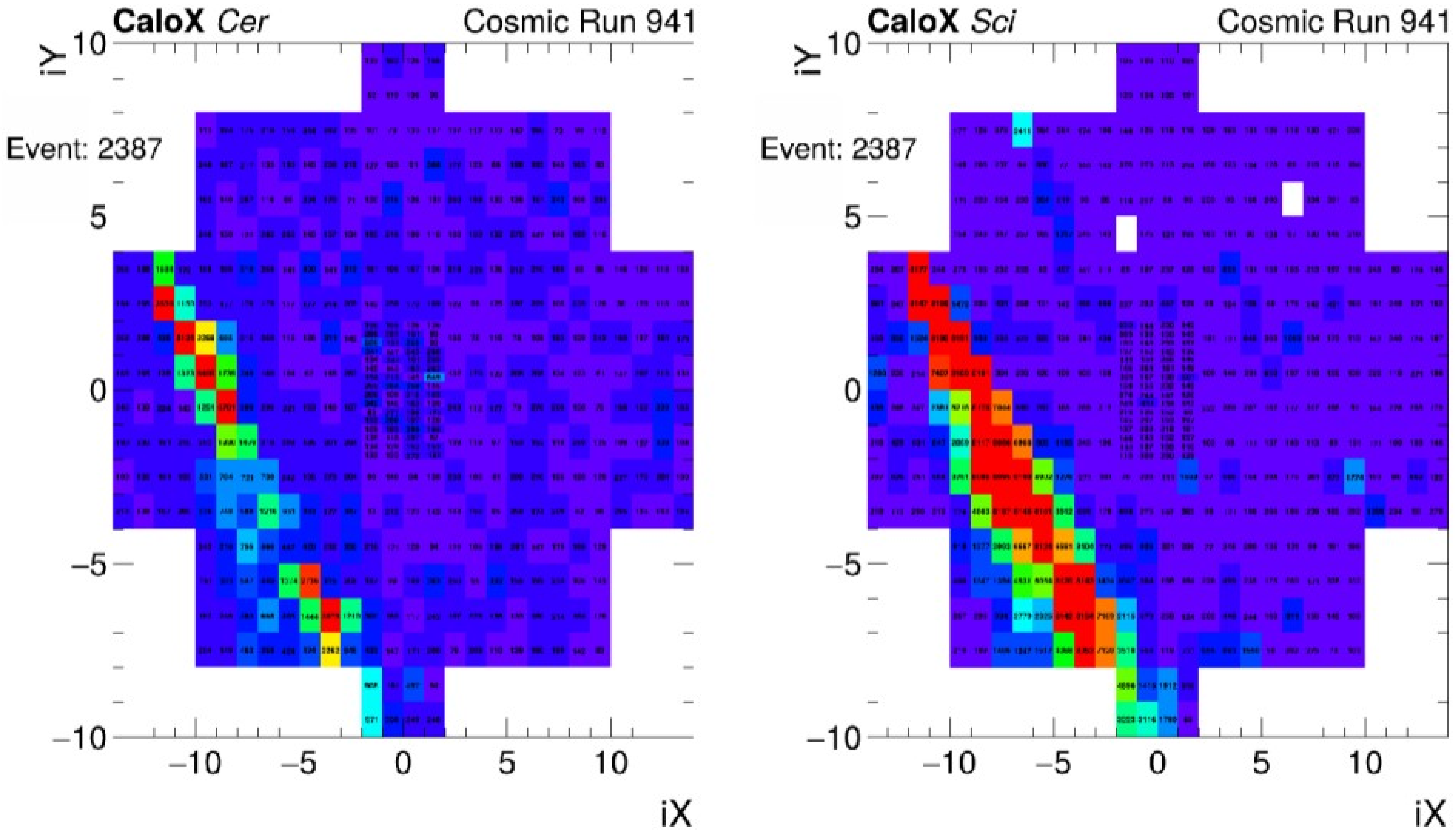


- Outputs from Cosmic runs. Left: FERS readout (energy). Can observe pedestal + individual photon peaks
- Right: DRS readout of pulses. (One time slice is 200ps)
    - Cherenkov signals (red) smaller than Scintillation signals
    - Cherenkov signals faster than Scintillation signals

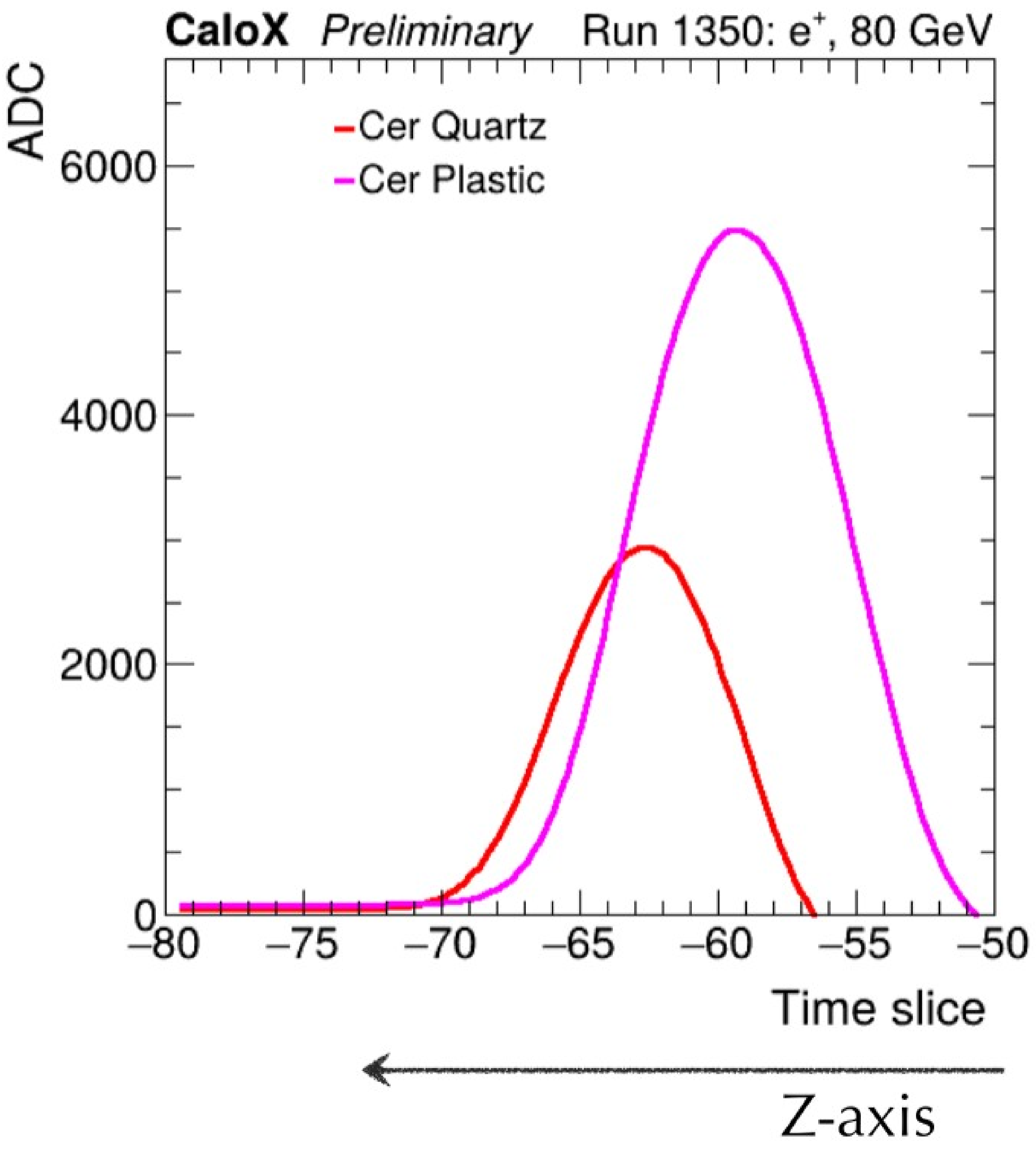
13

Energy deposition

Example Cosmic Event

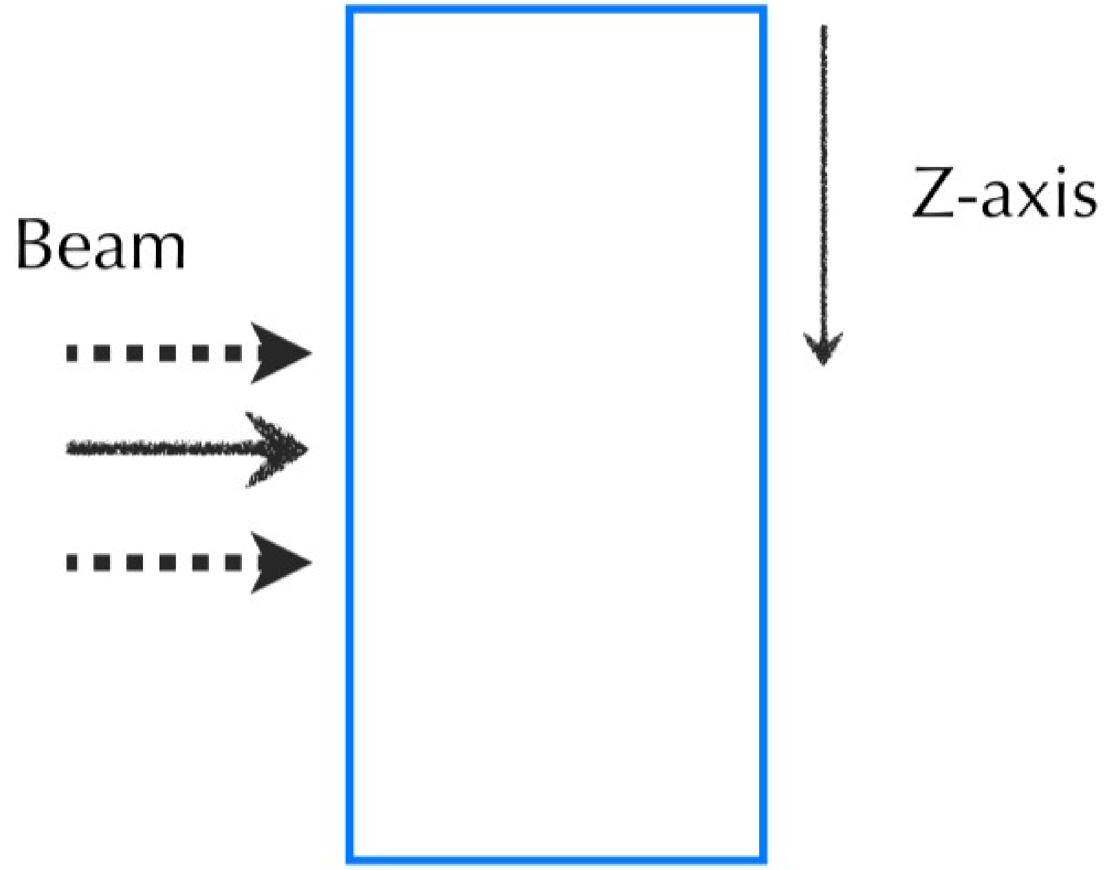


Cherenkov Signal vs Time (Positron)

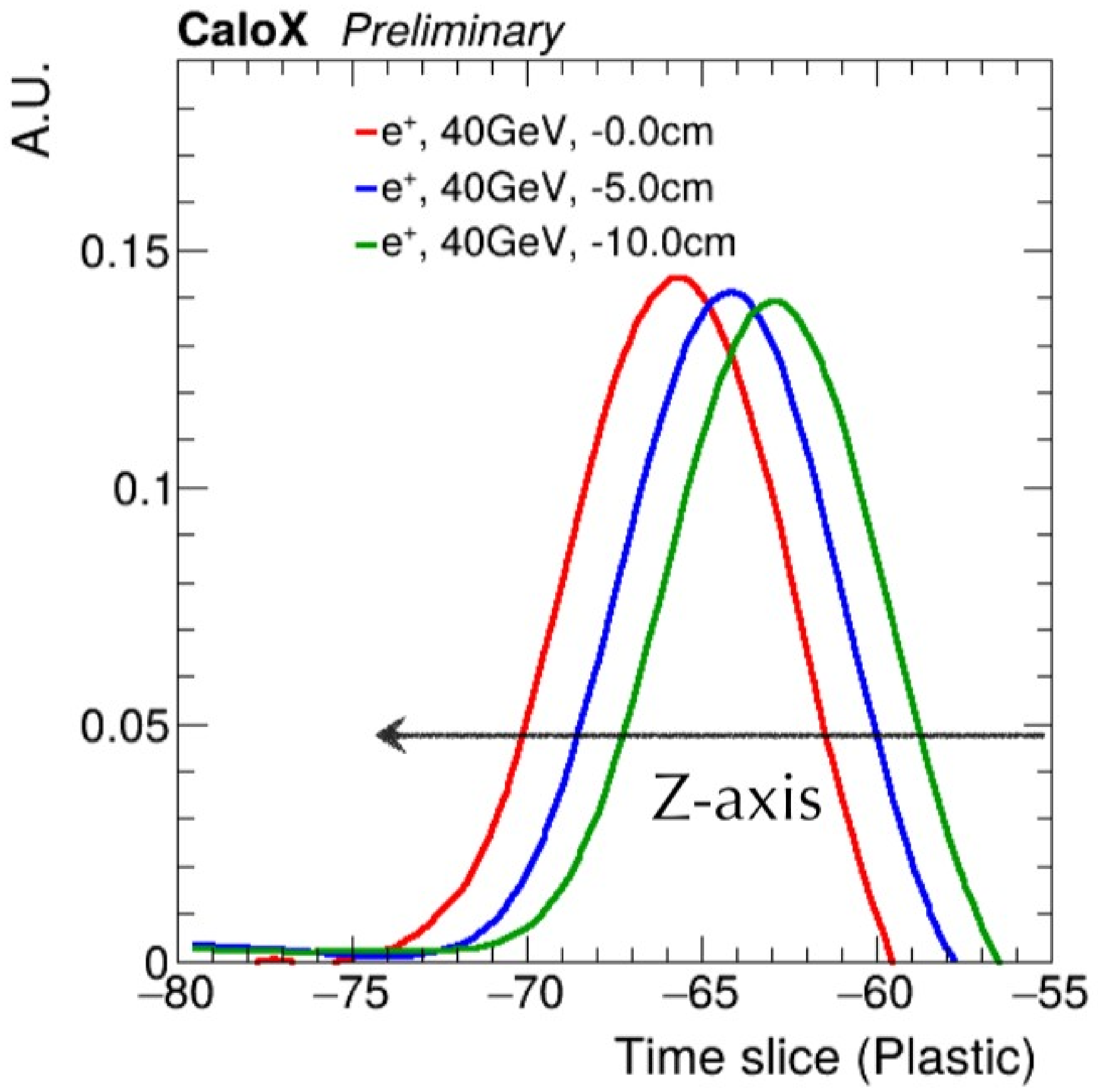


- Study the pulses as a function of time, in two different types of Cherenkov fibers (different refraction indices: 1.48 vs 1.62);
- Rightmost corresponds to the beginning of the shower, where the deltaT between the two fibers are maximal
- DeltaT reduces as shower moves deeper and deeper
- **Successfully observed longitudinal shower shapes from the timing information**

Longitudinal Position Scans



- Rotate the detector by 90 degree; move the detector along the z-axis to check the shower shape change as a function of z
- **Observed the expected shower shape change along the z-axis, using timing information**



Summary

- We validated the performance of energy measurement with HG-DREAM test beam data.
- The timing measurement shows the longitudinal information of showers
- Data analysis is still on-going (1 week old). Results shown are preliminary. The full results will be public by December

19

Backup

ASPIDES: digital SiPM platform for High-Energy Physics

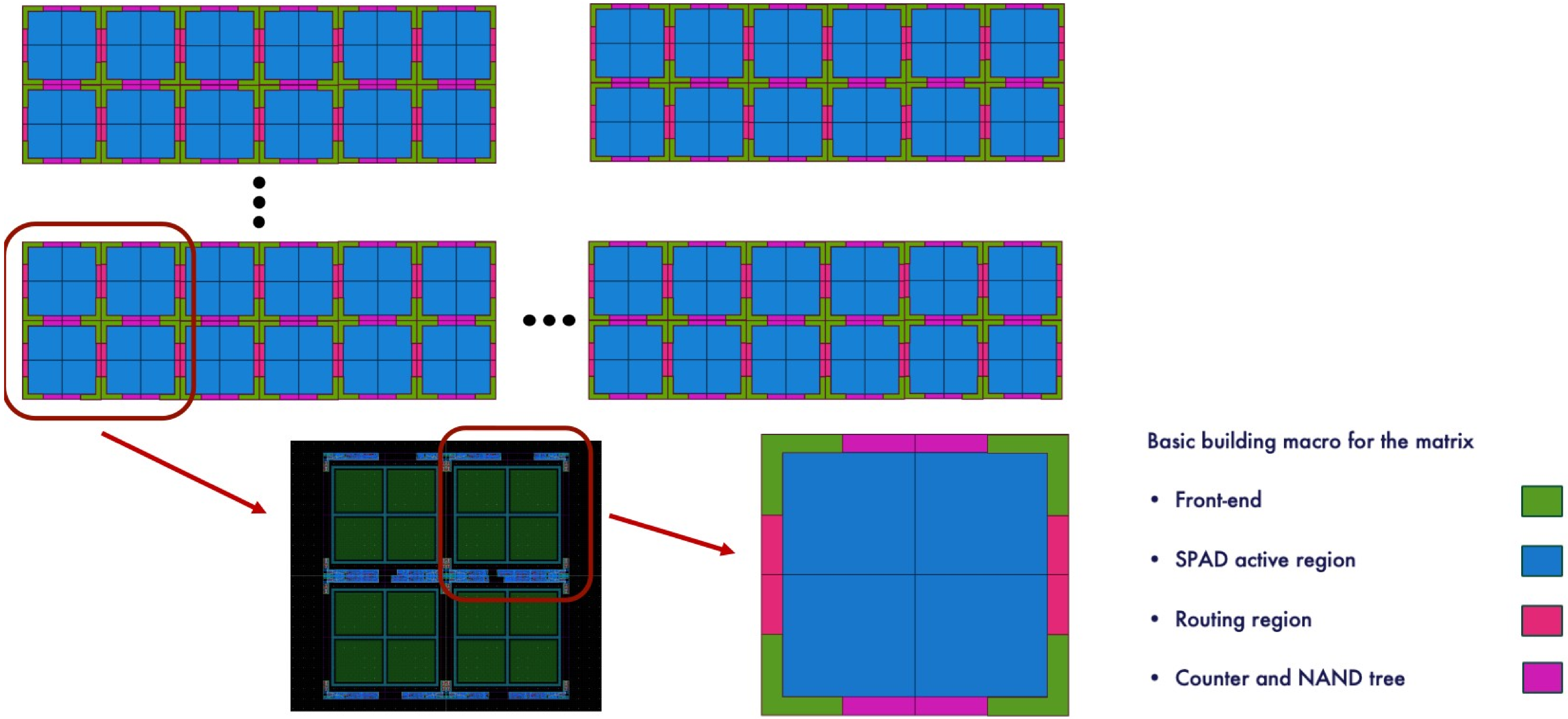
- ASPIDES: two-year CSN 5 project, coordinated by L. Ratti (INFN-PV)
- Goal: development of monolithic SiPMs in CMOS technology detectors with embedded functionalities (dSiPM)
  - Photon counting with wide dynamic range (30 pitch)
  - Fully digital output
  - ToA and ToT with resolution better than 100 ps
  - Threshold adjustment capabilities for noise rejection
  - Possibility to enable/disable individual microcells and global signal to enable/disable array
- Study of radiation damage and operation at cryogenic temperatures
- Modelling of new SPAD devices with improved performance in radiation environment and at cryogenic temperatures
- Submission planned for Q4 2025 (LFoundry 110 nm, 6 metal layers)

Sensor requirements for DR calorimetry

	Scintillating (Cherenkov)
Unit Area (mm^2)	1 × 1
Micro-cell pitch ()	15 or 30
Macro-pixel ()	500 × 500 (or less)
PDE (%)	(20 - 50)
DCR (kHz)	Not crucial
AP (%)	As low as possible (≈ 1)
Xtalk (%)	As low as possible (few %)
Trigger	External
Data: light intensity	Number of fired cells in 1 or 2 time windows (tenths ns long)
Data: time	Time of Arrival in time window (< 100 ps) possibly TOT
Final - Package	Strip with 8 units
Connection	BGA

Design ongoing

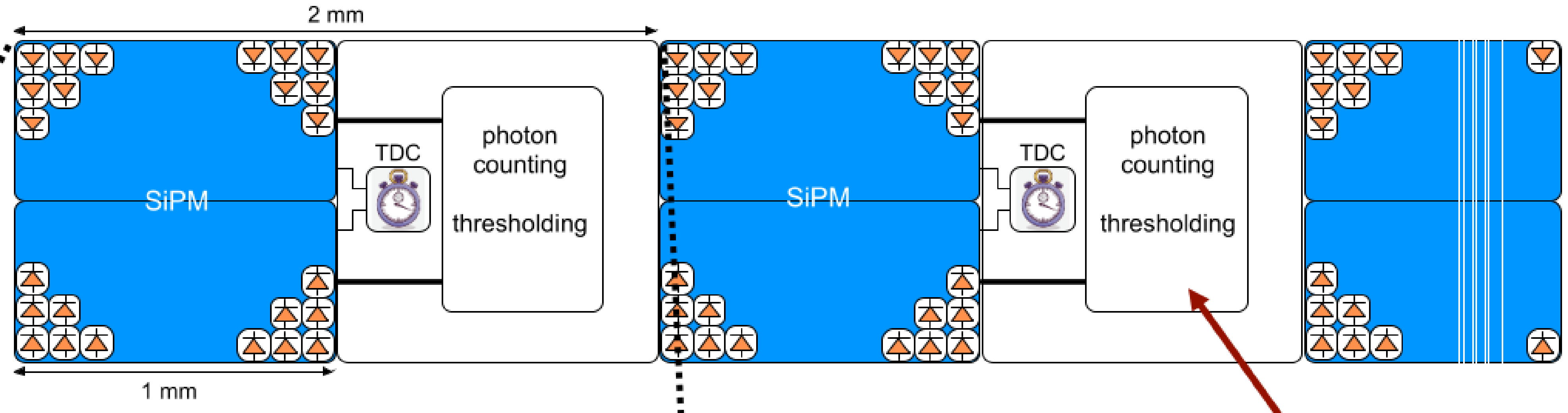
16 × 16 array, made of elementary clusters of 2×2 cells



[L. Ratti @ DRD4 WP1 meeting]

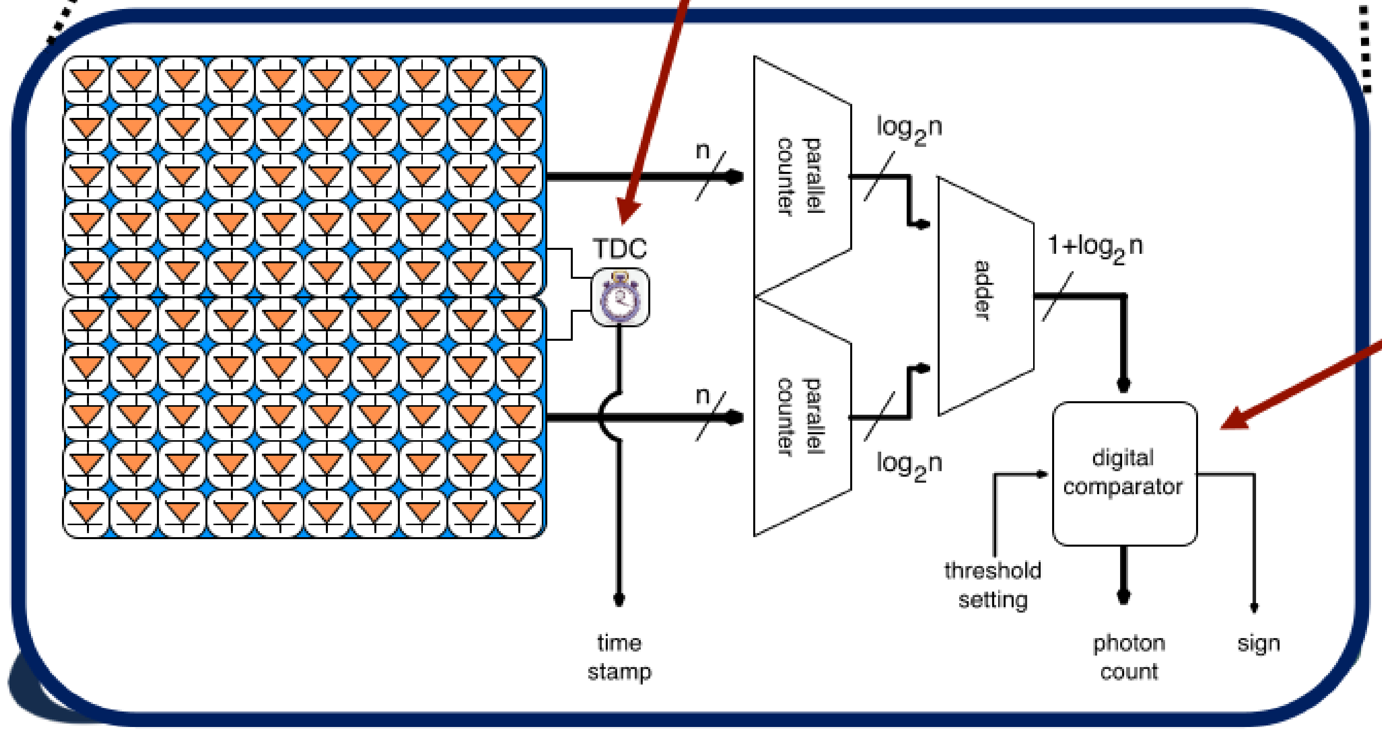
Demonstrator for DR calorimetry

1 Module = 8 dSiPMs 1x1 mm^2, interspaced by 2 mm



TDC close to the signal source: possibility to set a threshold on triggering signal

Electronics placed in the inter-SiPM region, taking advantage of the HiDRa geometry



Threshold: virtually any value can be set

L. Ratti @ DRD4 WP1 meeting

R. Santoro