Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

IDEA Dual Readout Fibre Calorimetry

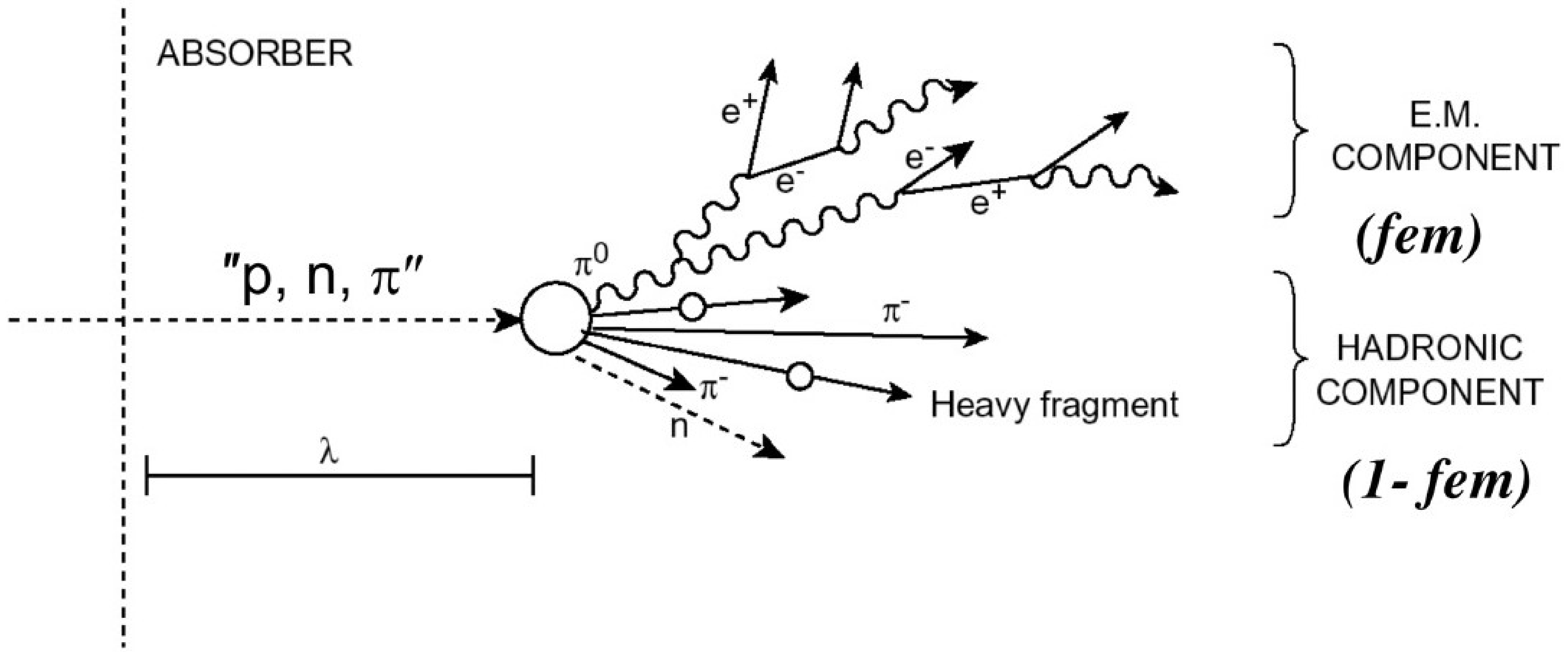
Roberto Ferrari

For the fibre-sampling dual-readout calorimetry groups

15 October 2024

dual-readout calorimetry

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 …

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

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

measurable if χ known

measurable event by event, if χ known

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

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

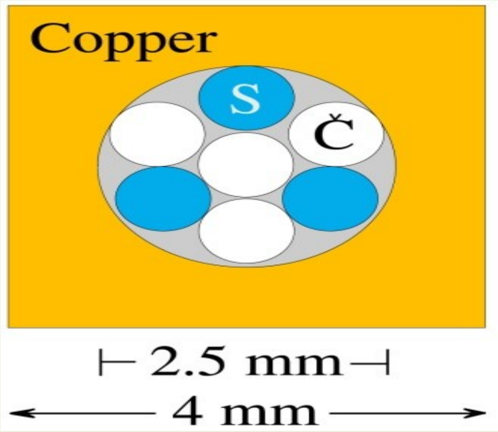
$$if \quad \left(\frac{h}{e}\right)_S > \left(\frac{h}{e}\right)_C \Rightarrow \chi < 1$$

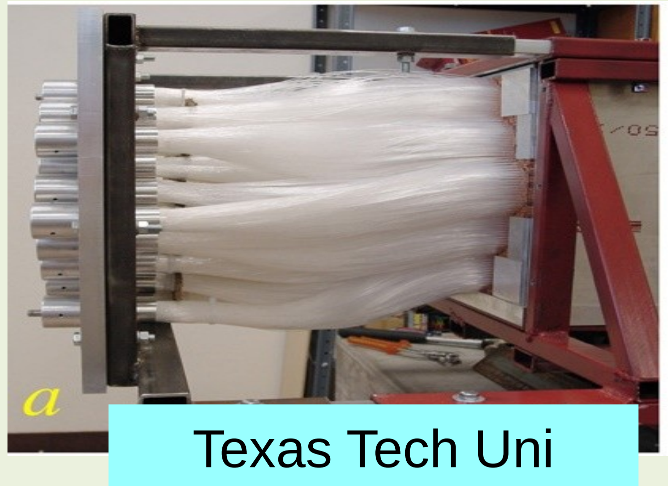
χ measurable if E known → **χ can be extracted from testbeam data**

DREAM/RD52 dual-readout "spaghetti" prototypes

2003
DREAM

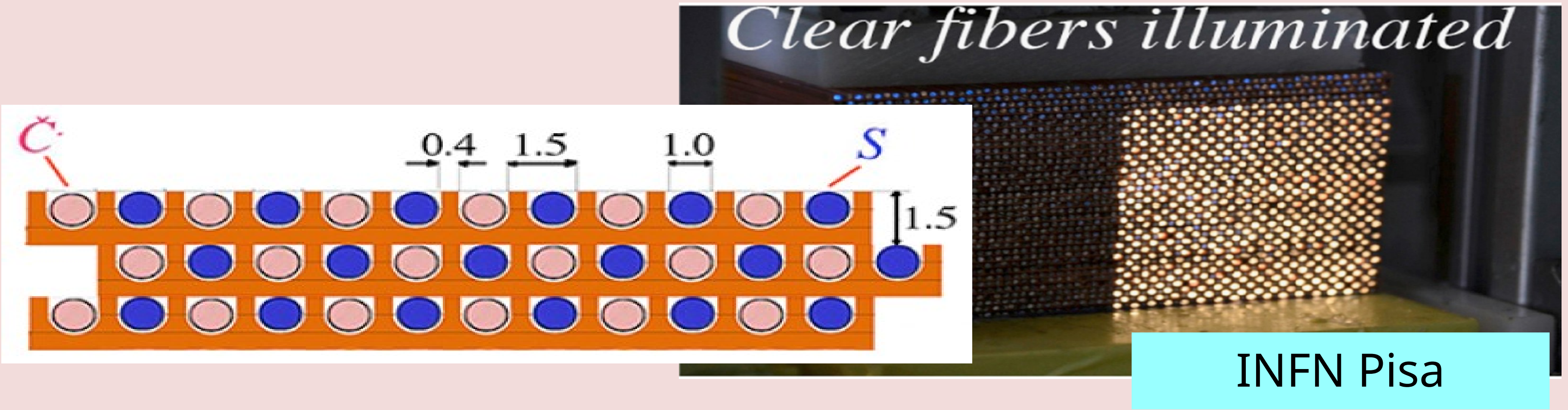
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}





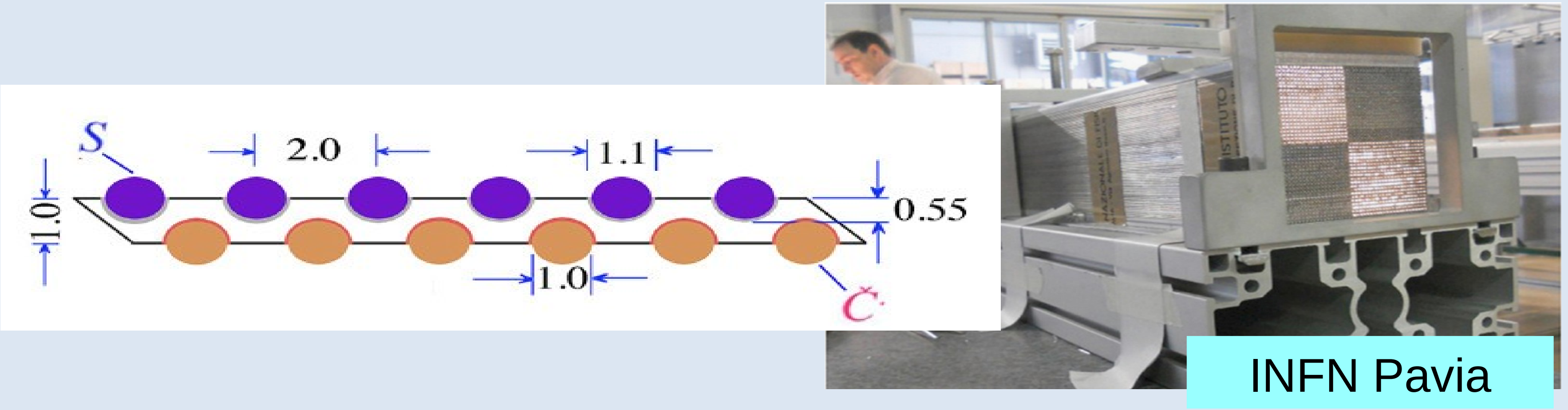
2012
RD52

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}



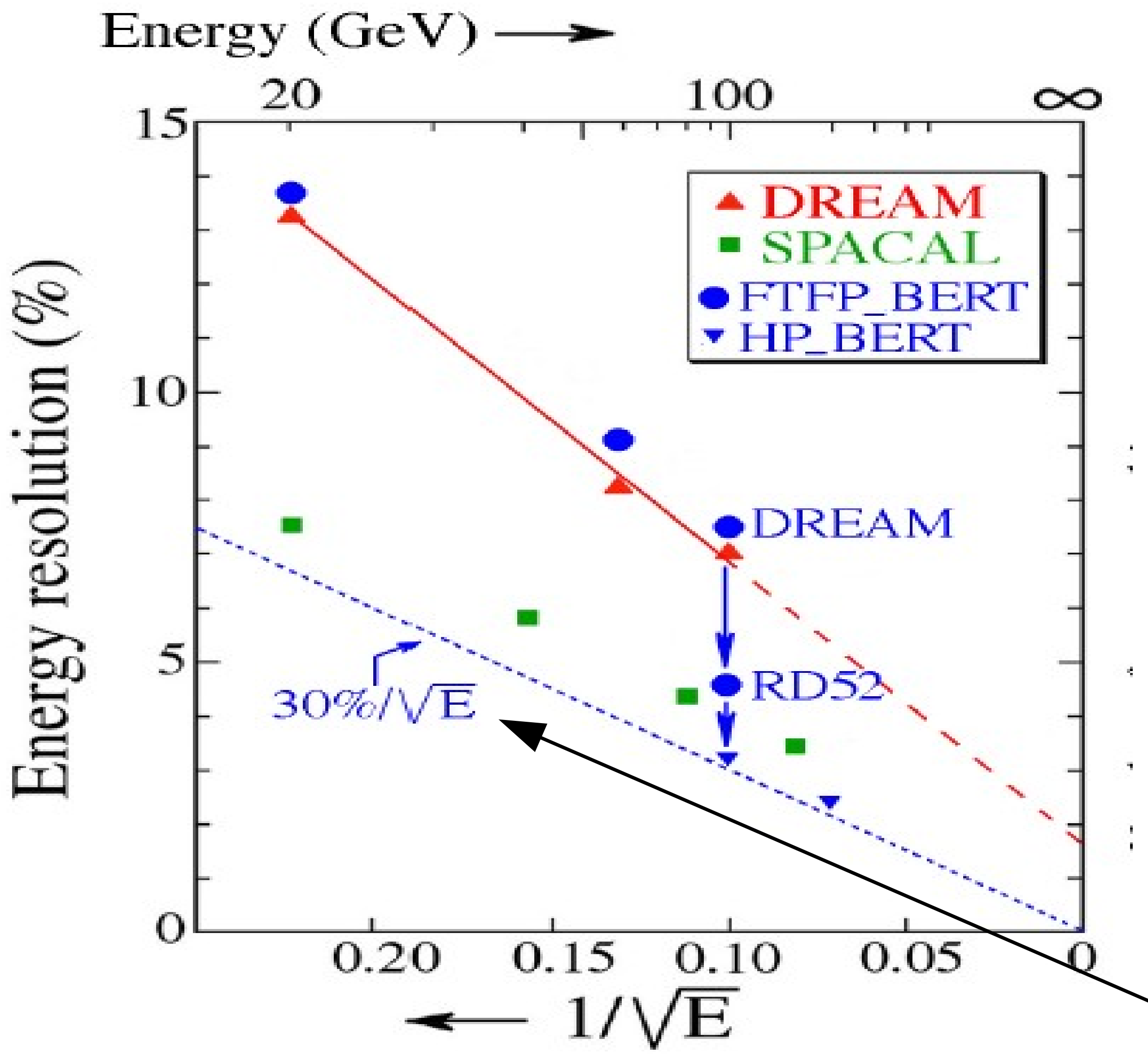
2012
RD52

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}

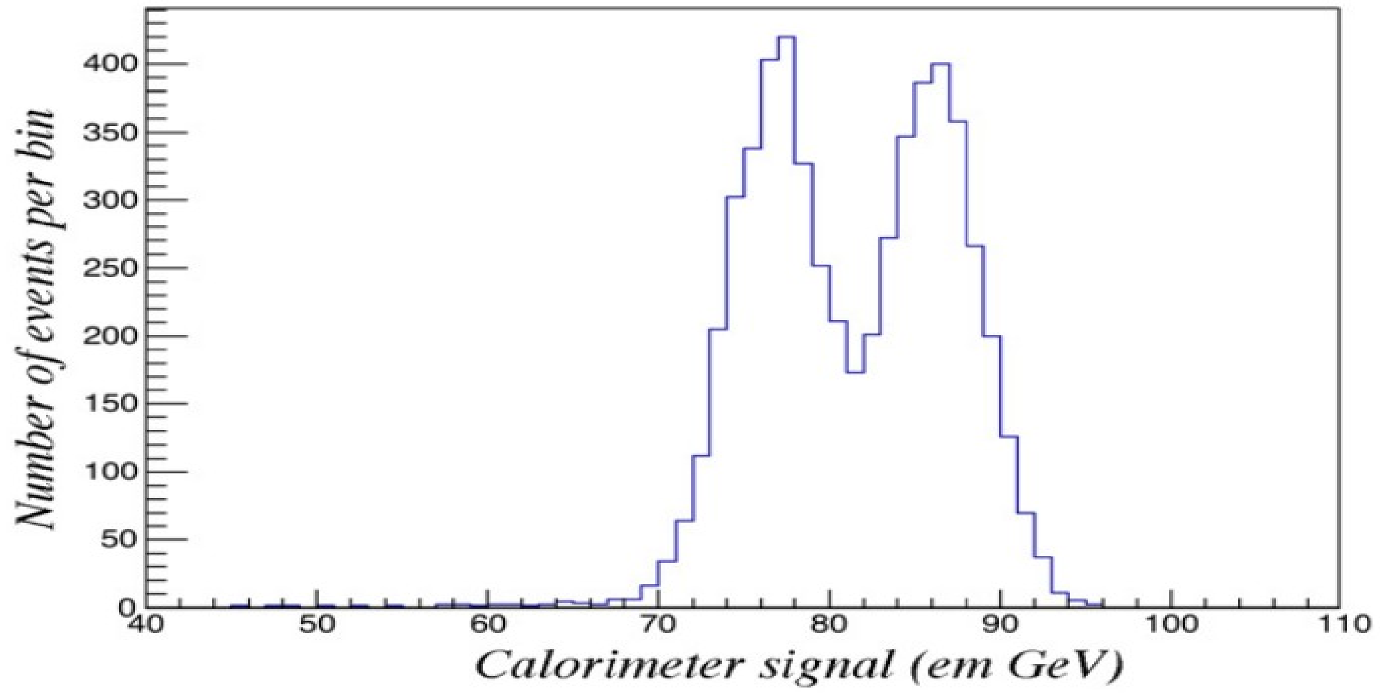


RD52 expected hadronic performance

Hadronic Resolution



W/Z separation



Geant4 simulations

NIM A 824 (2016) 721

particle ID (electron/hadron discrimination)

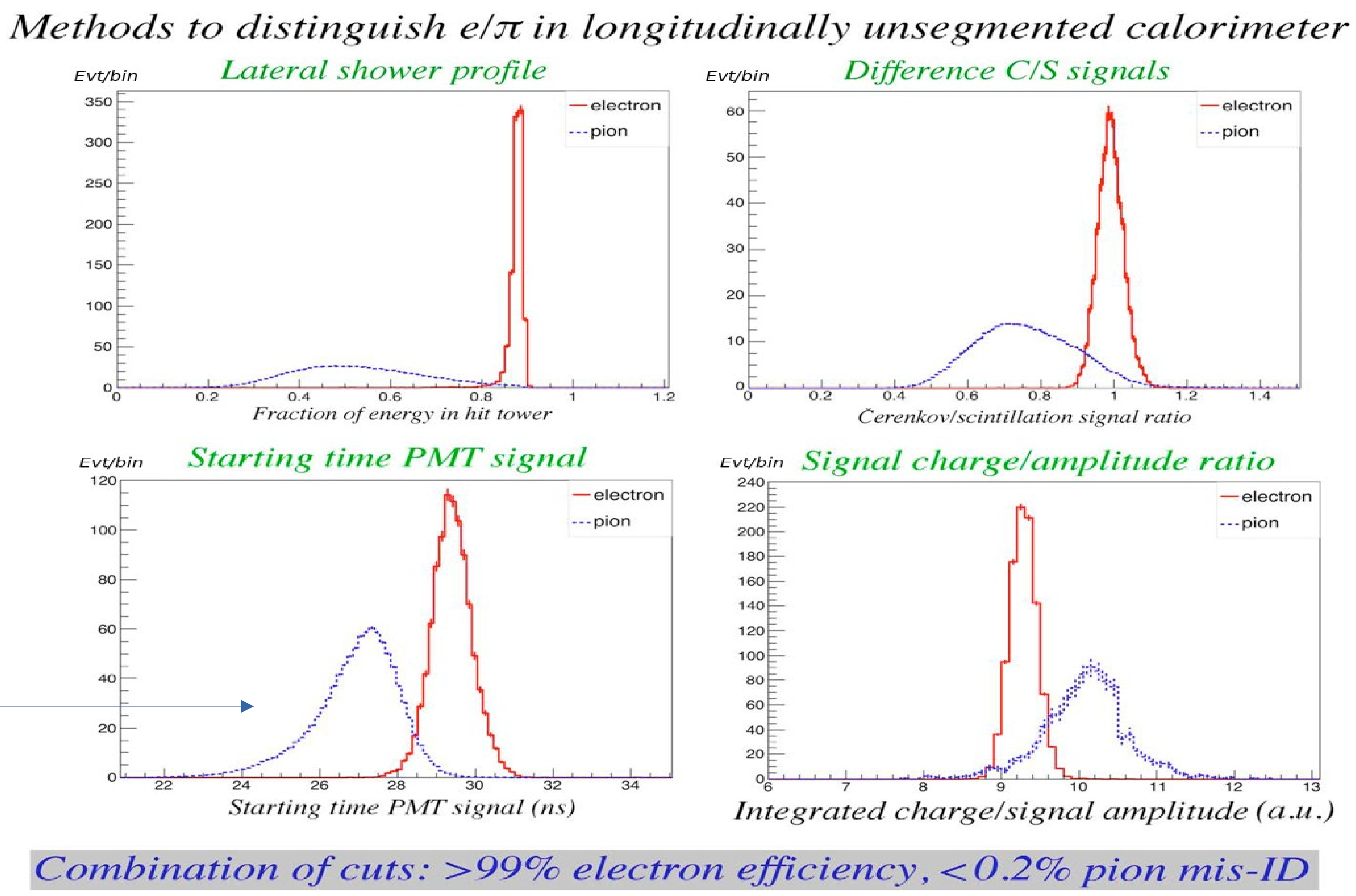
RD52 lead calorimeter

(60 GeV) e^- vs. π^-

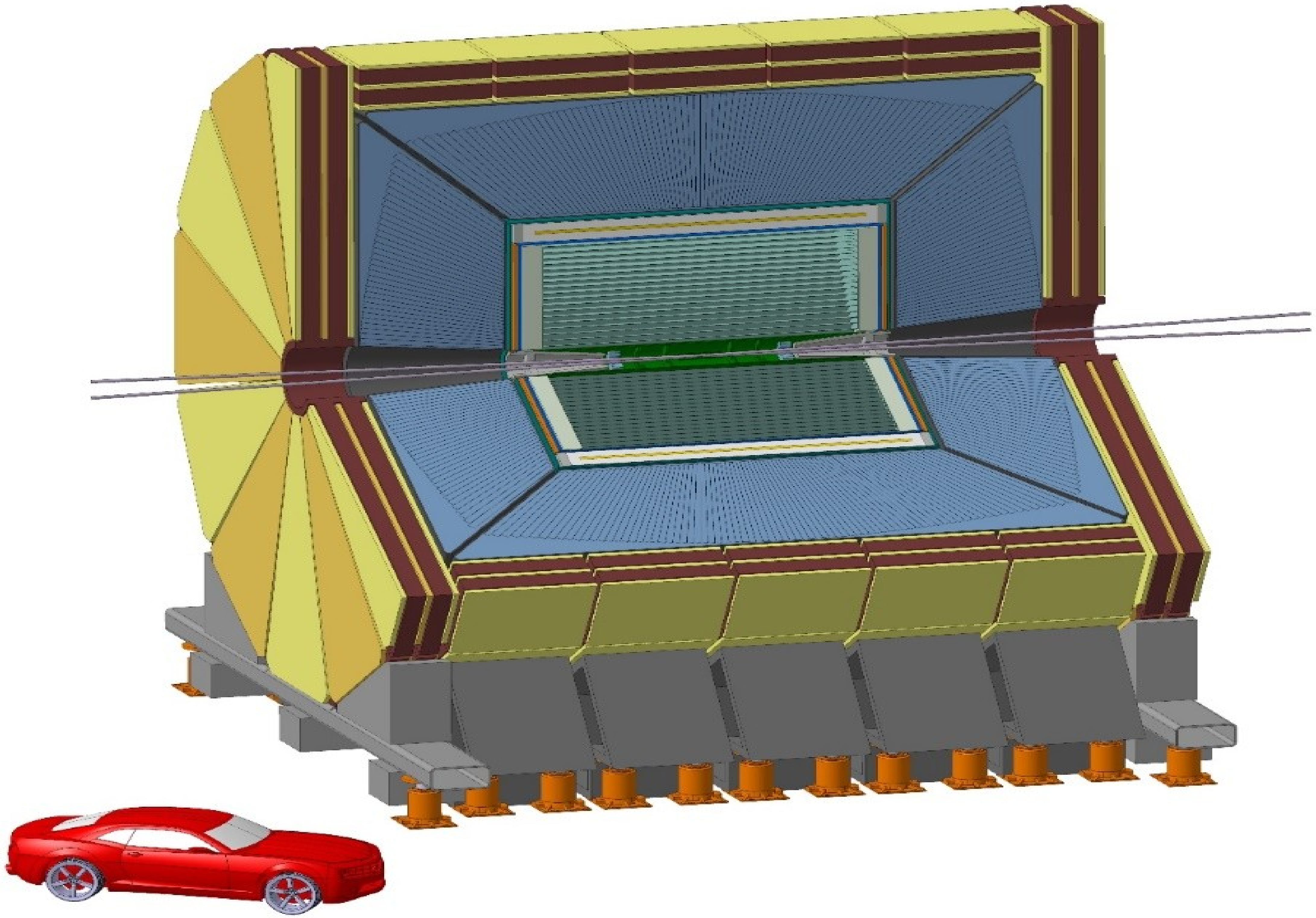
$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

NIM A 735 (2014) 120

time-of-arrival distribution
measured w/ TDC

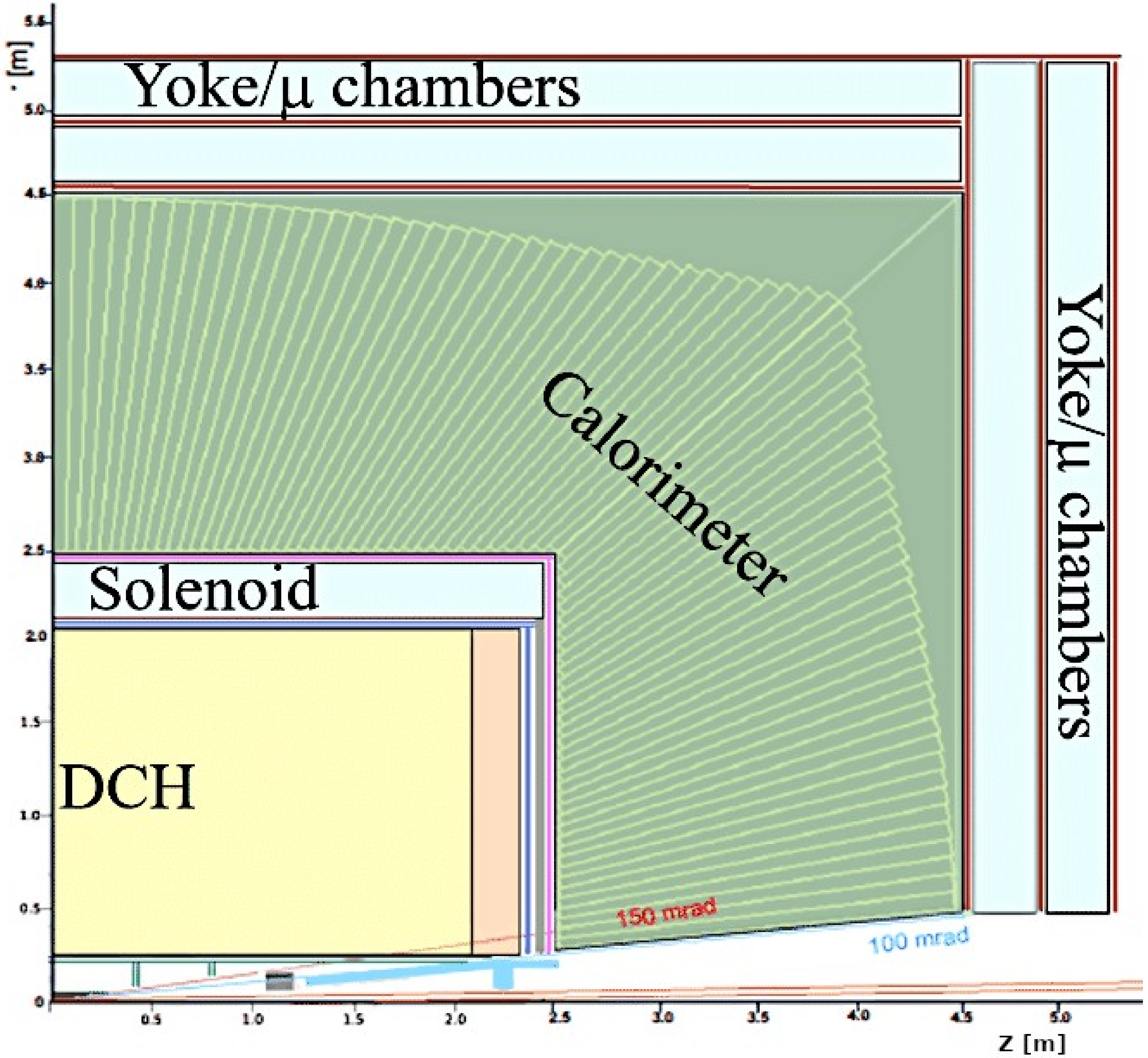


IDEA: Innovative Detector for e+e- Accelerators



IDEA baseline concept

- Muon chambers
  - μ-RWELL in return yoke
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - μ-RWELL preshower
- Thin superconducting solenoid
  - 2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°
- Highly transparent for tracking
  - Si pixel vertex detector
  - Drift Chamber
  - Si wrappers (strips)
- Beam pipe: r ~ 1.5 cm



IDEA dual-readout calorimetry group

Three main activity pillars:

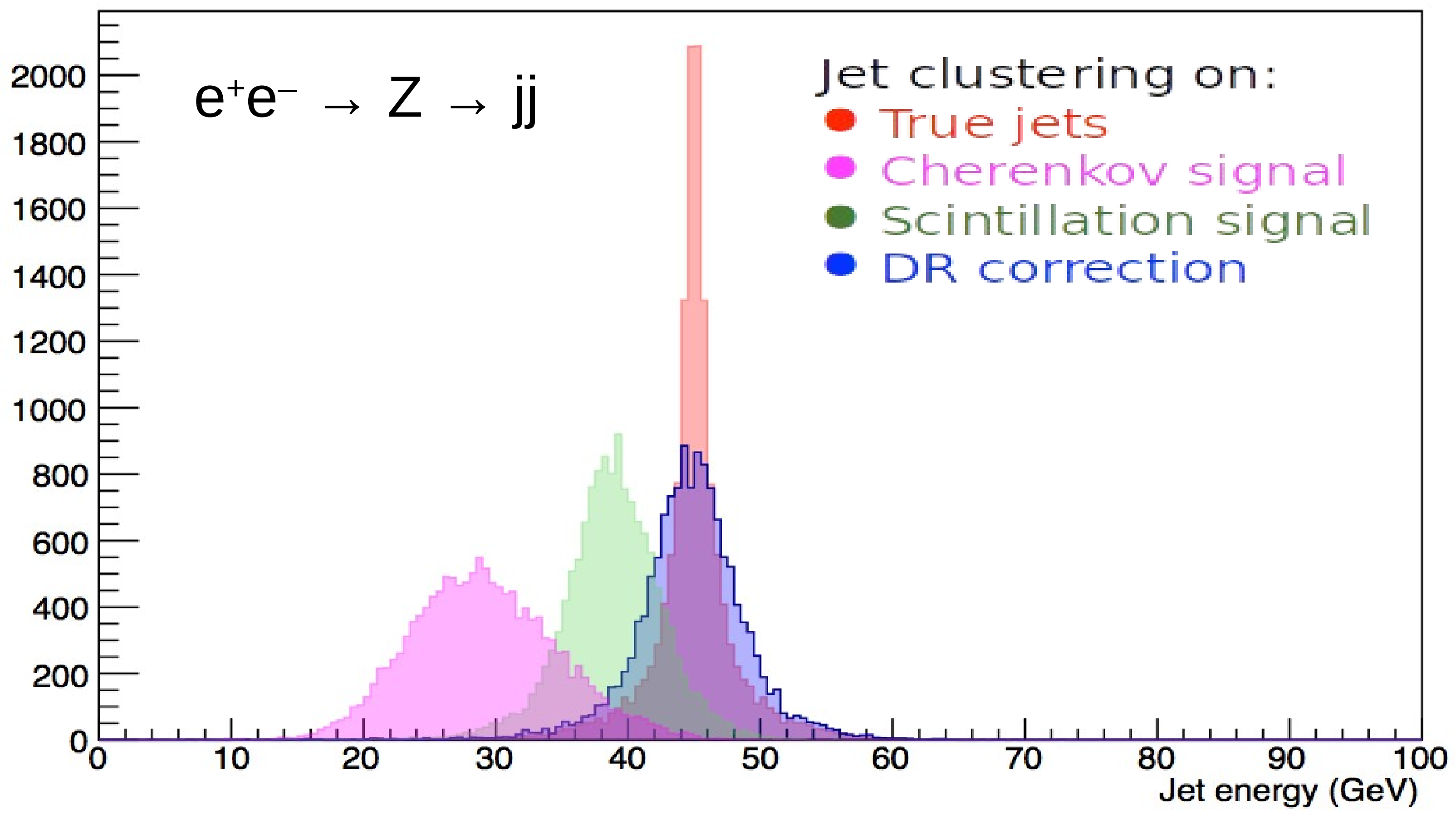
1. Europa: INFN, Sussex University → mainly (but not only) fibre-sampling calorimetry
2. Korea → projective fibre-sampling calorimetry
3. U.S. (Calvision project) → mainly (but not only) crystal em calorimetry

keywords: dual readout, high granularity & timing

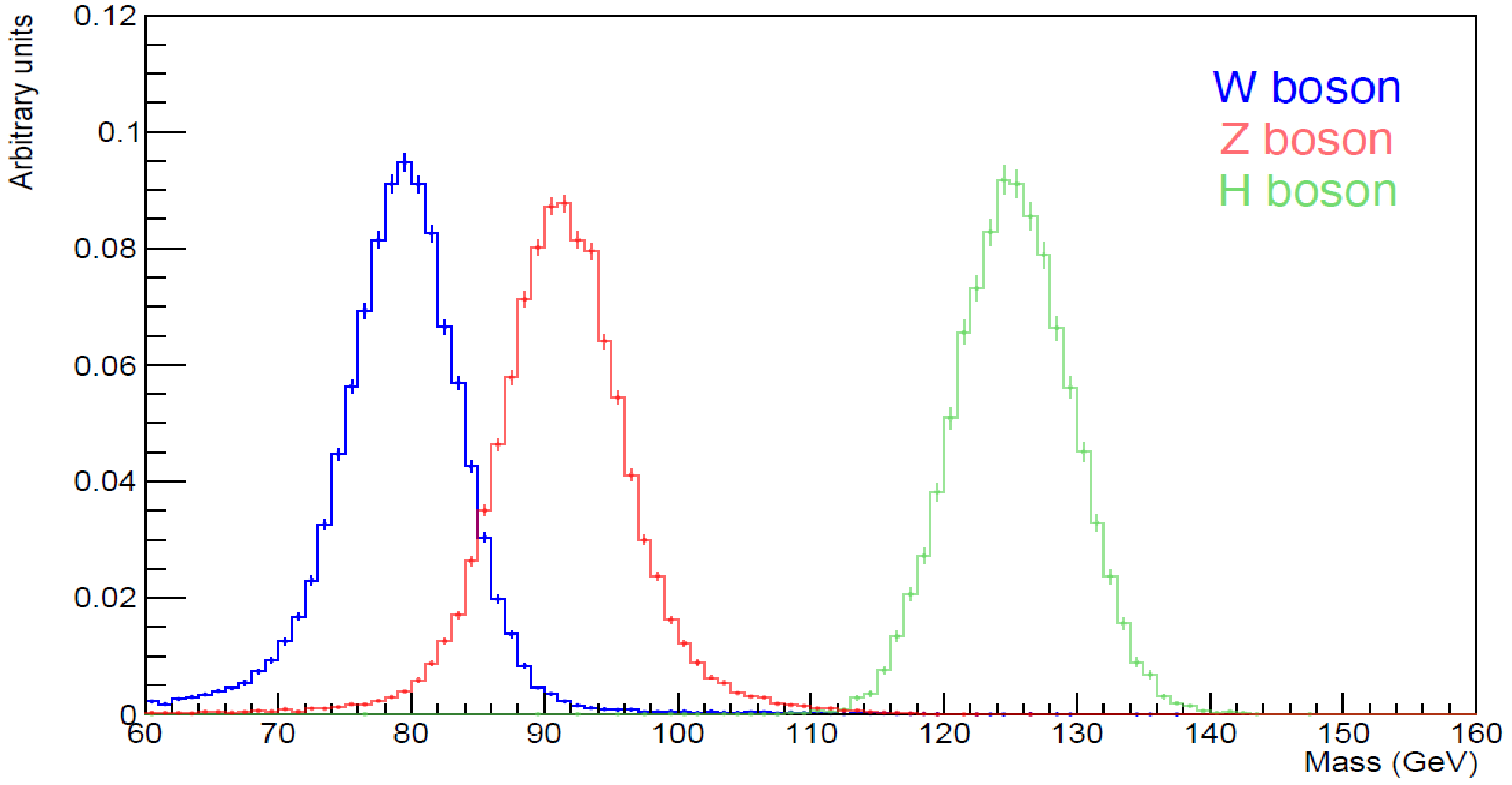
Geant4 simulations

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

Single jet resolution @ 45 GeV

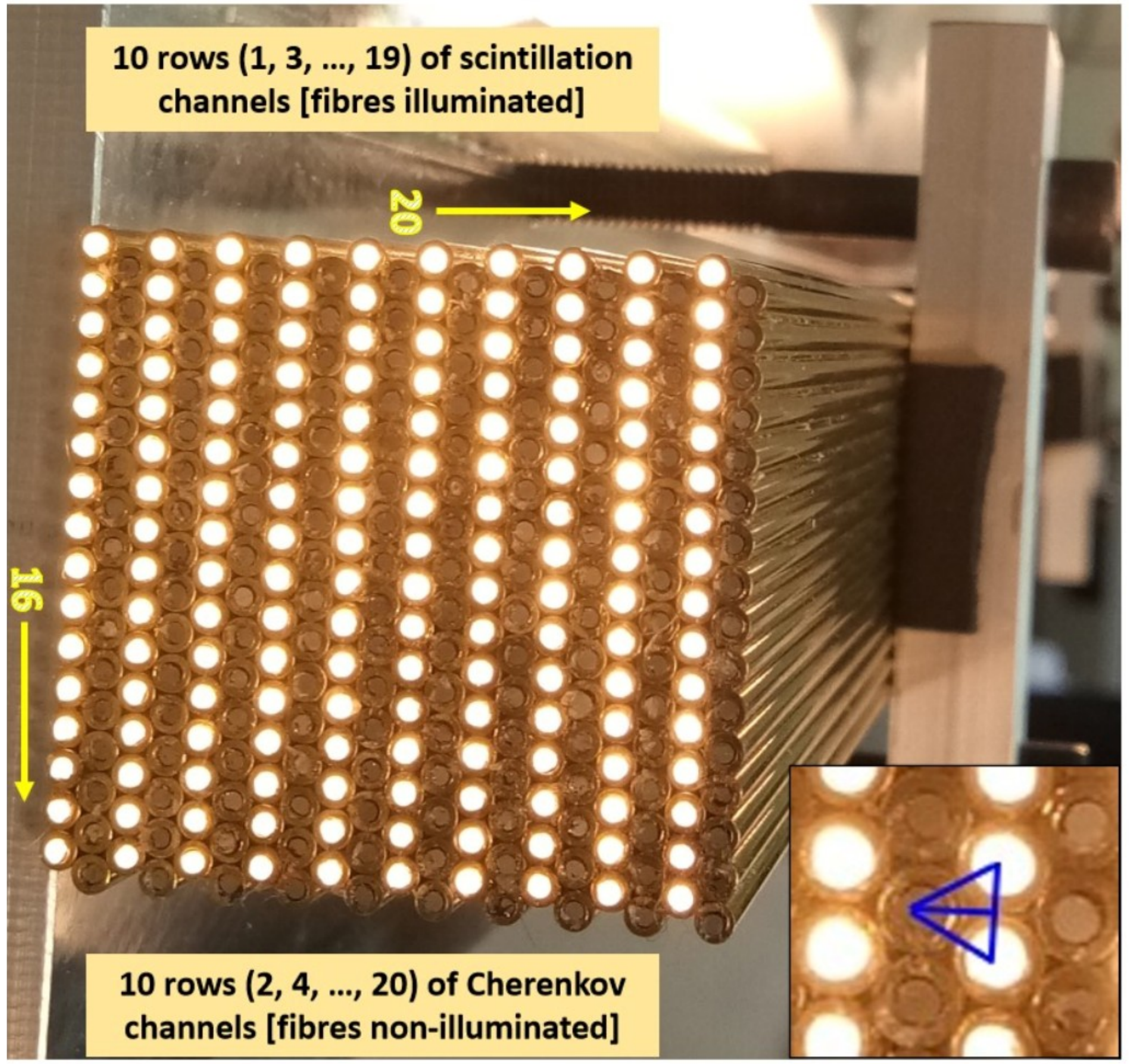


W/Z/H → jj invariant mass

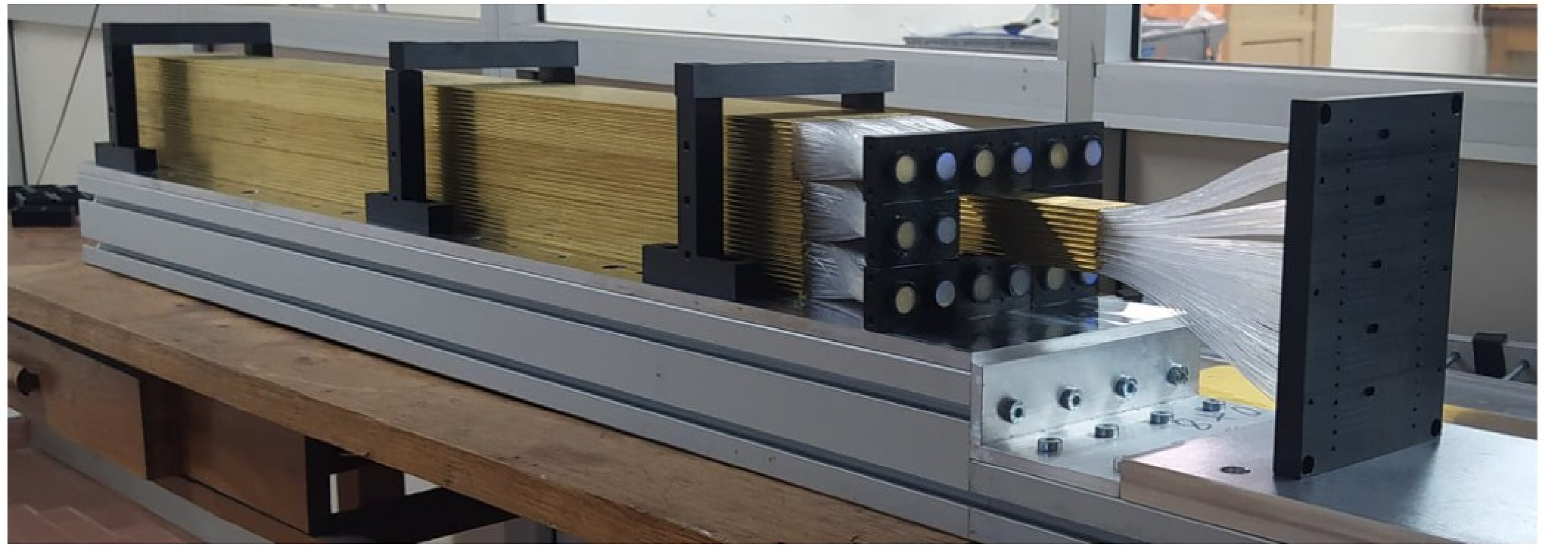


IDEA 2020 em-size bucatini prototype (EU)

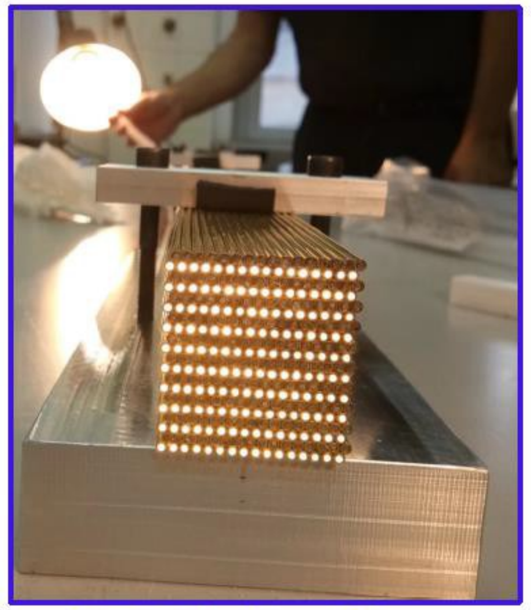
Nine ~3.5×3.3 cm^2 towers made of capillary brass tubes



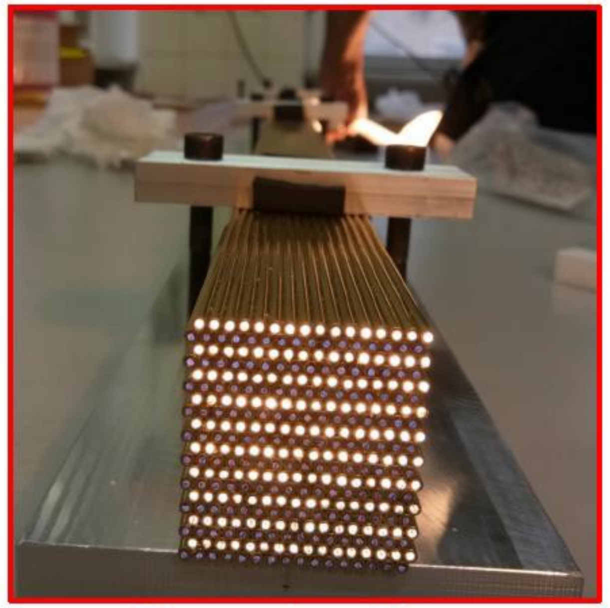
Central tower (360 fibres) w/ highly granular SiPM readout



Eight (surrounding) towers read out with PMTs



Scintillation fibers

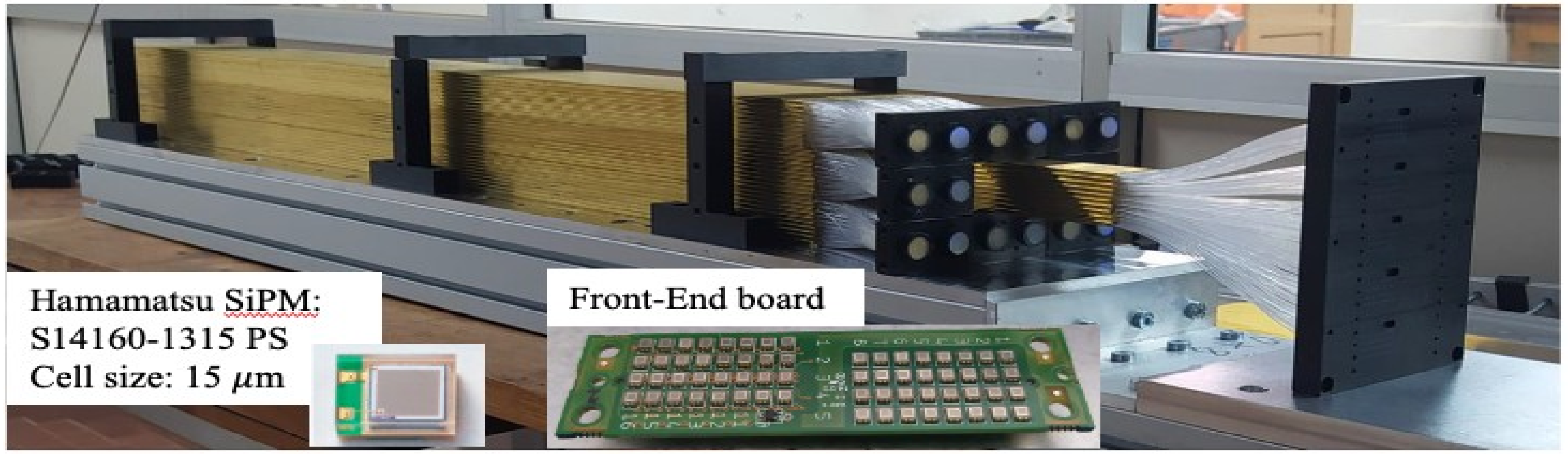


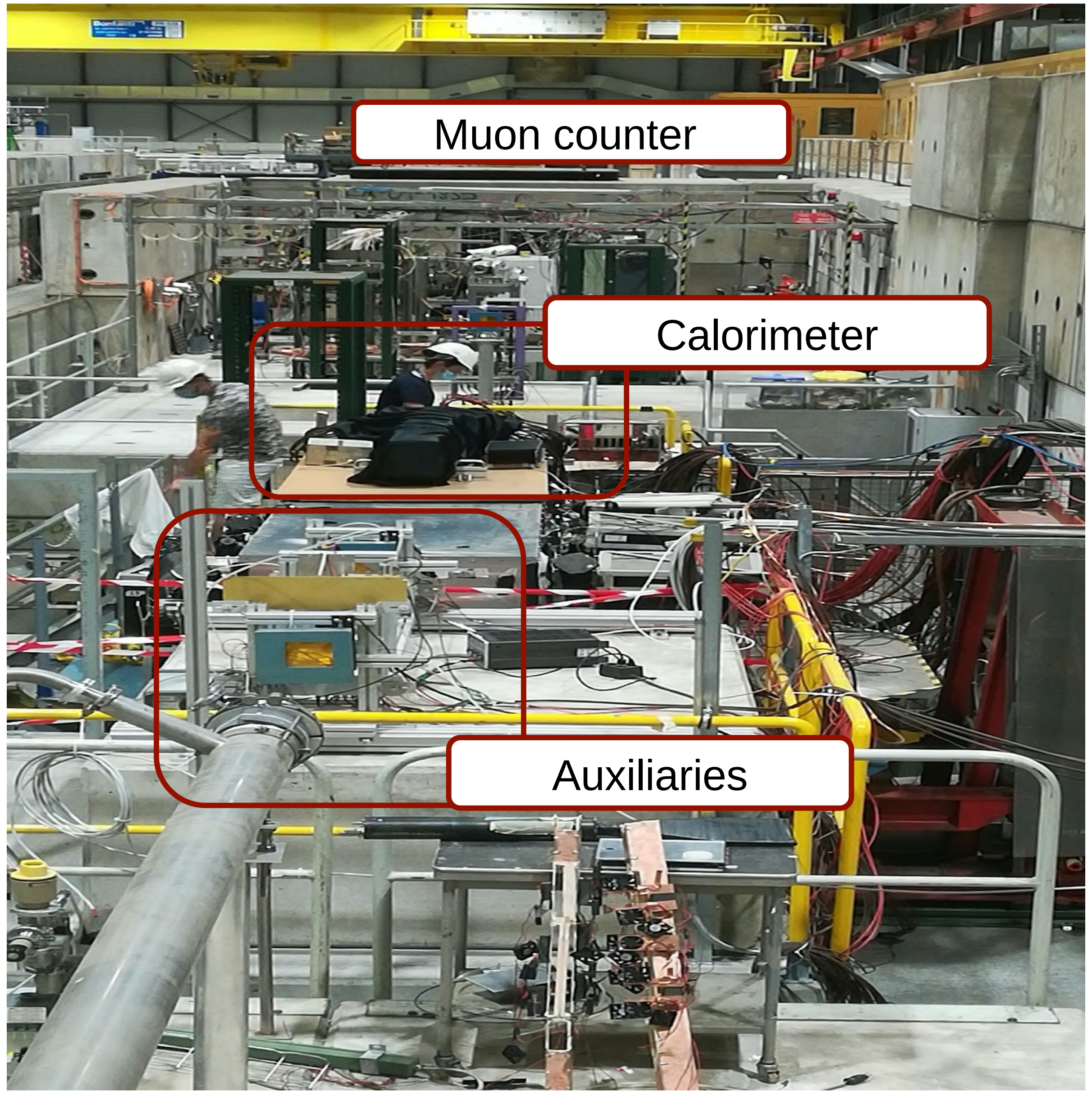
Cherenkov fibers

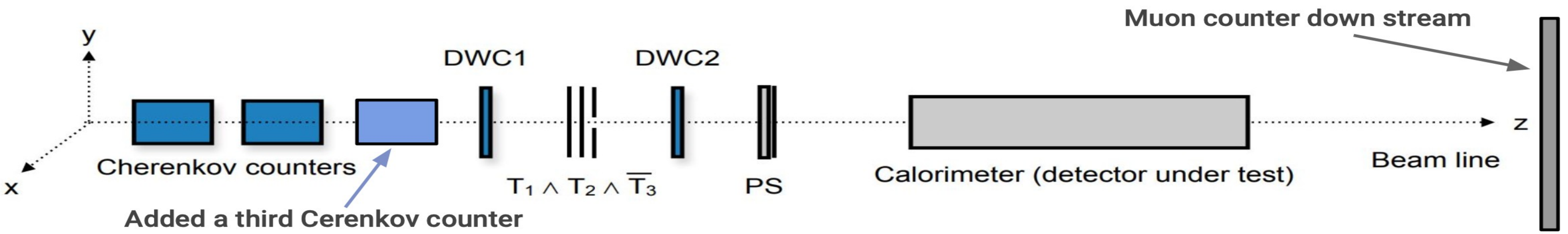
Beam tests in 2021 and 2023

CERN-SPS H8 beam line

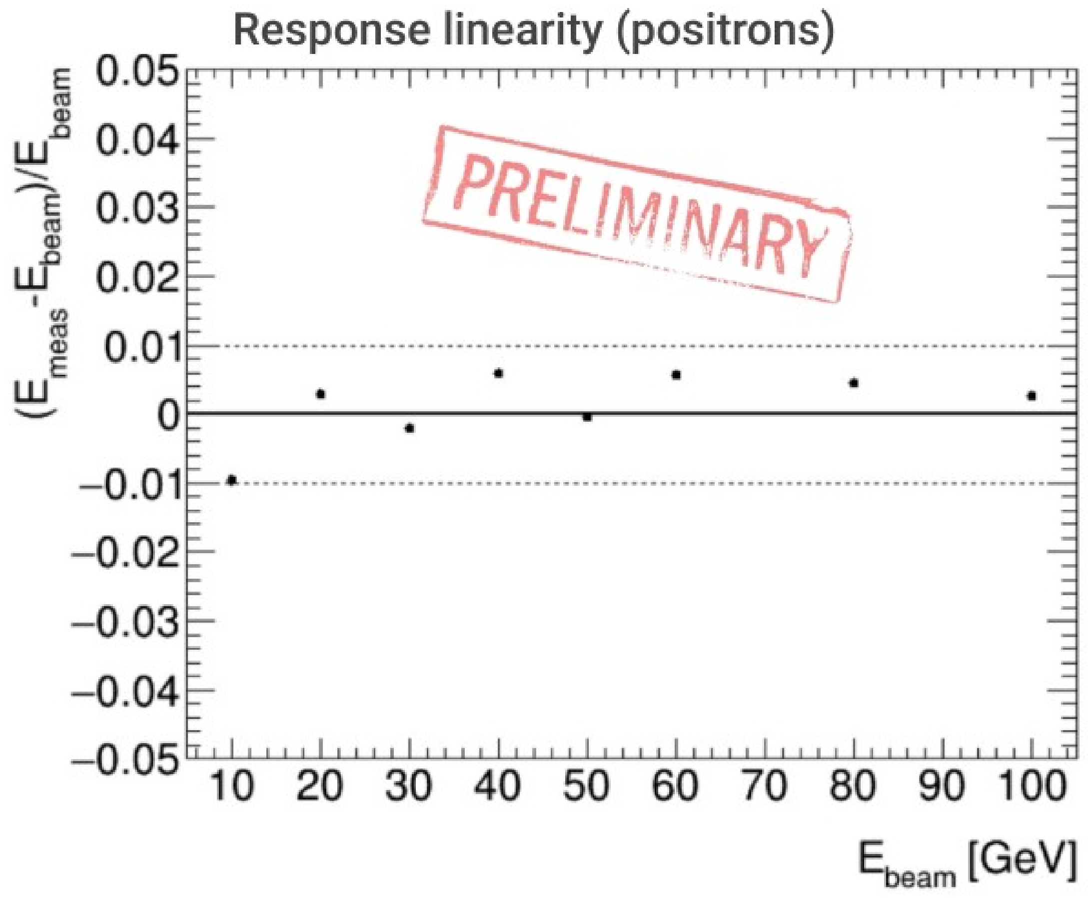
- e^+ beam in energy range of 10-100 GeV
- Energy and position scan
- Purity issues (critical in 2021)

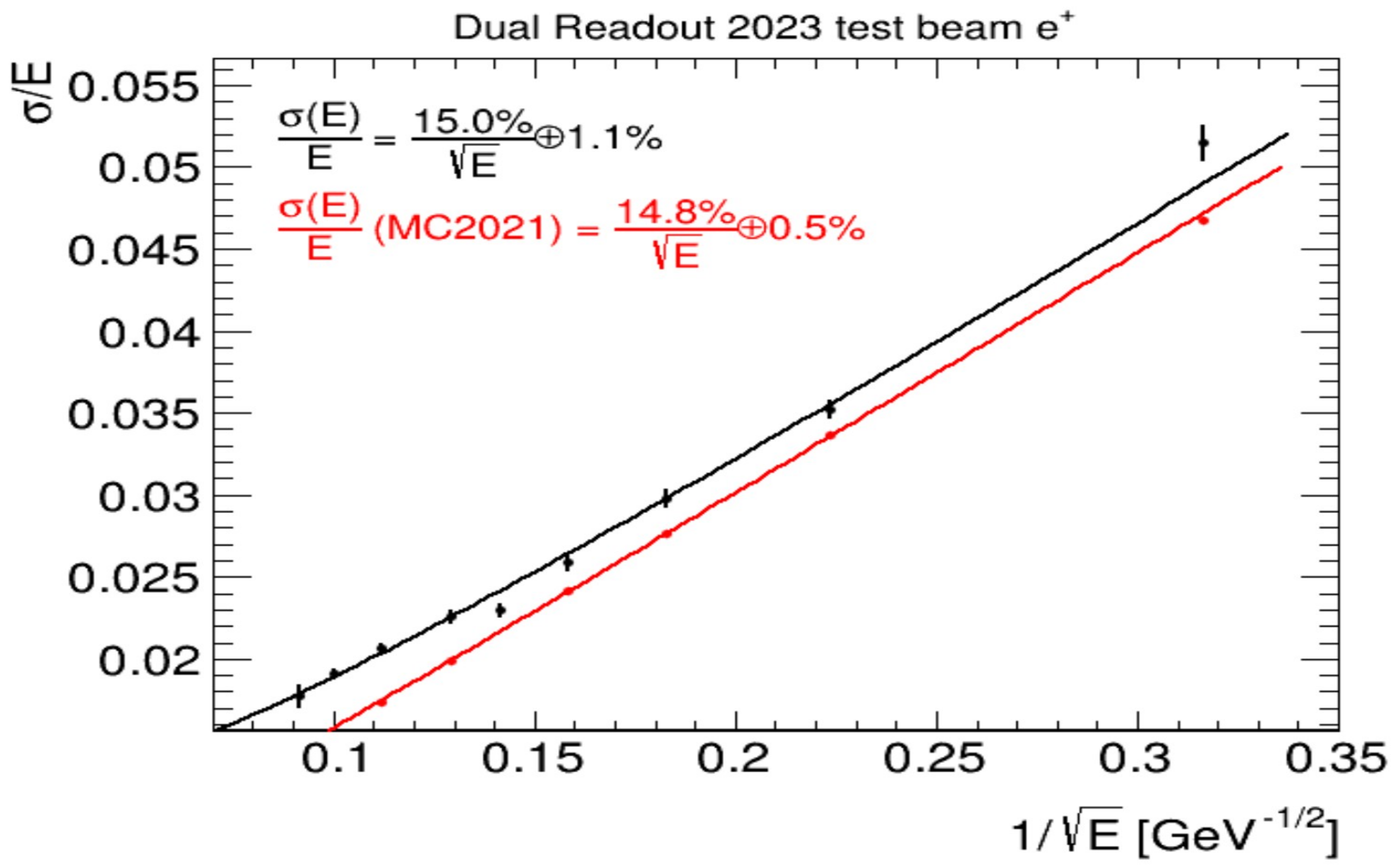




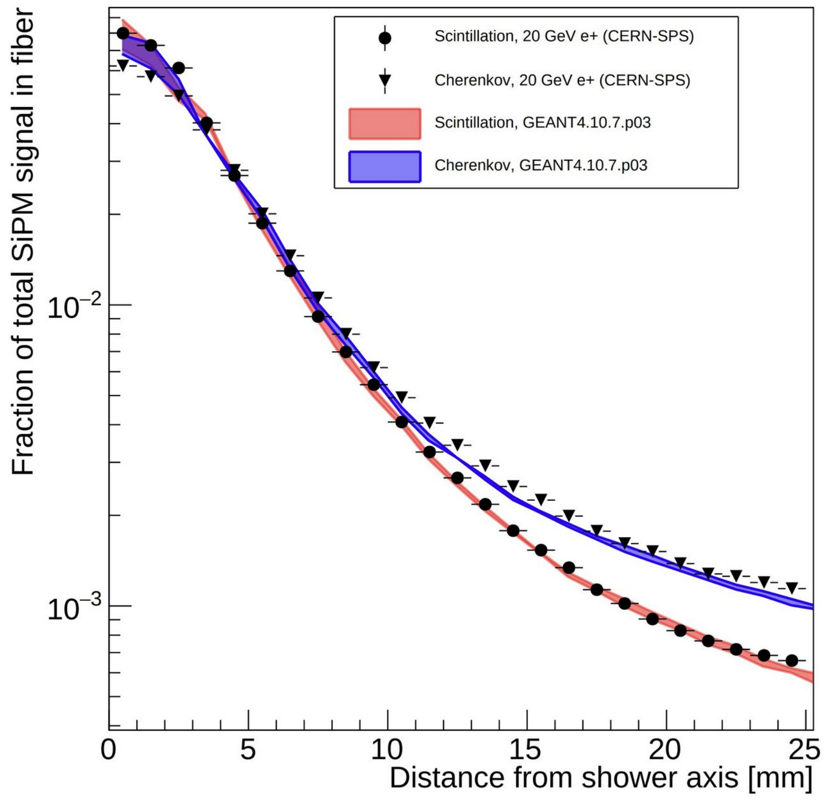


Few testbeam results



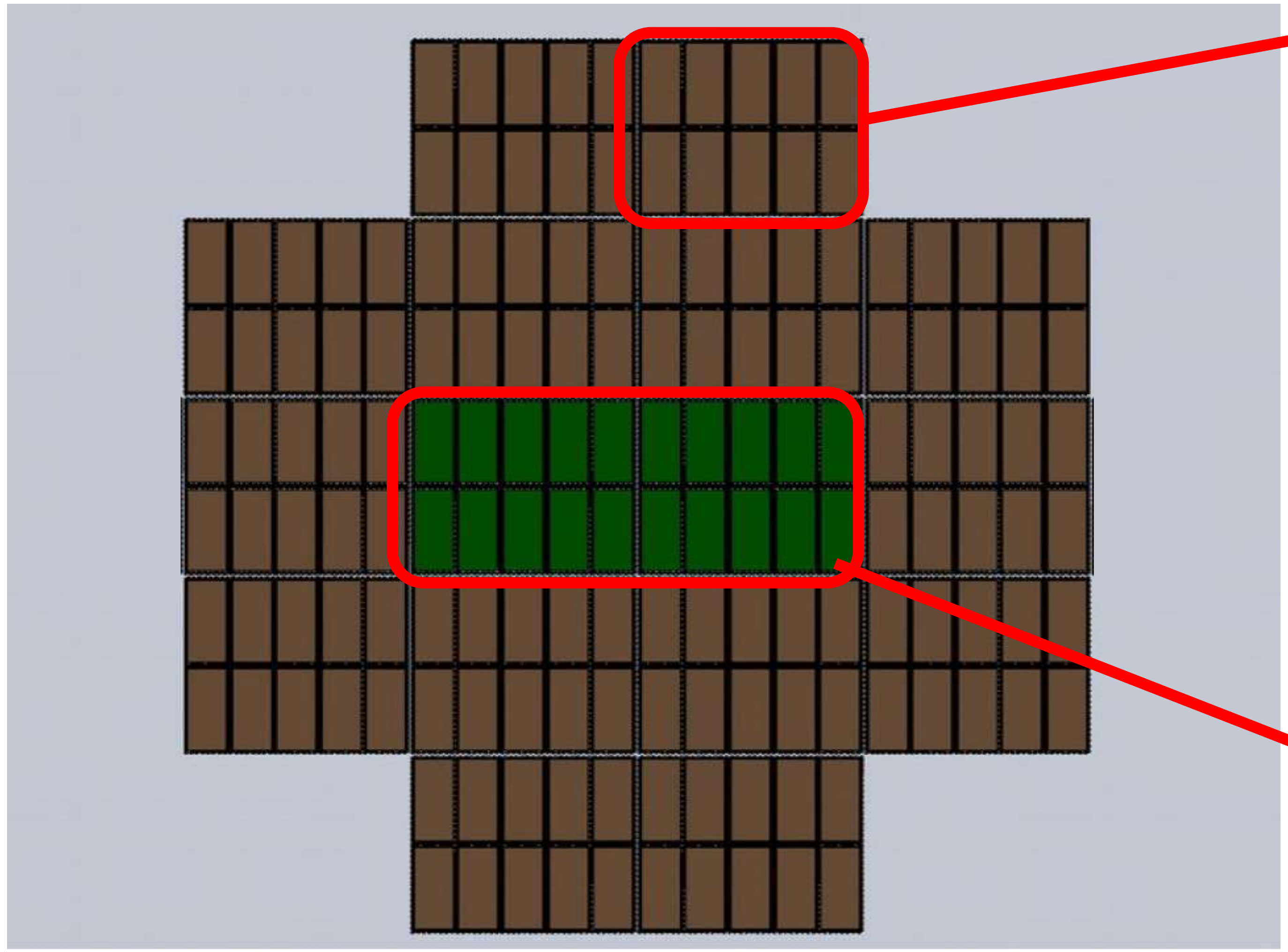


Lateral shower profile (2021 TB)

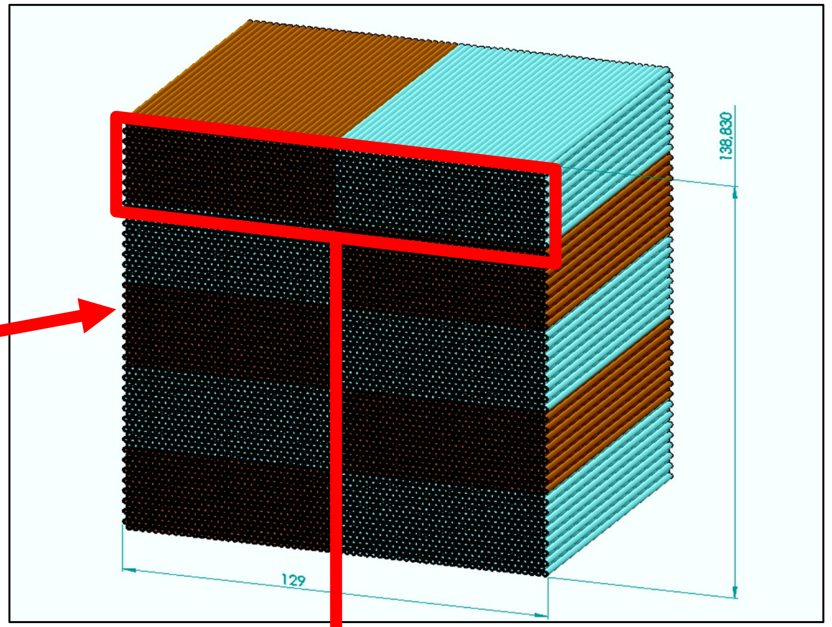


HiDRa – Highly granular Dual Readout demonstrator (EU)

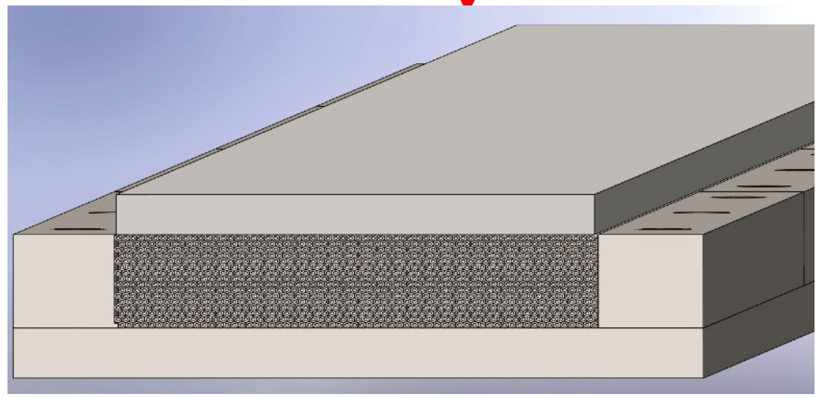
Hadronic-size prototype:
16 modules w/ highly granular core



~ 65 × 65 × 250 cm^3



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

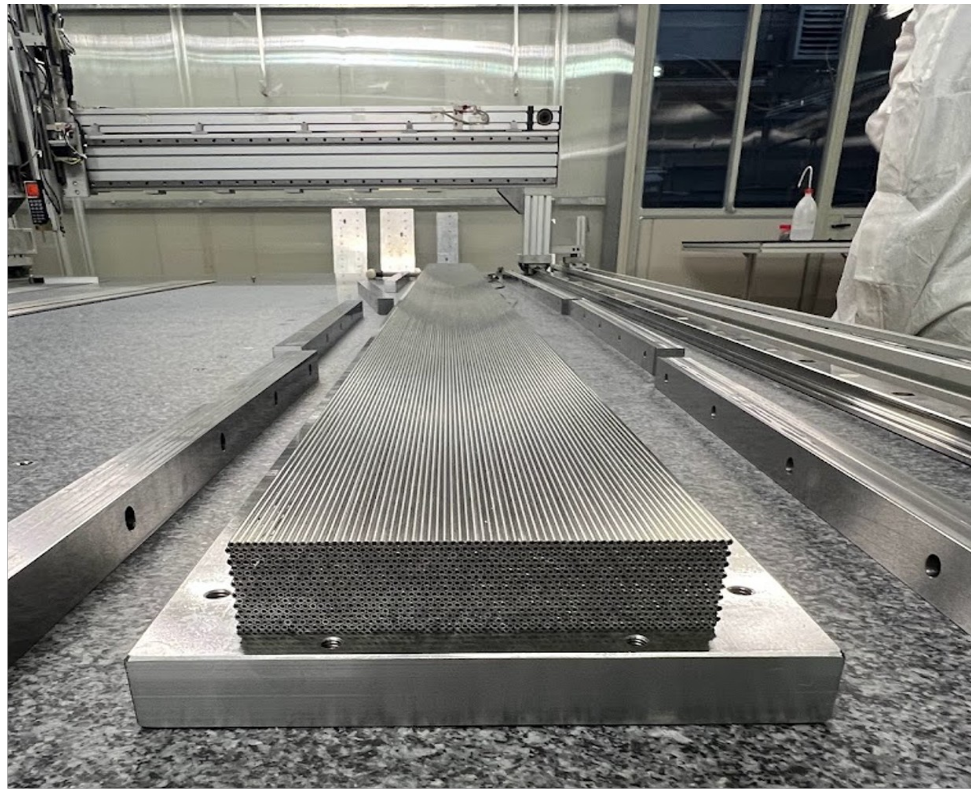


1 MiniModule:
64 × 16 = 1024 fibres in total
512 S + 512 C

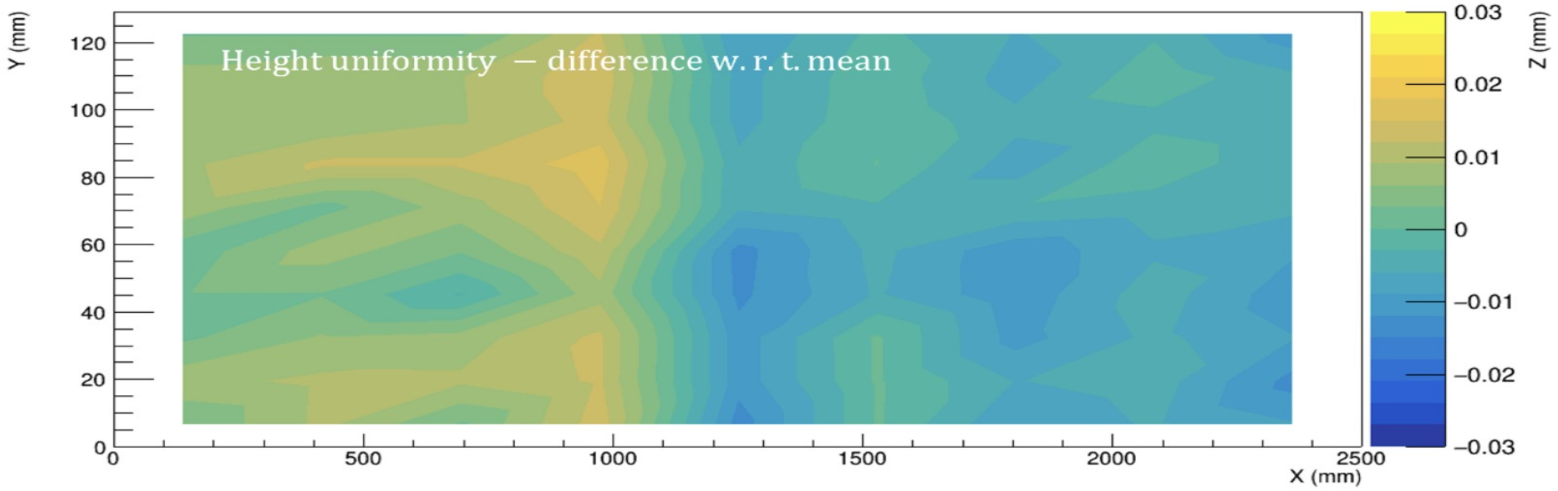
highly granular core:
10240 fibres to be read out with SiPMs

Construction technique and mechanical precision

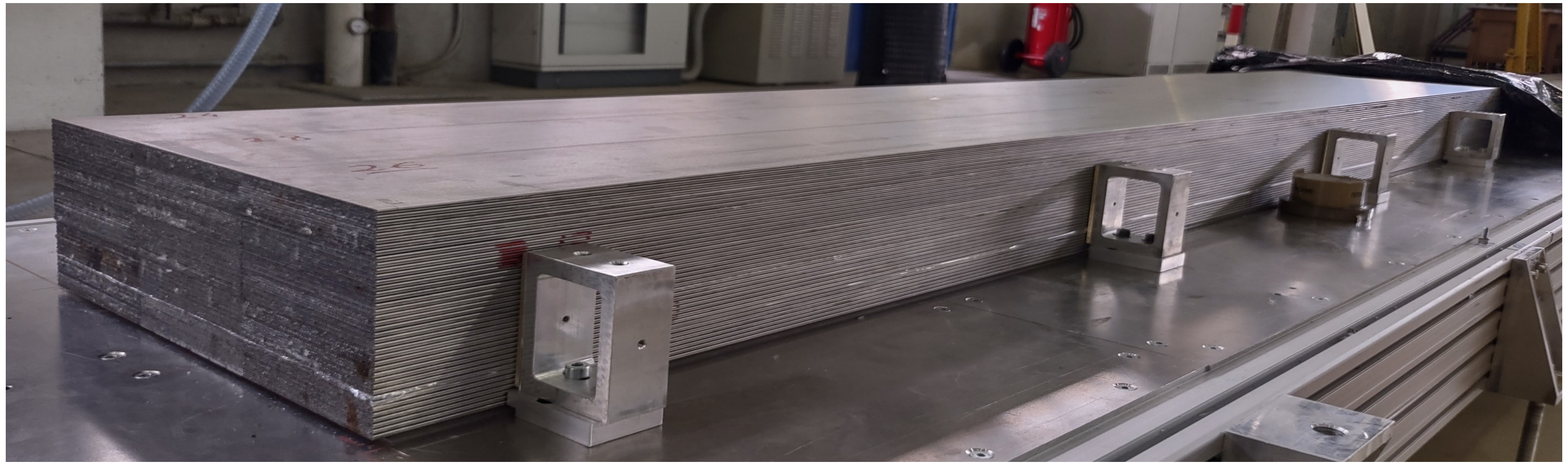
Semi-automatic system for planarity measurement: 90 measurements per minimodule

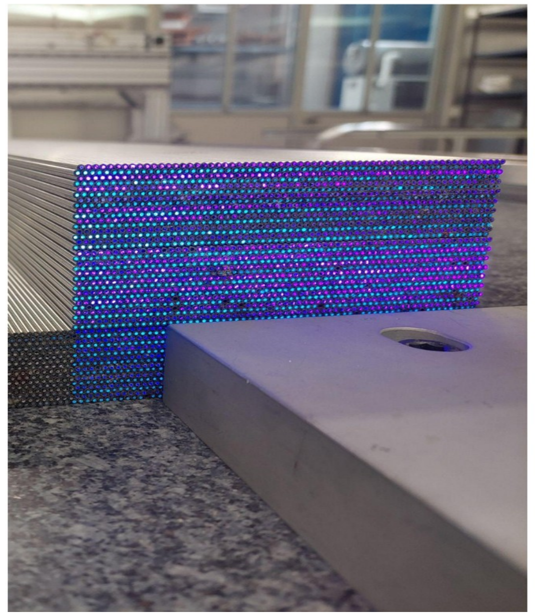


O(10 μm) precision on minimodule height (calor2024)

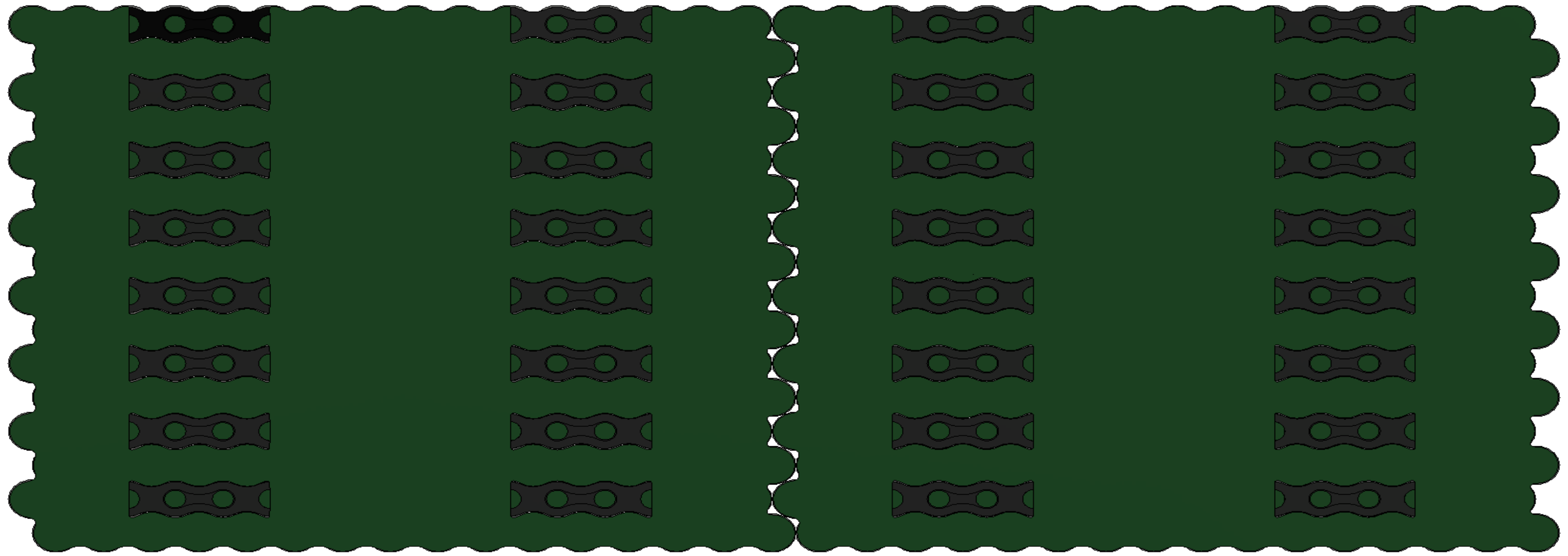


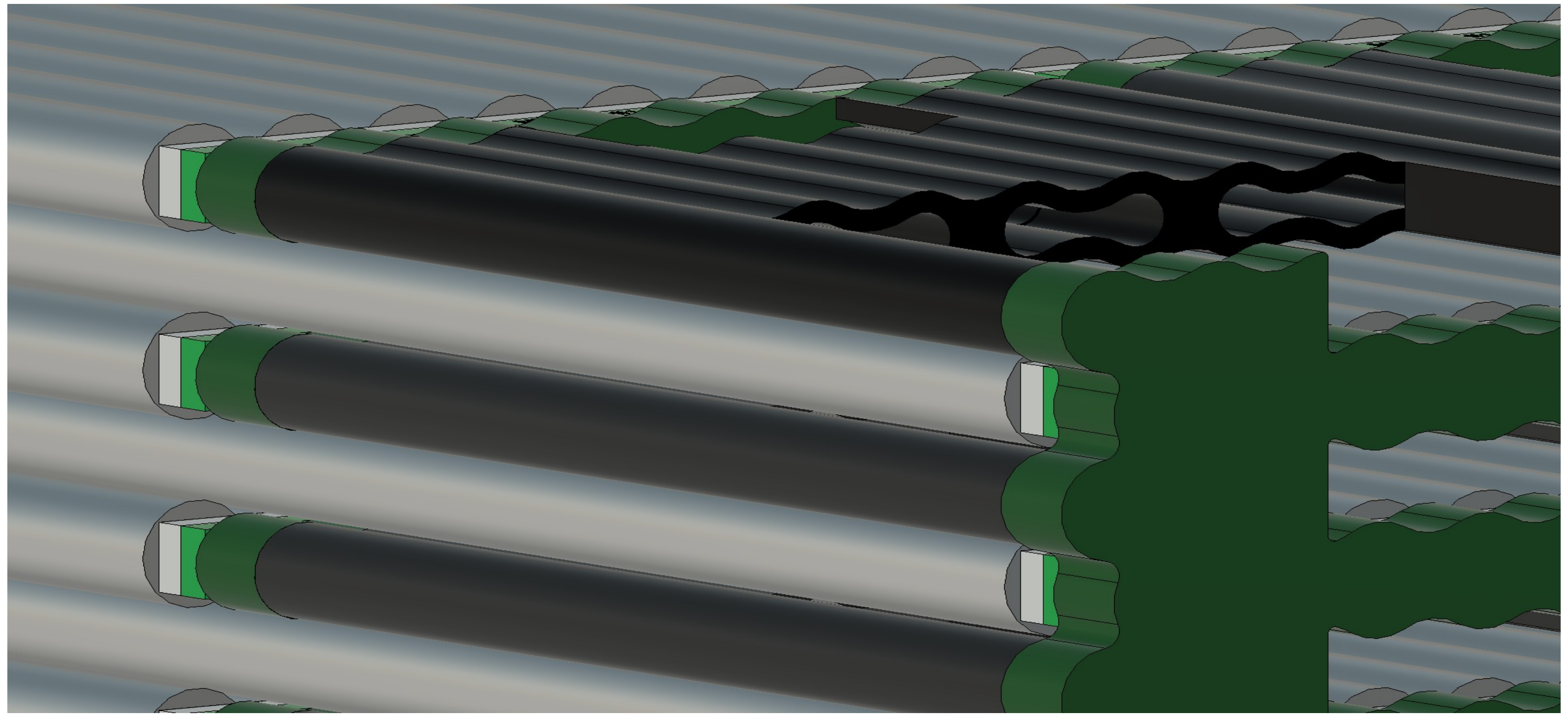
Production started in November 2023: 38/80 minimodules assembled
First test beam with 36 modules in August-September 2024 (PMT readout only)

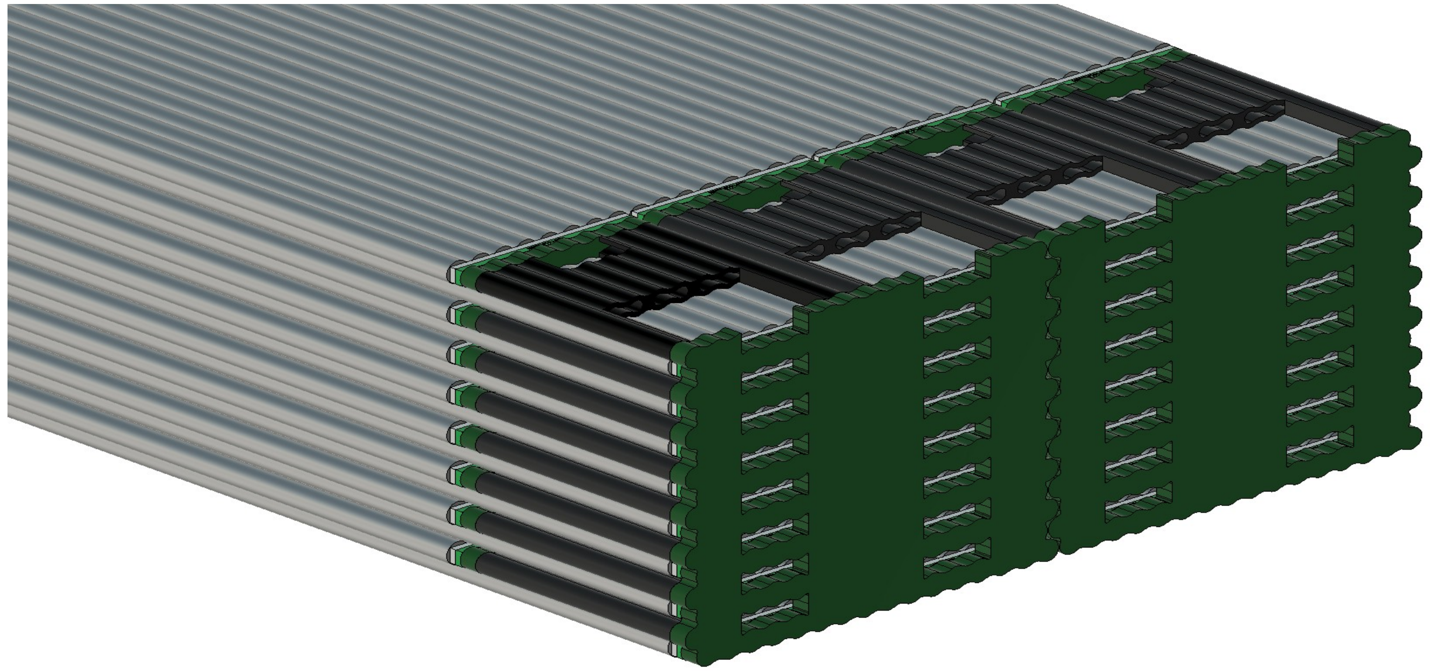


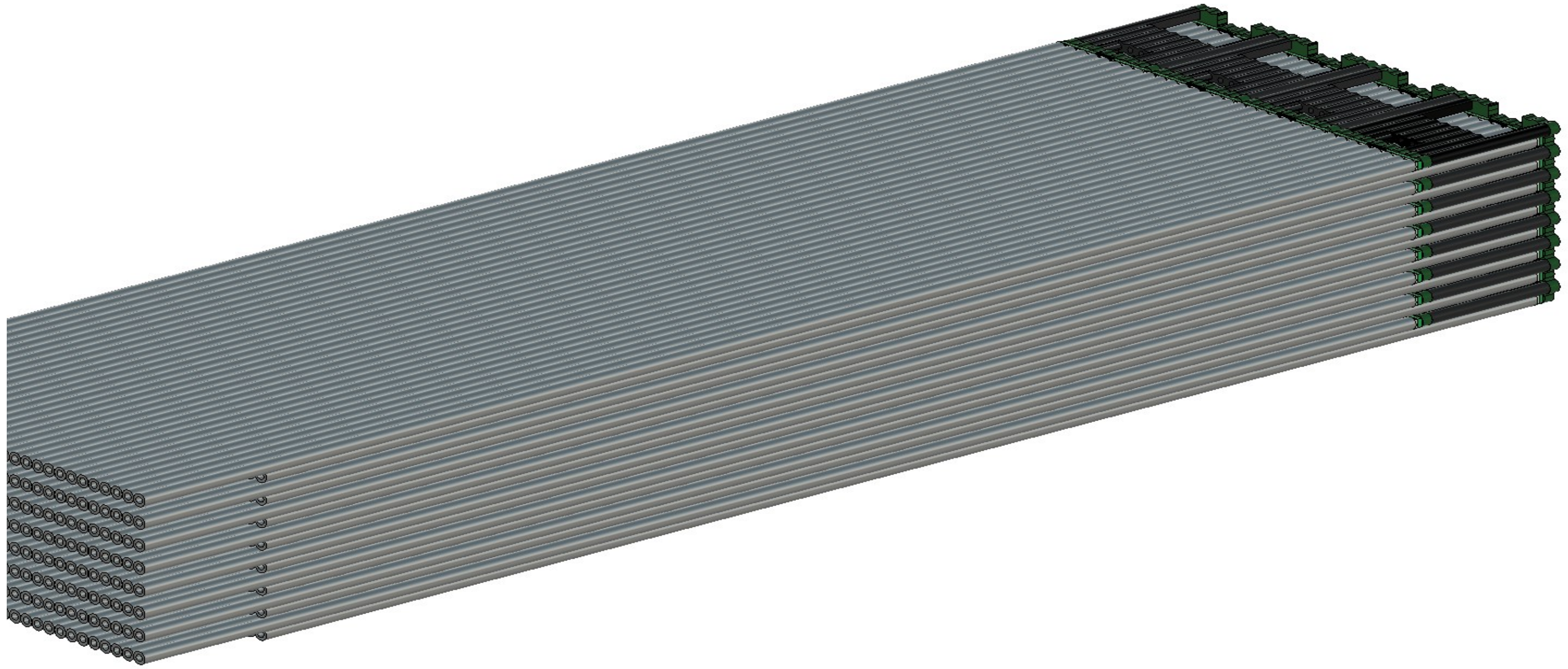


Integration of highly granular modules







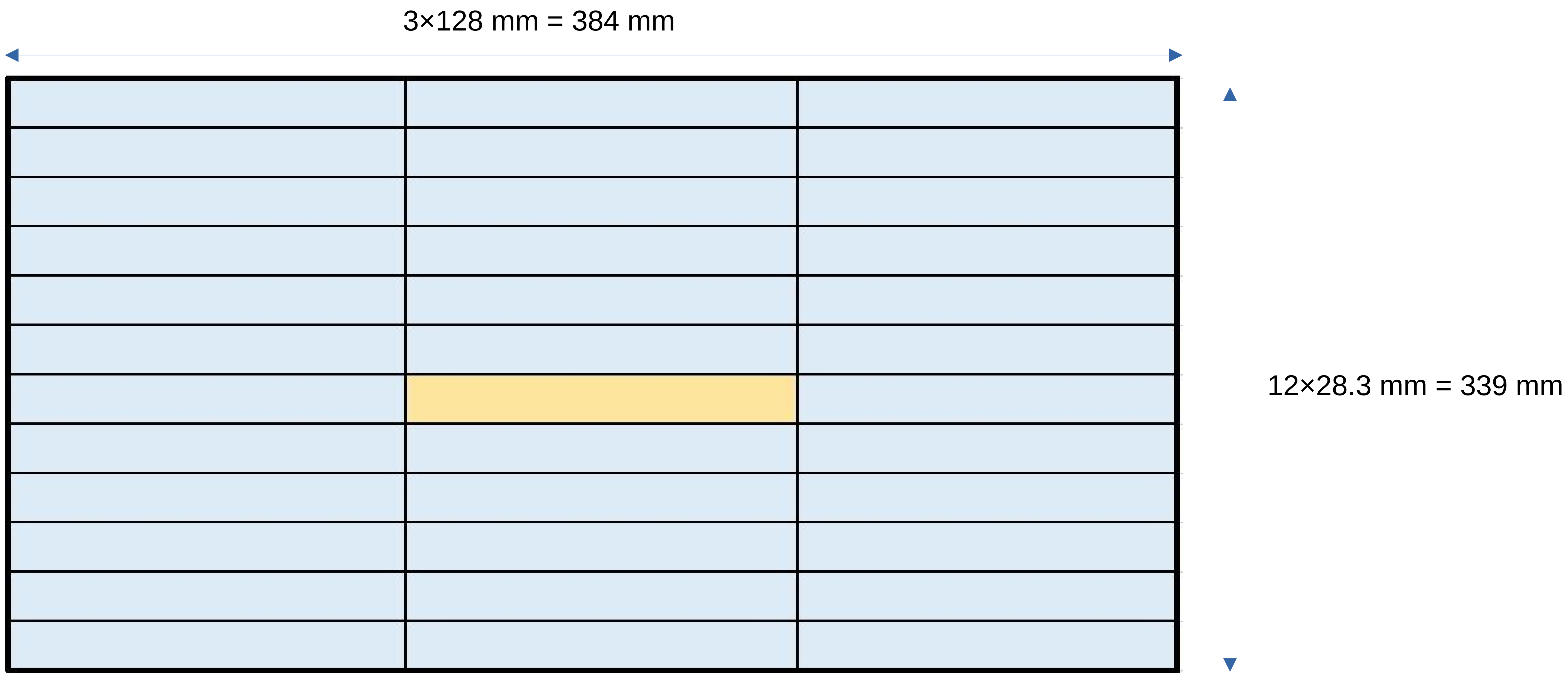


2024 TB

36 minimodules in 3×12 arrangement [+ integrate position measurement w/ ATLAS_PIX3 sensors]

PMT-only: 36 + 36 PMT signals to read out

Focus on: understand/assess calibration procedure, operation and G4 validation



2024 TB

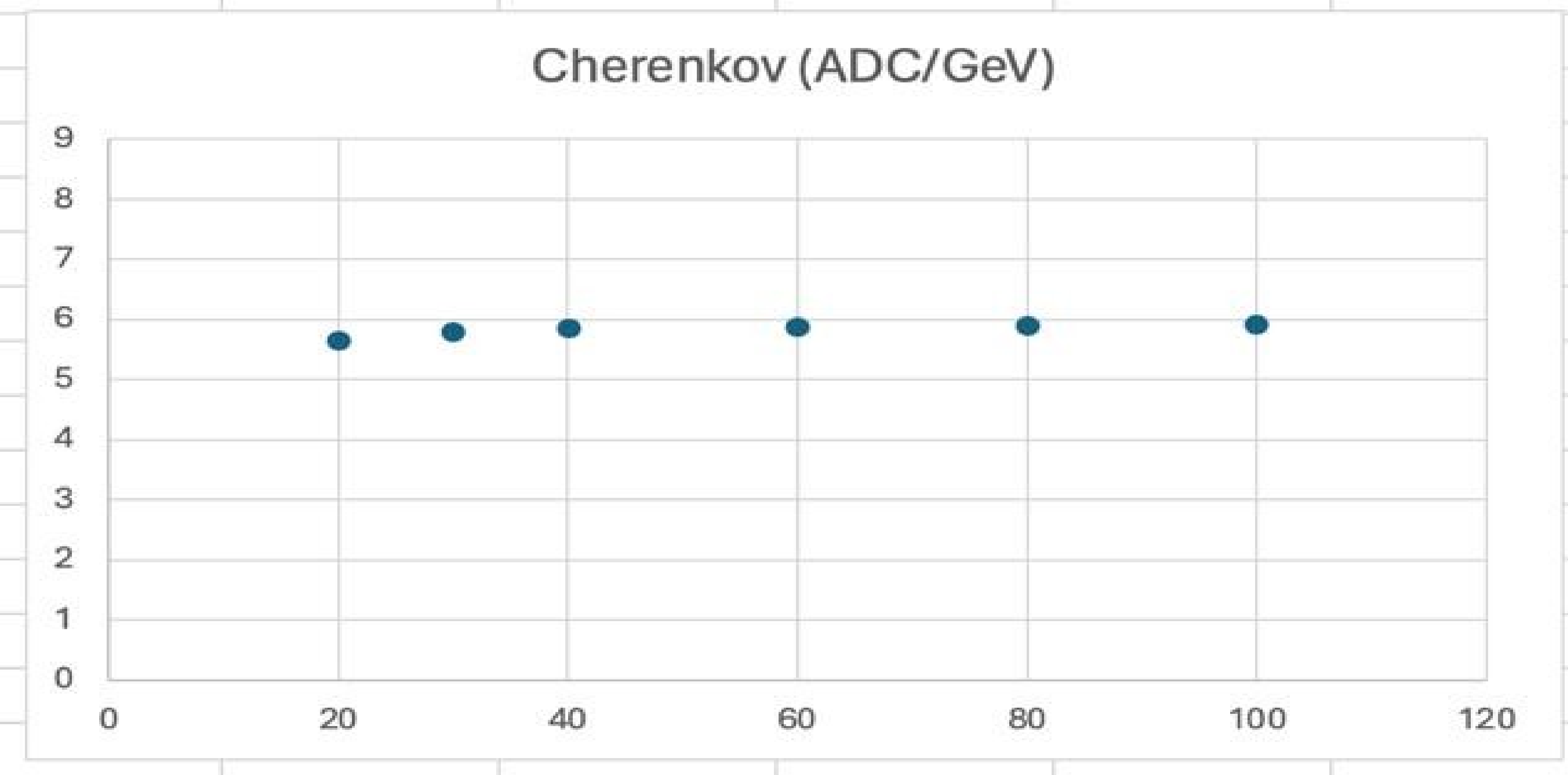
H8 beam line (as usual)

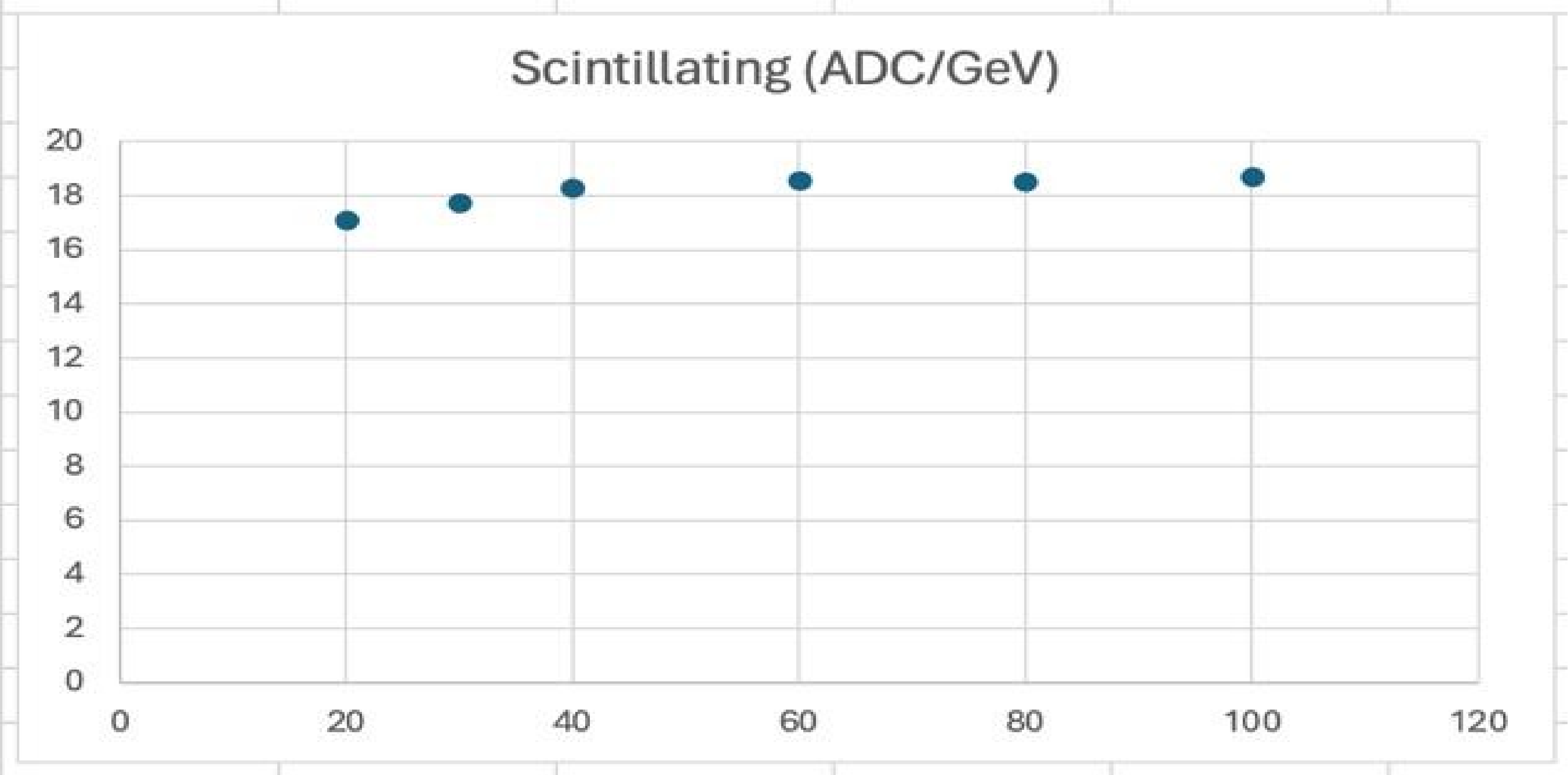
2 weeks of data taking [week of August 28th & September 11th]

understanding in progress

2024 TB

Very preliminar results on linearity





Work in progress

Status of HiDRa construction

Production in steady state: rate ~ 8 minimodules / month

- Target: finish ~ end 2024 / beg. 2025

Tube and fibre quality quite good but rejection close to threshold (5%) → need some more pieces

- Fibres → ok (replacement at no cost)
- Tube “refurbishing” → (after negotiation) expected ~4600 new pieces

Fibre: limiting factor in assembly procedure

- **fibre insertion: at present 1 minimodule / 12-16 h (!)**

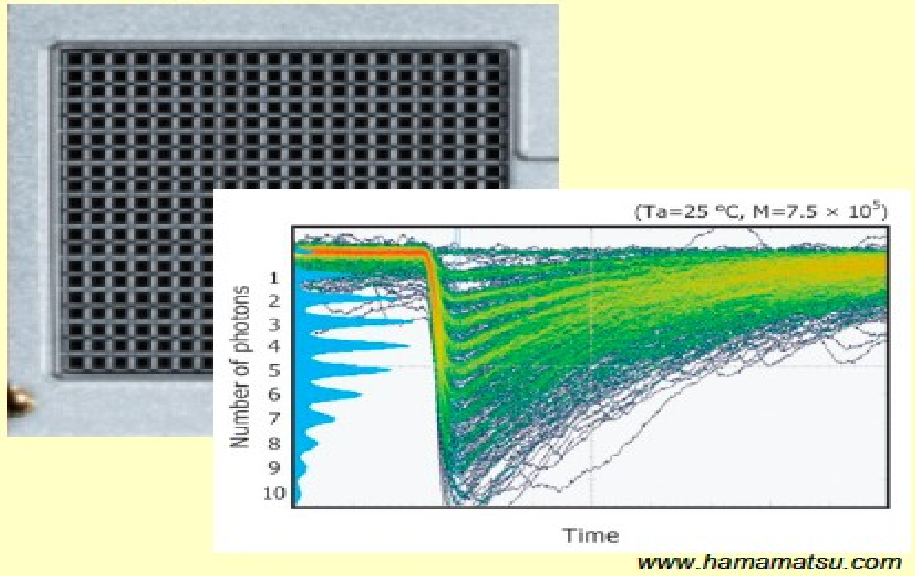
High-granularity modules

- SiPMs delivered early September
- Mounting strategy tuned
- Preproduction qualification expected within 1Q 2025

Beam test with a (PMT-only) 36 minimodule setup → define and tune calibration procedure

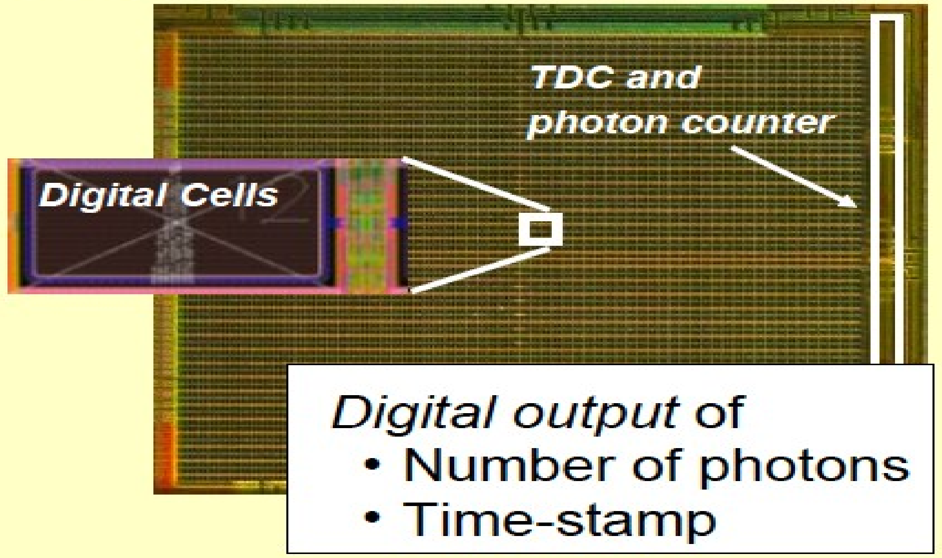
Alternative photosensors

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

digital SiPMs (dSiPMs)

no need for analogue-signal post-processing

- SPAD array in CMOS:
  - complex functions embedded in single substrate (e.g. SPAD masking, counting, TDCs)
  - front-end electronics optimised to preserve signal integrity (→ timing)
  - simplified assembly of large area detectors
  - R&D costs relatively low for design over standard process

longitudinal segmentation w/ timing (U.S.)

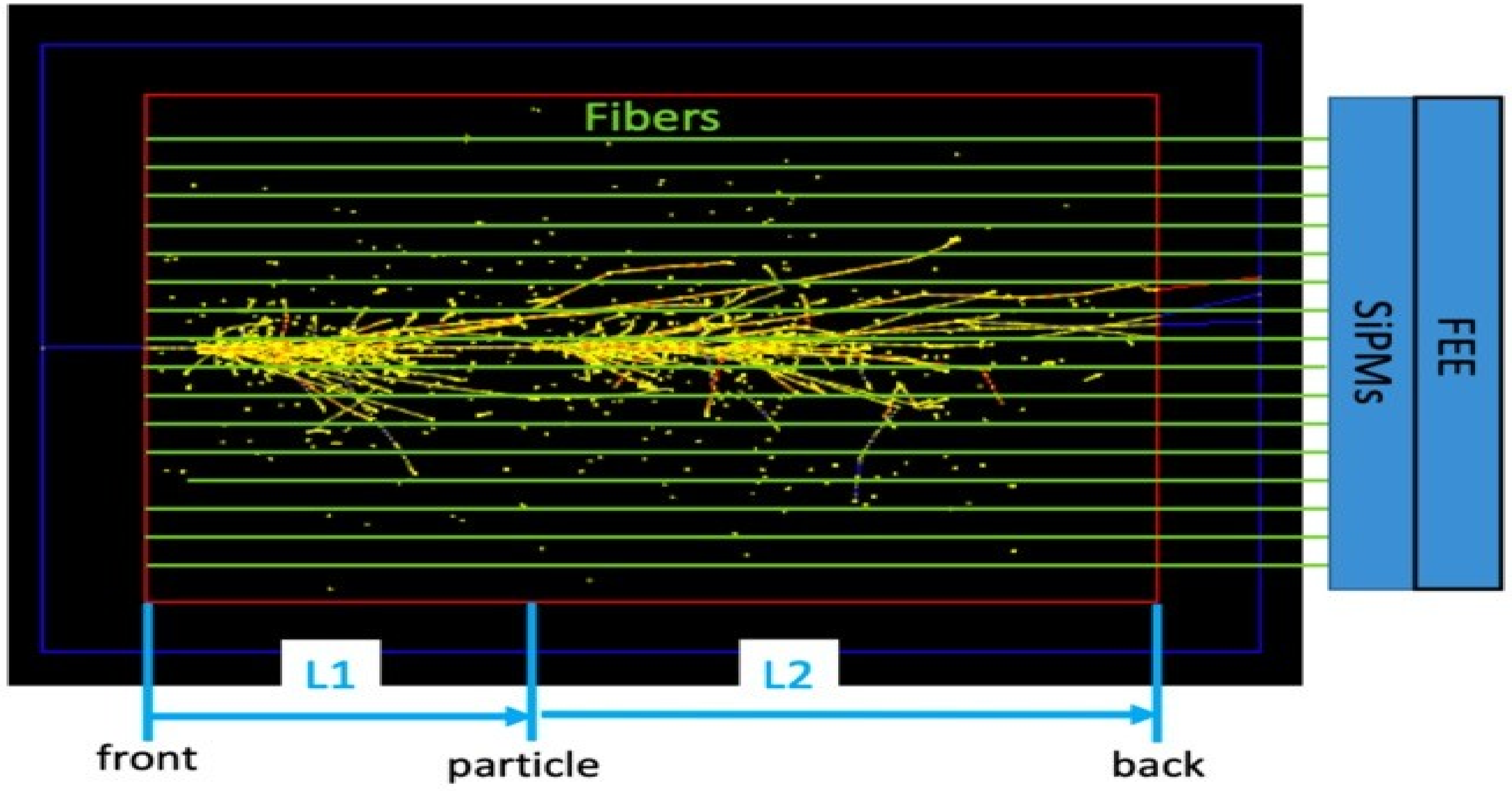


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

Timing Resolution $\Delta(t)$, ps	Position Resolution $\Delta(z)$, cm	Energy Resolution σ/E, %
0	0.0	3.6
100	5.0	3.9
150	7.5	4.0
200	10.0	4.2

@ 100 GeV

only Cherenkov fibres

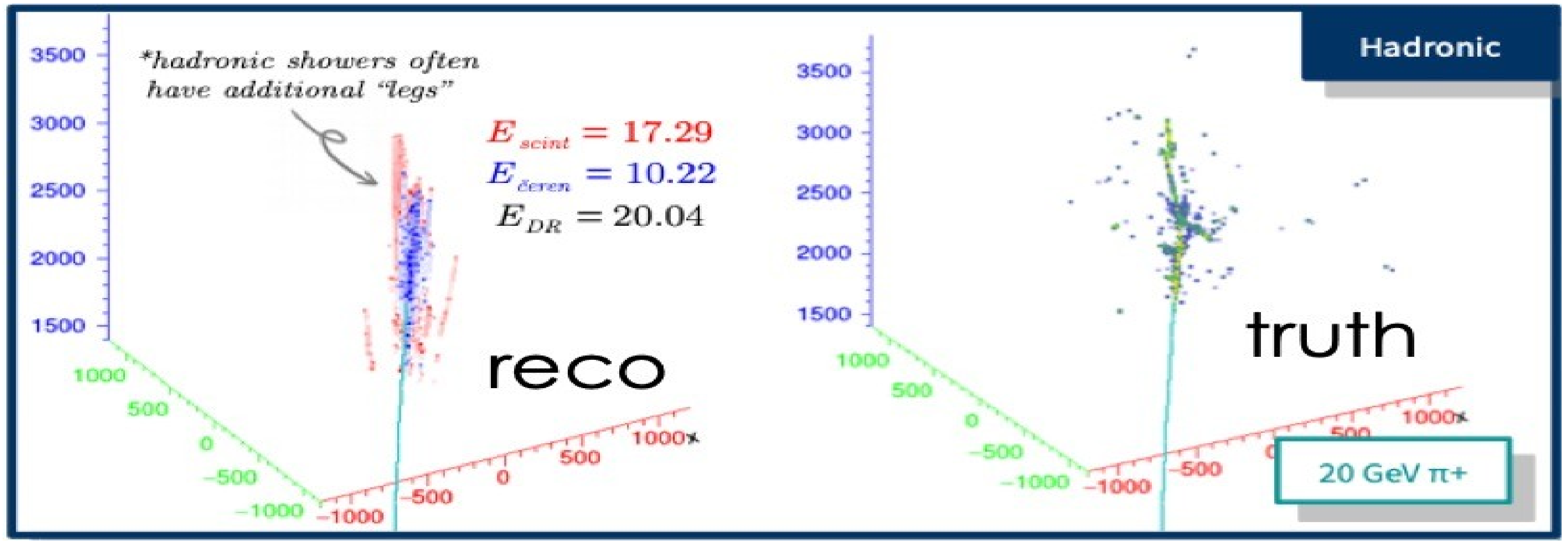
longitudinal segmentation w/ timing (Korea)

Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

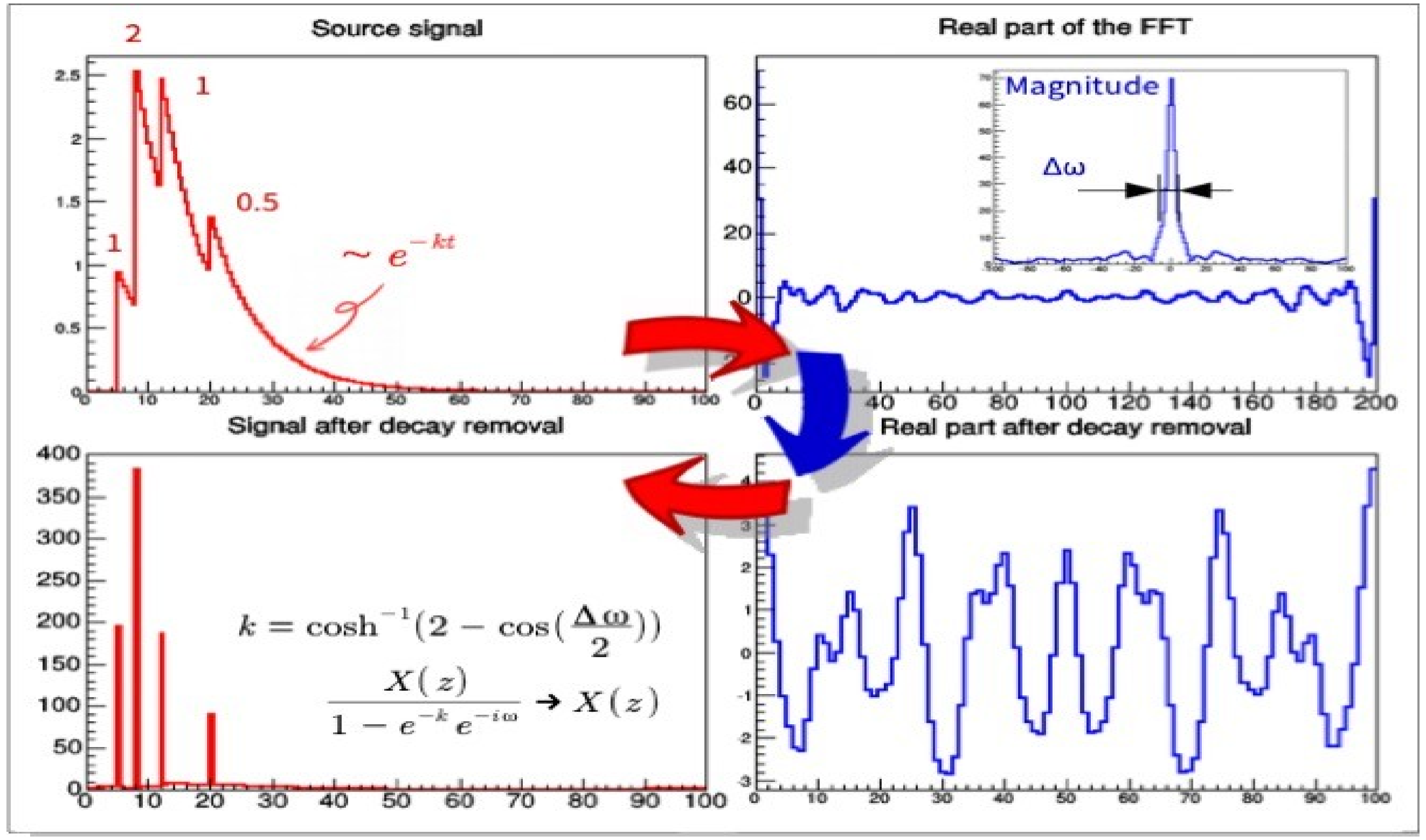
Unlocks full longitudinal information about energy deposit

Combined with DR information
allows in-shower cluster identification



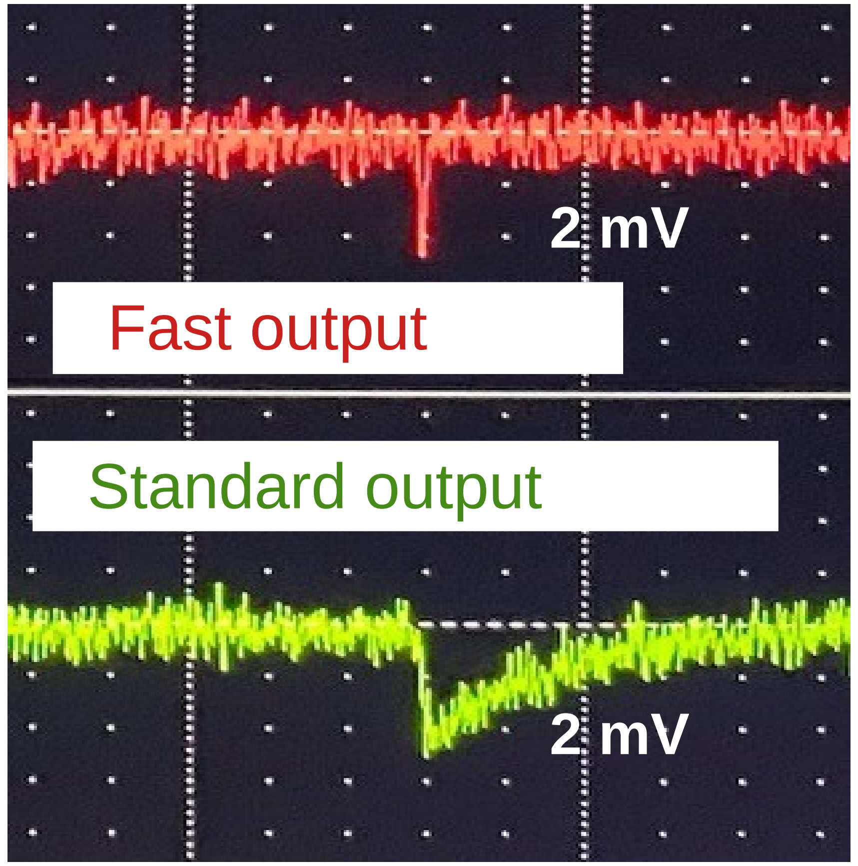
Time domain

Frequency domain

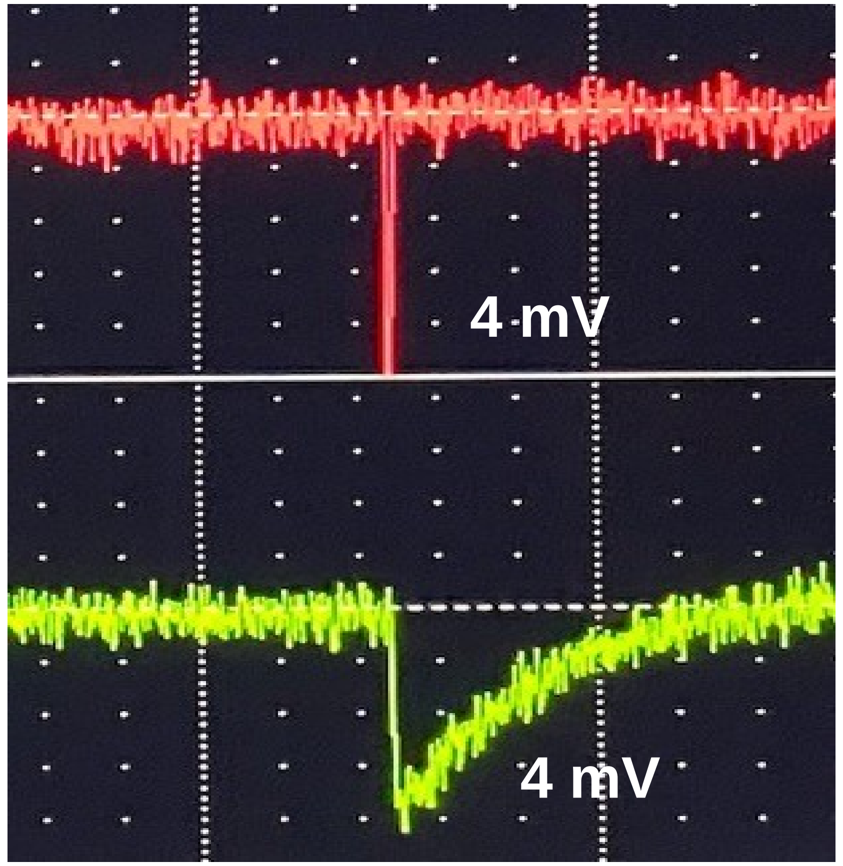


waveform digitisation (U.S.)

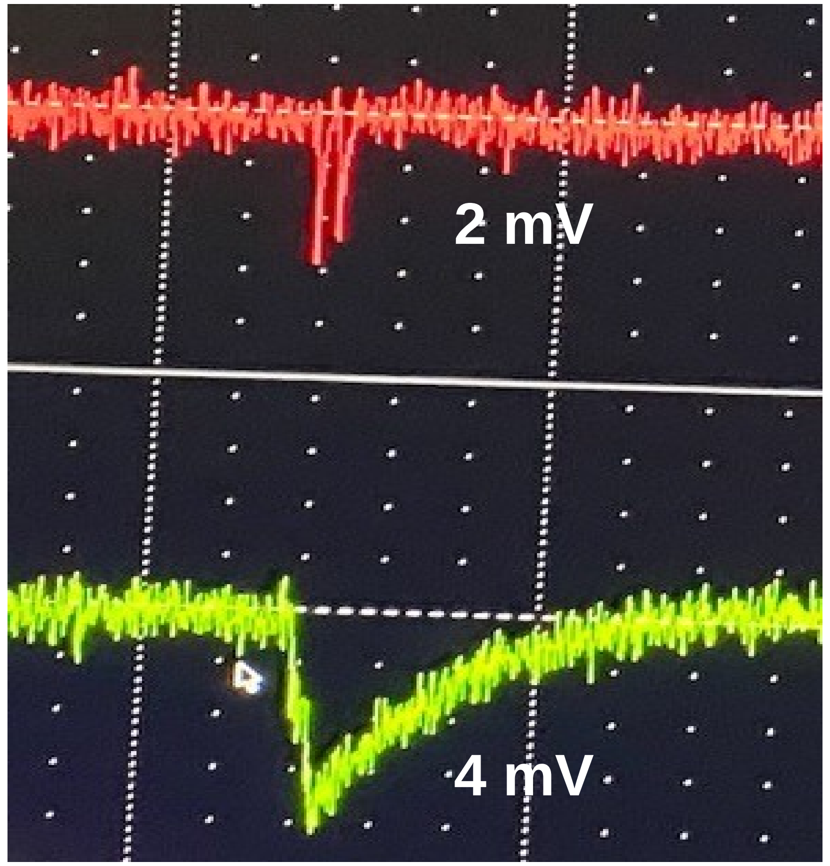
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard outputs



One-photon event



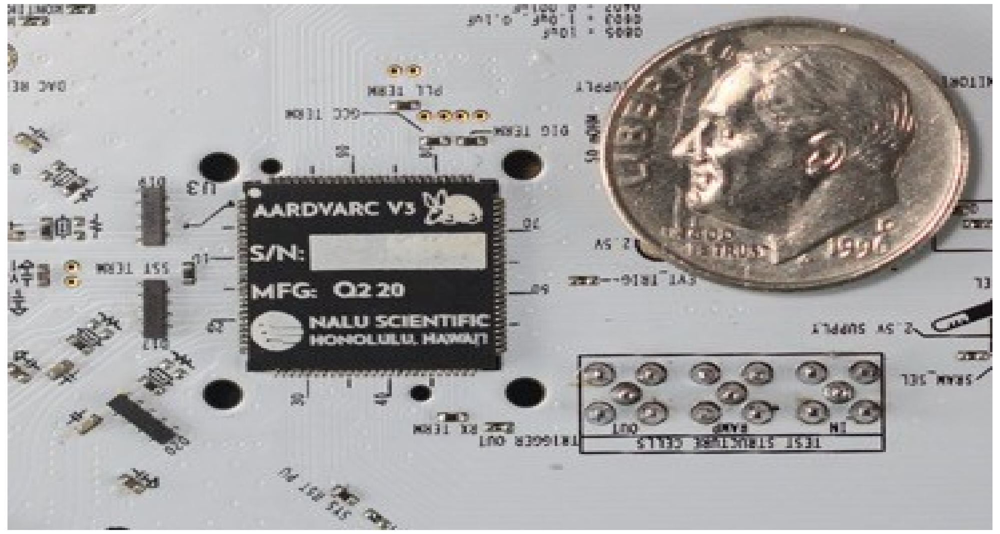
Two-photon event
(simultaneous)



Two-photon event
(5 ns apart)

NALU Scientific
AARDVARC v3

- Sampling rate 10-14 GS/s
- 12 bits ADC
- 4-8 ps timing resolution
- 32 k sampling buffer
- 2 GHz bandwidth
- System-on-Chip (CPU)



Summary

R&D on dual-readout fibre calorimetry ongoing over three legs (EU, Korea, U.S.) addressing different issues

- Partially exploring different solutions, partially looking at complementary issues

Hadronic scale demonstrators being build

High granularity and Timing as keyword → exploit information for both final state identification and event reconstruction

→ Expore PFAs

DNN being explored → first results very interesting

Target for next few years:

- Assess hadronic performance at all levels (single particles, jets, complex final states)
- Assess scalable assembly and readout solution
- Validate GEANT4 simulation in particular concerning hadron shower modeling

Goals

Demonstrate (assess) physics performance for both single hadrons and jets (and electrons)

Validate Geant4 shower modeling

Assess scalable solutions concerning construction and signal readout/handling

Exploit DNN architectures for physics analysis

Assess performance in relevant benchmark physics channels

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