Status and plans for the IDEA dual-readout fibre calorimetry

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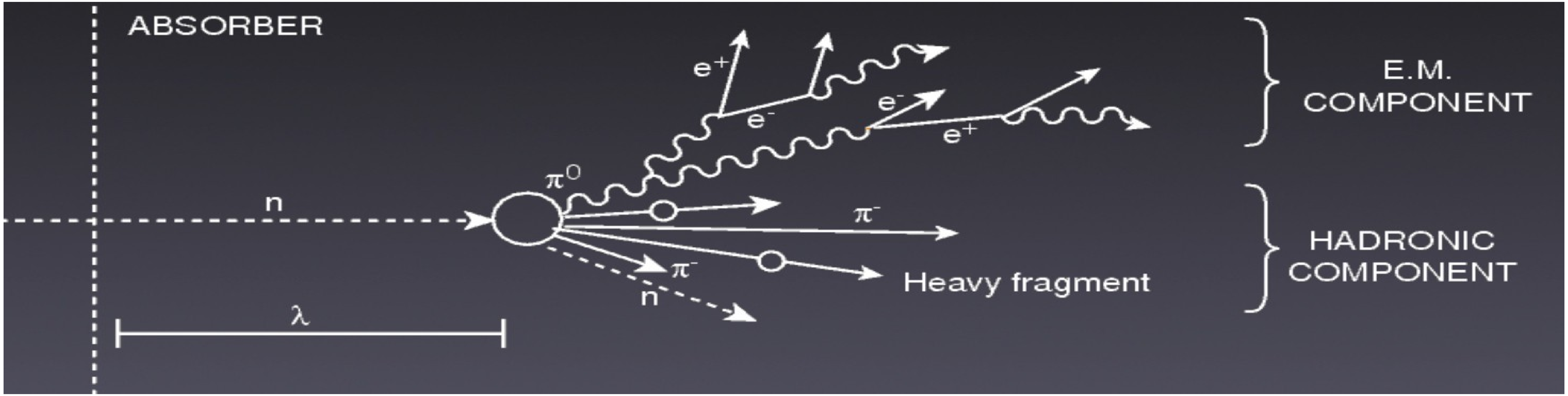
outline

1. Dual-readout calorimetry
2. IDEA dual-readout fibre calorimetry
3. Hadronic-containment prototype
4. Exploit timing & DNNs

Dual-readout calorimetry

hadron calorimetry



hadronic component: p, n, $\pi^{\pm}$, nuclear fission, … delayed photons, … invisible energy

- Large non-gaussian fluctuations in *em/non-em* energy sharing
- Increase of *em* component with energy
- Large, non-gaussian fluctuations in “invisible” energy losses

detector response

Response: detected signal per unit energy deposit

e.g. number of scintillating (or Cherenkov) p.e. / deposited GeV

Hadronic showers:

em component → response e

hadronic component → response h

e/h : detector characteristic, typically > 1

Dual-readout calorimetry: two sampling processes → compensate for e/h dependence

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

applying dual-readout formulae

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

measurable event by event, if χ known

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

measurable if χ known

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

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

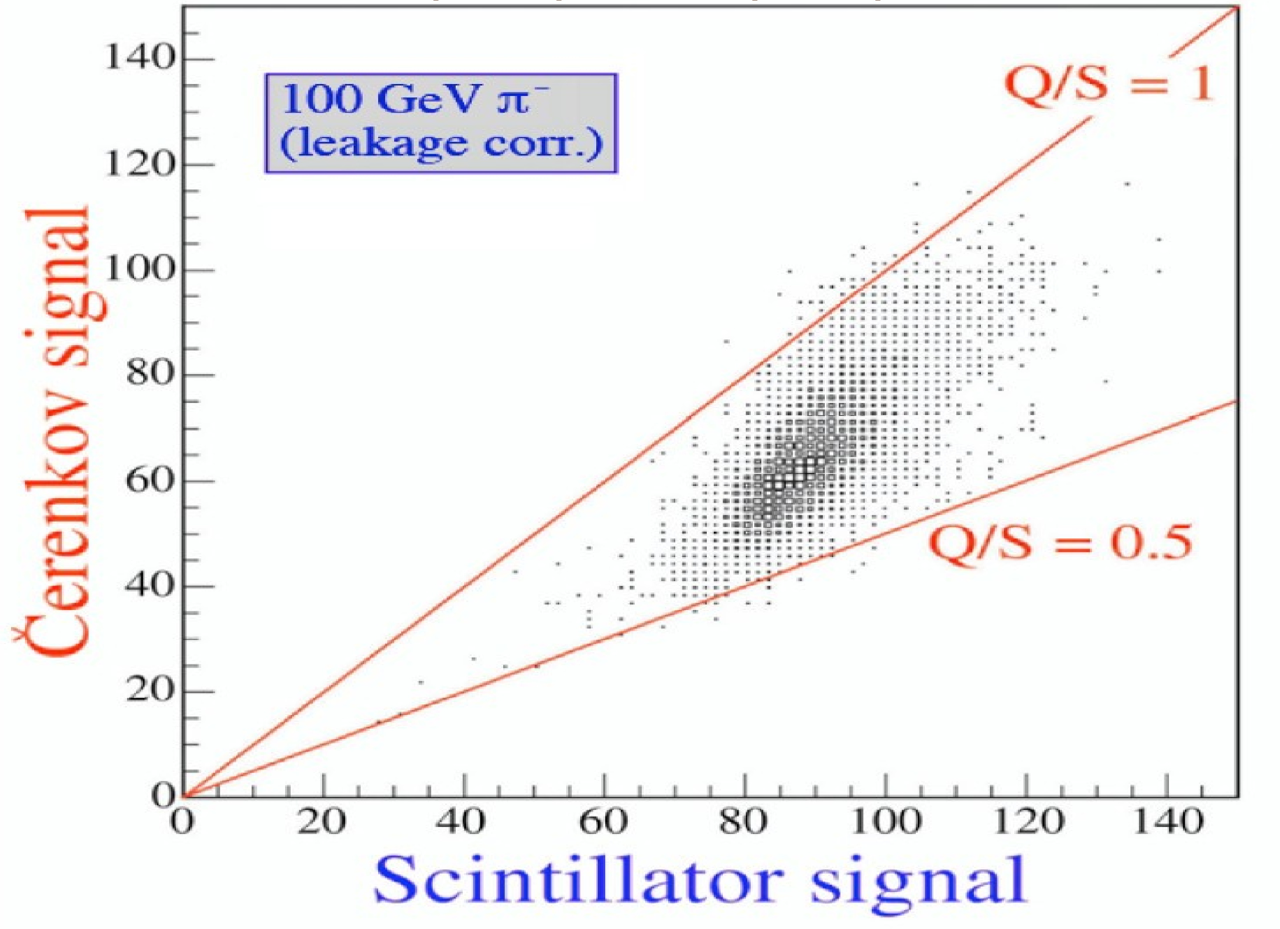
$$if \quad \left(\frac{h}{e}\right)_S > \left(\frac{h}{e}\right)_C \Rightarrow \chi < 1$$

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

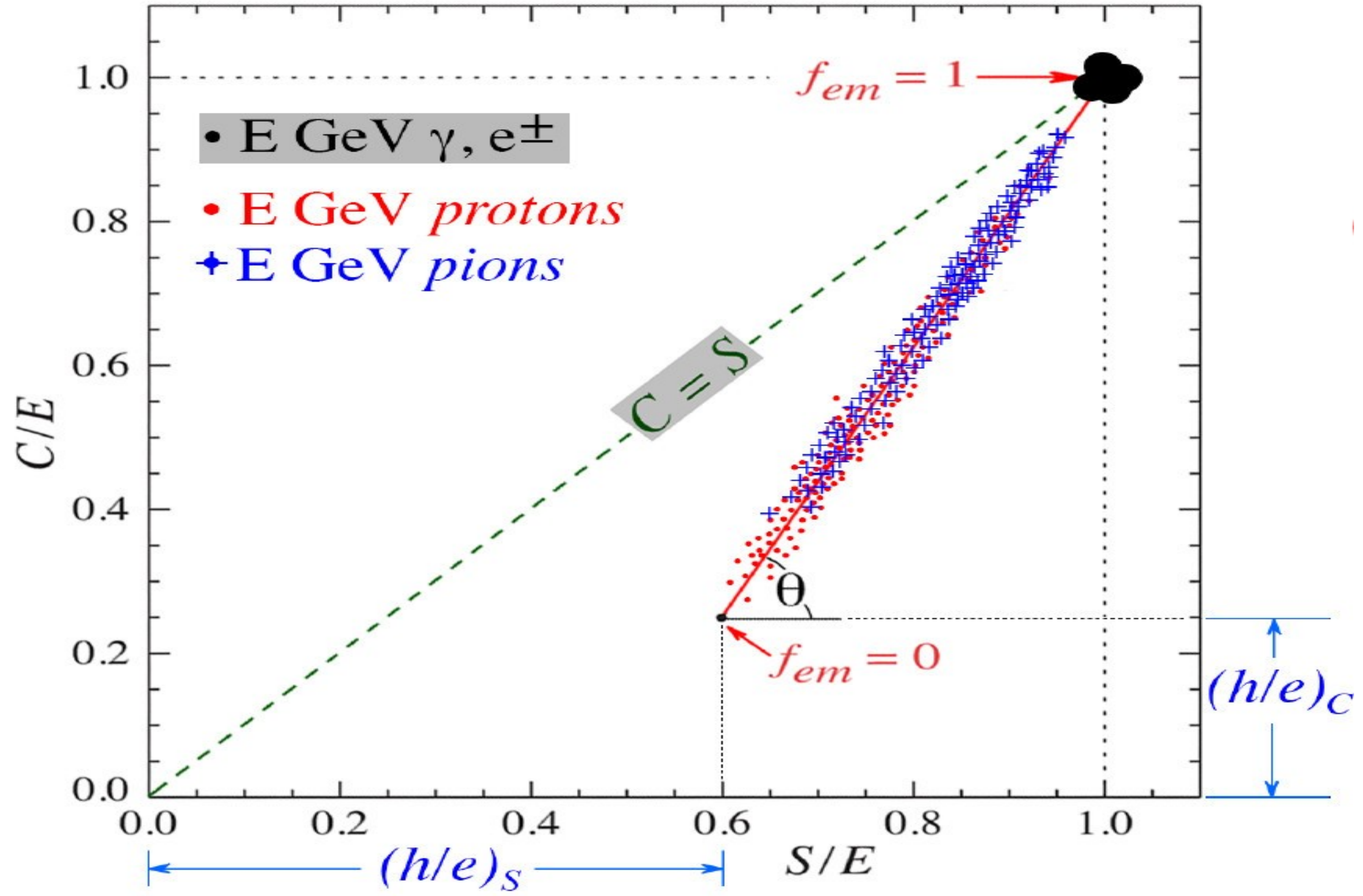
applying dual-readout formulae

GeV

C (GeV) vs. S (GeV)



C/E vs. S/E



Hadronic data points (S, C) located nearby straight lines

$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

θ, χ independent of both:

i) energy (!)

ii) type of hadron (!!)

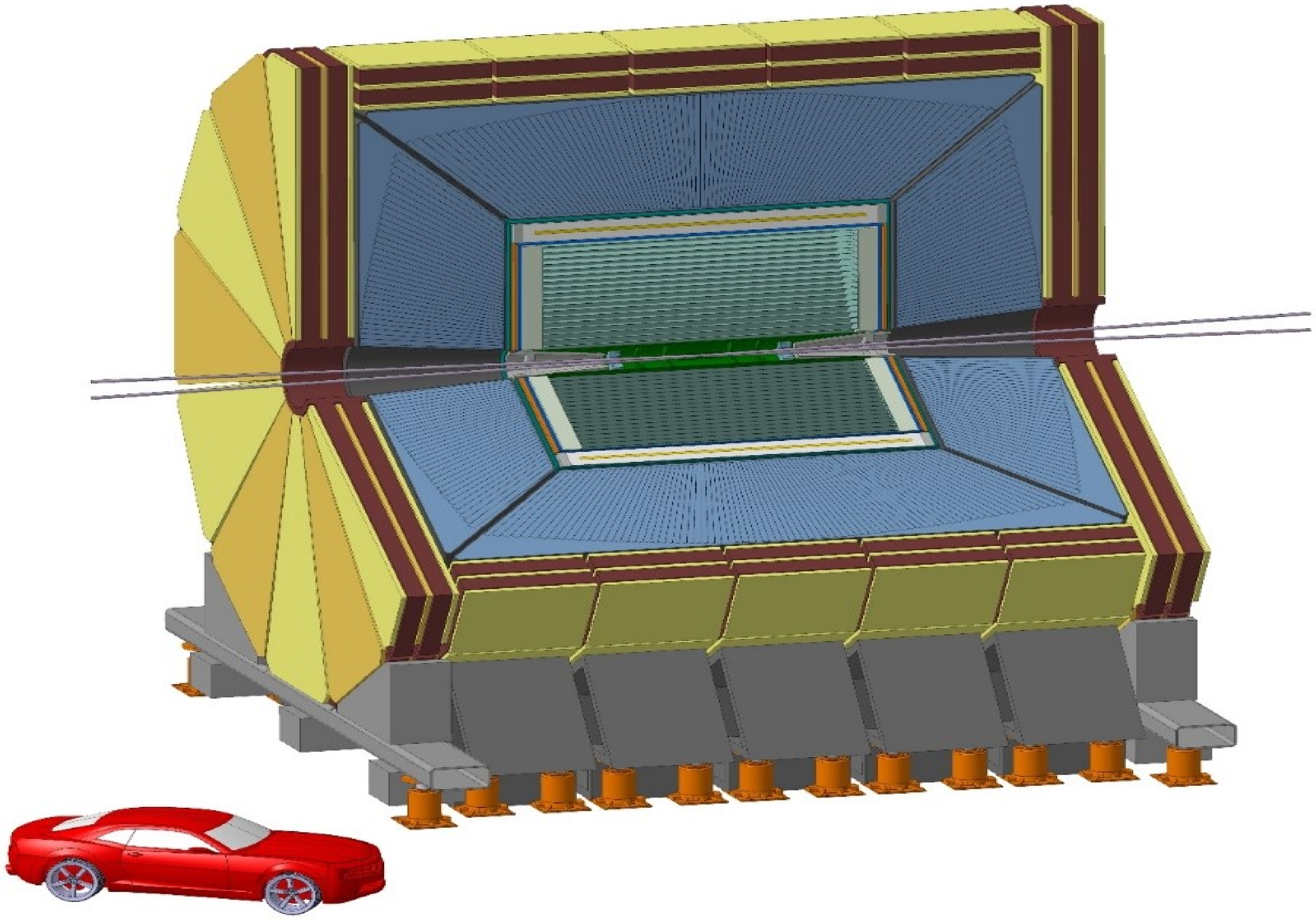
NIM A 537 (2005) 537

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

is universally valid

IDEA dual-readout fibre calorimetry

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°

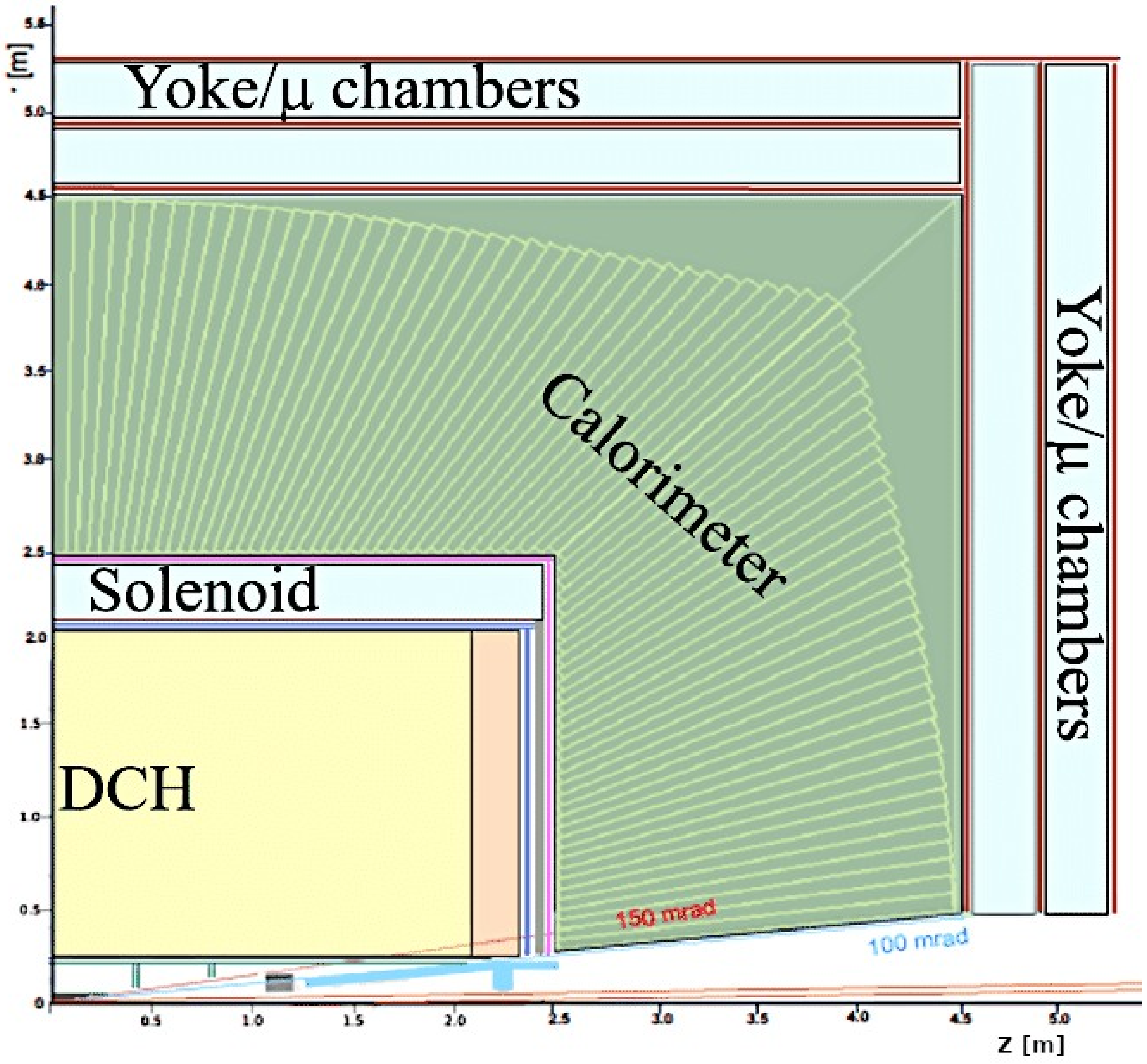
Highly transparent for tracking

Si pixel vertex detector

Drift Chamber

Si wrappers (strips)

Beam pipe: r ~ 1.5 cm

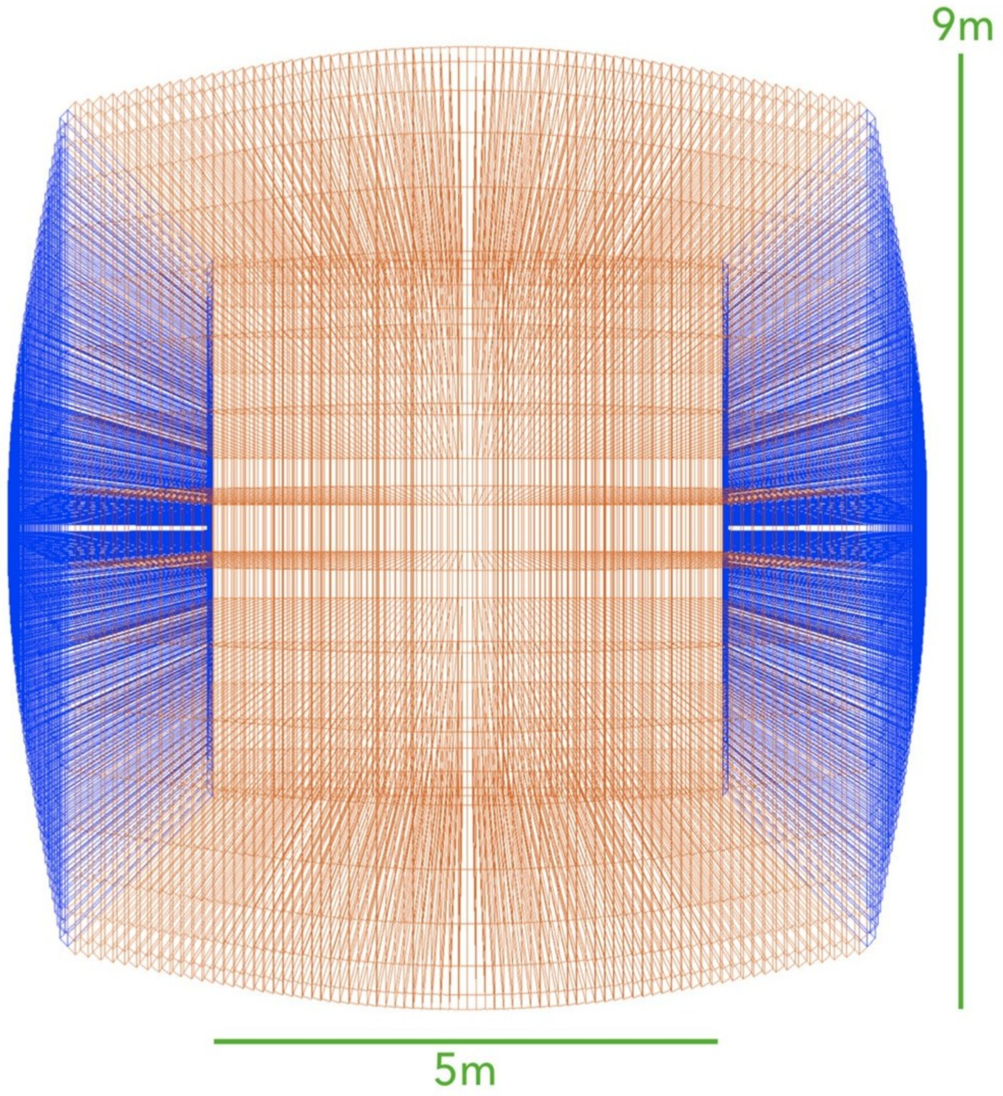


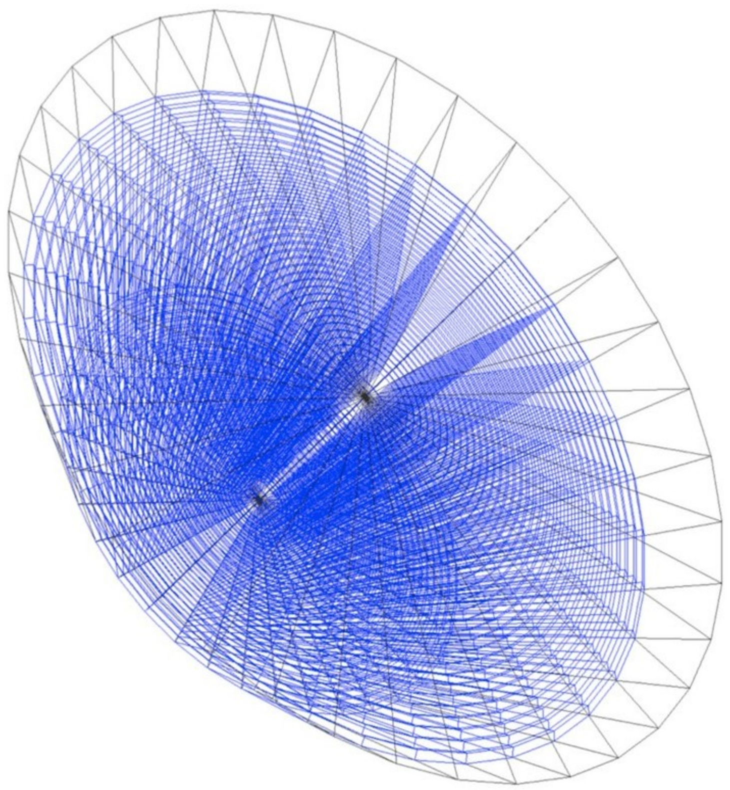
IDEA dual-readout calorimetry group

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

IDEA all-fibre DR calorimeter option



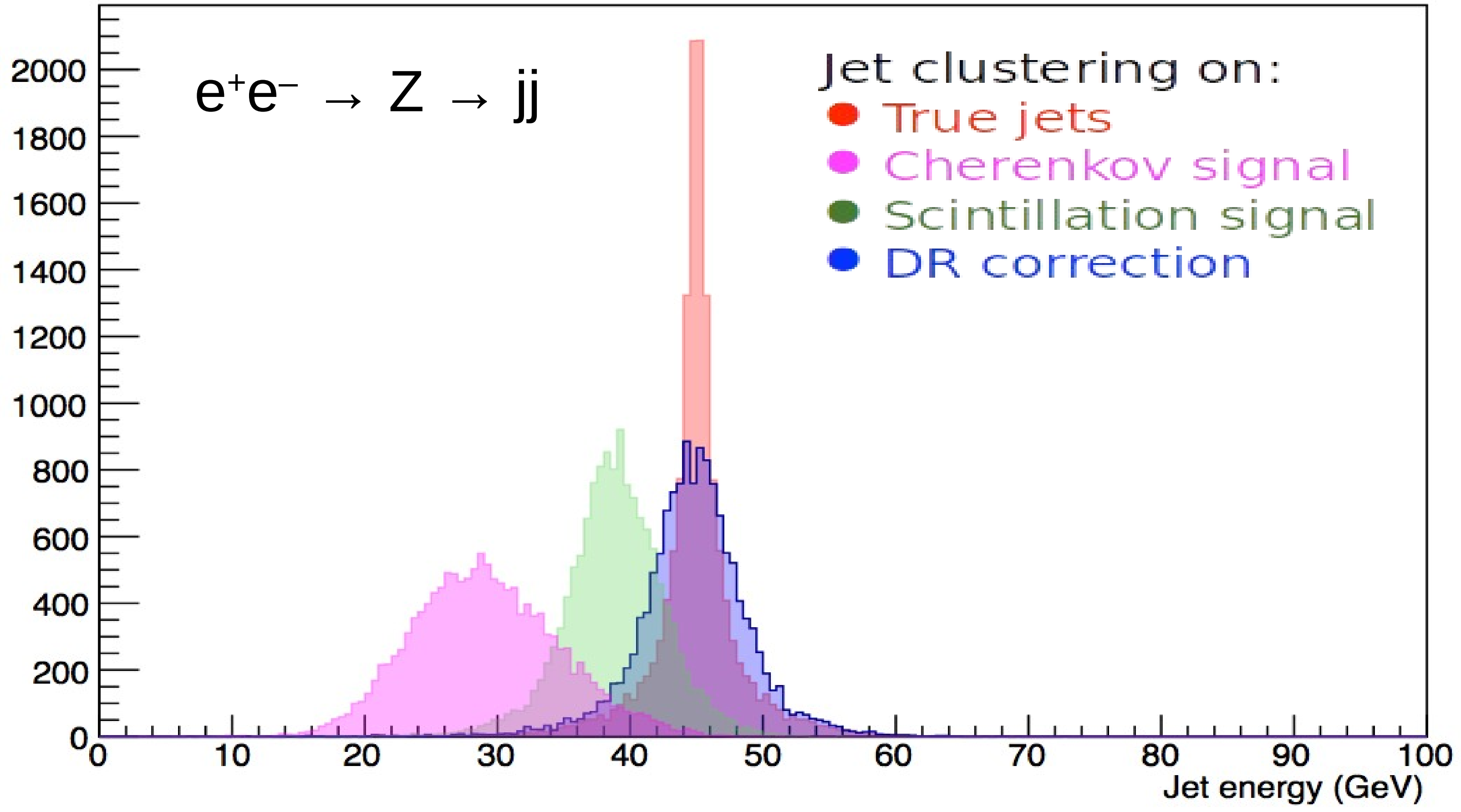


- DR fibre calorimeter
  - O(100 M) fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
    - ϑ coverage: $|\vartheta| > 100$ mrad
- G4 simulation available
  - tuned to RD52 TB data

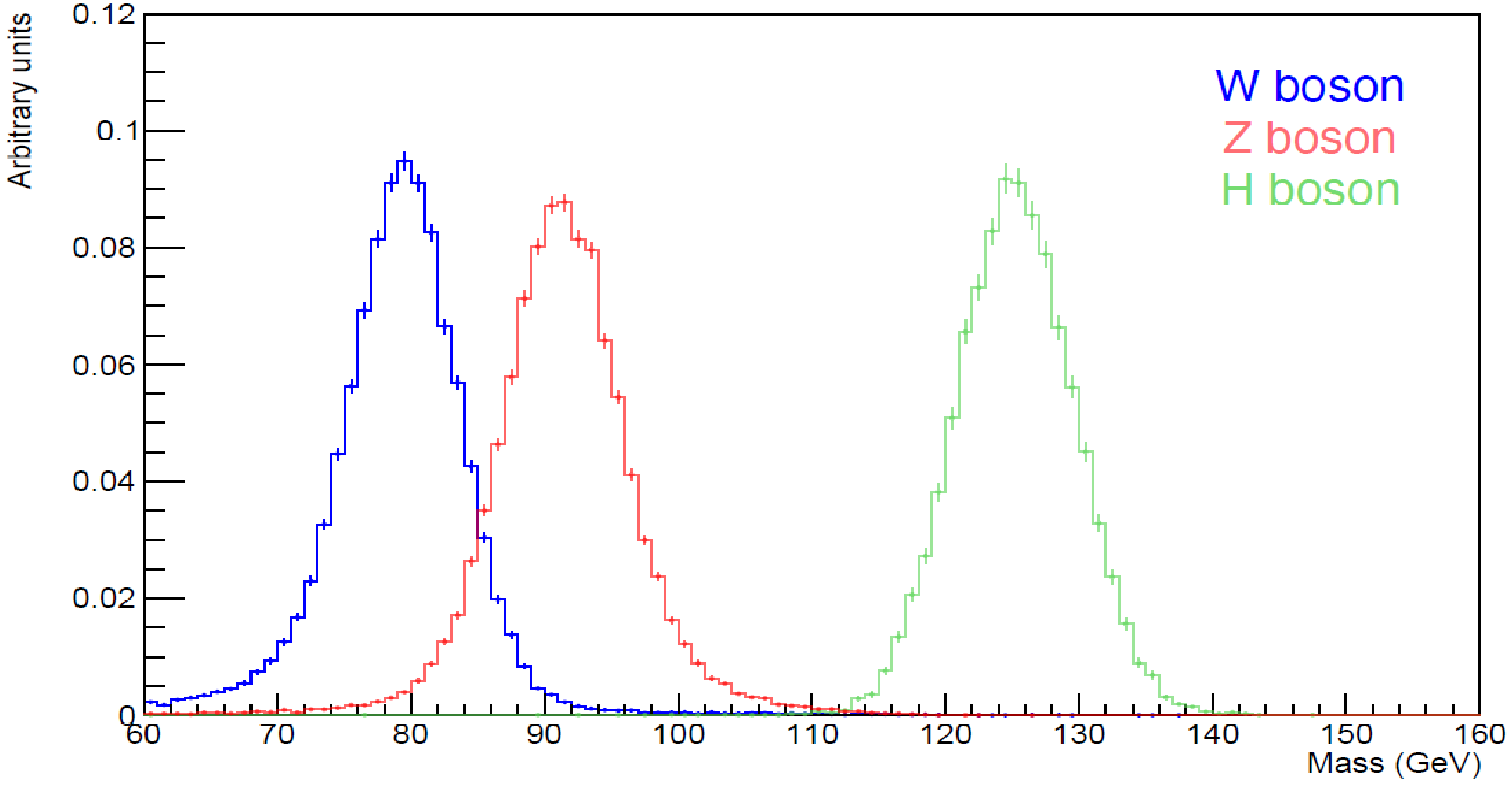
Geant4 simulations

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

Single jet resolution @ 45 GeV

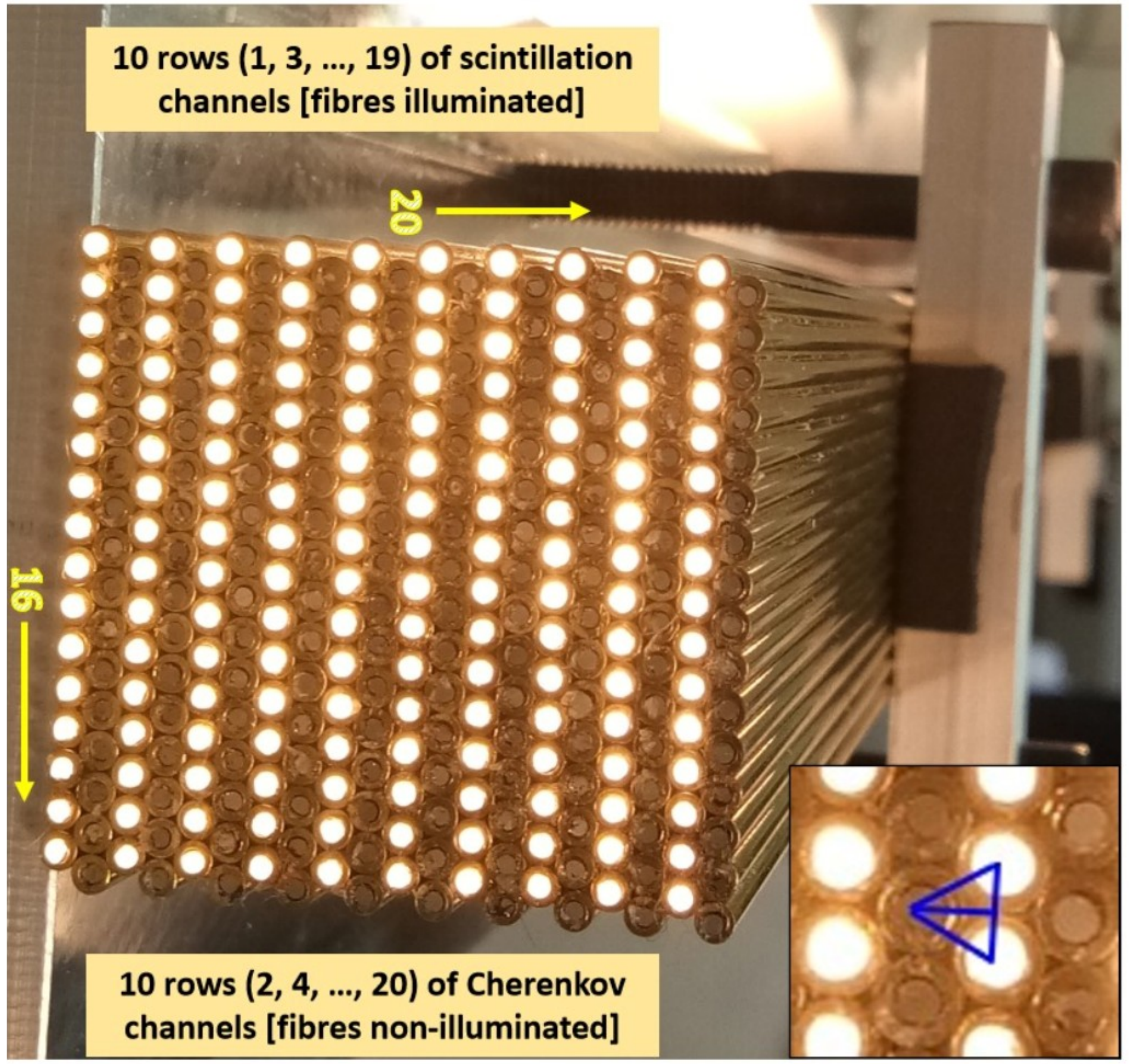


W/Z/H → jj invariant mass

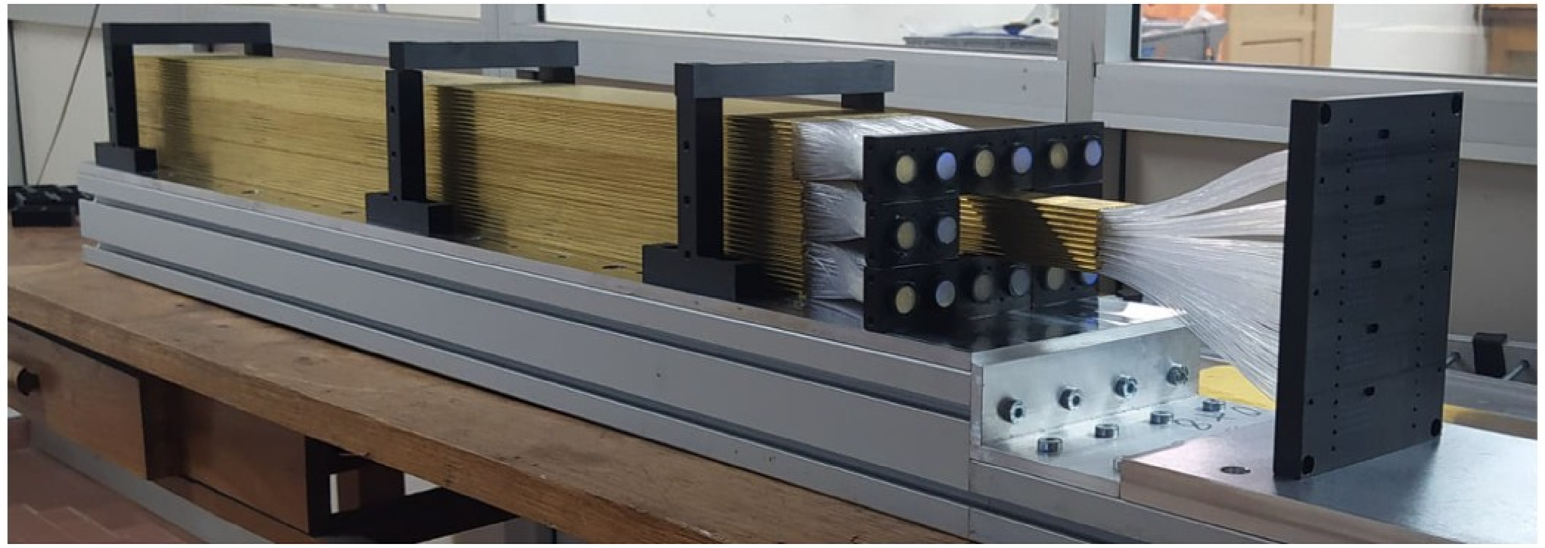


IDEA 2020 em-size bucatini prototype (EU)

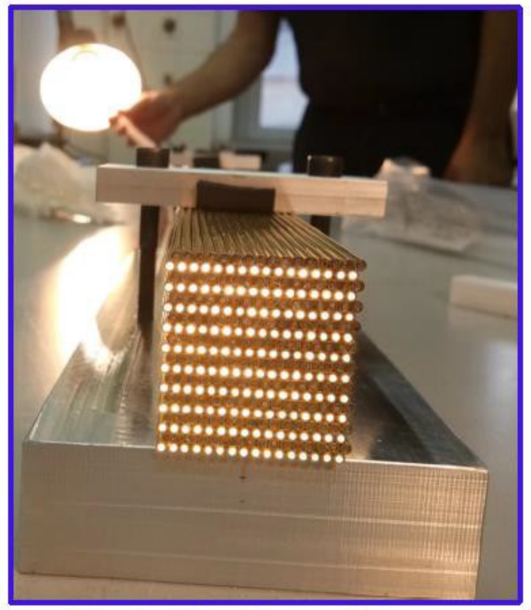
Nine ~3.5×3.3 cm^2 towers made of capillary brass tubes



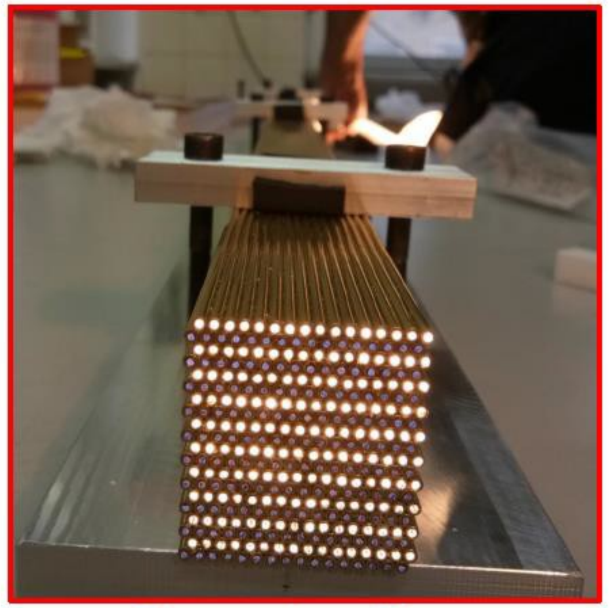
Central tower (360 fibres) w/ highly granular SiPM readout



Eight (surrounding) towers read out with PMTs



Scintillation fibers



Cherenkov fibers

2021 testbeam

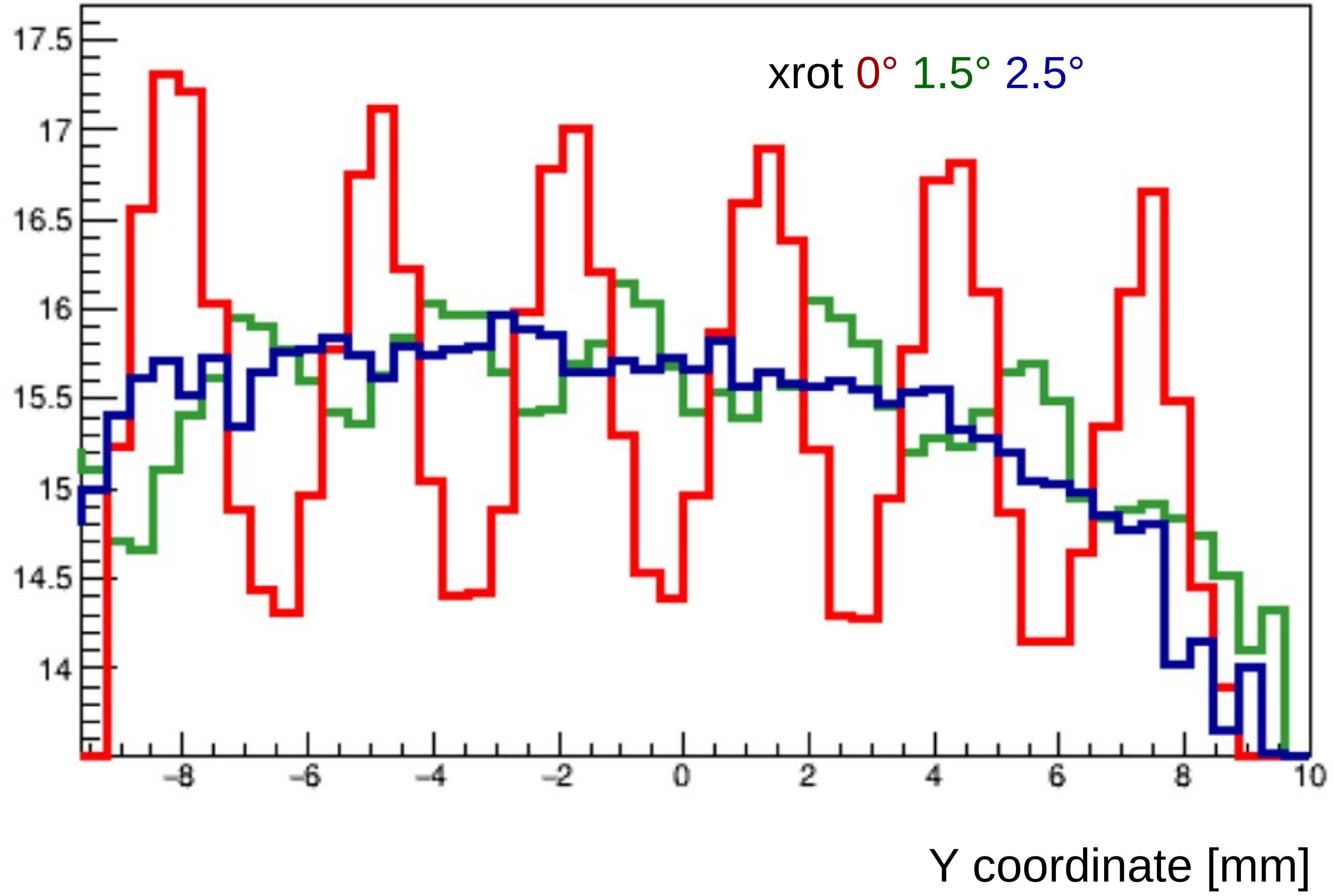
Test 2021 (CERN+DESY):

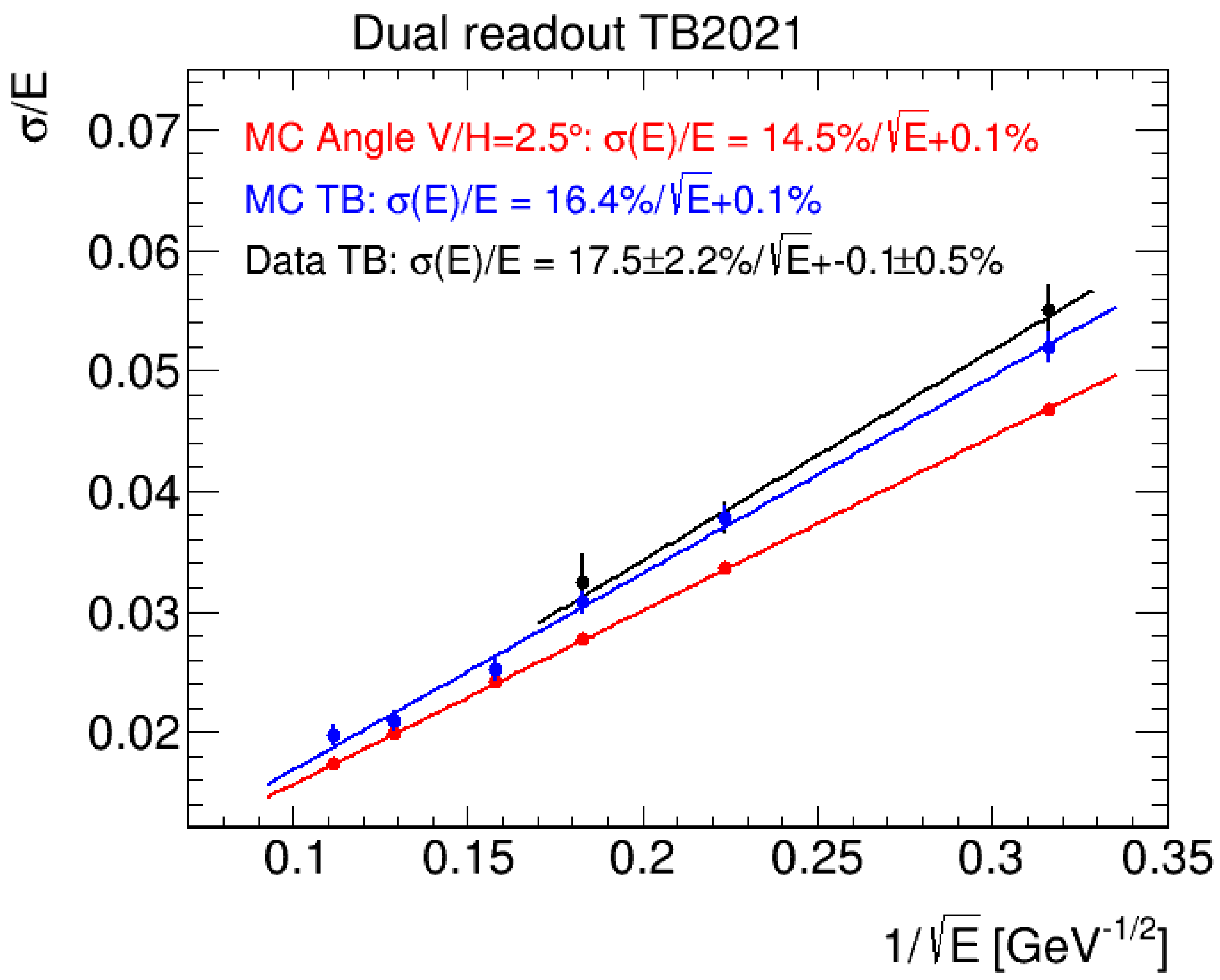
Verified strong dependence of response on impact angle

Very poor positron-beam purity in SPS H8 line only allowed limited testing

Electron resolution from
JINST 18 (2023) 09, P09021

Angular dependence (simulation)

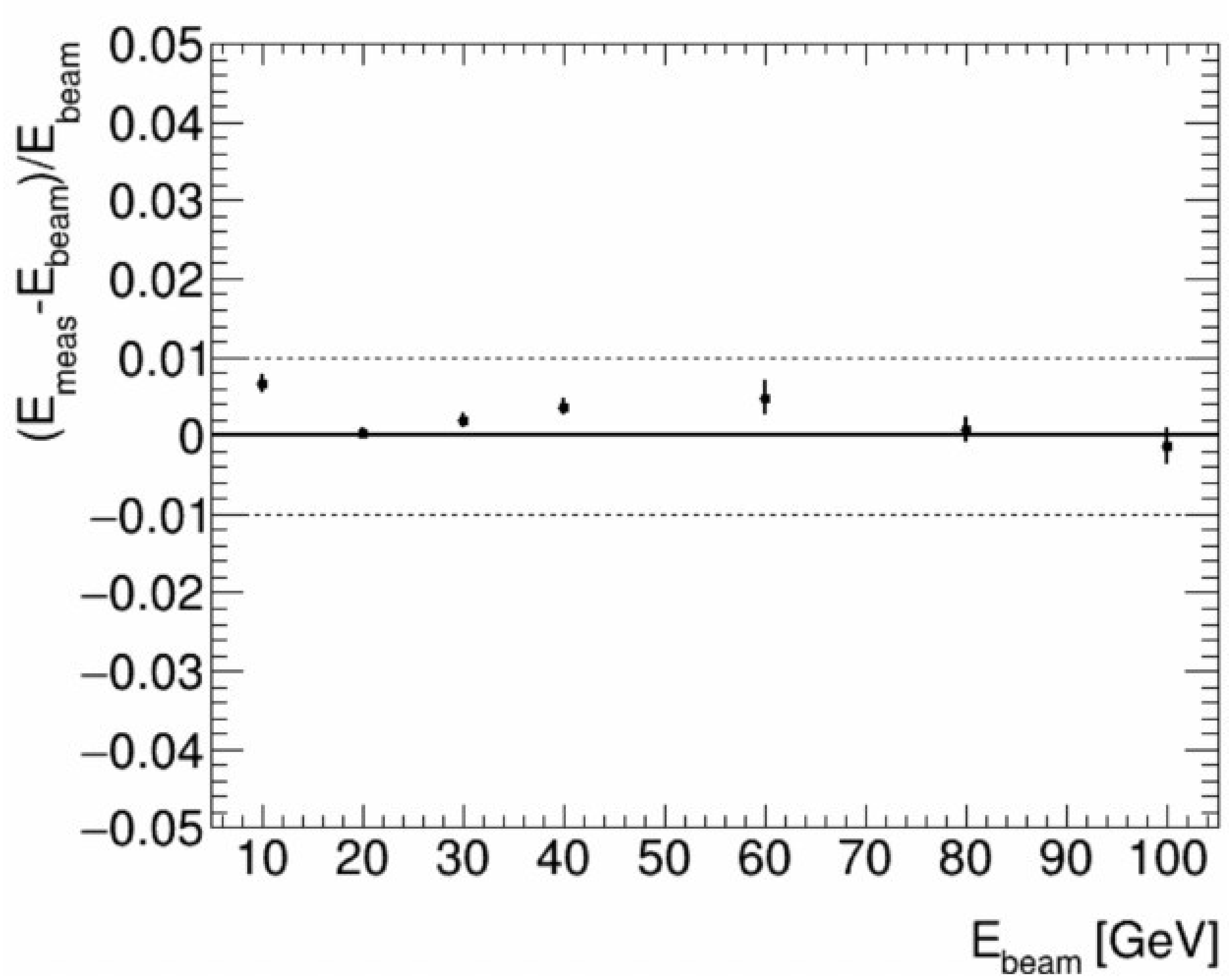




Testbeam results

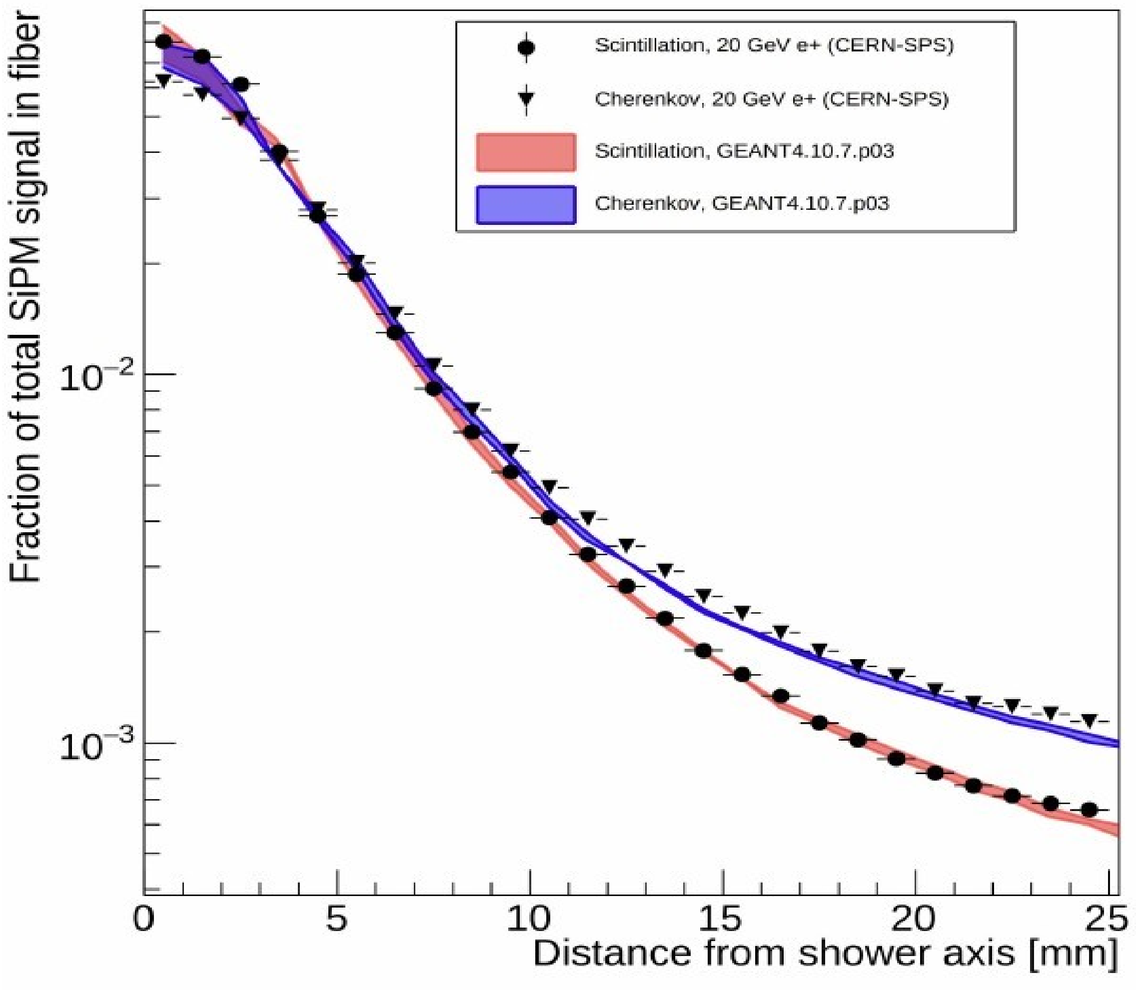
JINST 18 (2023) 09, P09021

Energy well reconstructed within 1%



Lateral shower profile compared to G4 simulation

→ **unprecedented resolution** ←



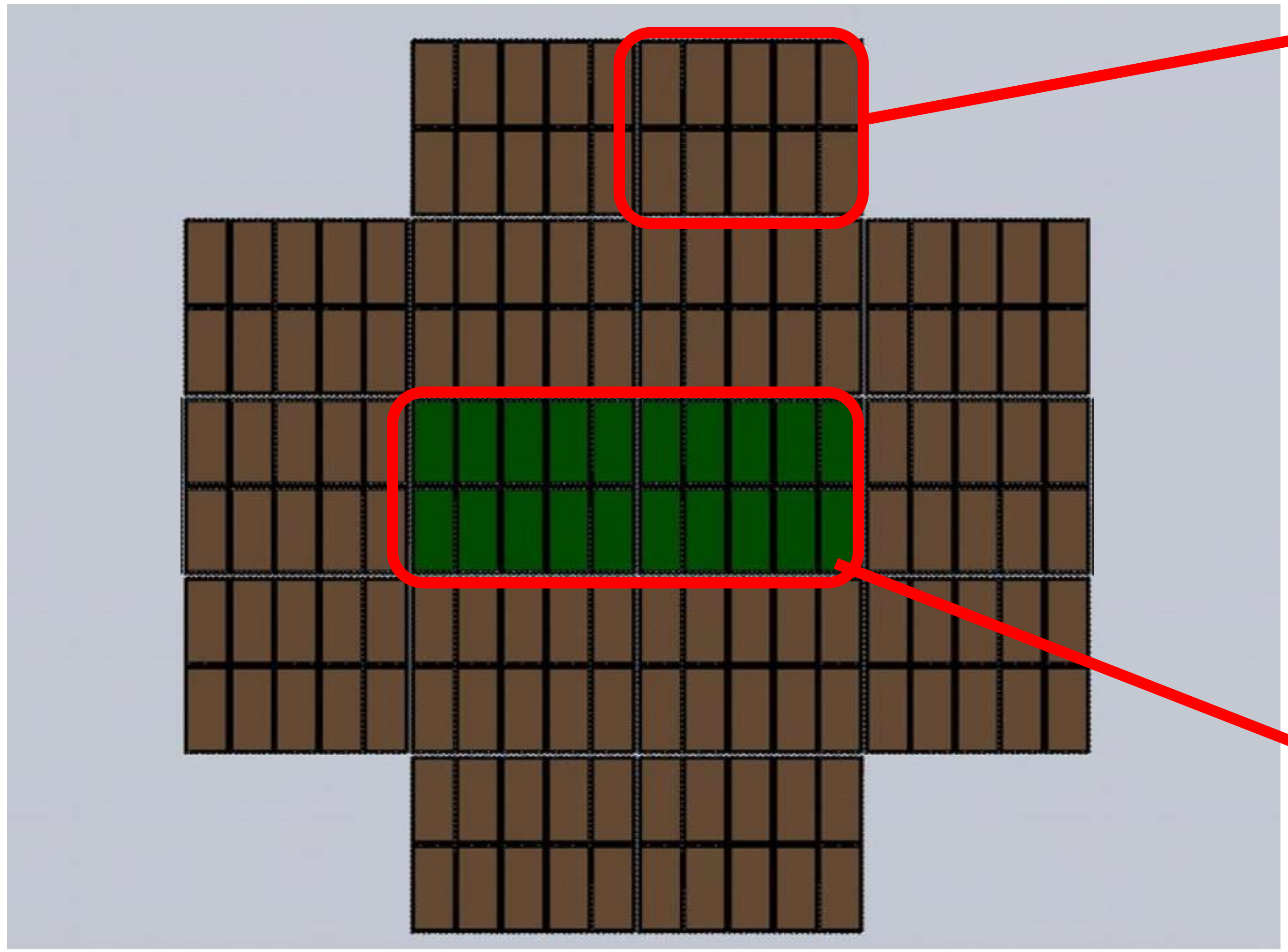
Additional data taken in 2023: analysis ongoing

Hadronic-containment prototype

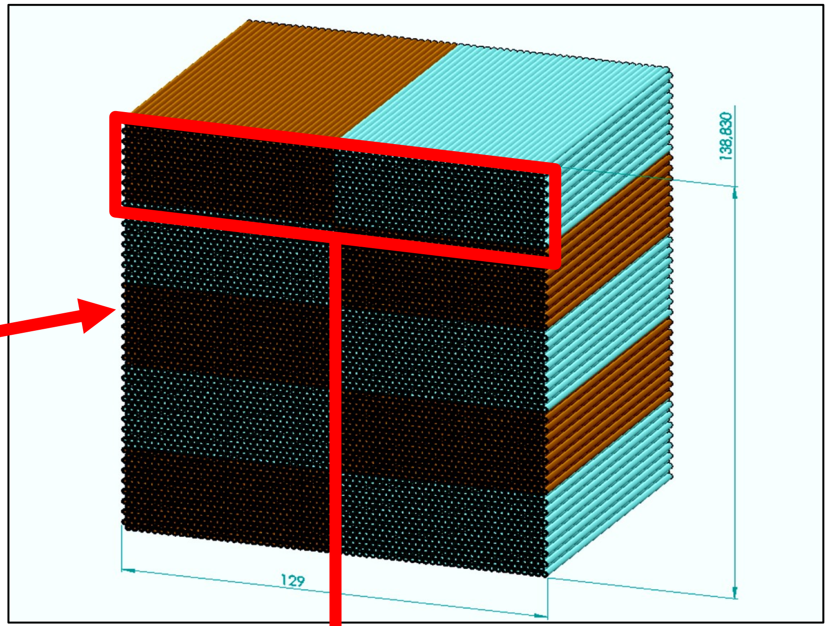
HiDRa – Highly granular Dual-Readout demonstrator (INFN)

Hadronic-size prototype:

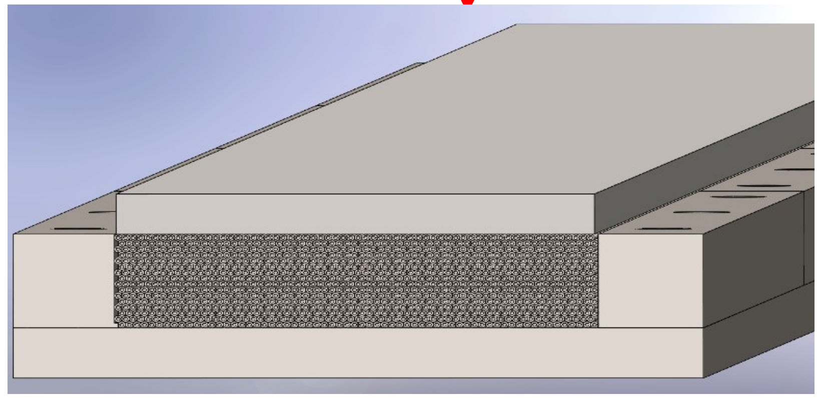
16 modules w/ highly granular core



~ 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

Objectives

Assess physics performance for both single hadrons and jets (and electrons)

Validate Geant4 shower modelling

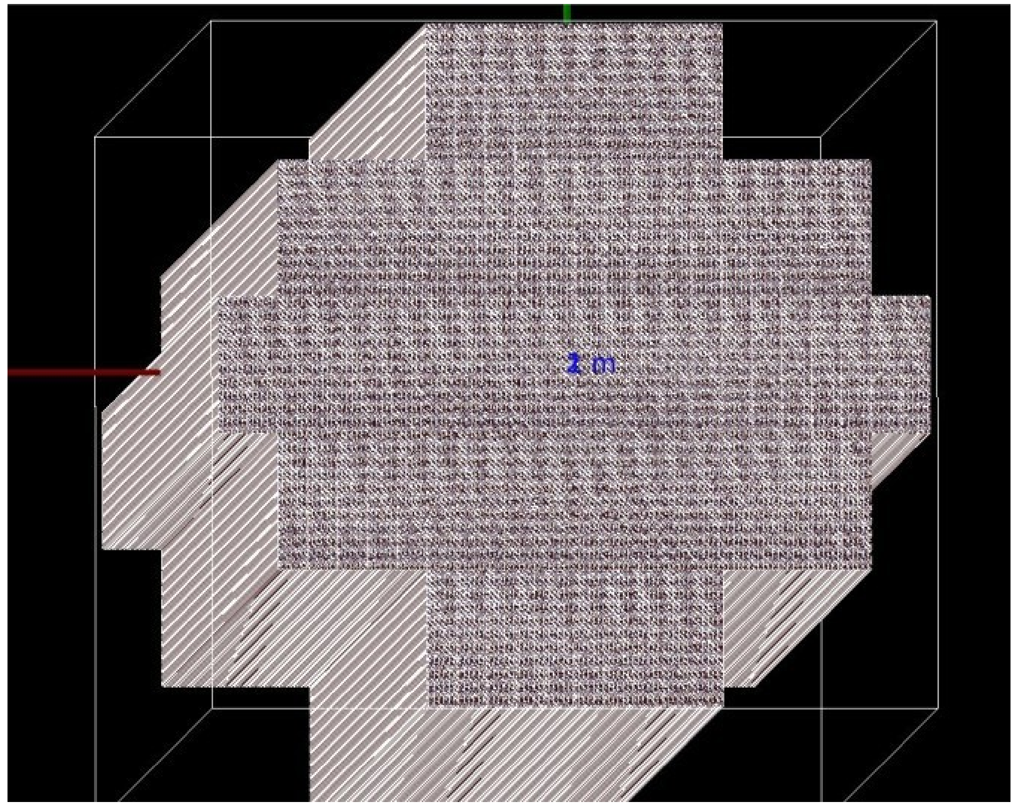
Assess scalable solutions concerning construction and signal readout/handling

Exploit DNN architectures for physics analysis

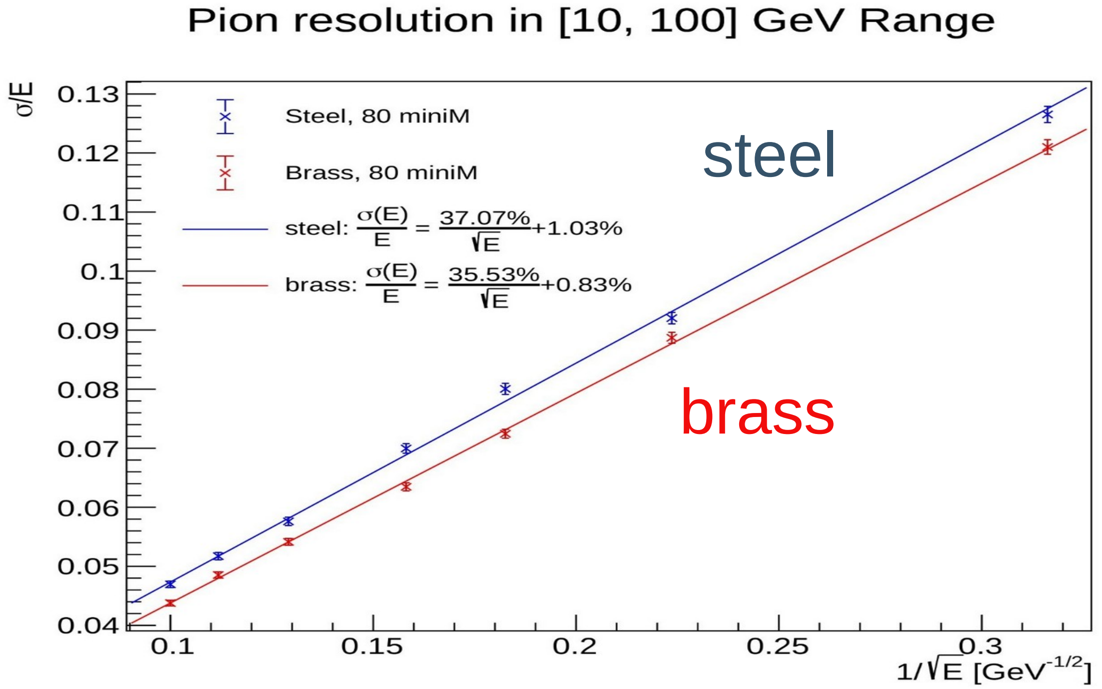
Assess performance in relevant benchmark physics channels

→ **Fully exploit D-R potential for physics programme at EWK/Higgs factories**

HiDRa Geant4 simulations

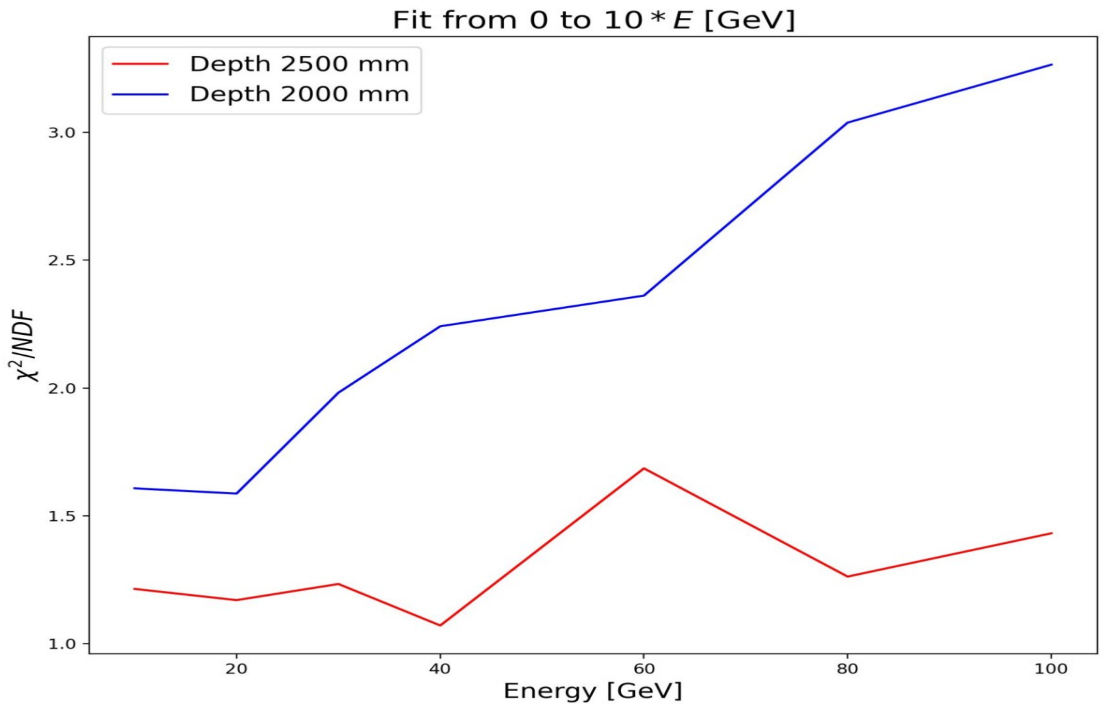


Absorber choice

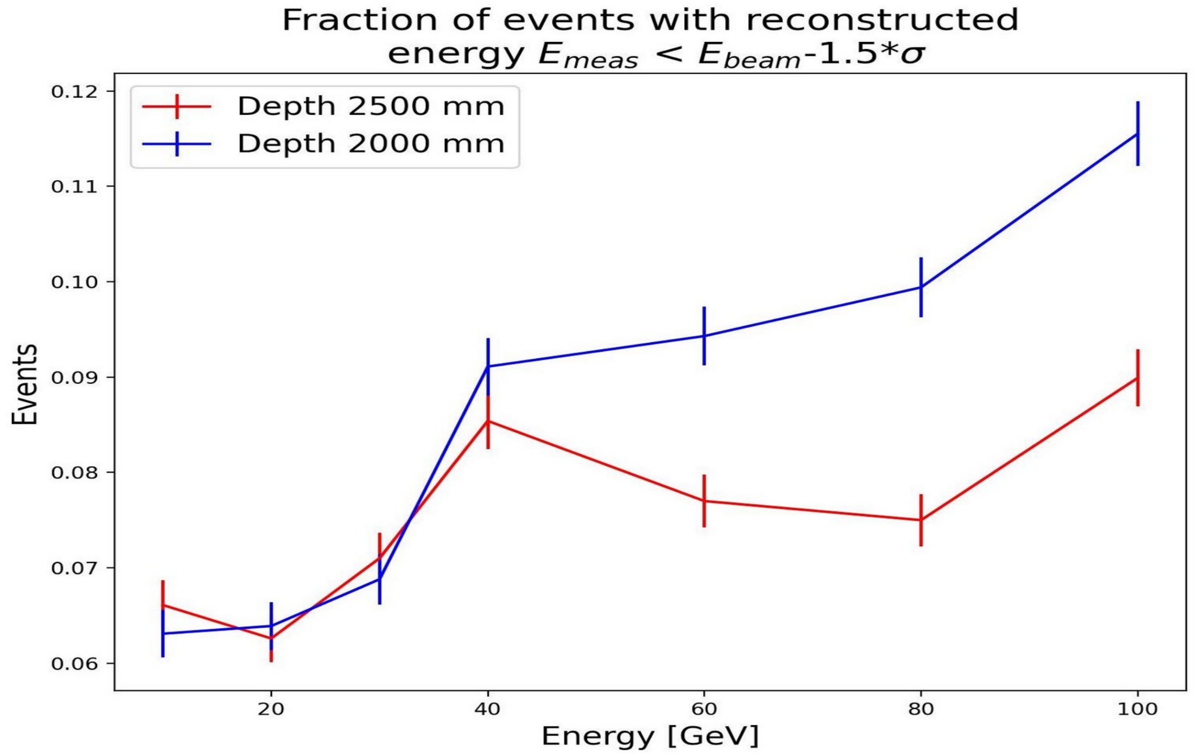


Calorimeter depth

χ2 / ndof



Low-energy tails

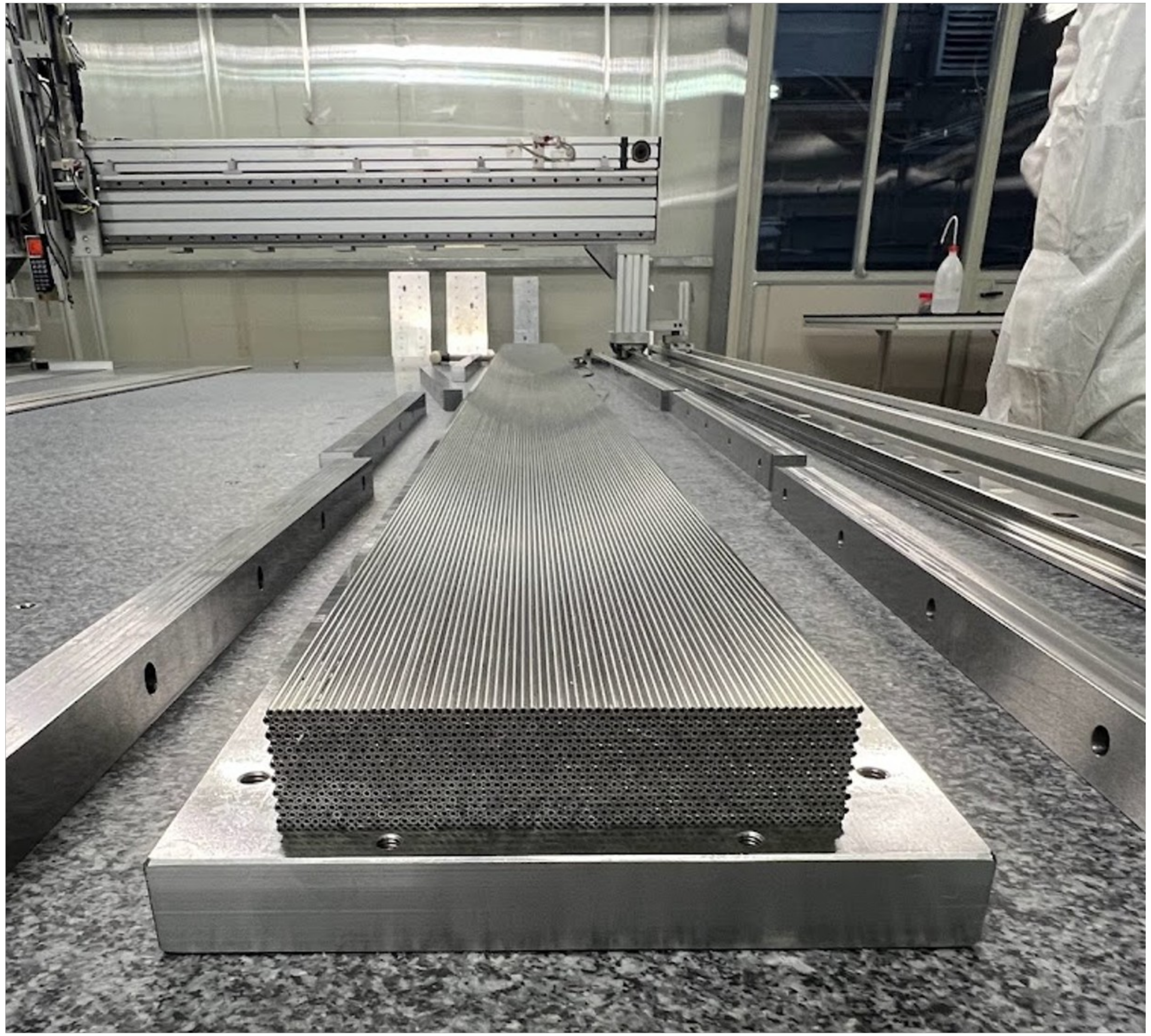


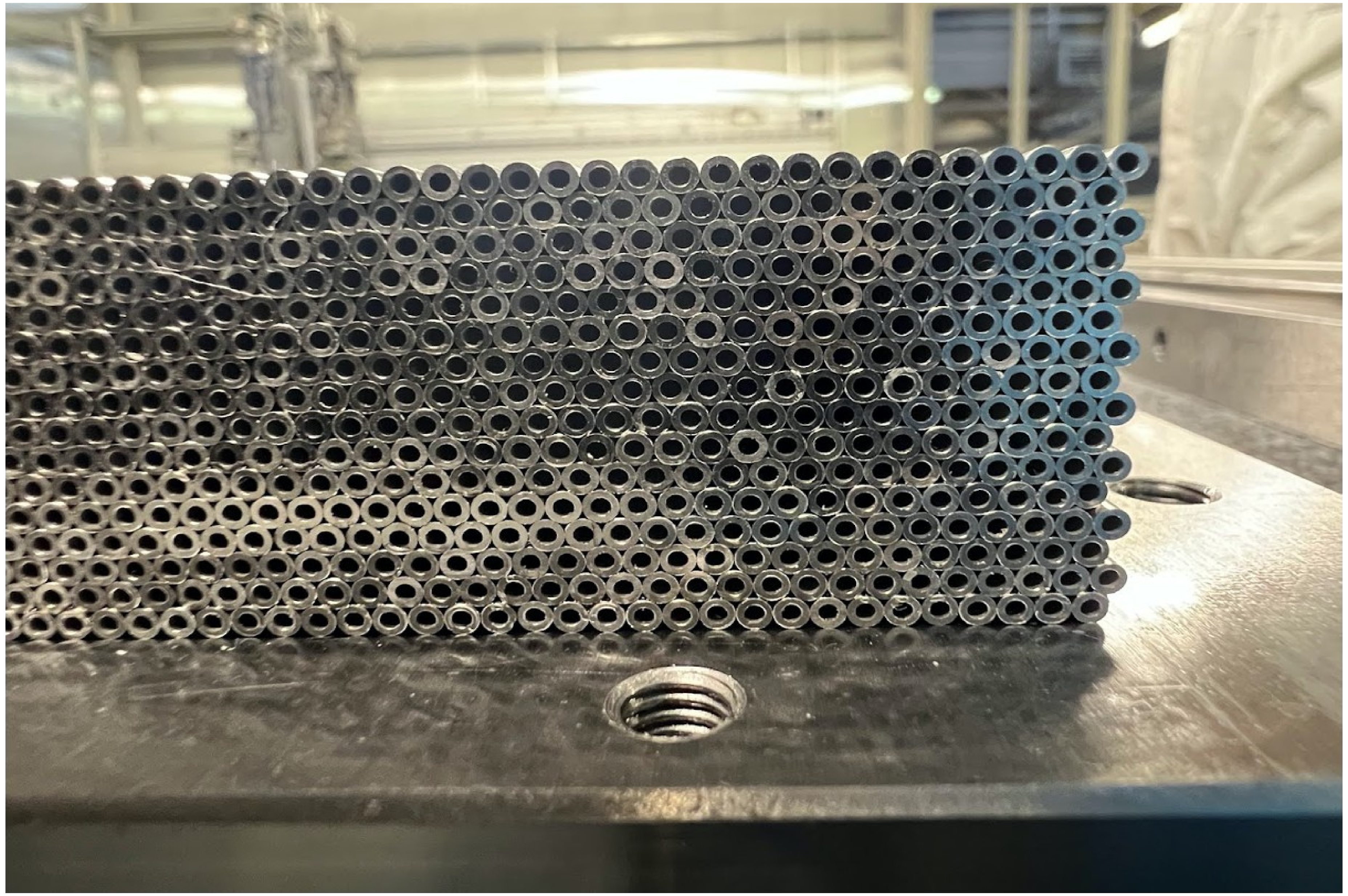
construction and QA/QC

Stiffback method for module handling

Semi-automatic system for planarity QA/QC

Minimodule 0

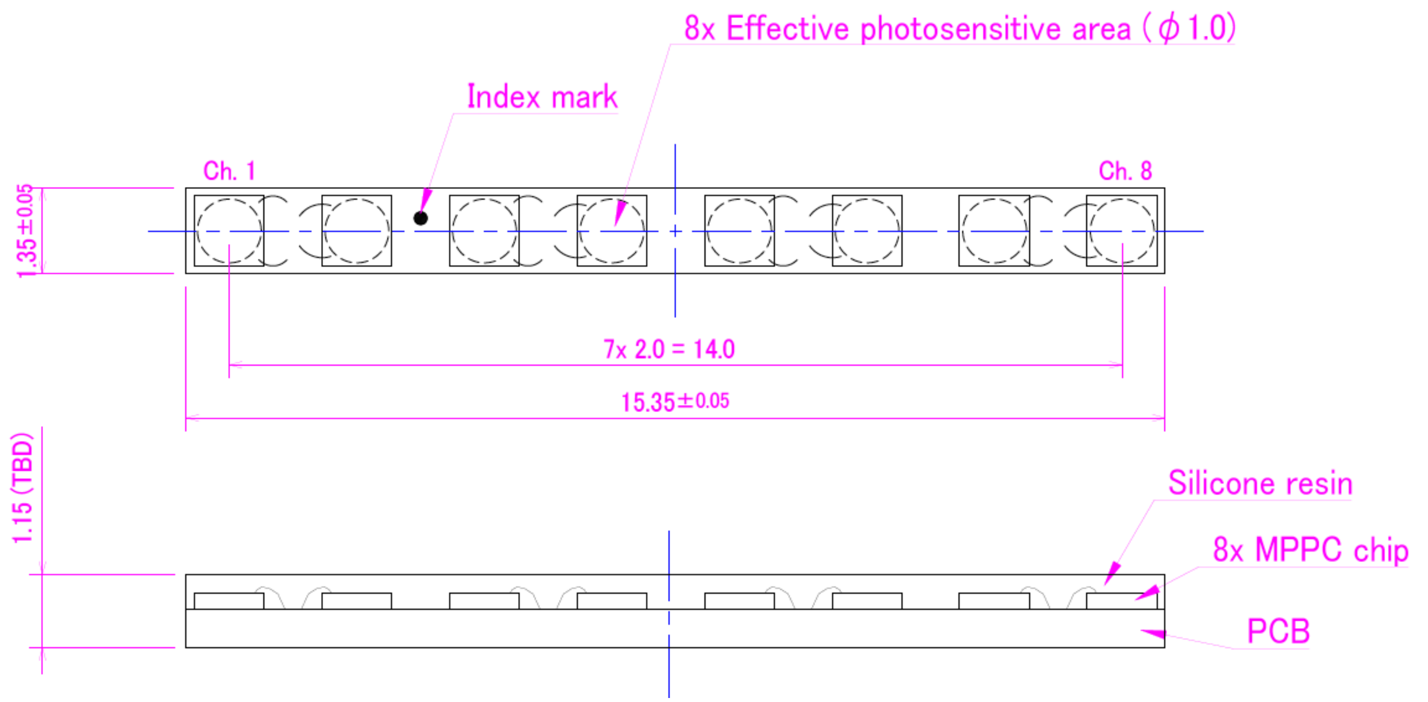




SiPMs for HiDRa

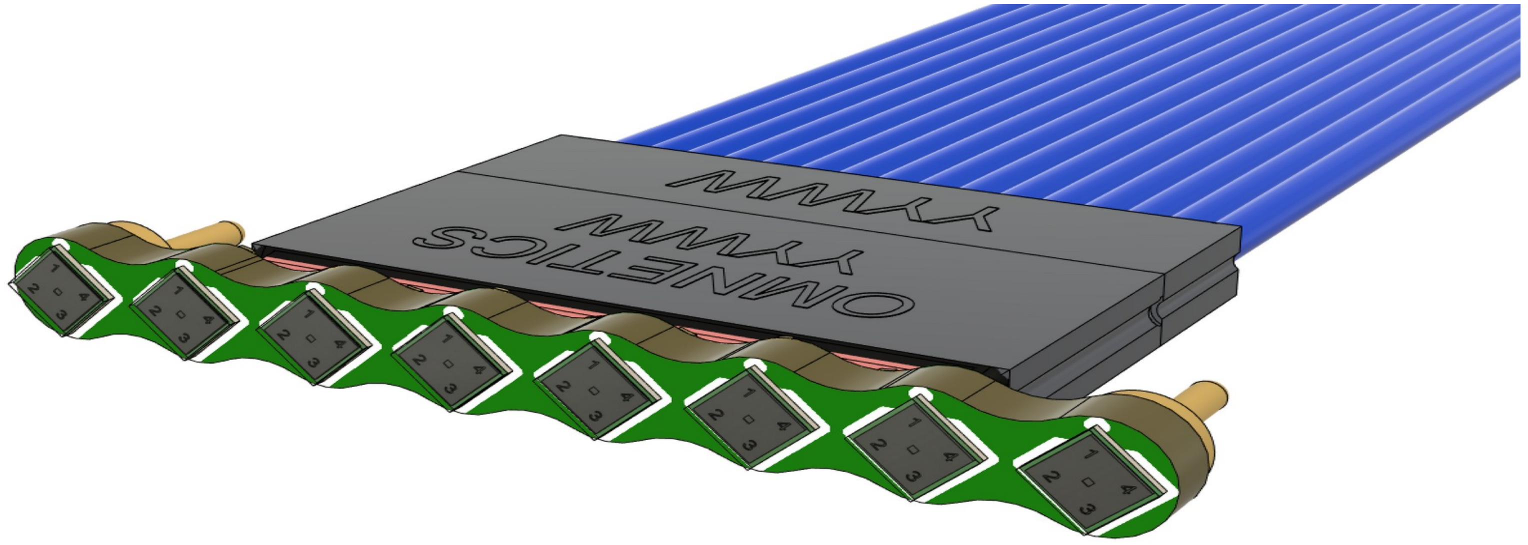
New solution by Hamamatsu:

boards with 8 “in-line” SiPMs
- dimension 1×1 mm^2
- 10 or 15 μm cell size
- SiPMs selected such that ΔV_{bd} < 100 mV



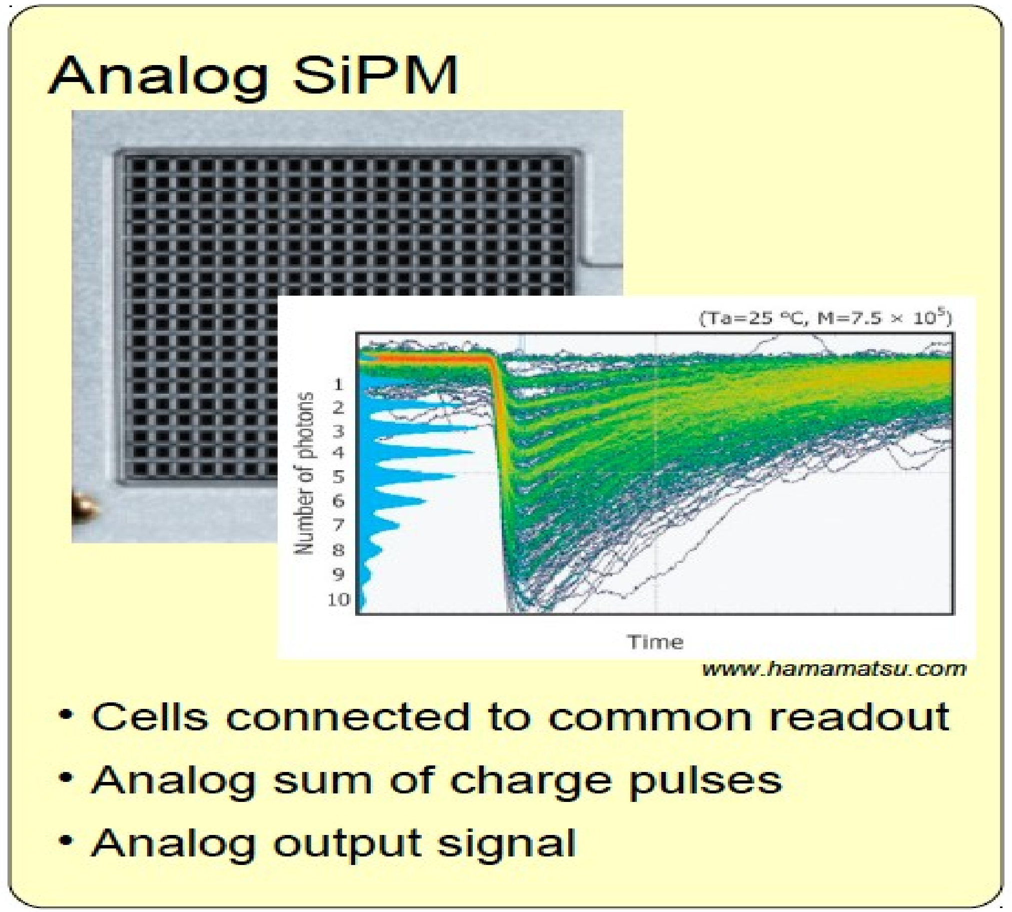
Actual choice:

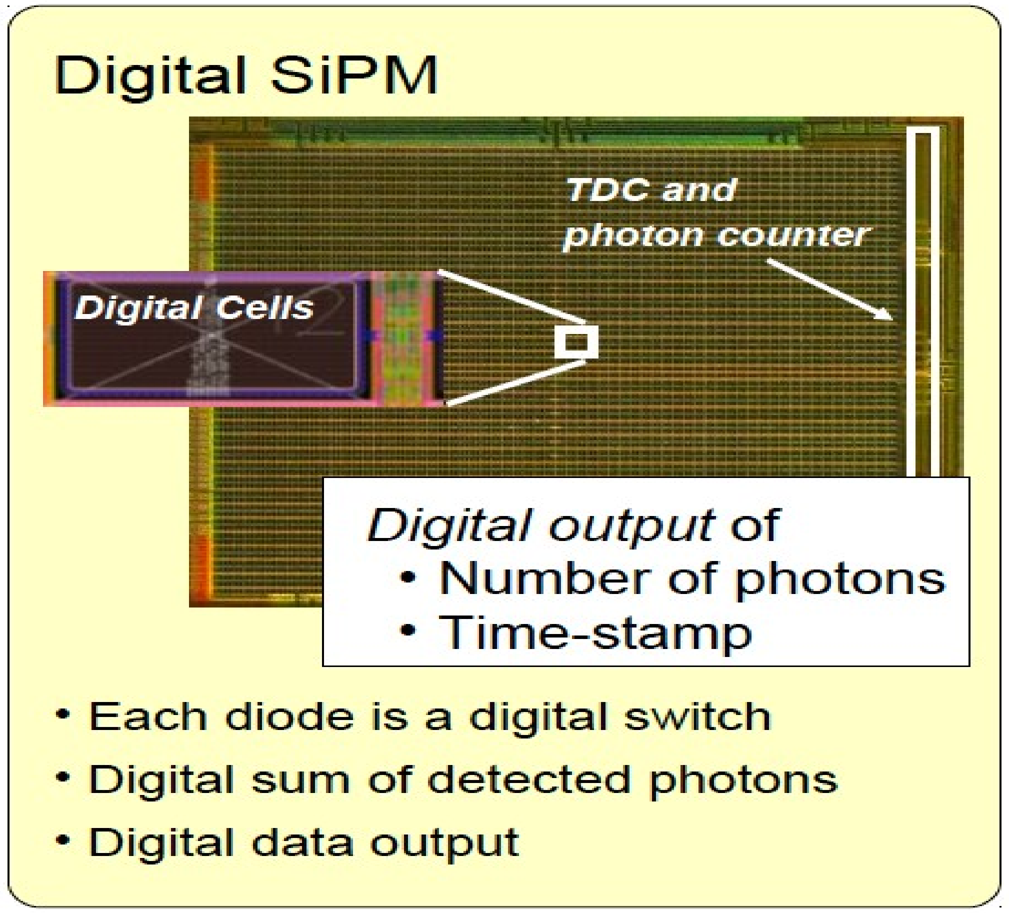
a) 10 μm cells for scintillating fibres
b) 15 μm cells for clear fibres



Testing 10 boards per cell-size type

Alternative to SiPMs?





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 ($\rightarrow$ timing)
  - simplified assembly of large area detectors
  - R&D costs relatively low for design over standard process

exploit timing & DNNs

τ-decay tagging w/ DNNs

Testbeam module (brass absorber): dimensions: 133.2×133.2×250 cm^3

Reduced granularity (1.2×1.2 cm^2, 32 S & 32 C fibres): 111×111 modules

Simulation of both detector and SiPM response

Feature extraction: E(Q), Pk, ToP, ToA, ToT

→ each event represented by 111×111×5×2 tensor

NN implementation

Two DNN architecture variants studied:

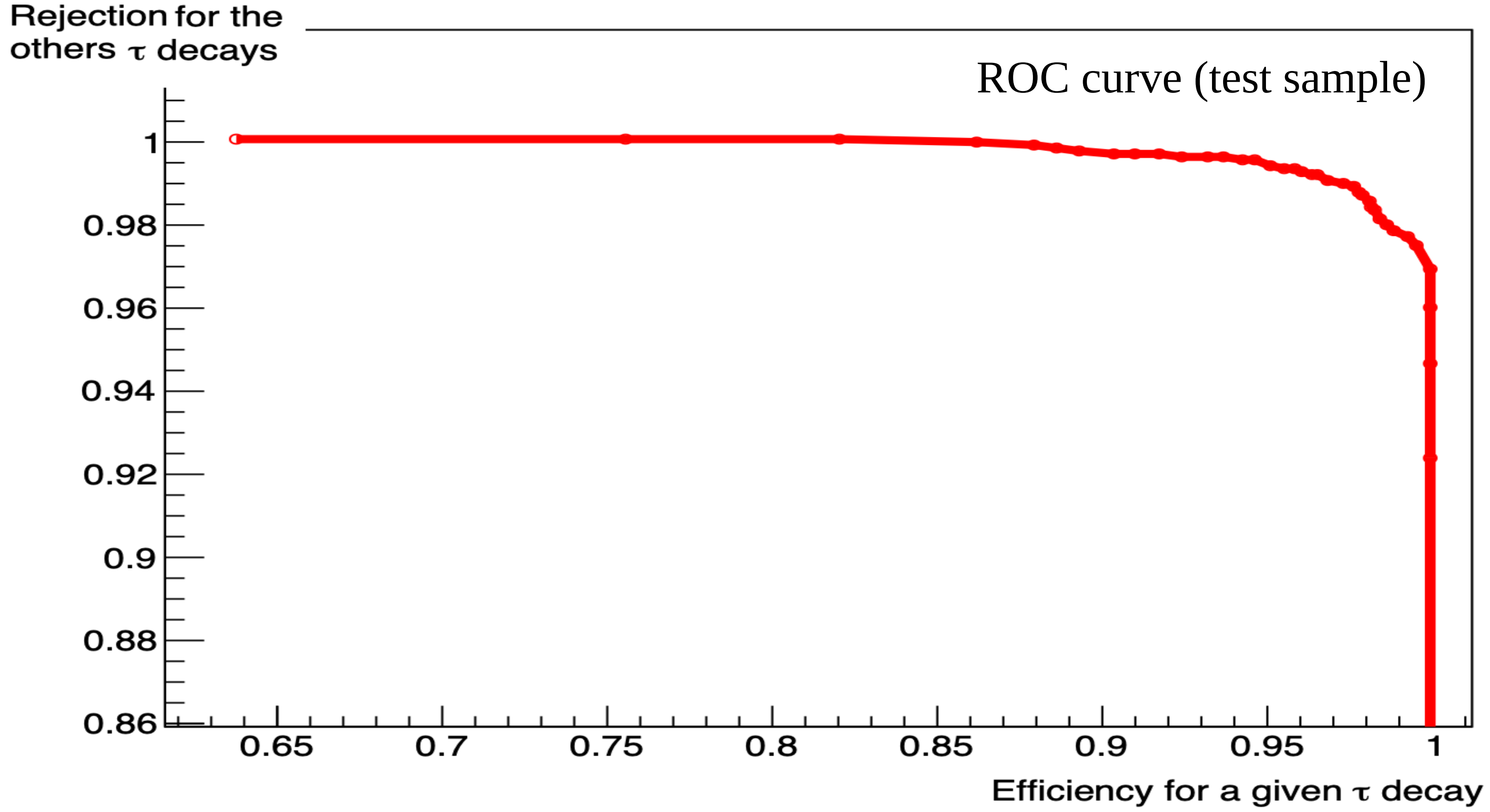
- VGG-11 like (VGG = Visual Geometry Group, Oxford Un.)
- Dynamic Graph CNN (DGCNN)

6 event classis (covering ~ 90% of τ decays)

Training set: 6 BR × 2000 evts

$\tau \to \pi\pi^0\nu$
$\tau \to \mu\nu\nu$
$\tau \to e\nu\nu$
$\tau \to \pi\nu$
$\tau \to \pi\pi\pi\nu$
$\tau \to \pi\pi^0\pi^0\nu$

VGG example



NN performance

Confusion matrix on test set

VGG-11

average accuracy: 97.3%

Truth BR \ Predicted BR	$\tau \to \pi\pi^0\nu$	$\tau \to e\nu\nu$	$\tau \to \mu\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi^0\pi^0\nu$
$\tau \to \pi\pi^0\nu$	100%					
$\tau \to e\nu\nu$	2%	95%	3%			
$\tau \to \mu\nu\nu$			100%			
$\tau \to \pi\nu$			6%	91%	3%	
$\tau \to \pi\pi\pi\nu$					98%	2%
$\tau \to \pi\pi^0\pi^0\nu$						100%

DGCNN

average accuracy: 99.9%

Truth BR \ Predicted BR	$\tau \to \pi\pi^0\nu$	$\tau \to e\nu\nu$	$\tau \to \mu\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi^0\pi^0\nu$
$\tau \to \pi\pi^0\nu$	100%					
$\tau \to e\nu\nu$		99.7%	0.3%			
$\tau \to \mu\nu\nu$			100%			
$\tau \to \pi\nu$				99.4%	0.6%	
$\tau \to \pi\pi\pi\nu$					100%	
$\tau \to \pi\pi^0\pi^0\nu$						100%

DNN w/ IDEA layout (but no time info)

No SiPM response simulation

→ information: fibre signal output (# p.e.)

3-class classification:

τ_{lep}, τ_{had}, QCD jet

8-class classification:

τ_0, τ_1, τ_2, τ_3, τ_4, τ_5, τ_6, QCD jet

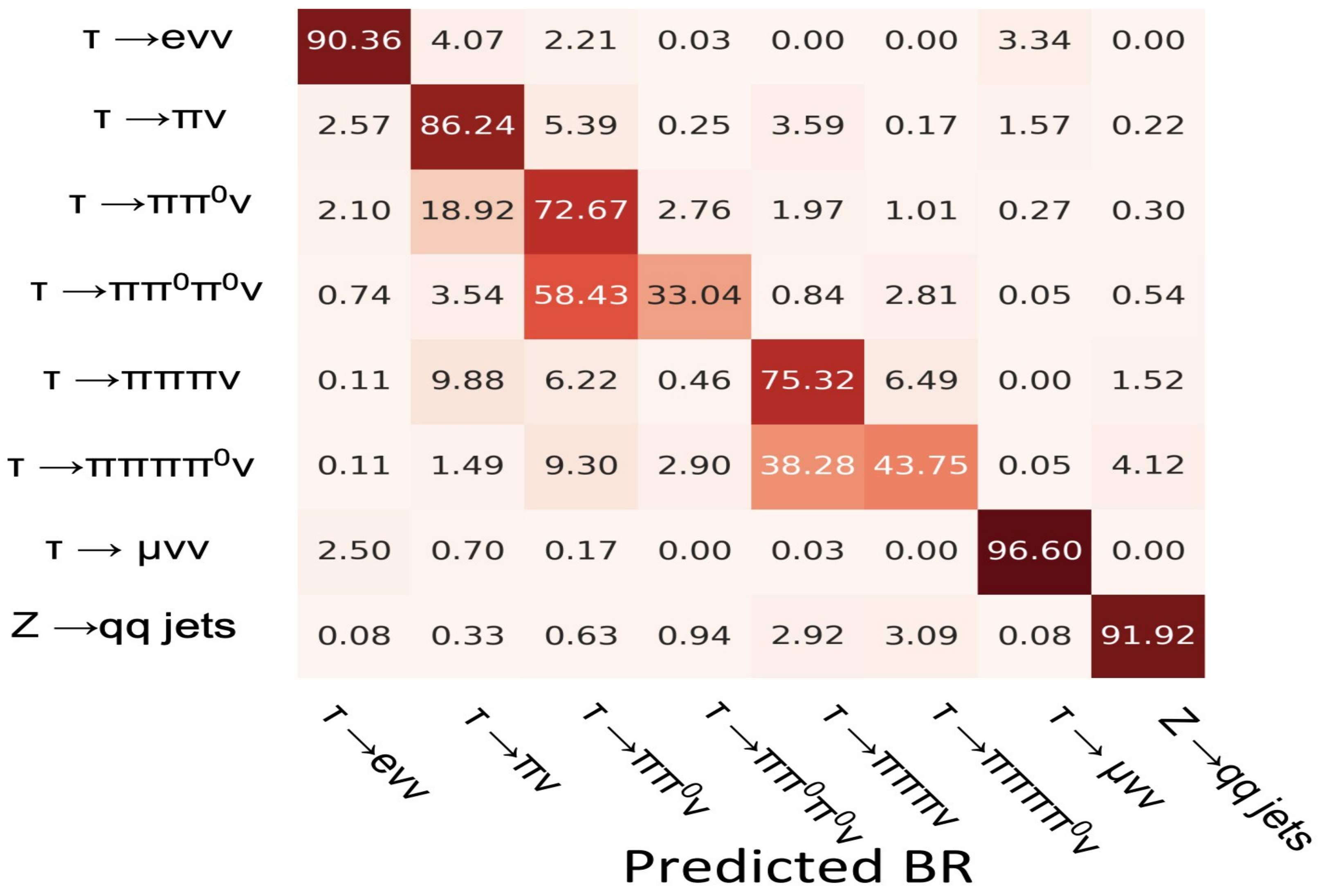
[τ from $Z \rightarrow \tau\tau$ decays]

3-class label	8-class label	
0	0	$\tau \rightarrow \mu\nu\nu$
0	1	$\tau \rightarrow e\nu\nu$
1	2	$\tau \rightarrow \pi\nu$
1	3	$\tau \rightarrow \pi\pi^0\nu$
1	4	$\tau \rightarrow \pi\pi^0\pi^0\nu$
1	5	$\tau \rightarrow \pi\pi\pi\nu$
1	6	$\tau \rightarrow \pi\pi\pi^0\nu$
2	7	$Z \rightarrow qq$ jets

DGCNN w/ geometrical information only

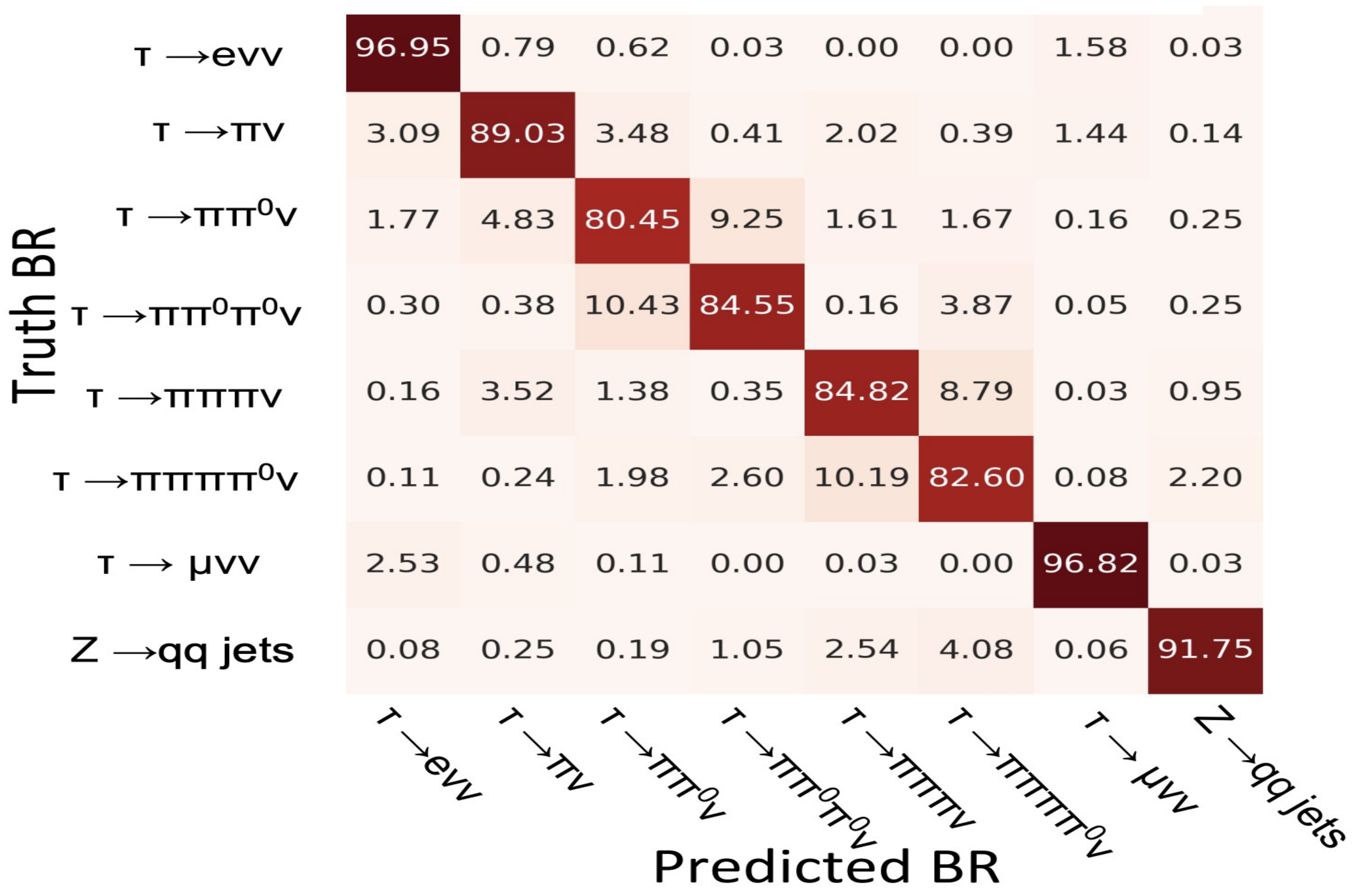
DGCNN optimised but w/o #pe as input feature

B field and material in



input: fibre coordinates only

avg accuracy: 73.7%



input: fibre coordinates + type

avg accuracy: 88.3% (w/ #p.e. 90.8%)

longitudinal segmentation w/ timing (U.S.)

Dual-readout fibre calorimeter → signal sampled at 20 GHz

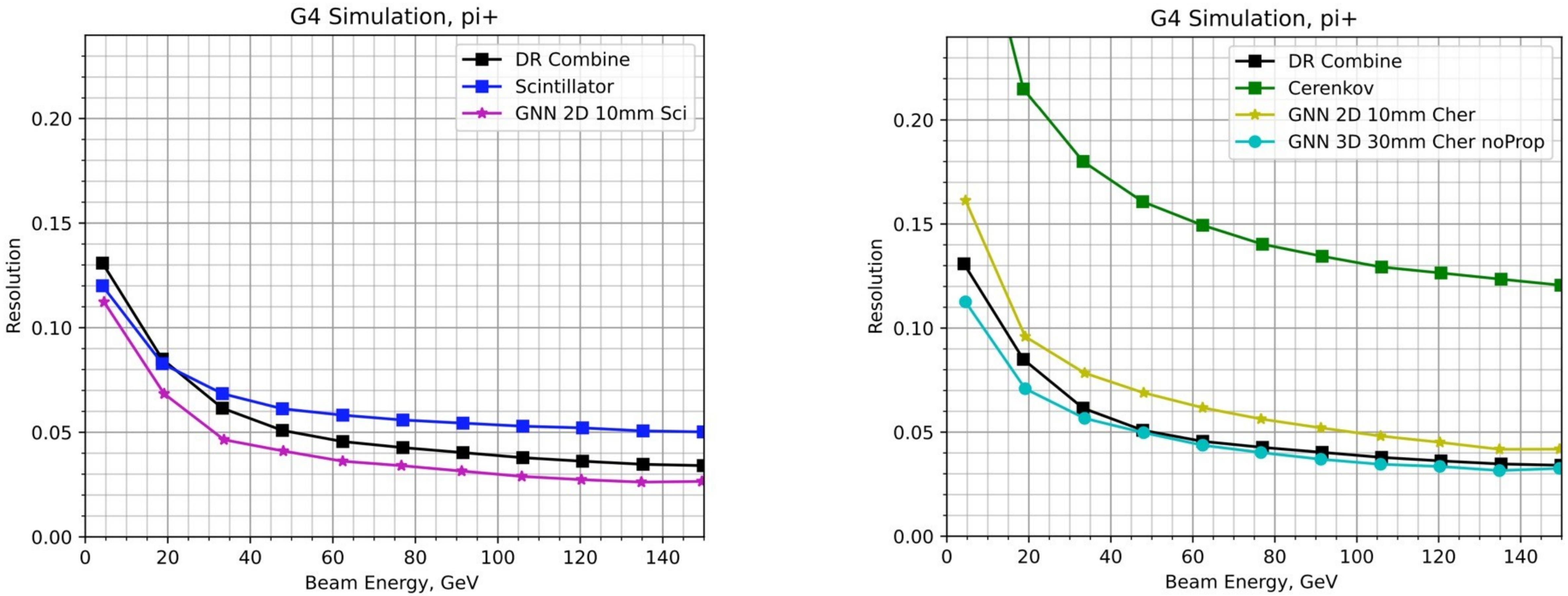
Preliminary results
No optimisation

Cu absorber (2 m deep)

Fibre axis aligned w/ beam direction: 1 mm Φ fibres, 1.5 mm spacing

Transverse segmentation: 1×1 cm^2 for 2D analysis, 3×3 cm^2 for 3D analysis

3D imaging fibre DR calorimeter coupled to Graph DNN



longitudinal segmentation w/ timing (U.S.)

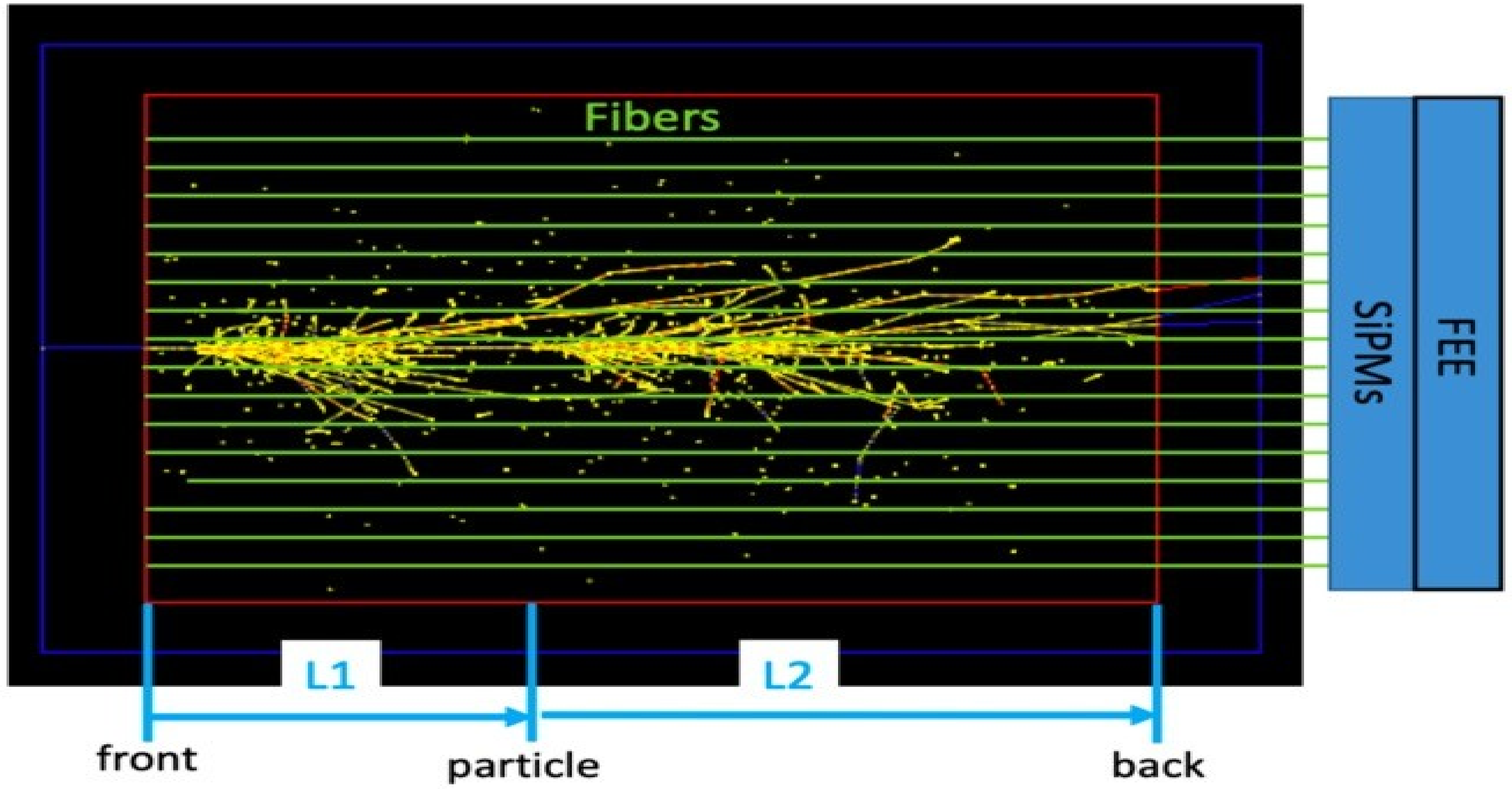


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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

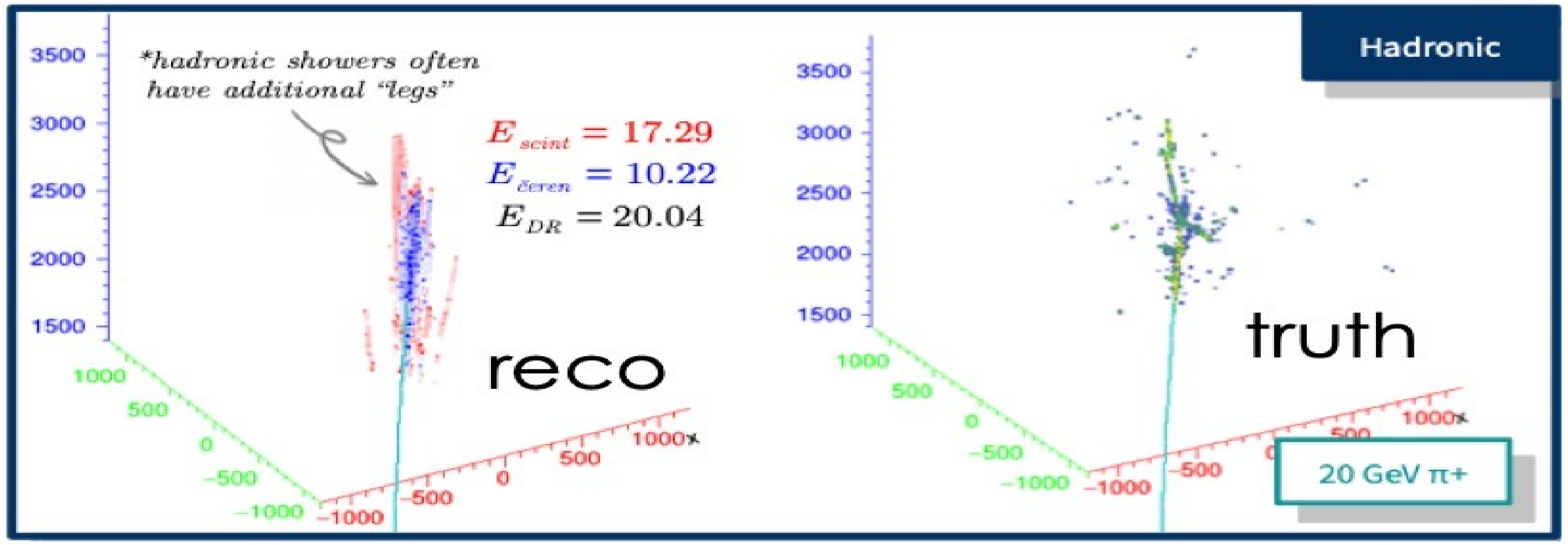
longitudinal segmentation w/ timing (Korea)

Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

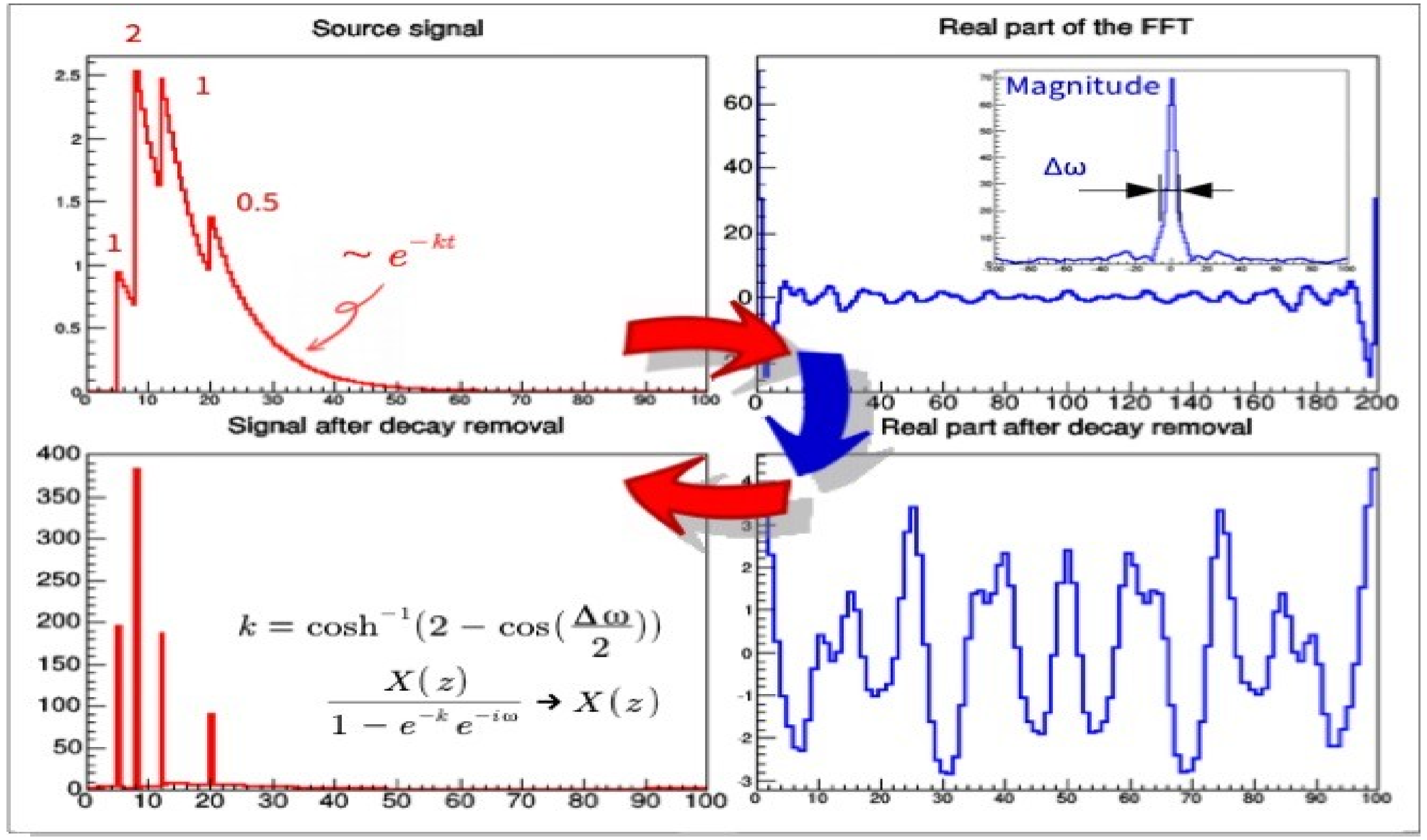
Unlocks full longitudinal information about energy deposit

Combined with DR information
allows in-shower cluster identification



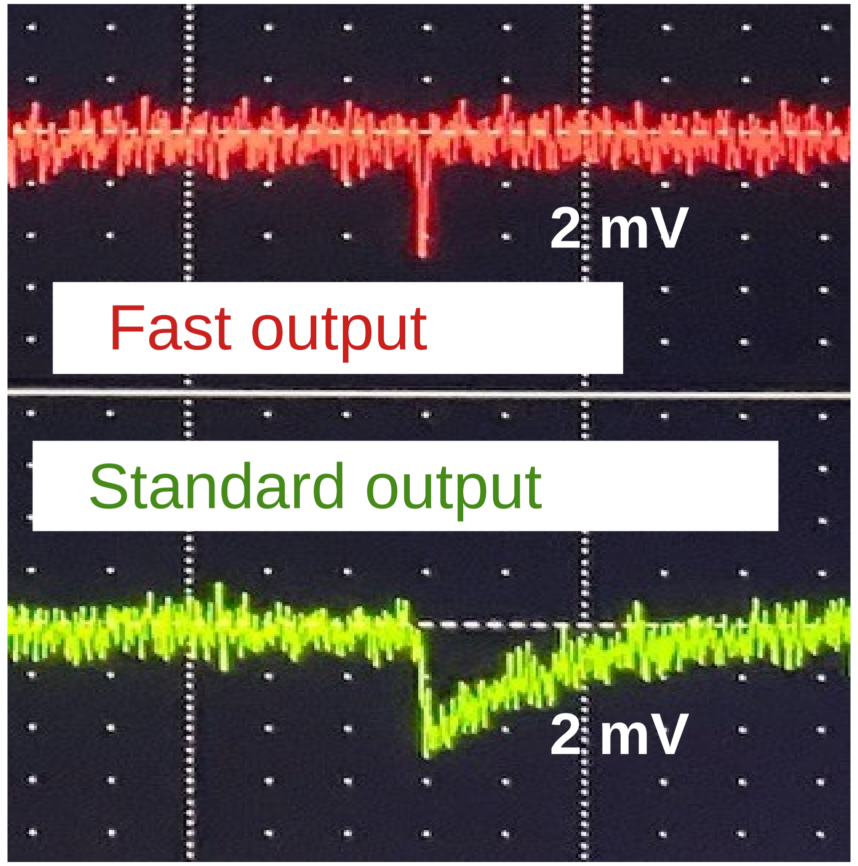
Time domain

Frequency domain

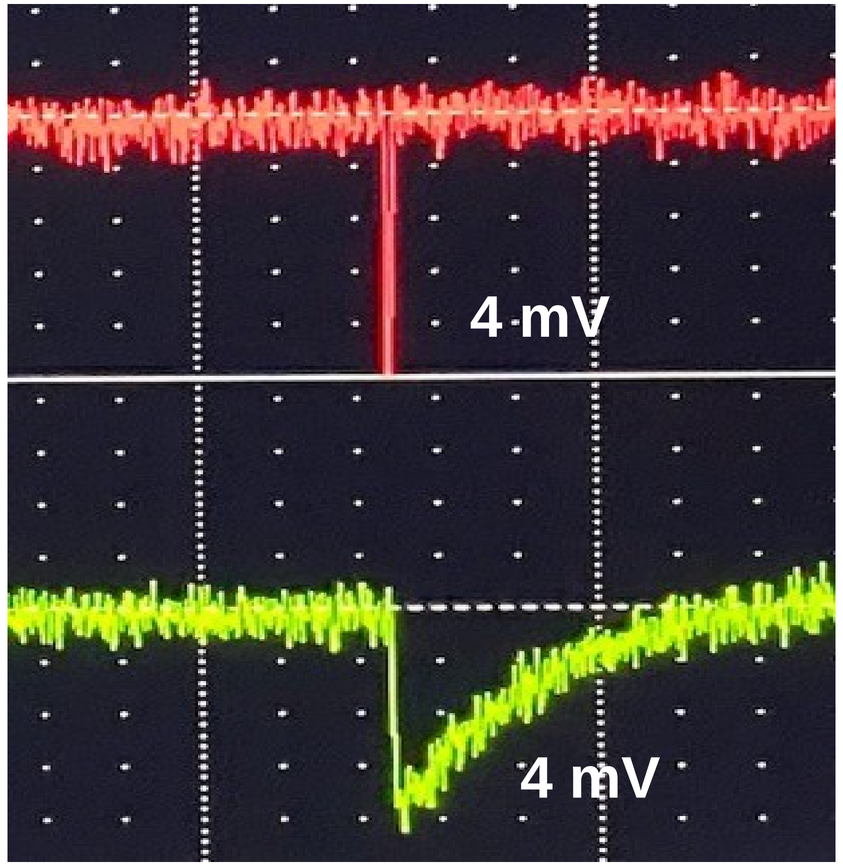


waveform digitisation (U.S.)

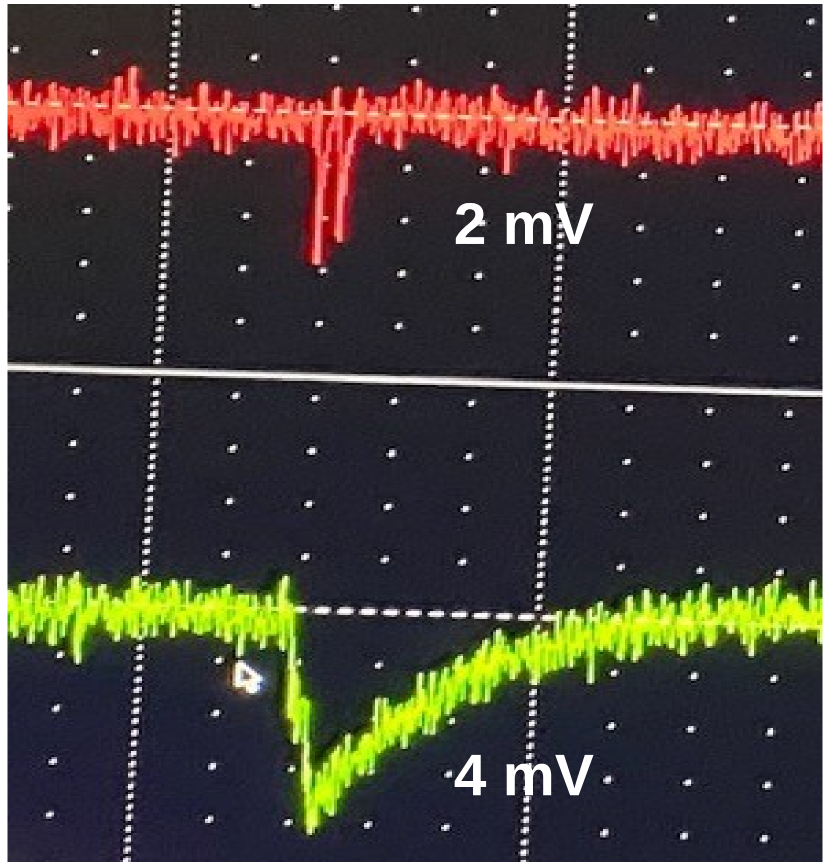
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard outputs



One-photon event



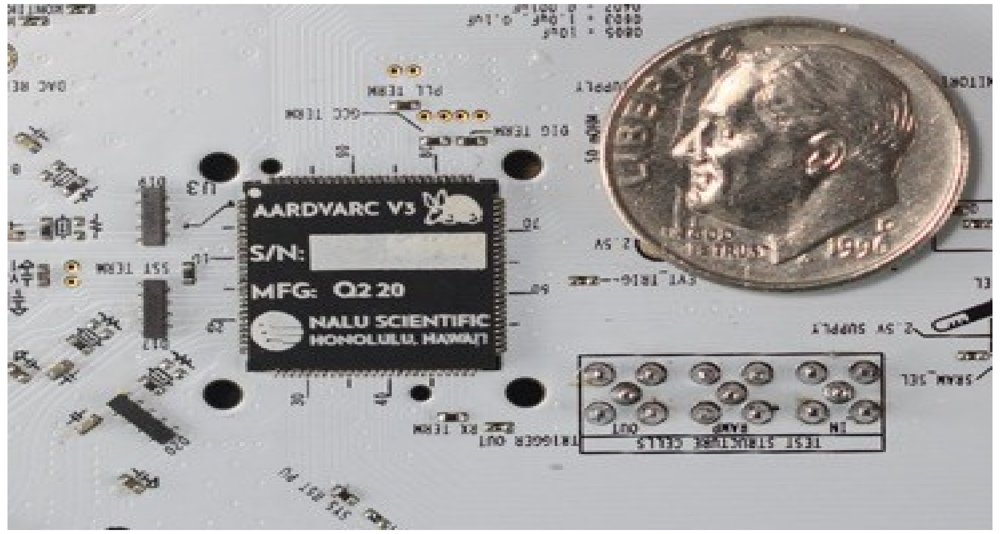
Two-photon event
(simultaneous)



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)



Conclusions

Dual-readout calorimetry excellent candidate for physics programme at EWK factories
→ growing interest for CEPC/FCC-ee detectors

IDEA fibre calorimeter: dual-readout + single-fibre light sensors (SiPM) + timing
→ highly granular 3D information
→ powerful input for deep-learning algorithms and/or PFA
→ highly performing final-state identification capabilities

Many R&D activities ongoing exploiting all directions → including different readout options (both charge-integrator and waveform sampling ASICs)

Hadronic-scale demonstrator(s) under construction

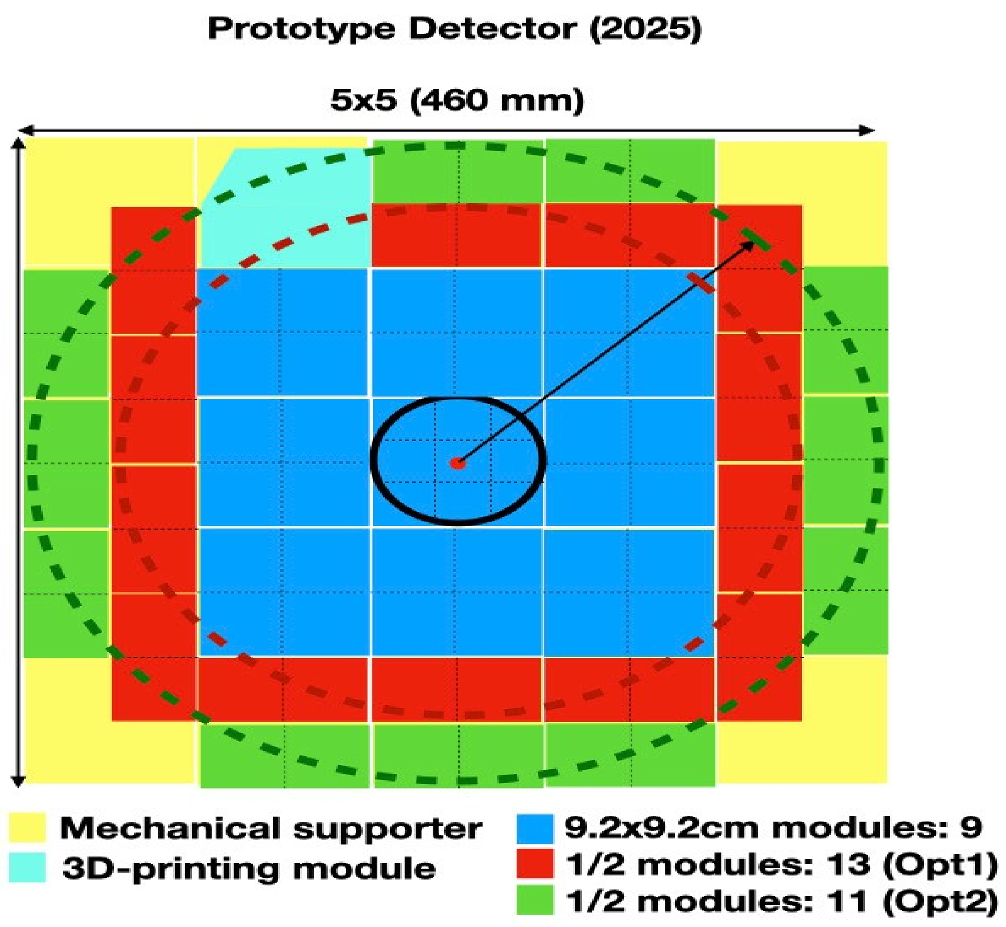
Crystal option (IDEA++) → boost em performance & do not spoil hadronic one
→ look at Marco Lucchini's talk

Backup

activities in S. Korea

Investigating:

- Absorber production and assembly procedure
- Fibre types (round, square, single/double cladding)
- Light sensors (PMTs, MCP-PMTs, SiPMs)

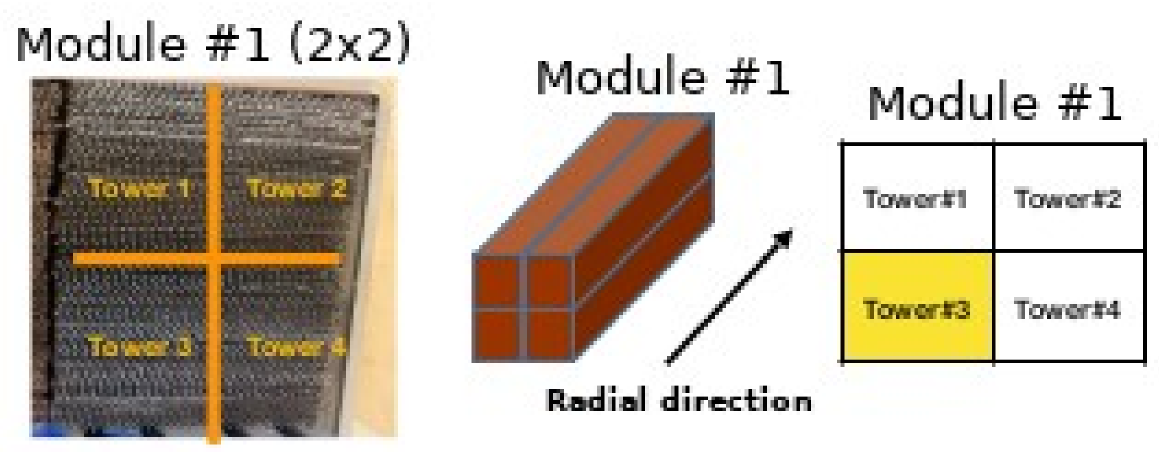


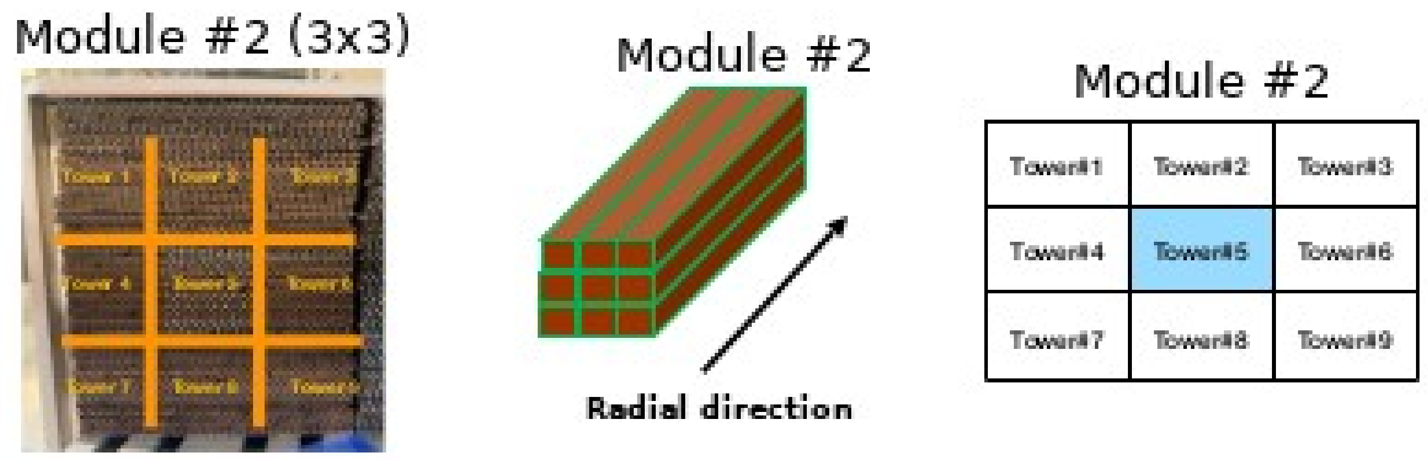
Absorber production:

- 3D printing → excellent accuracy but pretty expensive
- Stacking (LEGO-like) → good accuracy and quite cheap
- Skiving Fin Heat Sinks → high accuracy and low cost

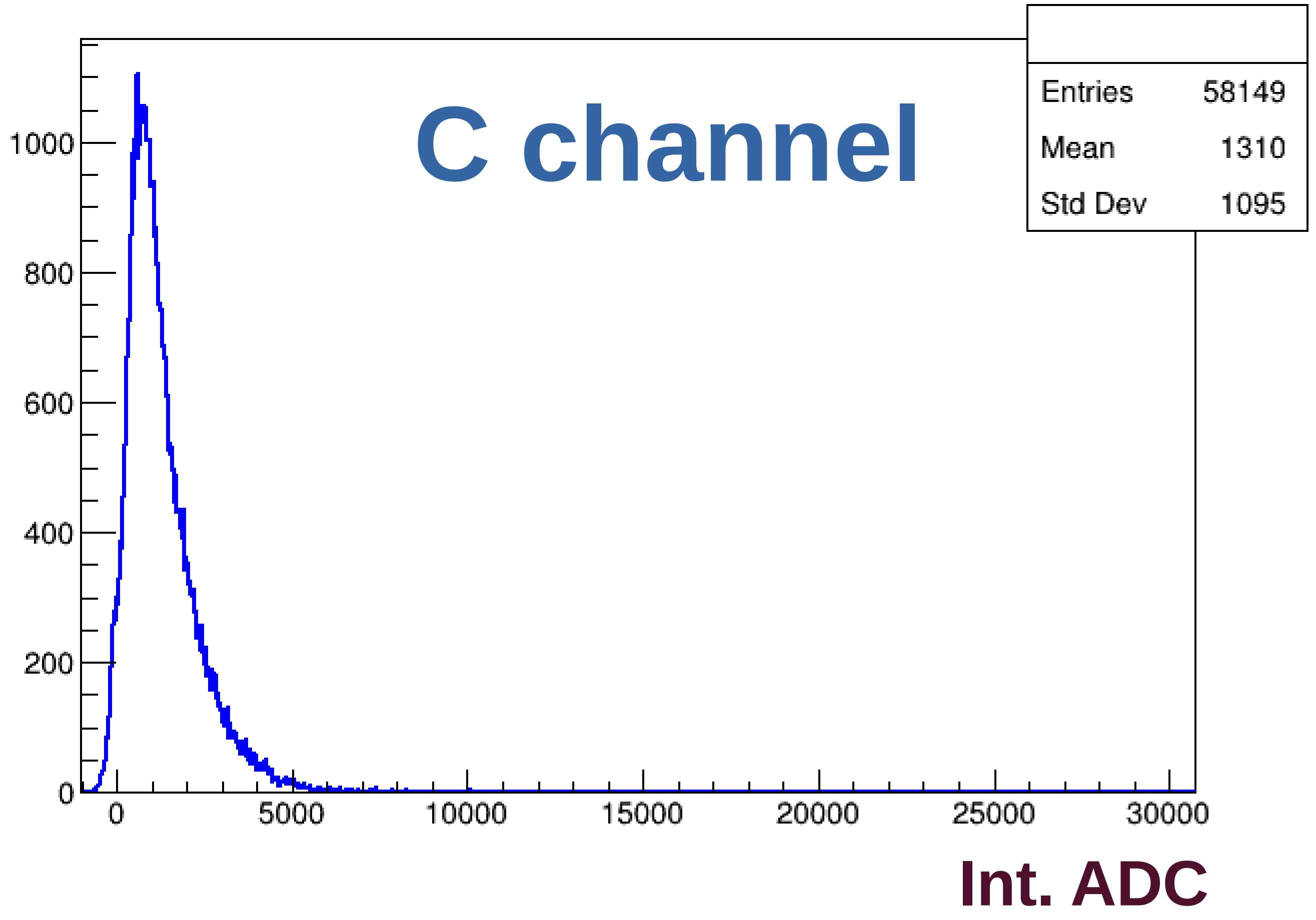
2025: full-size projective prototype

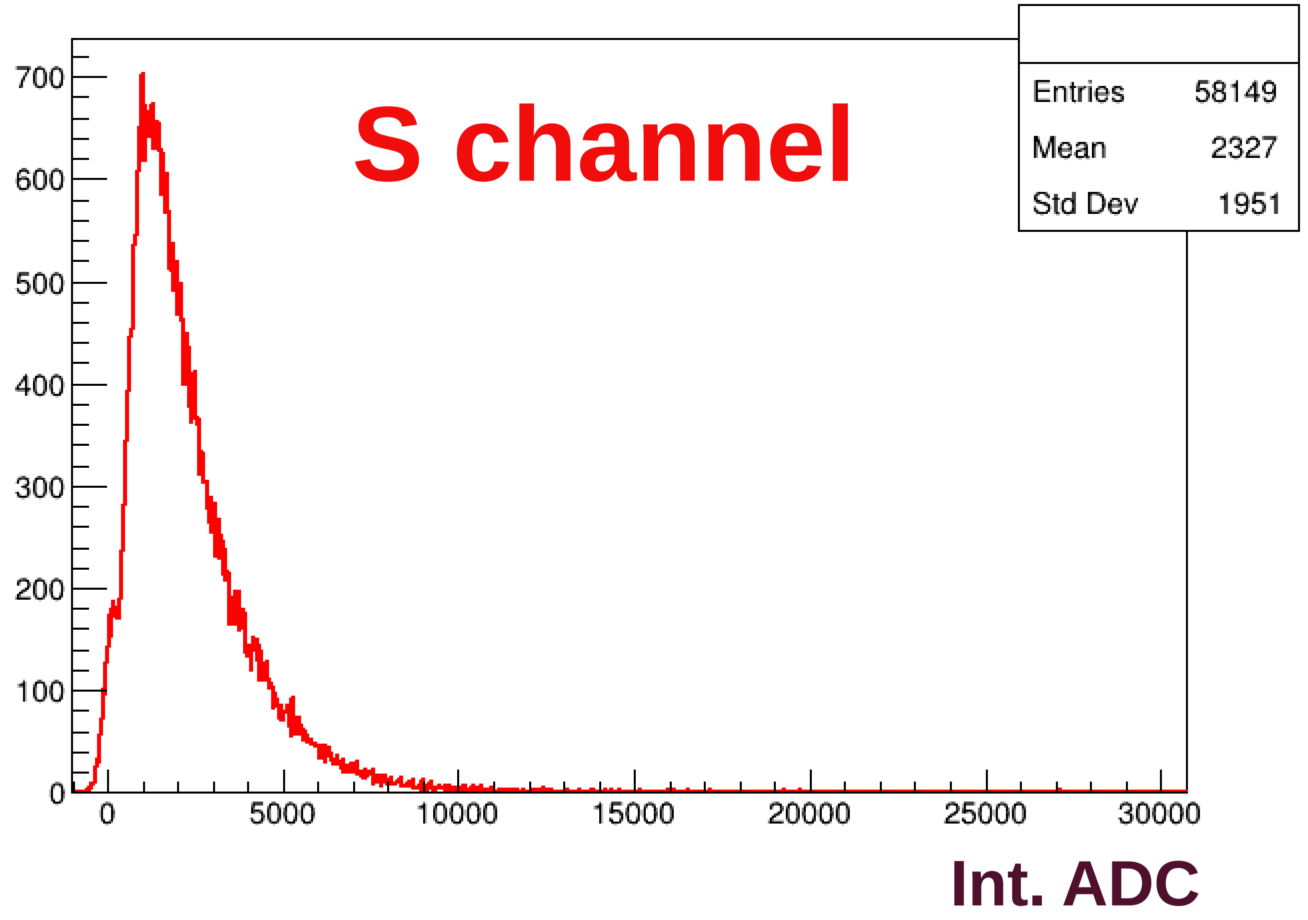
2022 Korean-prototype beam test





- Data analysis in progress





HiDRa capillary tube parameters

- Dimensions:
  - External diameter: 2 (± 0.050) mm ⟸ from SiPM dimensions
  - Internal diameter: 1.1 (-0 +0.1) mm ⟸ from fibre dimensions
  - Length: 2.5 m ⟸ from containment studies

→ 3% sampling fraction

- Material:
  - Stainless steel 304 ⟸ cheaper than brass, comparable performance