INFN
Istituto Nazionale
di Fisica Nucleare

Status of IDEA Dual-Readout Calorimetry

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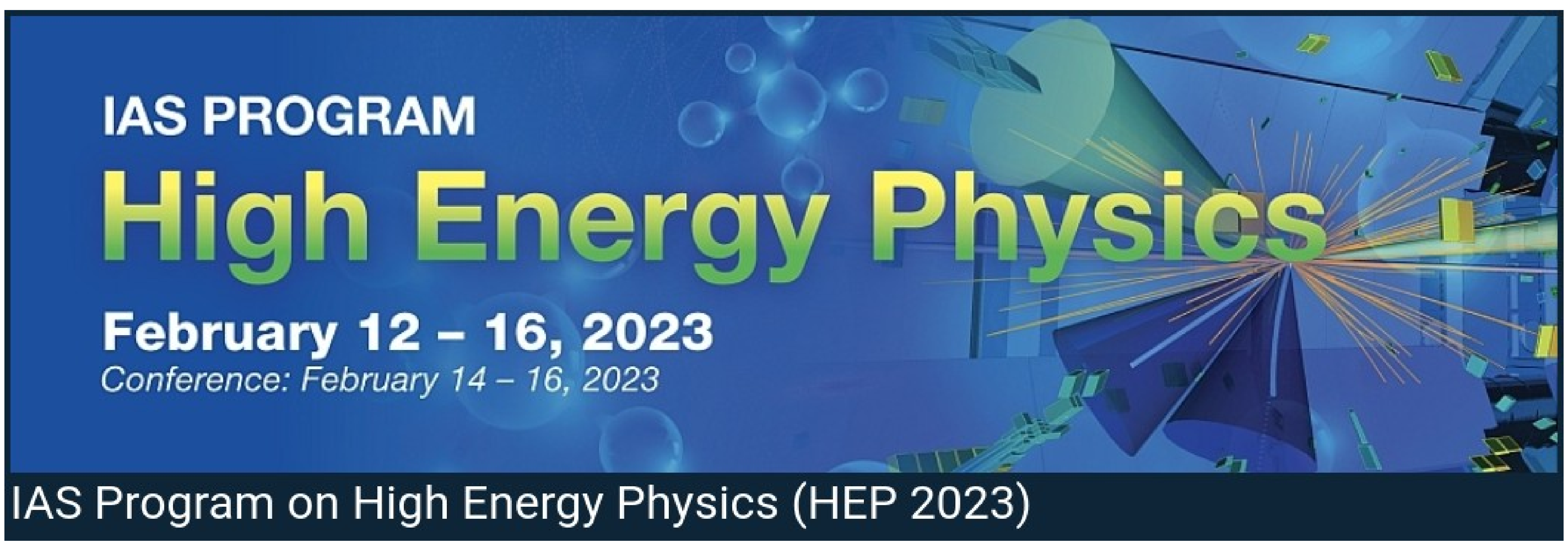
INFN Pavia
on behalf of the IDEA Calorimetry Group

Mini Workshop: Experiment and Detector
Hong Kong 12.02.2023



IDEA dual-readout calorimetry group

Three main activity pillars:

1) South Korea → projective fibre-sampling calorimeter

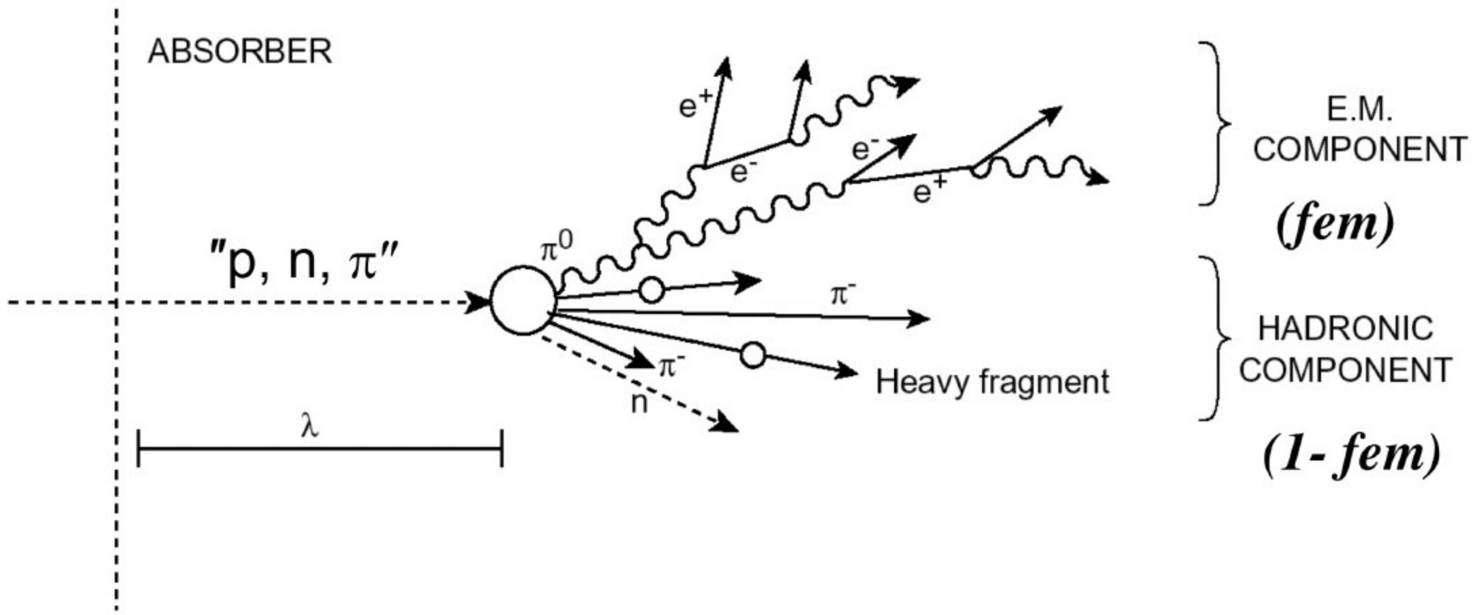
2) Europa: INFN, Sussex University → fibre-sampling calorimeter

3) U.S. (Calvision project) → mainly (but not only) on crystal em calorimeter

Highly granular dual-readout calorimetry

Recap

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



→ both scintillation & Cherenkov light

→ scintillation light only

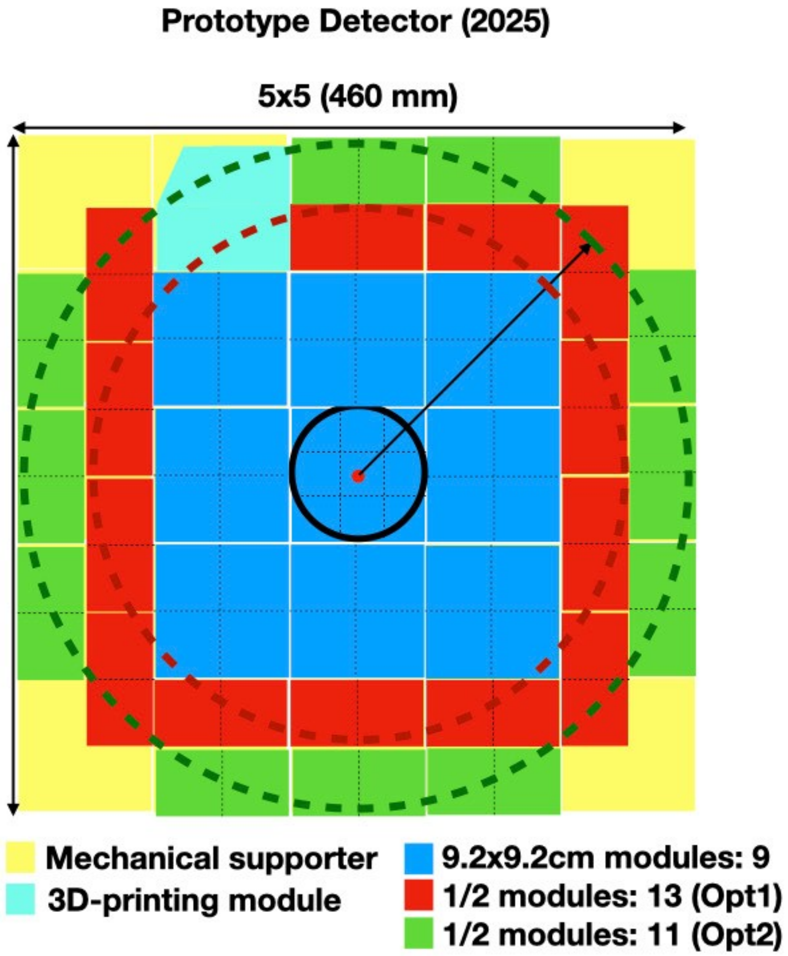
→ dramatically improve hadronic energy resolution

→ high granularity → improve PID + allow for PFA

South Korea activities

Investigating:

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



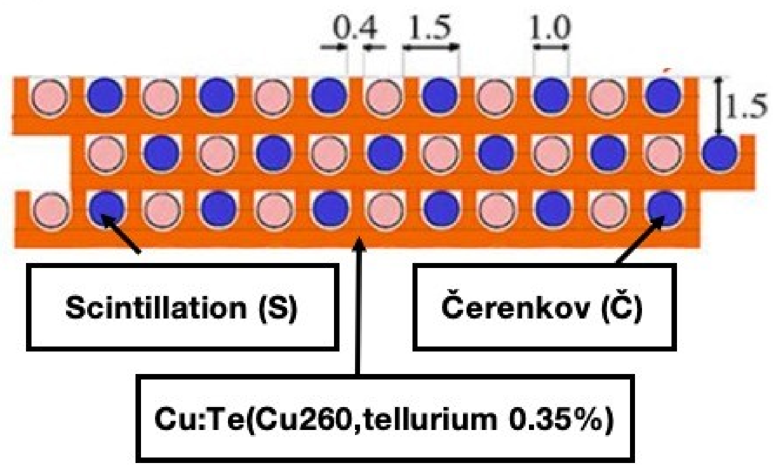
Absorber production:

- 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

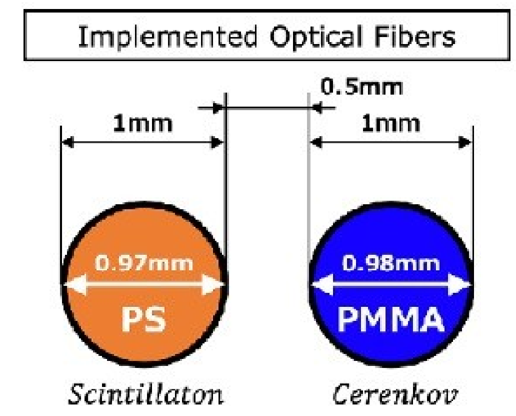
2 modules tested w/ beam in 2022

- **Copper Plate & Fibers**



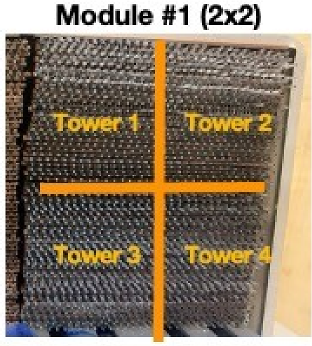
- Copper plate (60)
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

- Optical fibers
- Scintillation fibers & Cerenkov fibers
  (Kuraray SCSF-78) **(Mitsubishi SK-40)**

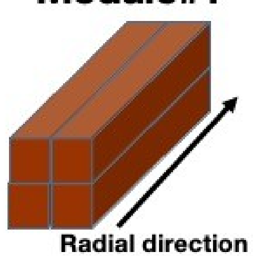


- **Configuration of Fibers & Readout detector for Test Beam**

Module #1 (2x2)



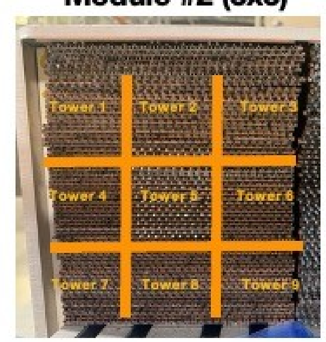
Module#1



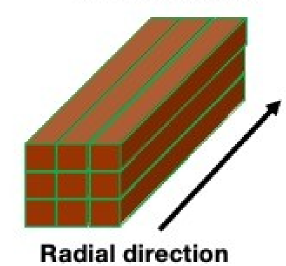
Module#1

Tower#1	Tower#2
Tower#3	Tower#4

Module #2 (3x3)



Module#2



Module#2

Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

Combination of fibers for Module#1

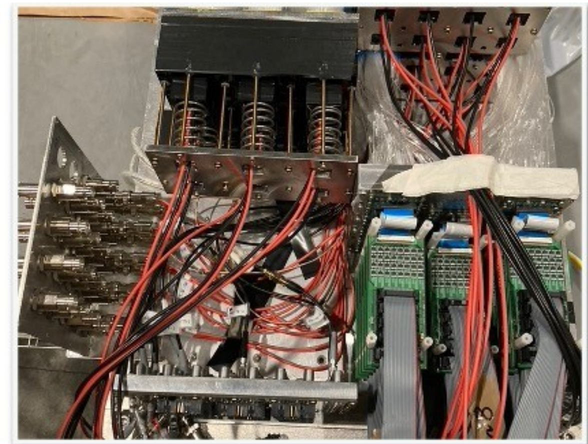
	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2 PMTs	2 MCP-PMTs	2 PMTs

Combination of fibers for Module#2

	Tower #1~4 and #6~9	Tower #5
Scintillation fibers	Round / Single cladding	Round / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding
Readout detector (400+16 ch)	16 PMTs	400 SiPMs

2 modules tested w/ beam in 2022

- Module 1
  - Read out information
    PMT (6ch) + MCP-PMT (2ch)
- Module 2
  - Read out information
    PMT (16ch) + SiPM (416ch, T.5)



MCP-PMT	Window size	light	Quantum Efficincy (Q.E.)	max. HV (V)	Rise time (ns)	Pulse width (ns)	photo
PLANACON XP85012	53x53 mm^2	scintillation	~7% at 550 nm	2400	0.6	1.8	
PLANACON XP85112		Cerenkov	~21% at 400 nm	2800	0.5	0.7	

PMT	Window size	Q.E. for Ck.	Q.E. for Sc.	max. HV (V)	Time response (ns)			photo
					anode pulse rise time	electron transit time	Transit time spread (FWHM)	
R8900 series (old)	23.5x23.5 mm^2	35% at 420 nm	~7% at 550 nm	1000	2.2	11.9	0.75	
R11265-100 (new)	**23x23 mm^2**	**~35% at 400 nm**	**~7% at 550 nm**		**1.3**	**5.8**	**0.27**	

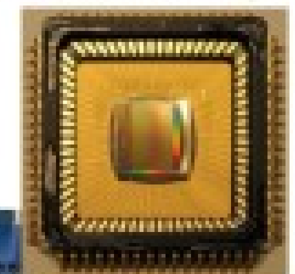
SiPM	photosensitive area	photo detection efficiency (PDE)		operating voltage	Gain at V_{BD}+5V	Linearity of Q.E.	number of pixels	geo. Fill factor
S14160-1310PS	1.3x1.3 (1.69 mm^2)	~15% at 400 nm	~17% at 550 nm	$V_{breaking\ Down}$ + 5 V	~1.75x10^5	~2x10^{10}/sec as incident photons	16675	31 % (0.524 mm^2)
fiber (Φ1 mm)	0.785 mm^2						~7745 (effectively)	

DAQ system

- System made of 15 DAQ Boards + 1 TCB Board

- DAQ Board:
  - One board covers 32 channels
  - DRS4 chip (from 0.7 Gsps to 5 Gsps with 1024 sampling points)
  - 16 pin Ribbon cable

DRS4 chip

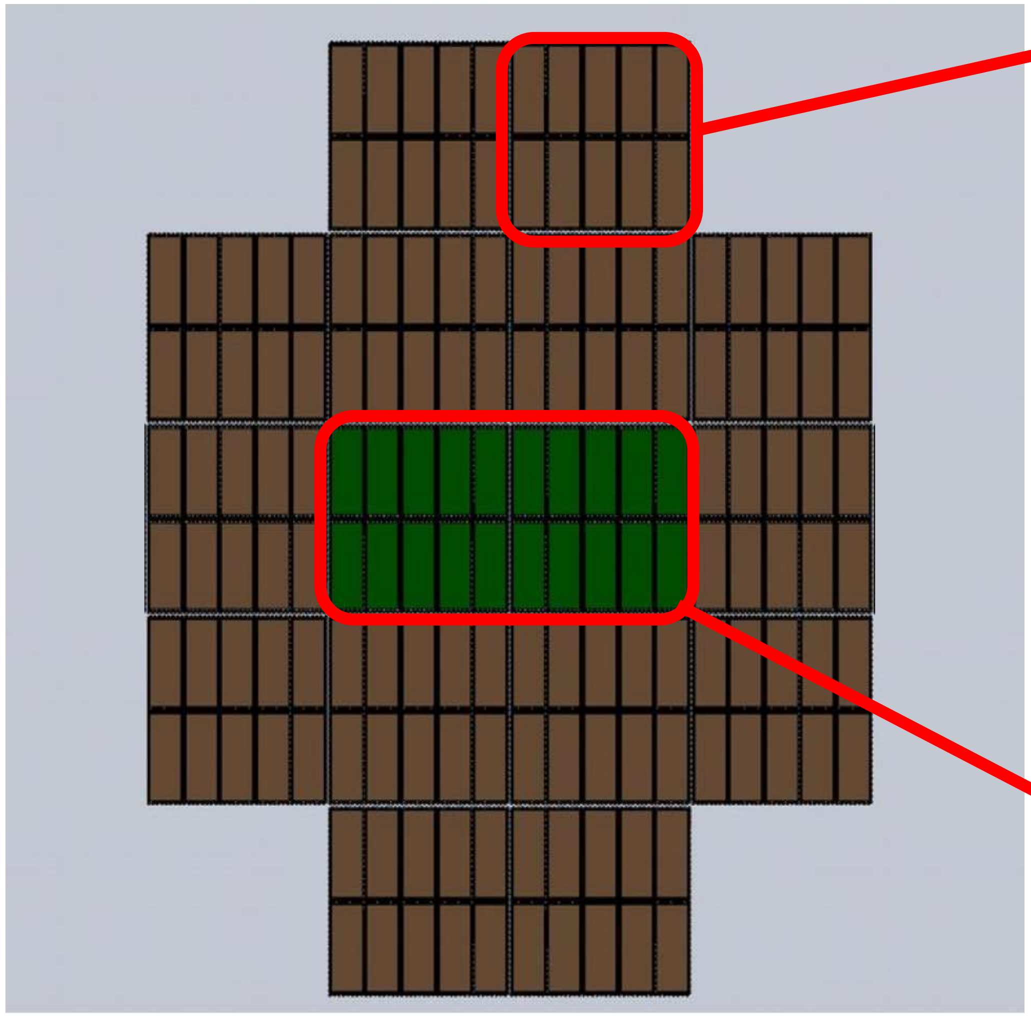


- TCB Board
  - Control the setting value of DAQ boards and the trigger system
  - Connect DAQ boards with TCP/IP cable, cover 40 ch DAQ

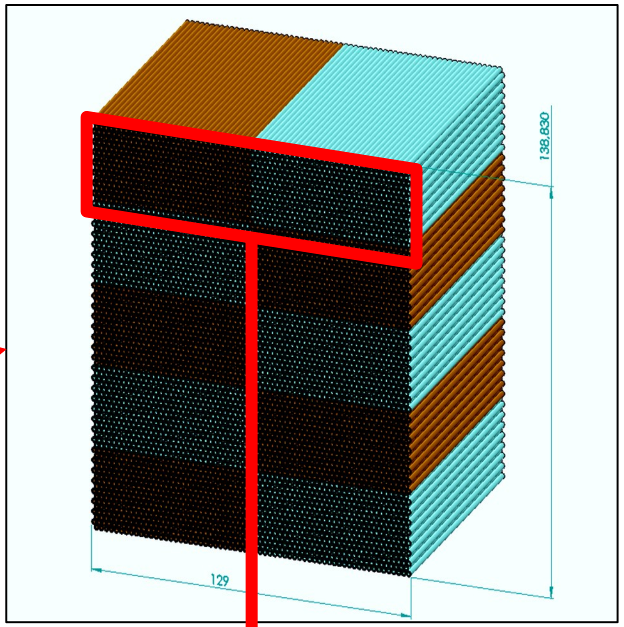
- All boards connected with PC using USB3 line

Dual-readout R&D in Europe (HiDRa)

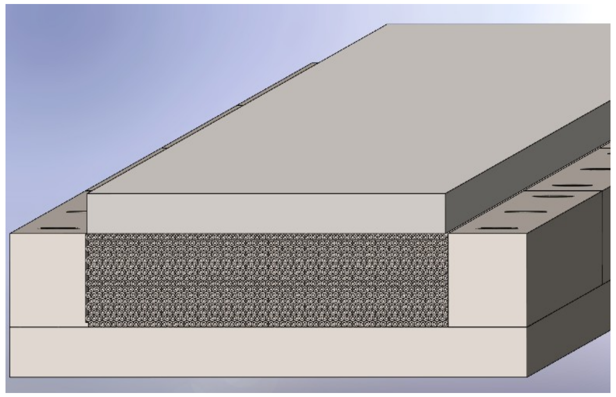
Hadronic-size prototype:
16 modules w/ highly granular core



HiDRa



1 Module:
5 MMs
~ 13 × 13 cm^2



1 MiniModule:

64 × 16 =
1024 fibres in total

512 S + 512 C

highly granular core:
1024 fibres to be readout with SiPMs

Capillary tube mechanical 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

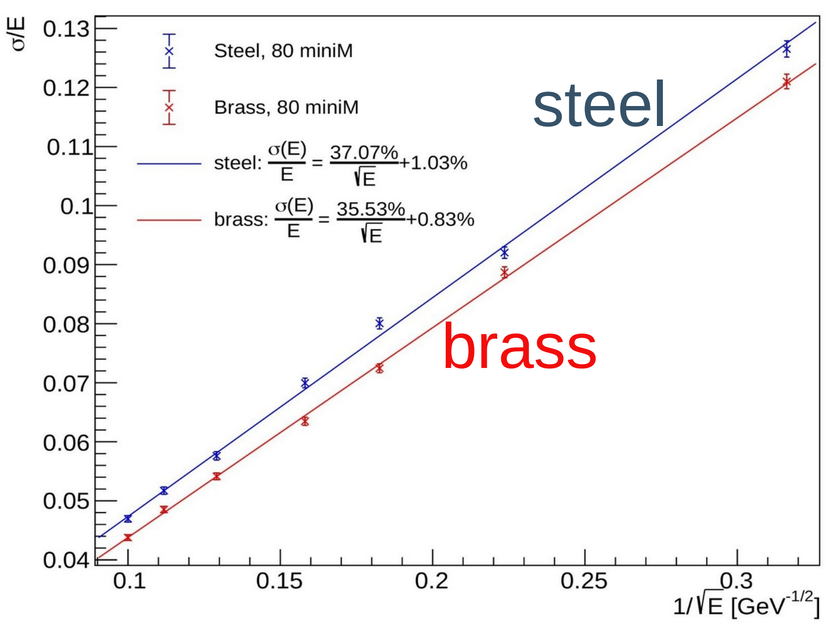
→ 3% sampling fraction

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

G4 simulation

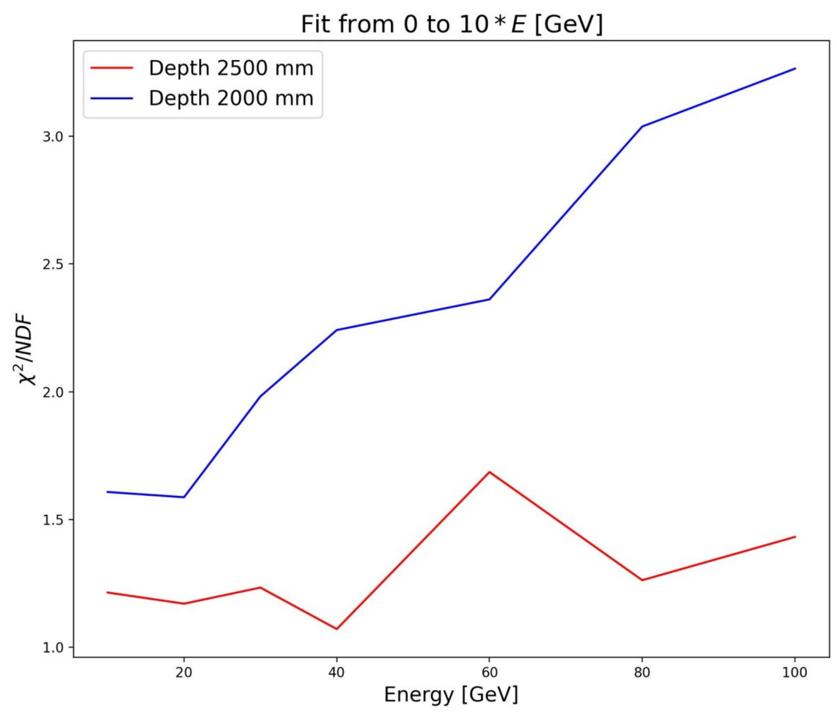
Absorber choice

Pion resolution in [10, 100] GeV Range

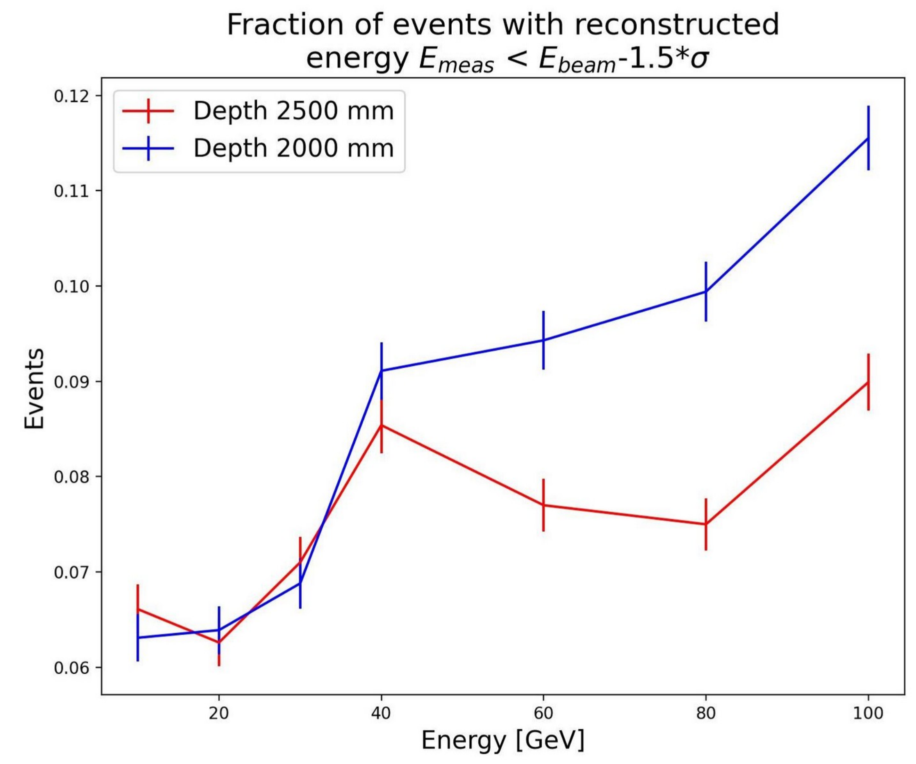


Calorimeter depth

χ2 / ndof



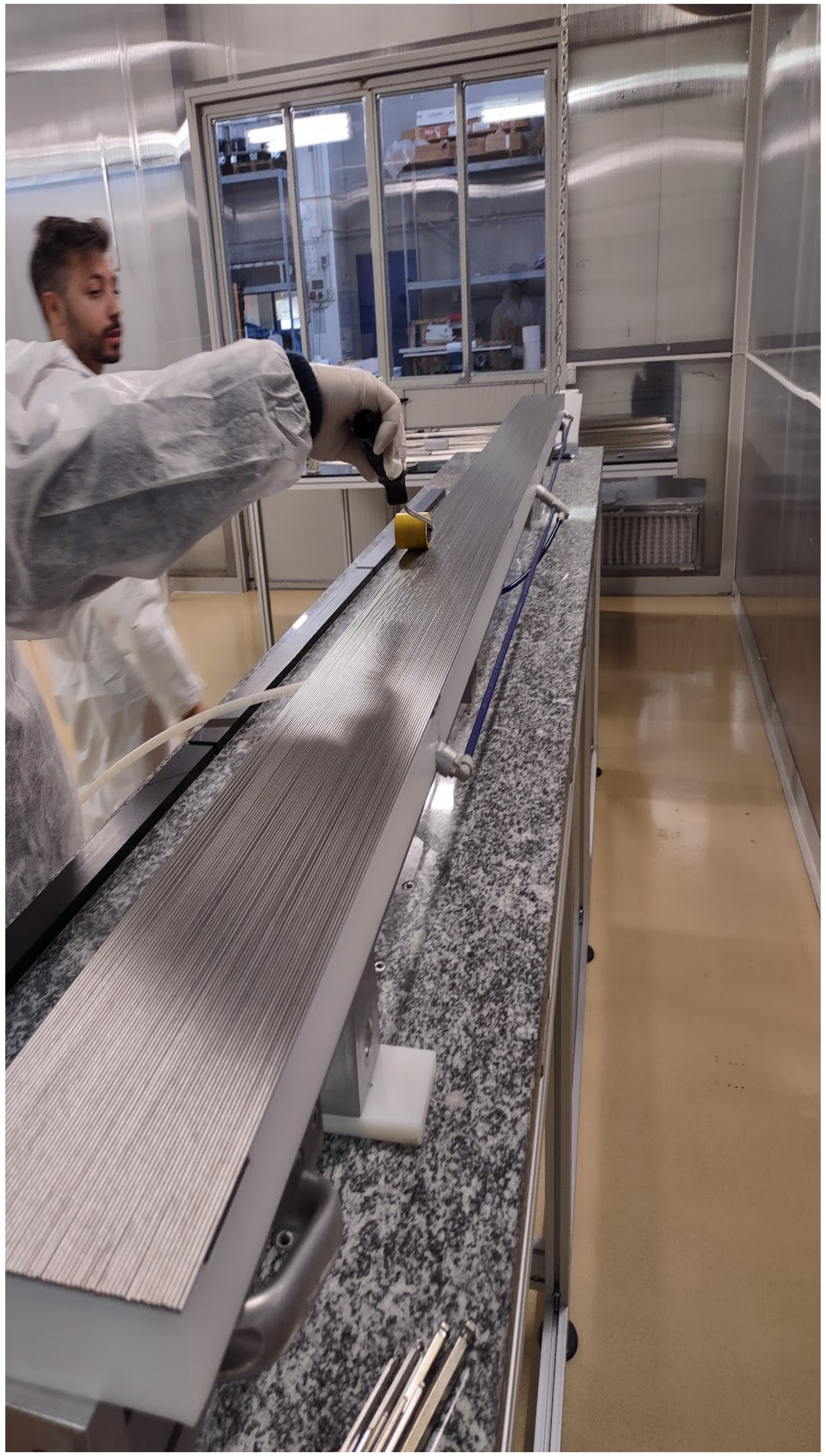
Low-energy tails

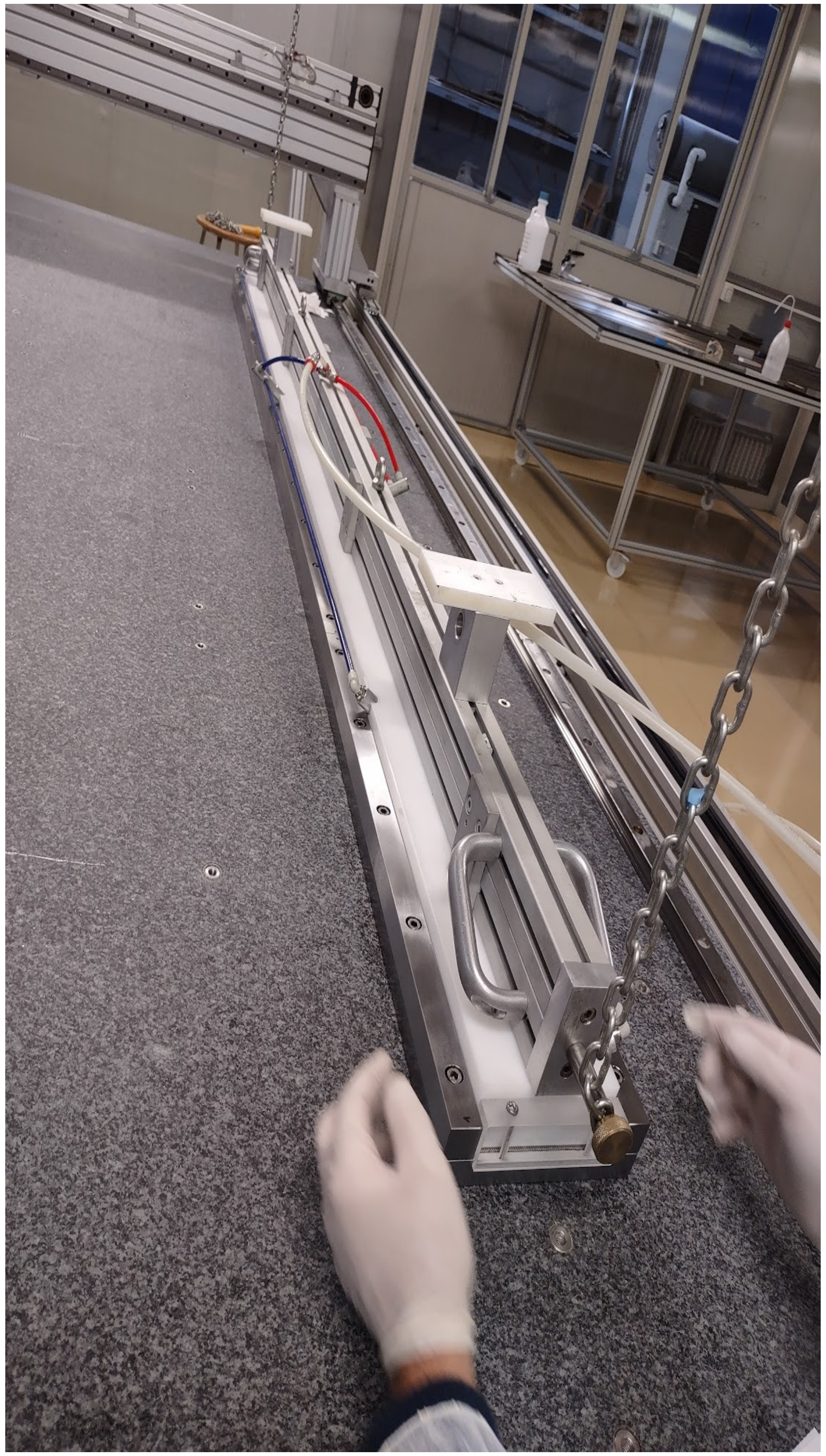


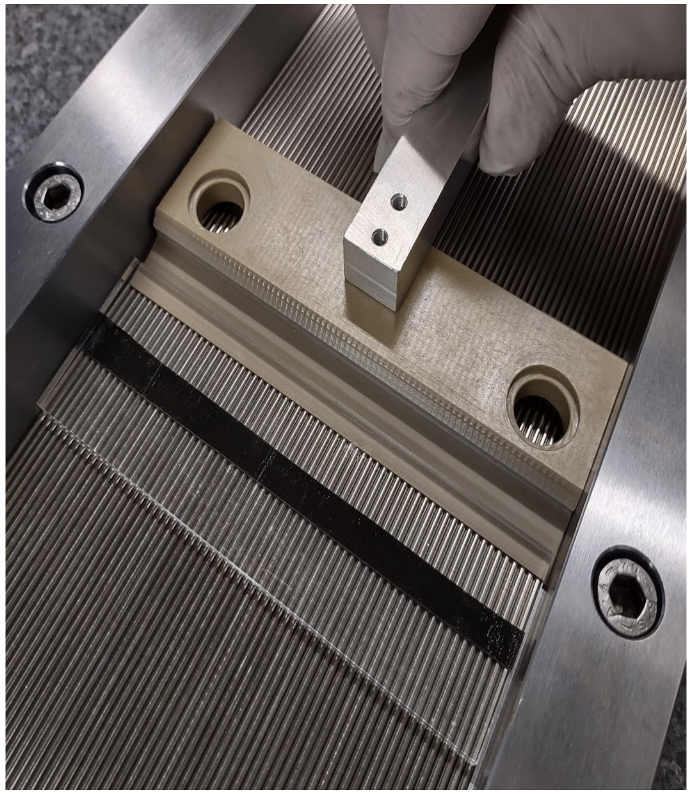
Capillary QA/QC

- Straightness: rolling on plane surface
- Length: checking relative length of tubes
- ID: pass/fail test with inserting fibres

Tube gluing







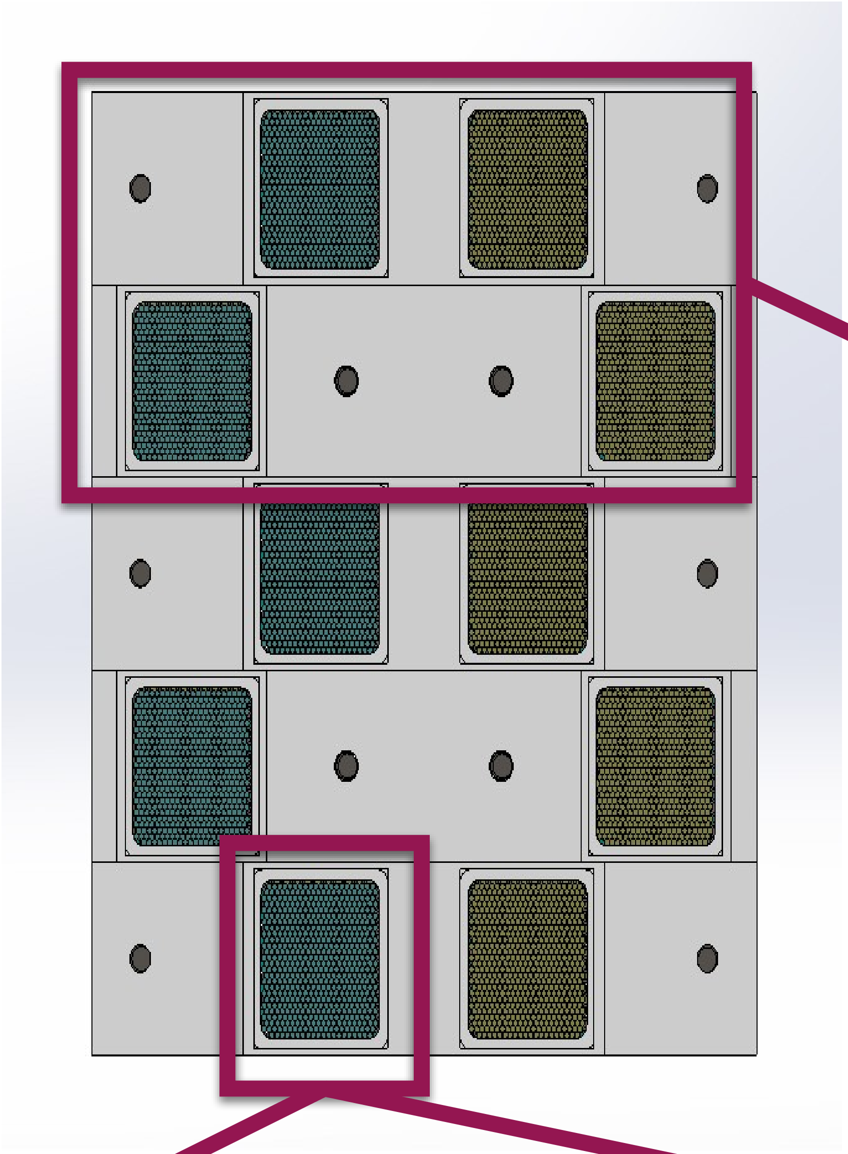
Stiffback-like technique for tube handling, gluing and positioning

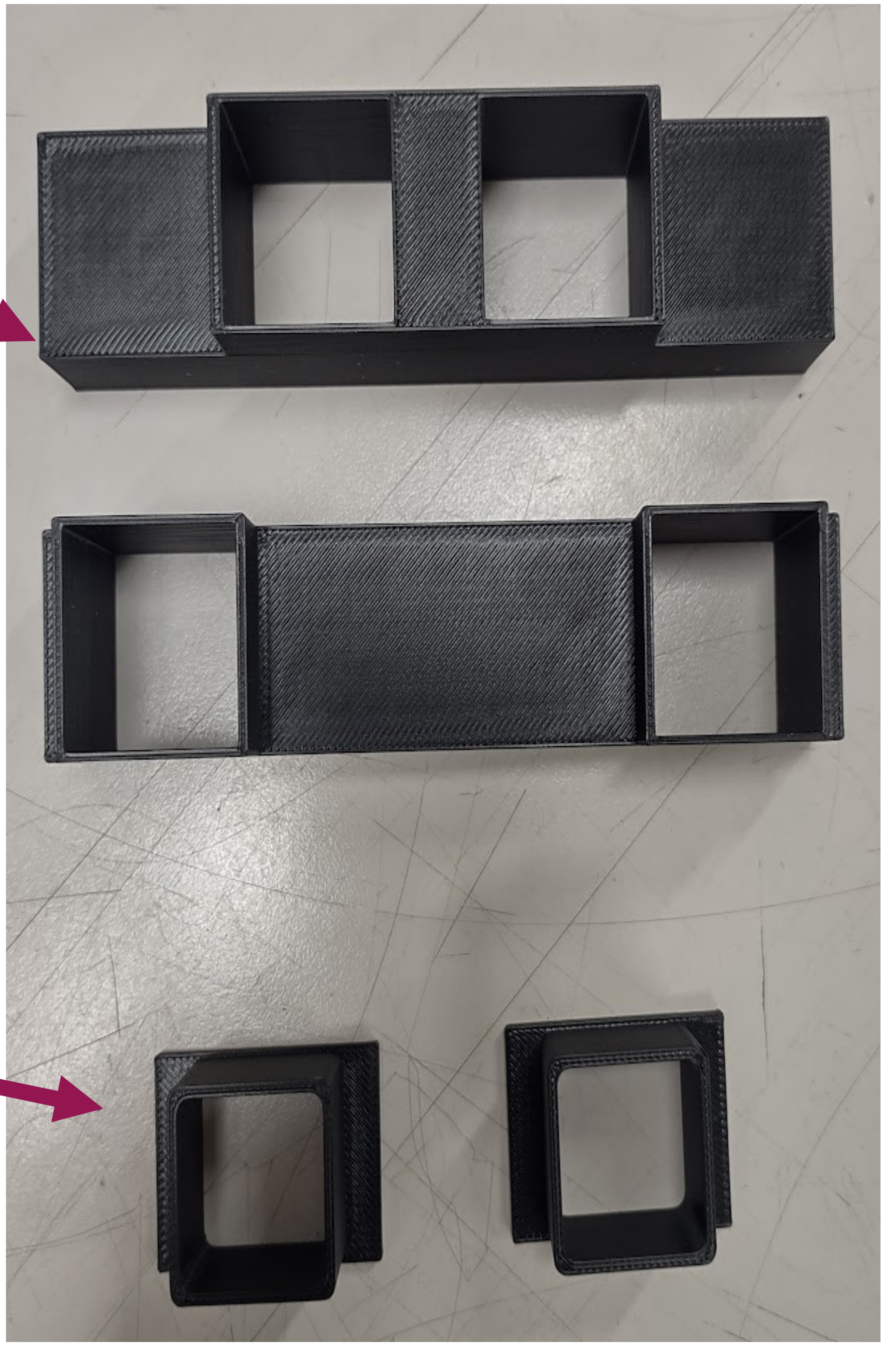
First gluing test

- Issue with tube cleaning (alcool)
- Some tubes unglued
- New cleaning procedure (with NGL + alcool) under test

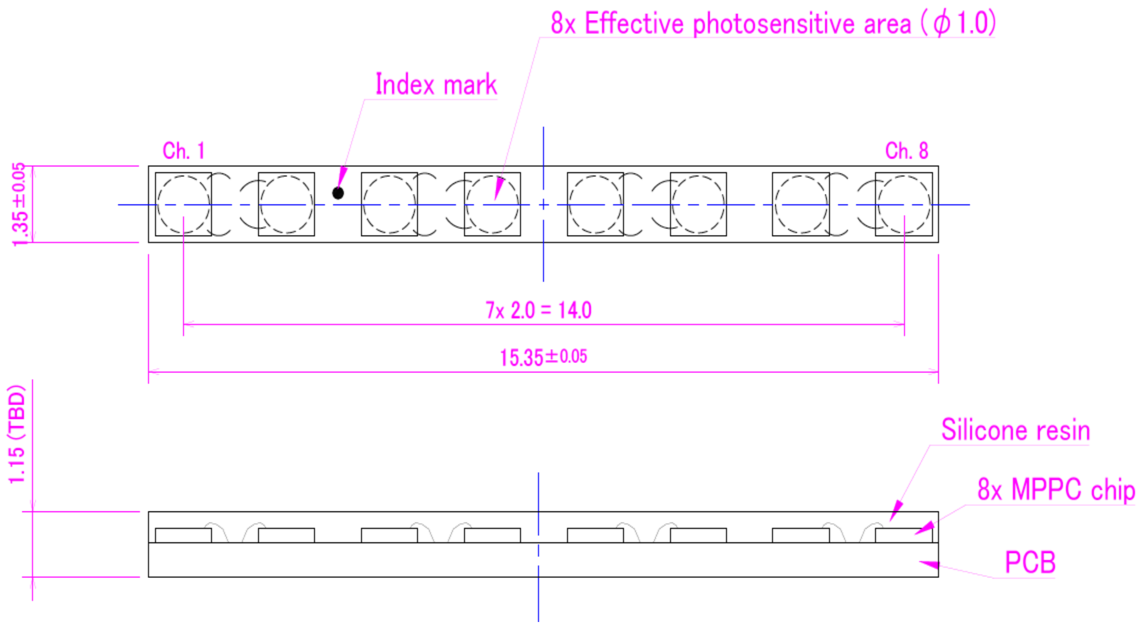
PMT readout: fibre grouping

3D-printed fibre and PMT holders

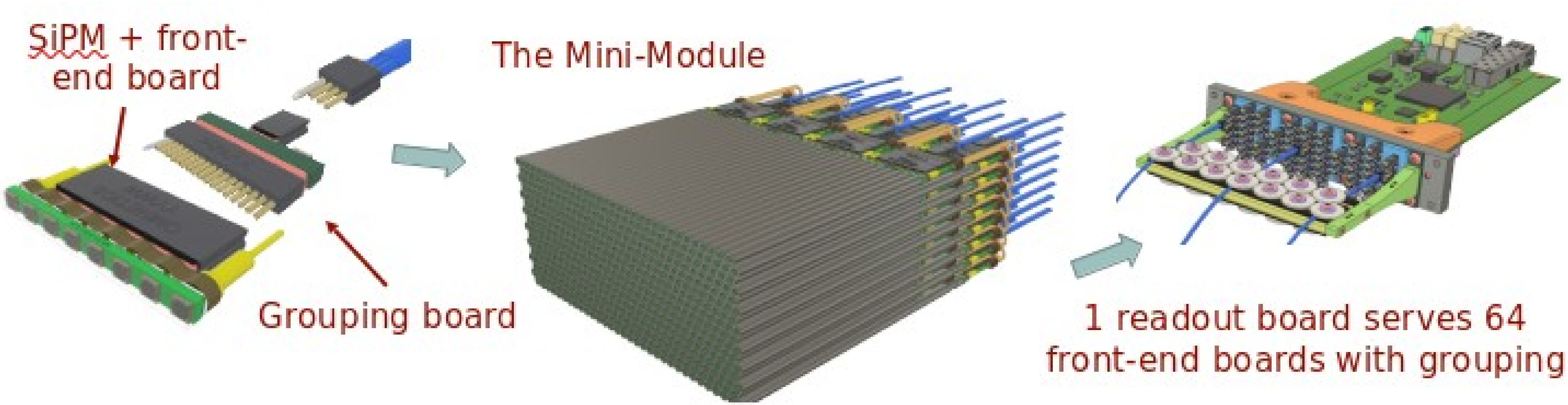




SiPM integration and readout



- Custom designed module with 8 SiPMs (1x1 mm^2) from Hamamatsu
- 2 mm SiPM interspace
- Two options under study: 10 and 15 μm pitch

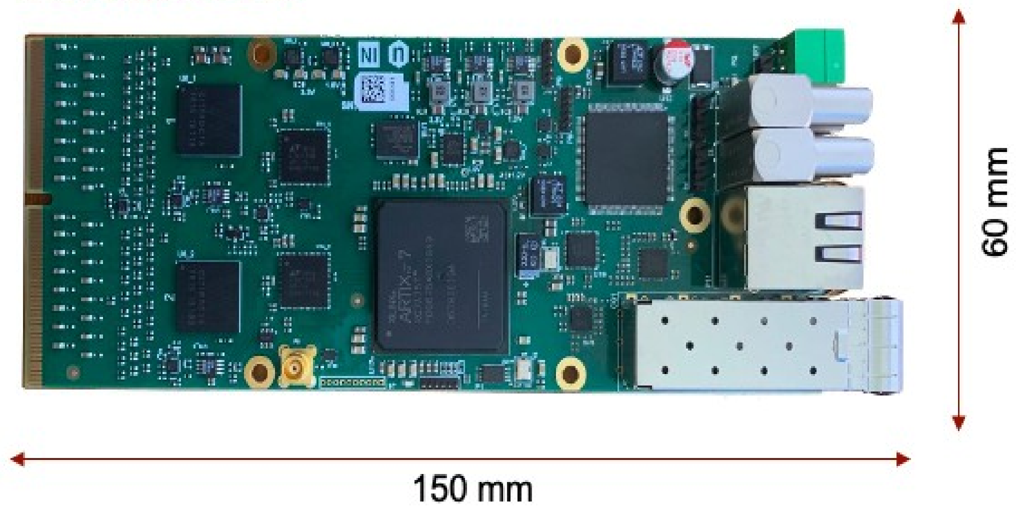


- Each SiPM bar operated at same voltage (V_{bd}<0.15V)
- Signals from 8 SiPMs summed up in grouping board

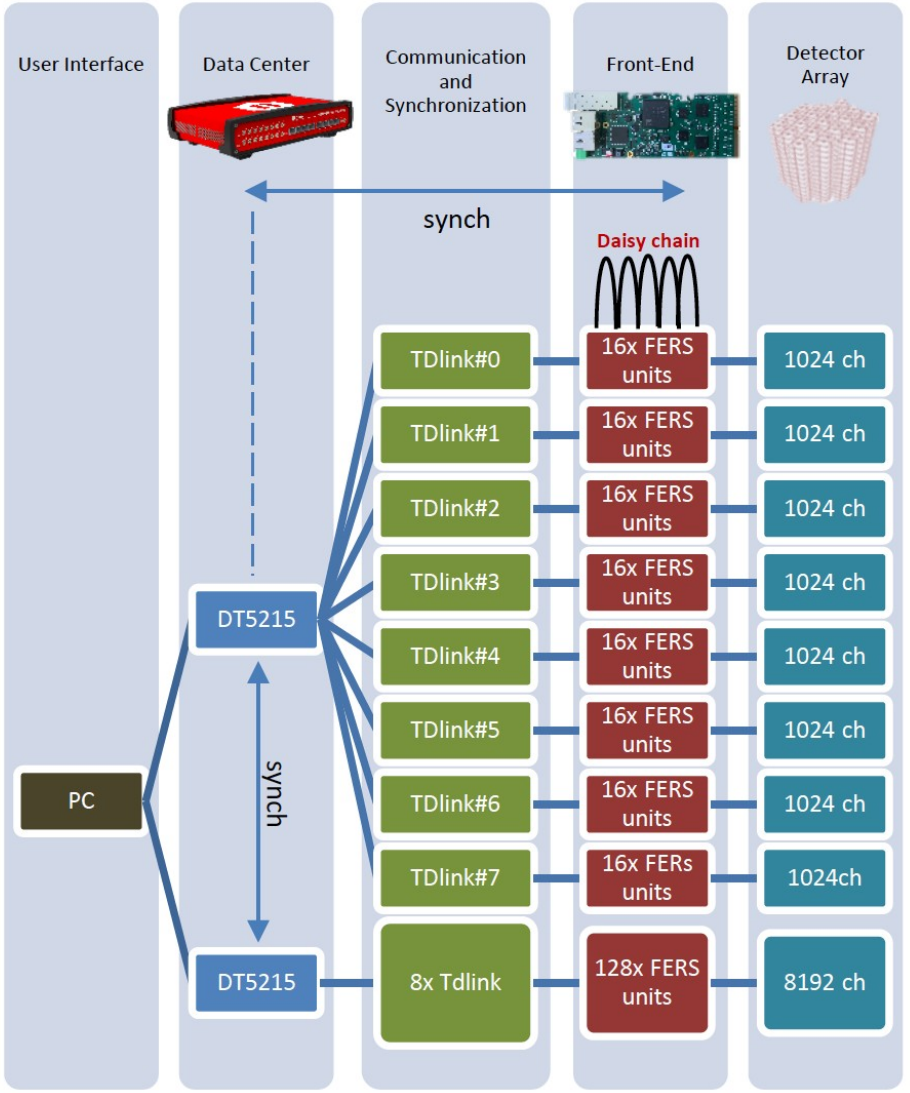
SiPM integration and readout

Readout based on Caen FERS system (5200) and A5202 boards

FERS: A5202



- 64 channels on two Citiroc1A
- Signal preamplification, shaping and integration
- HV power supply with temperature compensation
- Two 12-bit ADCs for charge measurement
- 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 high-resolution TDCs (LSB = 50 ps)
- Optical readout interface (6.25 Gbit/s)



Data concentrator delivered in September

FERS readout integration in EUDAQ

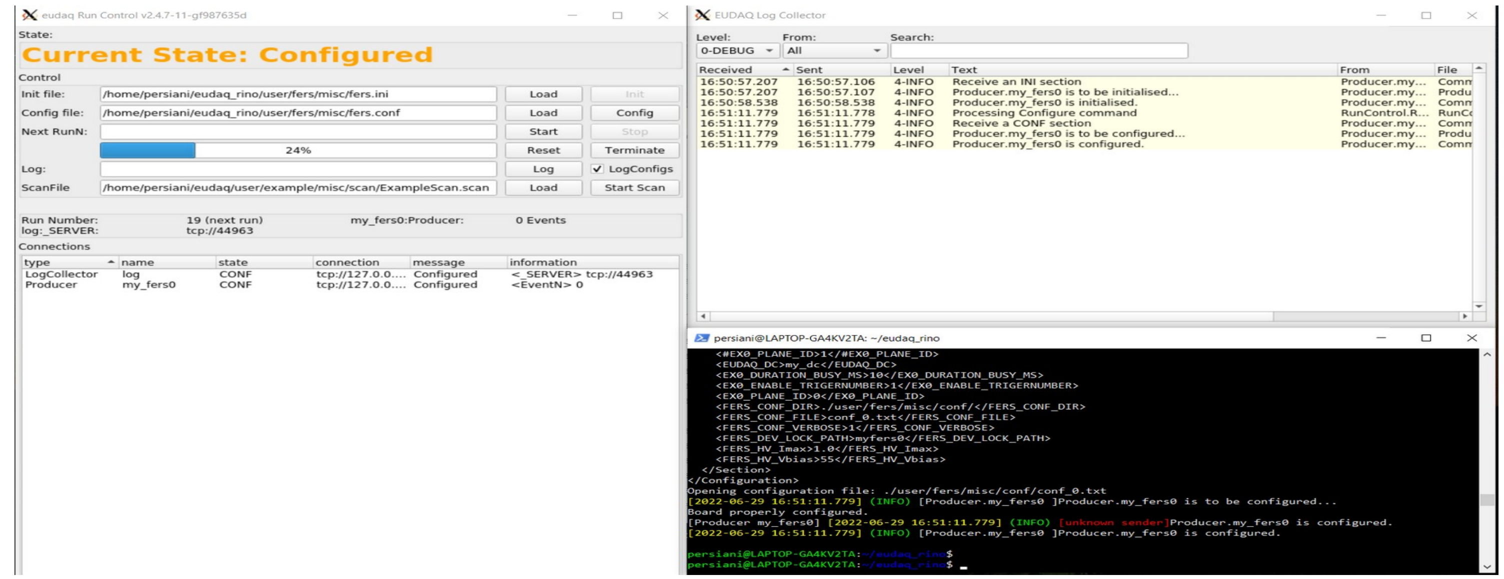
- Modular data acquisition framework, in C++
- Open source, compatible with different OSs
- Finite-State Machine implemented
- HW-specific parts decoupled from core software
- Raw data can be converted to LCIO format
- Many detector prototypes at DESY II Test Beam Facility integrated in EUDAQ
- EUDAQ used in several test setup at CERN: ALICE, ATLAS, Belle II, CALICE, CMS, and others

EUDAQ - A data acquisition software framework for common beam telescopes
P. Ahlburg et al 2020 JINST 15 P01038

FERS readout integration in EUDAQ

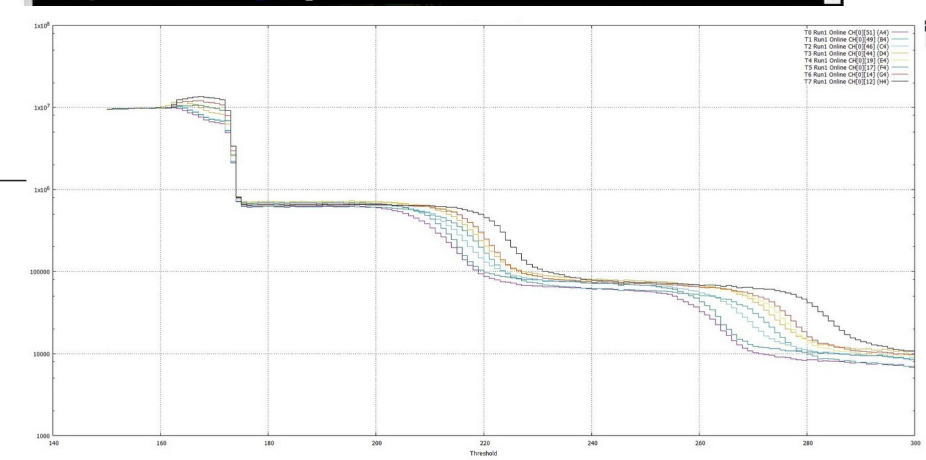
ALREADY DONE

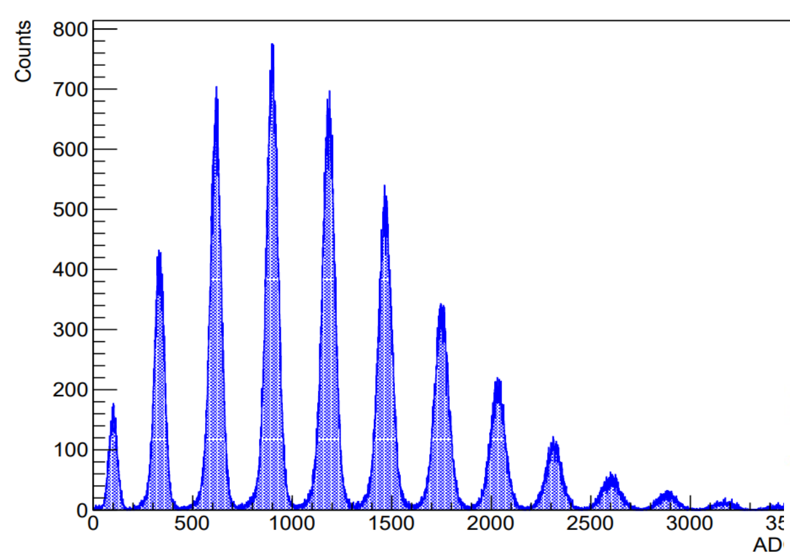
- CAEN FERS library integrated in EUDAQ
- FERS configuration implemented

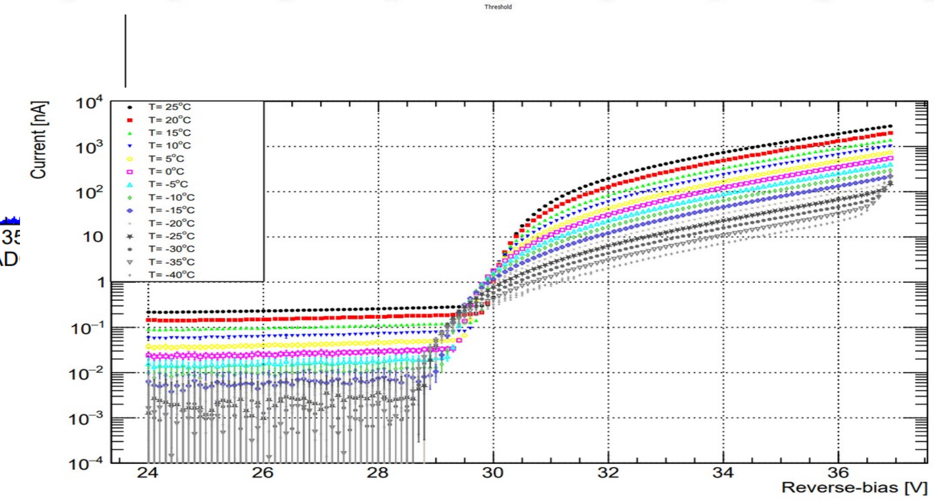


TO DO

- Development in EUDAQ of DCR and multiphoton spectrum measurements for SiPM mass characterisation
- Handling (storing and then uploading) of FERS & SiPM configurations with DB
- Setting up EUDAQ for test beam using FERS modules







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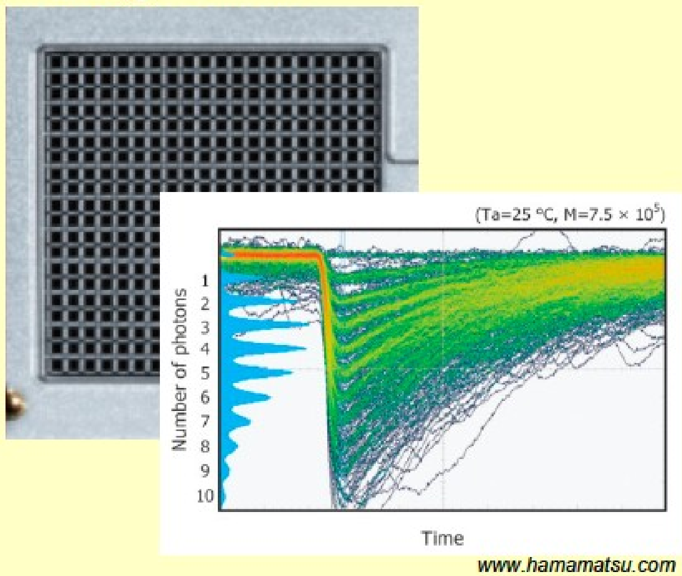
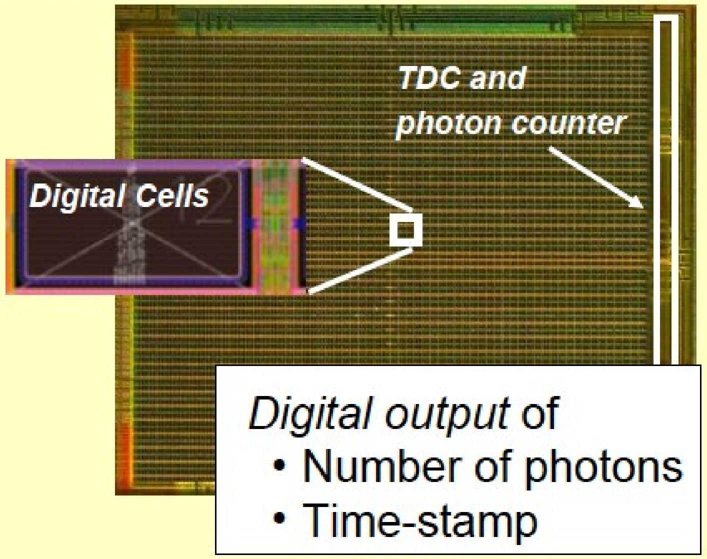
Alternatives to SiPMs?

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

Requirements

	Scintillating (Cherenkov)
Unit Area (mm^2)	1 x 1
Micro-cell pitch (µm)	10 or 15
Macro-pixel	500 x 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 the time window (< 100 ps) possibly TOT
Final - Package	Strip with 8 units
Connection	BGA

Testbeam data analysis

Two data taking periods in 2021 with the electromagnetic prototype (~10×10×100 cm^3 with highly granular core):

@ DESY (1-6 GeV electron beams) in June

@ SPS-H8 (10-100 GeV beams) in August

Unfortunately, serious issues in **both cases** with data reconstruction/analysis

Testbeam data analysis

@ DESY:

missing impact point information
→ still missing beam telescope (BT) data reconstruction
→ still missing BT (EUDAQ) data alignment with calorimeter data for merging

@ H8:

very bad beam purity at E > 40 GeV
preshower too far from calorimeter
too small beam angle → high dependence of signal on impact point

Testbeam data analysis

@ DESY:

missing impact point information
→ still missing beam telescope (BT) data reconstruction
→ still missing BT (EUDAQ) data alignment with calorimeter data for merging

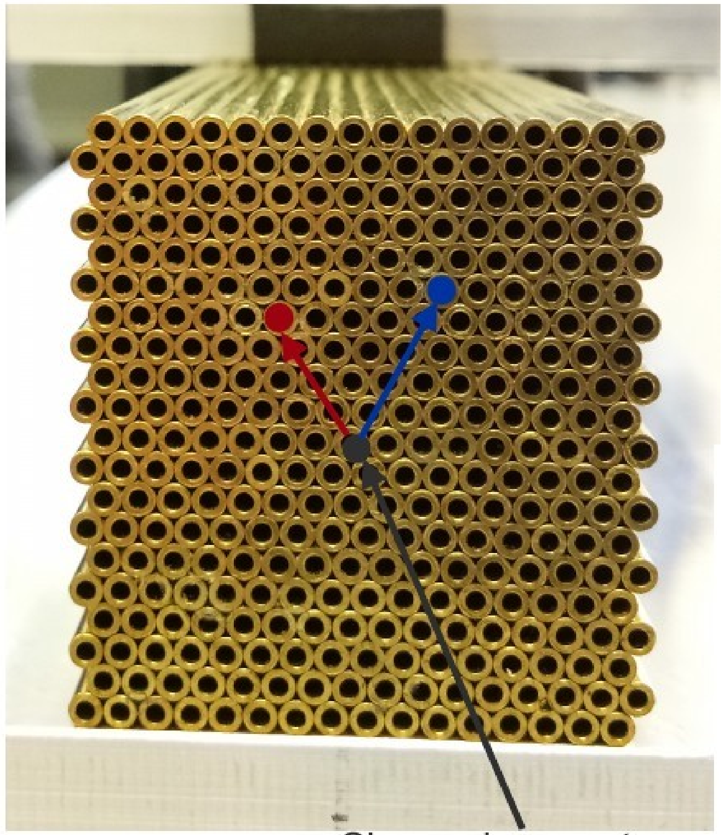
@ H8:

very bad beam purity over 40 GeV
preshower too far from calorimeter
too small beam angle → high dependence of signal on impact point

Ok, it looks we got it all wrong!

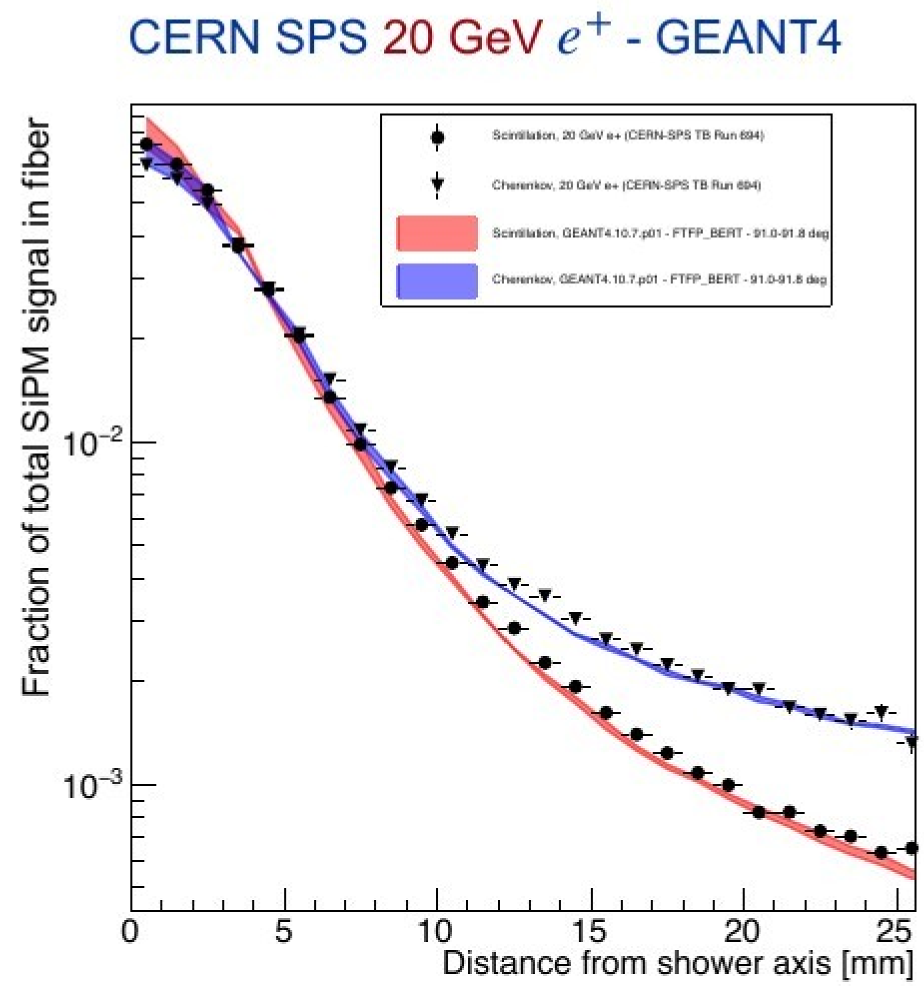
(have room for improvements)

Simulation wrt 2021 TB data



2020 em prototype

Lateral profile:
average signal in fibre at distance r from shower barycentre

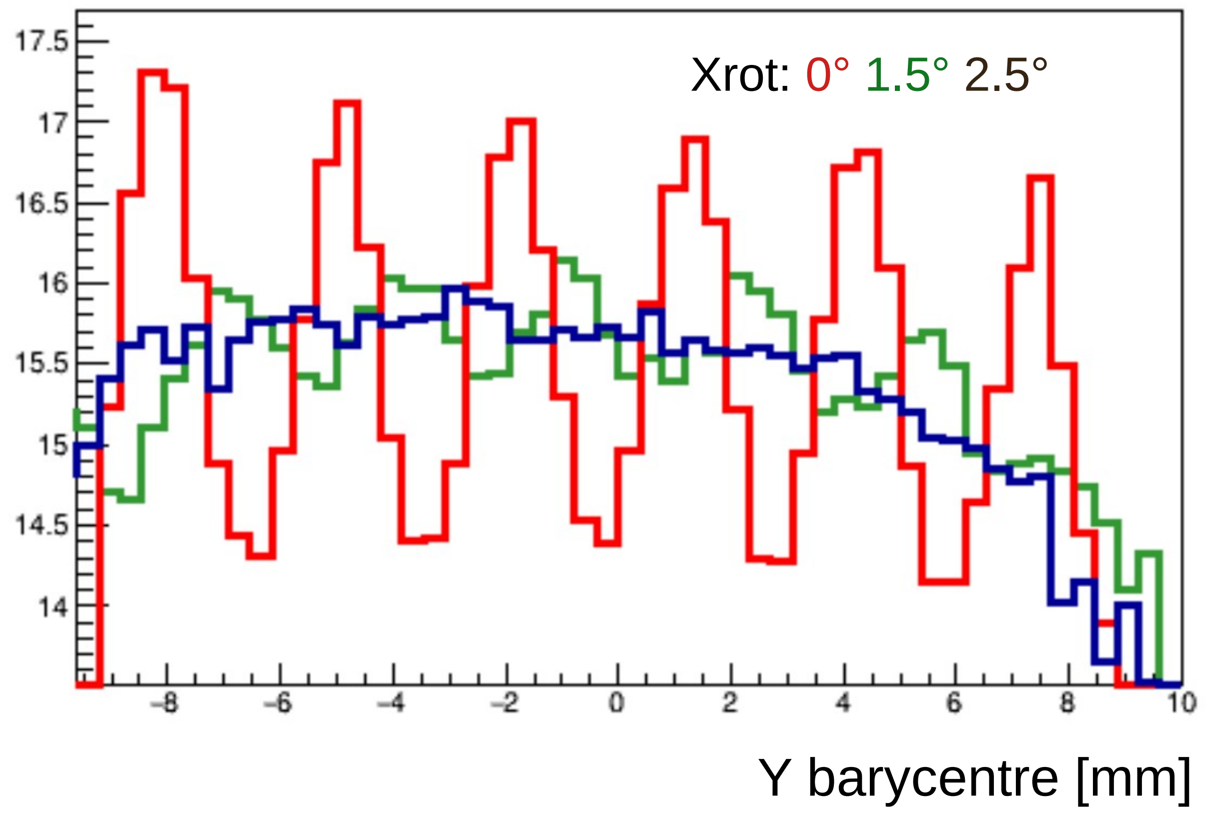


Measurement:
for every event and every fibre populate plot of signal vs. distance

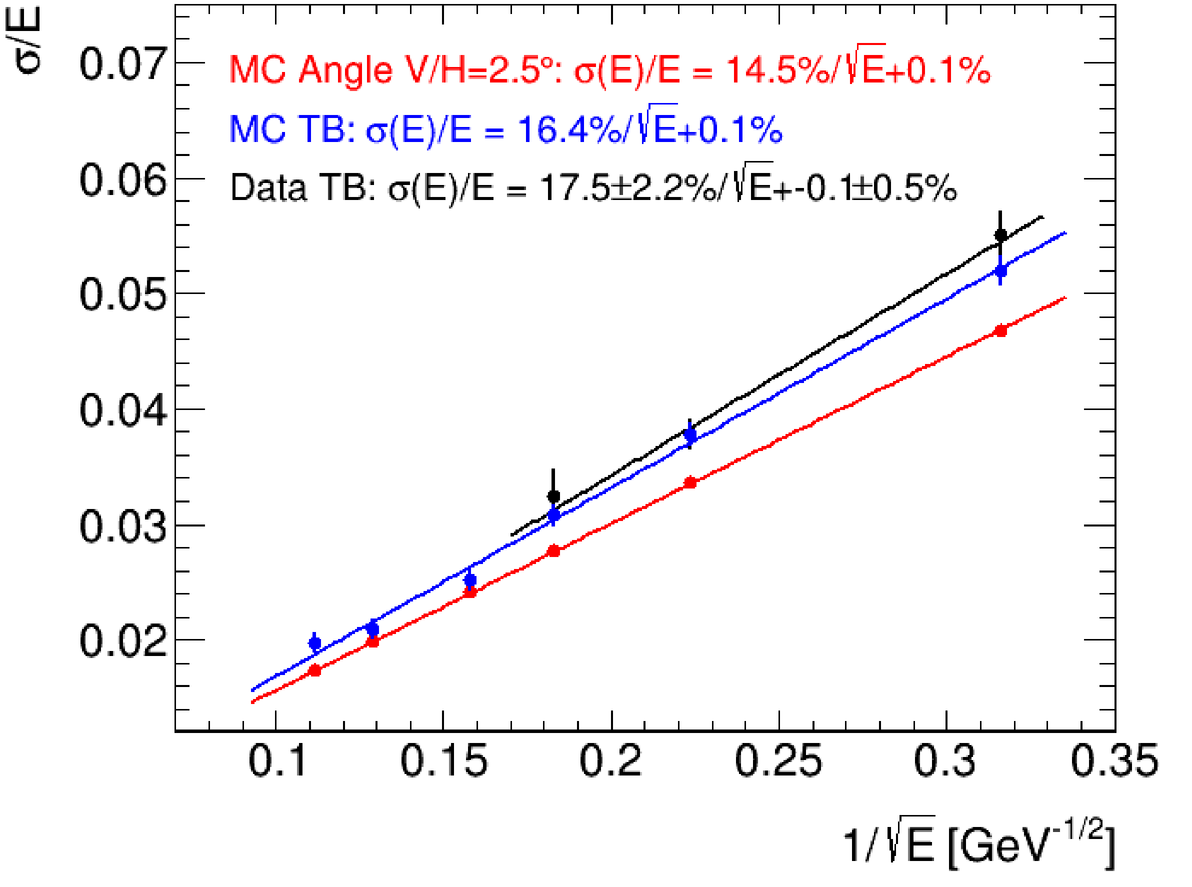
Lateral profiles extracted as average value for every x-bin

Other results

Angular dependence (from MC)



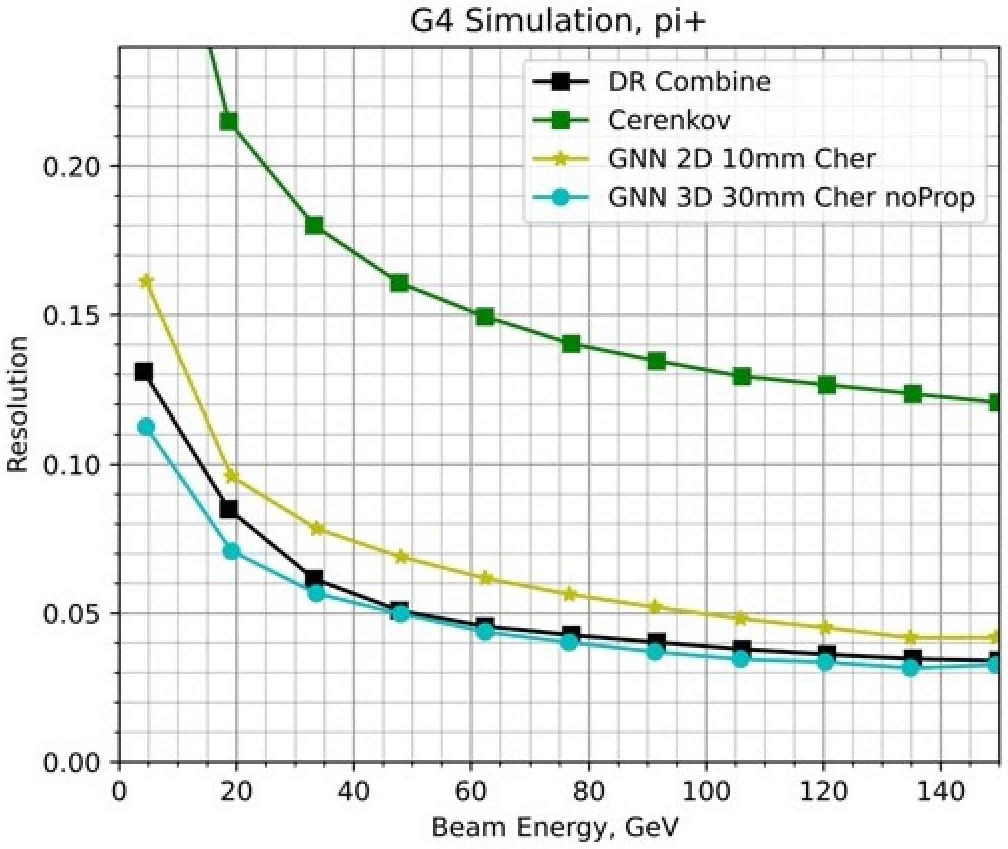
EM resolution



Need another beam test
Need beam purity
Need correct detector setup (angle, preshower)

Longitudinal segmentation w/ timing (U.S.)

3D imaging fibre DR calorimeter
coupled to Graph DNN



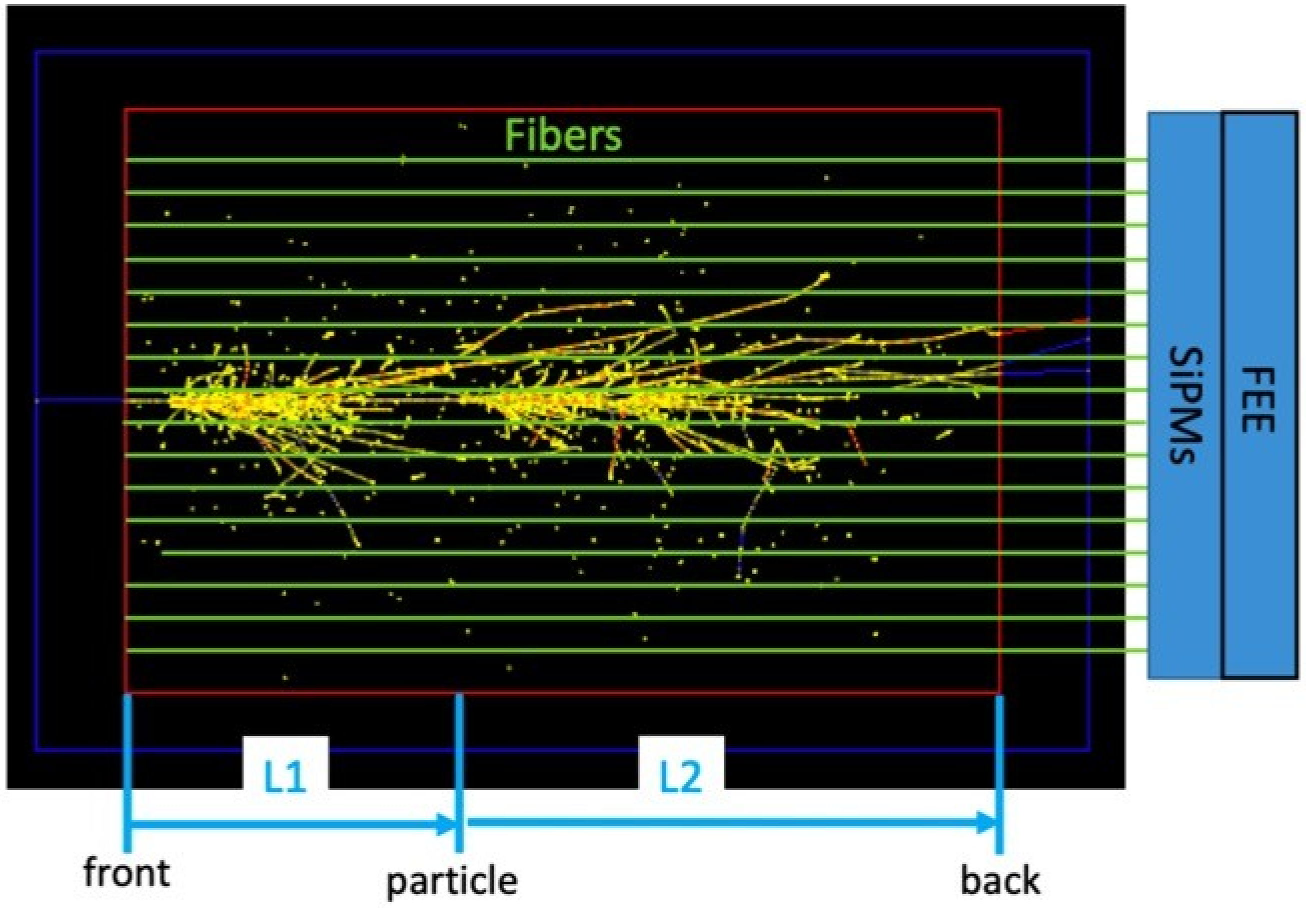


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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

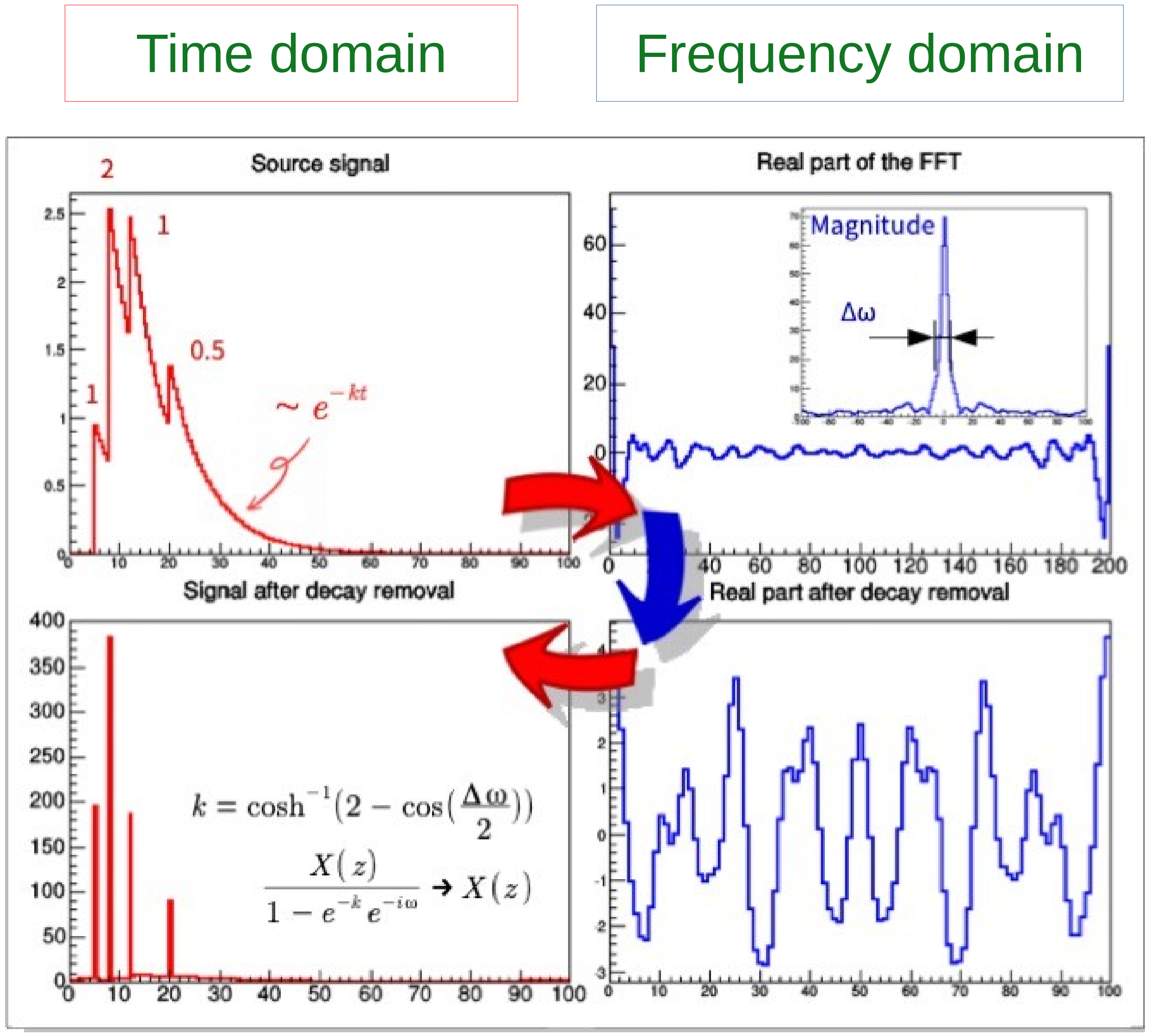
Longitudinal segmentation w/ timing (S.K.)

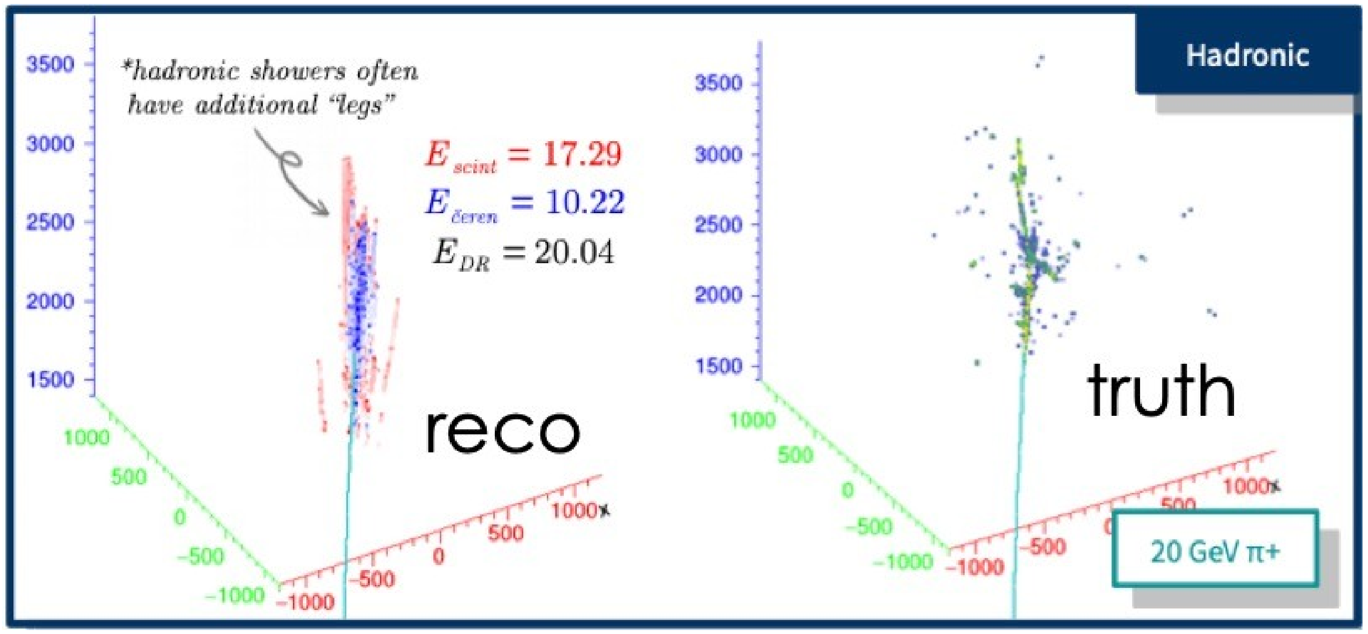
Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

Unlocks full longitudinal information about energy deposit

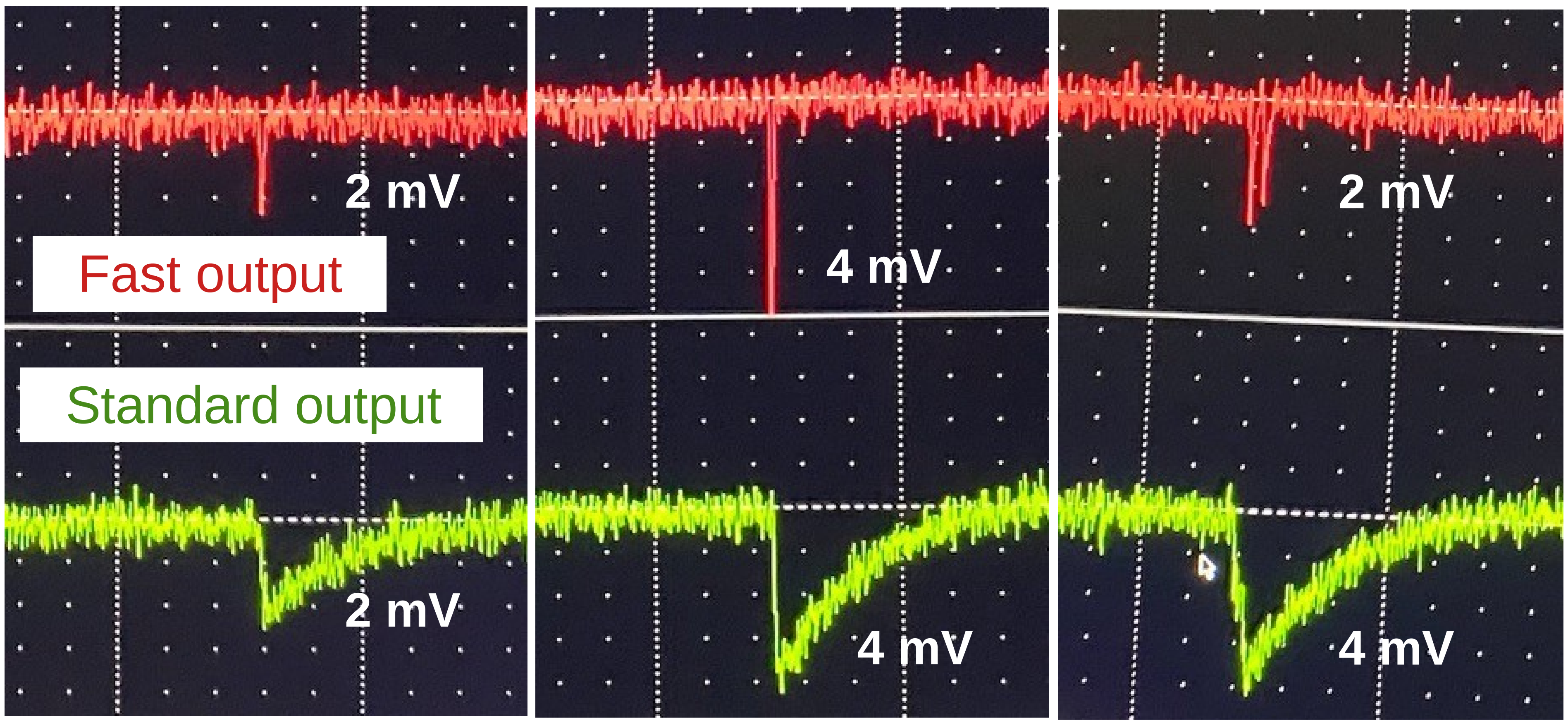
Combined with DR information allows in-shower cluster identification





Waveform digitisation (U.S.)

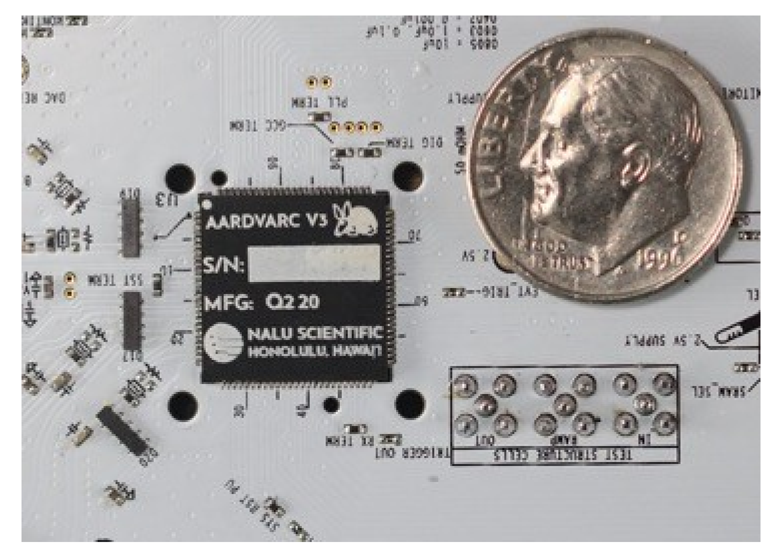
Results with SensL (MicroFC-30020SMT):
SiPM with fast and standard outputs.



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)



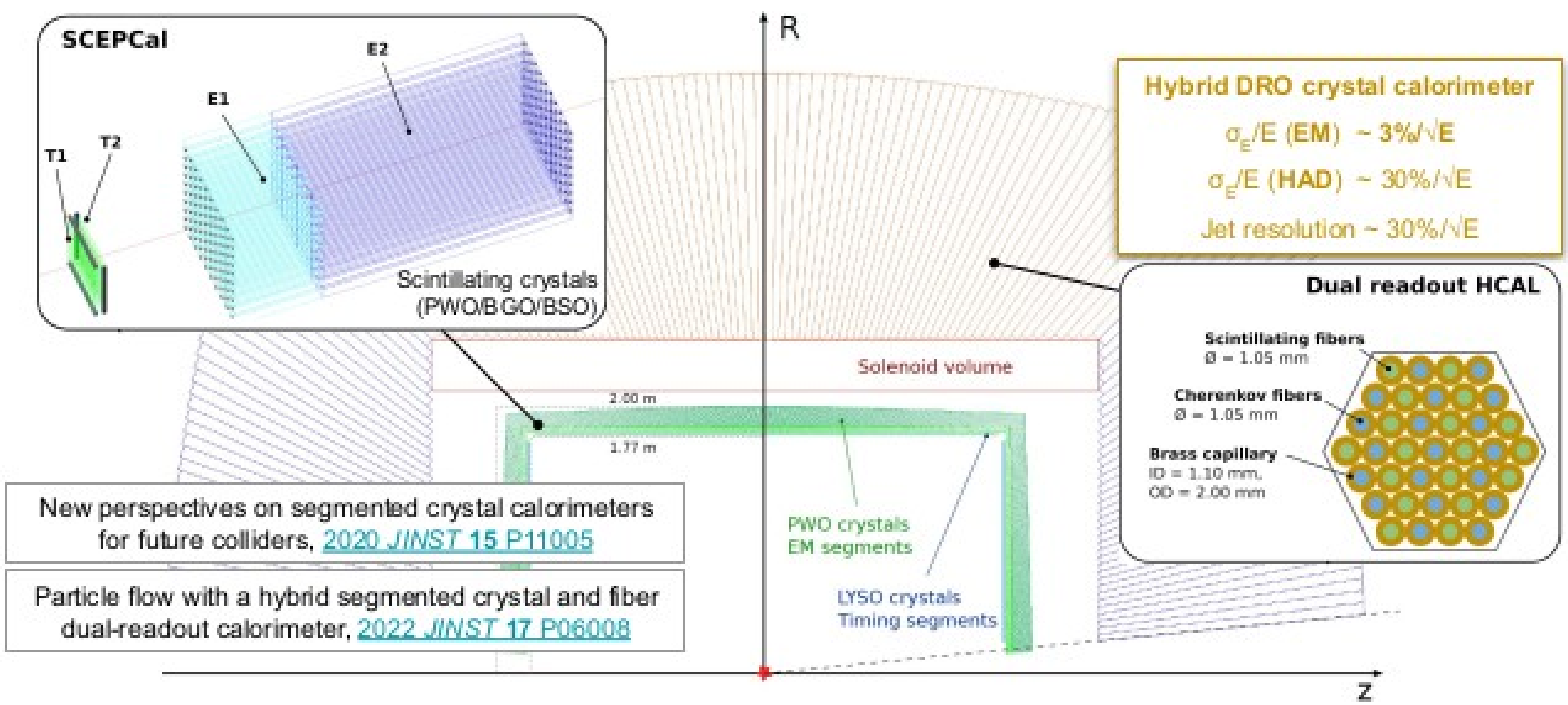
Dual-readout crystal option (IDEA++)

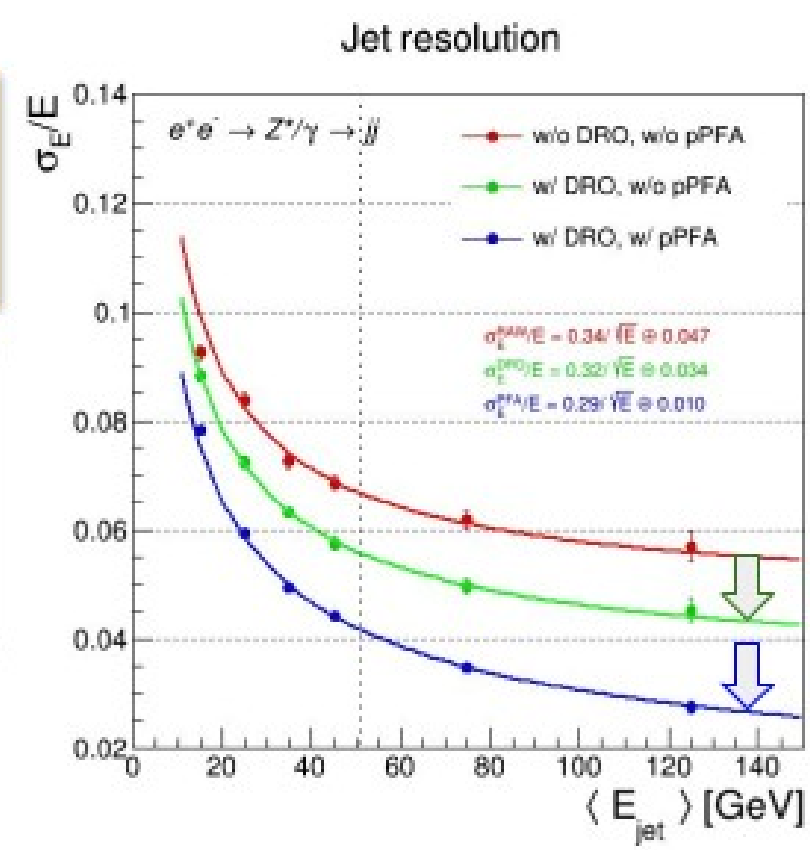
Segmented **C**rystal **E**M **P**recision **Cal**orimeter

Ongoing efforts within US Calvision, IDEA and Crystal Clear collaborations

Proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPMs)

Ongoing simulation effort in DD4HEP and FCC software + DR-PFA developments





Outlook

R&D on dual-readout calorimetry follows all possible directions

- Innovative absorber production for high quality and affordable cost
- Assembly solutions for large scale production
- Fibres and light sensors

Readout architecture: two baseline solutions but space for other ways

- Timing information improvements (AARDVARC v3, RADIOROC and dSiPM)
- High-performance waveform digitiser with feature extraction (AARDVARC v3)
- Cost reduction and reduced system complexity (dSiPM)

Detector performance

- Assess performance for single physics objects (energy resolutions and PID)
- Validate G4 simulation
- Optimisation of transverse and longitudinal segmentation
- Exploit DNN method
- PFA performance assessment