15th Workshop on Detector Development

Kirchhoff-Institut für Physik Heidelberg University

1-3 March 2023

The IDEA Calorimetry Concept and how to extend it to PFA

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on behalf of the IDEA dual-readout calorimetry group

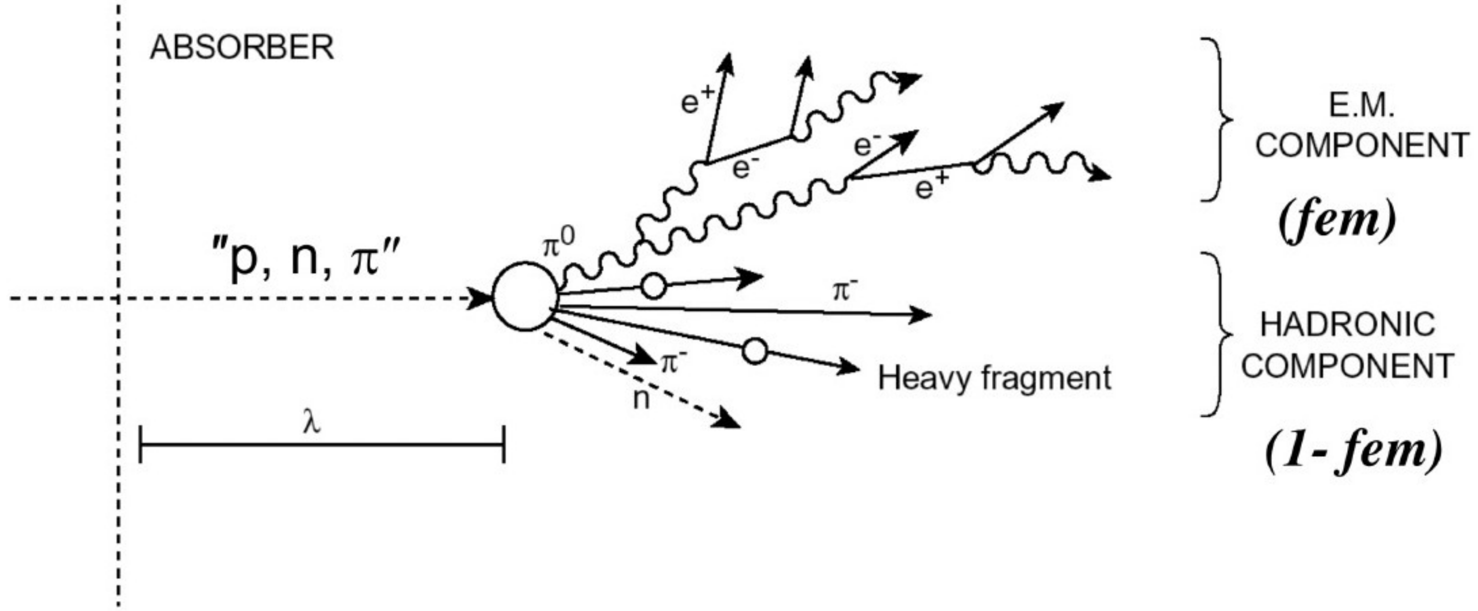
Heidelberg 02.03.2023

Foto: Heidelberg Marketing / Tobias Schwerdt

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

→ get fem event by event
→ dramatically improve hadronic energy resolution
→ high granularity → improve PID + allow for PFA

Dual-readout algebra

$$S = E \times [\ f_{em} + (h/e)_S \times (1 - f_{em})\ ]$$

$$C = E \times [\ f_{em} + (h/e)_C \times (1 - f_{em})\ ]$$

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

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

$$E = (S - \chi C) / (1 - \chi)$$

where:

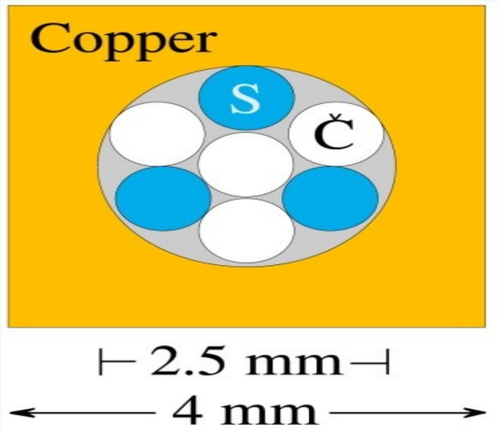
$$\chi = (1 - (h/e)_S) / (1 - (h/e)_C)$$
$$= (E - S) / (E - C)$$

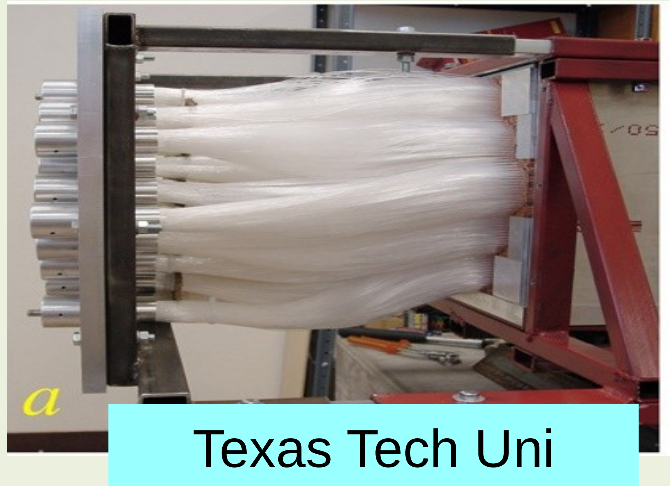
→ ***χ can be extracted from testbeam data***

DREAM/RD52 dual-readout spaghetti prototypes

2003
DREAM

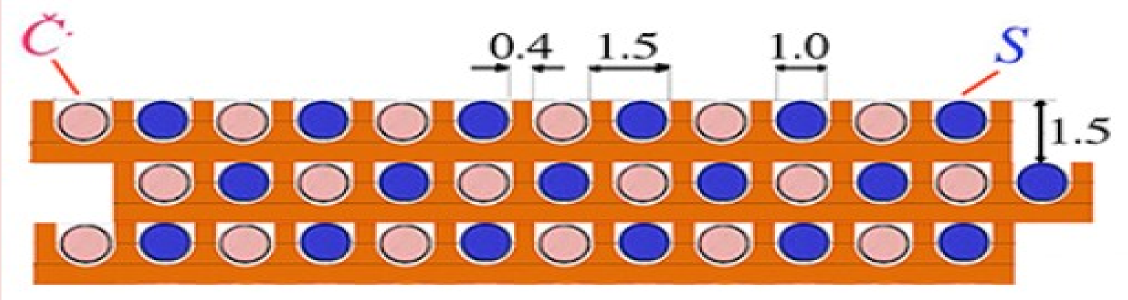
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}





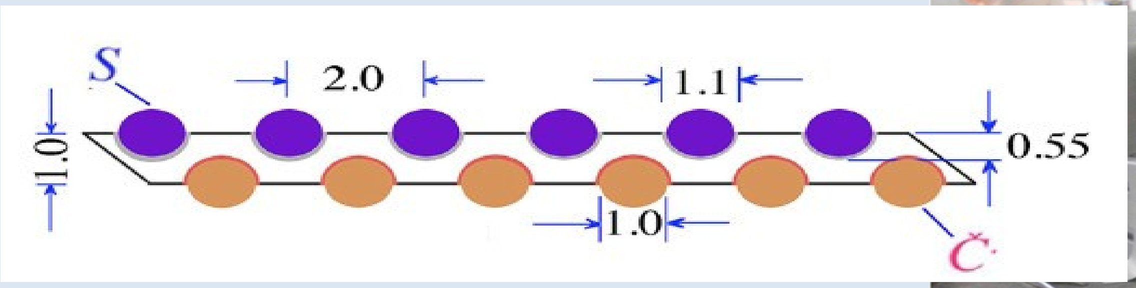
2012
RD52

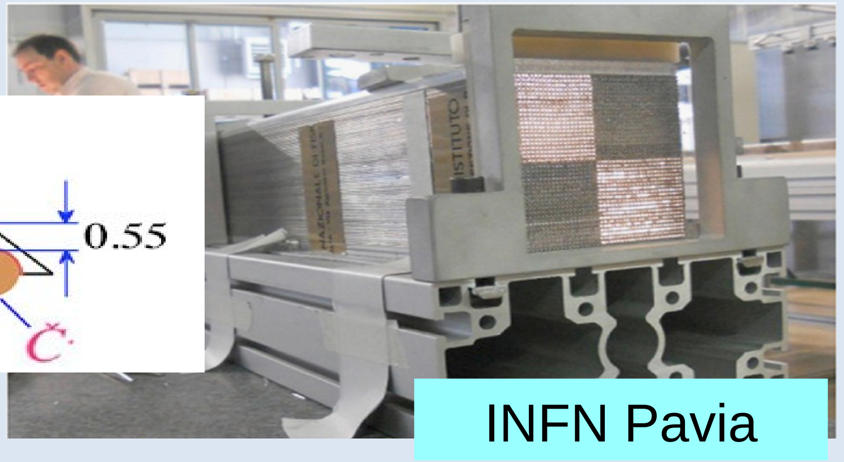
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



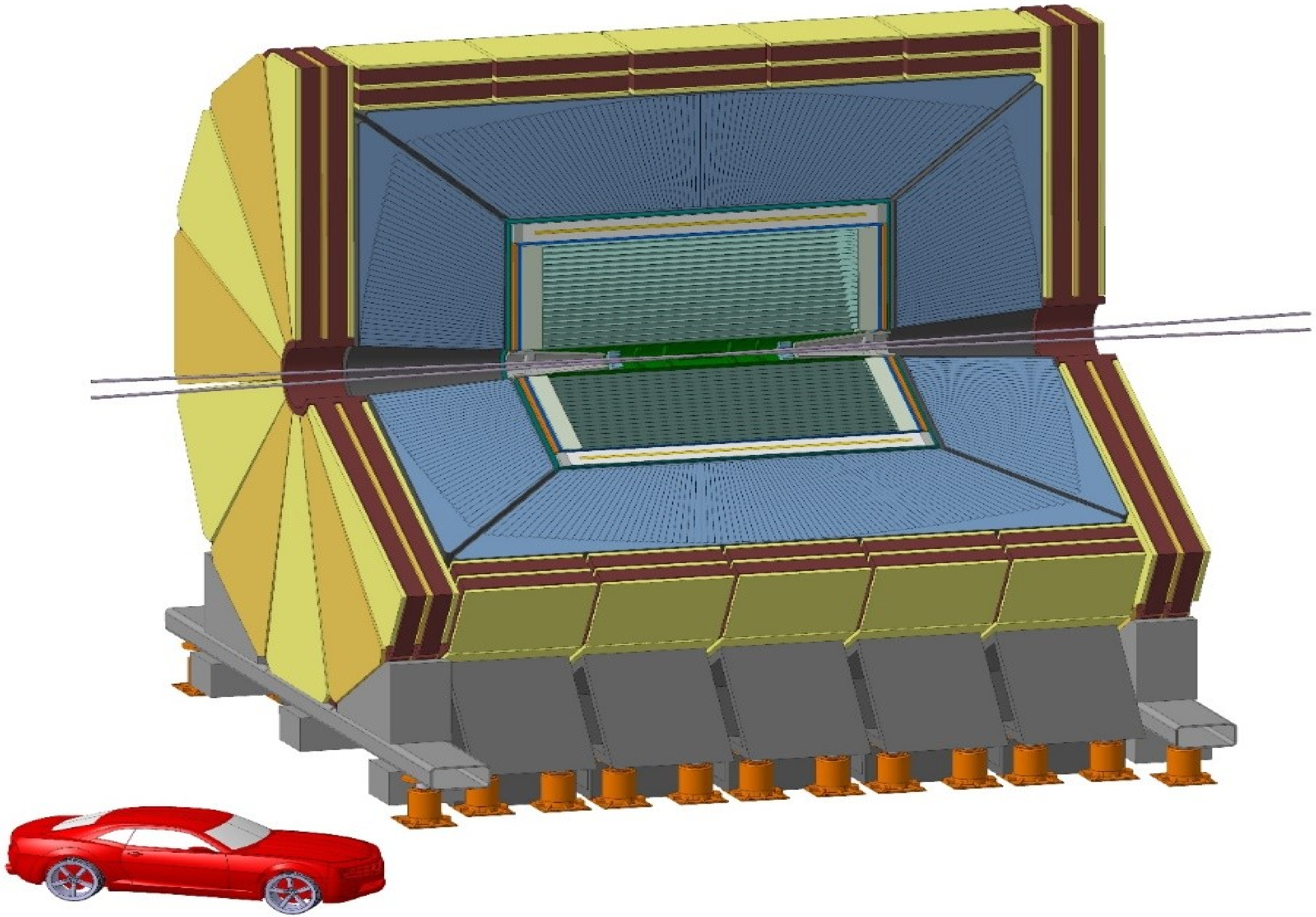
2012
RD52

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}



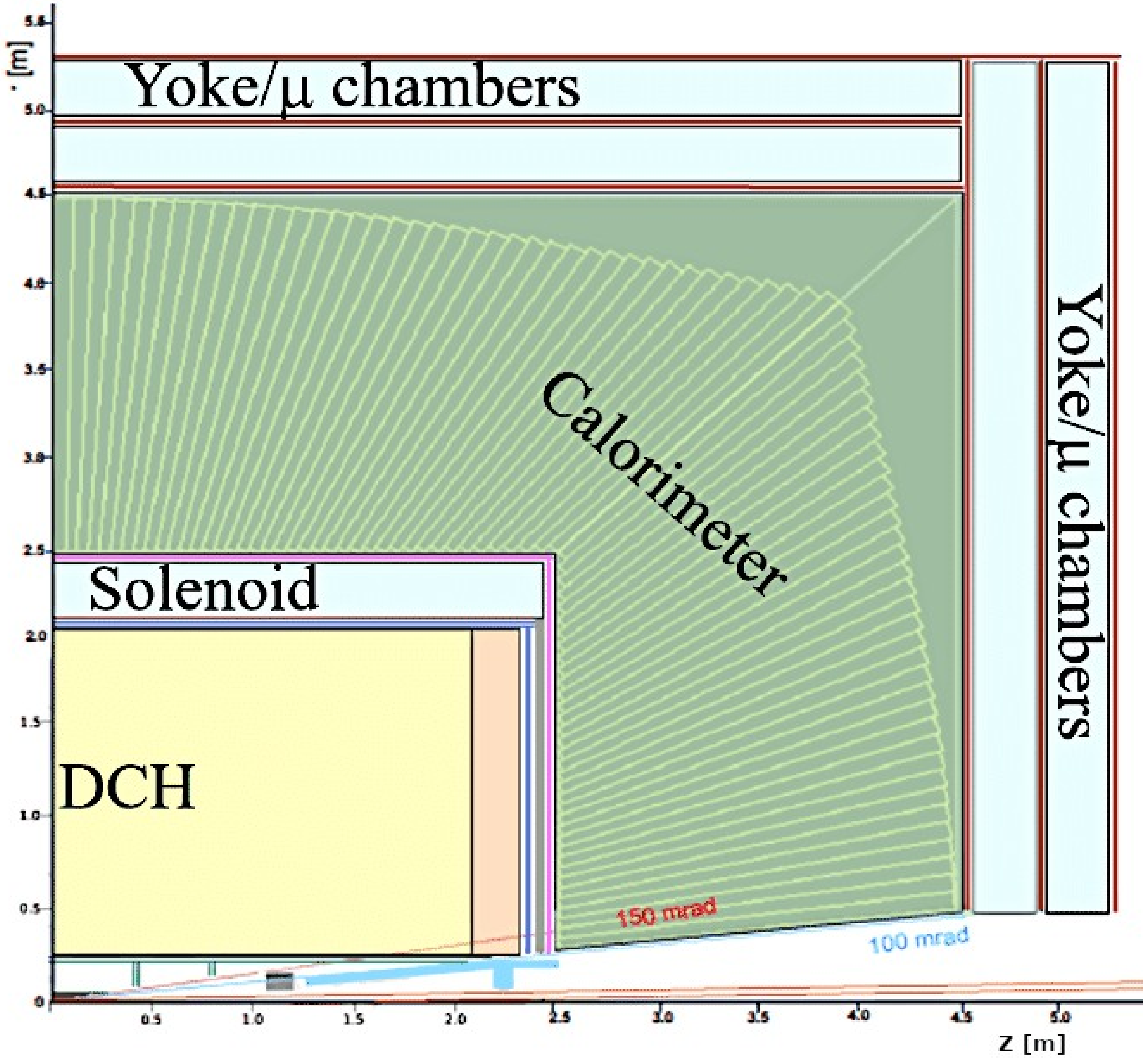


IDEA: Innovative Detector for e+e- Accelerator



IDEA baseline concept

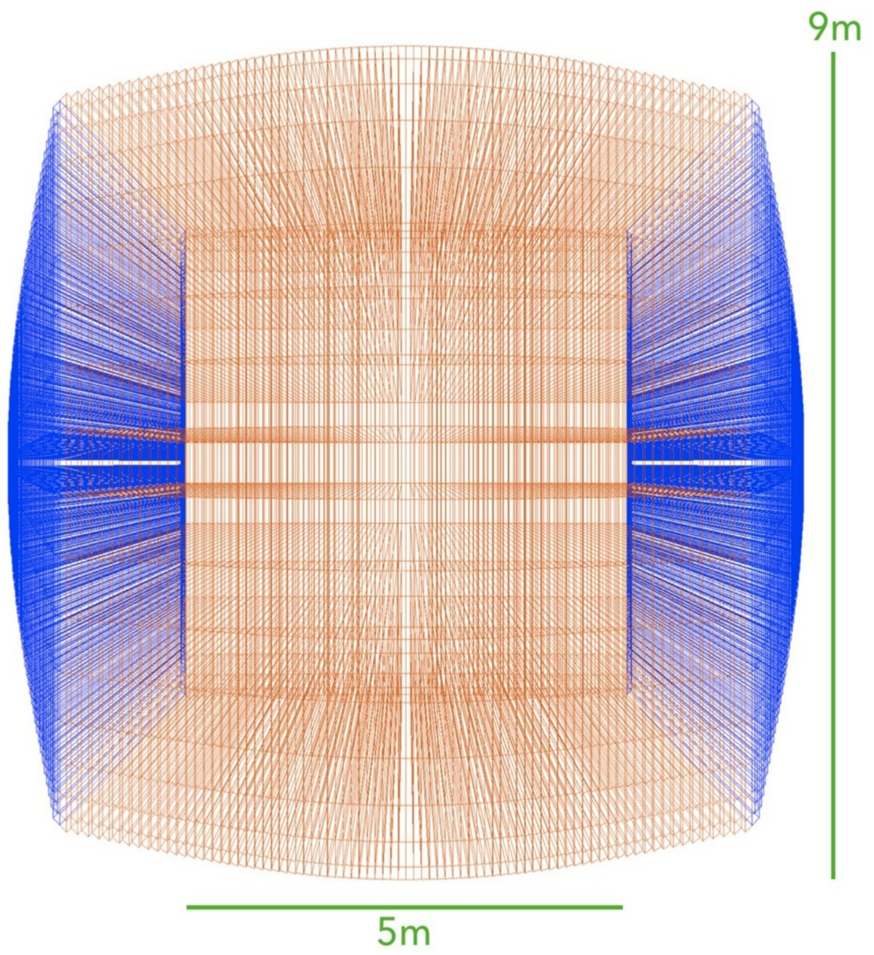
- Muon chambers
  - μ-RWELL in return yoke
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - μ-RWELL preshower
- Thin superconducting solenoid
  - 2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°
- Highly transparent for tracking
  - Si pixel vertex detector
  - Drift Chamber
  - Si wrappers (strips)
- Beam pipe: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

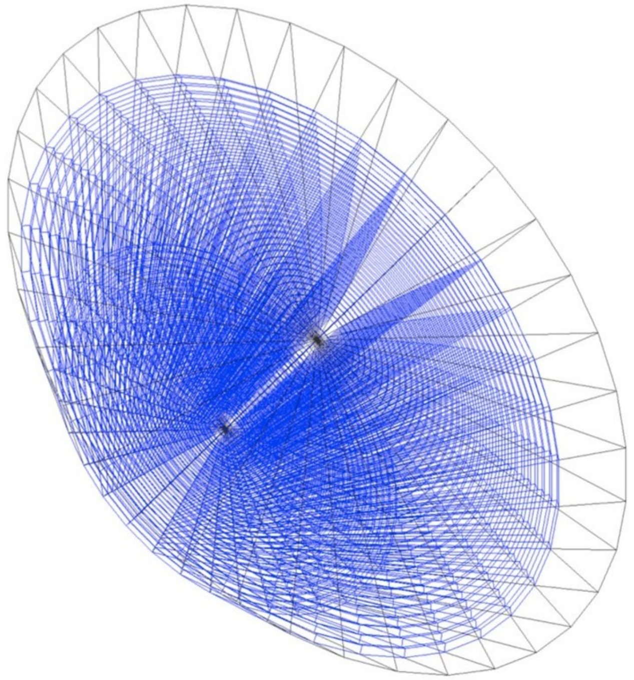


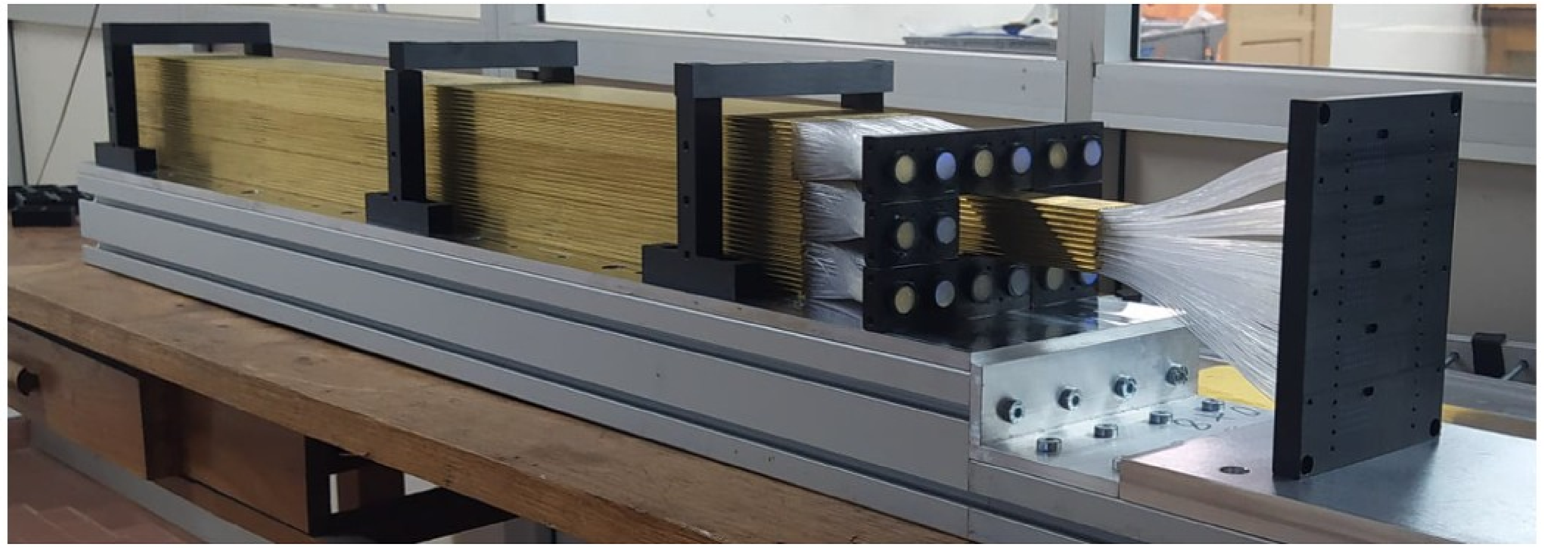
IDEA all-fibre DR calorimeter option

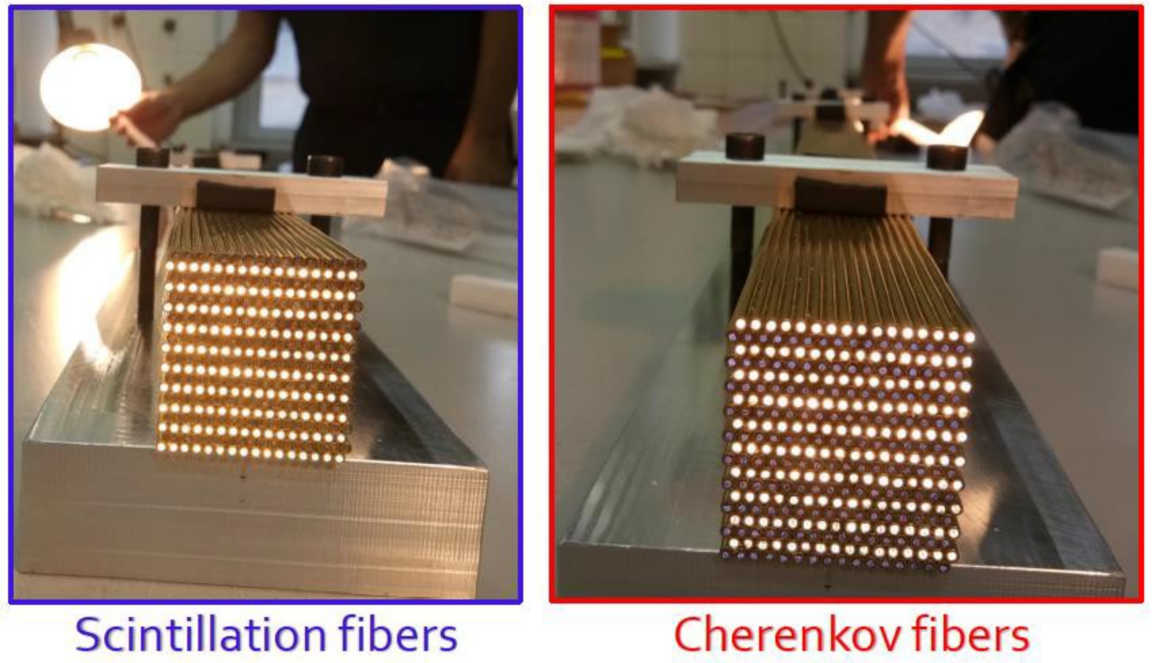
- DR fibre calorimeter
  - ~ 130 M fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
    - ϑ coverage: down to ∼100 mrad

- G4 simulation available
  - tuned to RD52 TB data



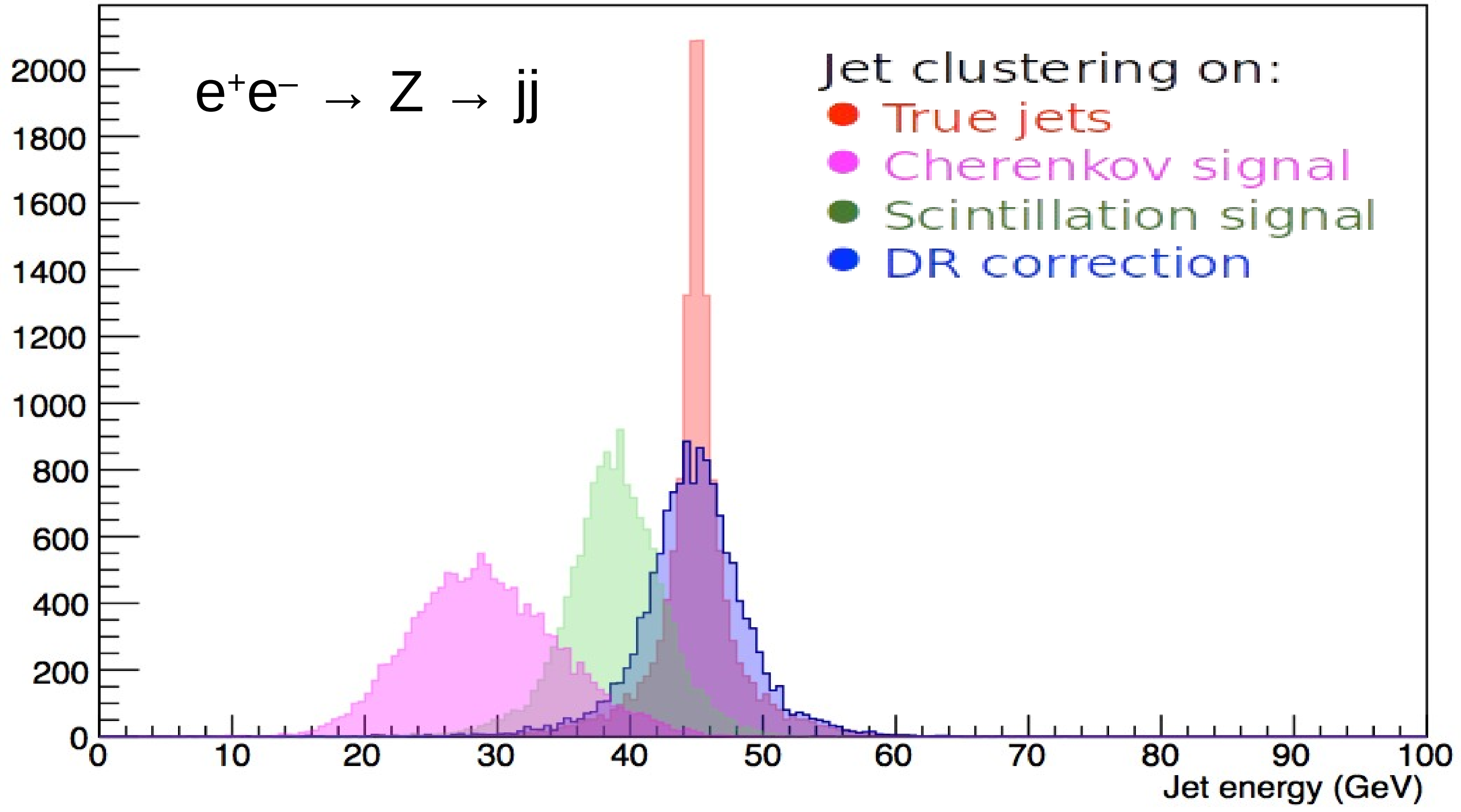


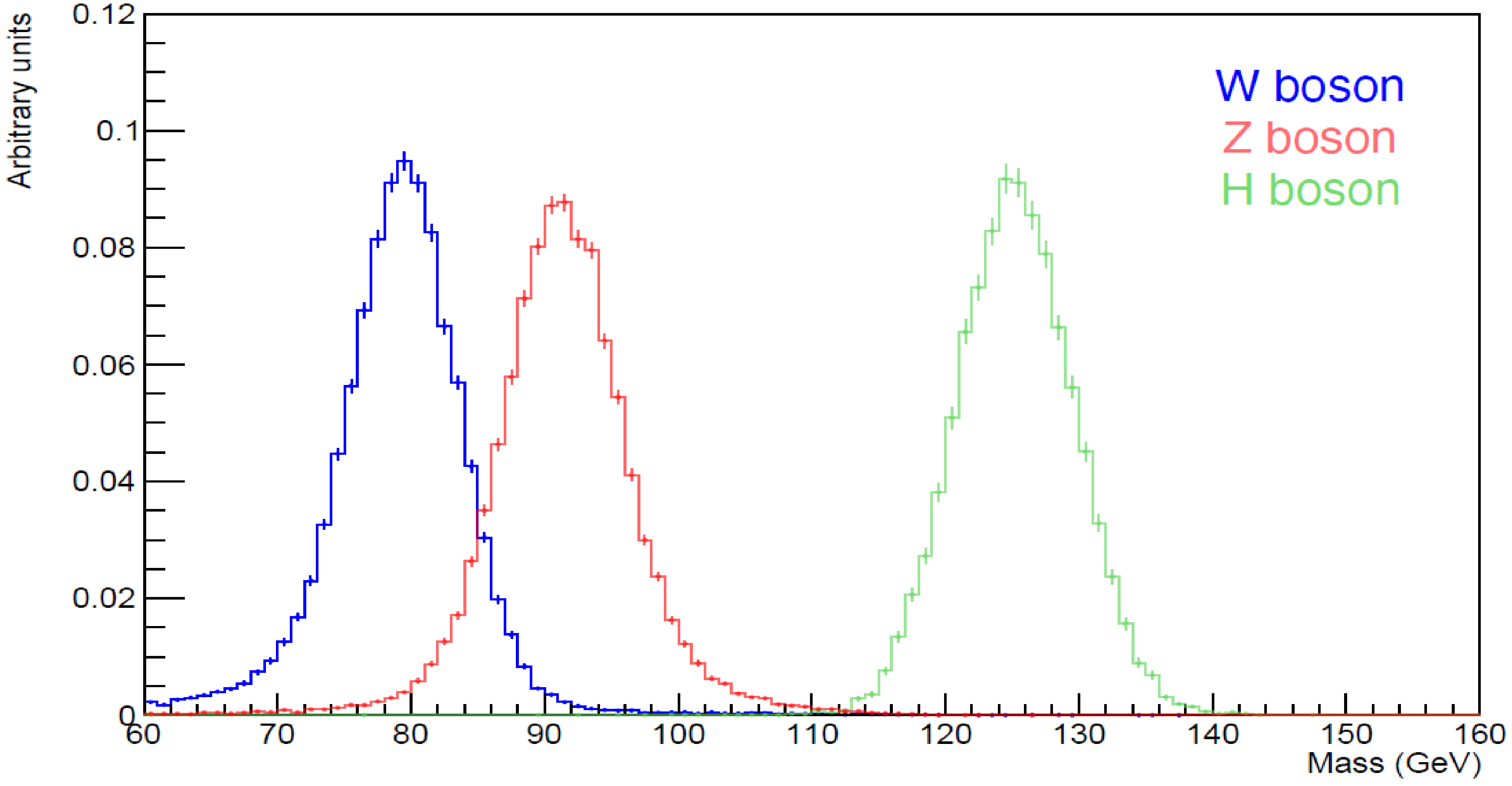




Geant4 simulation

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





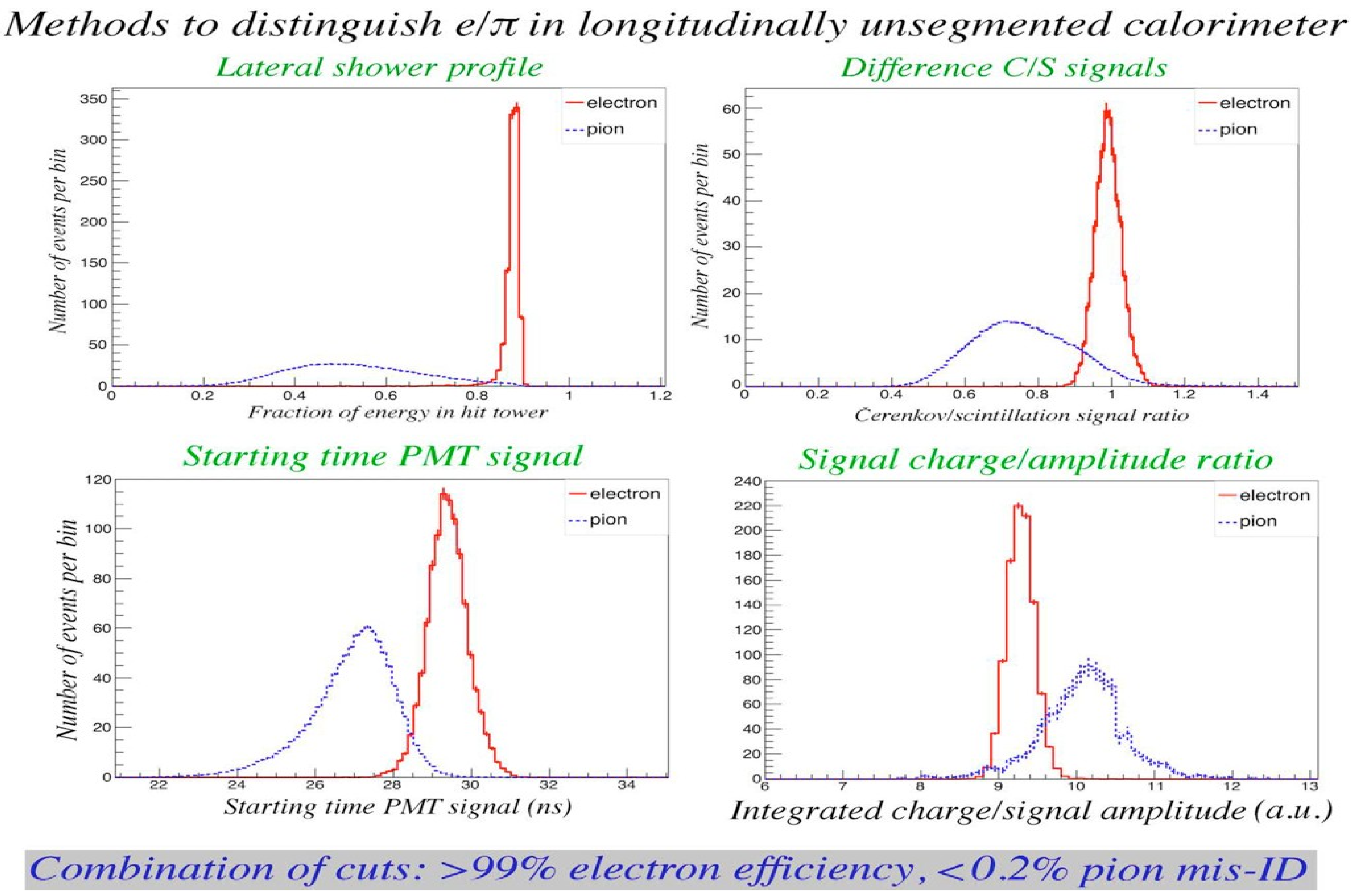
Usage of timing for e/π separation (RD52 results)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

NIM A 735 (2014) 120



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

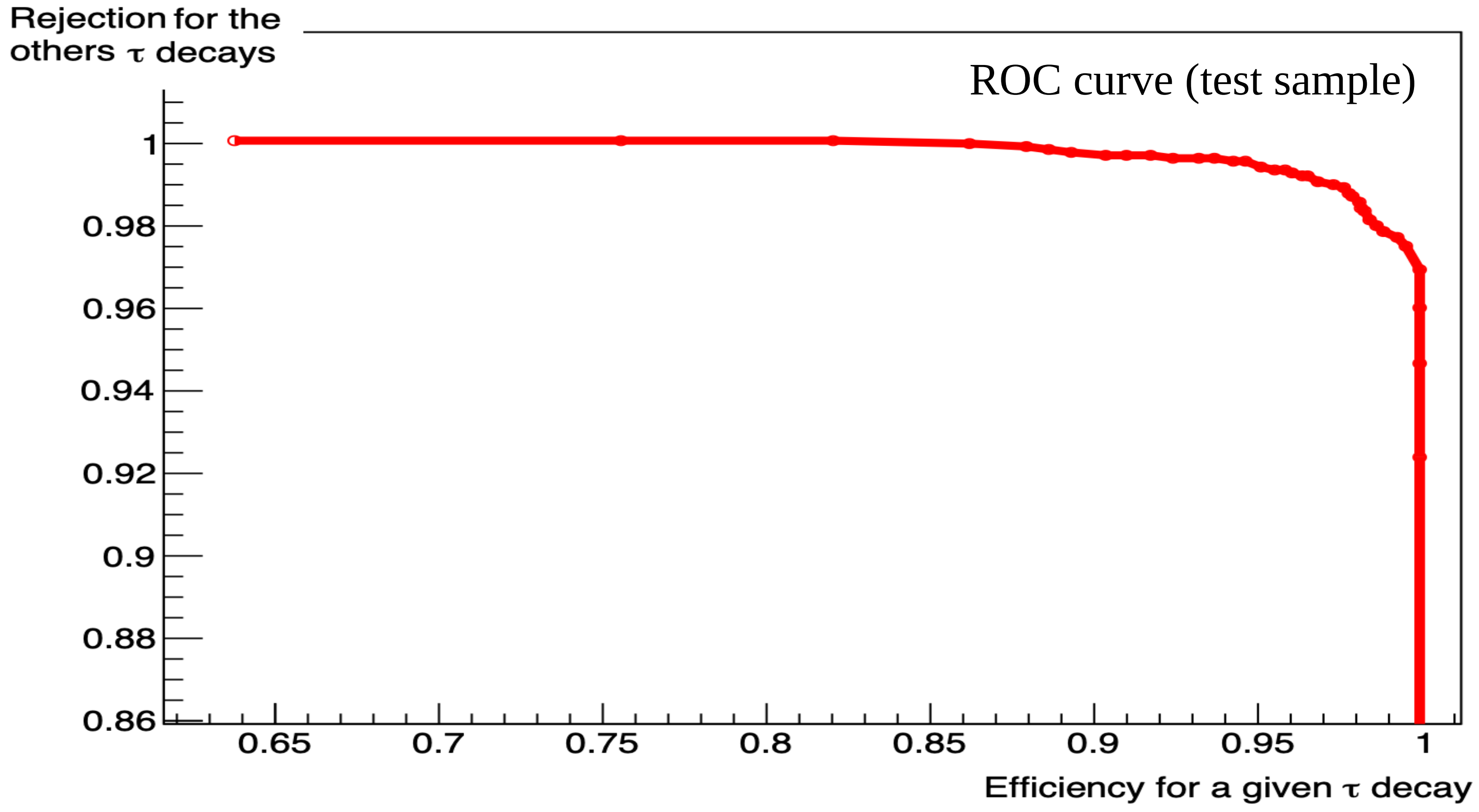
Two DNN architecture variants studied:

- 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

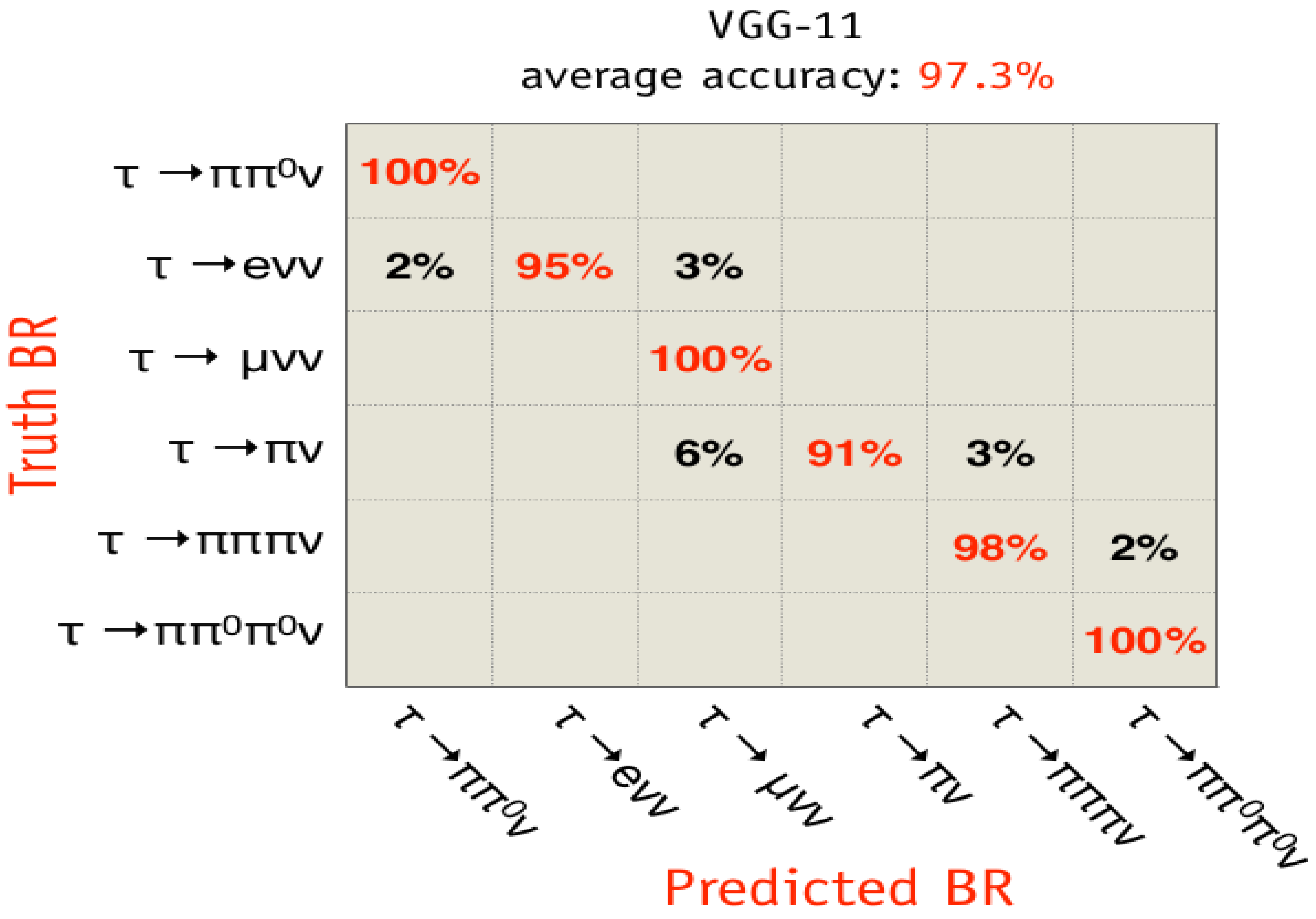
$\tau \to \pi\pi^0\nu$
$\tau \to \mu\nu\nu$
$\tau \to e\nu\nu$
$\tau \to \pi\nu$
$\tau \to \pi\pi\pi\nu$
$\tau \to \pi\pi^0\pi^0\nu$

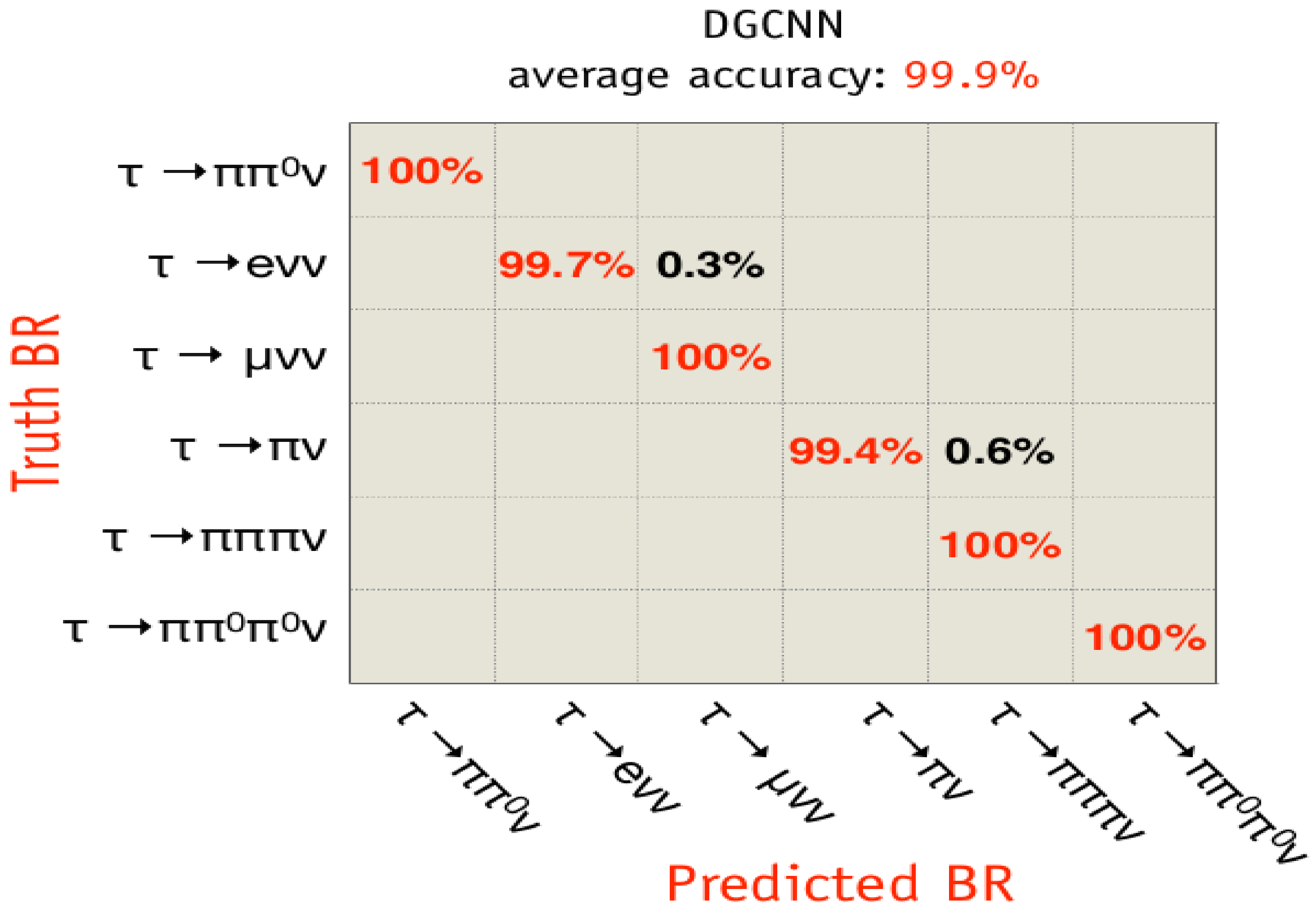
VGG example



NN performance

Confusion matrix on test set





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

Truth BR \ Predicted BR	$\tau \to e\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi^0\nu$	$\tau \to \pi\pi^0\pi^0\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi\pi\pi^0\nu$	$\tau \to \mu\nu\nu$	$Z \to qq$ jets
$\tau \to e\nu\nu$	90.36	4.07	2.21	0.03	0.00	0.00	3.34	0.00
$\tau \to \pi\nu$	2.57	86.24	5.39	0.25	3.59	0.17	1.57	0.22
$\tau \to \pi\pi^0\nu$	2.10	18.92	72.67	2.76	1.97	1.01	0.27	0.30
$\tau \to \pi\pi^0\pi^0\nu$	0.74	3.54	58.43	33.04	0.84	2.81	0.05	0.54
$\tau \to \pi\pi\pi\nu$	0.11	9.88	6.22	0.46	75.32	6.49	0.00	1.52
$\tau \to \pi\pi\pi\pi^0\nu$	0.11	1.49	9.30	2.90	38.28	43.75	0.05	4.12
$\tau \to \mu\nu\nu$	2.50	0.70	0.17	0.00	0.03	0.00	96.60	0.00
$Z \to qq$ jets	0.08	0.33	0.63	0.94	2.92	3.09	0.08	91.92

input: fibre coordinates only

avg accuracy: 73.7%

Truth BR \ Predicted BR	$\tau \to e\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi^0\nu$	$\tau \to \pi\pi^0\pi^0\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi\pi\pi^0\nu$	$\tau \to \mu\nu\nu$	$Z \to qq$ jets
$\tau \to e\nu\nu$	96.95	0.79	0.62	0.03	0.00	0.00	1.58	0.03
$\tau \to \pi\nu$	3.09	89.03	3.48	0.41	2.02	0.39	1.44	0.14
$\tau \to \pi\pi^0\nu$	1.77	4.83	80.45	9.25	1.61	1.67	0.16	0.25
$\tau \to \pi\pi^0\pi^0\nu$	0.30	0.38	10.43	84.55	0.16	3.87	0.05	0.25
$\tau \to \pi\pi\pi\nu$	0.16	3.52	1.38	0.35	84.82	8.79	0.03	0.95
$\tau \to \pi\pi\pi\pi^0\nu$	0.11	0.24	1.98	2.60	10.19	82.60	0.08	2.20
$\tau \to \mu\nu\nu$	2.53	0.48	0.11	0.00	0.03	0.00	96.82	0.03
$Z \to qq$ jets	0.08	0.25	0.19	1.05	2.54	4.08	0.06	91.75

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

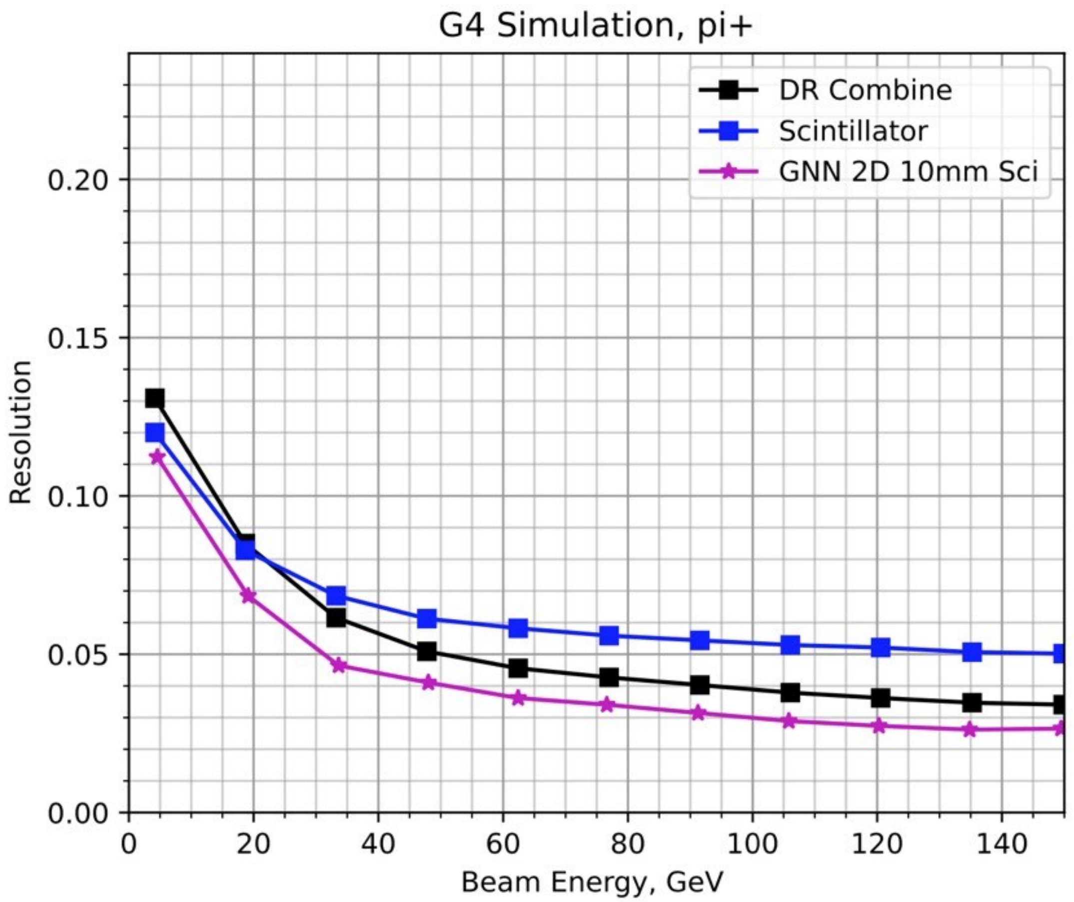
Preliminary results
No optimisation

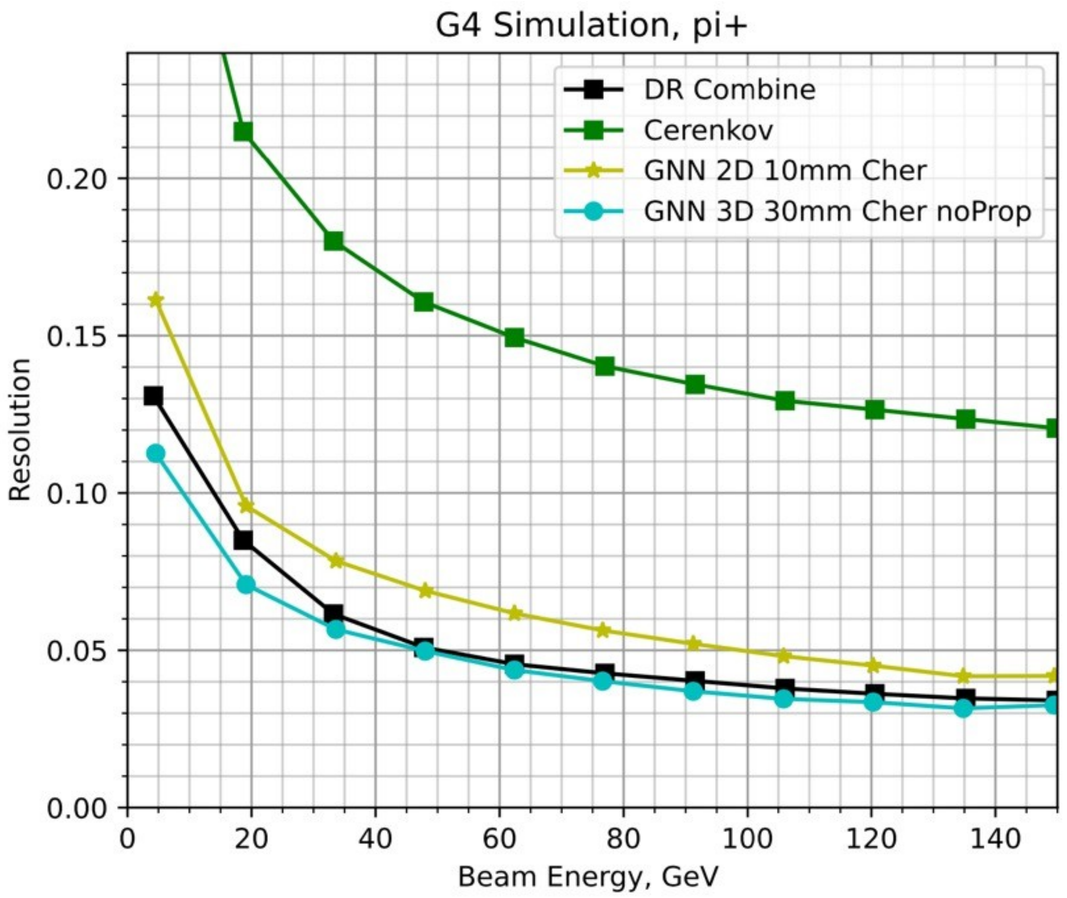
Cu absorber (2 m deep)

Fibres along 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.)

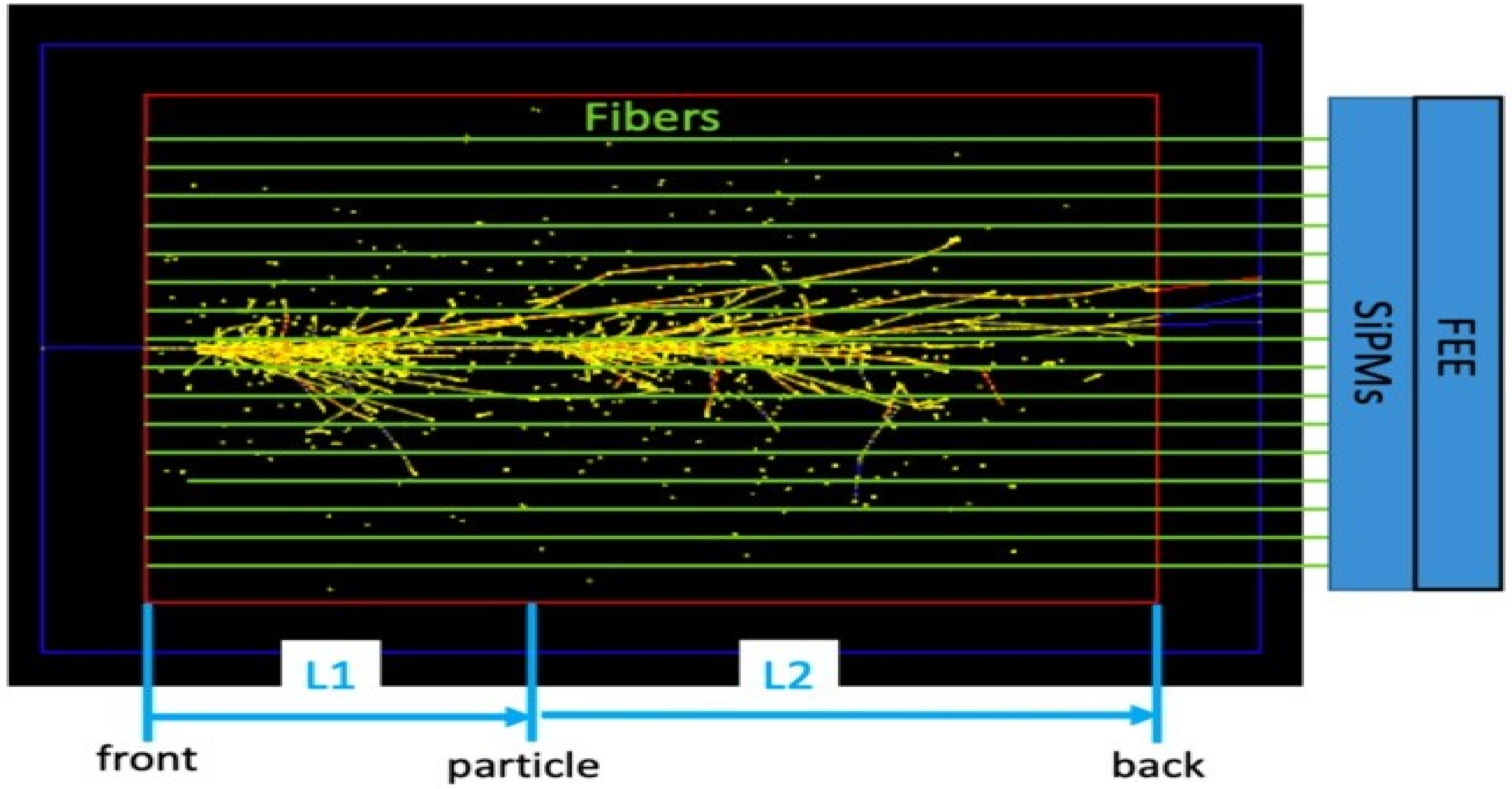


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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

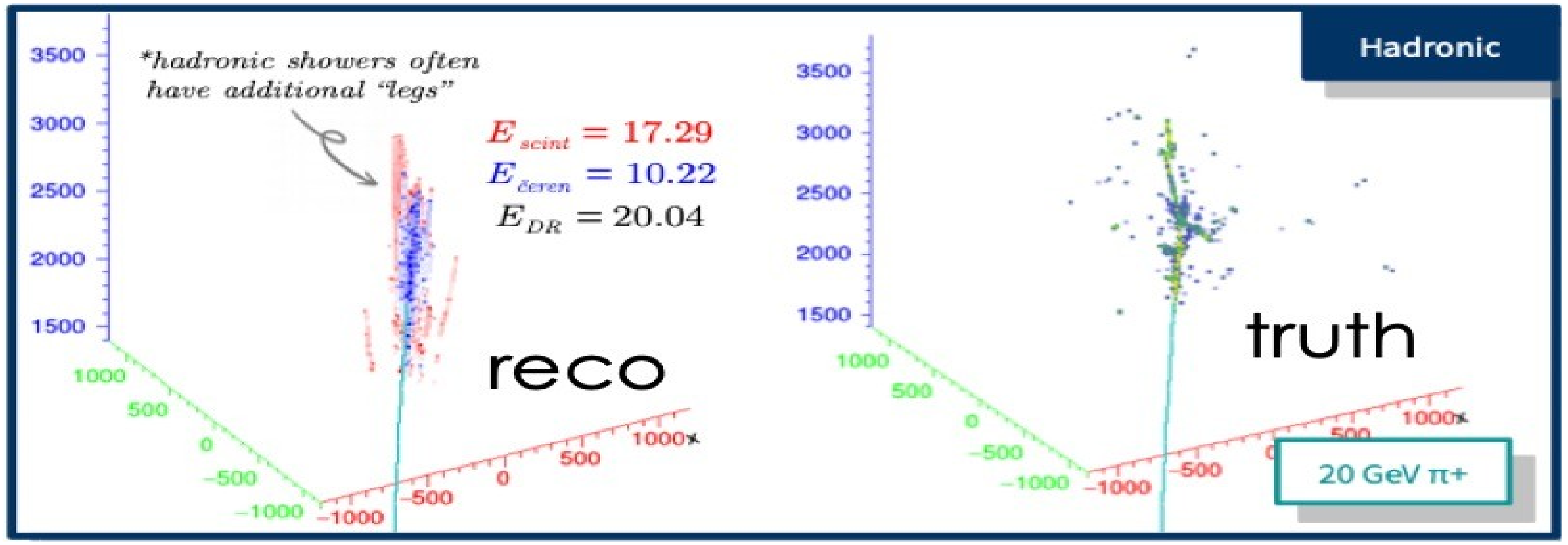
Longitudinal segmentation w/ timing (S.K.)

Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

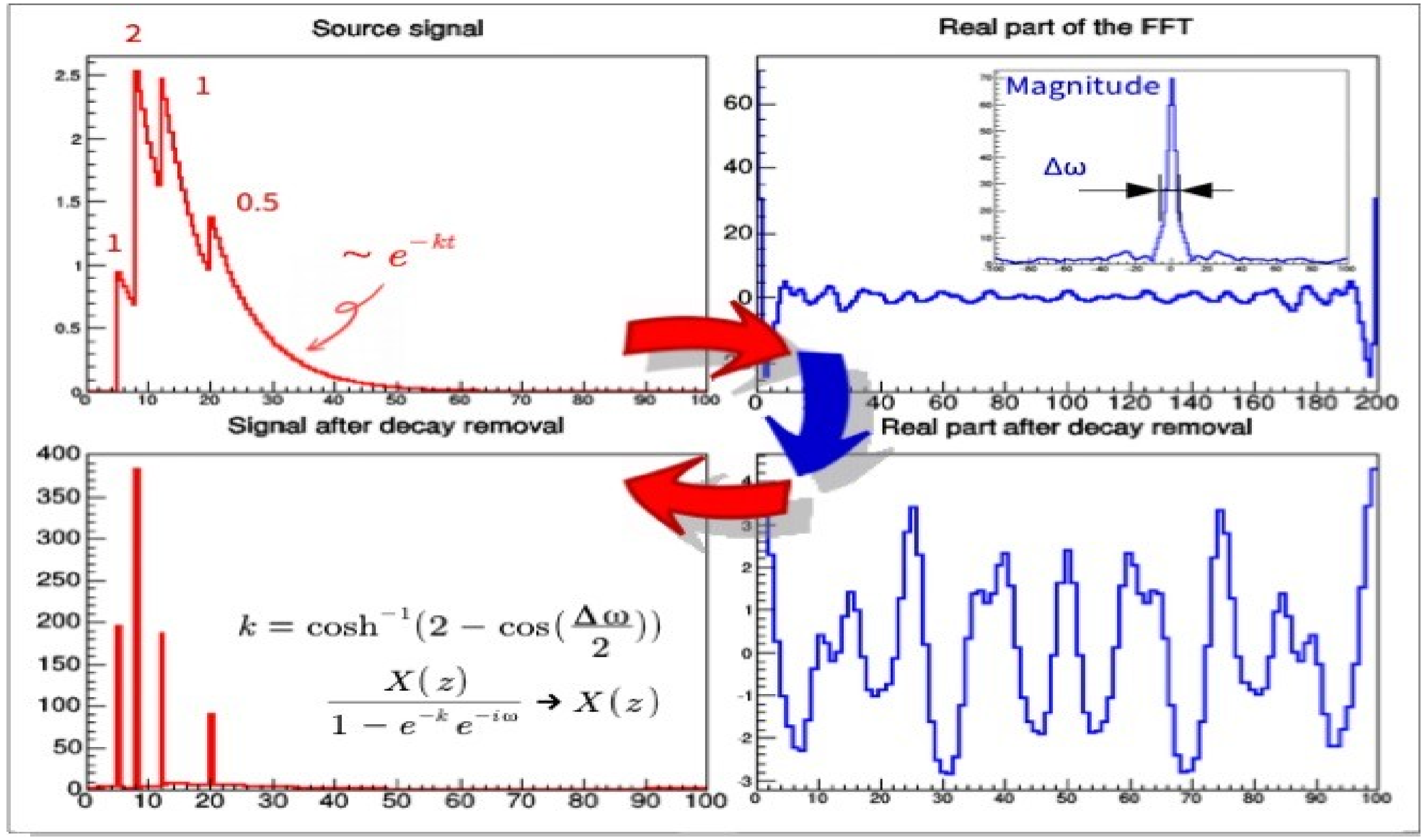
Unlocks full longitudinal information about energy deposit

Combined with DR information
allows in-shower cluster identification



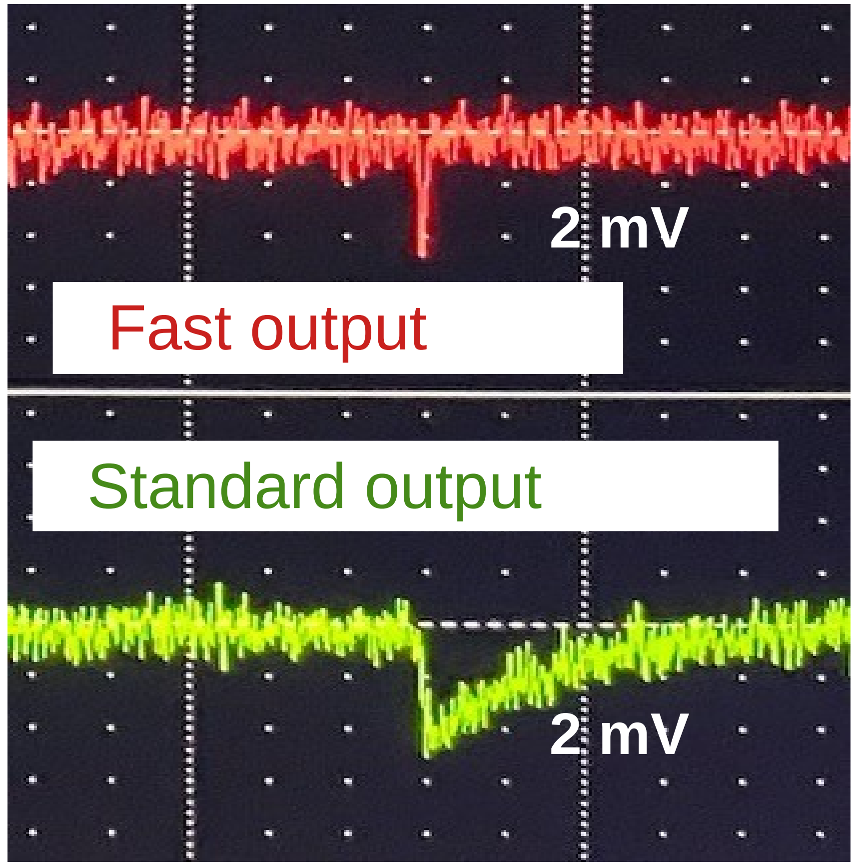
Time domain

Frequency domain

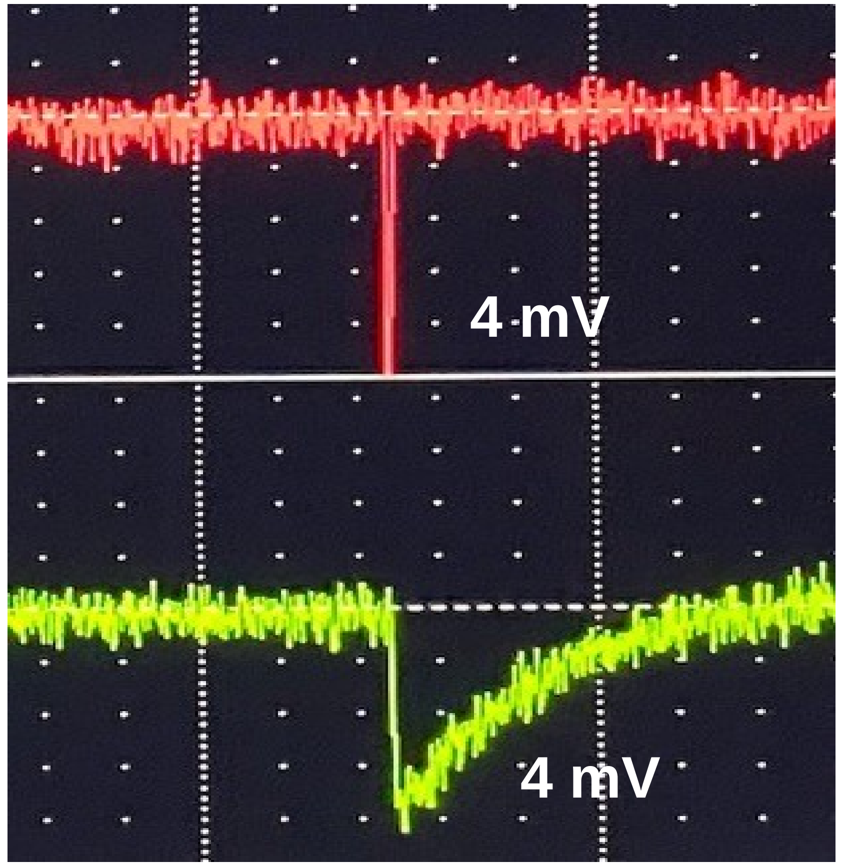


Waveform digitisation (U.S.)

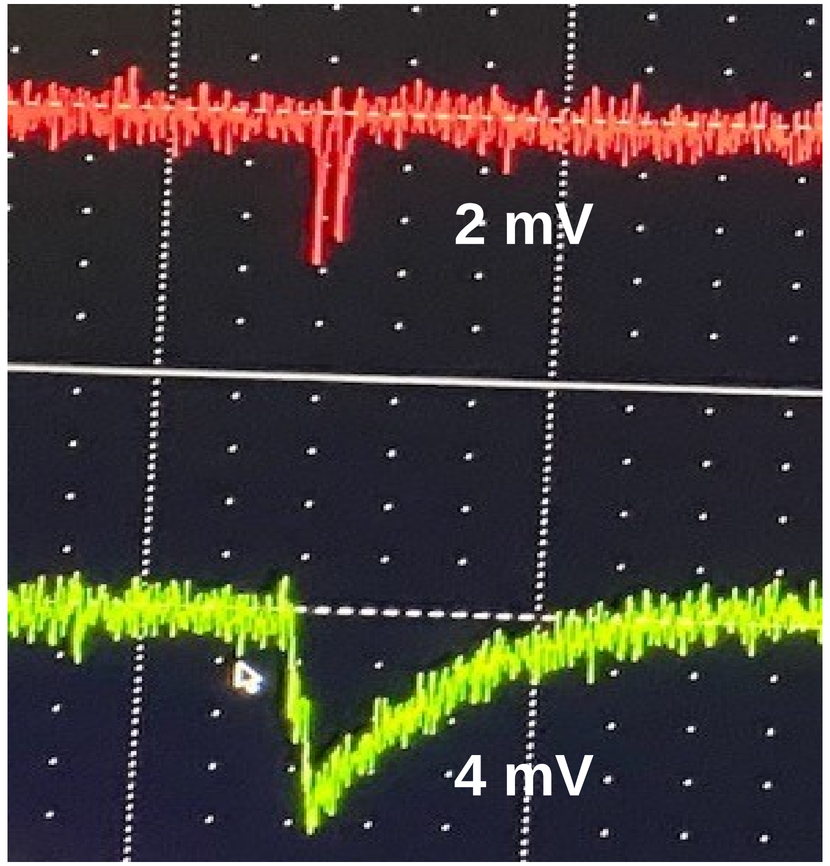
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard outputs



One-photon event



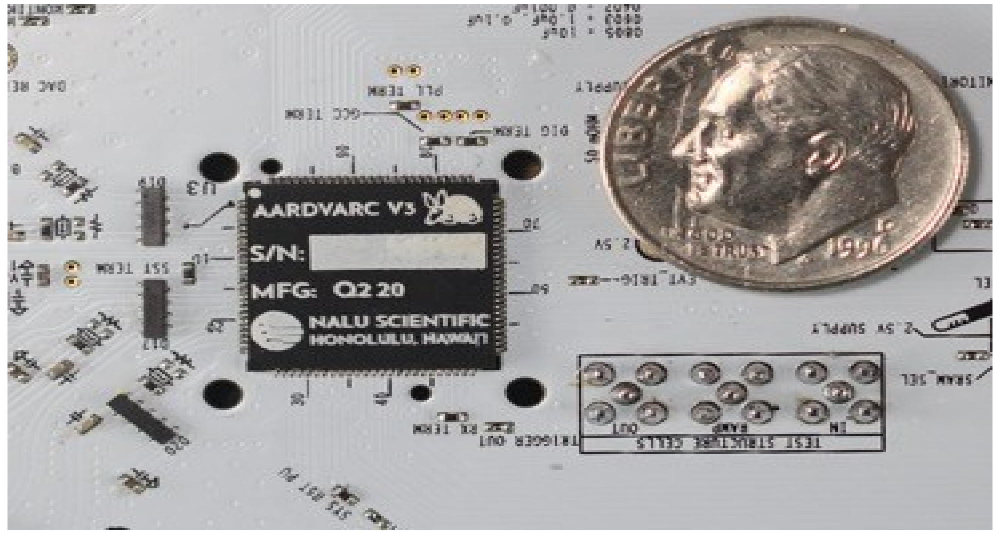
Two-photon event
(simultaneous)



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)



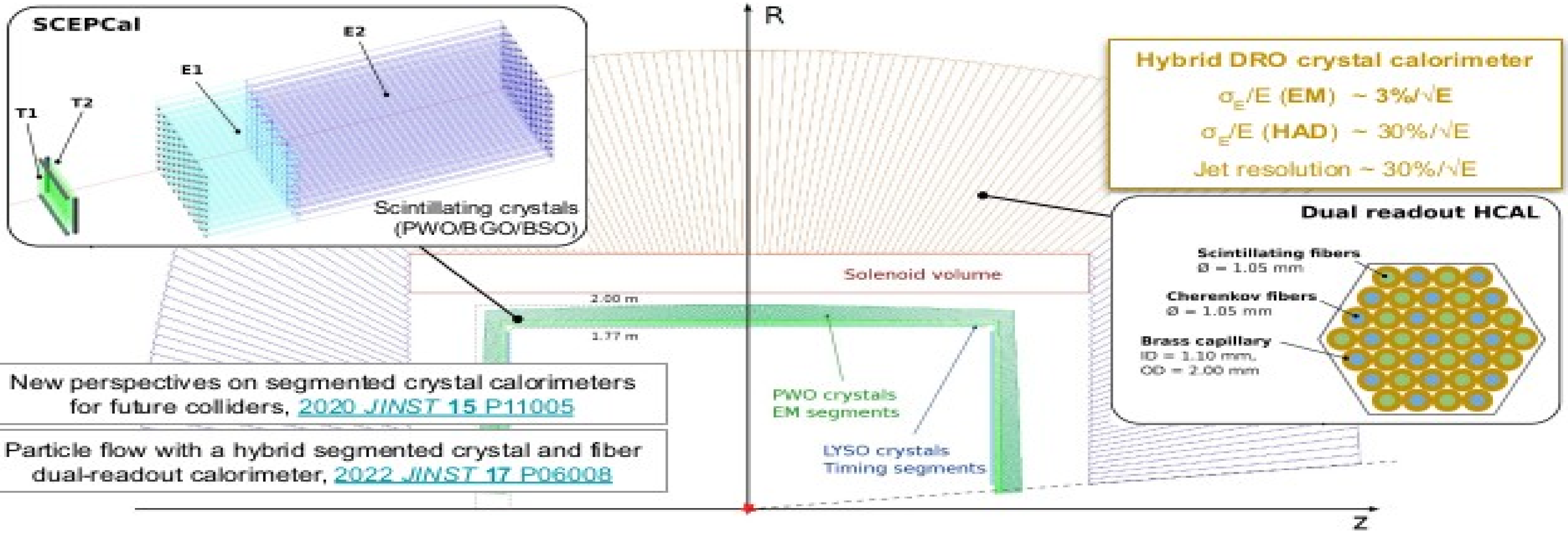
Dual-readout crystal options (IDEA++)

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

Ongoing efforts within US Calvision, IDEA and Crystal Clear collaborations

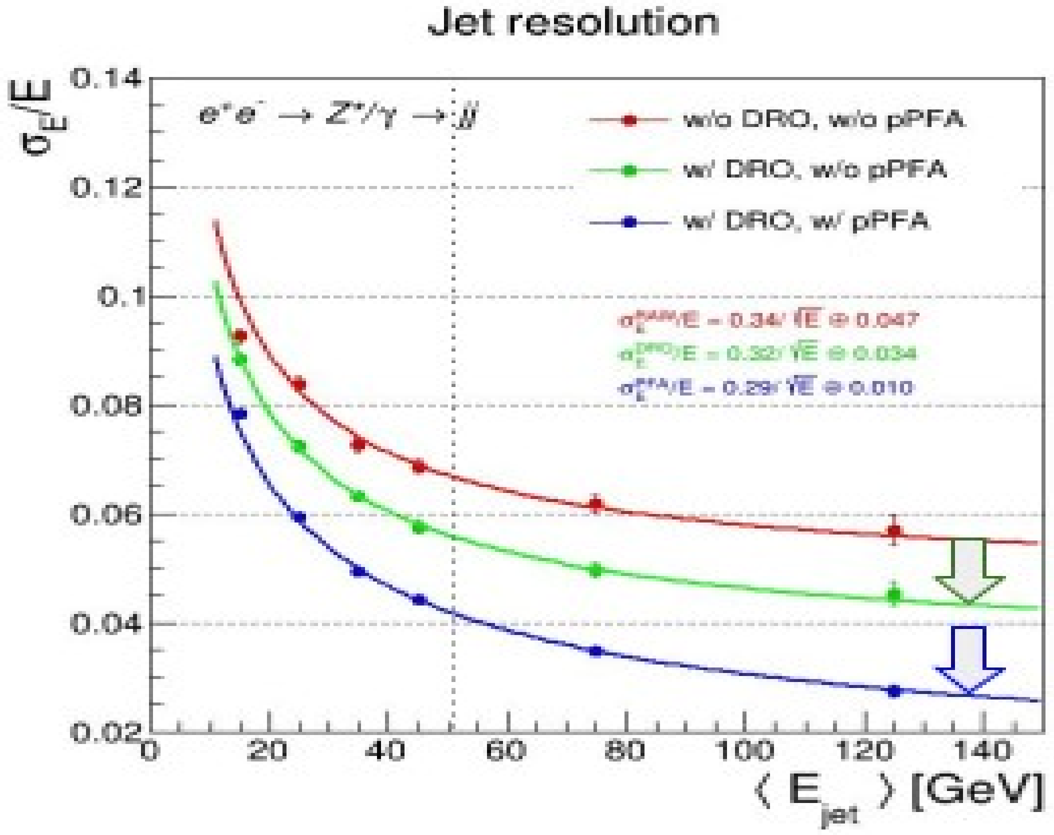
Proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPMs)

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



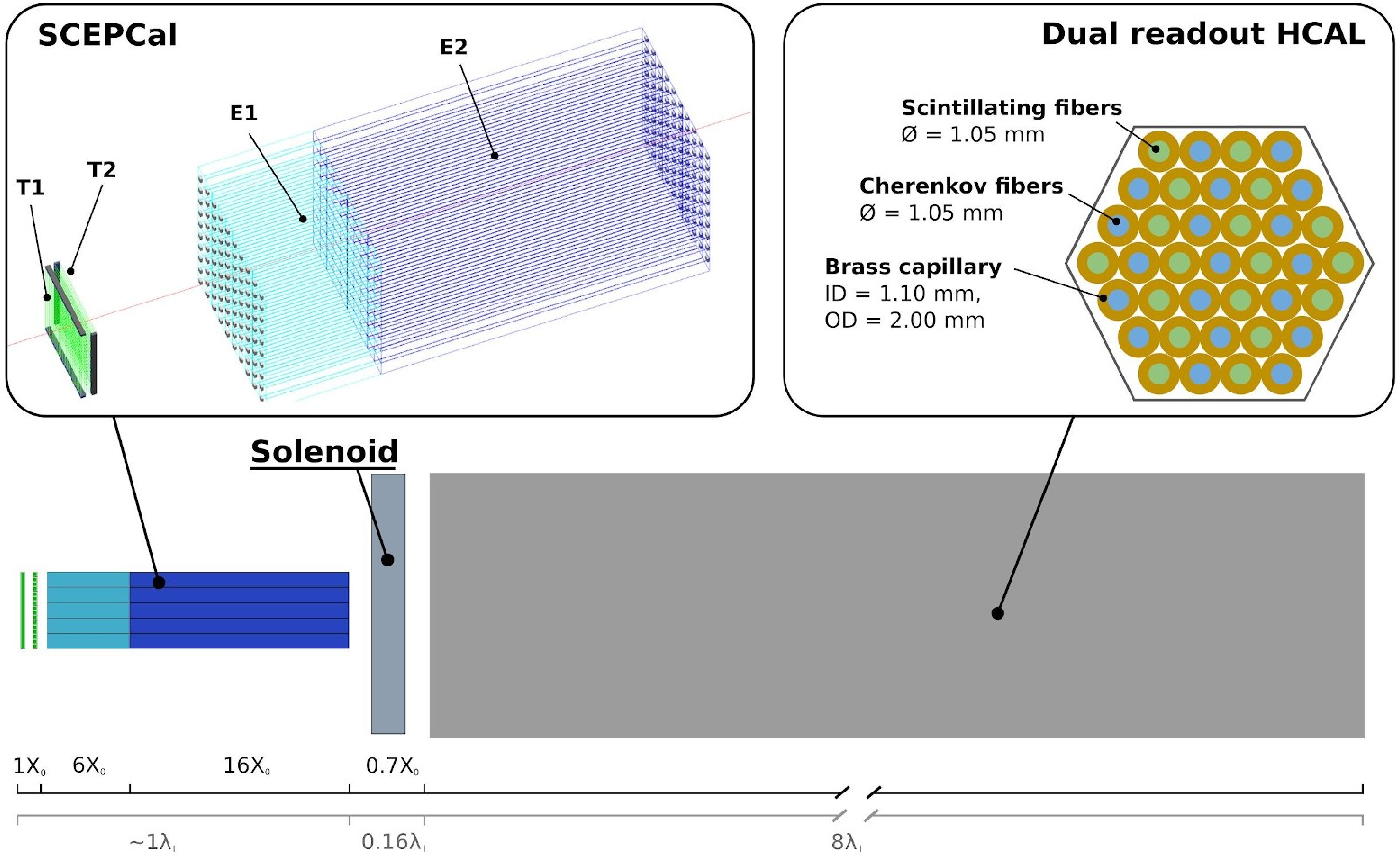
New perspectives on segmented crystal calorimeters for future colliders, 2020 *JINST* 15 P11005

Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter, 2022 *JINST* 17 P06008



Crystal option (IDEA++)

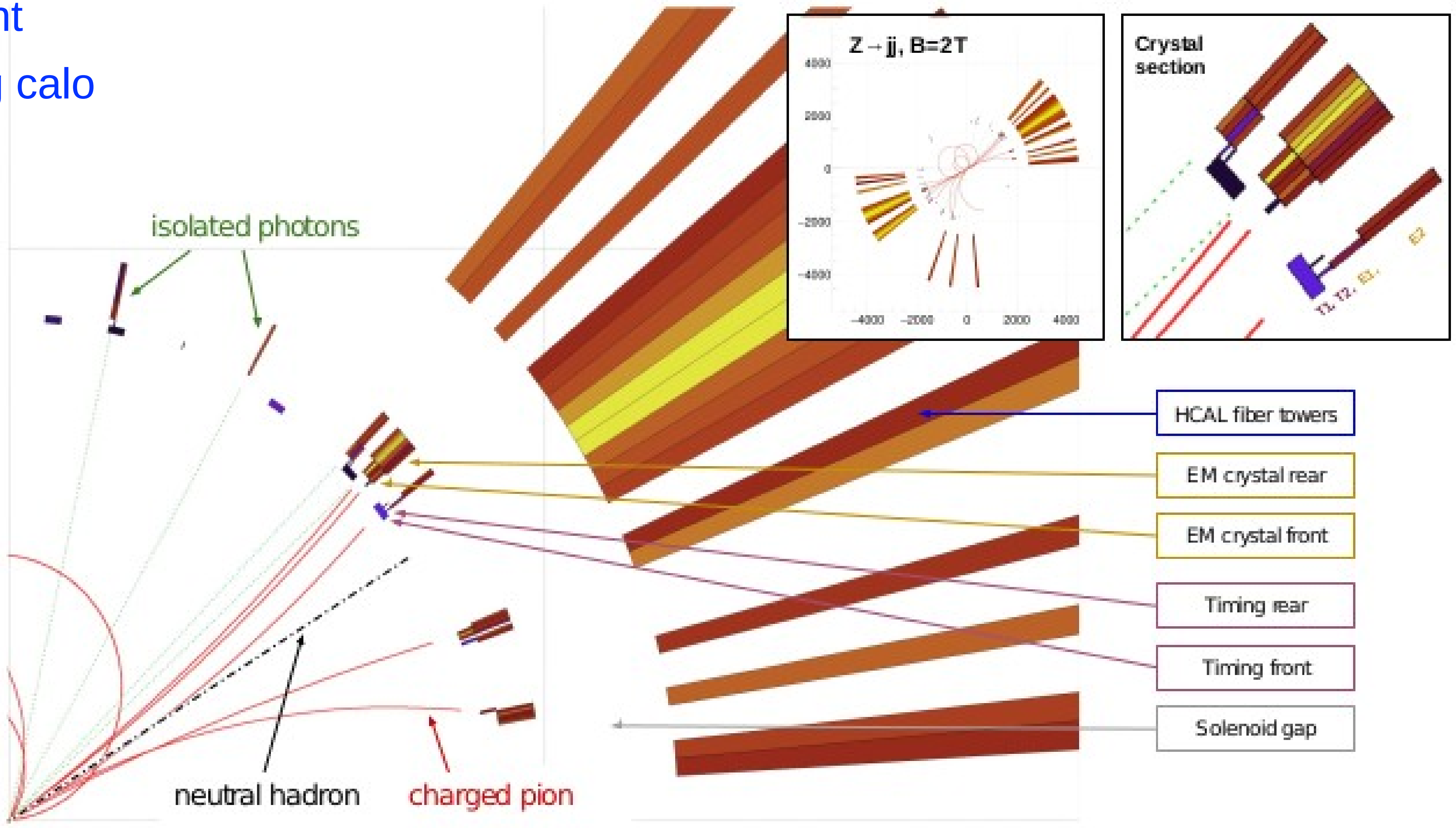
- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% /\sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$



IDEA++ dual-readout-PFA

Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo



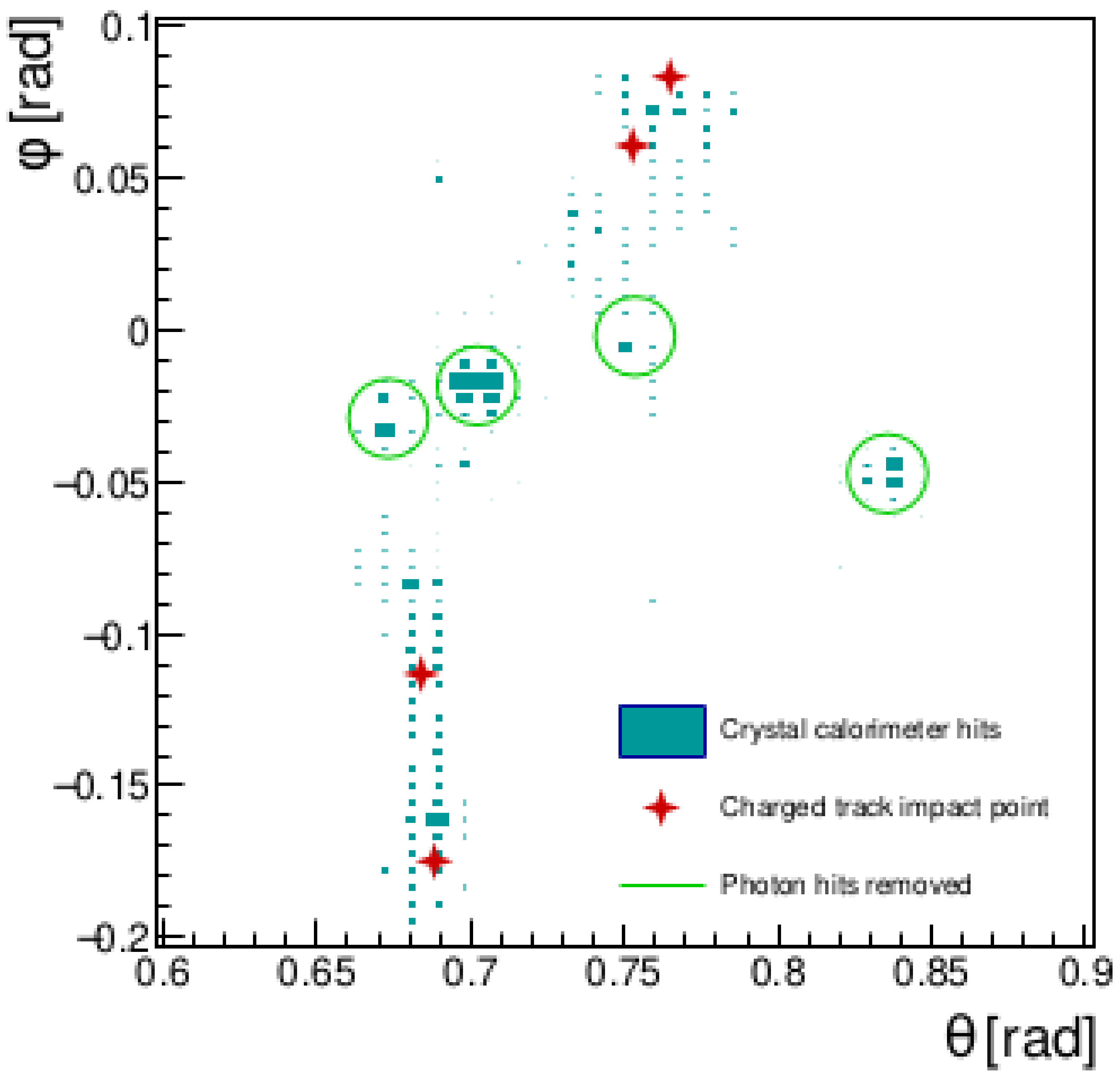
IDEA++ dual-readout-PFA

Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)



IDEA++ dual-readout-PFA

Geant4 simulation of $Z \to jj$ events:

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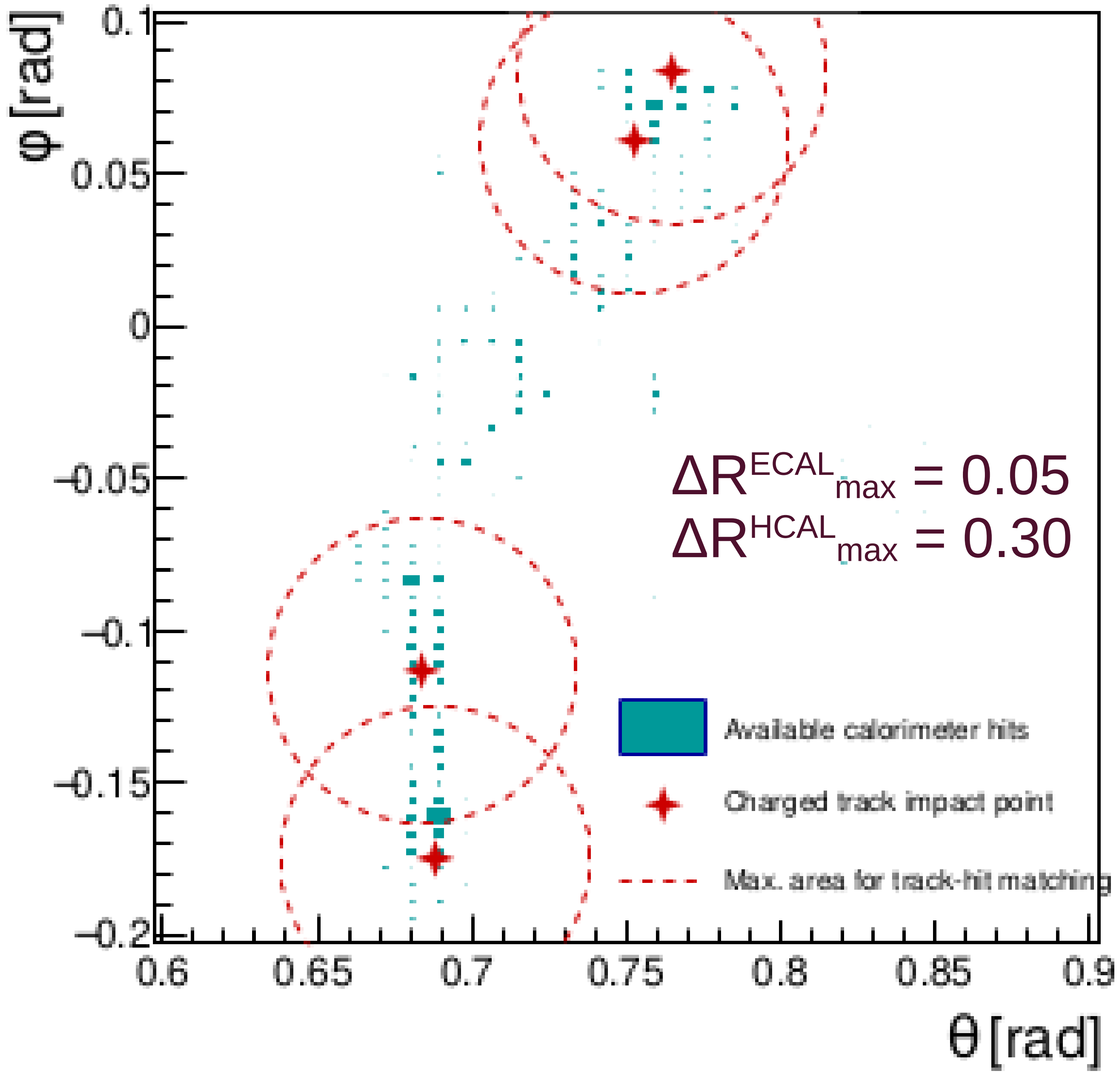
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance



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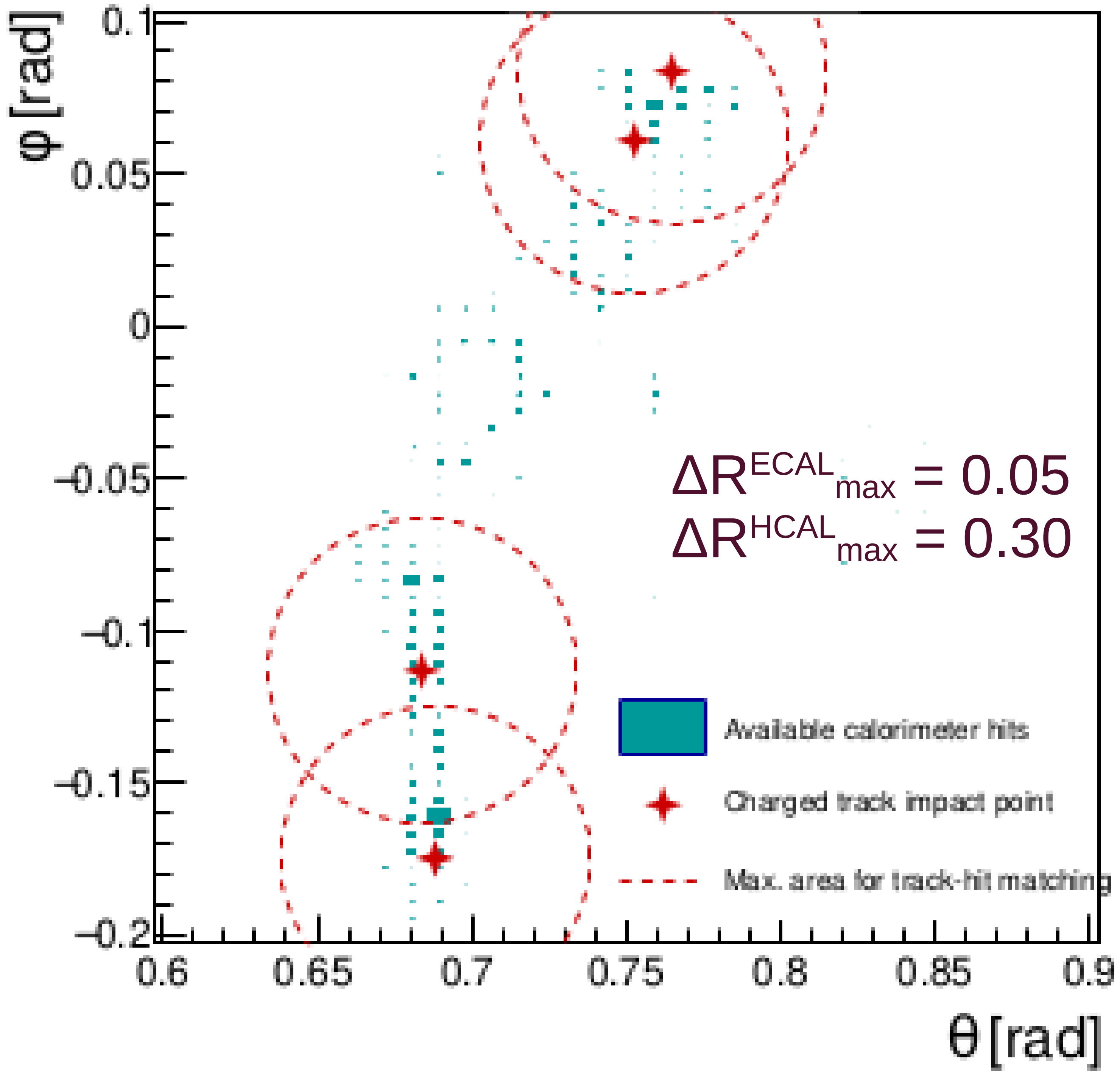
$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone(s)



$\Delta R^{ECAL}_{max} = 0.05$
$\Delta R^{HCAL}_{max} = 0.30$

IDEA++ dual-readout-PFA

Geant4 simulation of Z→jj events:

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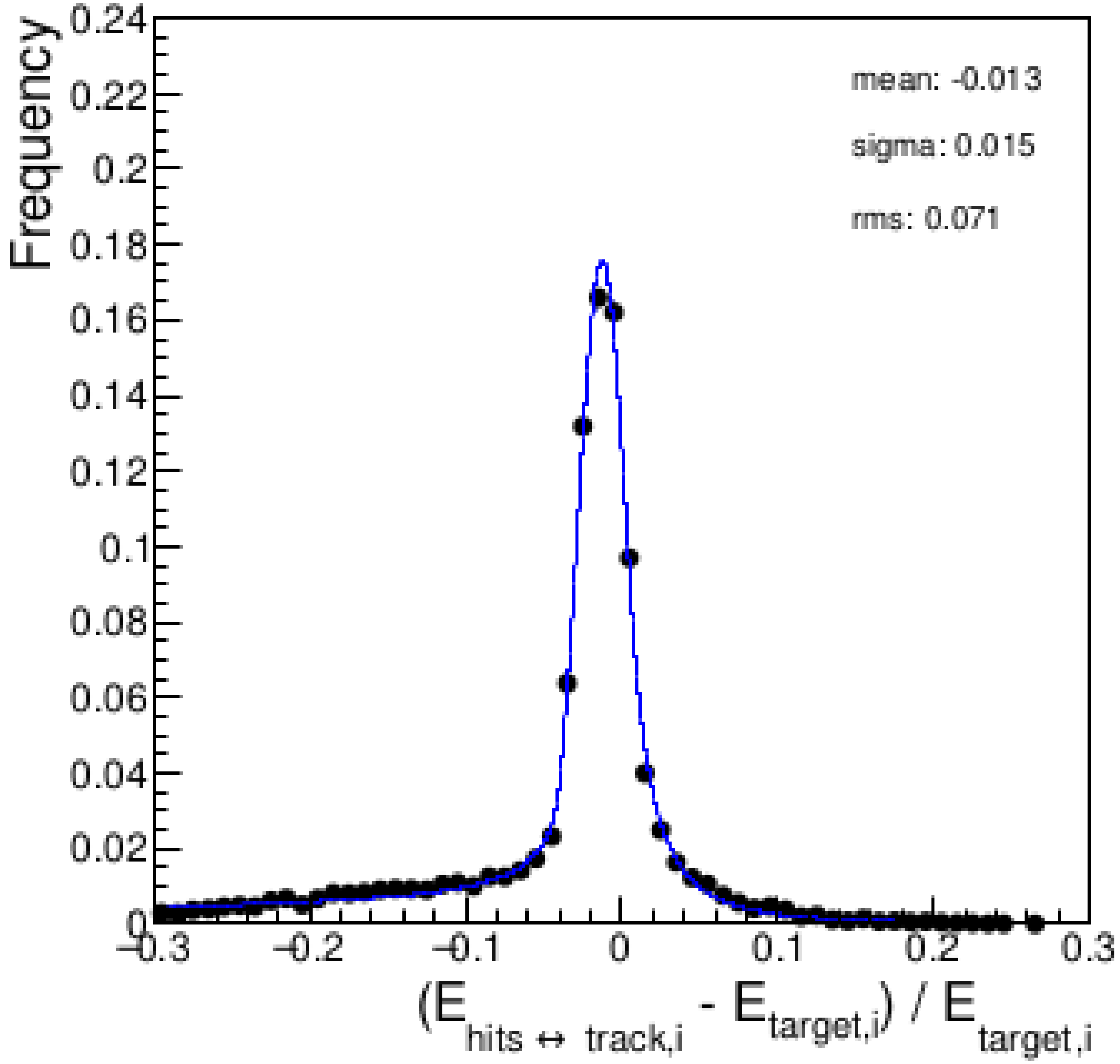
$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone(s)
- compare with E_{target}(track)



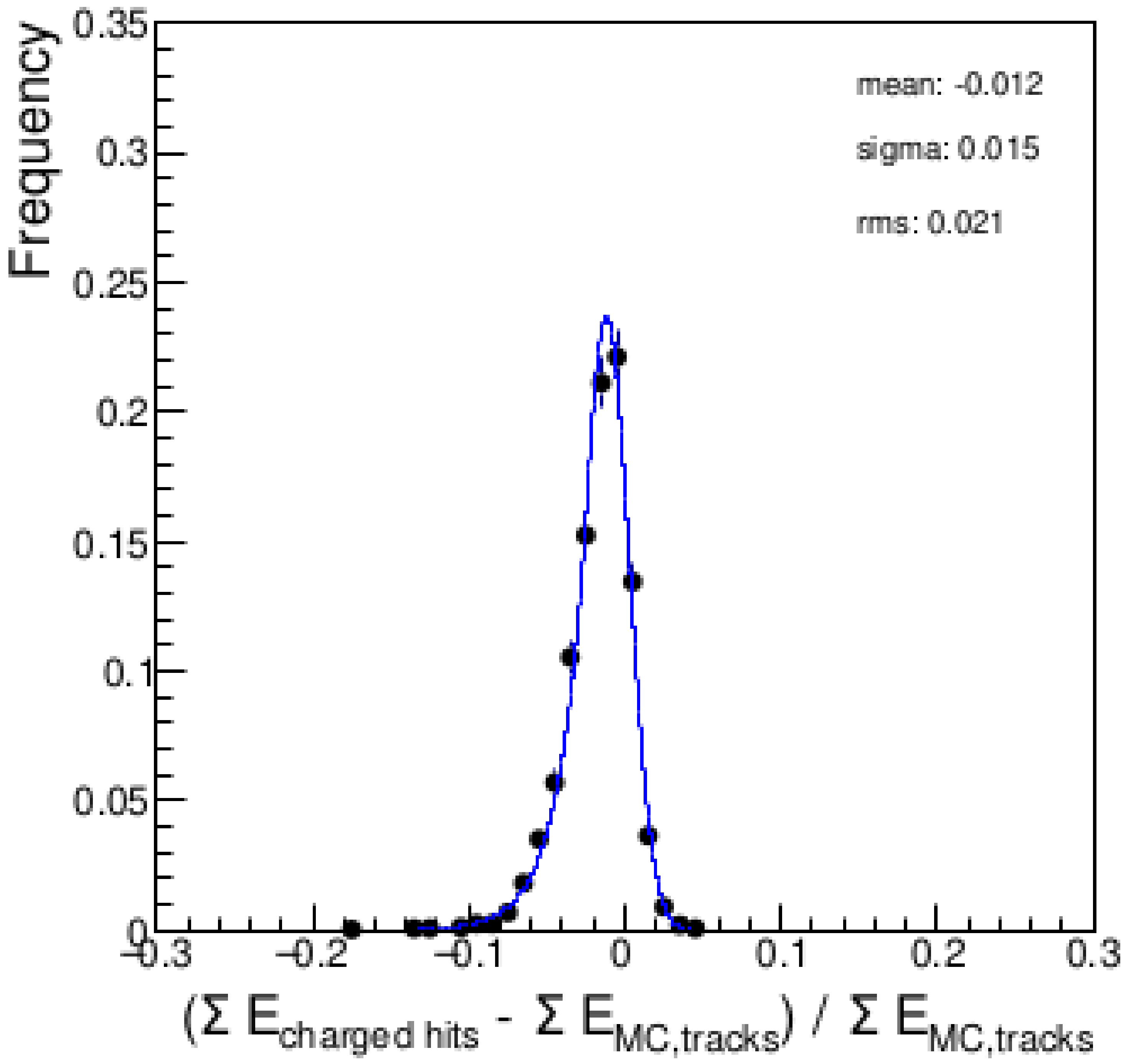
IDEA++ dual-readout-PFA

Geant4 simulation of $Z \rightarrow jj$ events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

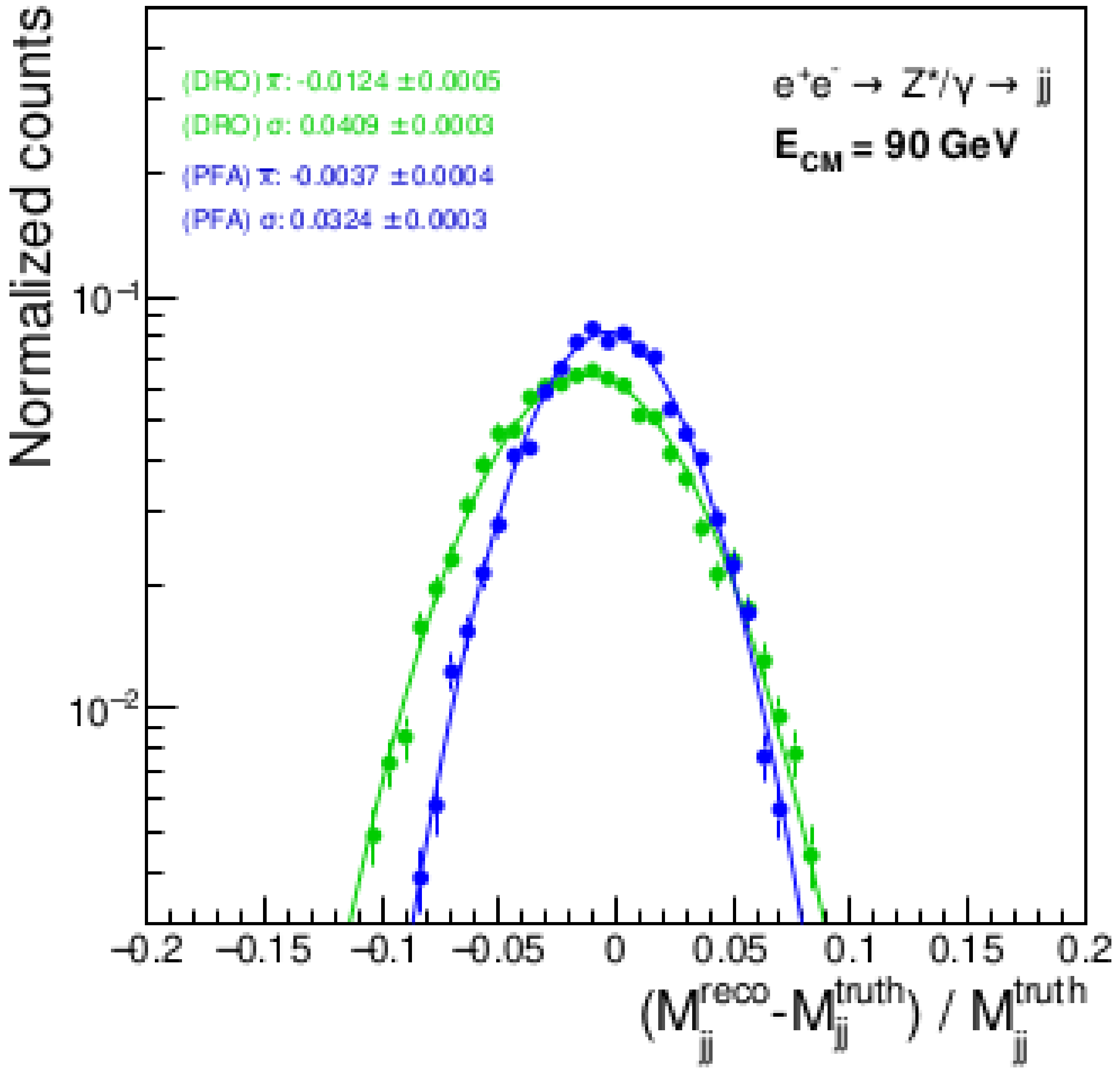
- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone(s)
- compare with E_{target}(track)
- if “good” agreement remove hits and track

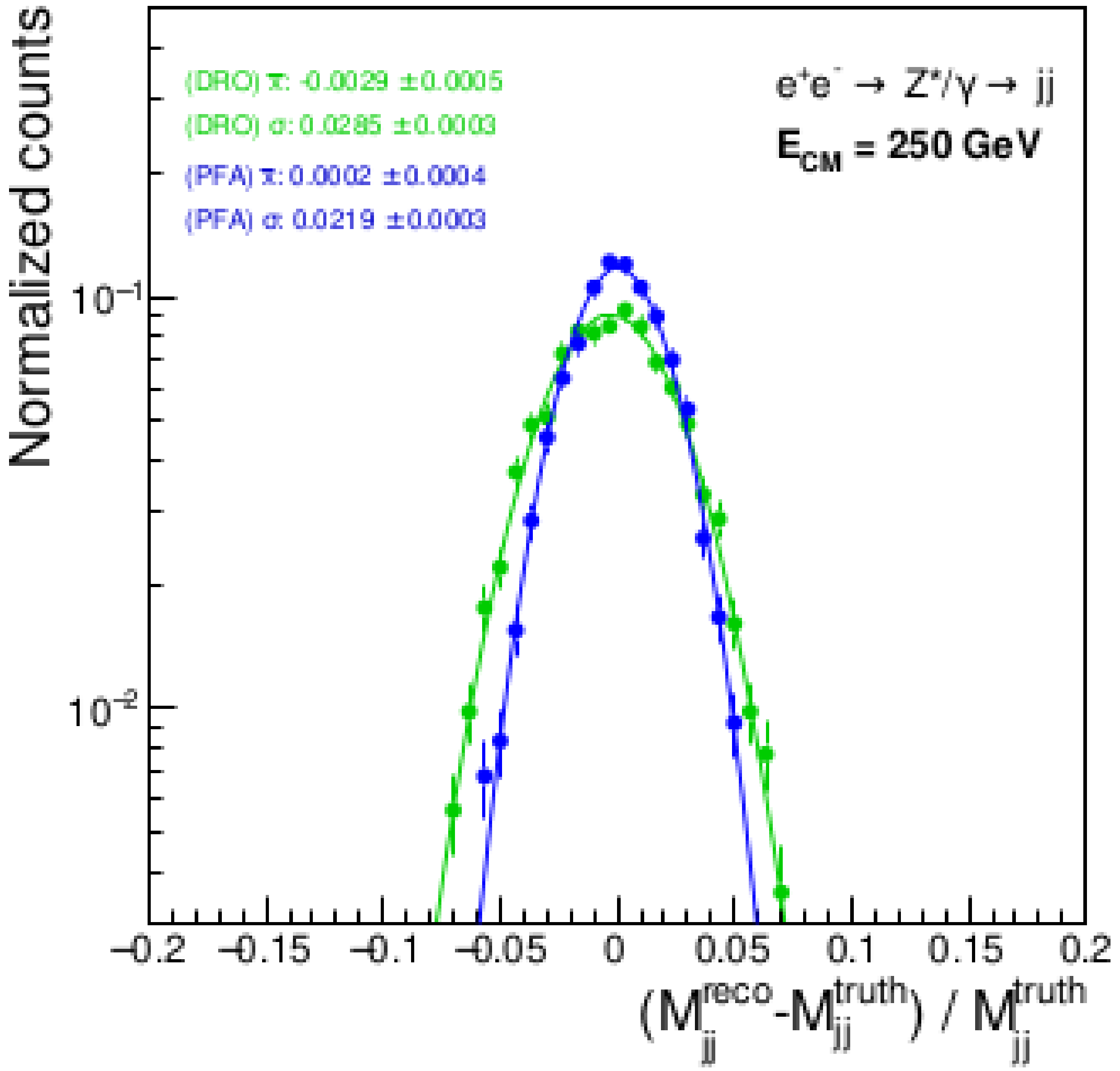


IDEA++ dual-readout-PFA

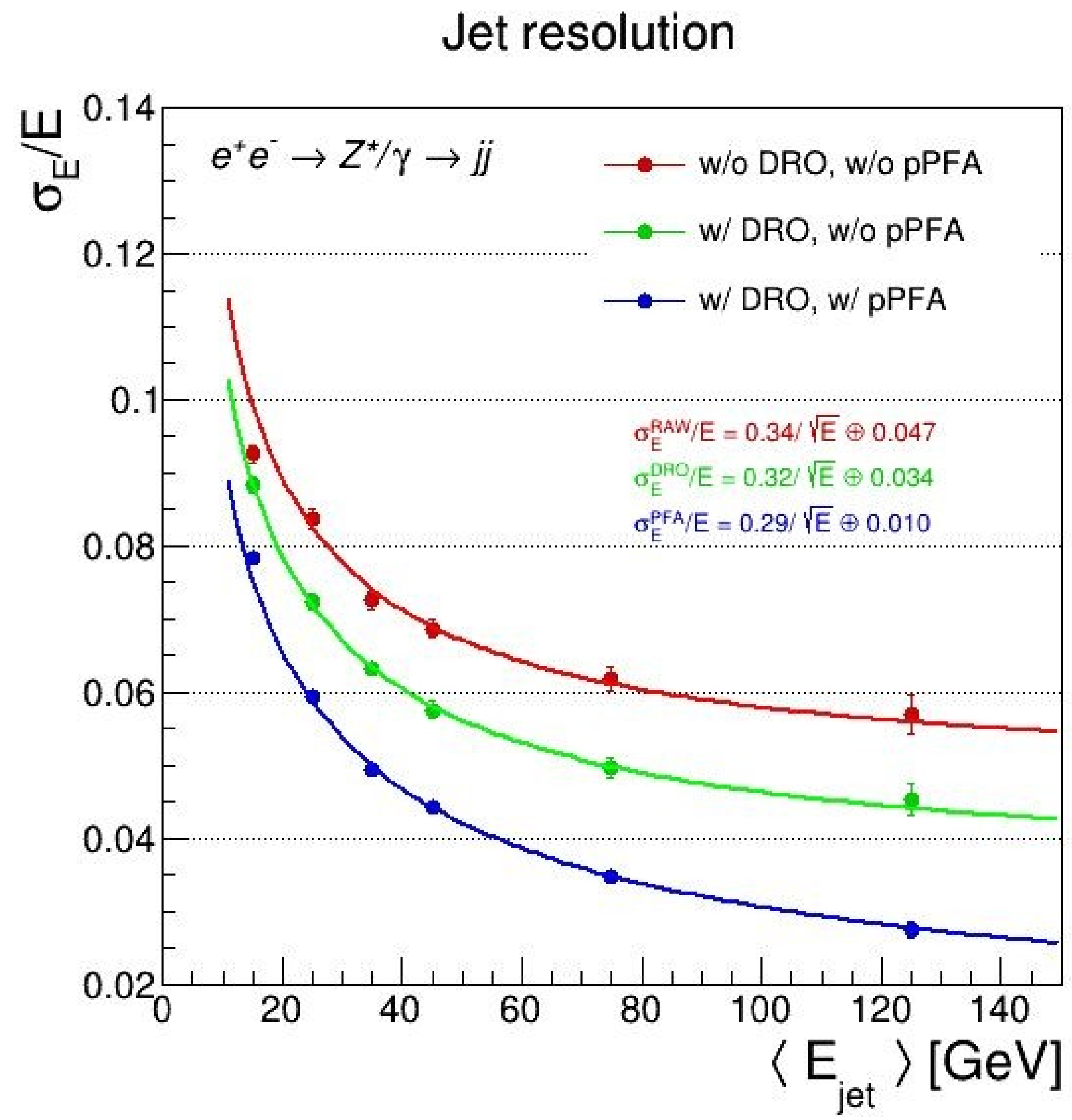
... continue

- apply k_t algorithm (e.g. Durham) for two jets





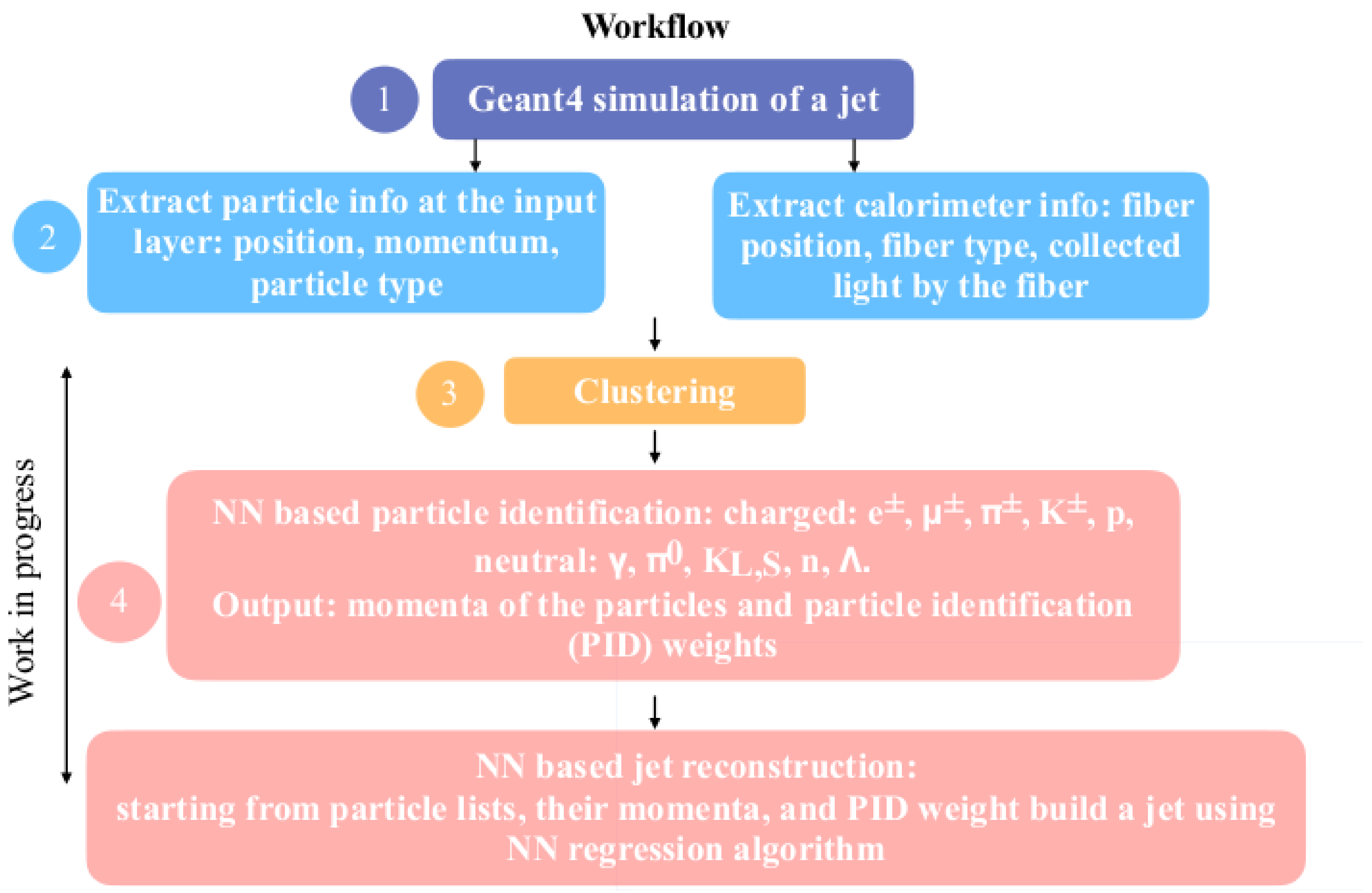
finally ...

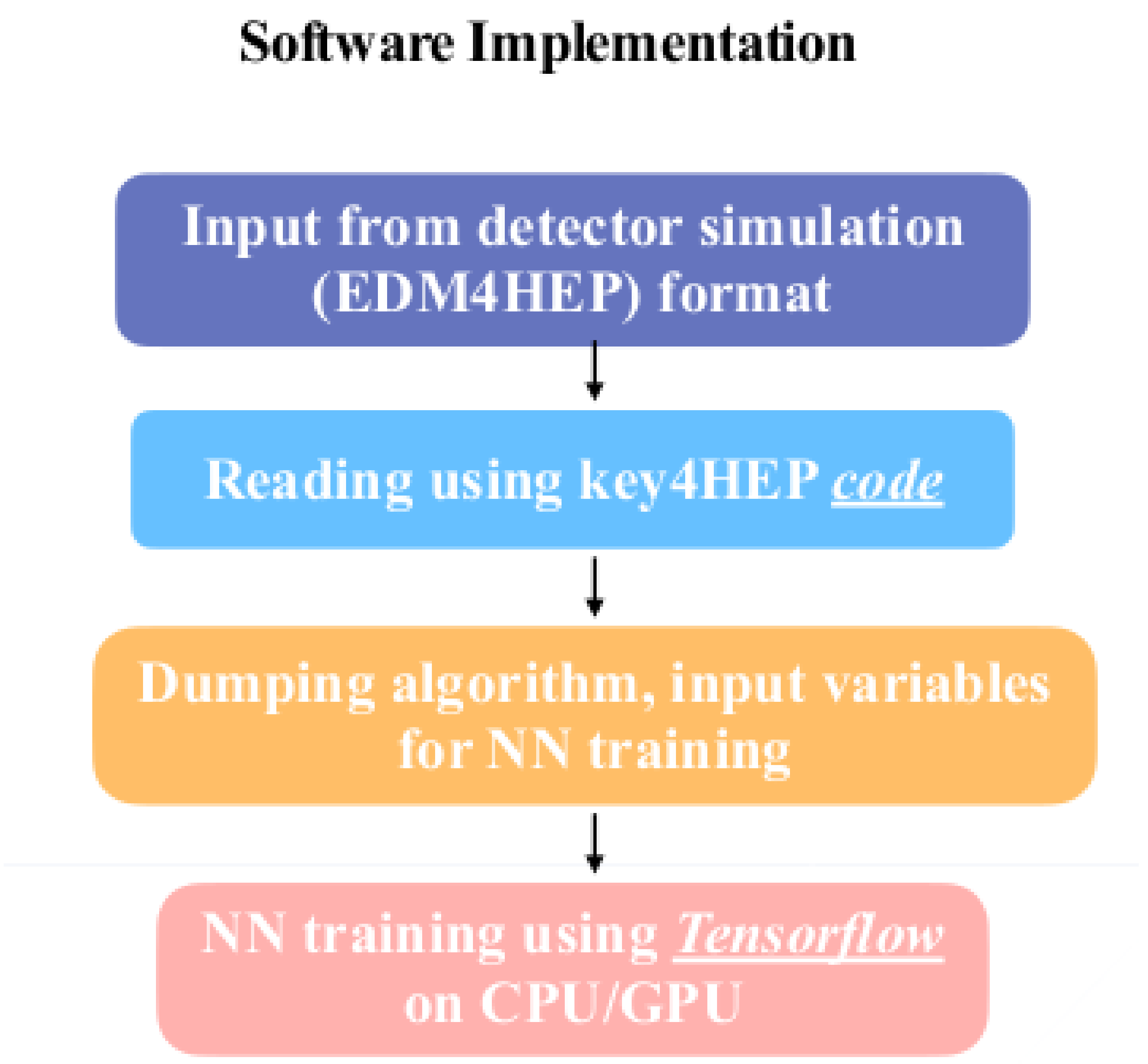


Jet resolution
σ_E/E
$e^+e^- \to Z^*/\gamma \to jj$
w/o DRO, w/o pPFA
w/ DRO, w/o pPFA
w/ DRO, w/ pPFA
$\sigma_E^{RAW}/E = 0.34/\sqrt{E} \oplus 0.047$
$\sigma_E^{DRO}/E = 0.32/\sqrt{E} \oplus 0.034$
$\sigma_E^{PFA}/E = 0.29/\sqrt{E} \oplus 0.010$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
20
40
60
80
100
120
140
$\langle E_{jet} \rangle$ [GeV]

dual-readout in Pandora PFA

build a NN based algorithm for jet reconstruction and insert it in Pandora interfaced to key4HEP

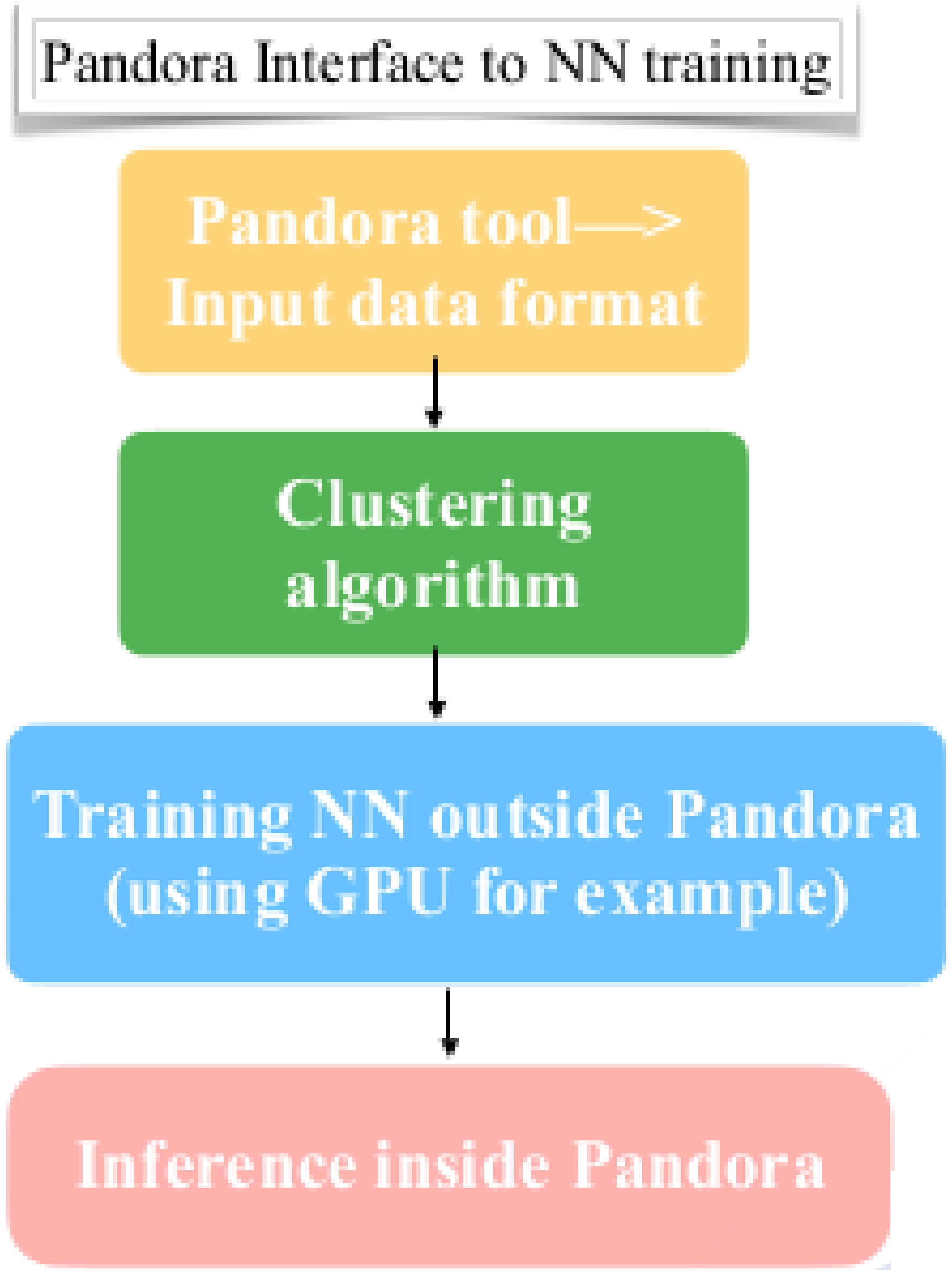




dual-readout in Pandora PFA

flowchart:

1. build calorimeter clusters with one of Pandora algorithms

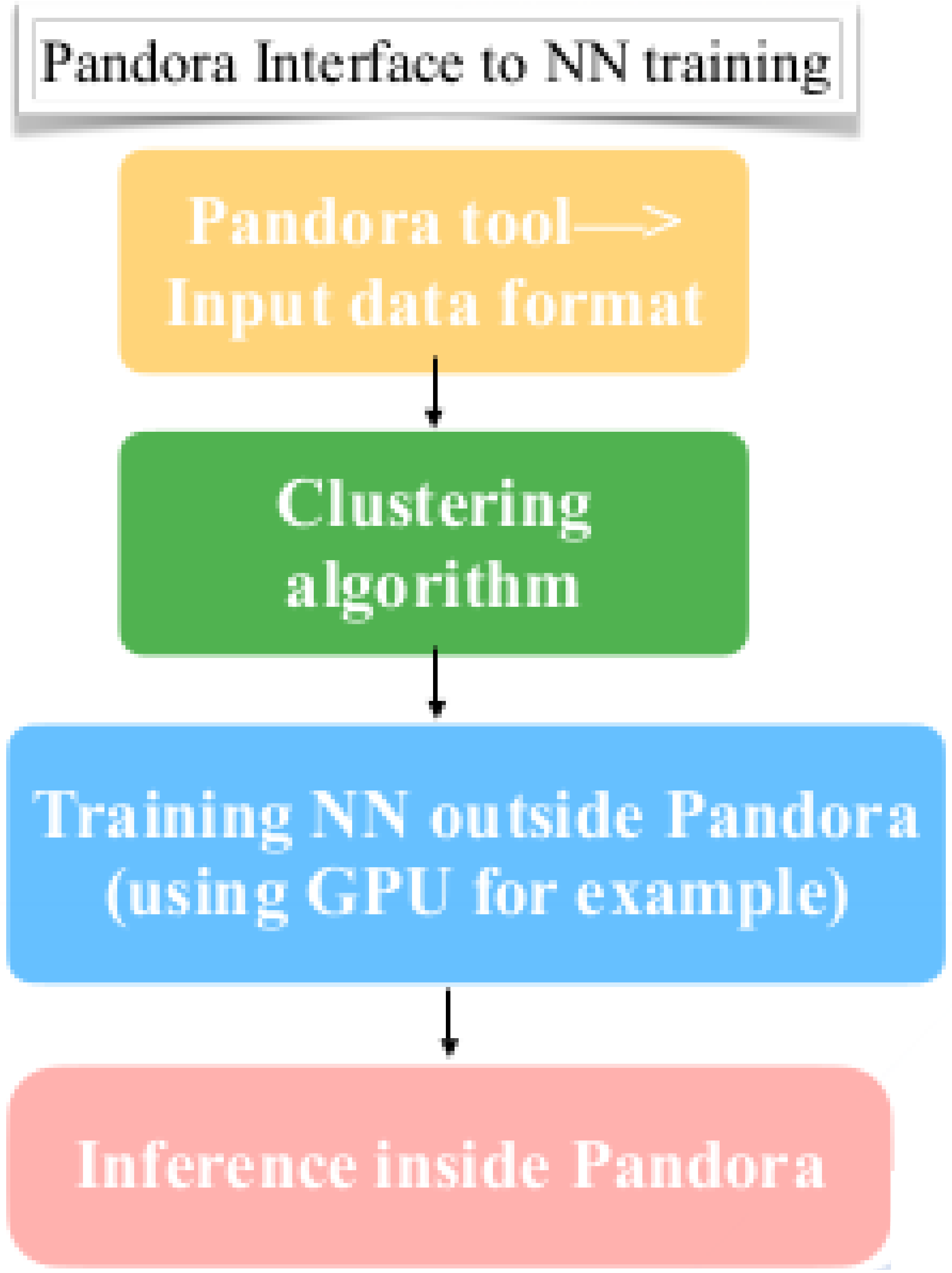


dual-readout in Pandora PFA

flowchart:

1. build calorimeter clusters with one of Pandora algorithms

2. apply dual-readout formula



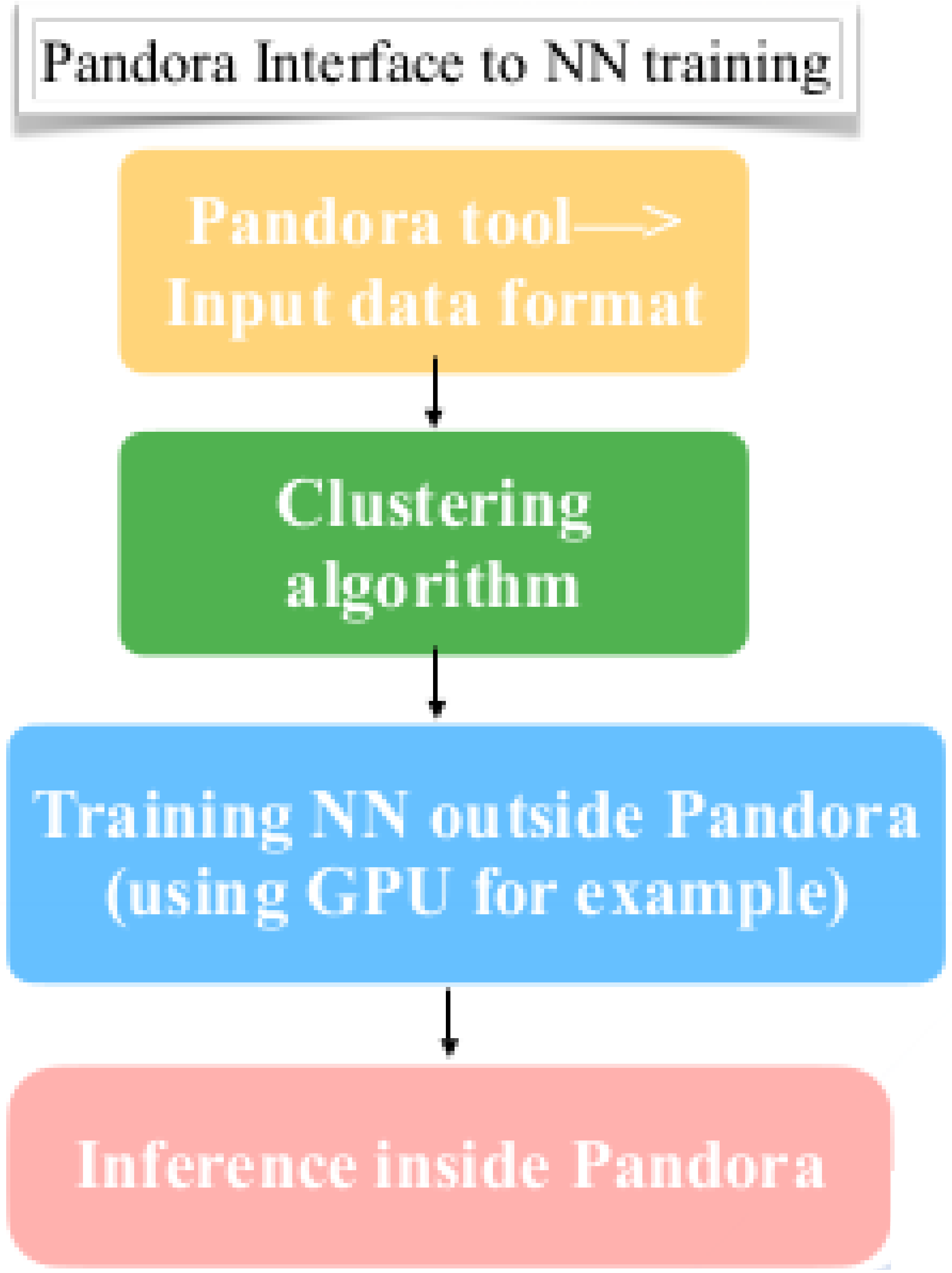
dual-readout in Pandora PFA

flowchart:

1. build calorimeter clusters with one of Pandora algorithms

2. apply dual-readout formula

3. NN particle identification (with "charged" cluster removal)
   to be developed for Pandora



dual-readout in Pandora PFA

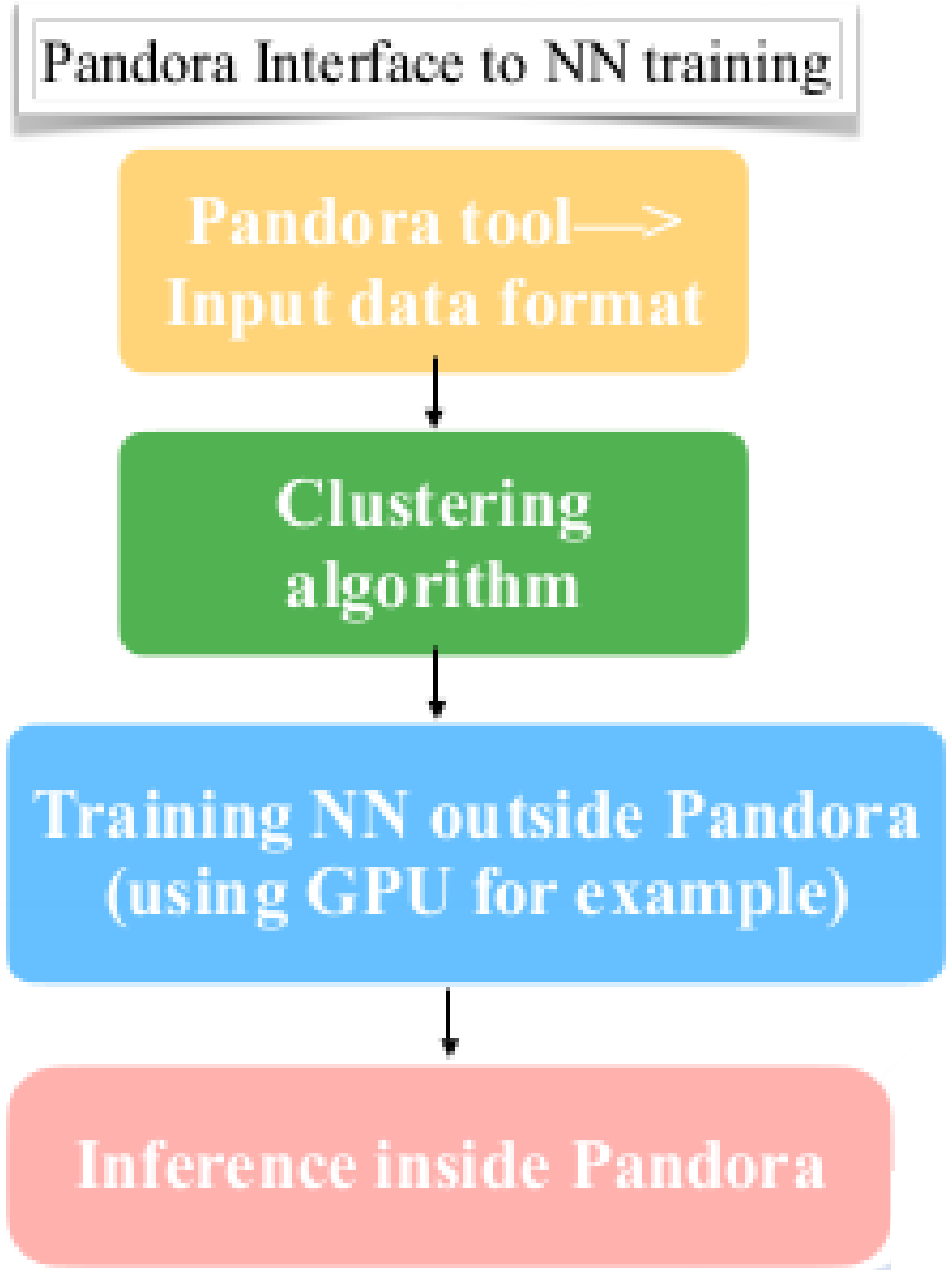
flowchart:

1. build calorimeter clusters with one of Pandora algorithms

2. apply dual-readout formula

3. NN particle identification (with “charged” cluster removal)
   to be developed for Pandora

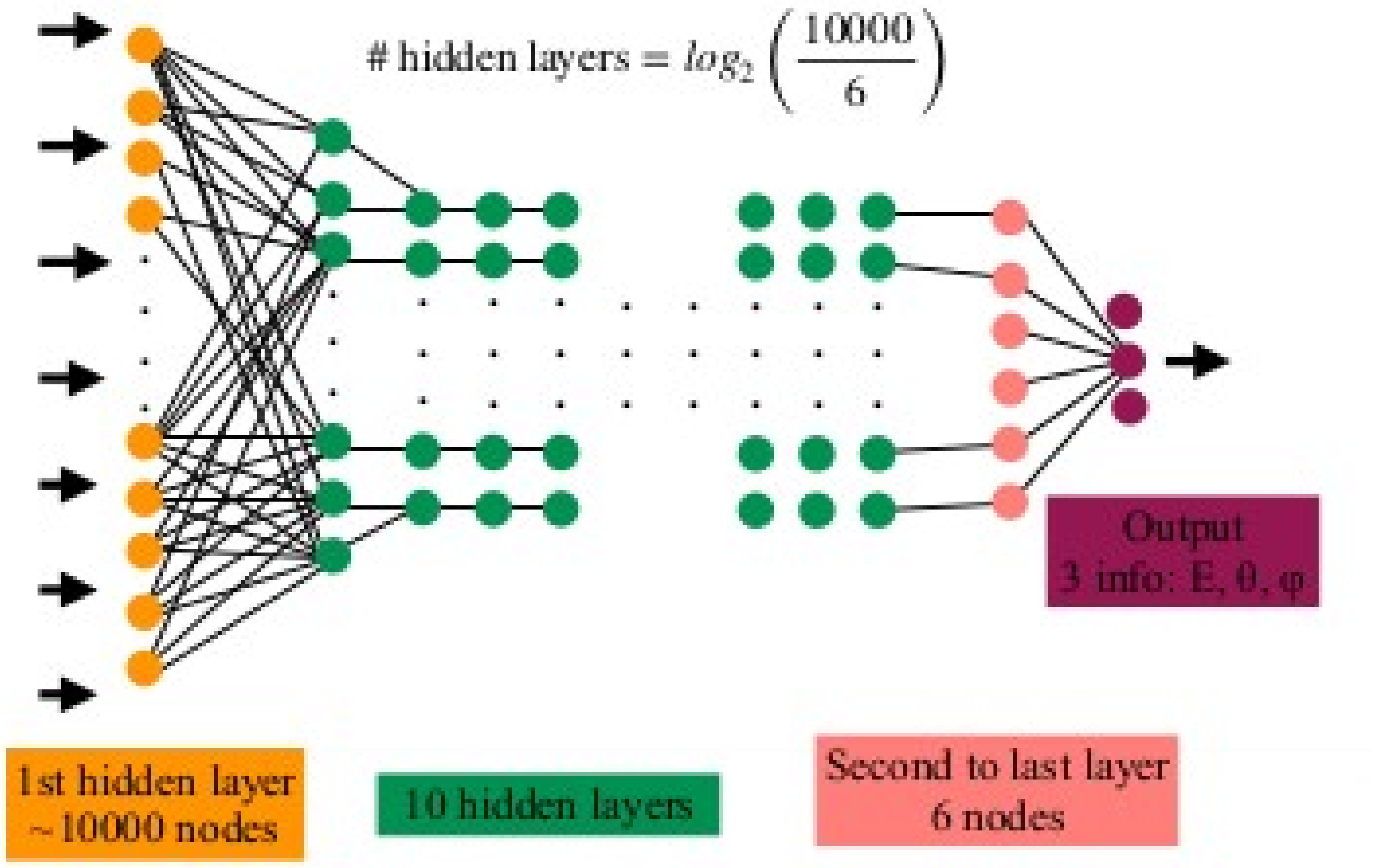
4. NN jet reconstruction algorithm to be developed for Pandora



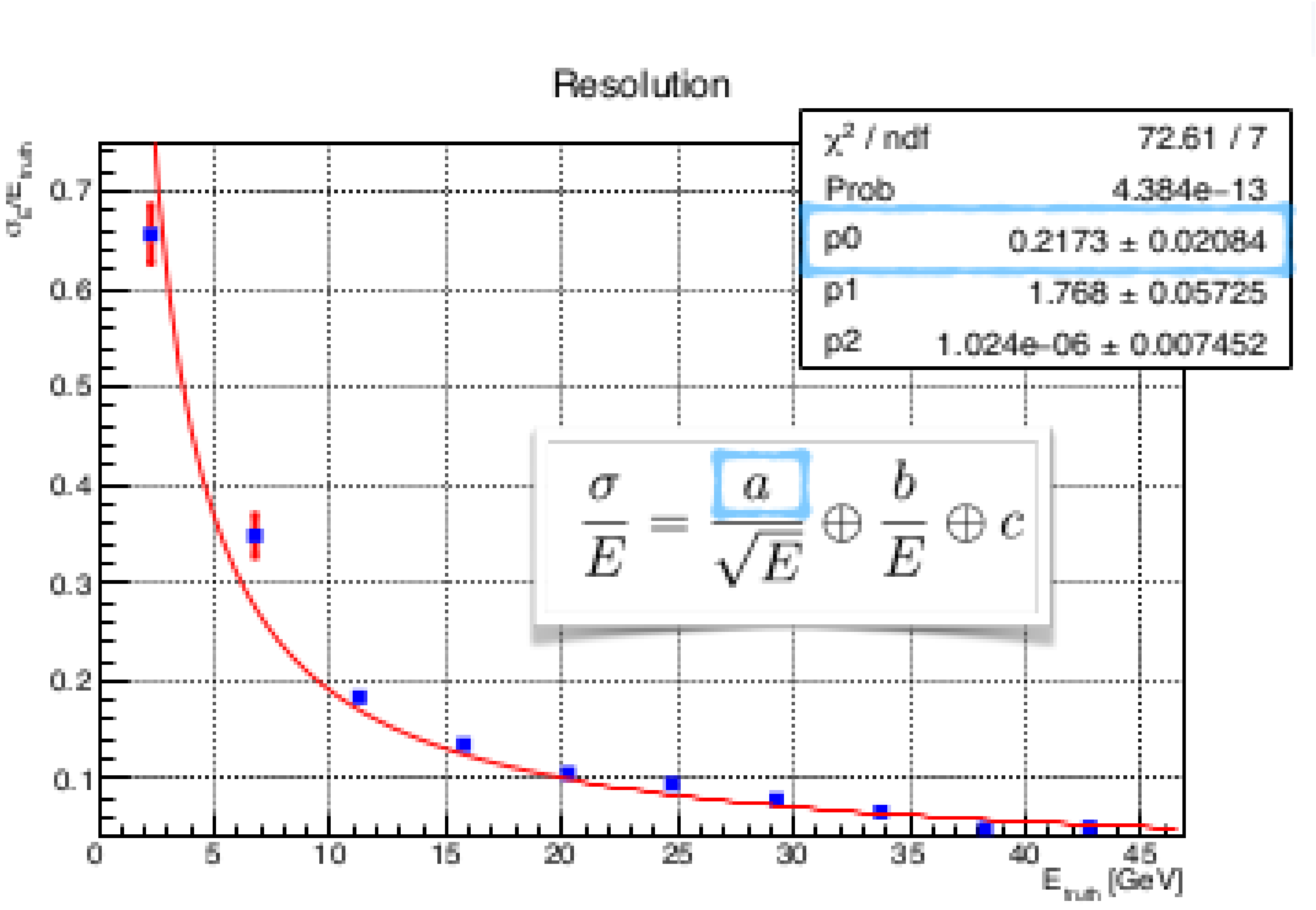
NN training on GPUs

started working on electrons

- using Tensorflow interfaced with Keras
- 60000 info per event in average
- GPU memory issues / CPU time issues



Very preliminary results



Performance still worse than standard reconstruction

Too naive architecture? ***Work in progress***

Conclusions

IDEA calorimetry concept evolving

R&D ongoing on many directions

High (pointing) granularity complemented by timing measurements may provide highly performant results

Usage of PFA should also boost it

EM crystal option appears to boost EM calorimetry performance without spoiling hadronic one

… but …

Conclusions

IDEA calorimetry concept evolving

R&D ongoing on many directions

High (pointing) granularity complemented by timing measurements may provide highly performant results

Usage of PFA should also boost it

EM crystal option appears to boost EM calorimetry performance without spoiling hadronic one

… but …

we need to demonstrate it with working and sizeable prototypes → work in progress
hopefully we will soon get dual-readout and Pandora speaking each other

Backup

IDEA dual-readout group

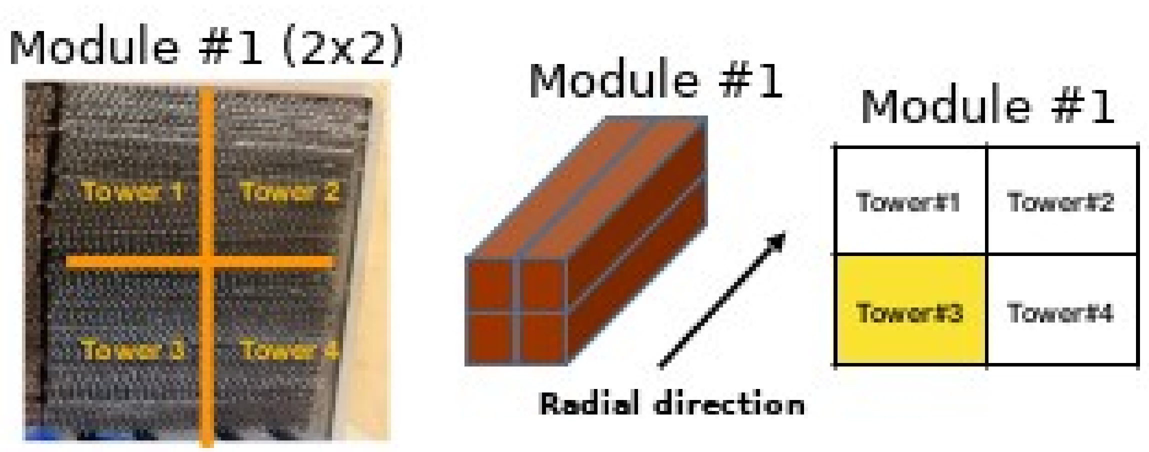
Three main activity pillars:

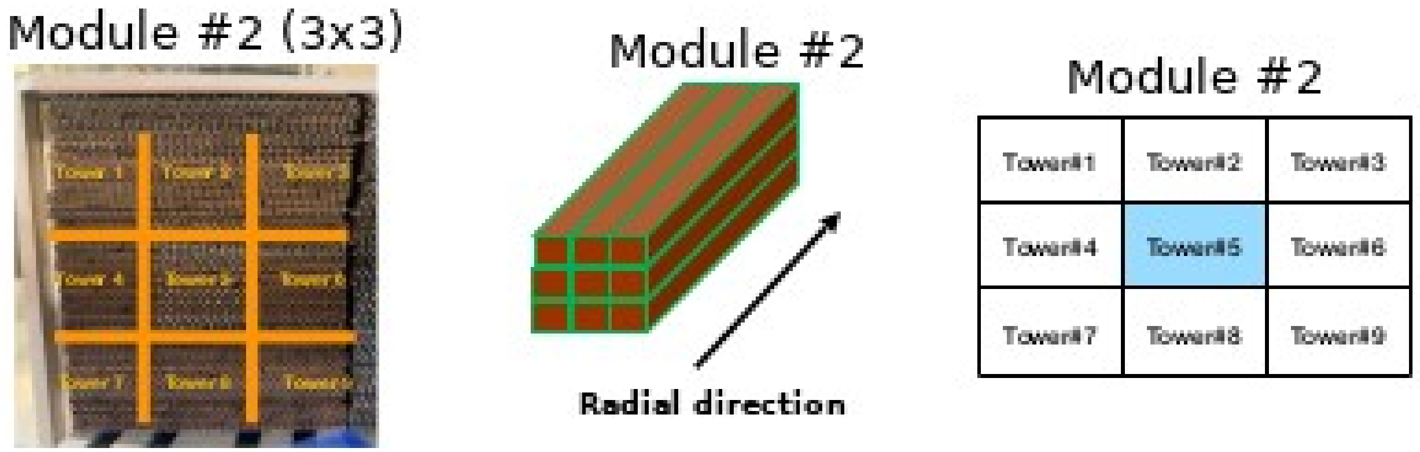
1) South Korea → projective fibre-sampling calorimeter

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

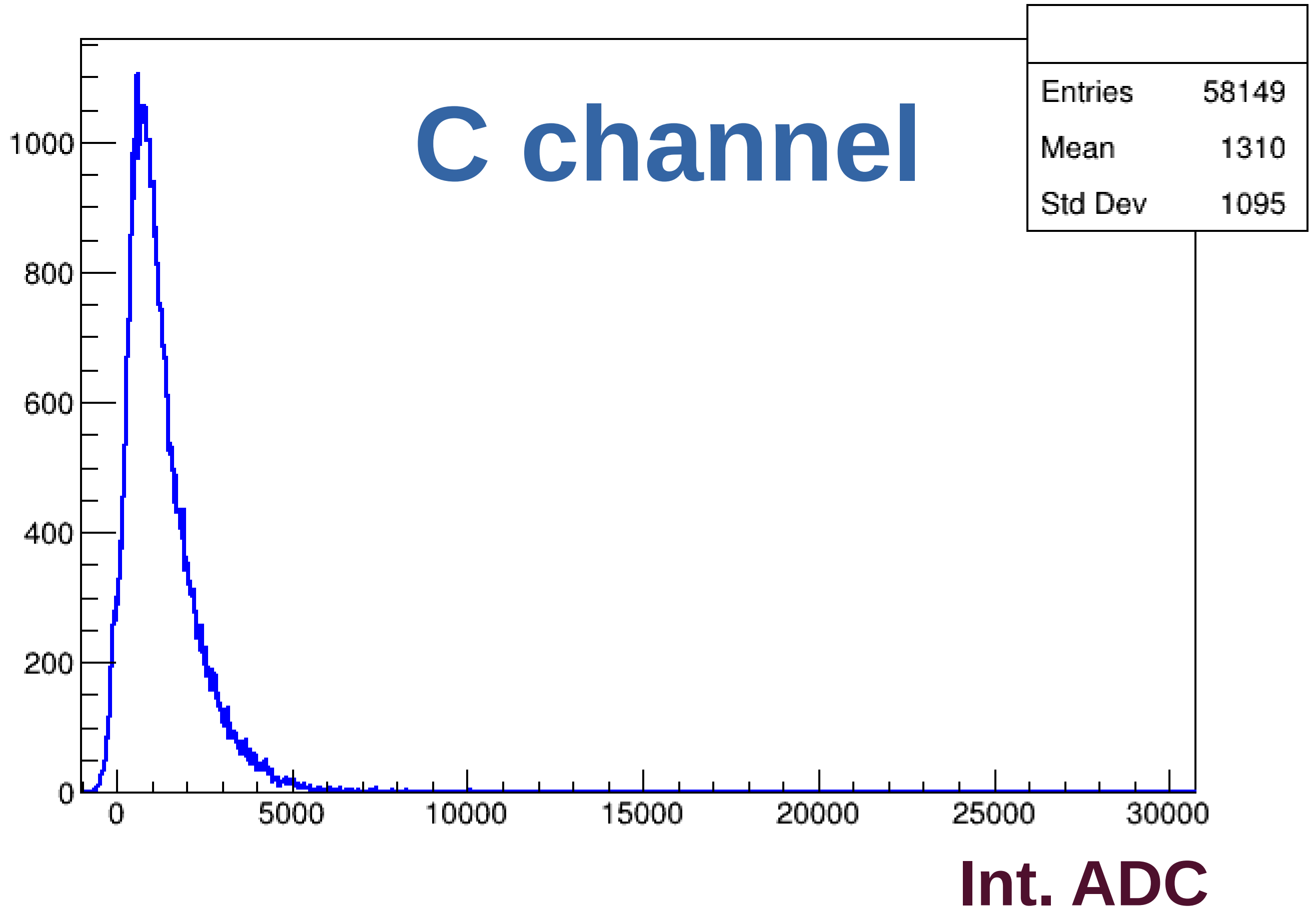
3) U.S. (Calvision project) → mainly (but not only) on crystal em calorimeter

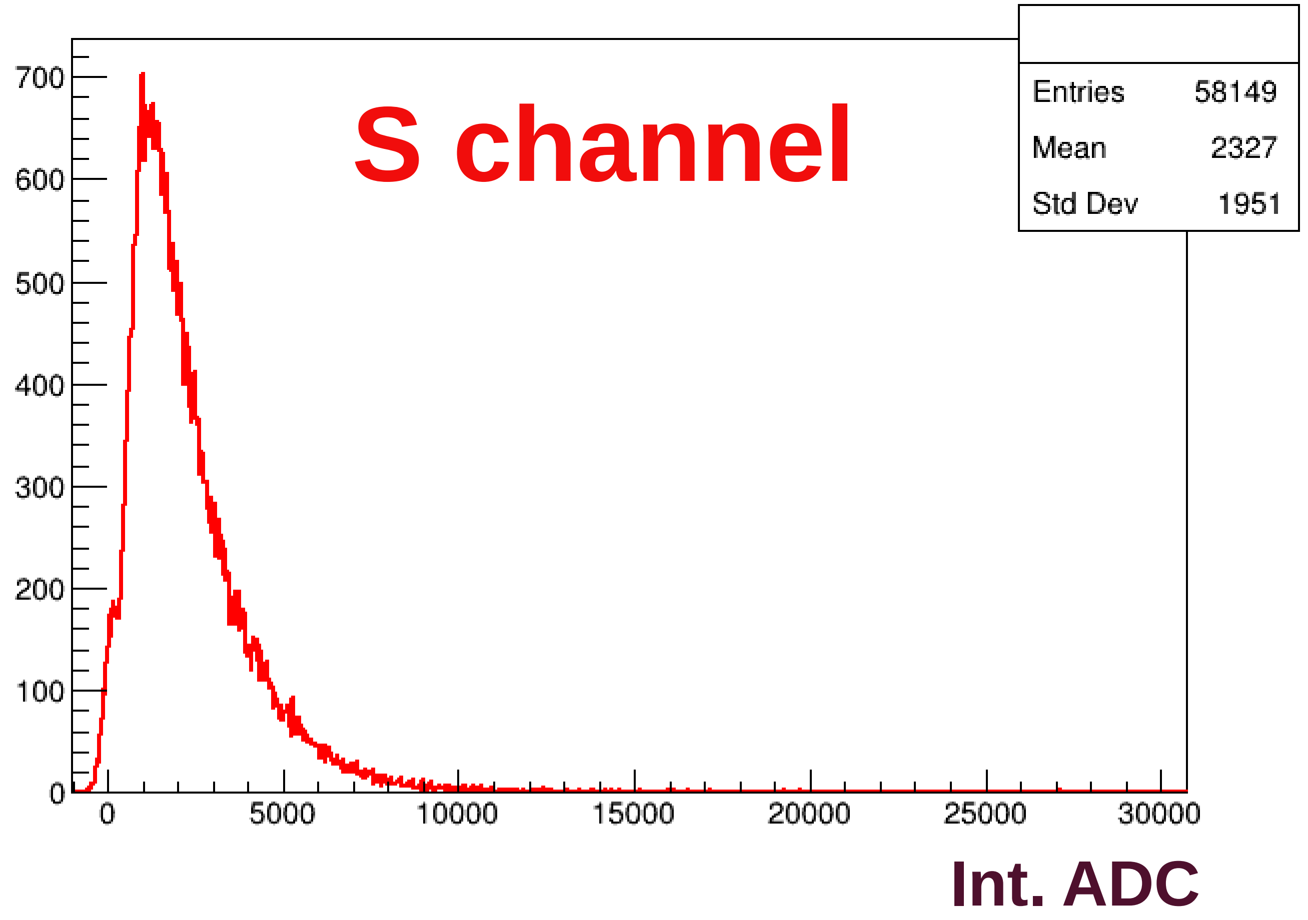
2022 Korean-prototype beam test





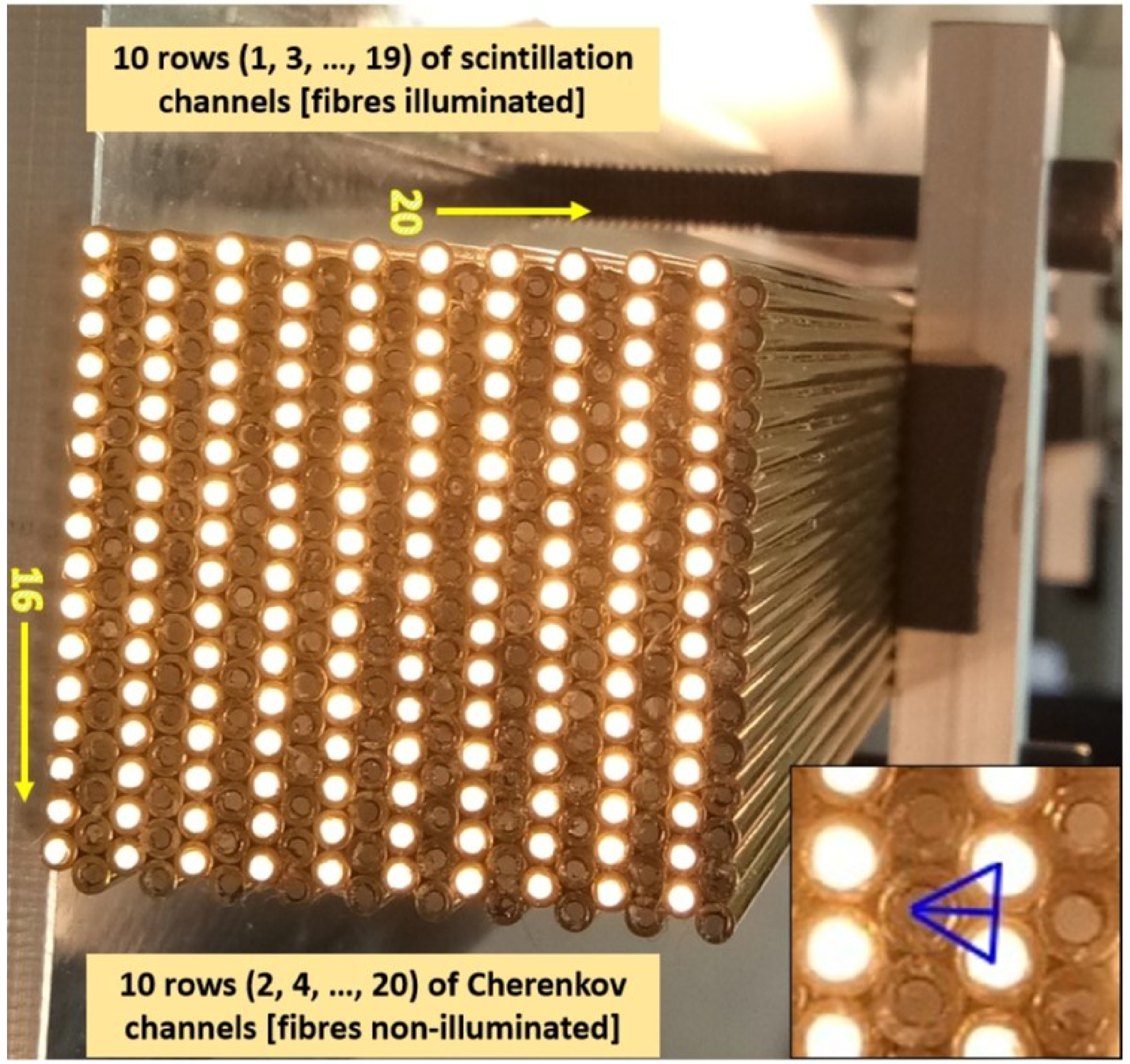
- Data analysis in progress



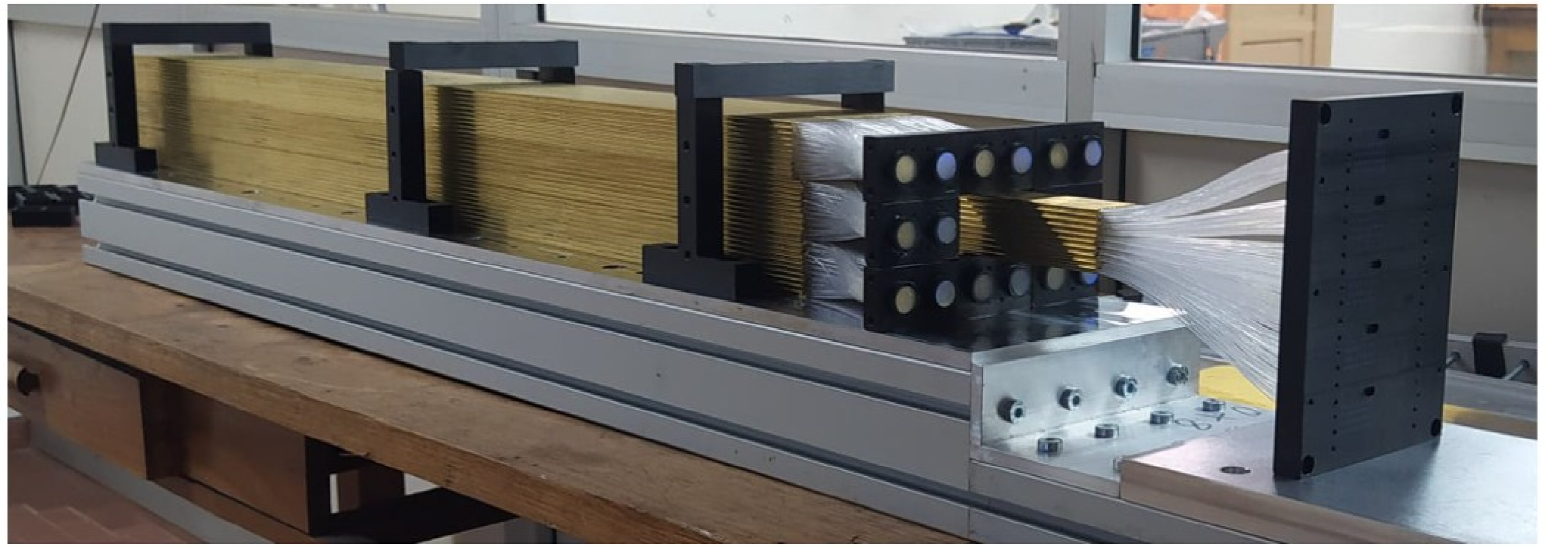


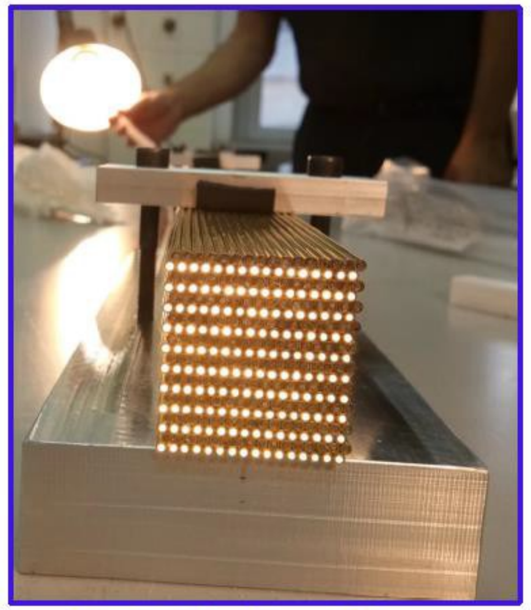
IDEA 2020 em-size bucatini prototype (EU)

Nine ~3.5×3.3 cm^2 towers

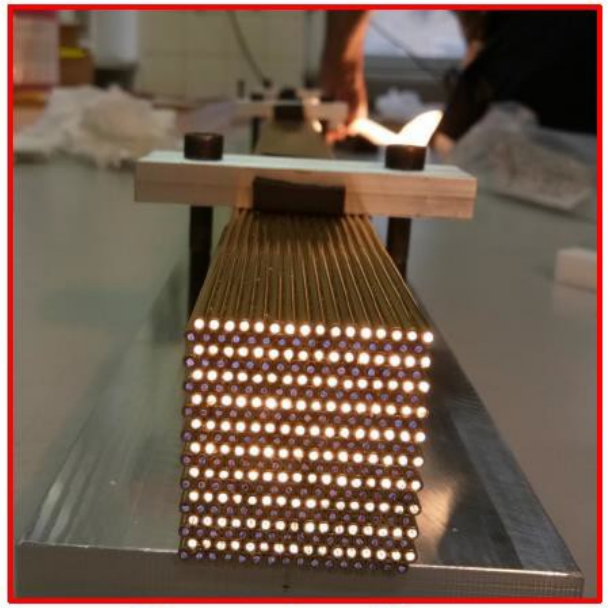


One tower (i.e. 360 fibres) w/ highly-granular (SiPM) readout





Scintillation fibers



Cherenkov fibers

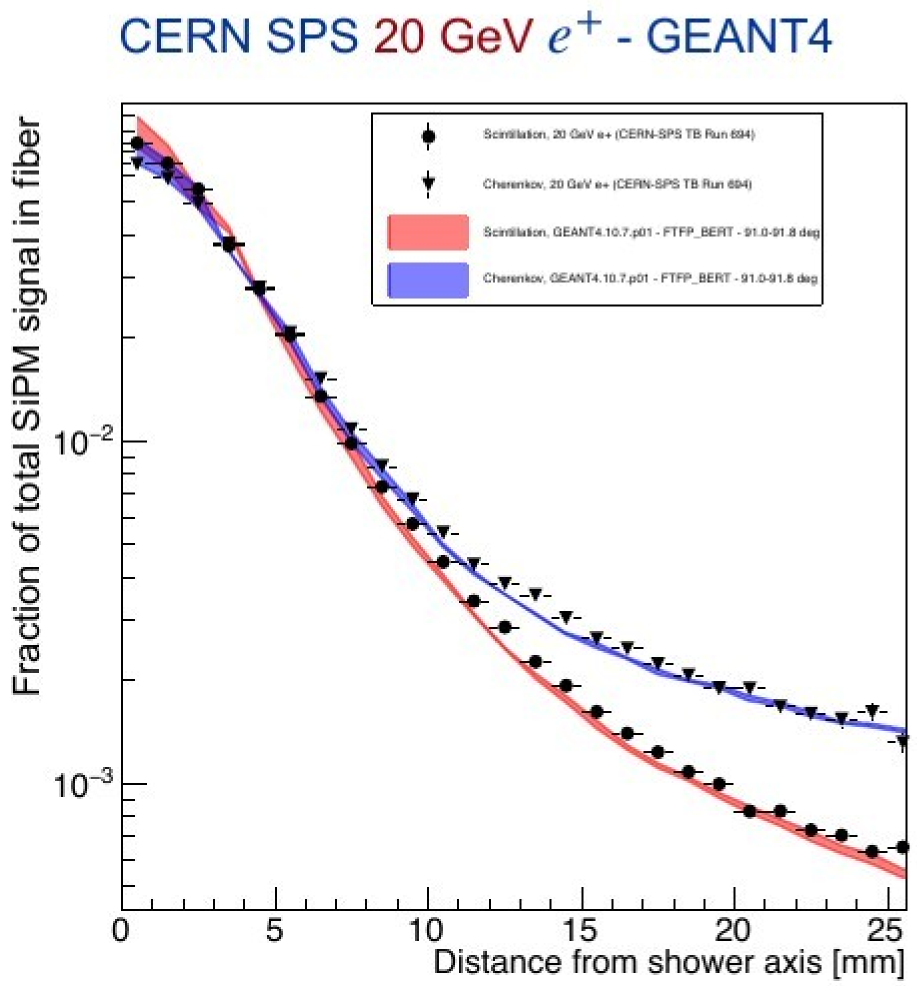
IDEA 2020 em-size bucatini prototype (EU)

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

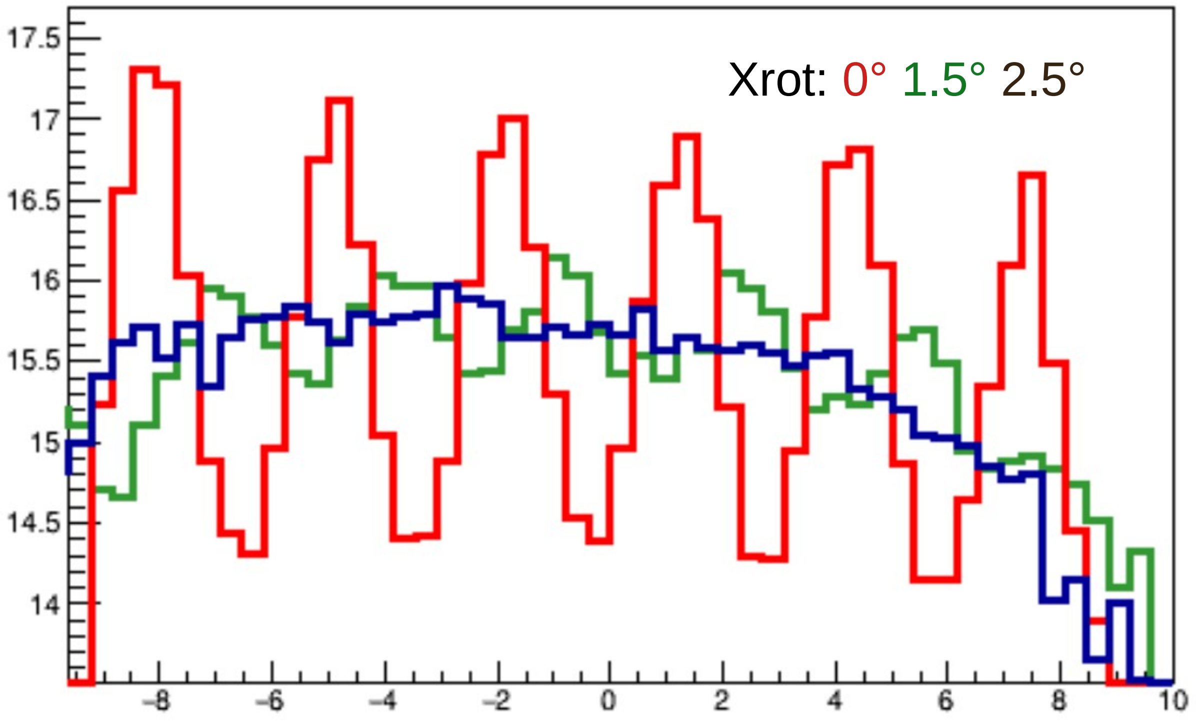
Lateral profiles extracted as average value for every x-bin

Data vs. Geant4 simulation

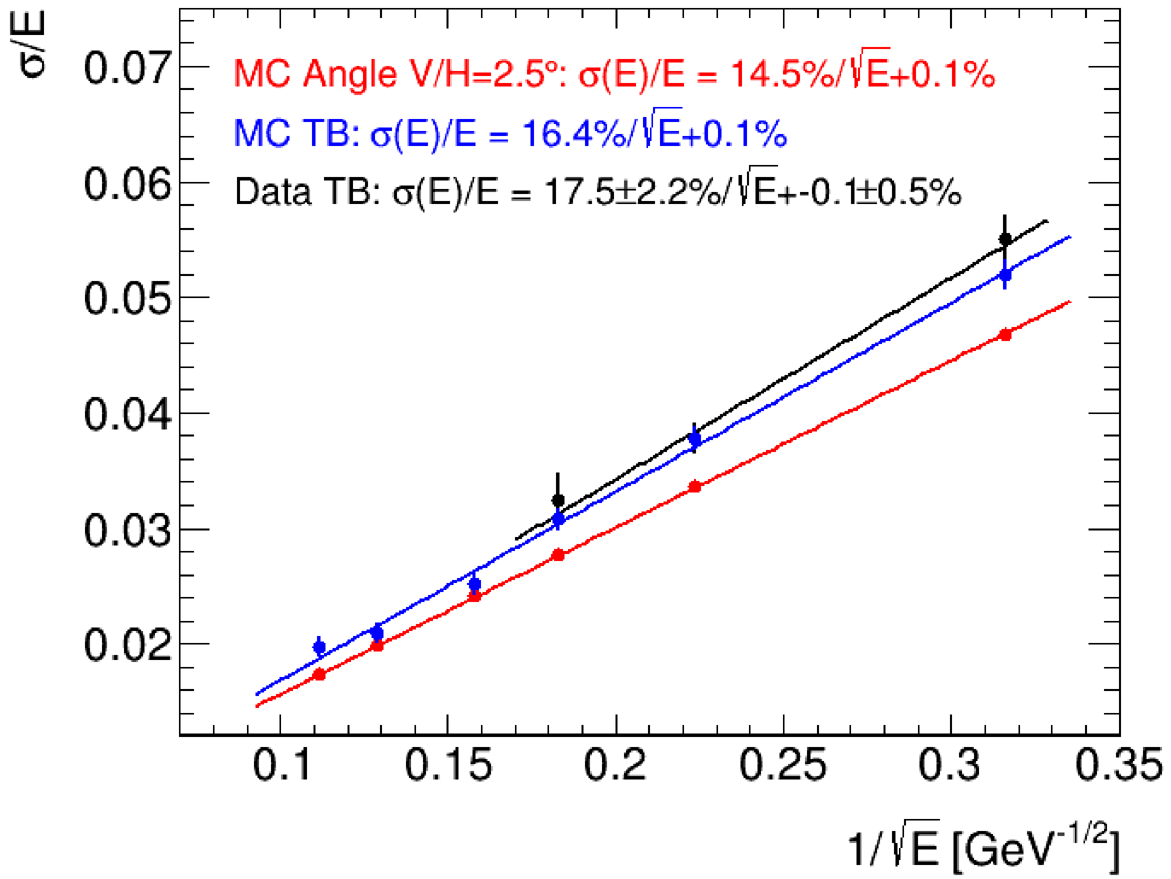


Other results

Angular dependence (from MC)



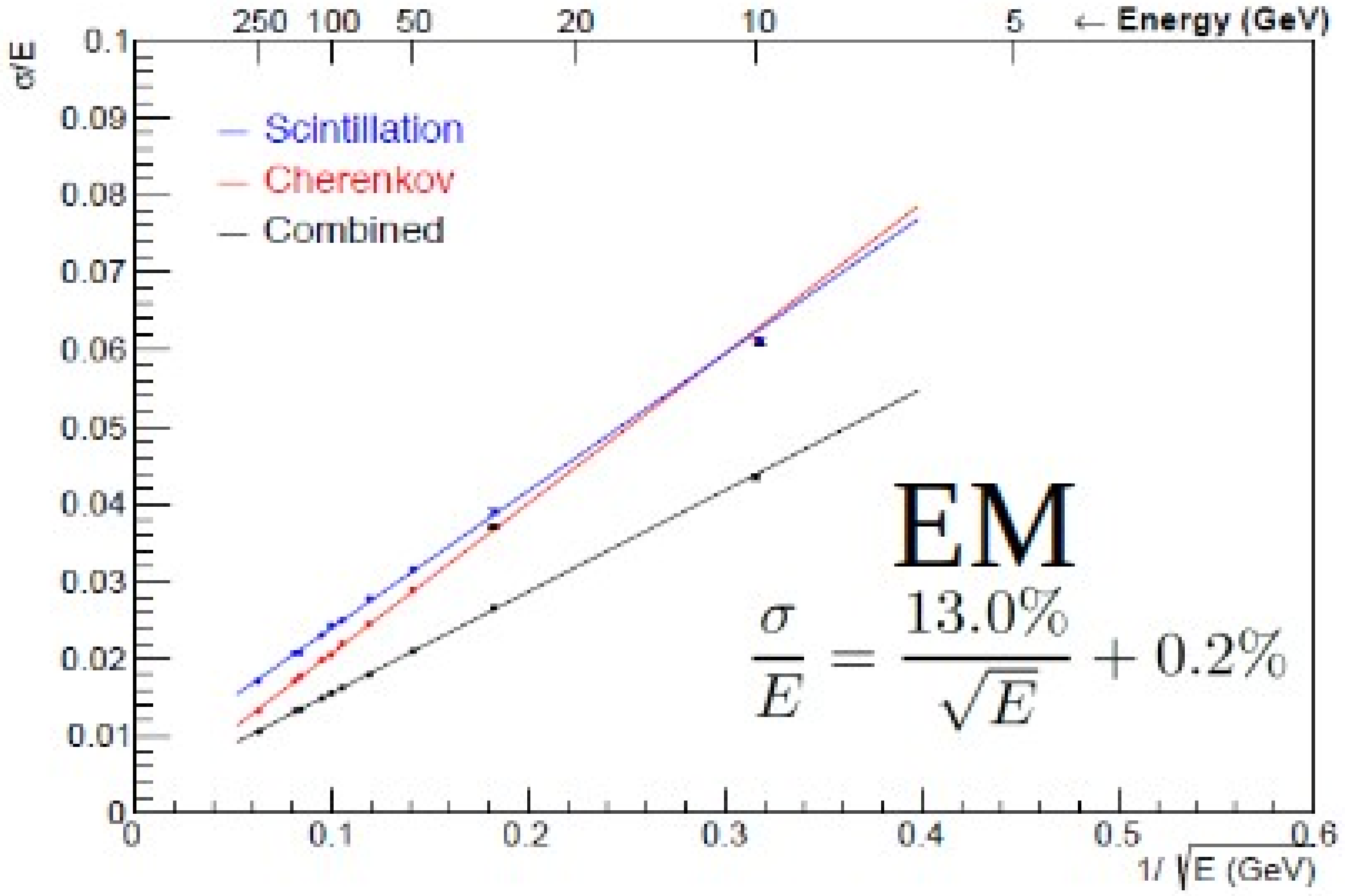
EM resolution

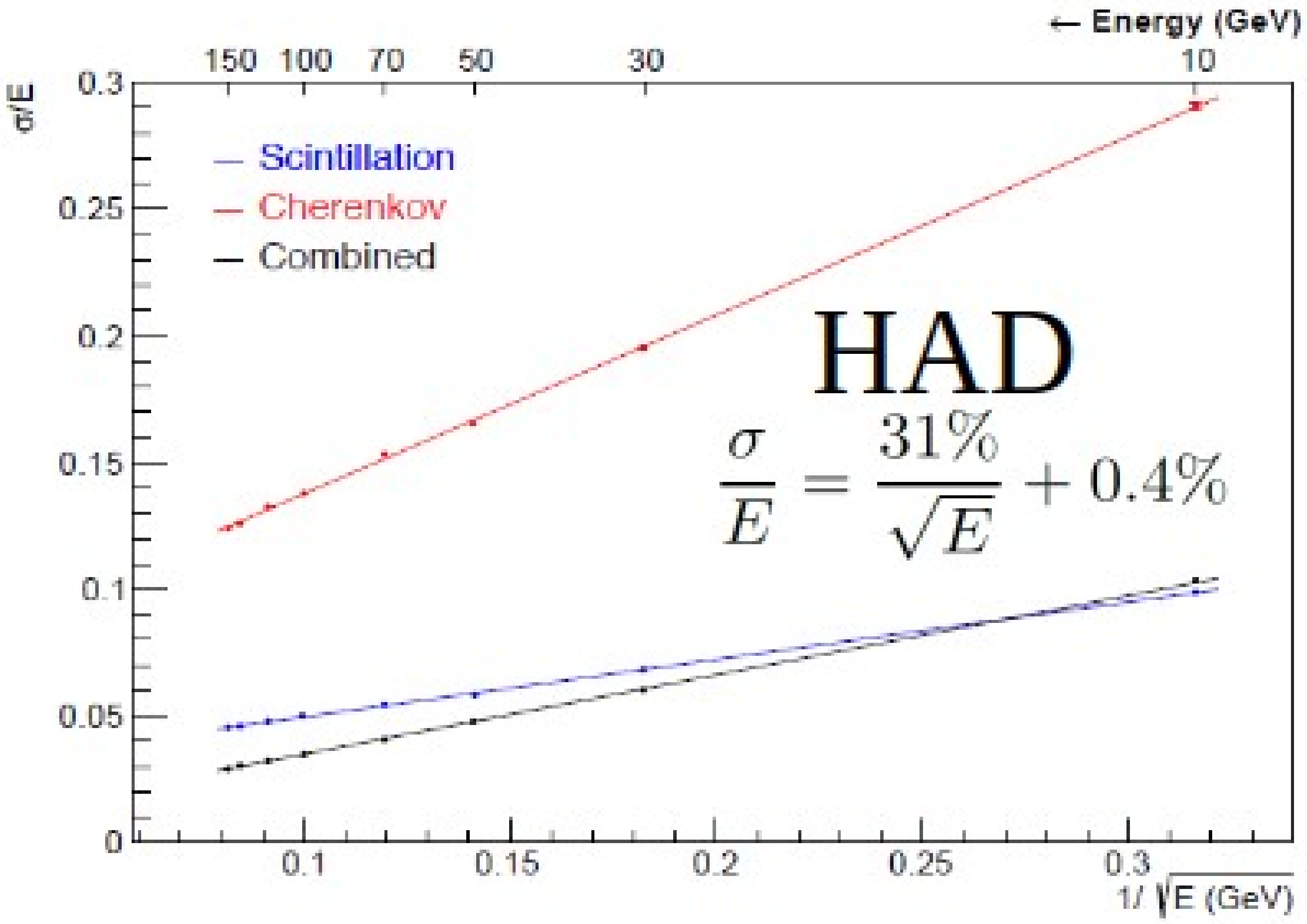


Need another beam test
Need beam purity
Need correct detector setup (angle, preshower)

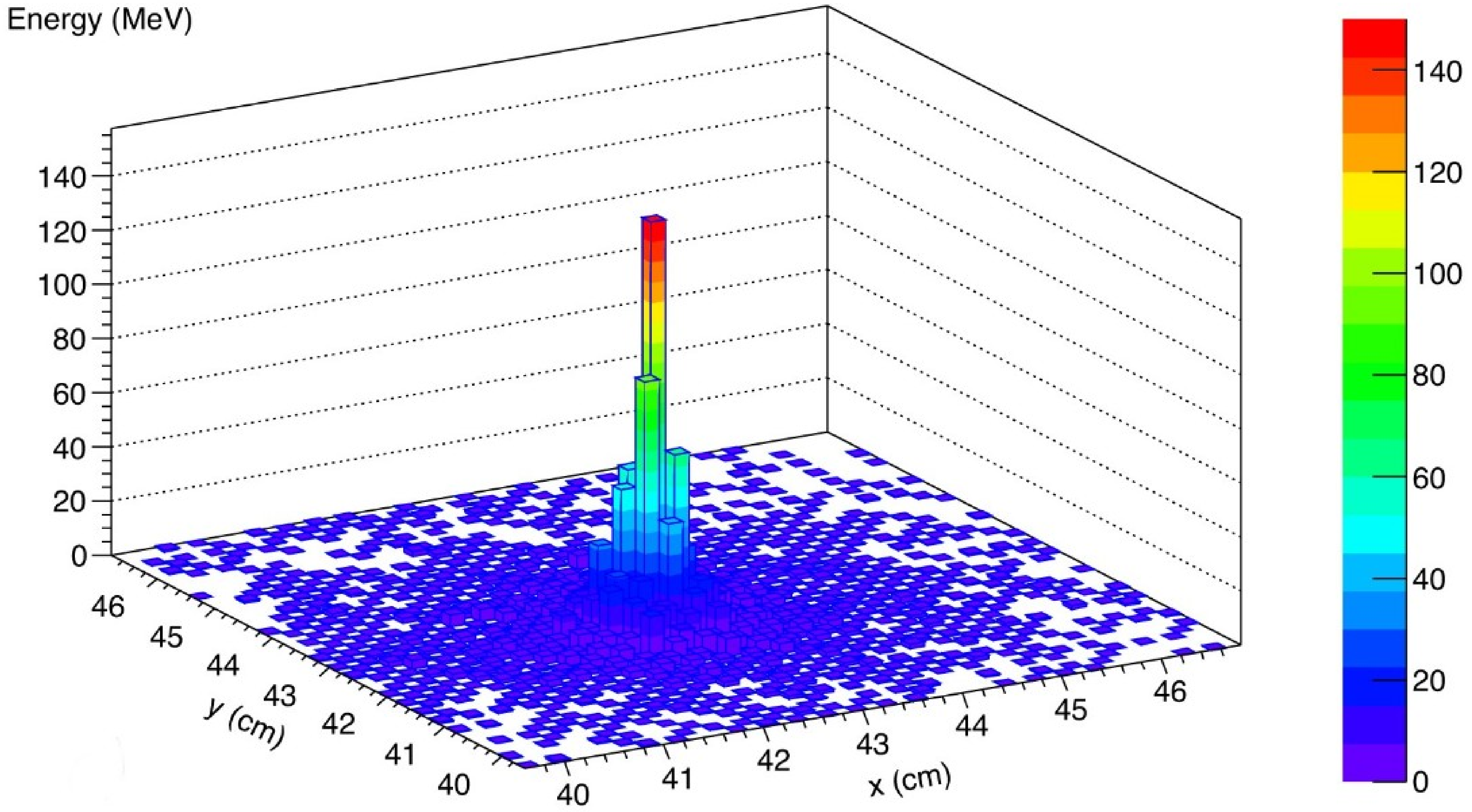
Geant4 simulation

- Good resolutions averaged over eta and phi

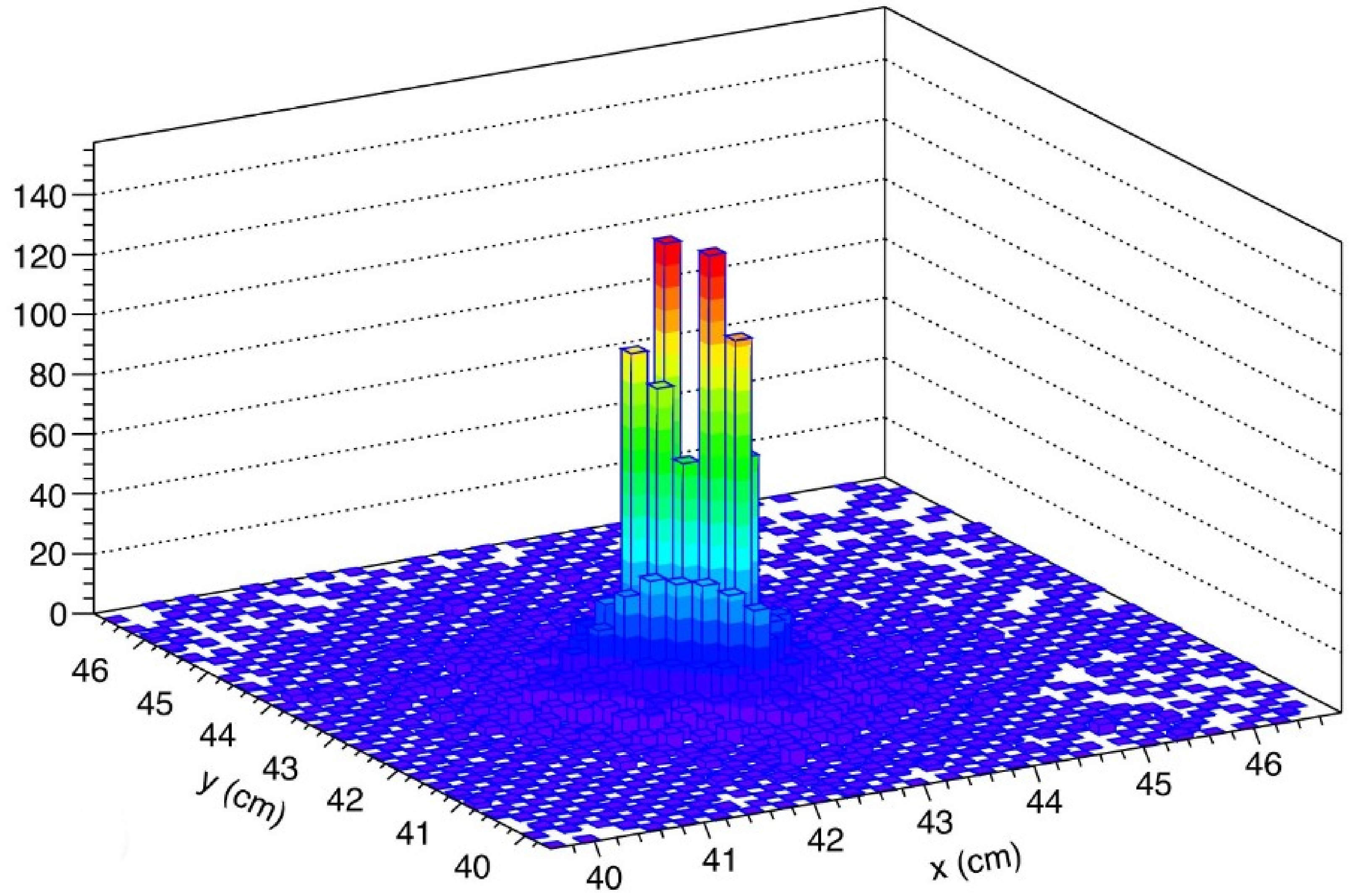




Event displays

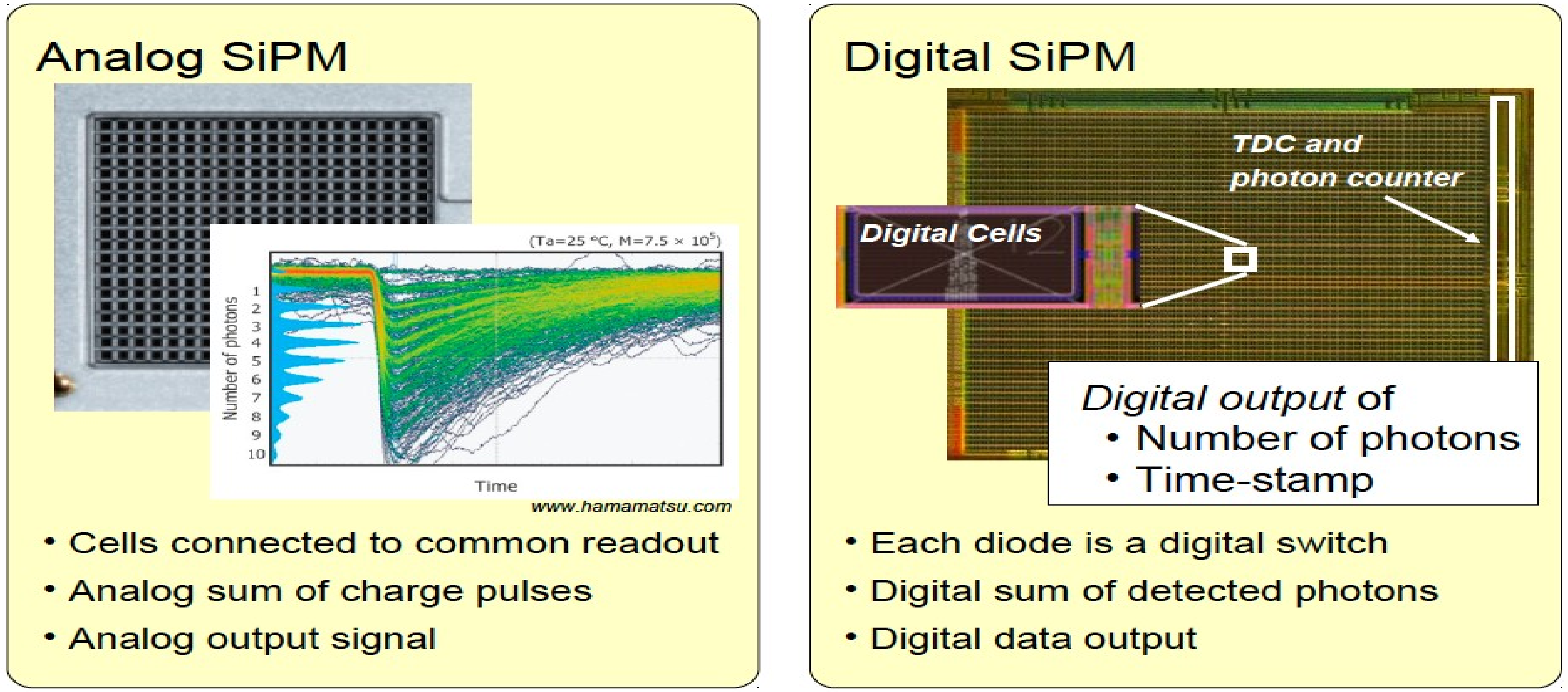


50 GeV e^-



100 GeV π^0

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

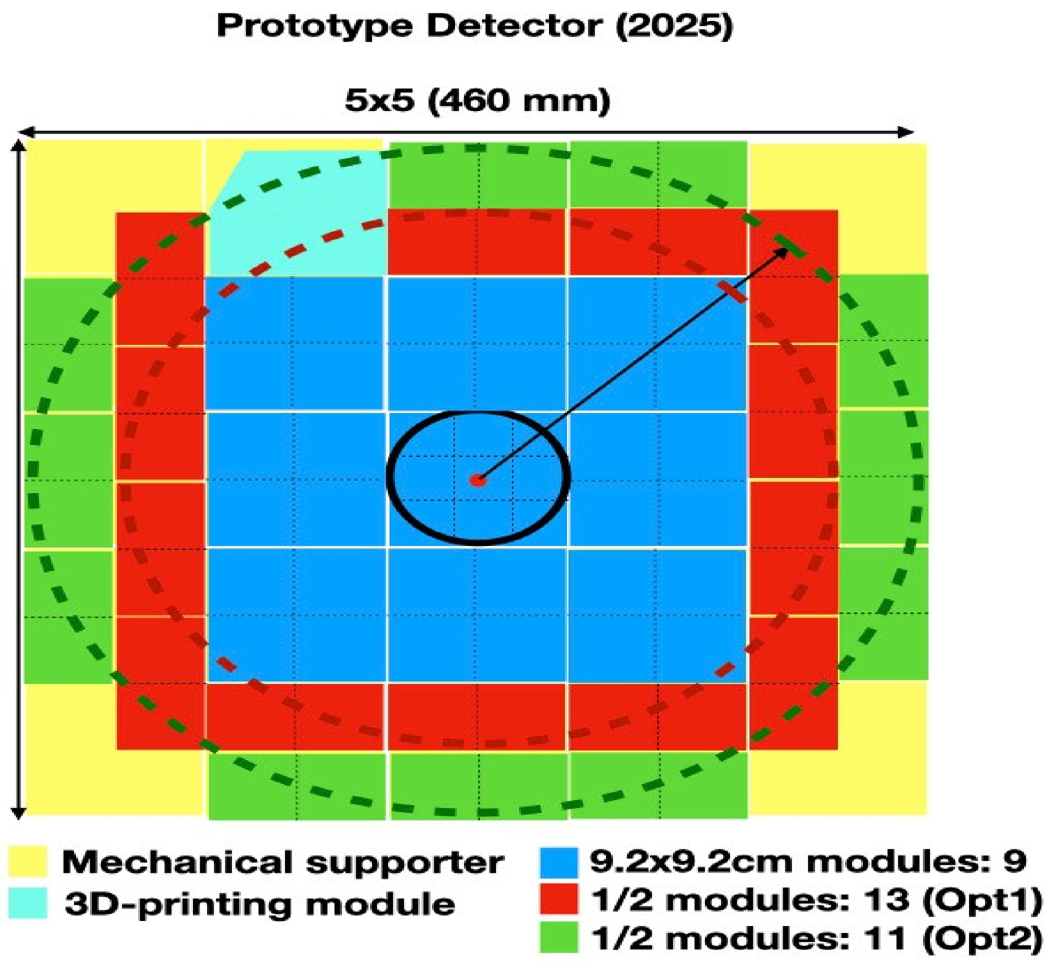
Requirements

	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

South Korea activities

Investigating:

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



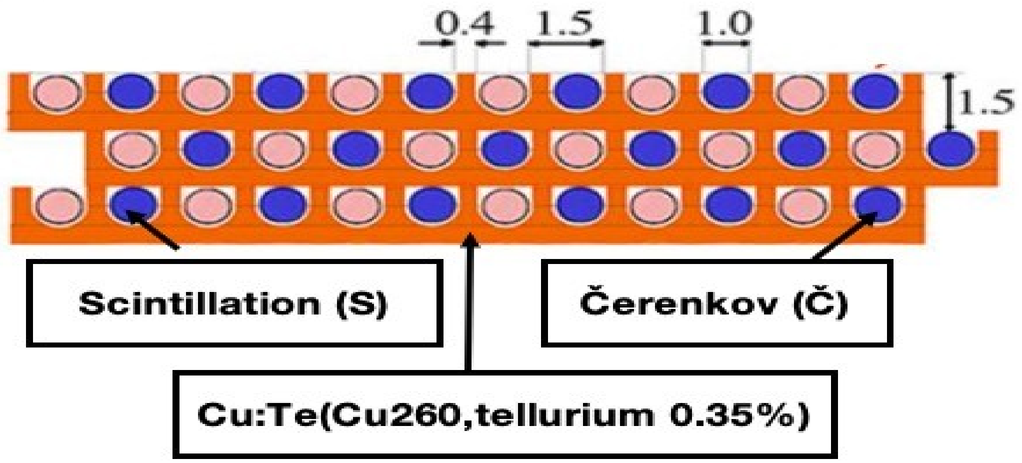
Absorber production:

- 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

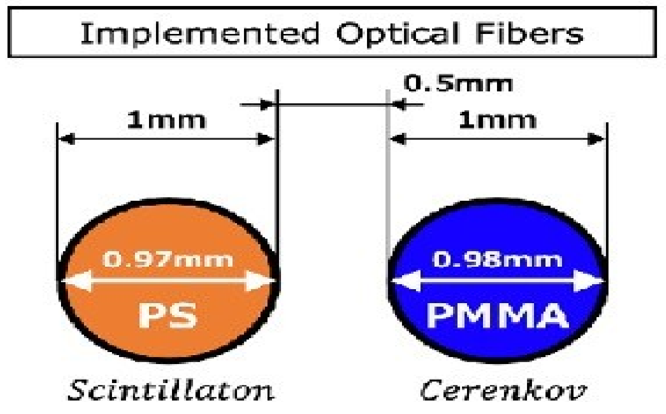
2 modules tested w/ beam in 2022

- **Copper Plate & Fibers**



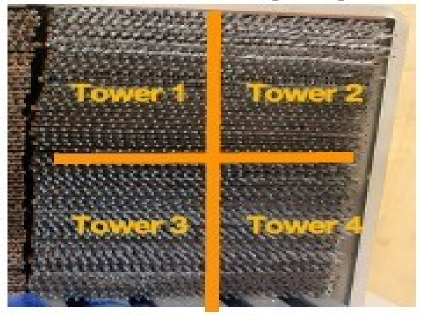
- **Copper plate (60)**
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

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

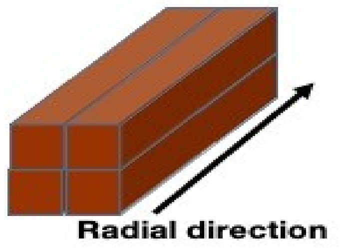


- **Configuration of Fibers & Readout detector for Test Beam**

Module #1 (2x2)



Module#1

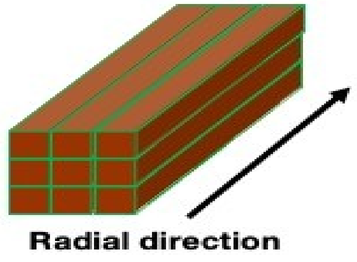


Module#1

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

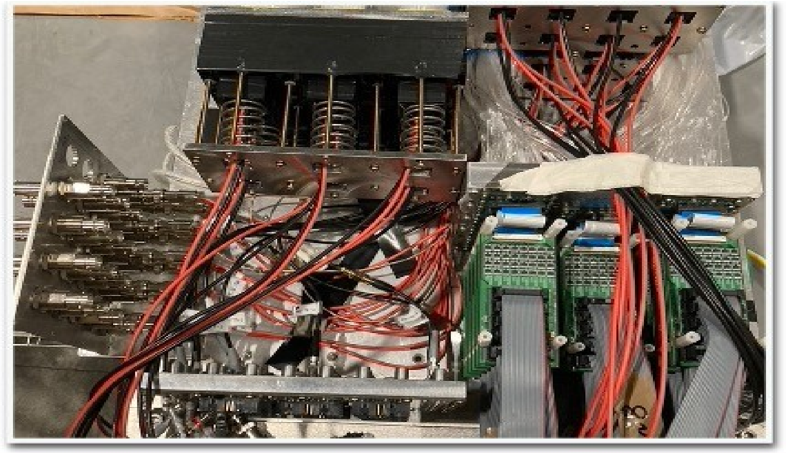
	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2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

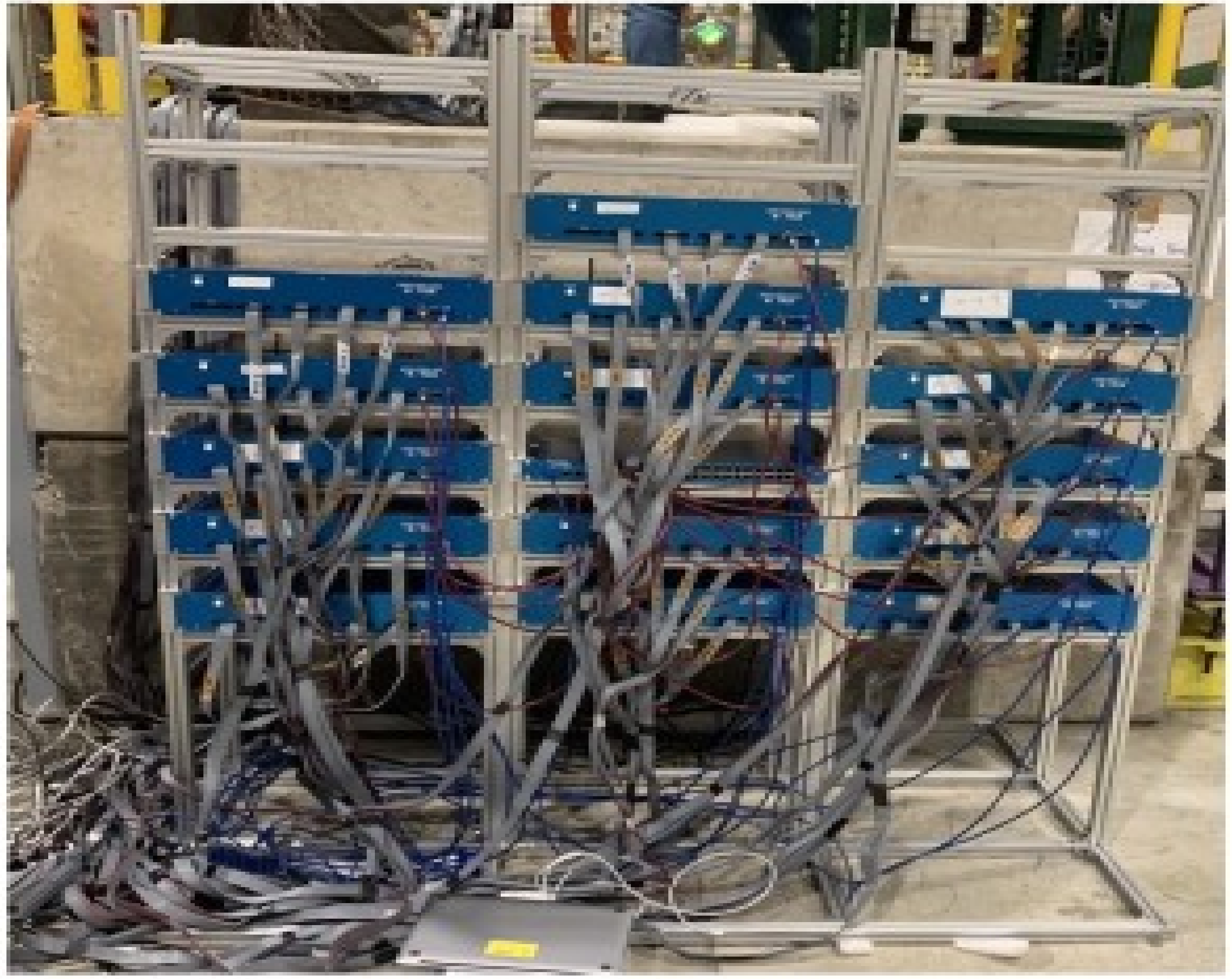
- System made of 15 DAQ Boards + 1 TCB Board

- 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

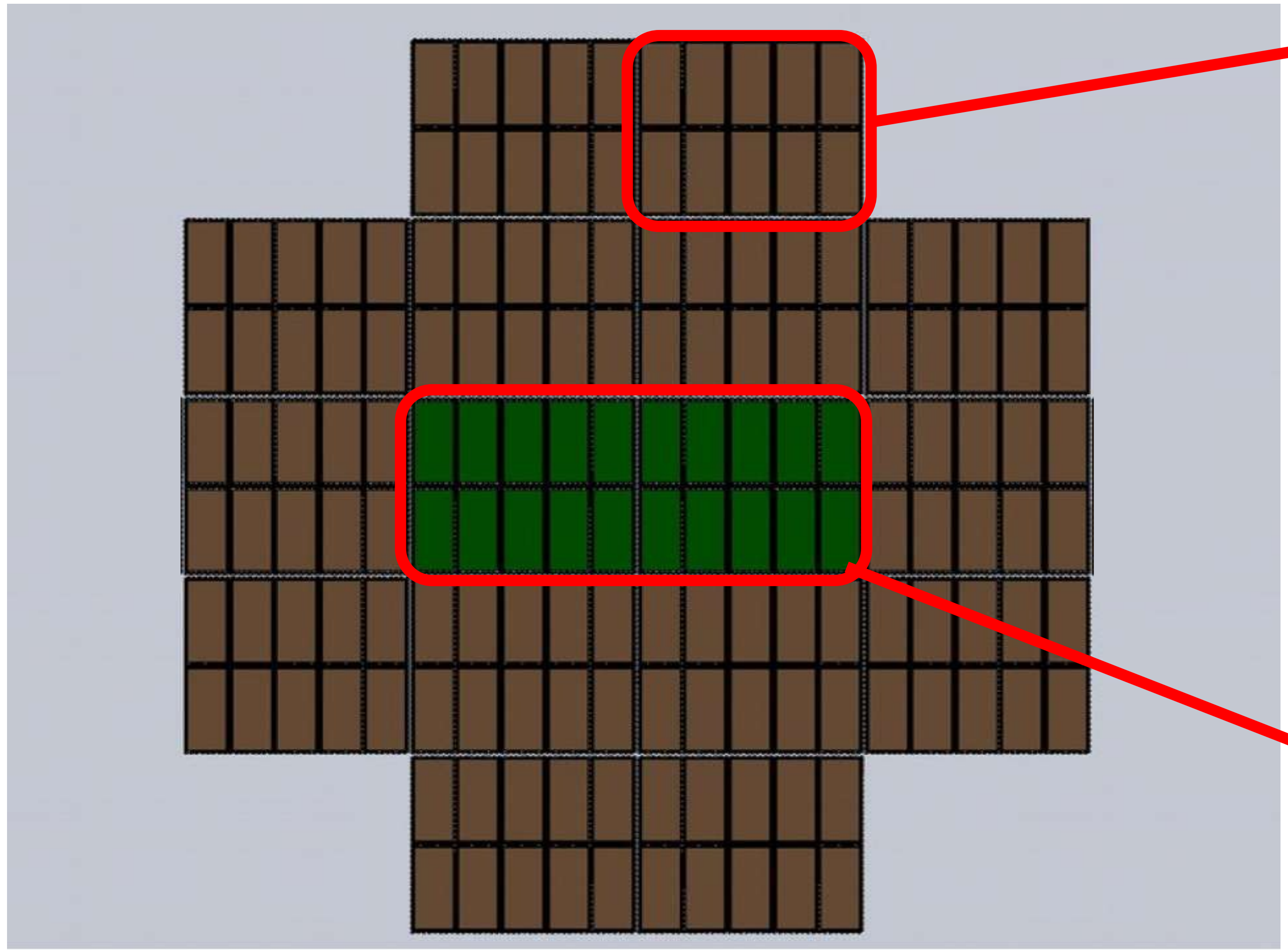
- TCB Board
  - Control the setting value of DAQ boards and the trigger system
  - Connect DAQ boards with TCP/IP cable, cover 40 ch DAQ

- All boards connected with PC using USB3 line

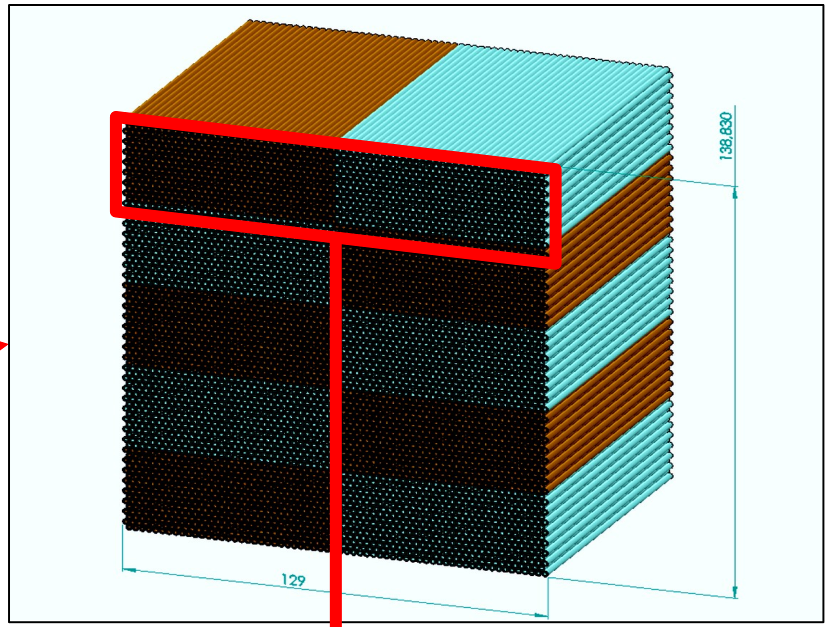


HiDRa – Highly granular Dual-Readout demonstrator (INFN)

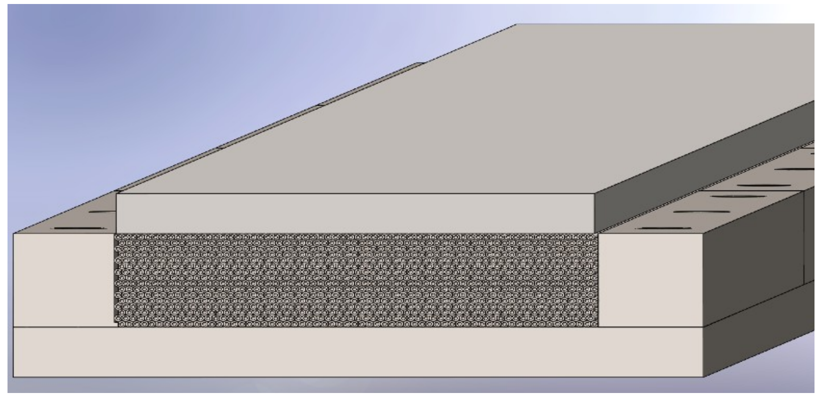
Hadronic-size prototype:
16 modules w/ highly granular core



HiDRa



1 Module:
5 MMs
~ 13×13 cm^2



1 MiniModule:

$64 \times 16 =$
1024 fibres in total

512 S + 512 C

highly granular core:
1024 fibres to be readout with SiPMs

Capillary tube parameters

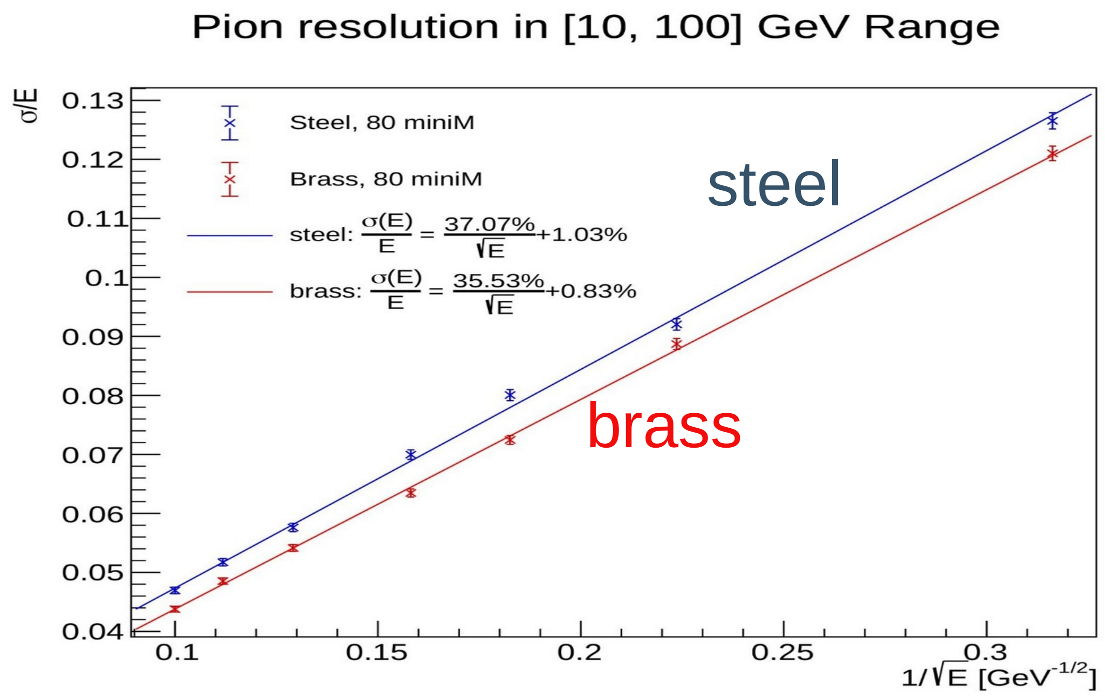
- Dimensions:
  - External diameter: 2 (± 0.050) mm $\Longleftarrow$ from SiPM dimensions
  - Internal diameter: 1.1 (-0 +0.1) mm $\Longleftarrow$ from fibre dimensions
  - Length: 2.5 m $\Longleftarrow$ from containment studies

→ 3% sampling fraction

- Material:
  - Stainless steel 304 $\Longleftarrow$ cheaper than brass, comparable performance

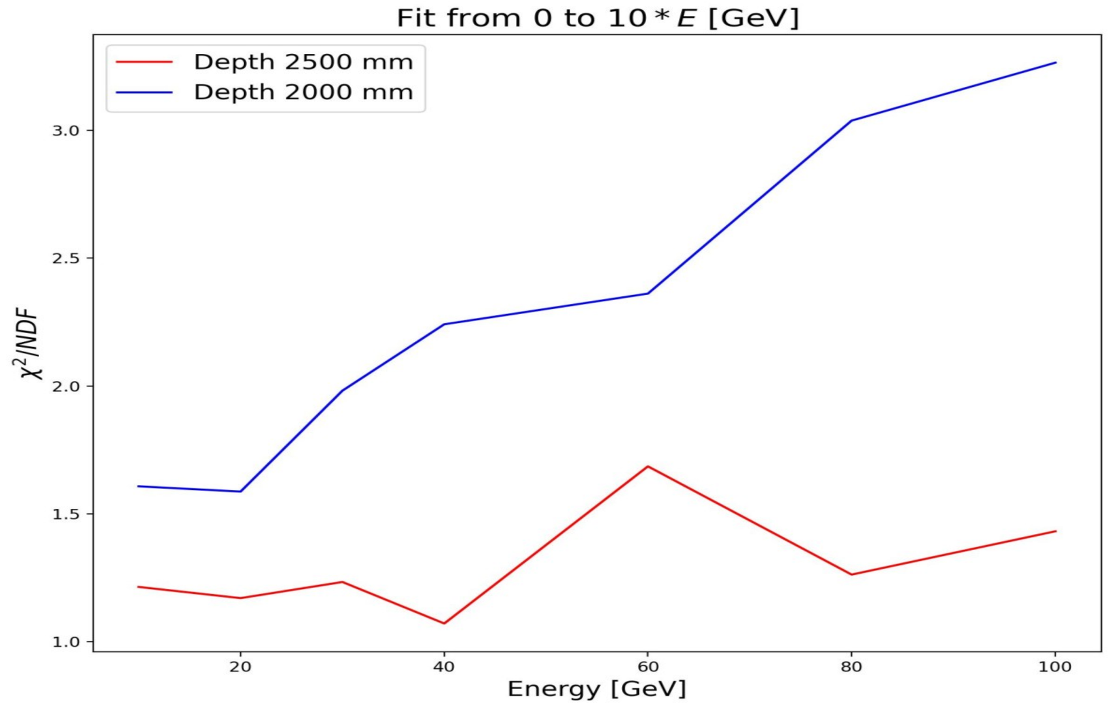
Geant4 simulations

Absorber choice

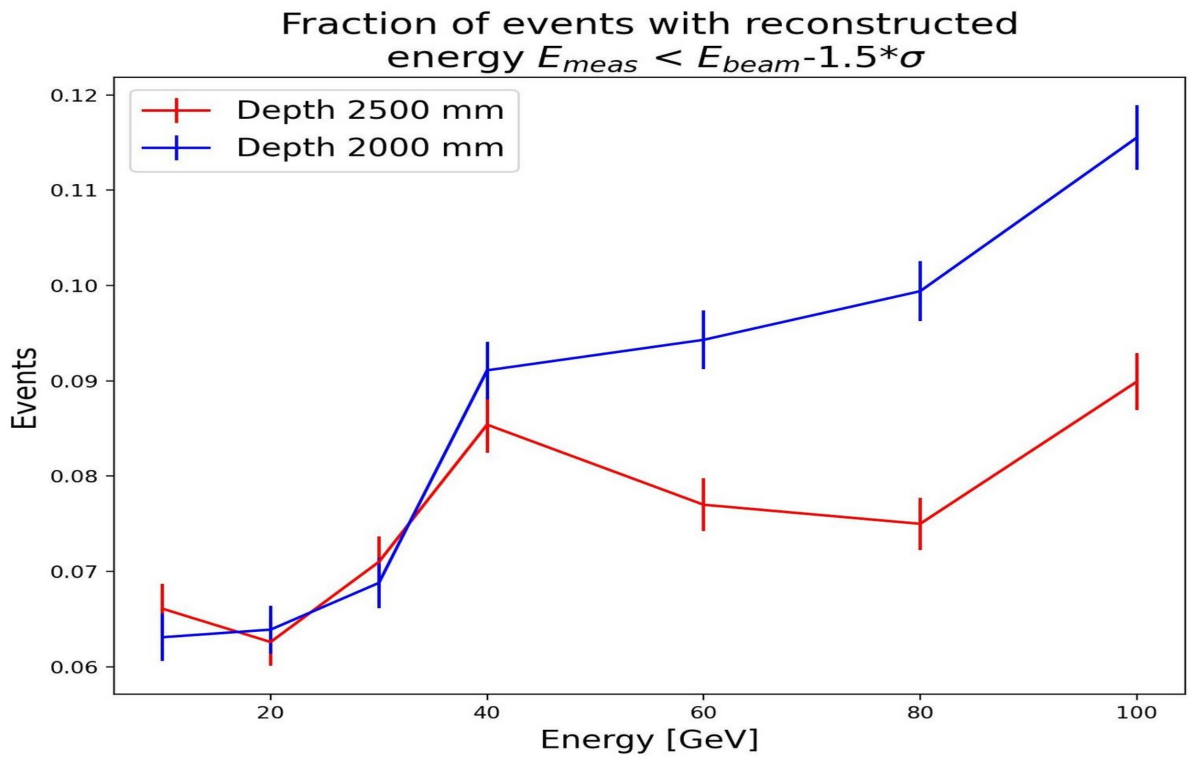


Calorimeter depth

χ2 / ndof



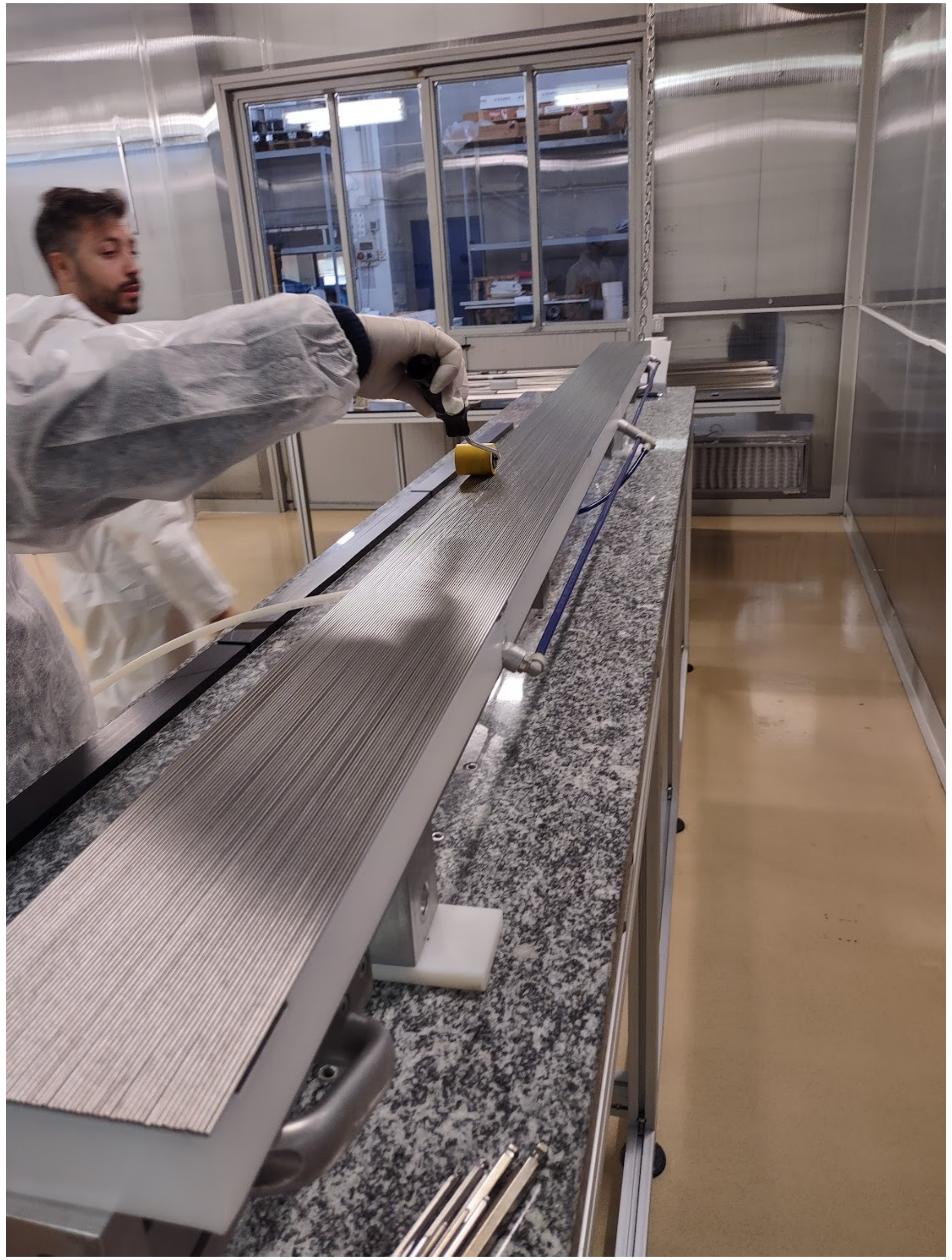
Low-energy tails

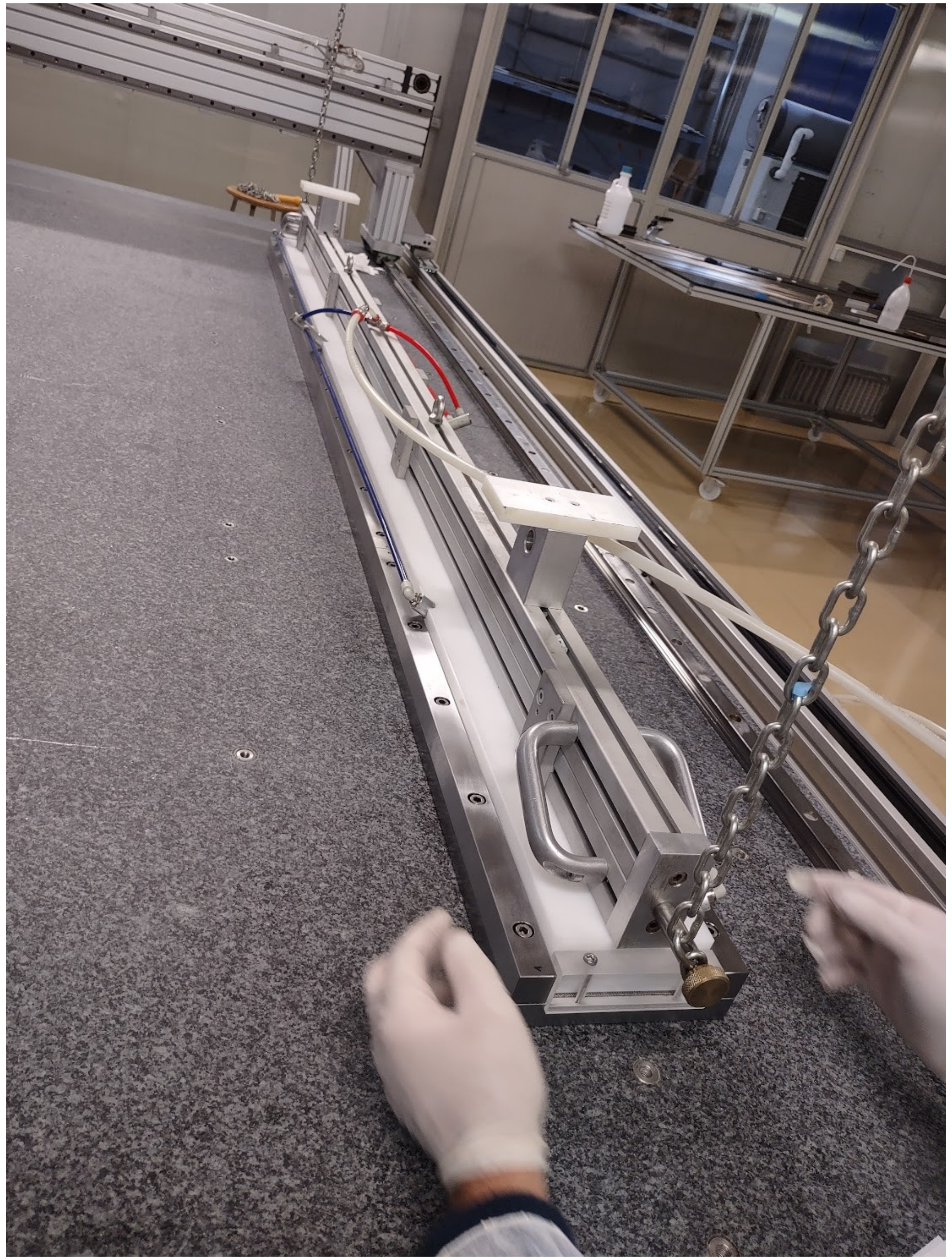


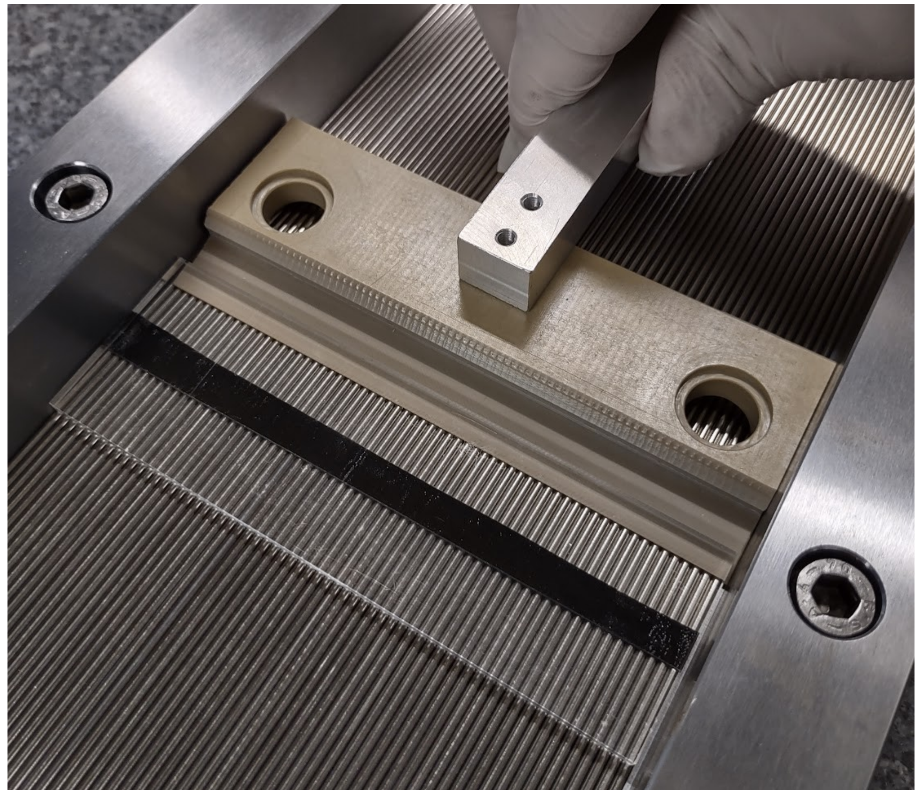
Capillary QA/QC

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

Tube gluing

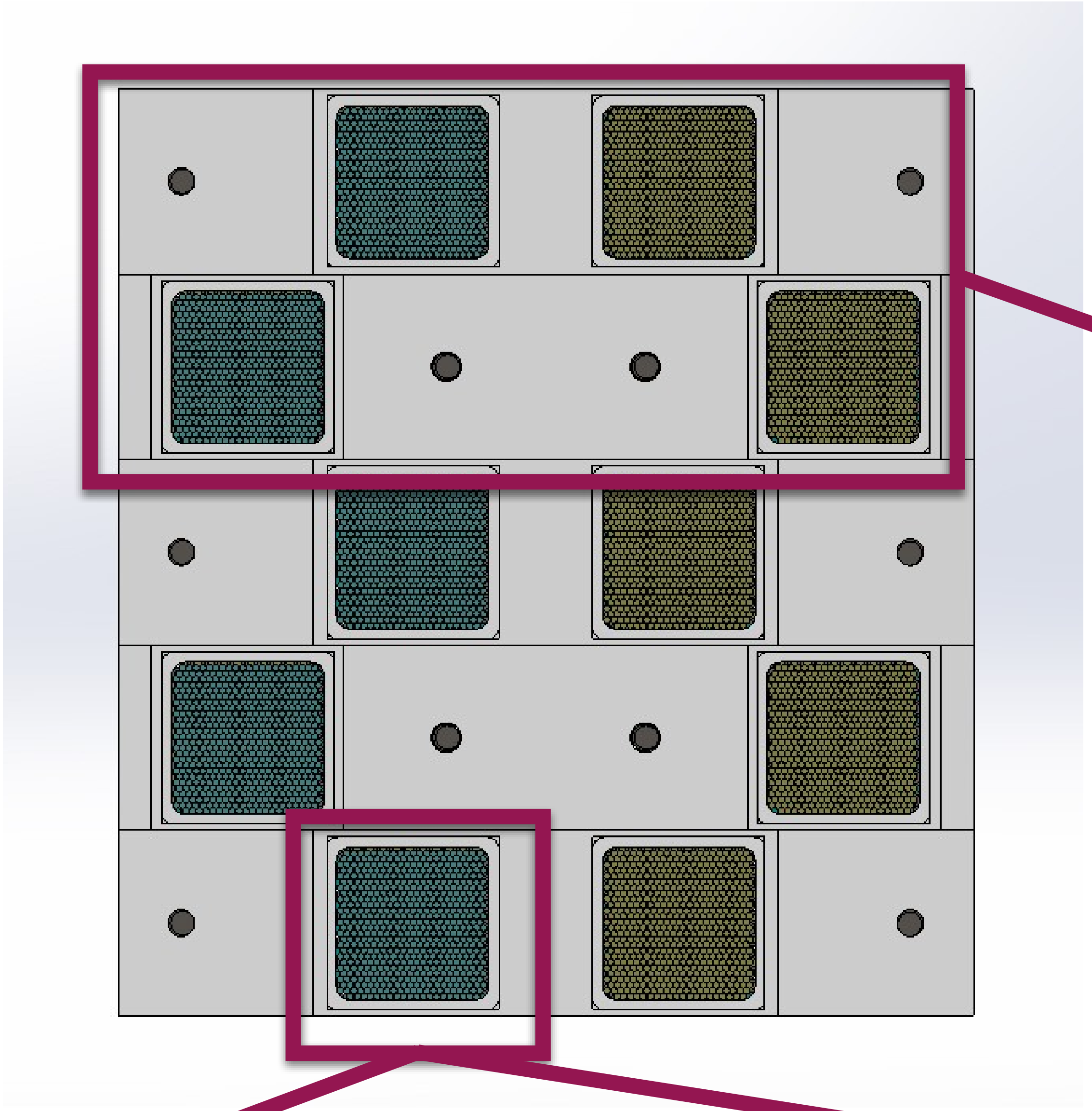


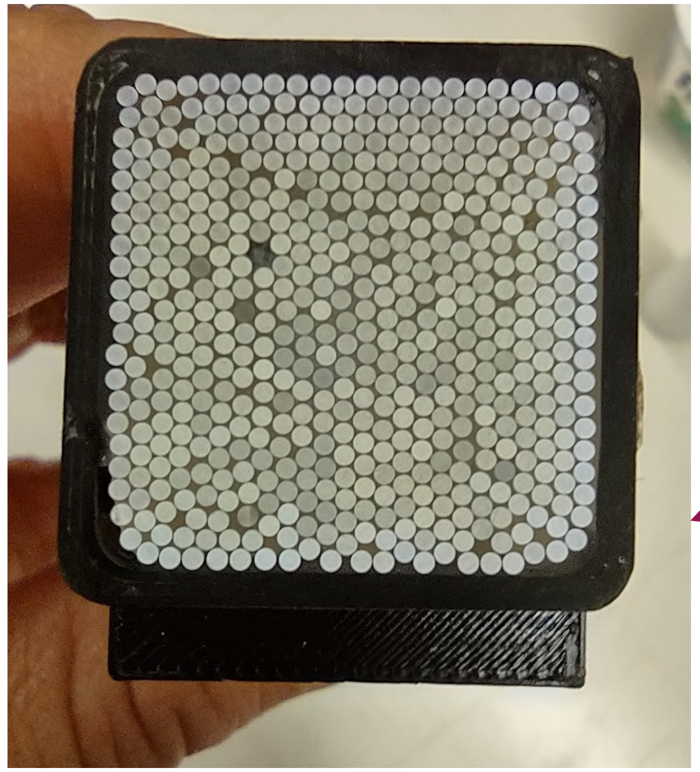




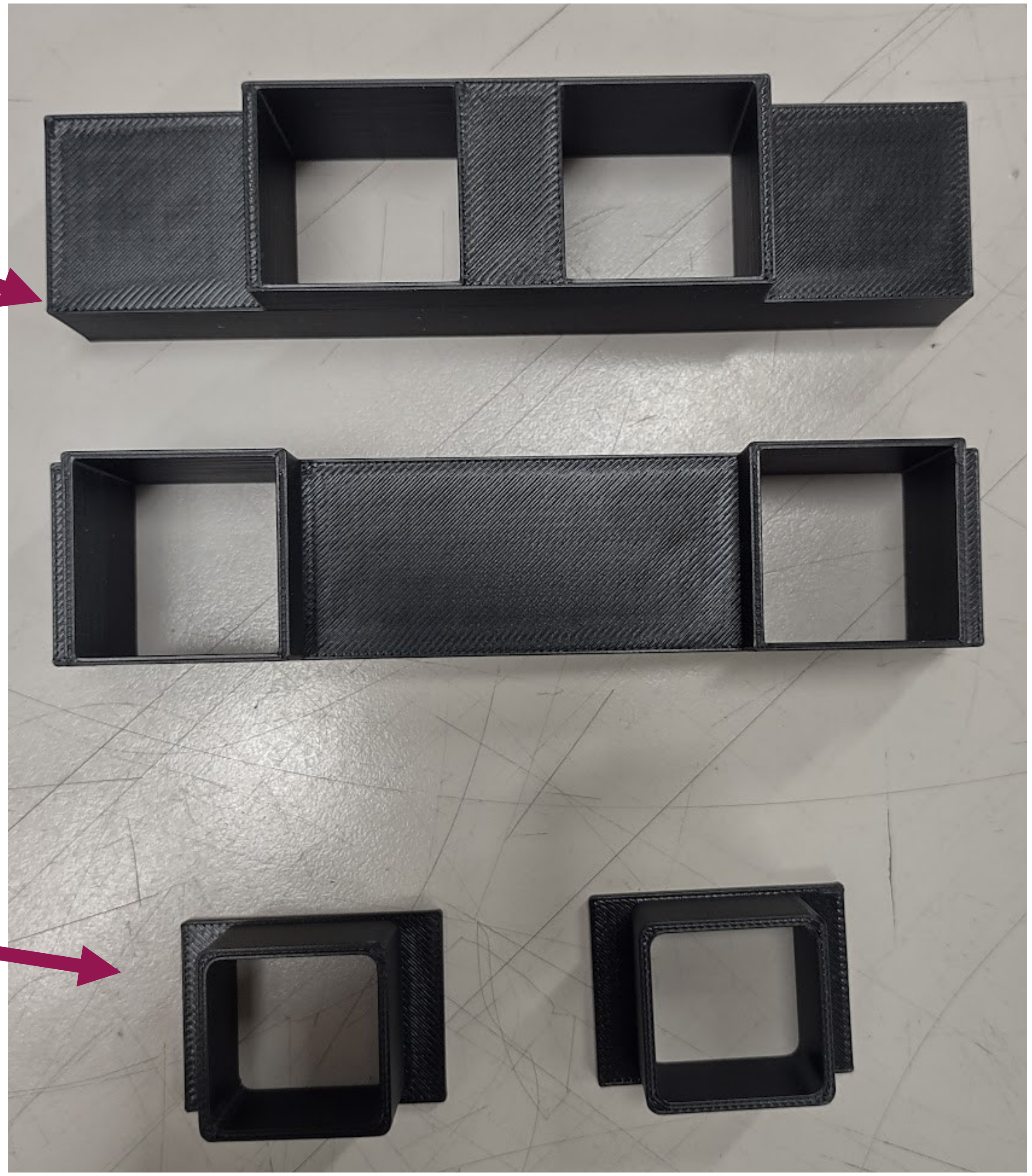
Stiffback-like technique for tube handling, gluing and positioning

PMT readout: fibre grouping

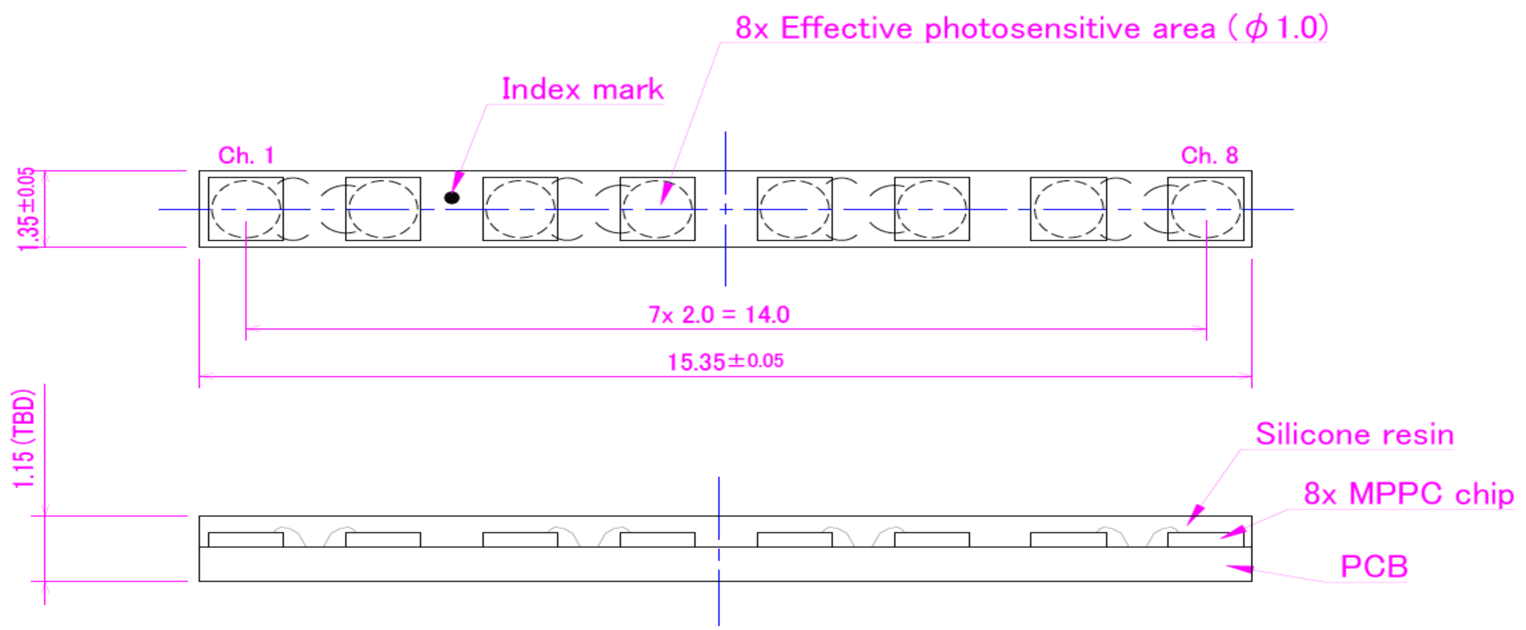




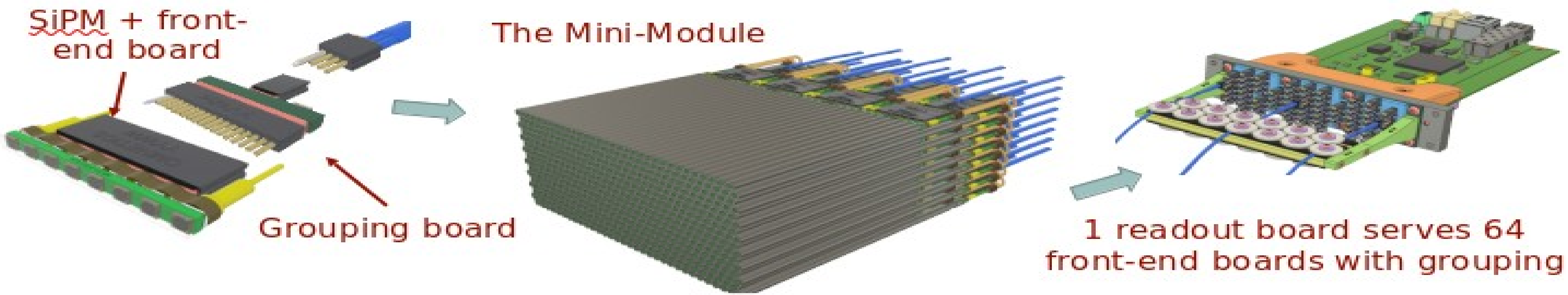
3D-printed fibre and PMT holders



SiPM integration and readout



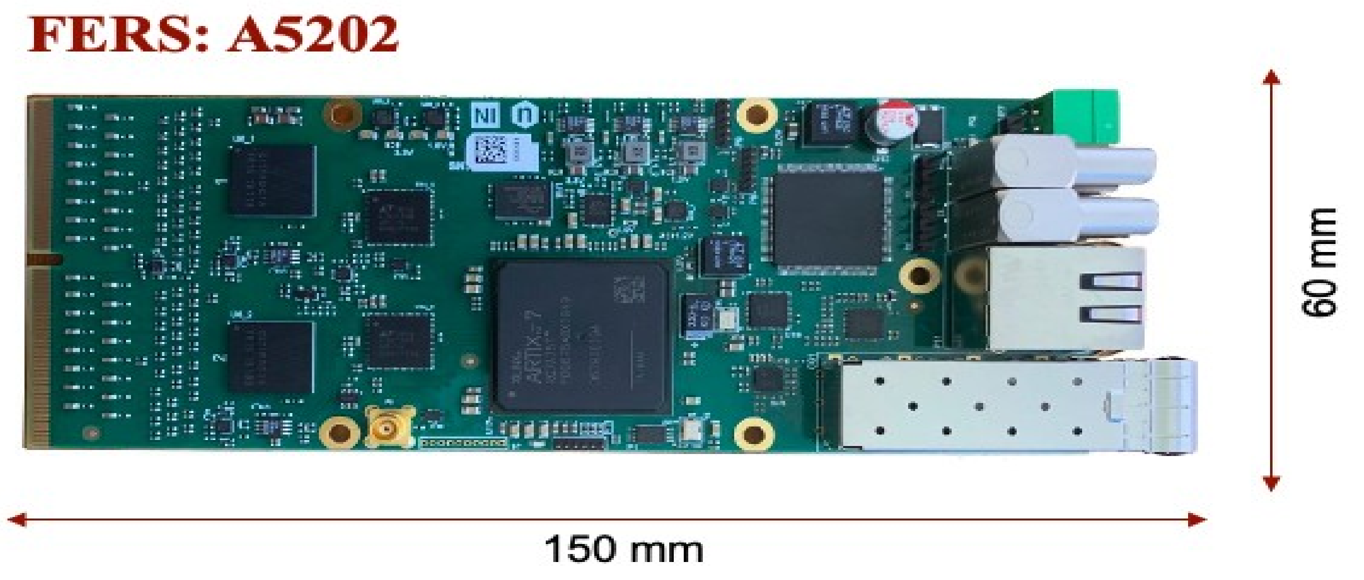
- Custom designed module with 8 SiPMs (1x1 mm^2) from Hamamatsu
- 2 mm SiPM interspace
- Two options under study: 10 and 15 µm pitch



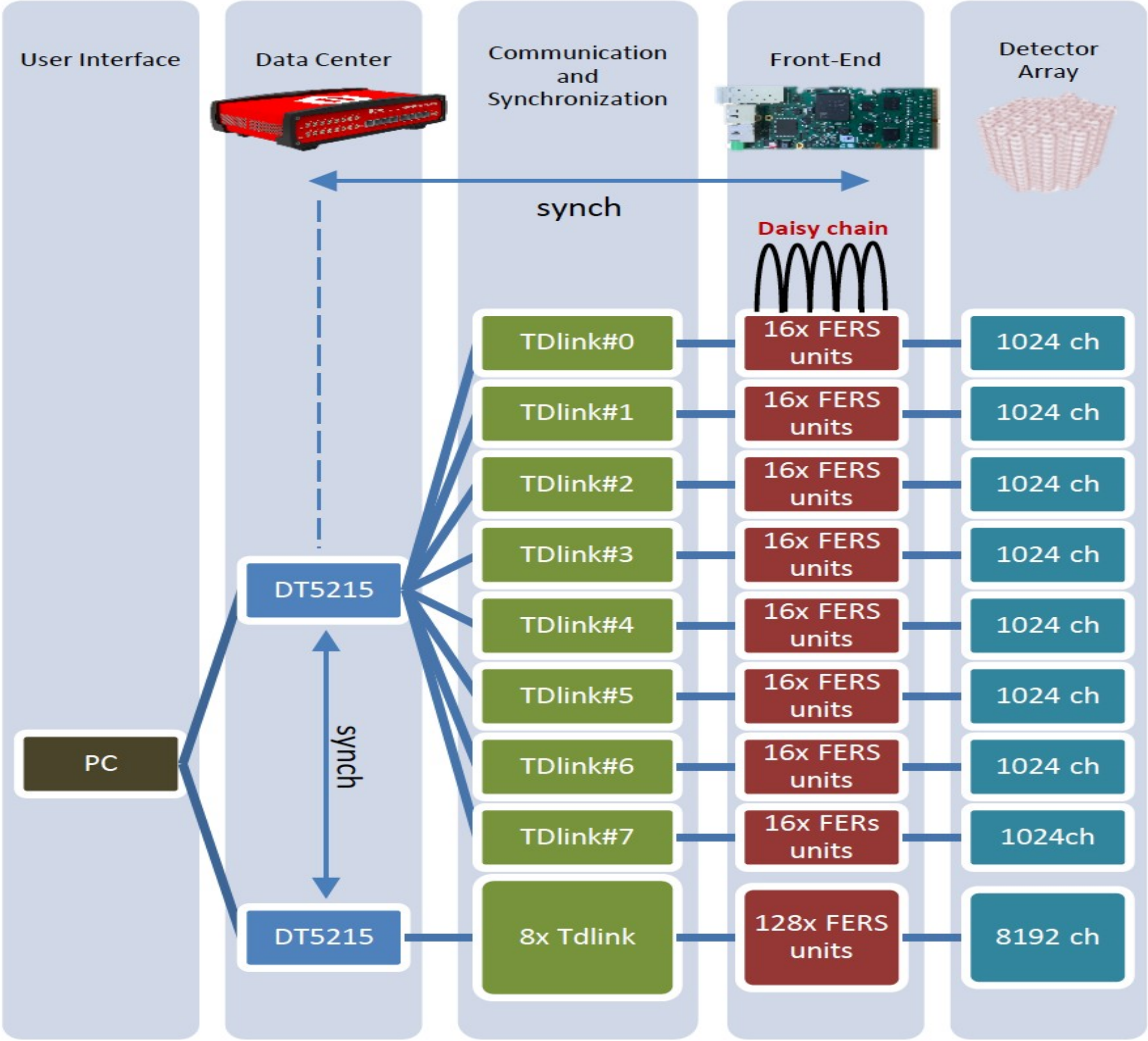
- Each SiPM bar operated at same voltage (V_{bd}<0.15V)
- Signals from 8 SiPMs summed up in grouping board

SiPM integration and readout

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

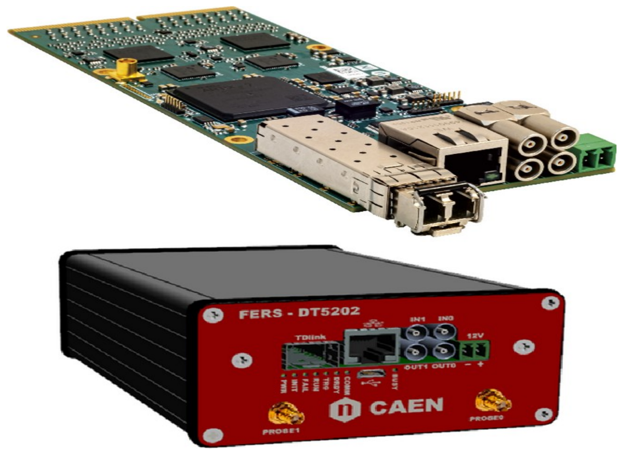


- 64 channels on two Citiroc1A
- Signal preamplification, shaping and integration
- HV power supply with temperature compensation
- Two 12-bit ADCs for charge measurement
- 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 high-resolution TDCs (LSB = 50 ps)
- Optical readout interface (6.25 Gbit/s)



Data concentrator delivered in September

FERS readout integration in EUDAQ



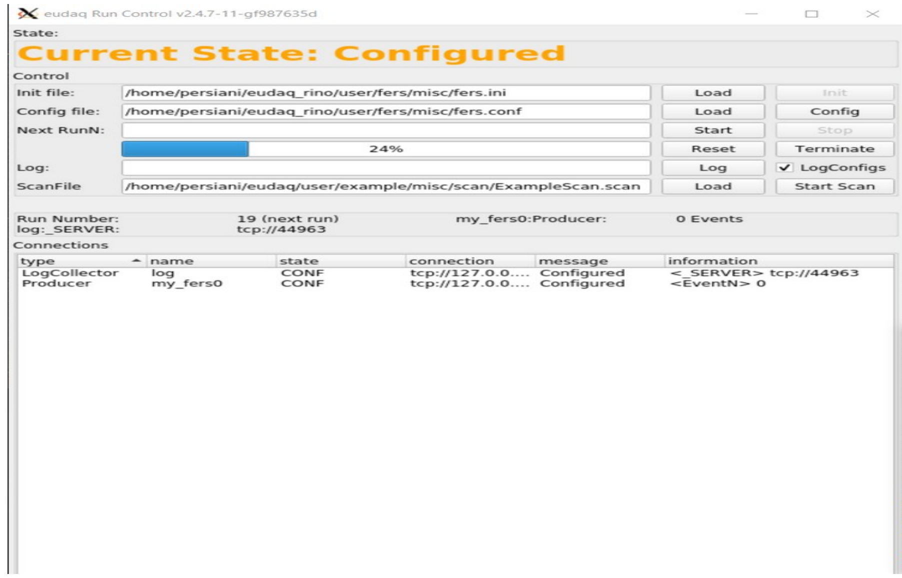
- Modular data acquisition framework, in C++
- Open source, compatible with different OSs
- Finite-State Machine implemented
- HW-specific parts decoupled from core software
- Raw data can be converted to LCIO format
- Many detector prototypes at DESY II Test Beam Facility integrated in EUDAQ
- EUDAQ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

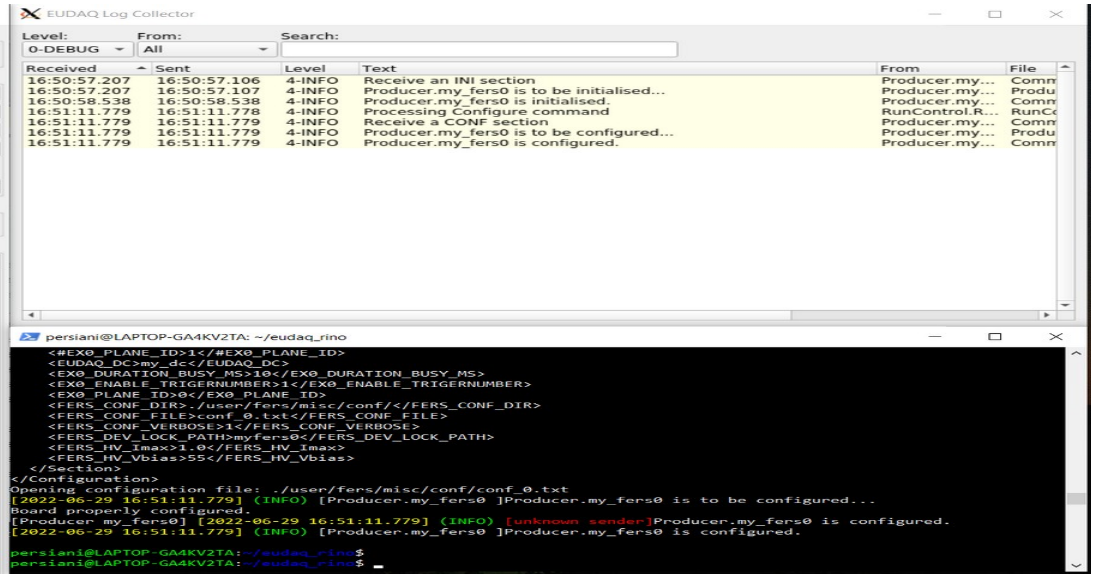
EUDAQ - A data acquisition software framework for common beam telescopes
P. Ahlburg et al 2020 JINST 15 P01038

FERS readout integration in EUDAQ

ALREADY DONE

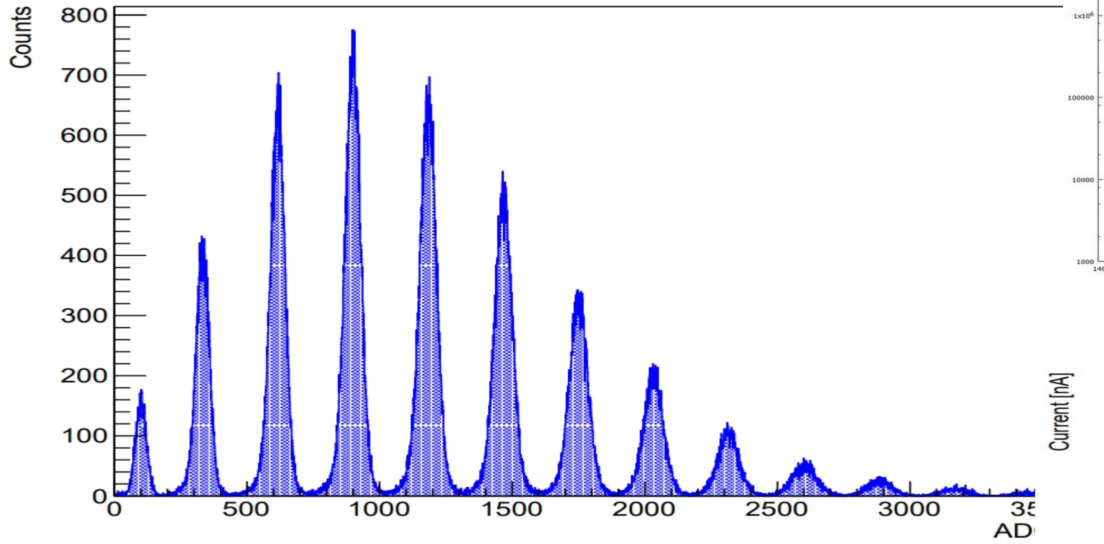
- CAEN FERS library integrated in EUDAQ
- FERS configuration implemented

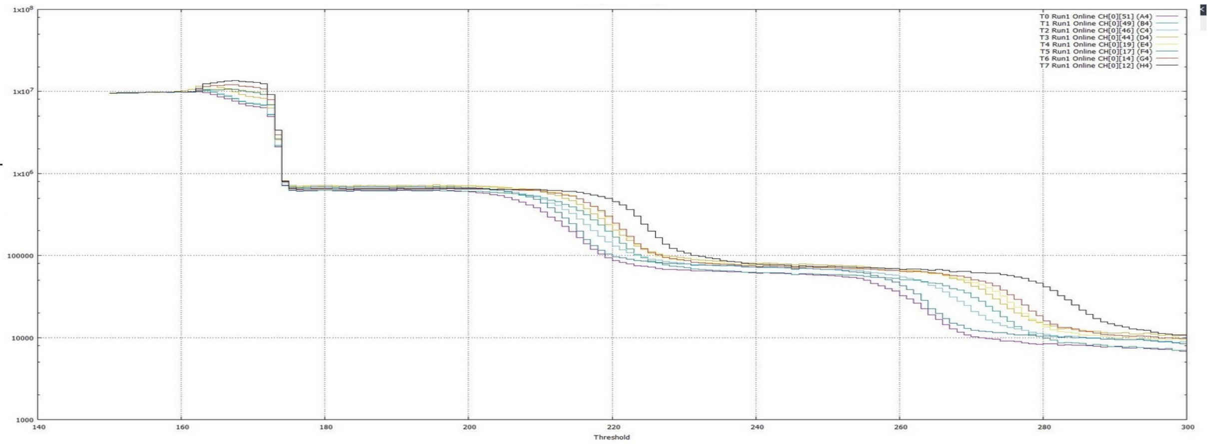


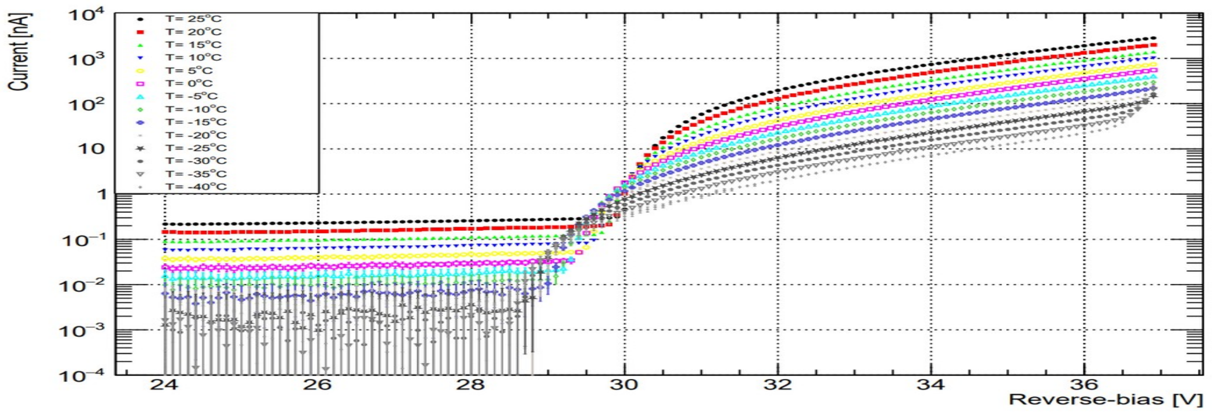


TO DO

- 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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