Dual-readout calorimetry overview and development plans for future electroweak factories

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Napoli, 25.05.2023

Outline

Hadron calorimetry issues

Dual-readout calorimetry

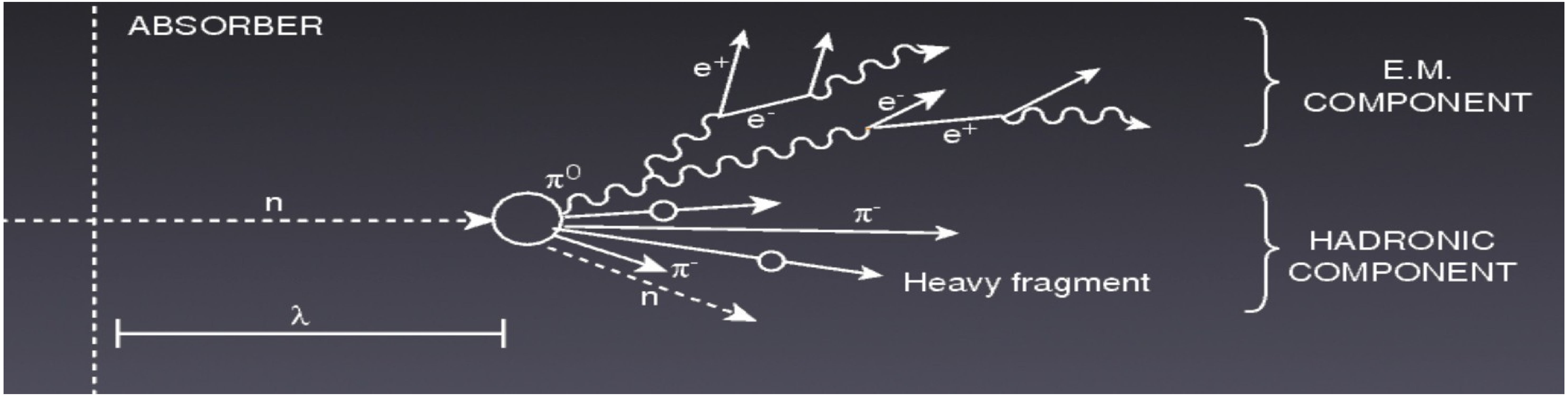
DREAM/RD52 prototype results

IDEA fibre calorimeter: exploit high granularity + timing

Hadron calorimetry issues

Hadron calorimetry

due to π^0 and η production, hadronic showers develop 2 main components:

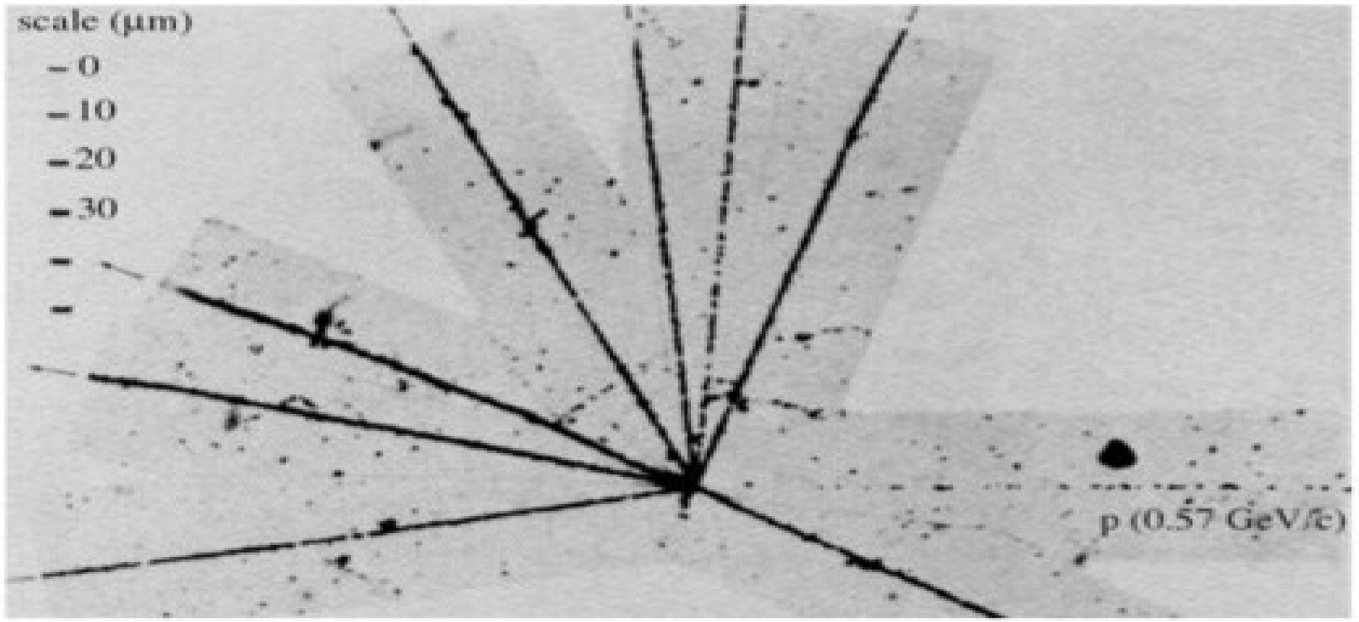


hadronic component: p, n, $\pi^\pm$, nuclear fission, … delayed photons, …

typical size: $\lambda_I \sim 35\ \mathrm{g/cm^2} \cdot A^{1/3}$

Hadronic showers

- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,K$^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



Many components w/ large fluctuations in relative yield

1. Large non-gaussian fluctuations in em/non-em energy sharing
2. Increase of *em* component with energy
3. Large, non-gaussian fluctuations in "invisible" energy losses

invisible energy

- in nuclear reactions, energy lost (binding energy) to free protons and neutrons
- no measurable signal (invisible energy)
- on average about 30-40% of non-em shower energy

Large event-by-event fluctuations limit resolution

Correlation between invisible energy and kinetic energy carried by released nucleons

Evaporation nucleons: soft spectrum, mostly neutrons (2-3 MeV)

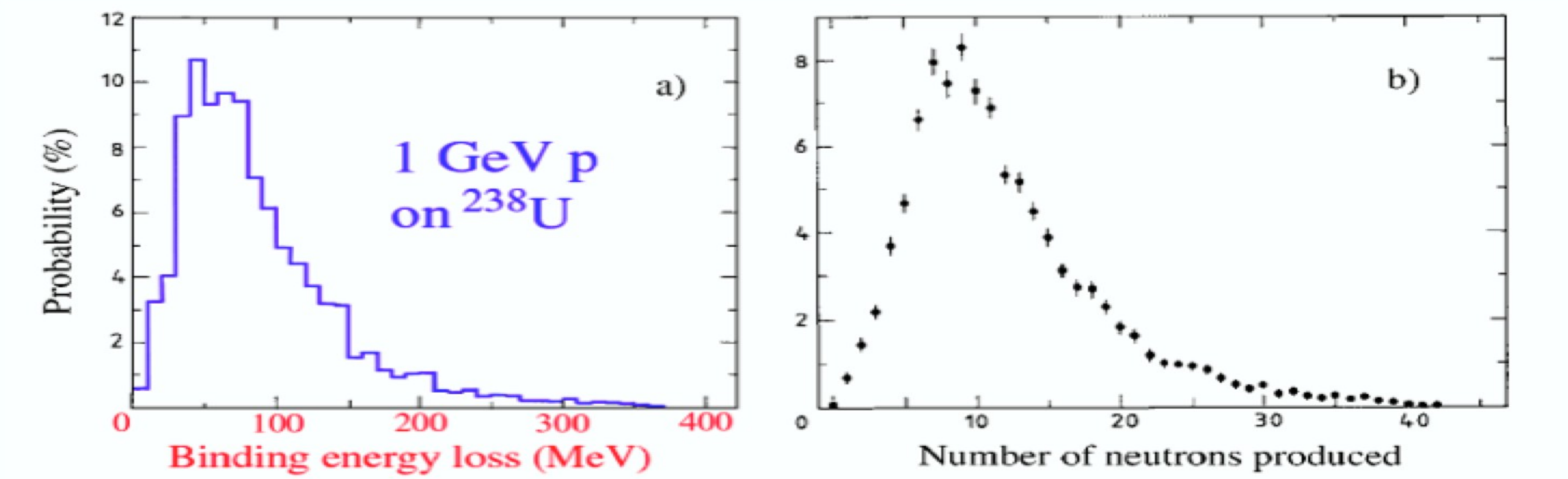


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (a), and the number of neutrons produced in such reactions (b). From [Wig 87].

em fraction f_{em}

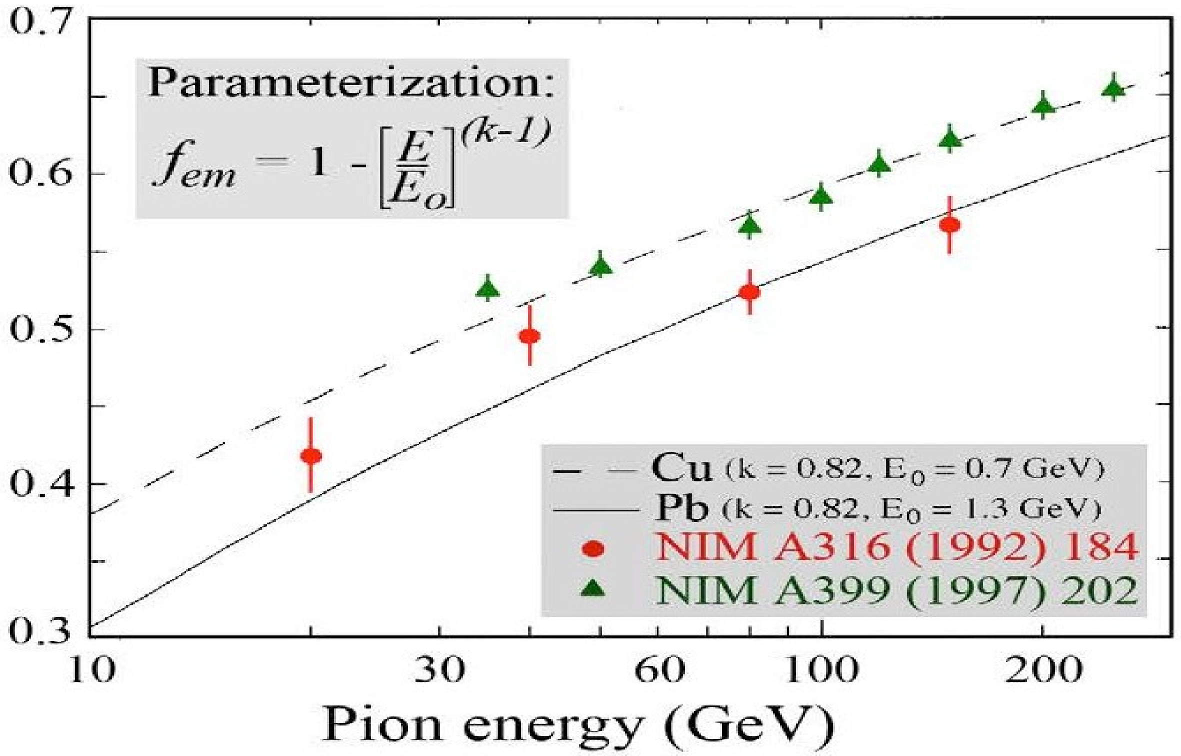
energy fraction carried by mainly π^0 (but also η)

f_{em}, on average, large and energy dependent
fluctuations in f_{em} large and non-poissonian

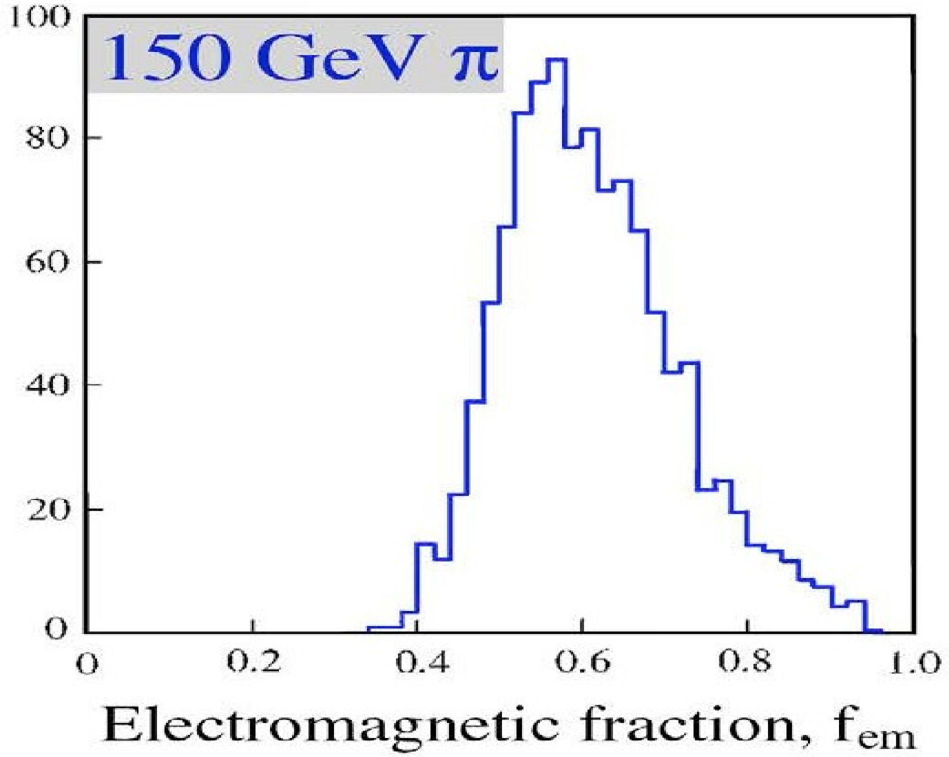
$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

E_0 = average energy to produce a π^0
$k < \sim 1$ (≈ 0.8)

< f_{em}> vs. pion energy



f_{em} for 150 GeV pions



detector response

Response:

detected signal per unit energy deposit

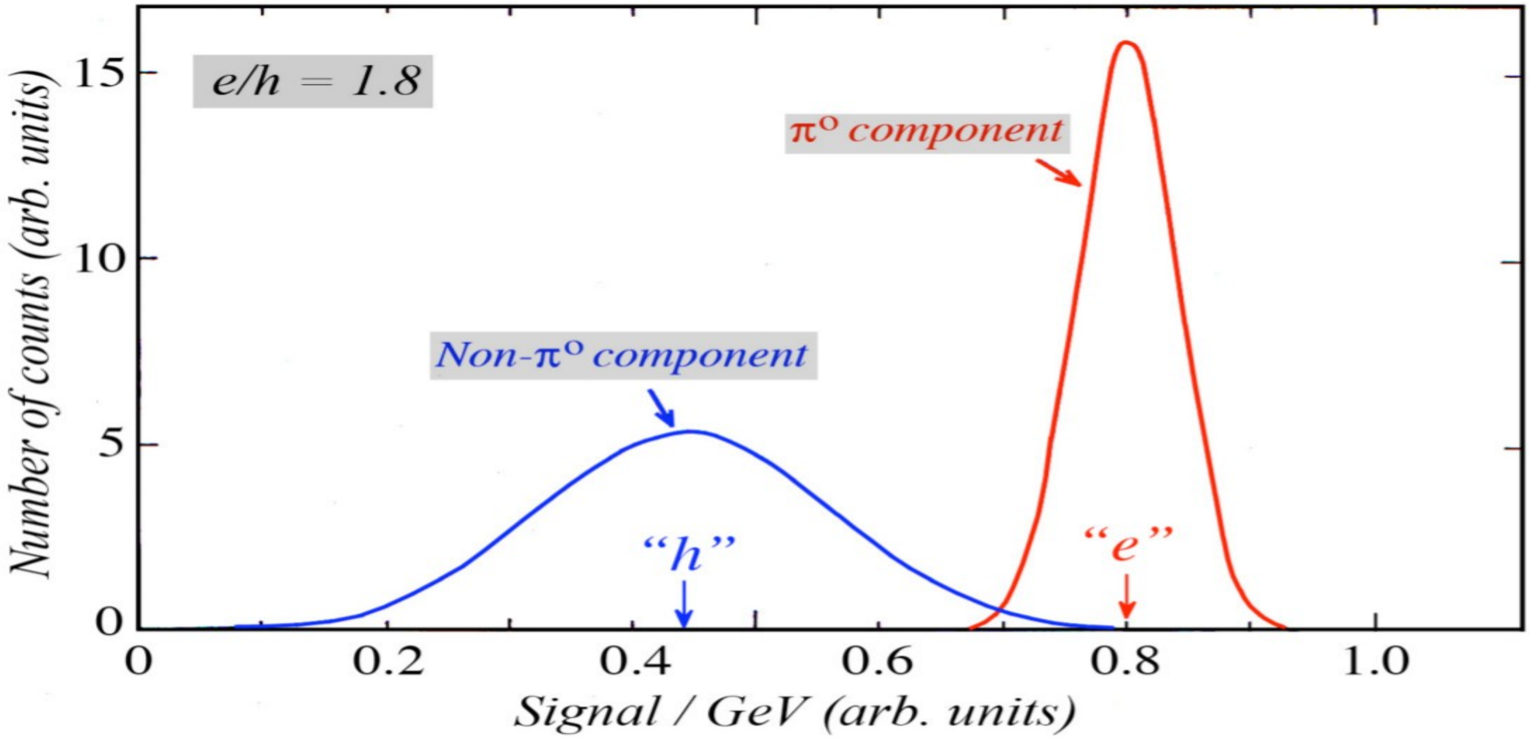
e.g. number of scintillating (or Cherenkov) p.e. / deposited GeV

Hadronic showers:

em component → response e
hadronic component → response h

what about relative ratio (e/h) ?

detector response to hadronic showers



e ≠ h

e.g. (left plot):

only 1/1.8 ≈ 56% of non-π° energy accounted by signal

Note:

e/h ratio: detector characteristic

typically, ~2 for crystals, in range 1-1.8 for sampling calorimeters

Nevertheless:

1) e/π depends on energy (f_{em} depends on E and shower "age")
2) $<f_{em}>$ different for π, K, p → response depends on particle type

e/mip ratio

mip : minimum ionising particle → only ionisation

dE/dx (mip) :

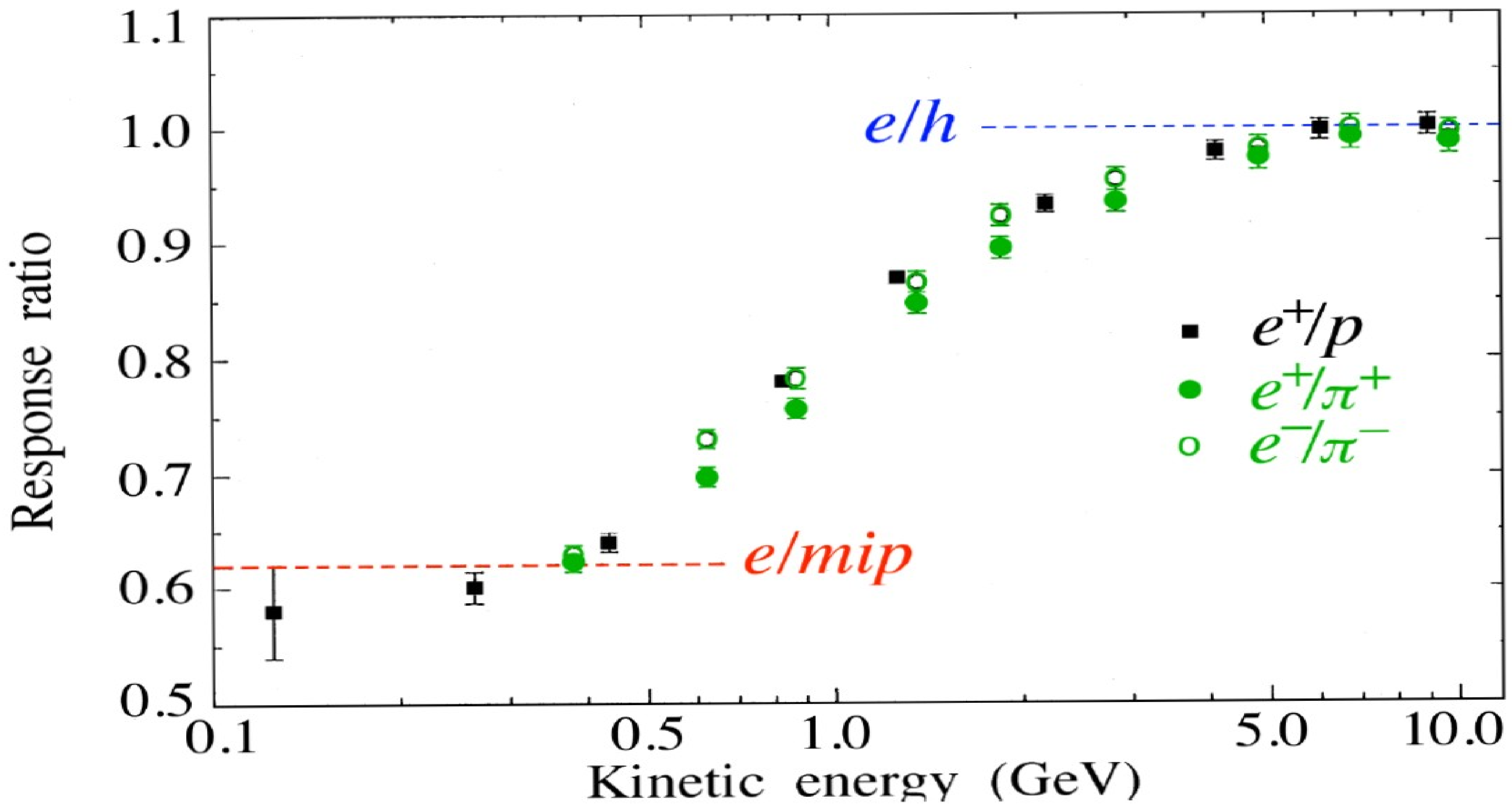
lead ~ 12.6 MeV/cm → 7.15 MeV/X_0
copper ~ 12.7 MeV/cm → 18.0 MeV/X_0
(PMMA ~ 2.3 MeV/cm → 78.2 MeV/X_0)

Moreover in high-Z absorbers :

Z^5 dependence of photoelectric effect
→ most soft-γ interact in absorber
photoelectrons have very short range
→ will contribute to signal only close to boundaries

→ response to em showers suppressed wrt. mips

e/mip ratio



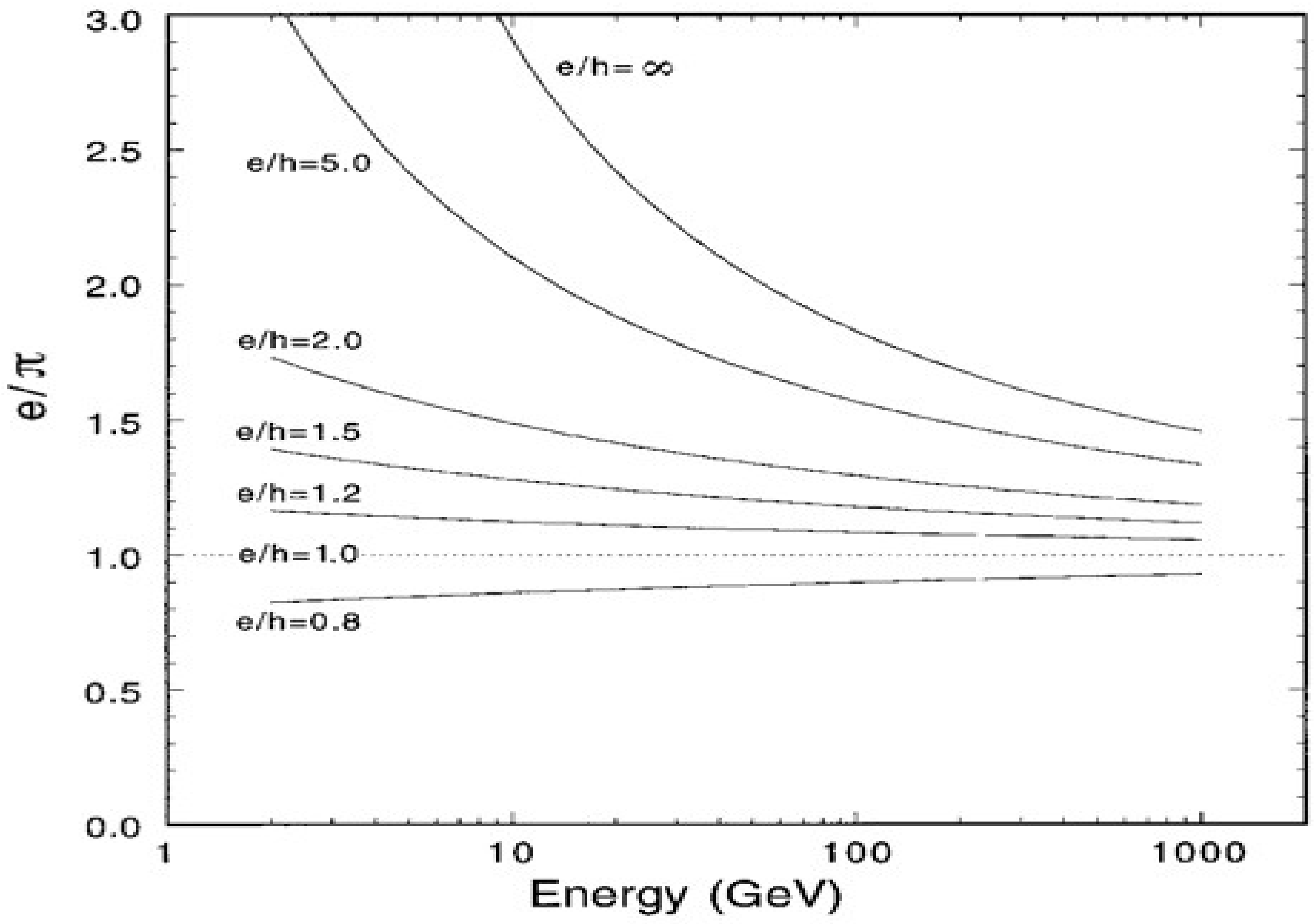
Non-linearity at low energy with high-Z absorber

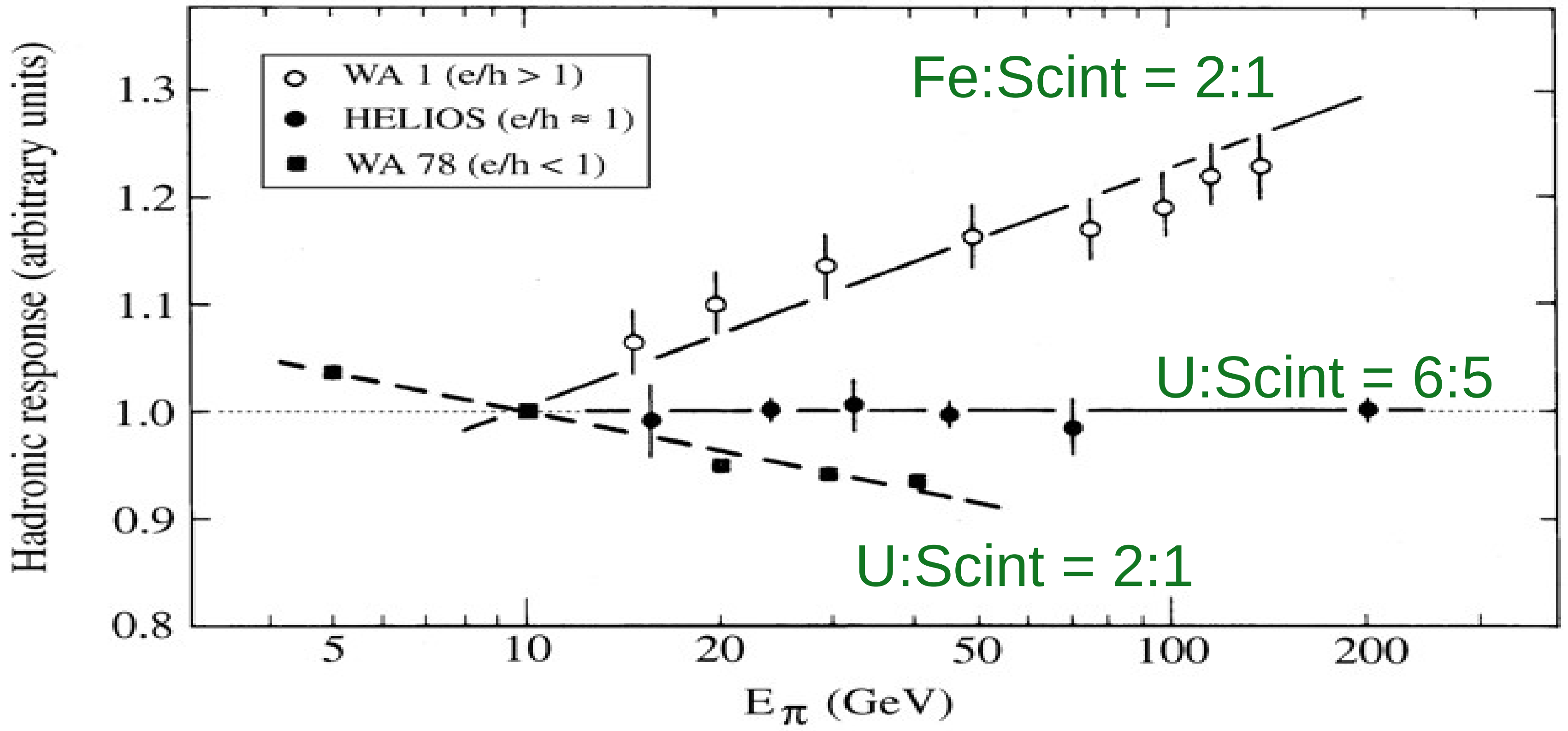
Important for jet detection

e/π ratio

calorimeter response to π : $\pi = f_{\mathrm{em}} \cdot e + (1 - f_{\mathrm{em}}) \cdot h$

$$\rightarrow \qquad e/\pi = \frac{e/h}{1 - f_{\mathrm{em}}\left[1 - e/h\right]}$$





response to π as function of E

compensation in hadron calorimetry

e/h = 1 → compensating calorimeter

1) increase h → boost hadron response

e.g. by adding hydrogen or Uranium, both acting as “neutron converters”

→ large integration volume and time

2) decrease e → decrease em sampling fraction or frequency (i.e. spoil em performance)

→ tune active / passive material ratio

what compensation does and does not

- NO guarantee for high resolution
  - fluctuations in f_{em} are canceled but others may be very large
- Has drawbacks
  - high-Z absorber required → small e/mip → non linearity @ low energy
  - low sampling fraction required → em resolution limited
  - relies on neutrons → integration over large volume and time

    SPACAL: to get 30%/√E ~15 tonnes of lead and ~50 ns integration time

- high-res em and high-res hadron calorimetry mutually exclusive:
  - good jet energy resolution ⇒ compensation

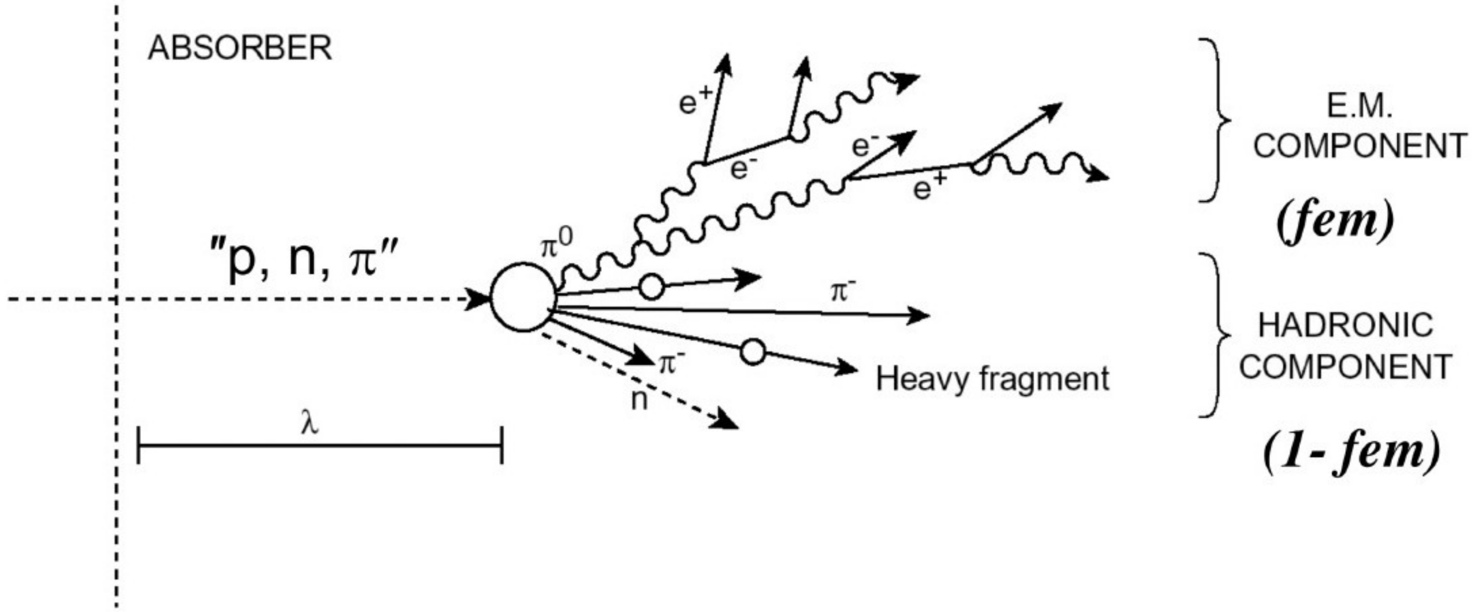
    ⇒ small sampling fraction (□3 %) ⇒ poor em resolution
  - good em resolution ⇒ high sampling fraction (100% crystals, 20% LAr)

    ⇒ large non compensation ⇒ poor jet resolution

Dual-readout calorimetry

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

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)

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

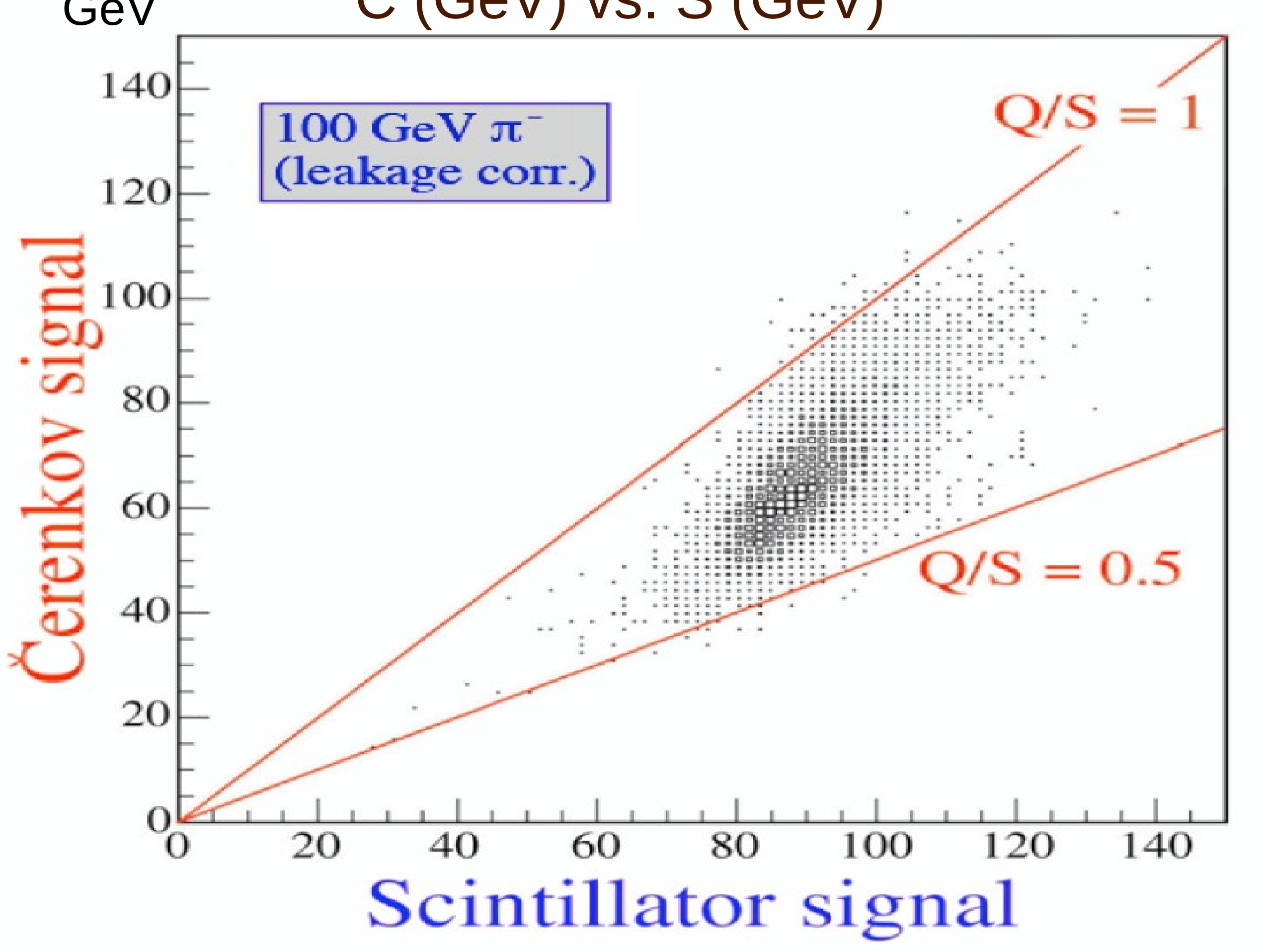
$$if \quad \left(\frac{h}{e}\right)_S > \left(\frac{h}{e}\right)_C \Rightarrow \chi < 1$$

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

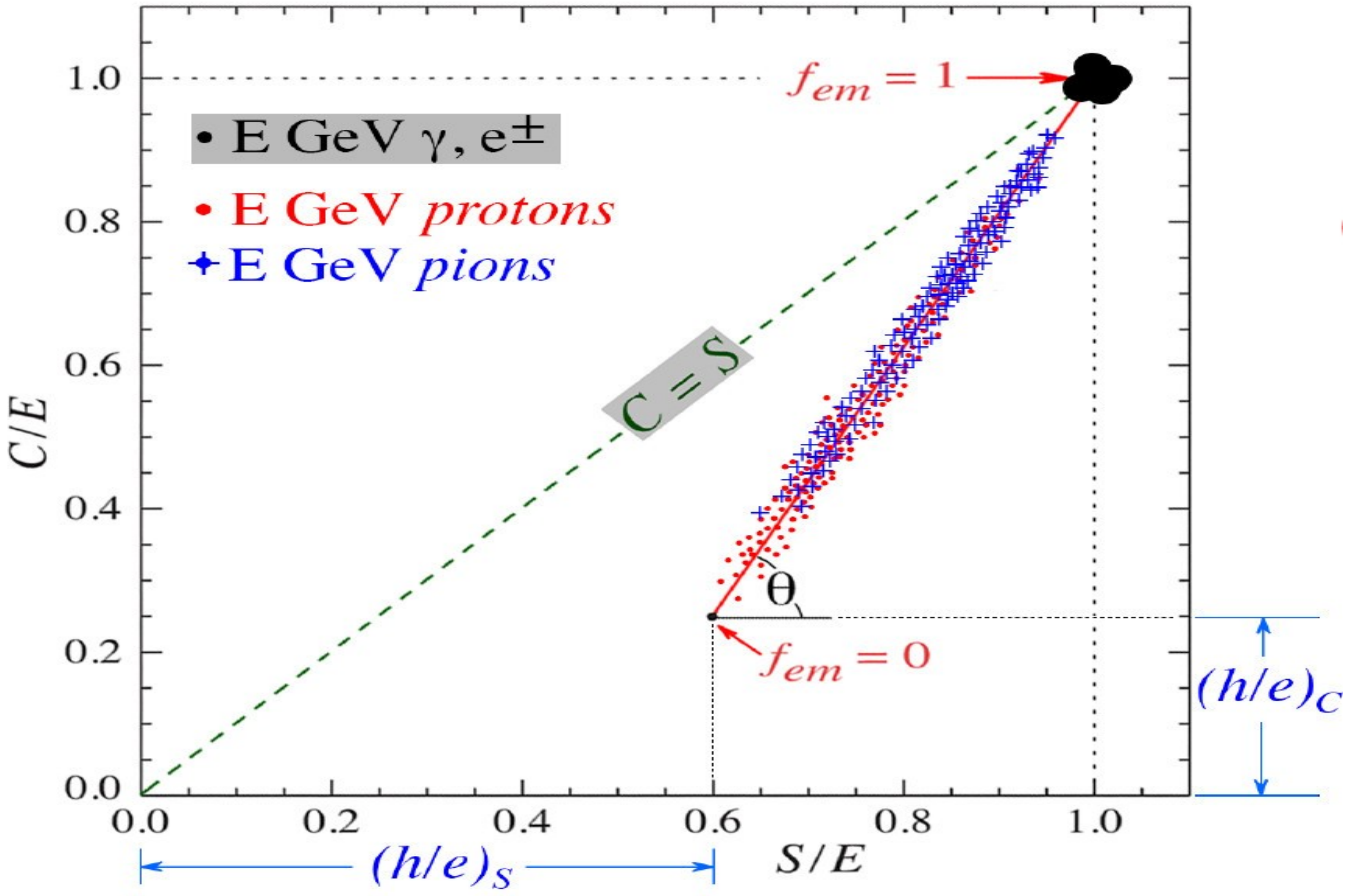
applying dual-readout formulae

GeV

C (GeV) vs. S (GeV)



C/E vs. S/E



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

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

θ, χ independent of both:

i) energy (!)

ii) type of hadron (!!)

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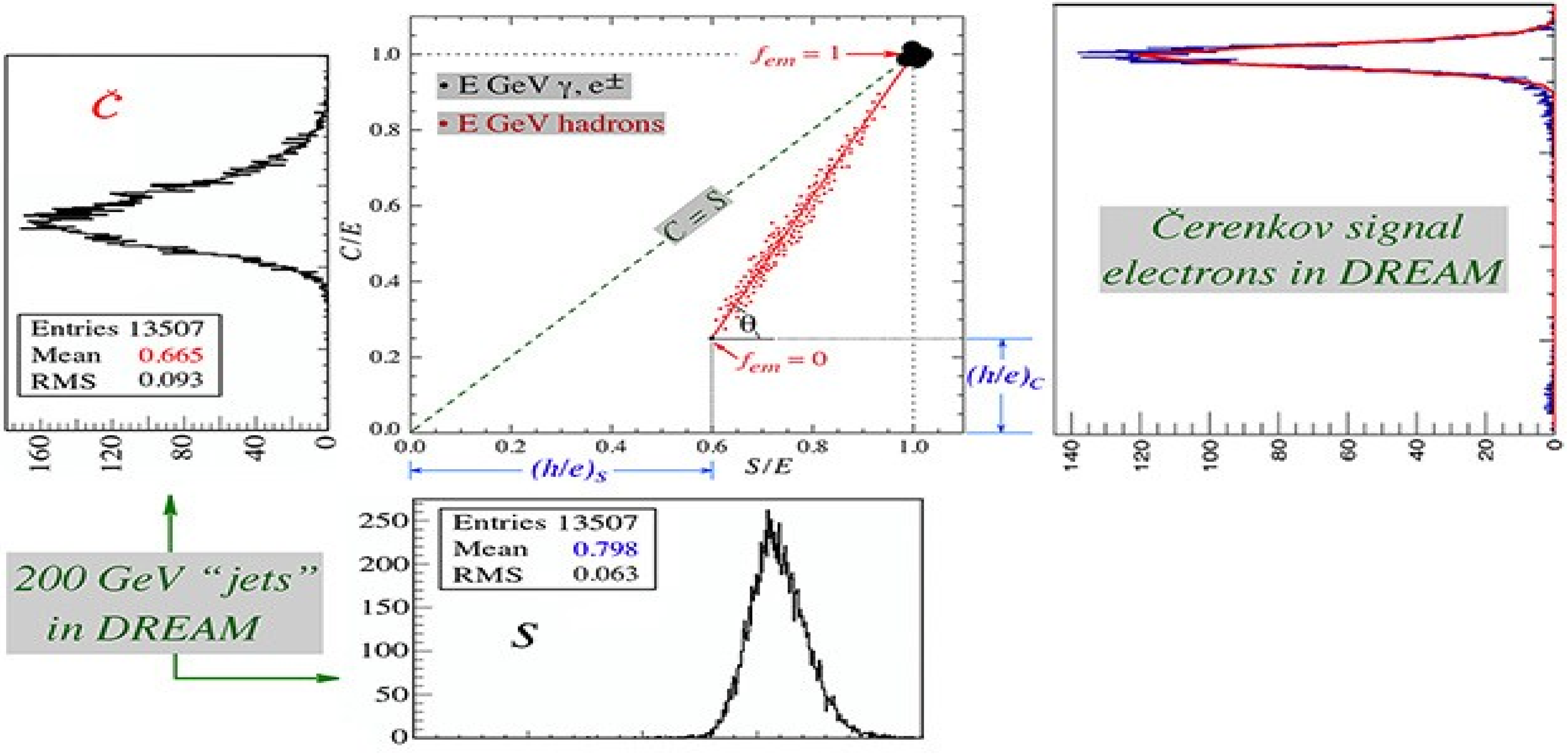
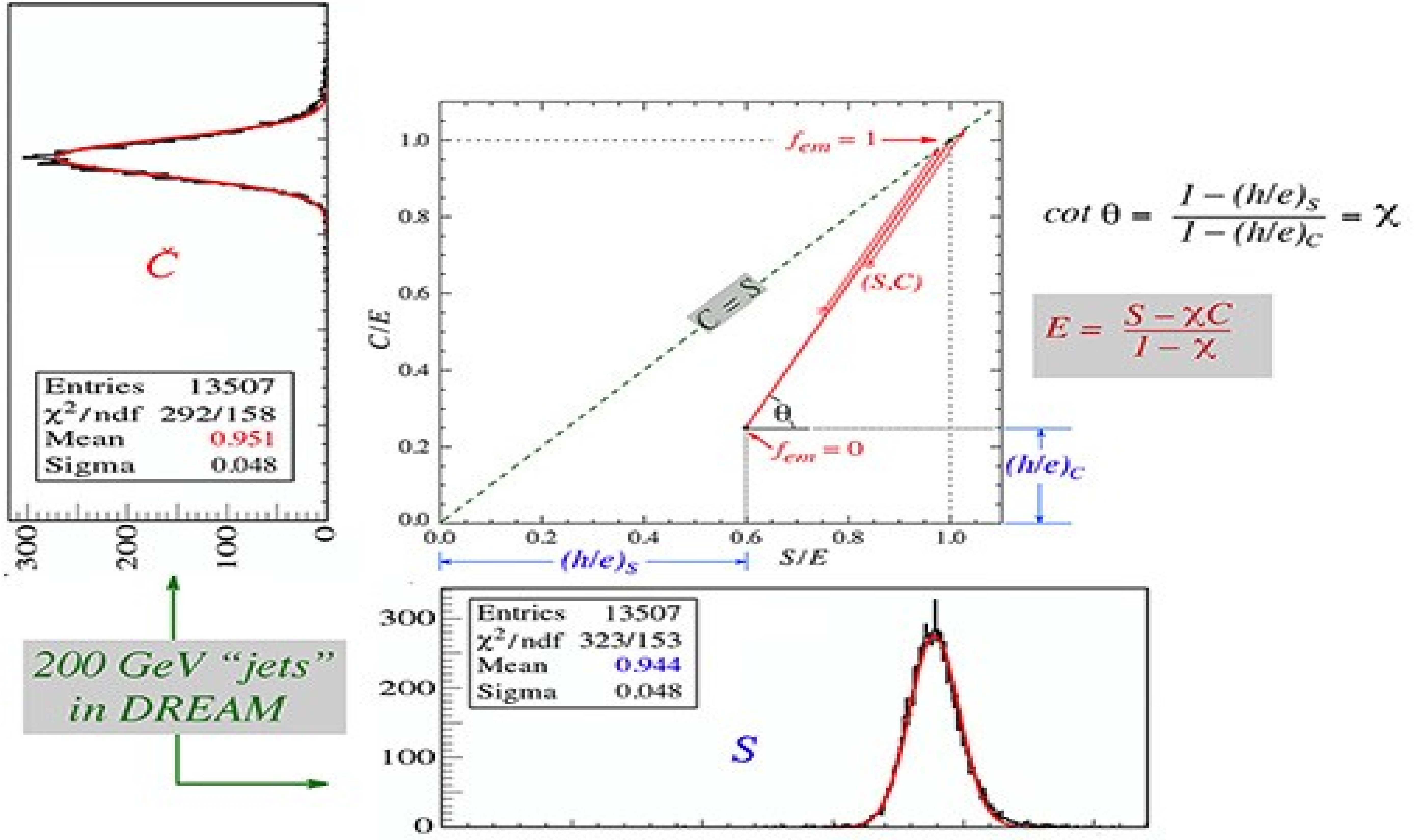
$$E = \frac{S-\chi C}{1-\chi}$$

is universally valid

before dual-readout corrections



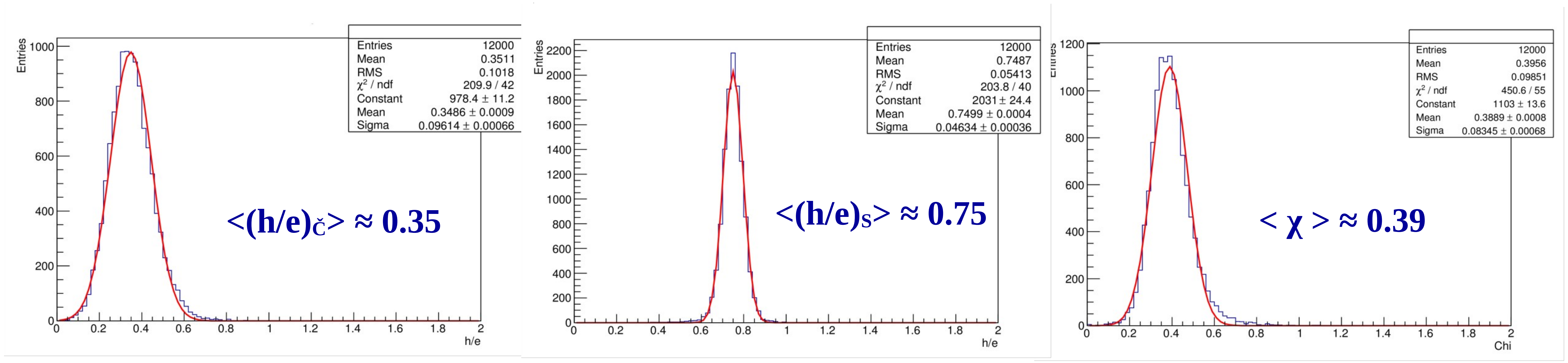
after dual-readout corrections



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

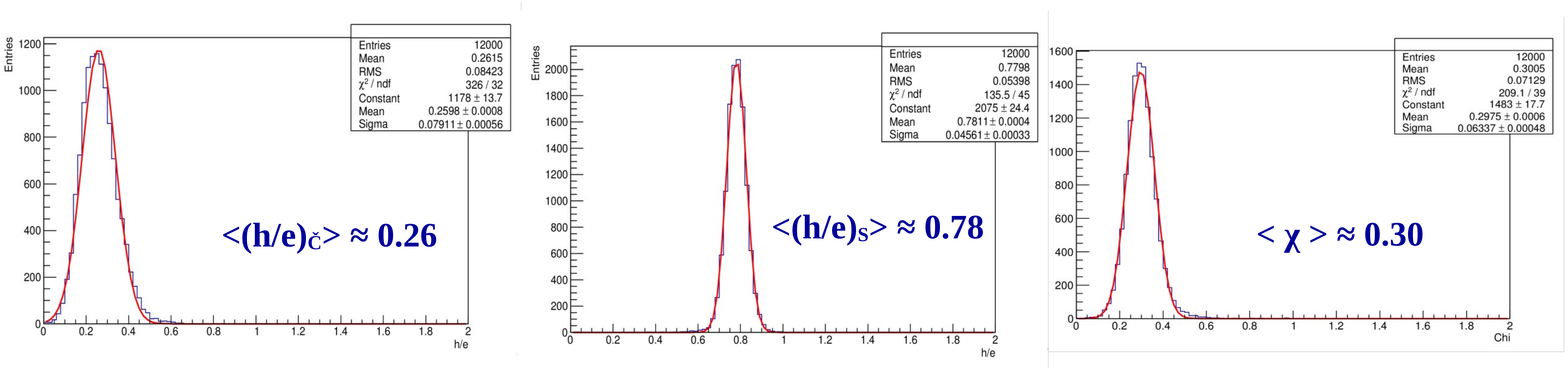
$$E = \frac{S-\chi C}{1-\chi}$$

Geant4 simulations – (h/e) and χ factors



$\langle (h/e)_{\check{C}} \rangle \approx 0.35$ $\langle (h/e)_{S} \rangle \approx 0.75$ $\langle \chi \rangle \approx 0.39$

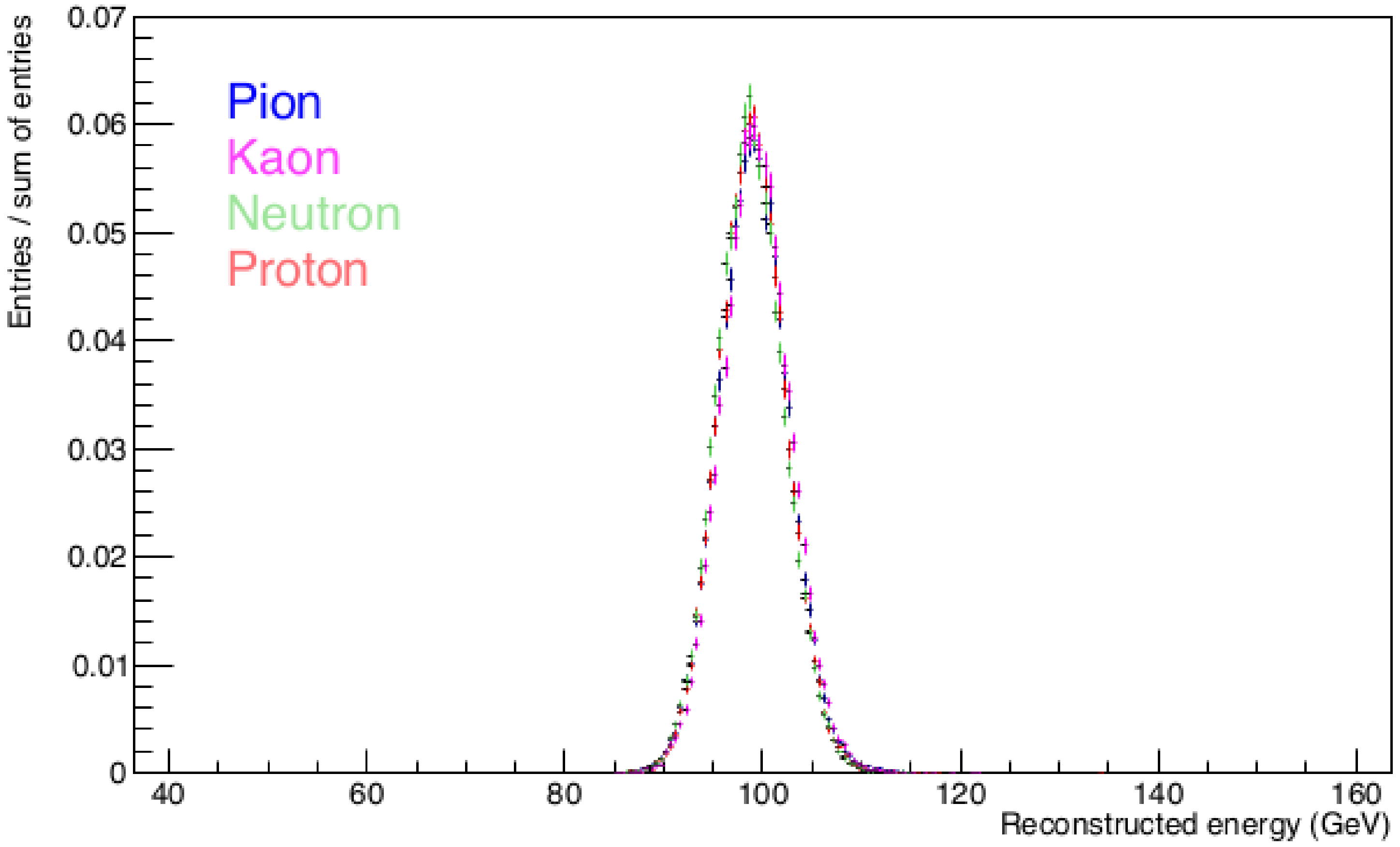
80 GeV protons in Copper ↑ & Lead ↓



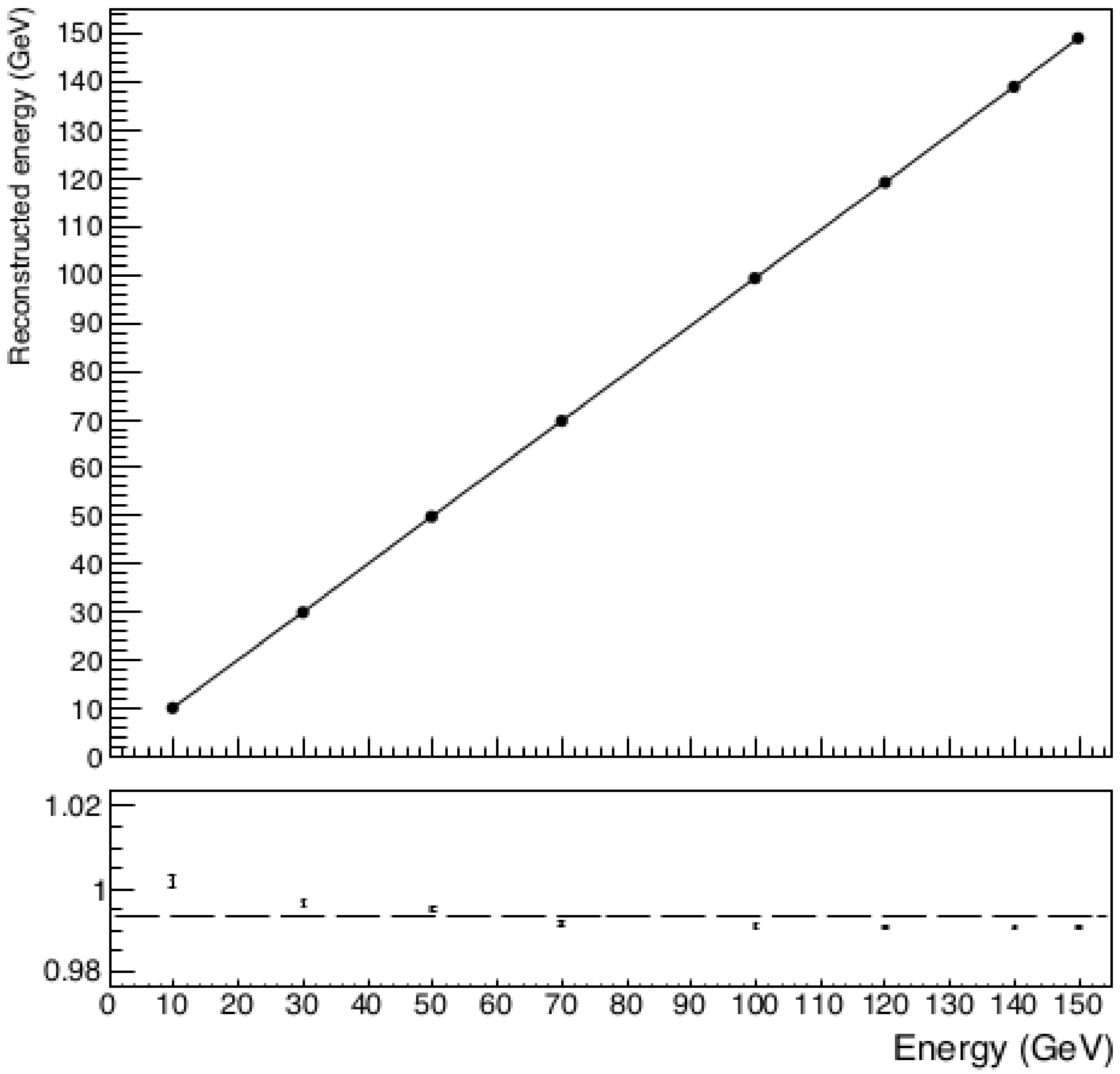
$\langle (h/e)_{\check{C}} \rangle \approx 0.26$ $\langle (h/e)_{S} \rangle \approx 0.78$ $\langle \chi \rangle \approx 0.30$

Geant4 simulations

100 GeV hadrons



10-150 GeV π^-



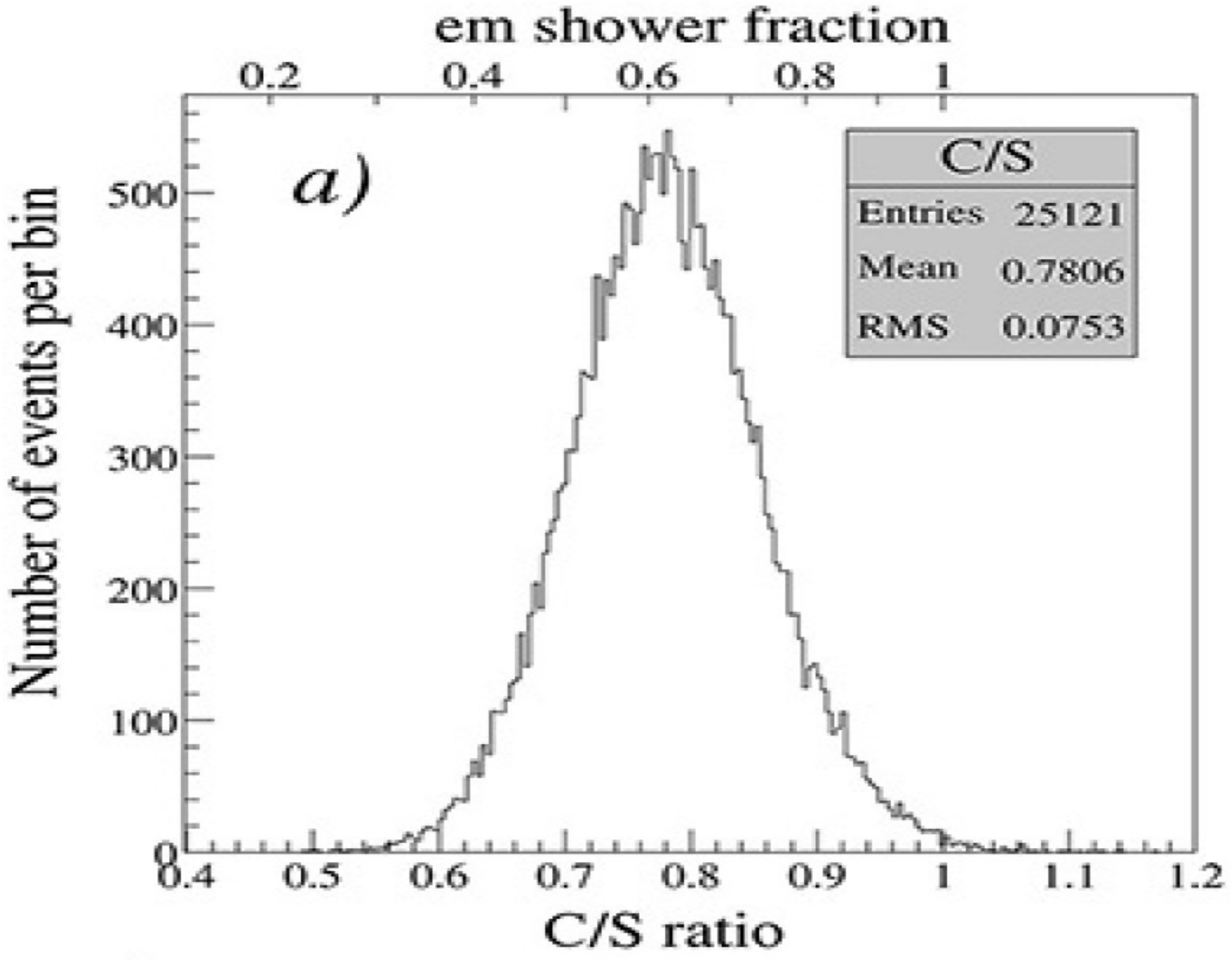
f_{em}

$$f = \frac{c - s(C/S)}{(C/S)(1 - s) - (1 - c)}$$

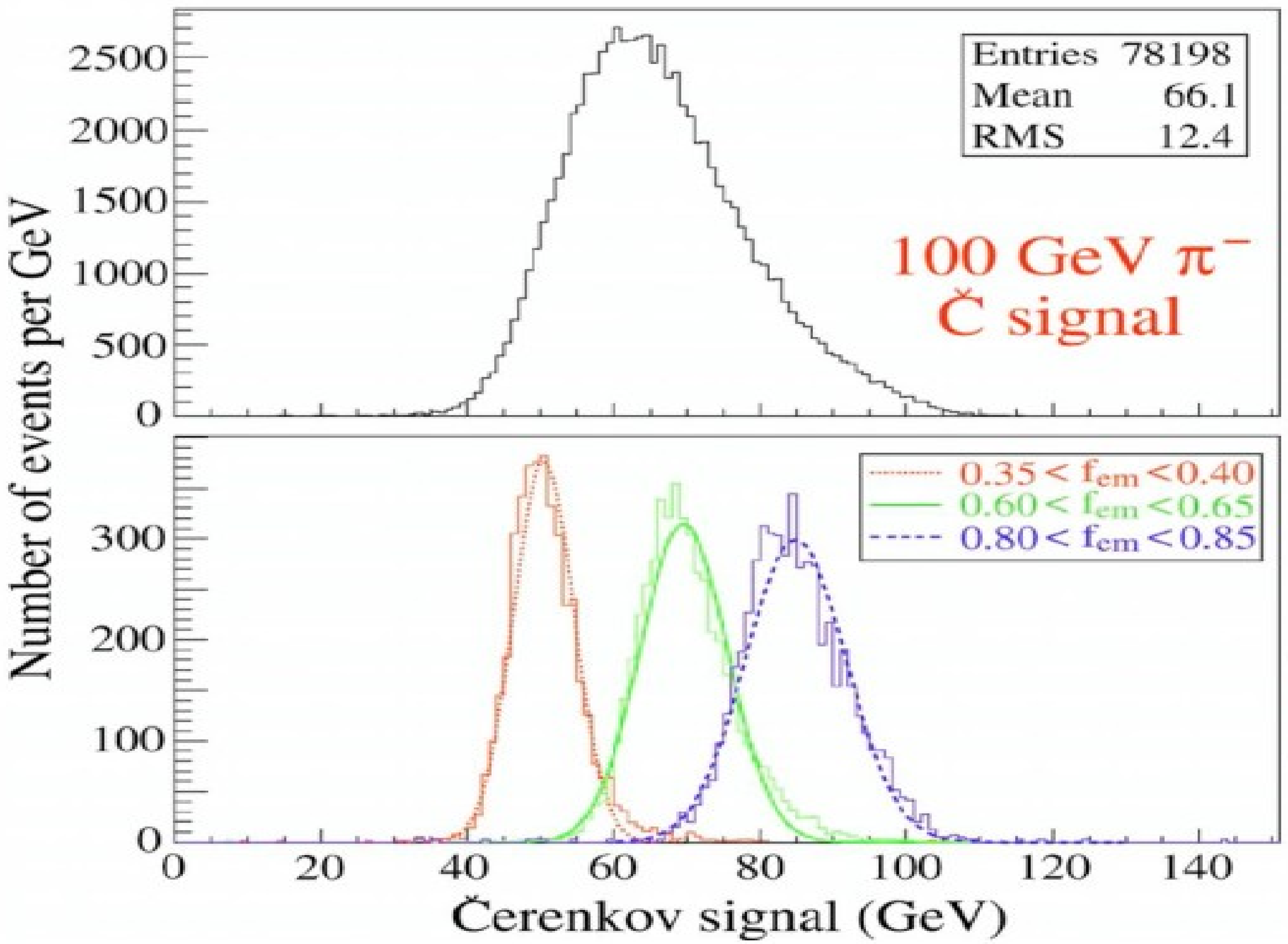
→ depends only on C/S → can use C/S to select f_{em} subsamples

→ to get f_{em} absolute value, at least one of (h/e) factors needs to be known

f_{em} fluctuations



DREAM: Effect of event selection based on f_{em}



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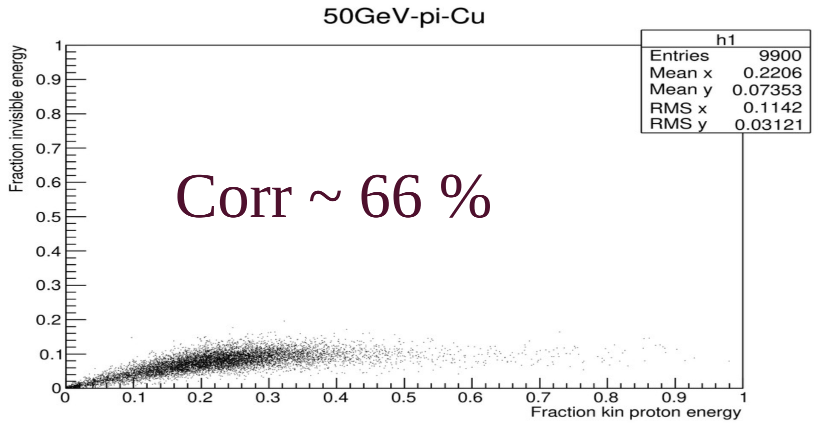
Invisible energy fraction – Geant4 simulations

$f(E)_{neutron}$ →

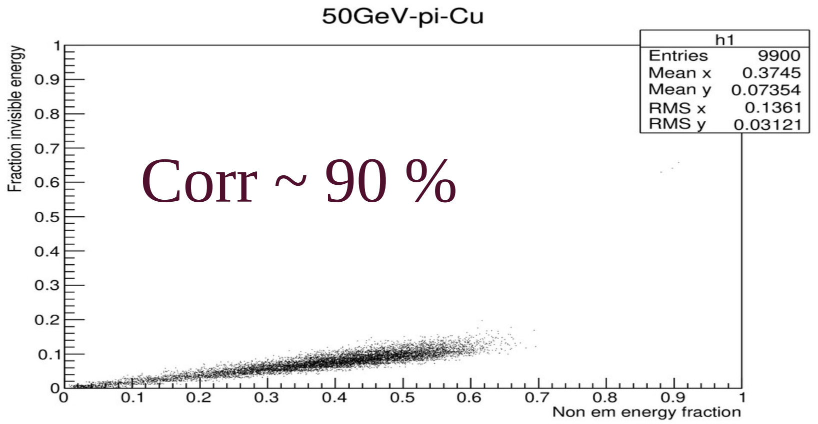
$1 - f_{em}$ →

f_{inv} ↑

Copper

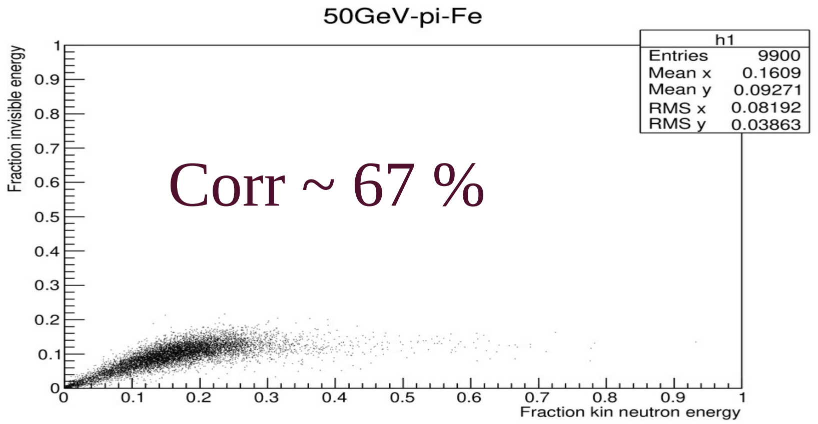


Corr ~ 66 %

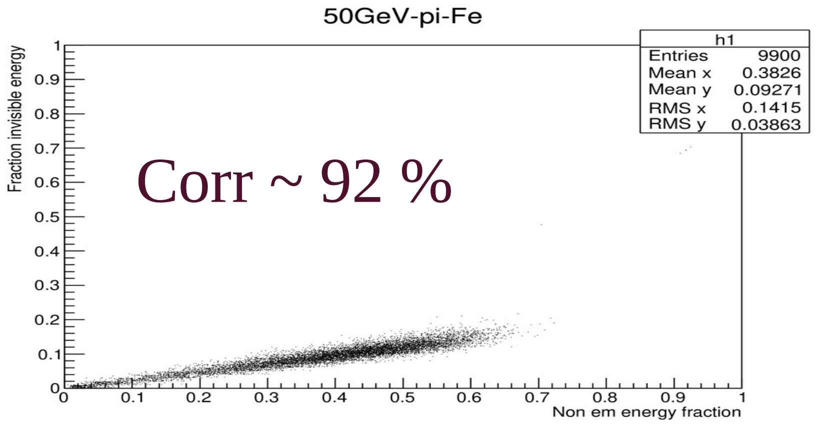


Corr ~ 90 %

Iron

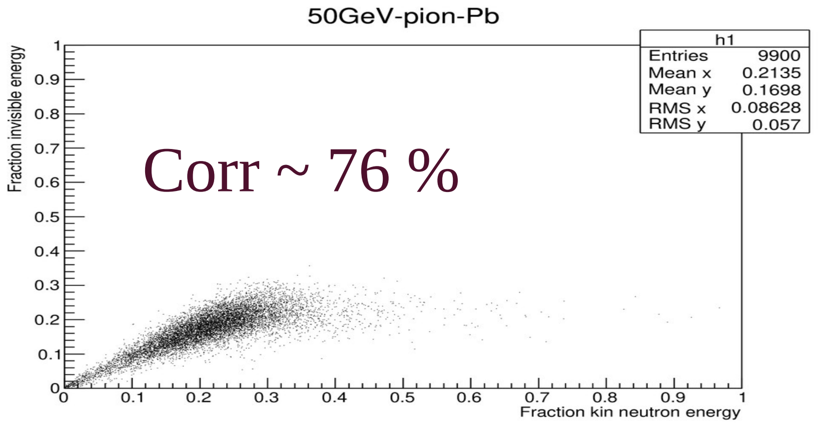


Corr ~ 67 %

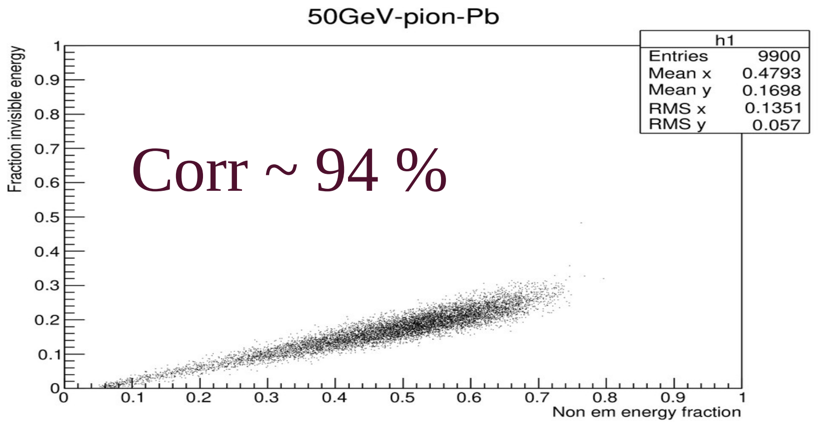


Corr ~ 92 %

Lead



Corr ~ 76 %



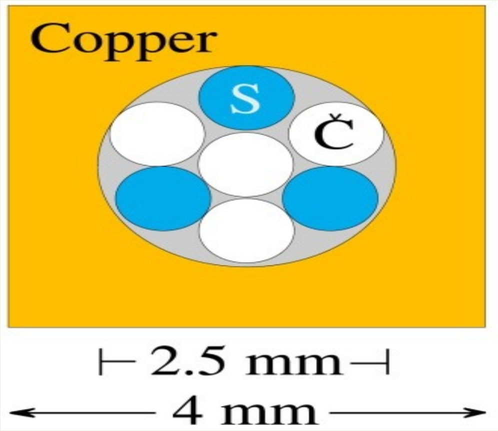
Corr ~ 94 %

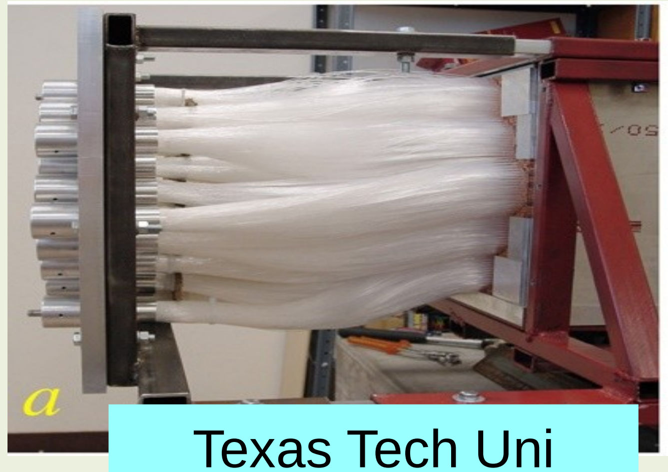
DREAM/RD52 prototype results

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}

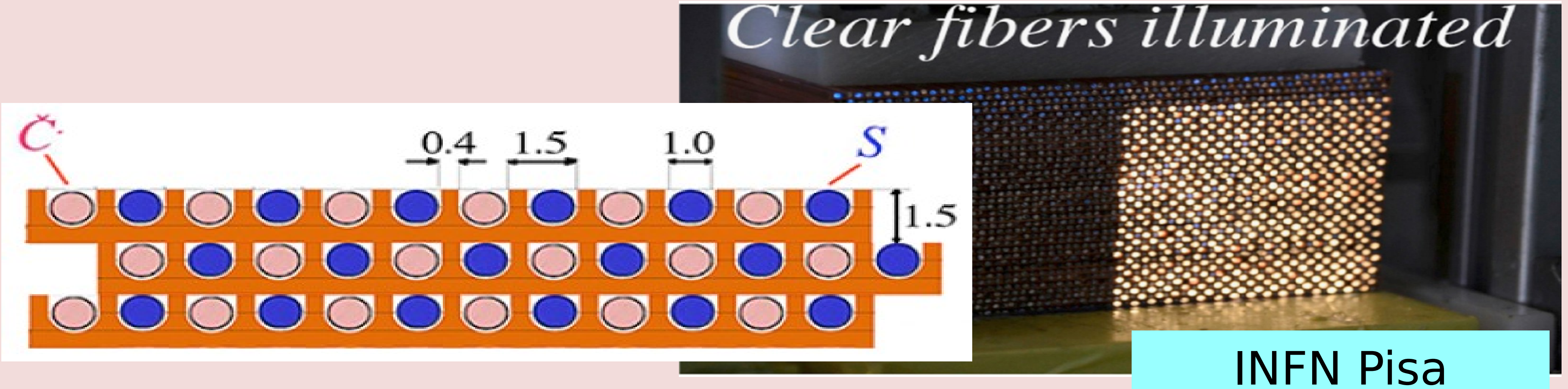




Texas Tech Uni

2012
RD52

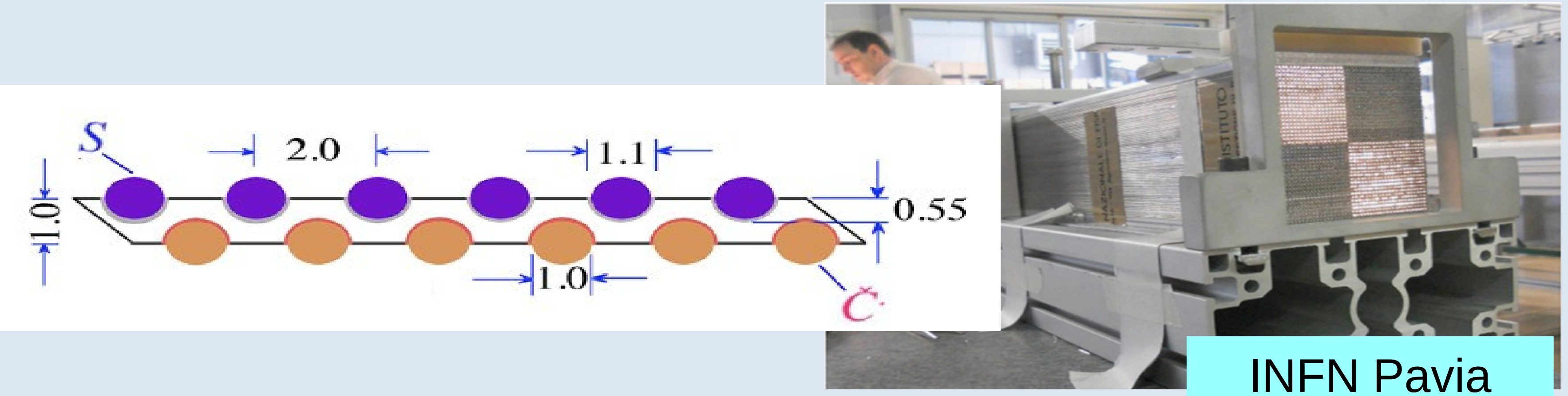
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

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}



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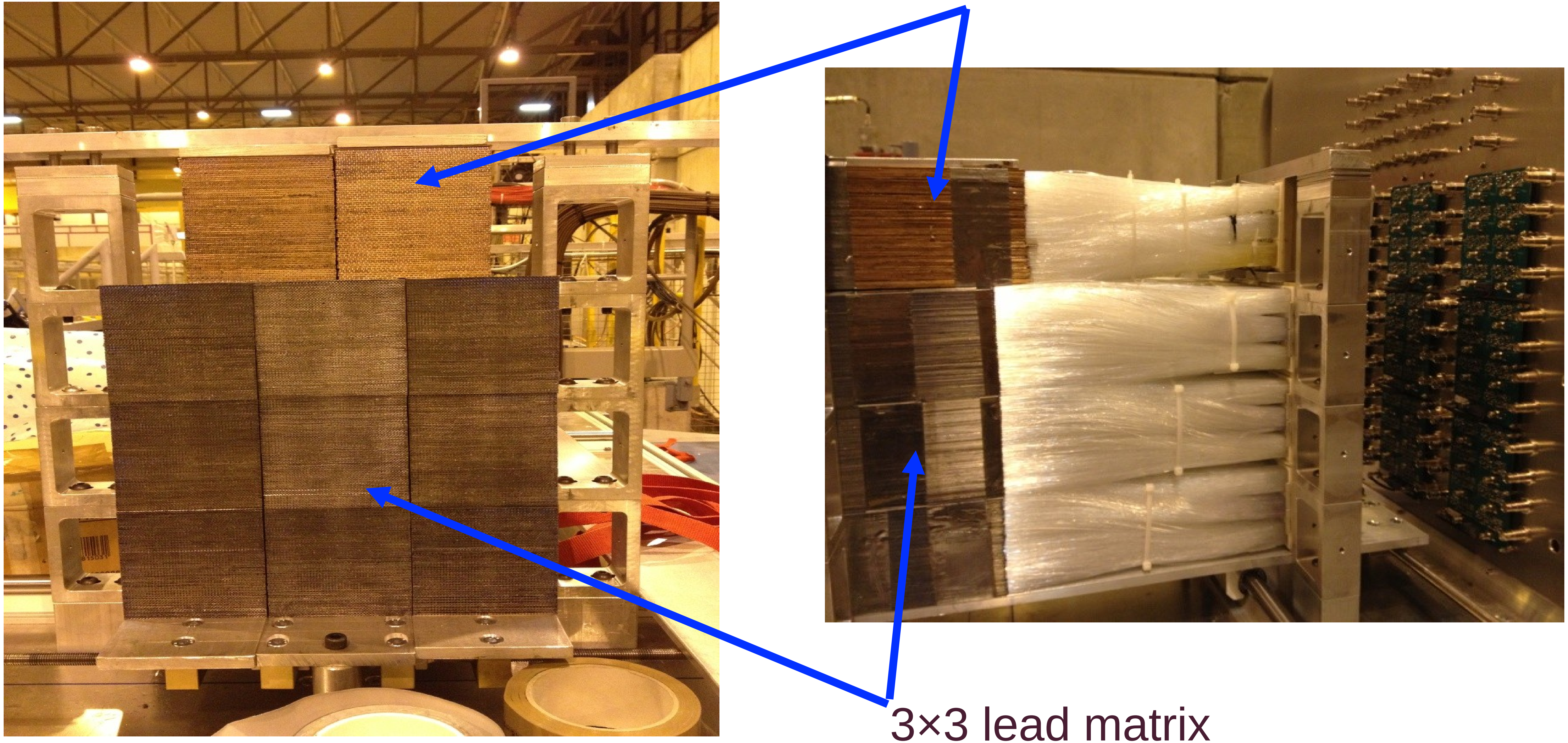
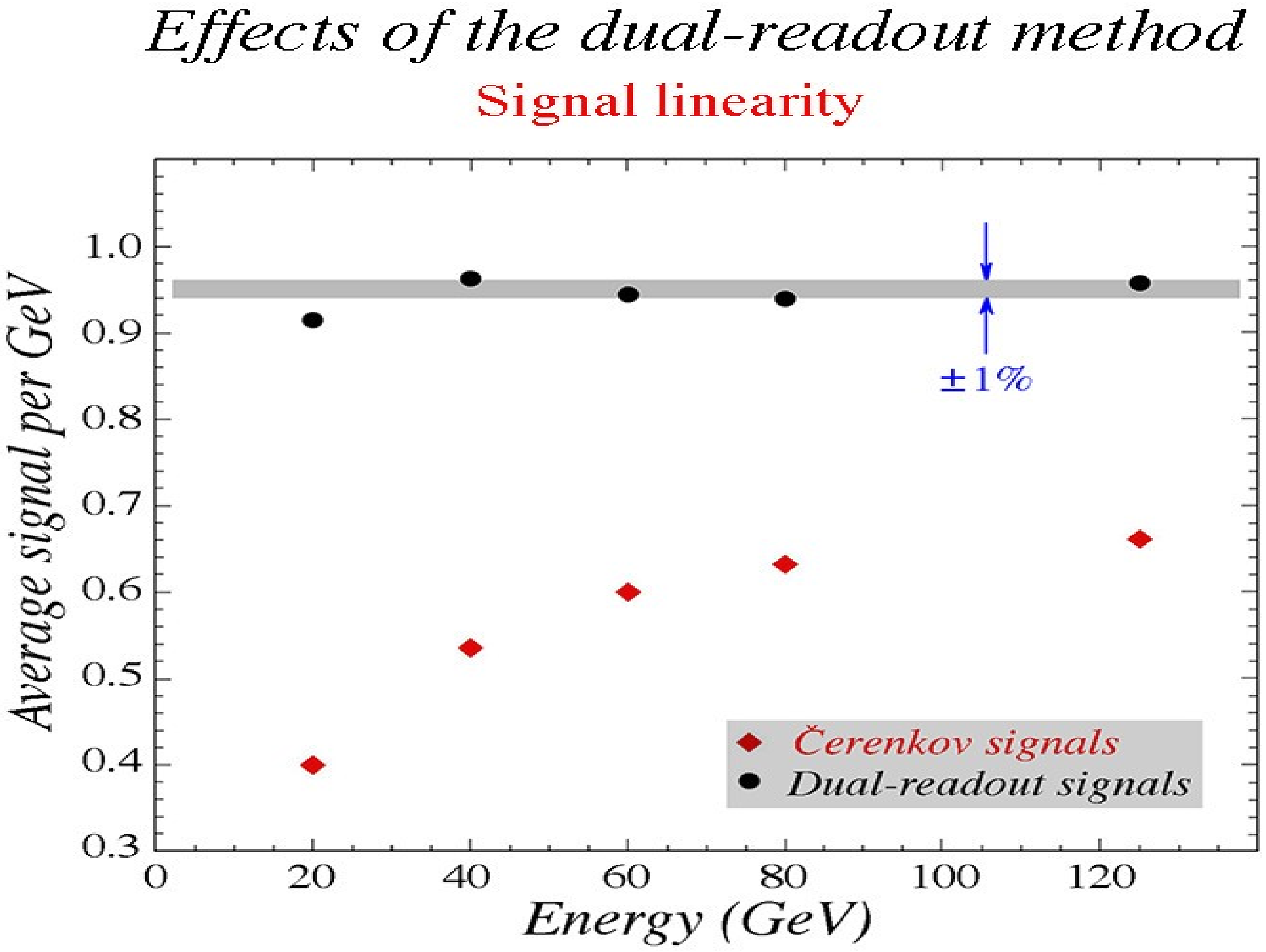
RD52 dual-readout spaghetti prototypes

2 Cu modules



3×3 lead matrix

dual-readout at work (1)



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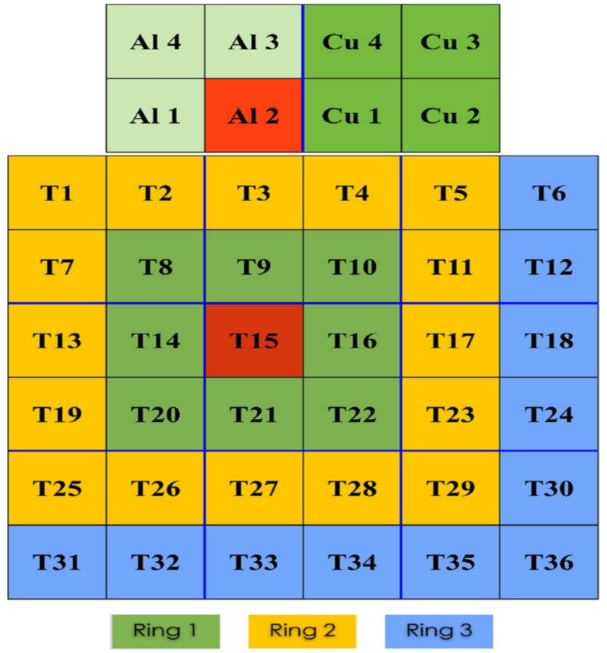
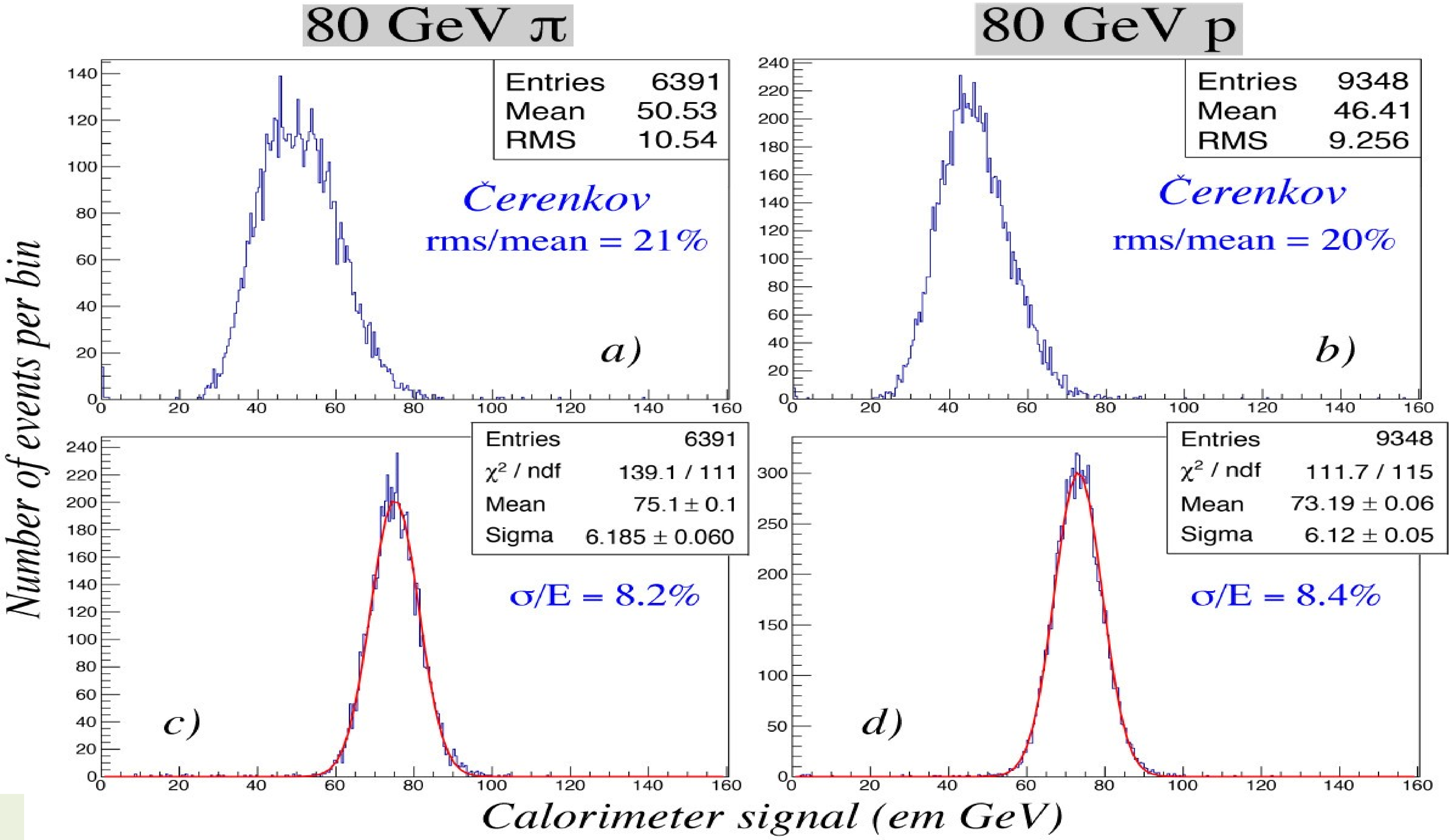
dual-readout at work (2)



	Al 4	Al 3	Cu 4	Cu 3	
	Al 1	Al 2	Cu 1	Cu 2	
T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

🟩 Ring 1 🟨 Ring 2 🟦 Ring 3



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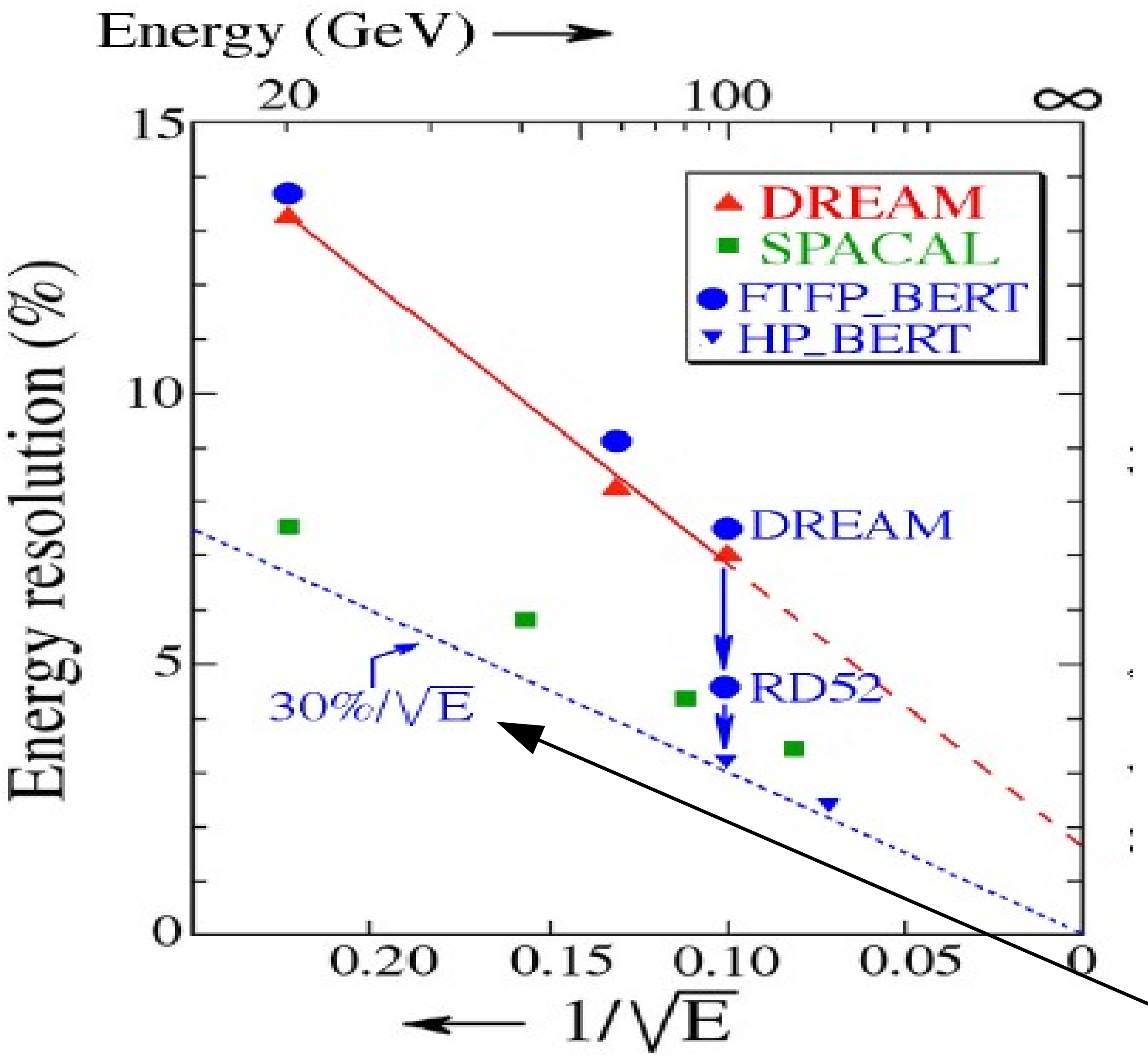
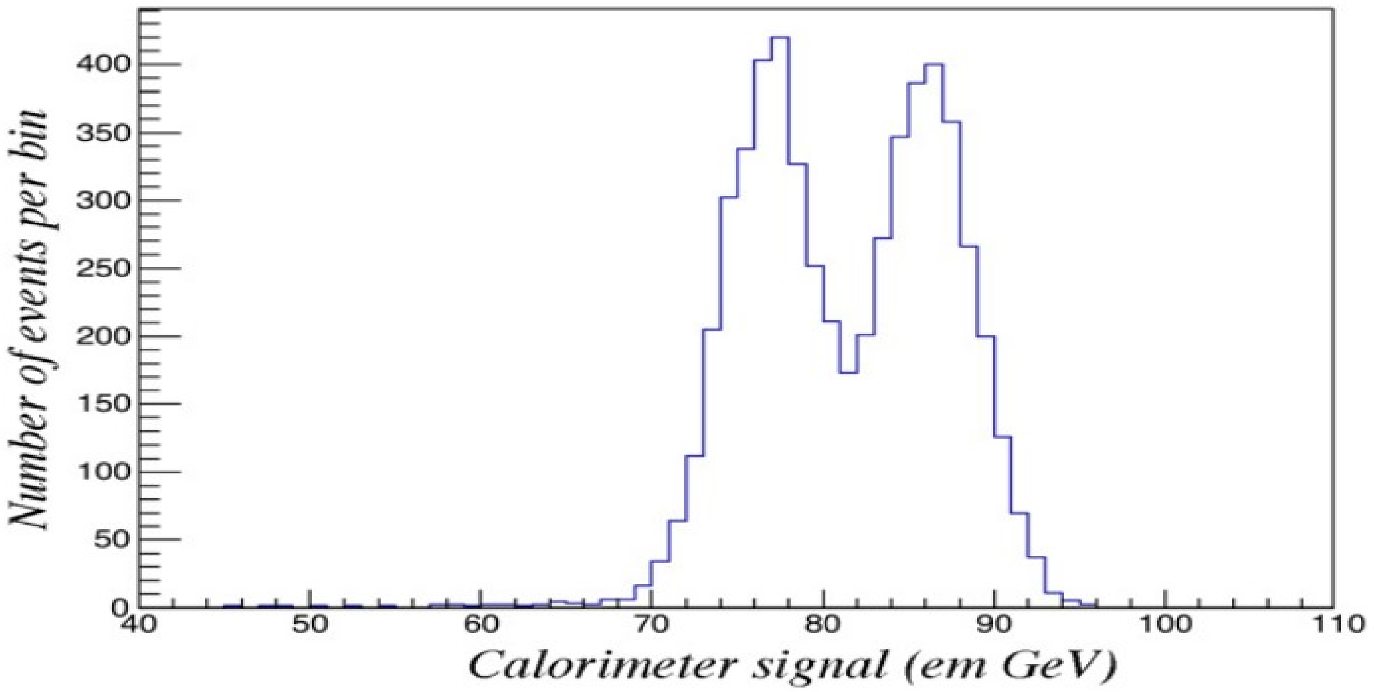
RD52 expected hadronic performance

Hadronic Resolution



W/Z separation



Geant4 simulations

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Particle ID (electron/hadron discrimination)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

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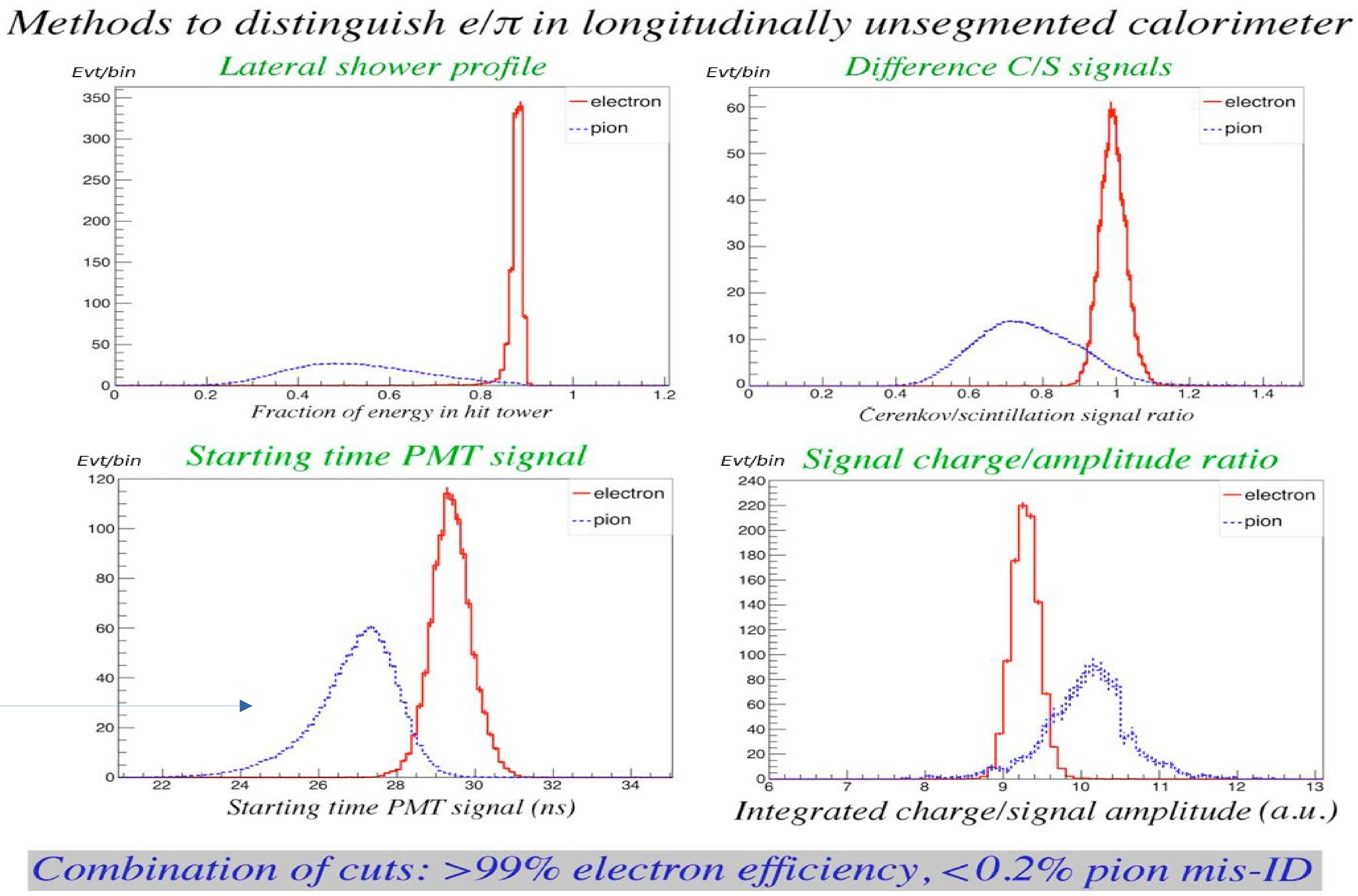
time-of-arrival distribution
measured w/ TDC



Methods to distinguish e/π in longitudinally unsegmented calorimeter

Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

(dual readout goes granular ...)

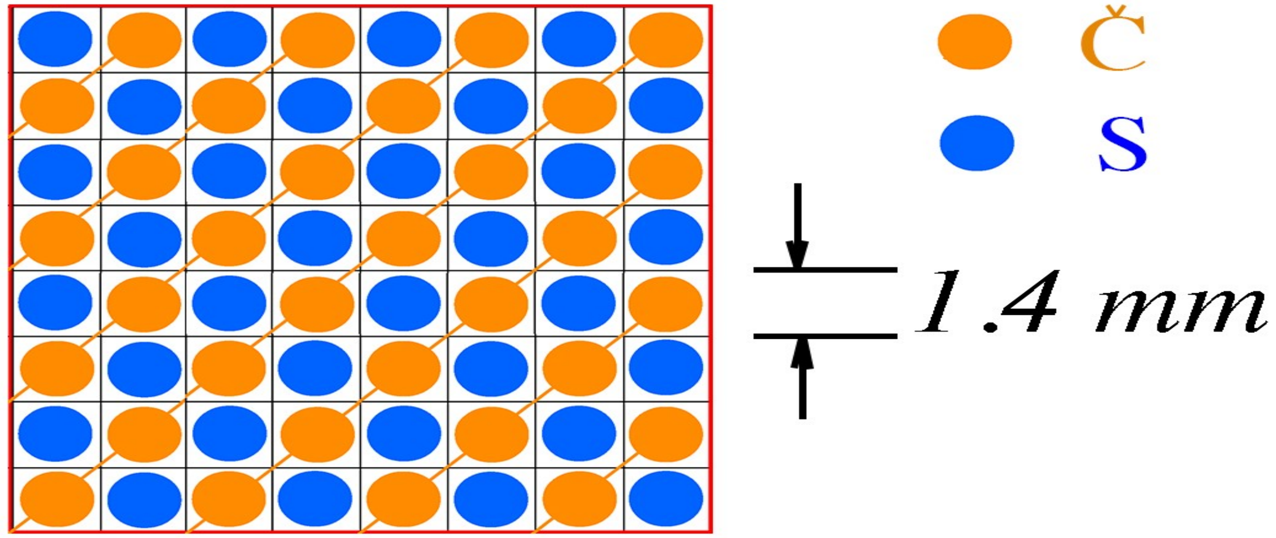
RD52 SiPM module

Brass module, dimensions: ~ 112 cm long, 12 x 12 mm^2

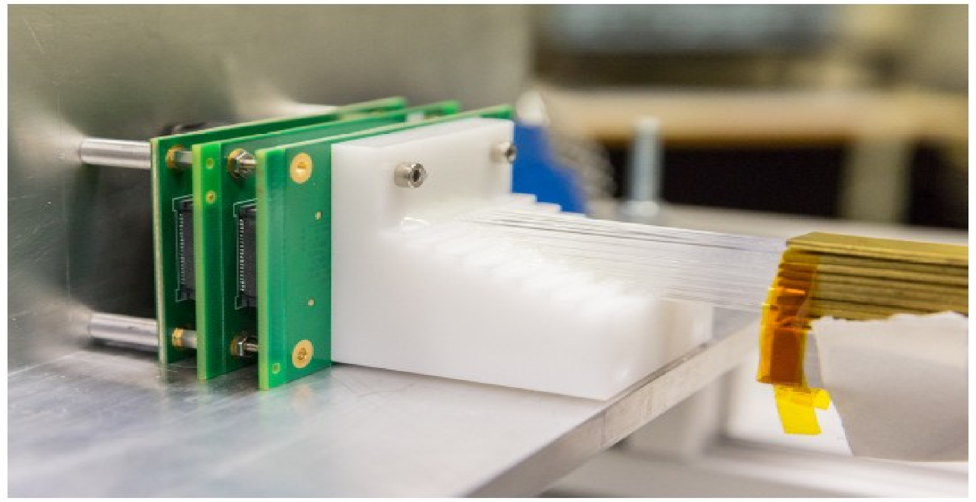
32 (S) + 32 (Č) fibres
X_0 ~ 29 mm
R_M ~ 31 mm

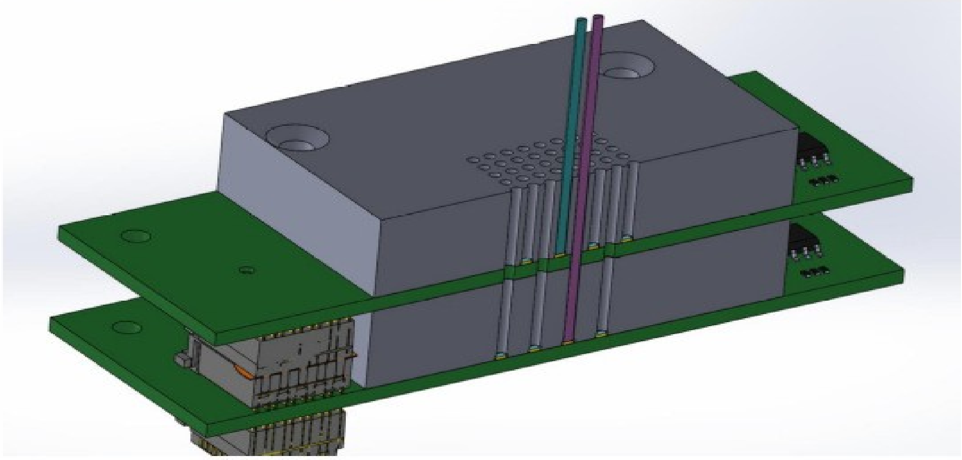
~ $(0.4\ R_M)^2 \times 39\ X_0$

shower cont. ~ 45%
f_{sampl} ~ 5-6%



Light sensors (SiPM)

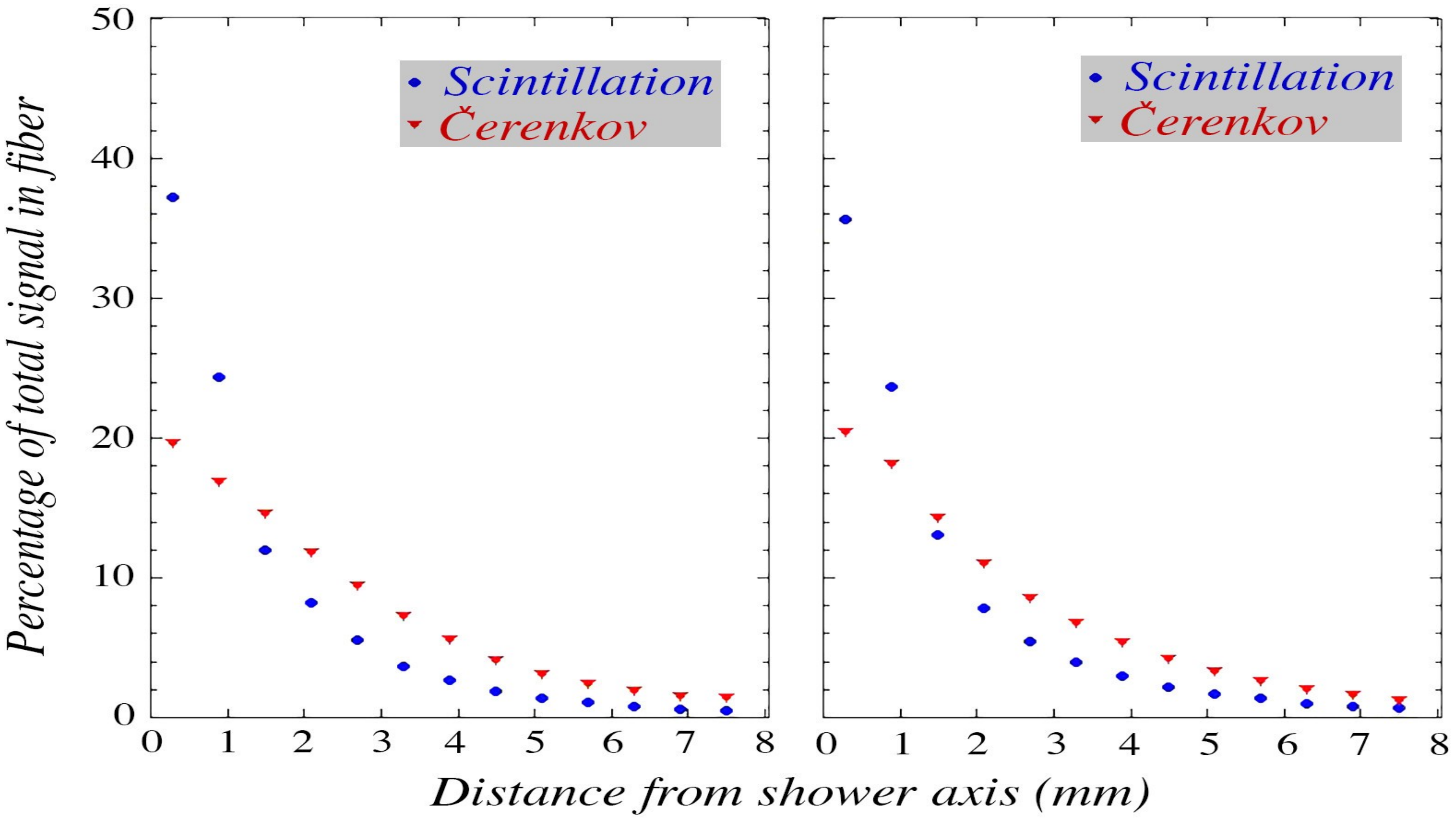




Lateral shower profile w/ SiPMs

10 / 40 GeV e^-

θ, Φ = 0°



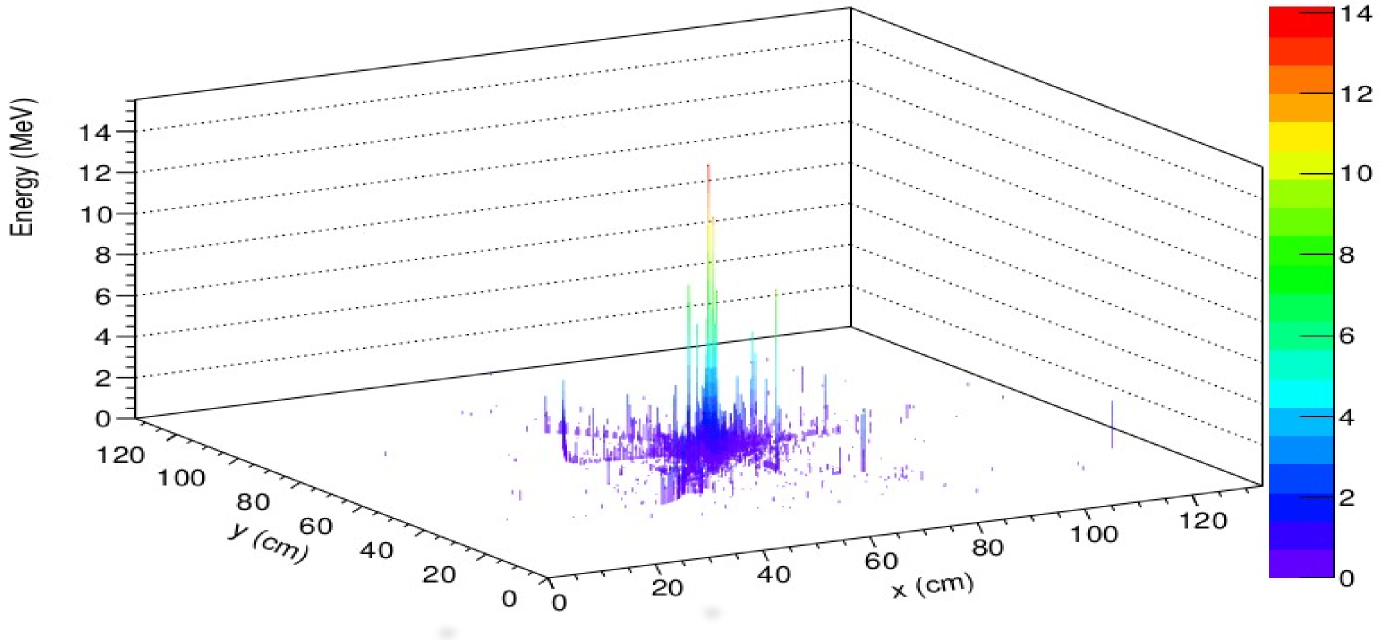
em shower very narrow:

~10% (~50%) within ~1 (~10) mm from shower axis

→ fibre readout can easily provide (powerful) input to PFA

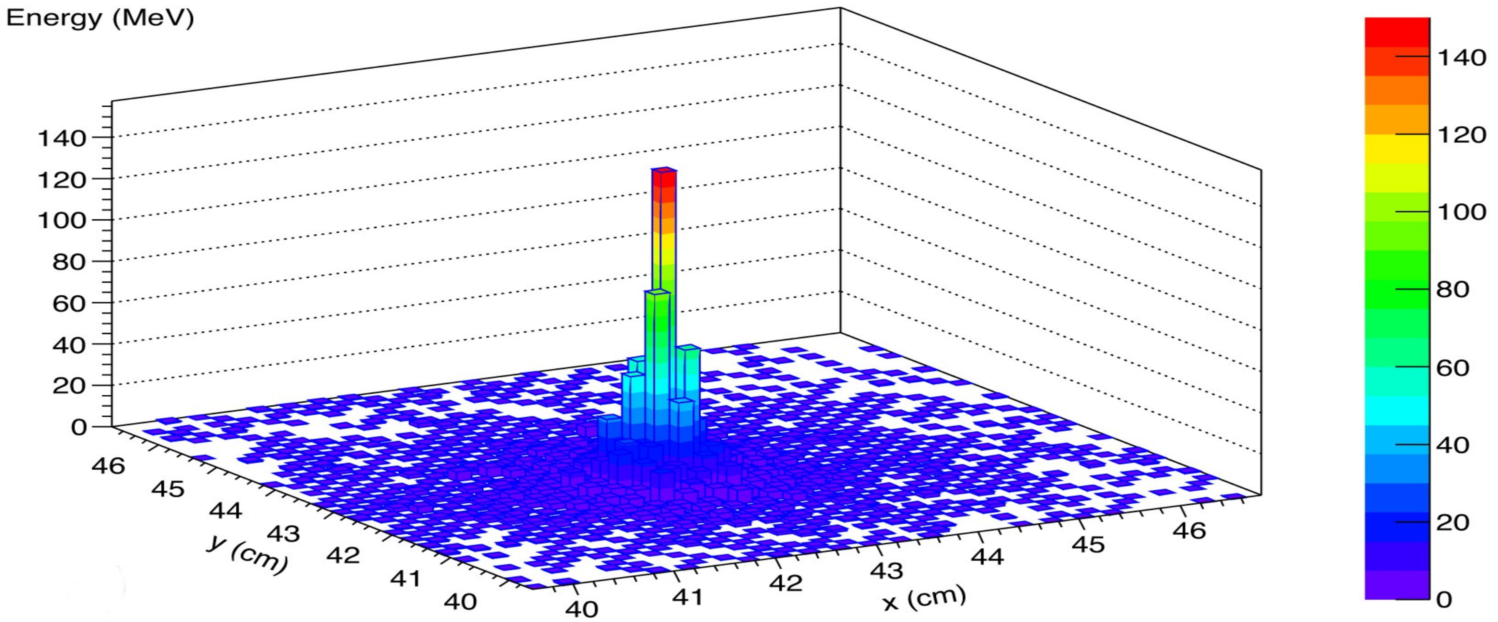
2D fibre imaging

80 GeV π^-

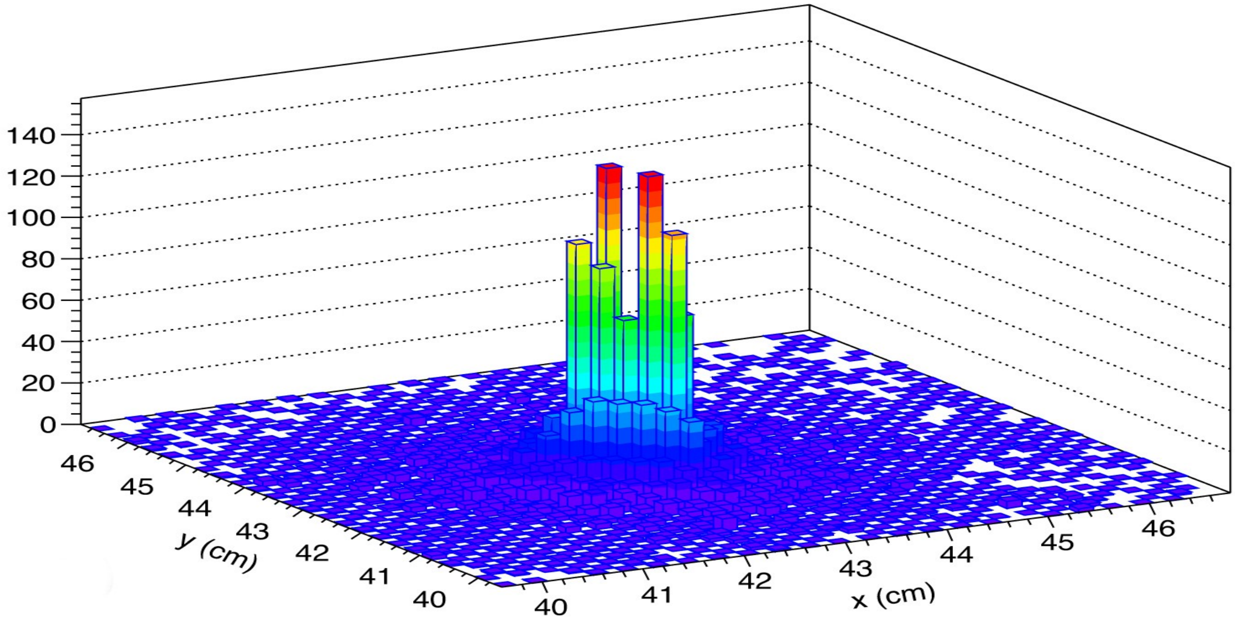


Geant4 single-particle simulations

50 GeV e^-

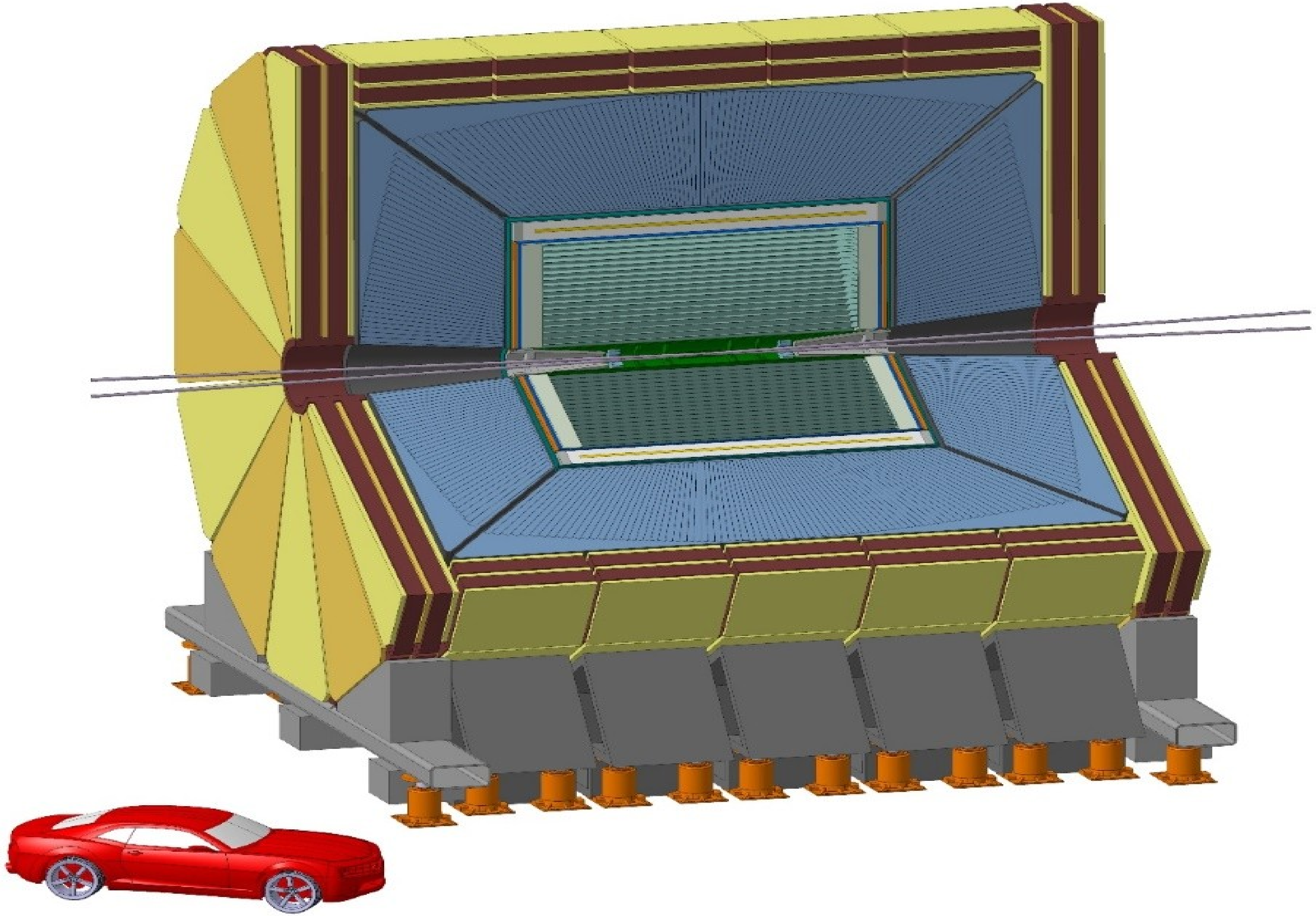


100 GeV π^0



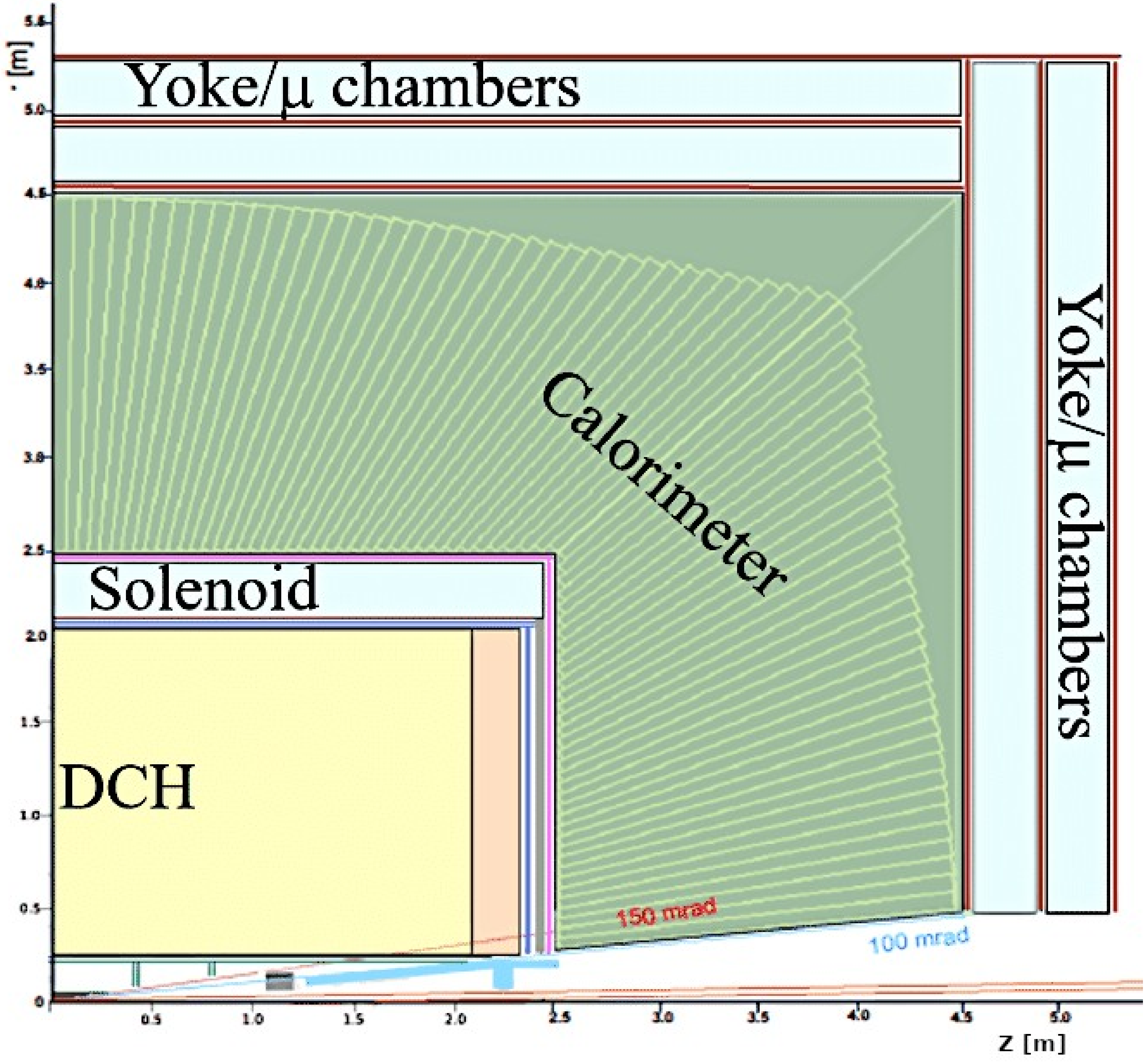
IDEA fibre calorimeter: exploit high granularity + timing

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 dual-readout calorimetry group

Three main activity pillars:

1) South Korea → projective fibre-sampling calorimeter

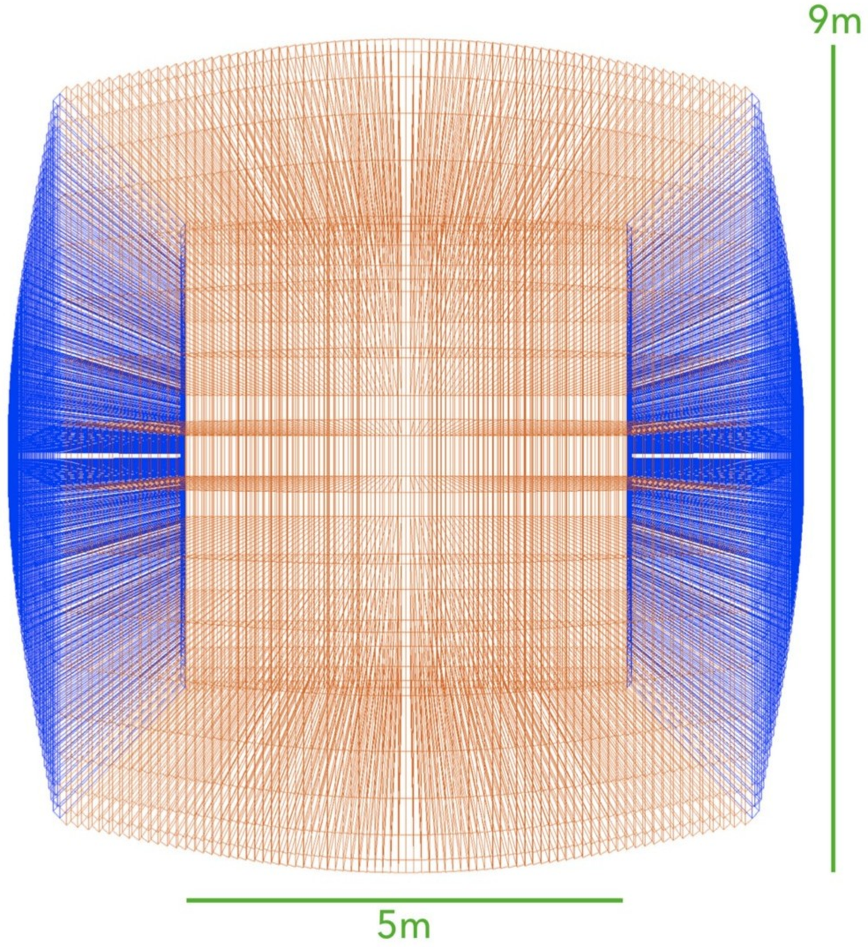
2) Europa: INFN, Sussex University → fibre-sampling calorimeter

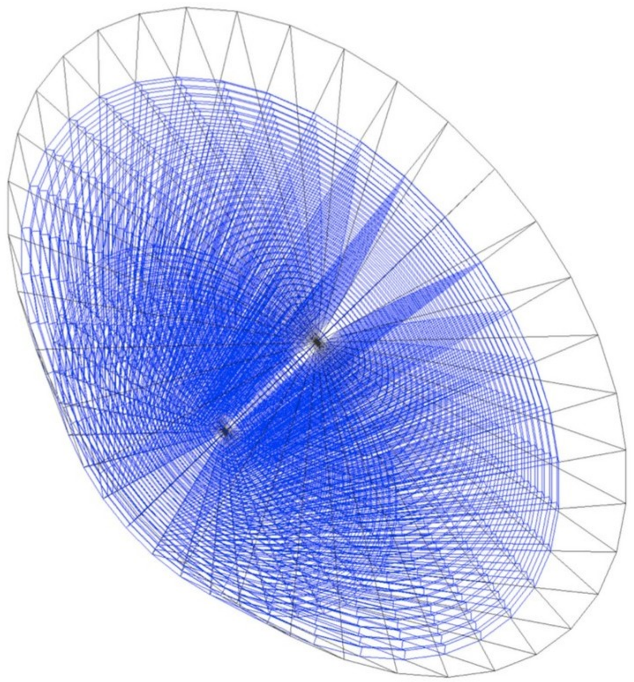
3) U.S. (Calvision project) → mainly (but not only) on crystal em calorimeter

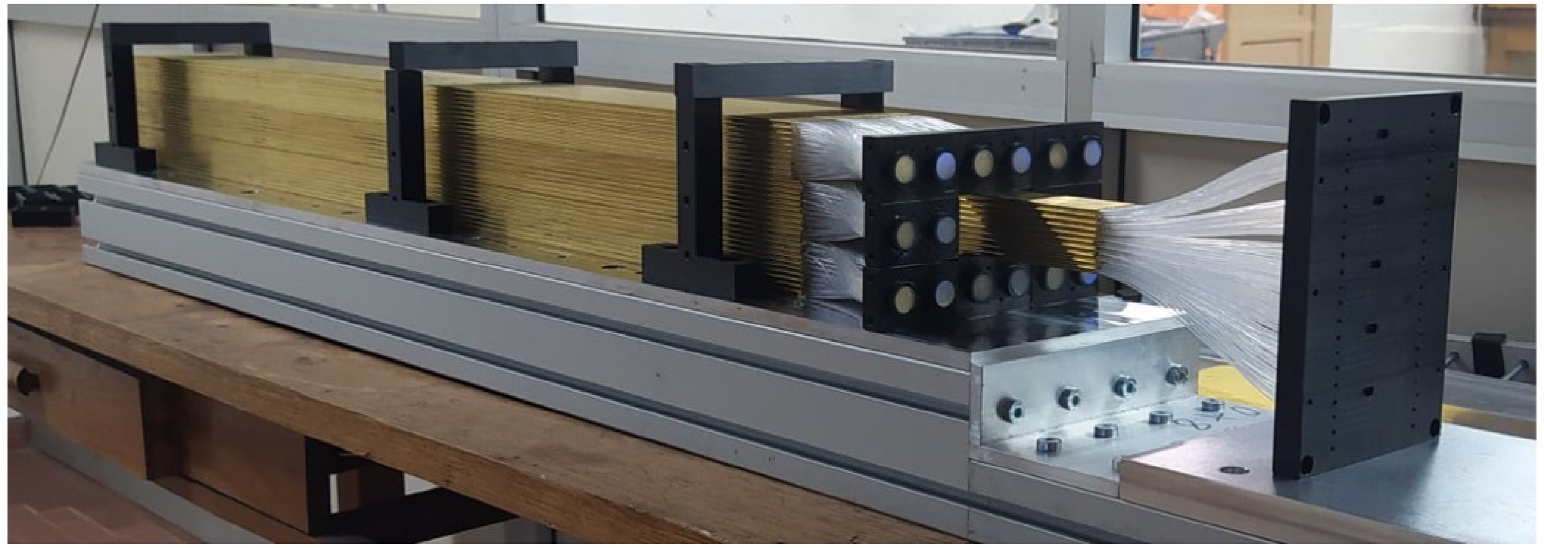
IDEA all-fibre DR calorimeter option

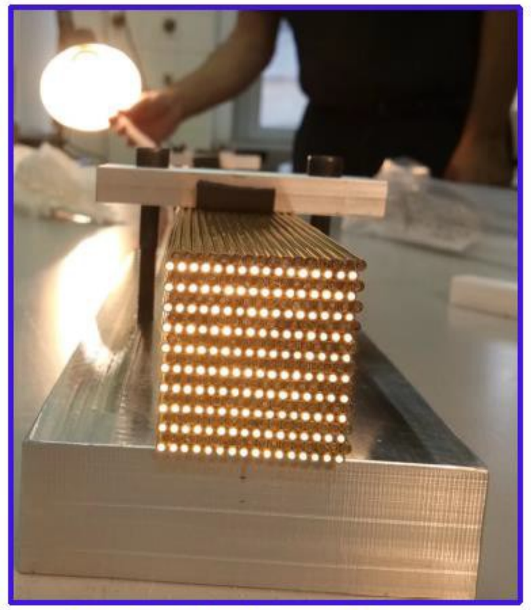
- DR fibre calorimeter
  - ~ 130 M fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
    - ϑ coverage: down to ∼100 mrad

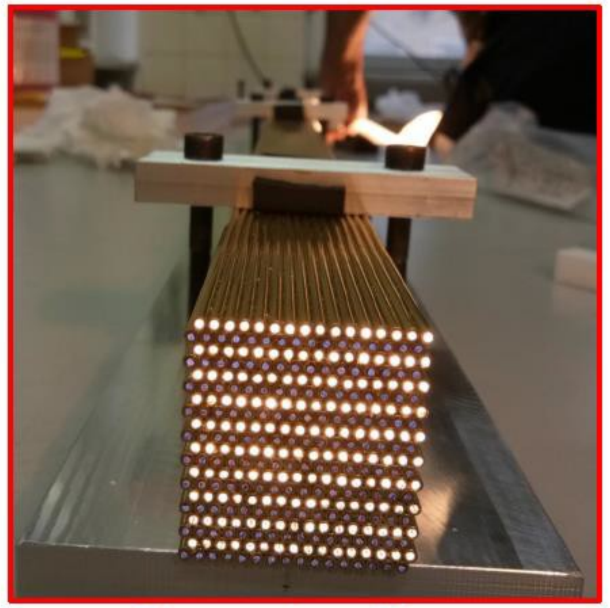
- G4 simulation available
  - tuned to RD52 TB data







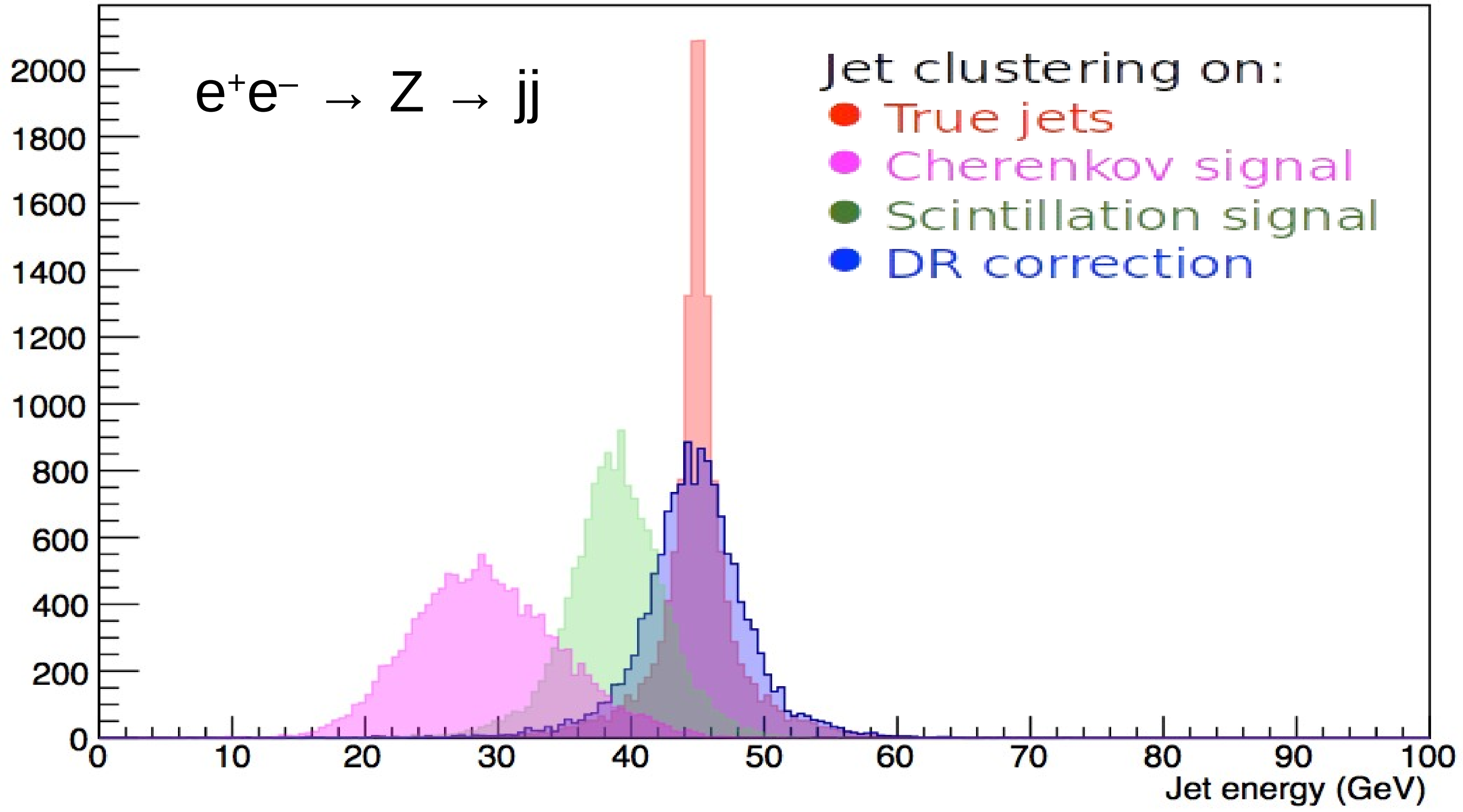

Scintillation fibers


Cherenkov fibers

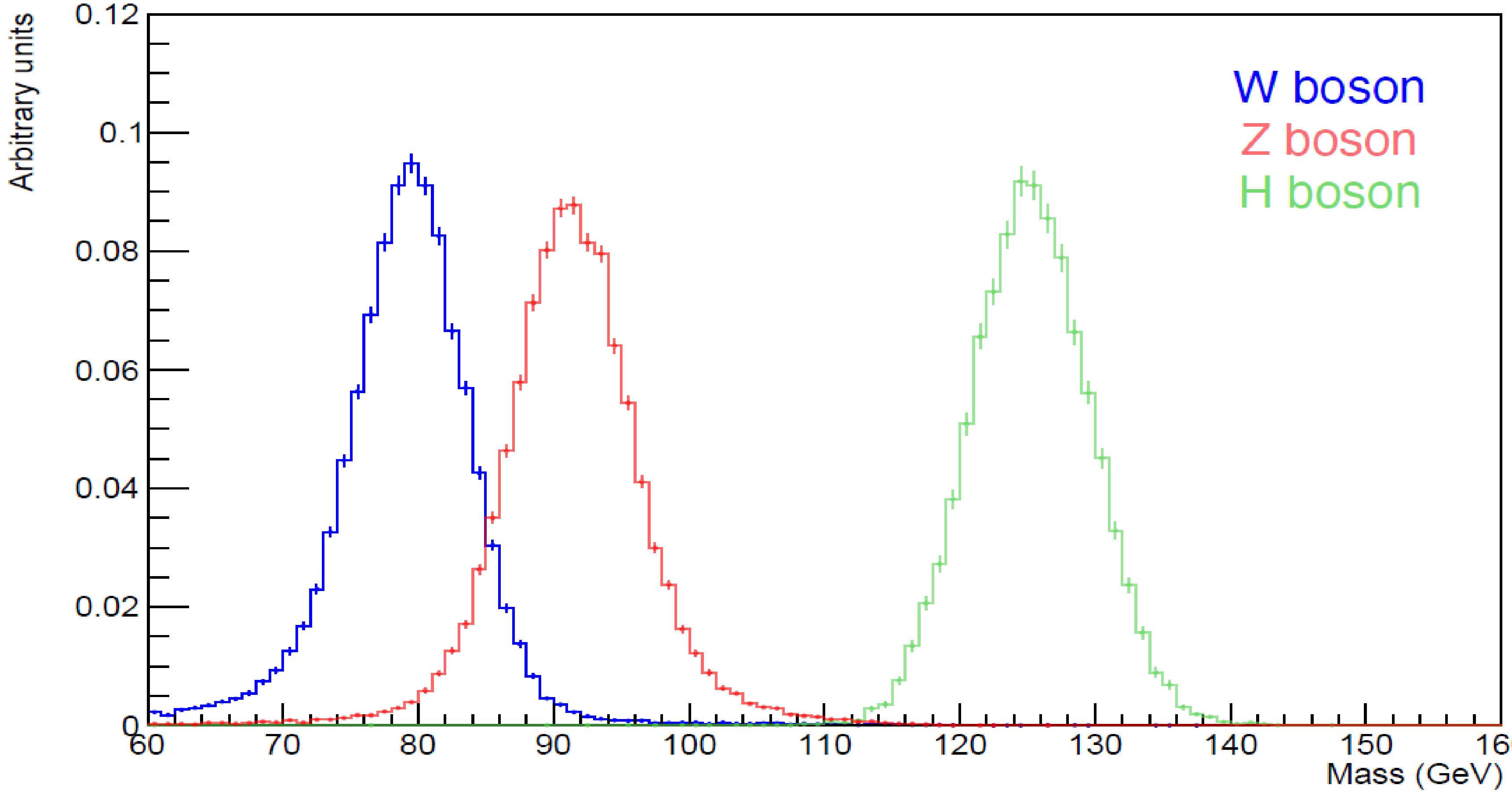
Geant4 simulations

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

Single jet resolution @ 45 GeV



W/Z/H → jj invariant mass



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

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

$\tau \to \mu\nu\nu$

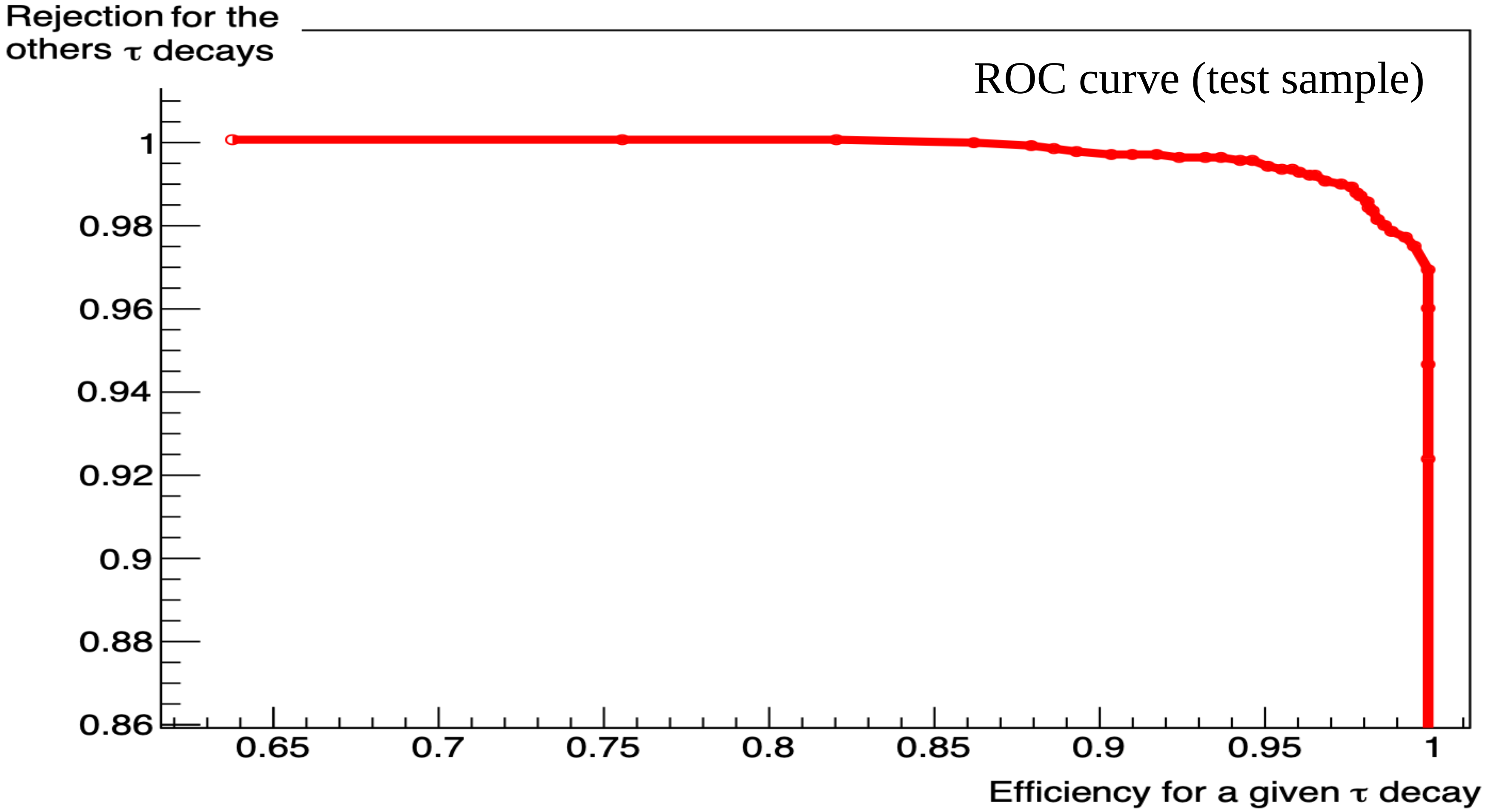
$\tau \to e\nu\nu$

$\tau \to \pi\nu$

$\tau \to \pi\pi\pi\nu$

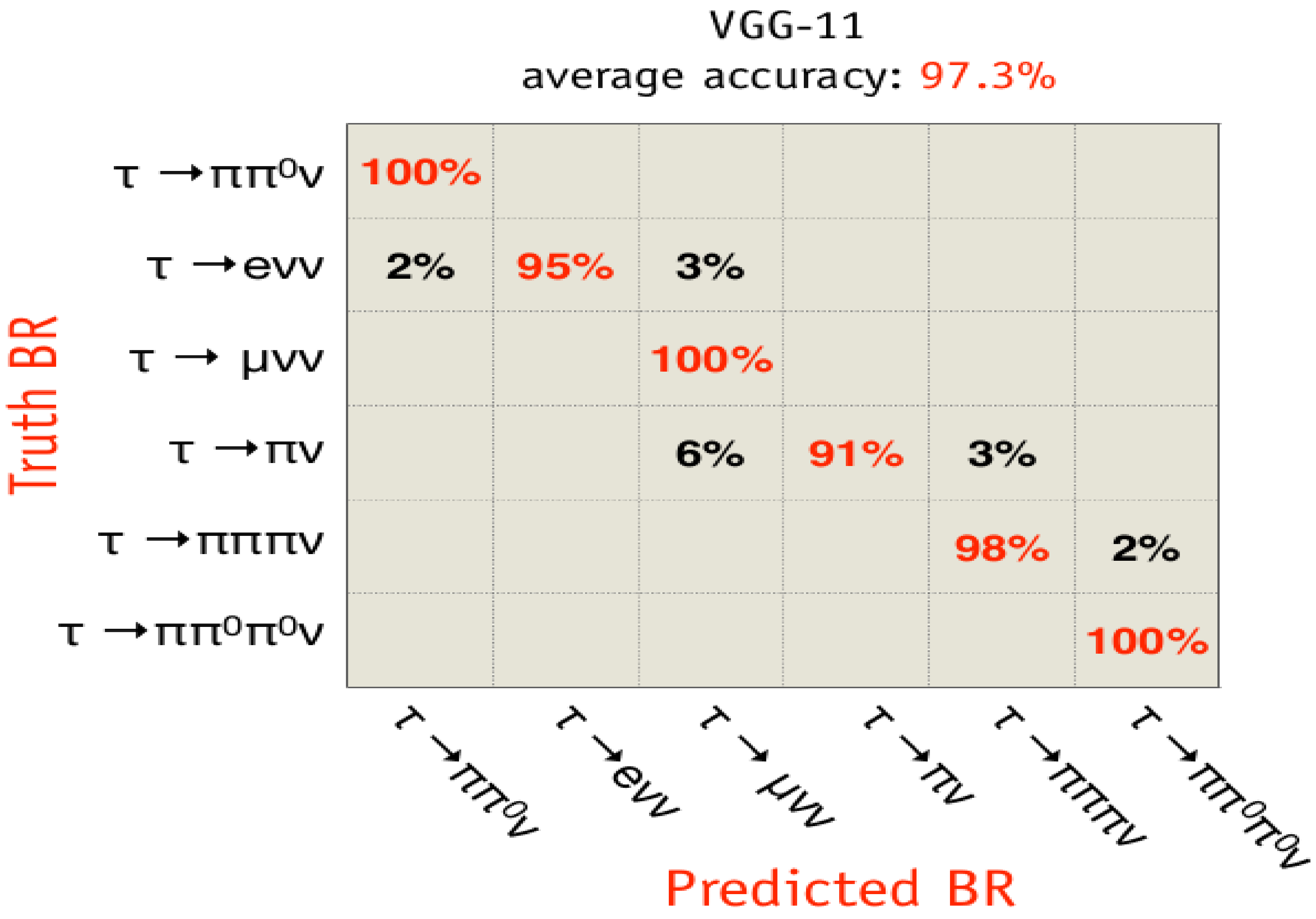
$\tau \to \pi\pi^0\pi^0\nu$

VGG example



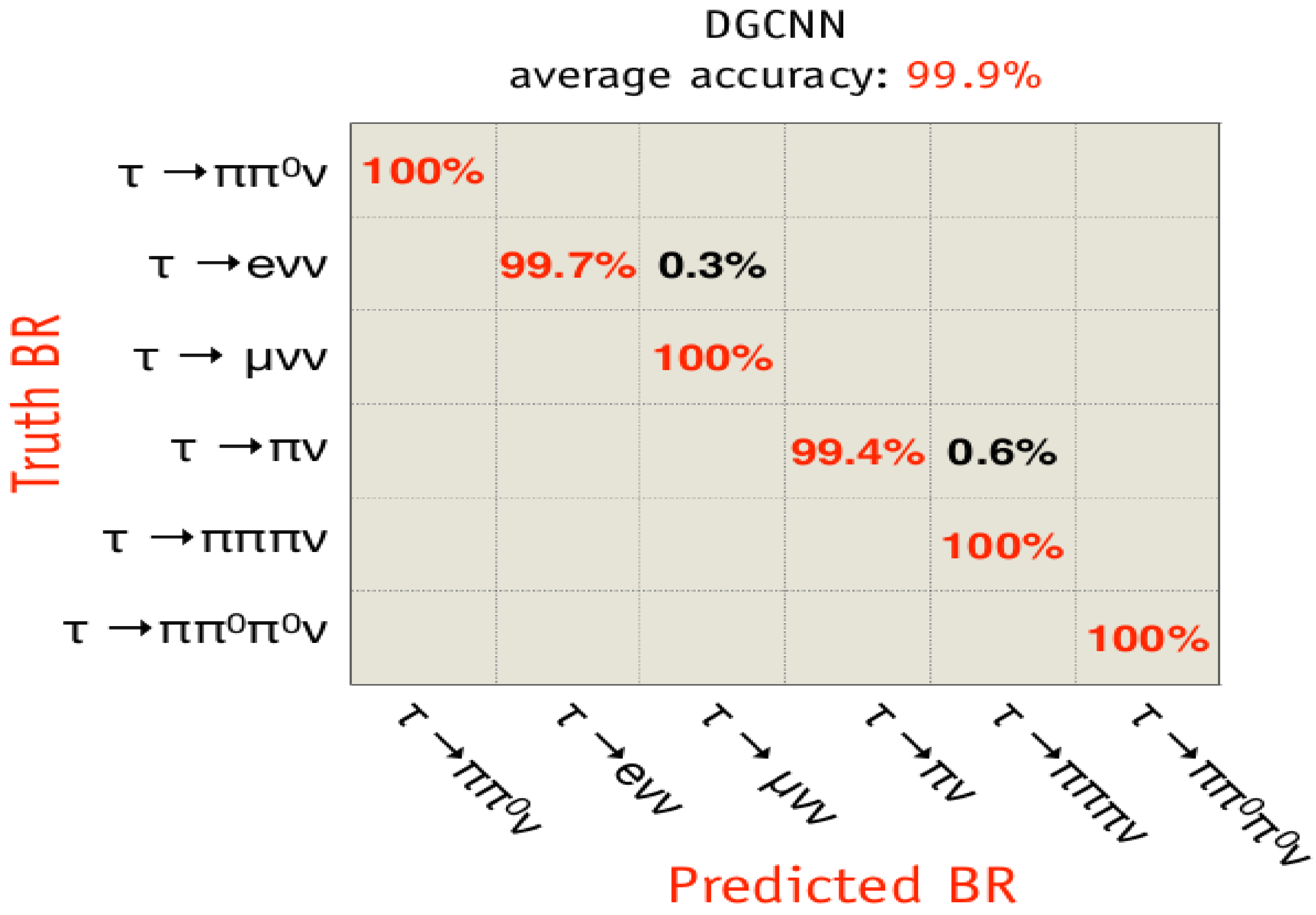
NN performance

Confusion matrix on test set



VGG-11
average accuracy: 97.3%

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

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

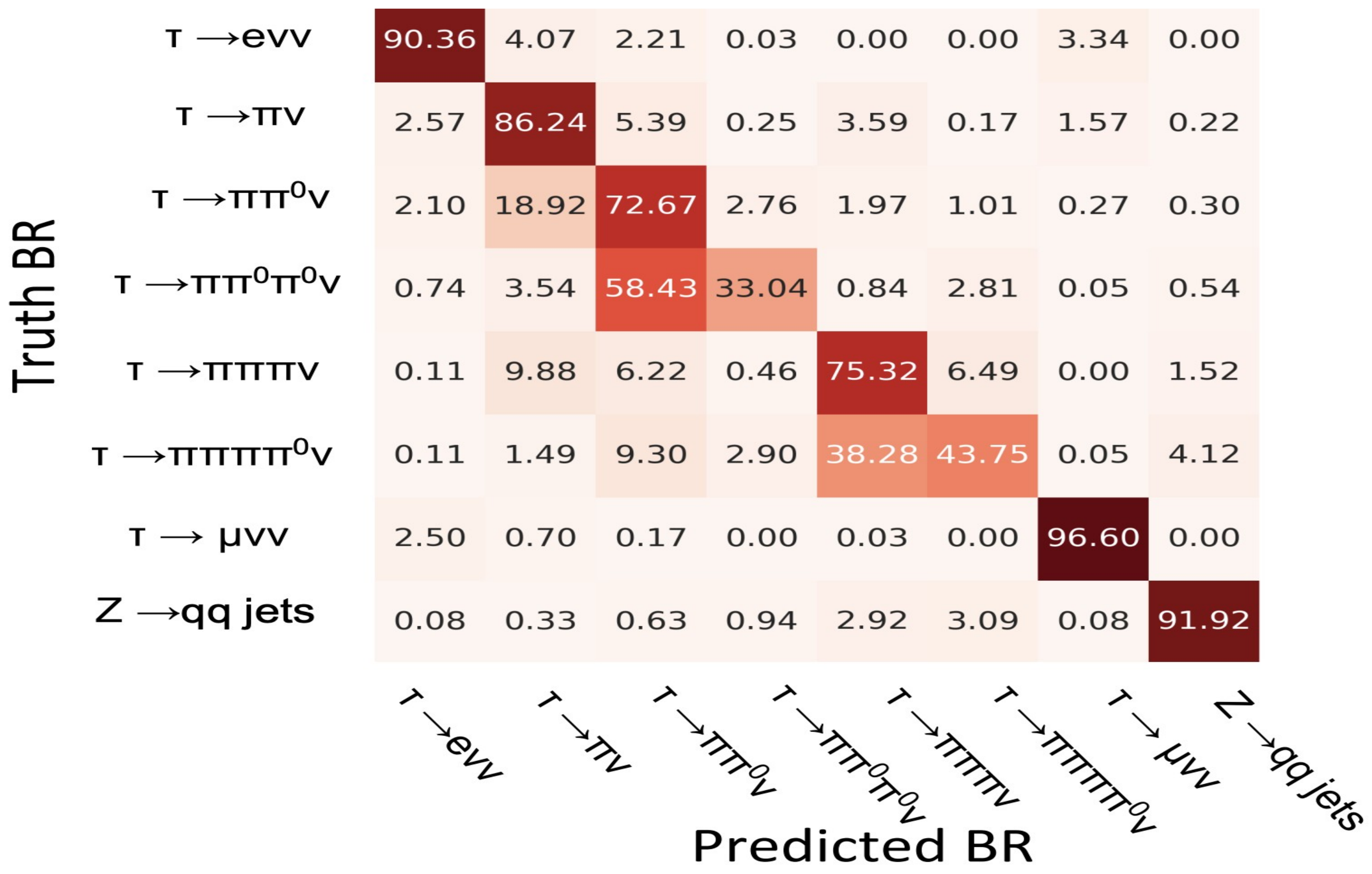
[τ from $Z \to \tau\tau$ decays]

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

DGCNN w/ geometrical information only

DGCNN optimised but w/o #pe as input feature

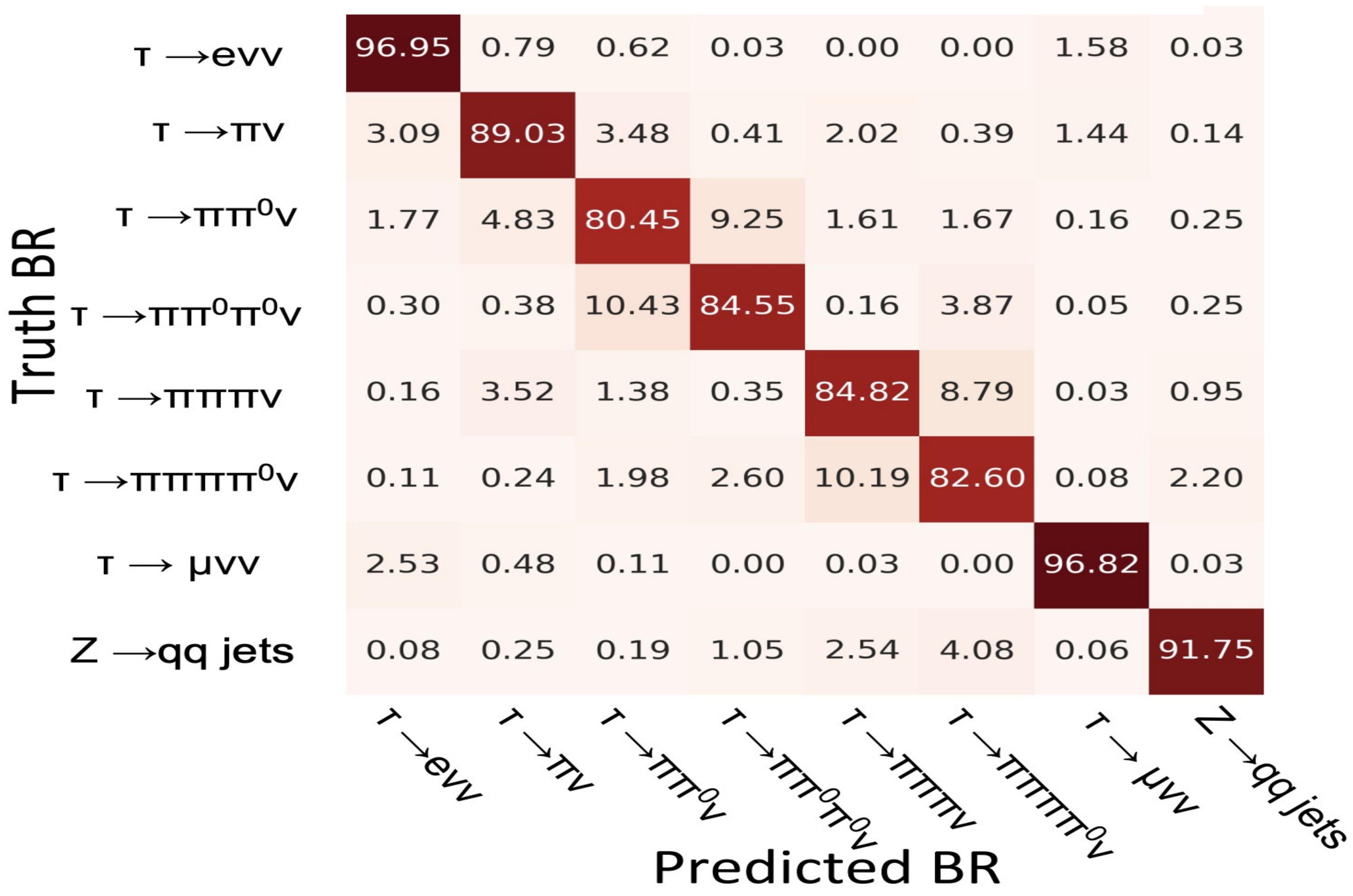
B field and material in



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



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

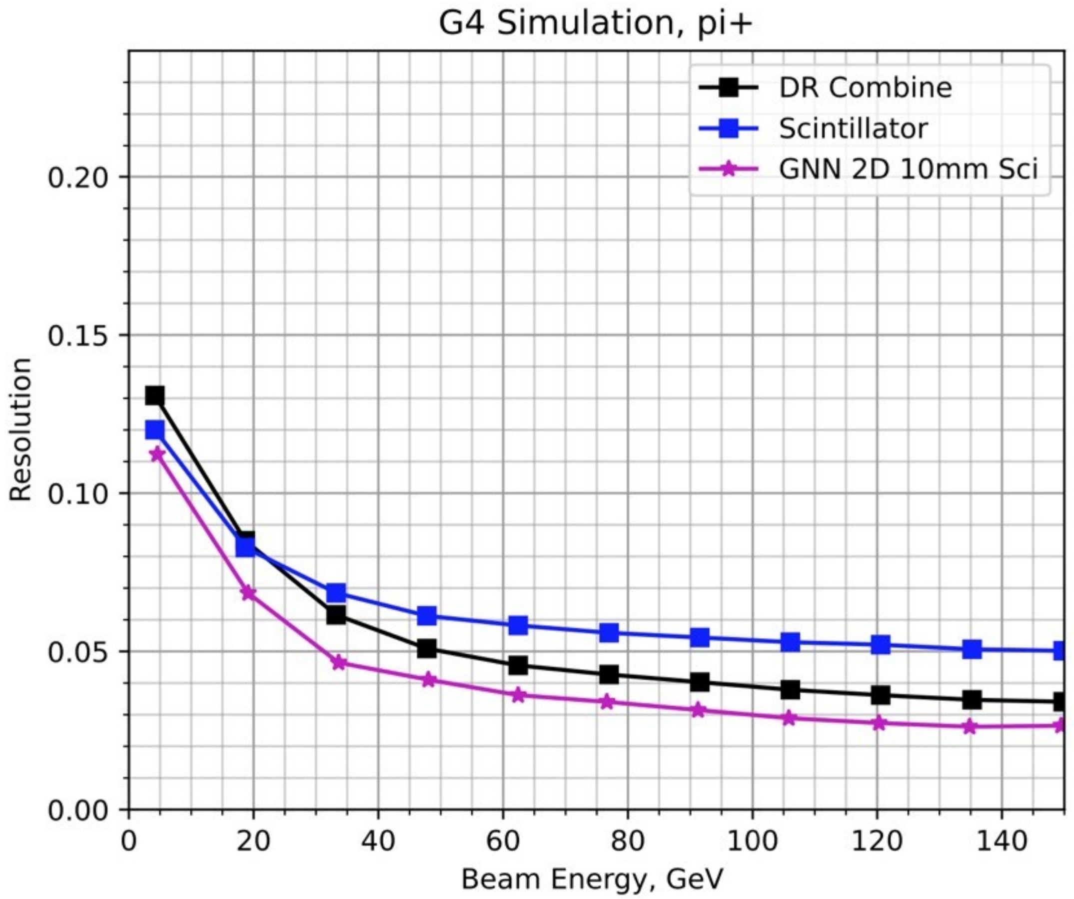
Preliminary results
No optimisation

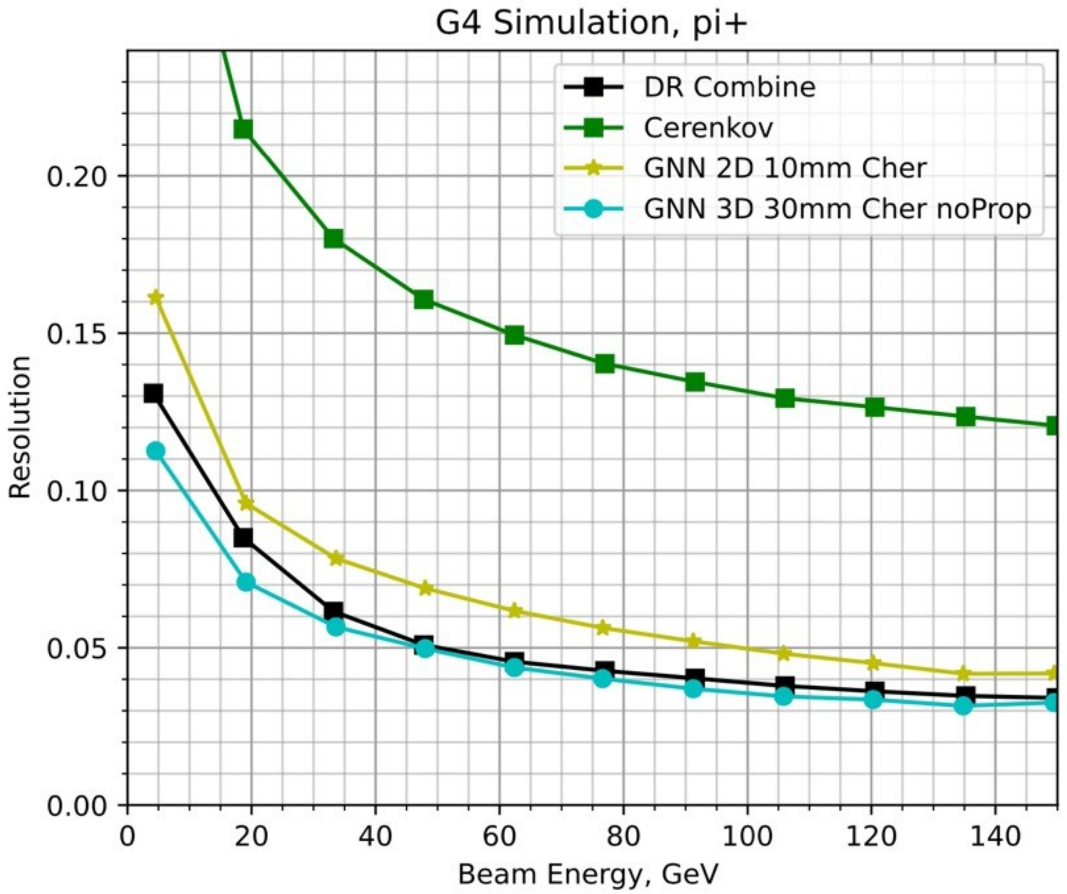
Cu absorber (2 m deep)

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

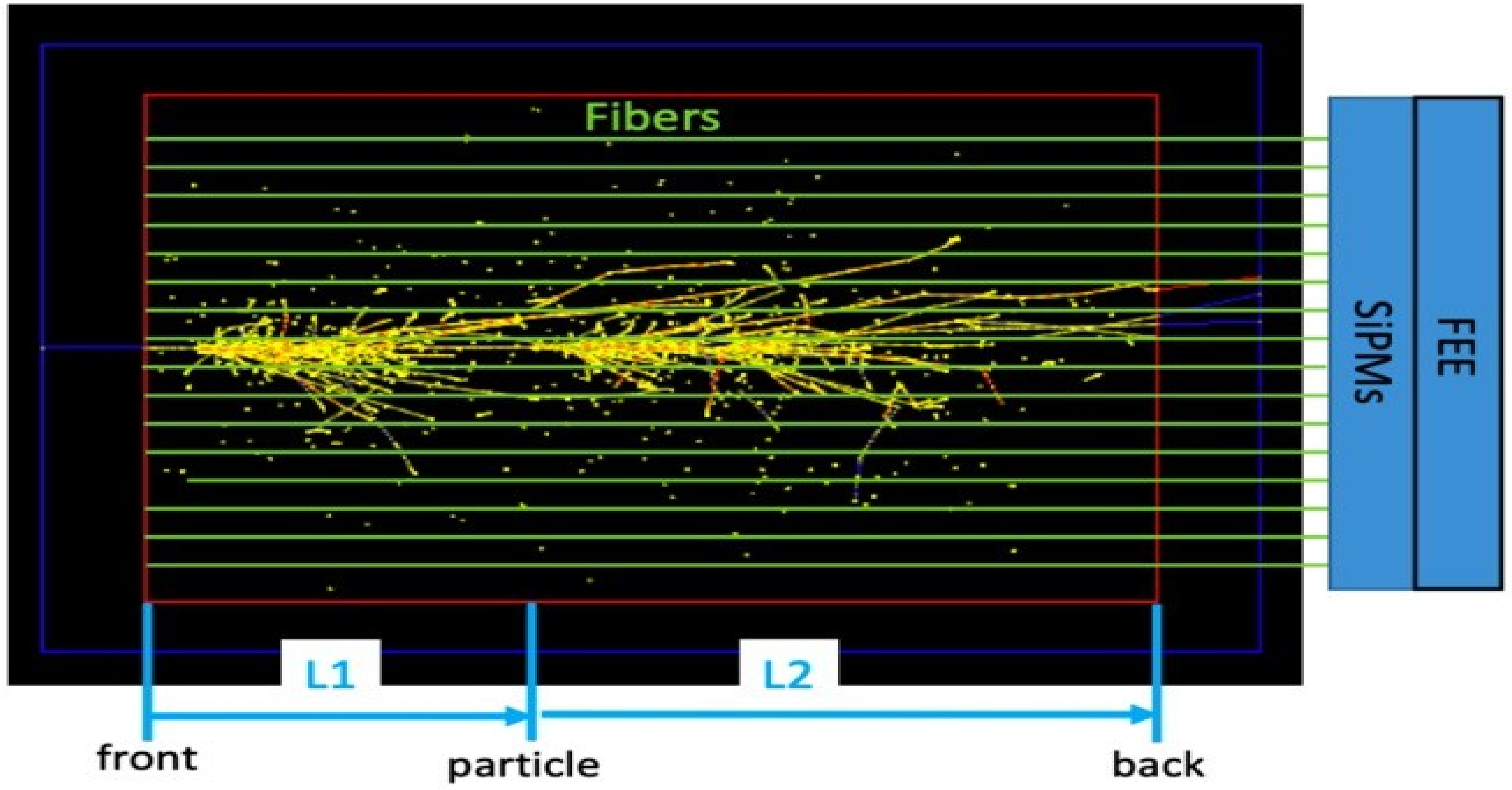
Transverse segmentation: 1×1 cm^2 for 2D analysis, 3×3 cm^2 for 3D analysis

3D imaging fibre DR calorimeter coupled to Graph DNN





Longitudinal segmentation w/ timing (U.S.)



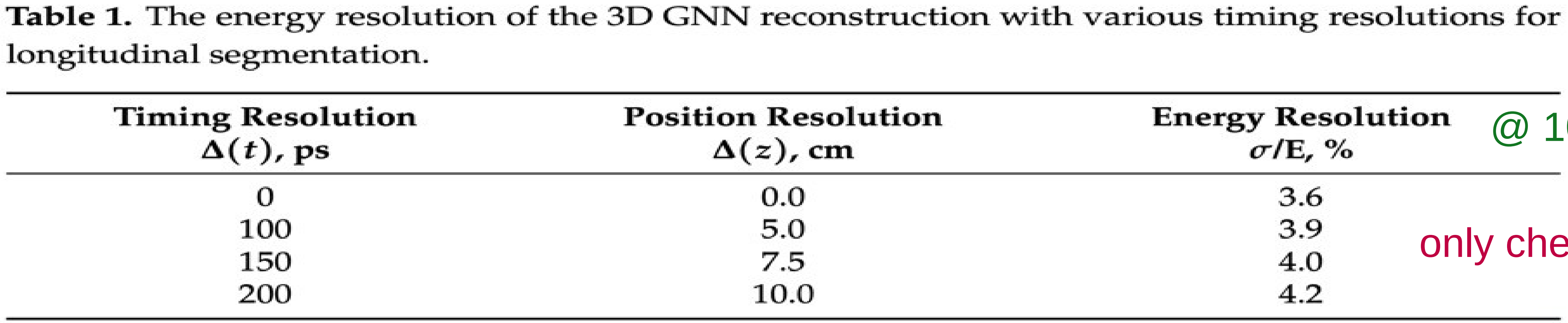


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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 (S.K.)

Full SiPM signal sampled at 10 GHz

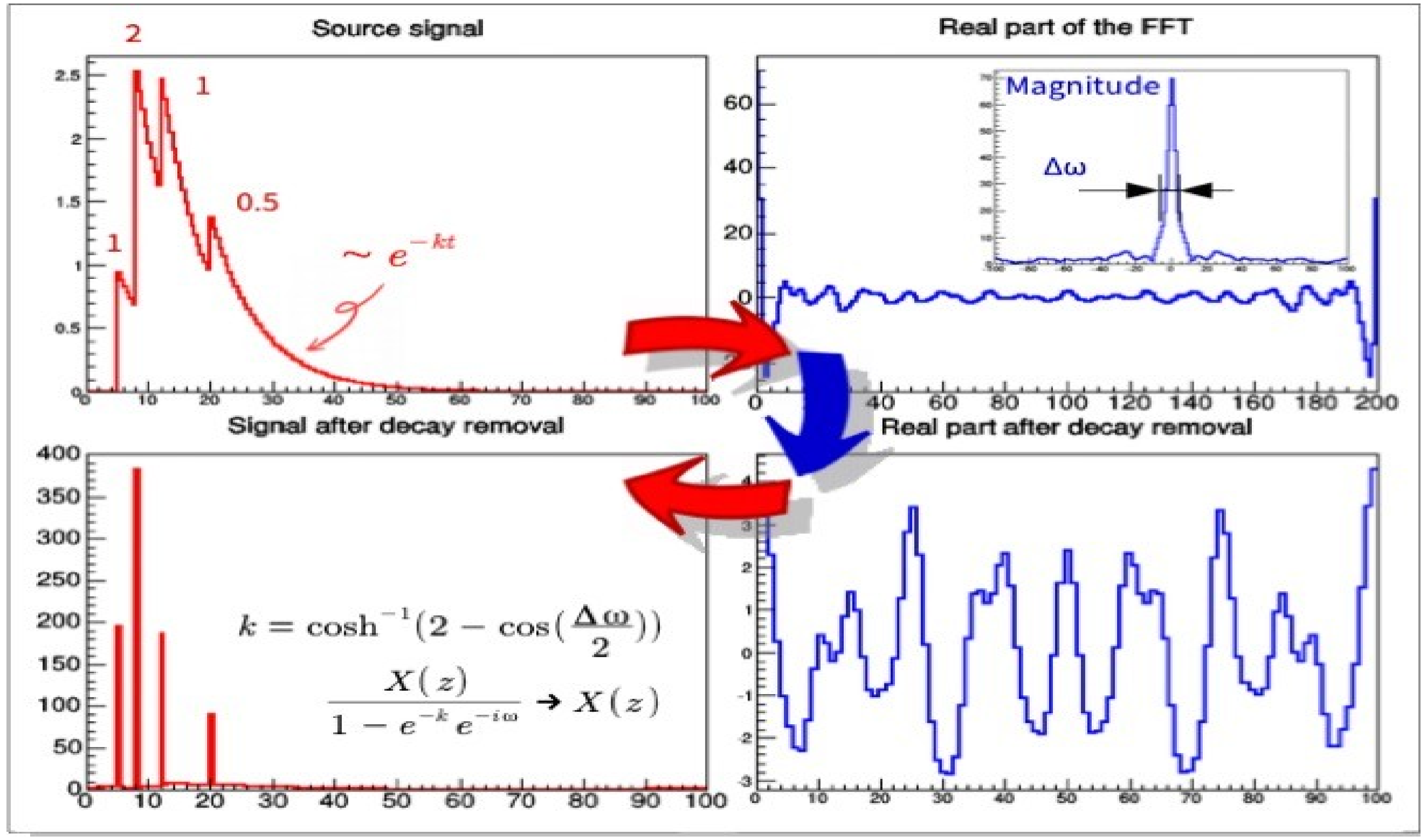
FFT used to mitigate exponential tail

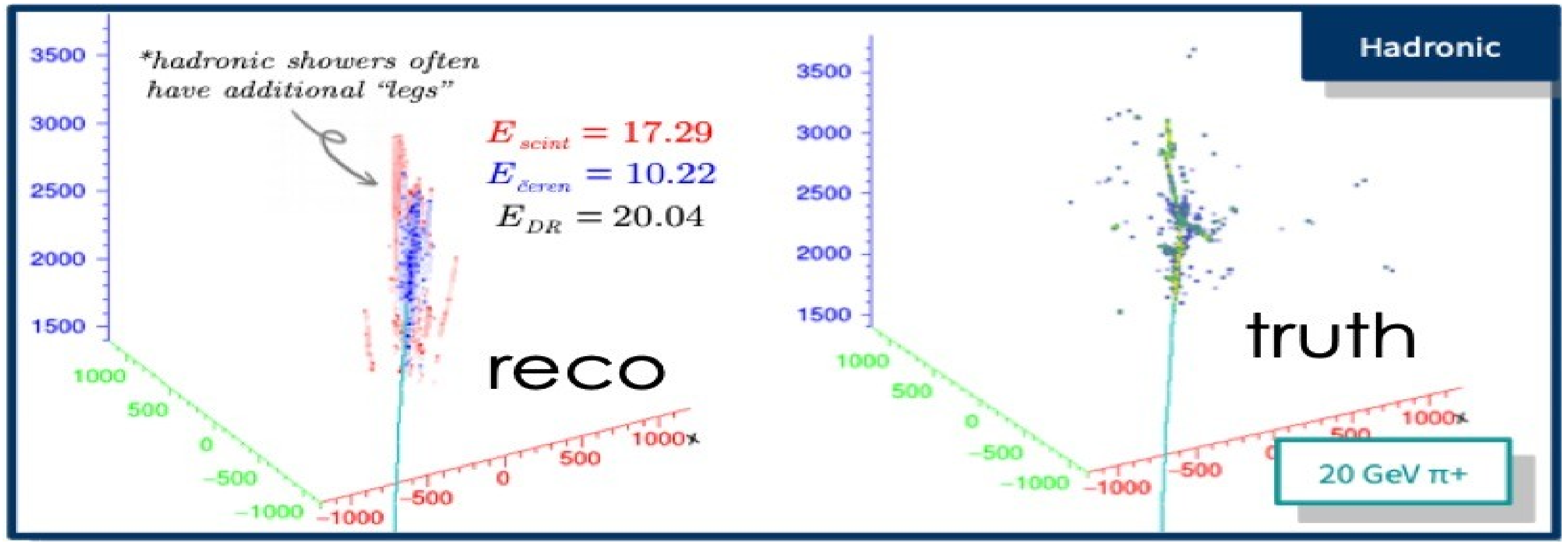
Unlocks full longitudinal information about energy deposit

Combined with DR information allows in-shower cluster identification

Time domain

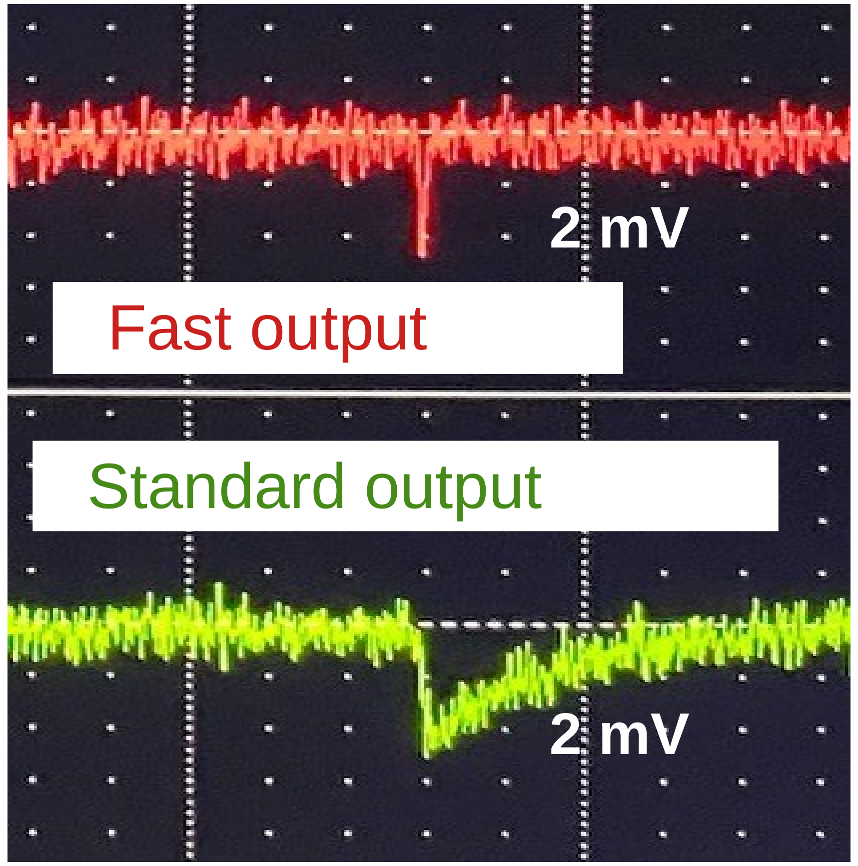
Frequency domain



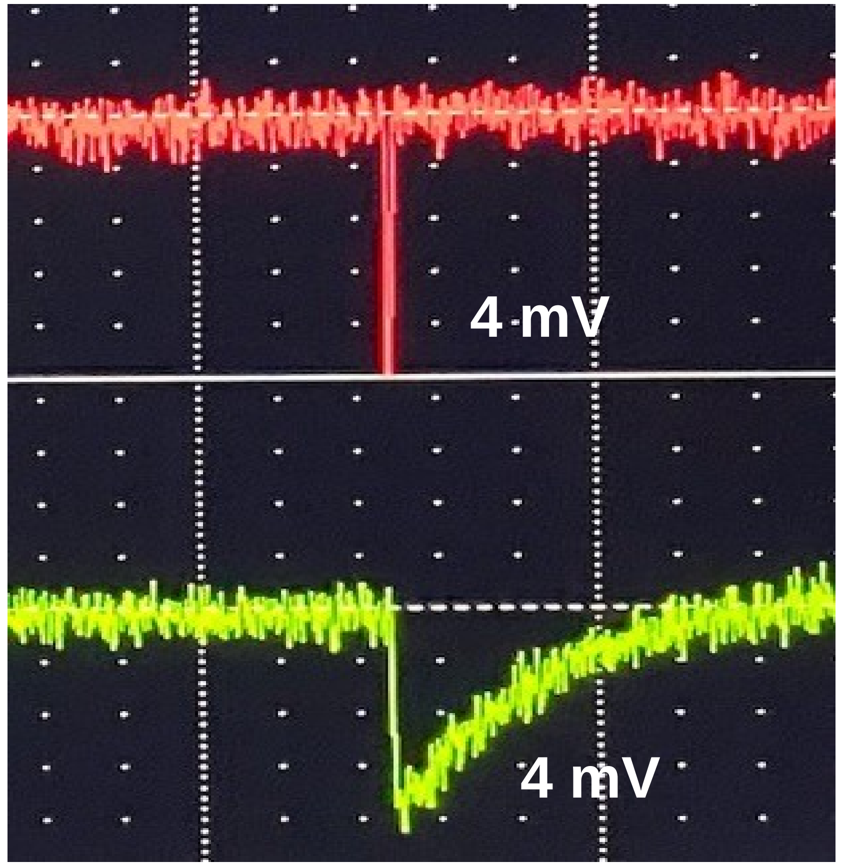


Waveform digitisation (U.S.)

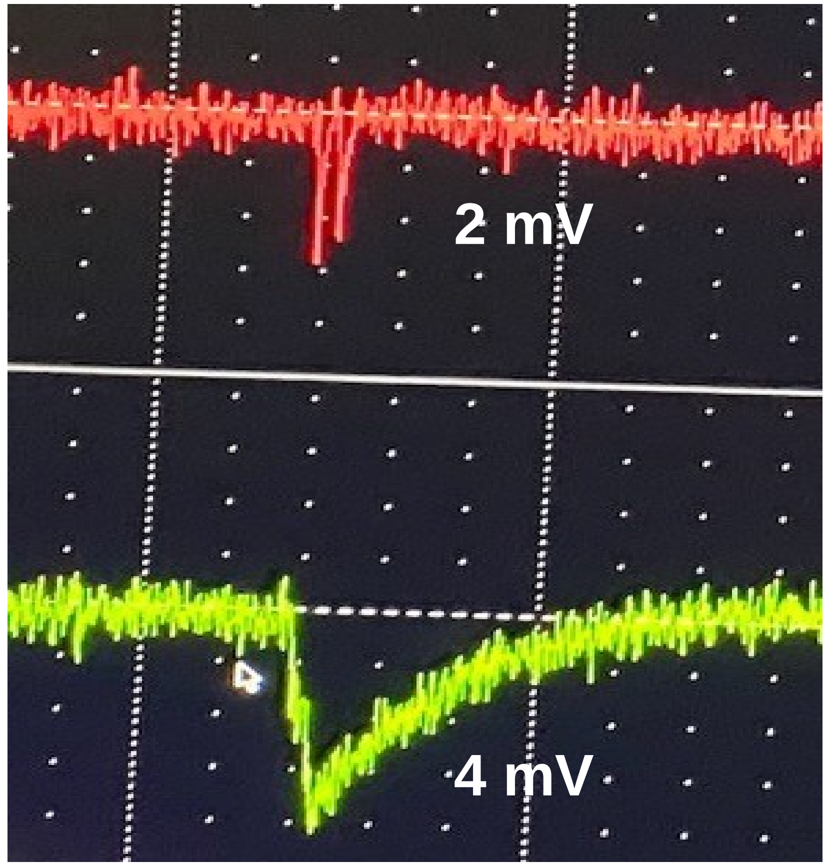
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard outputs



One-photon event



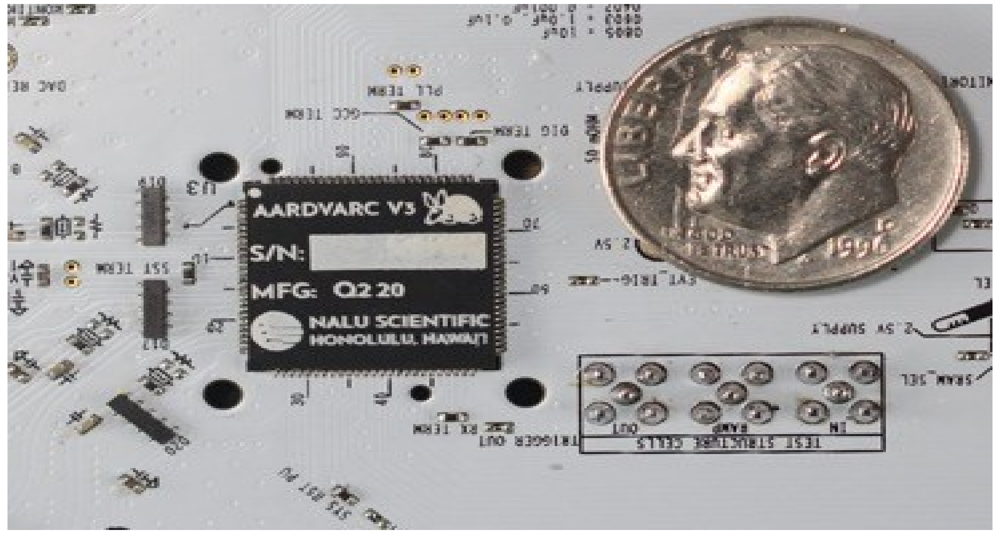
Two-photon event
(simultaneous)



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)



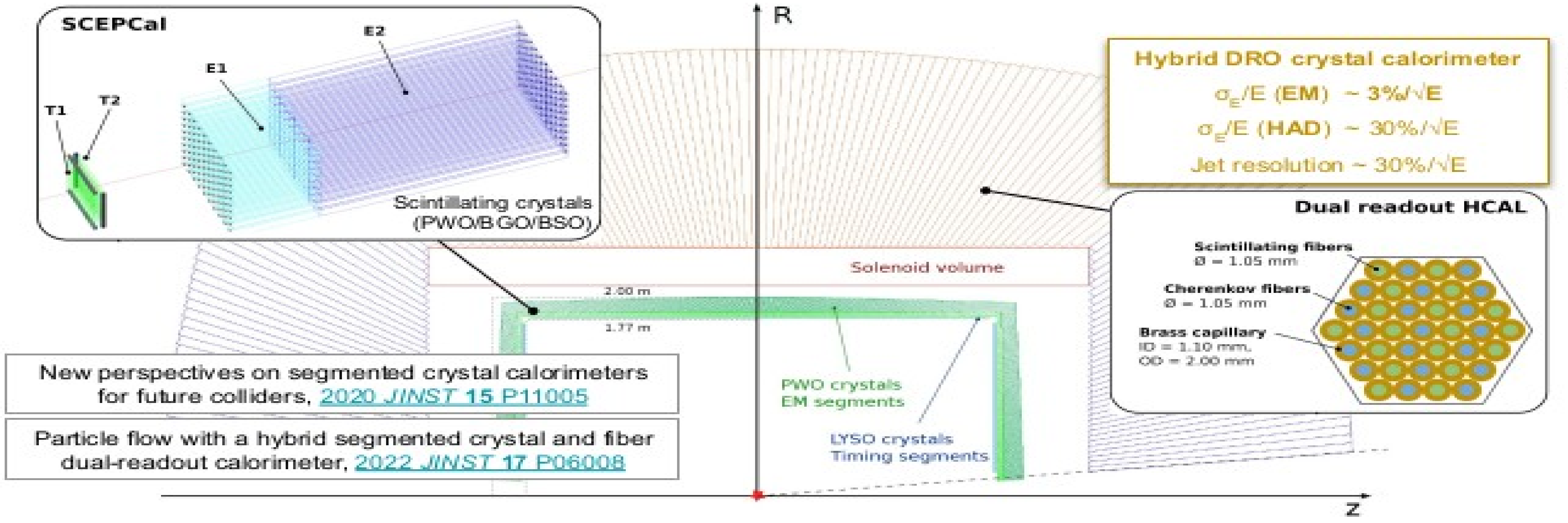
Crystal option (IDEA++) and PFA

Dual-readout crystal options (IDEA++)

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

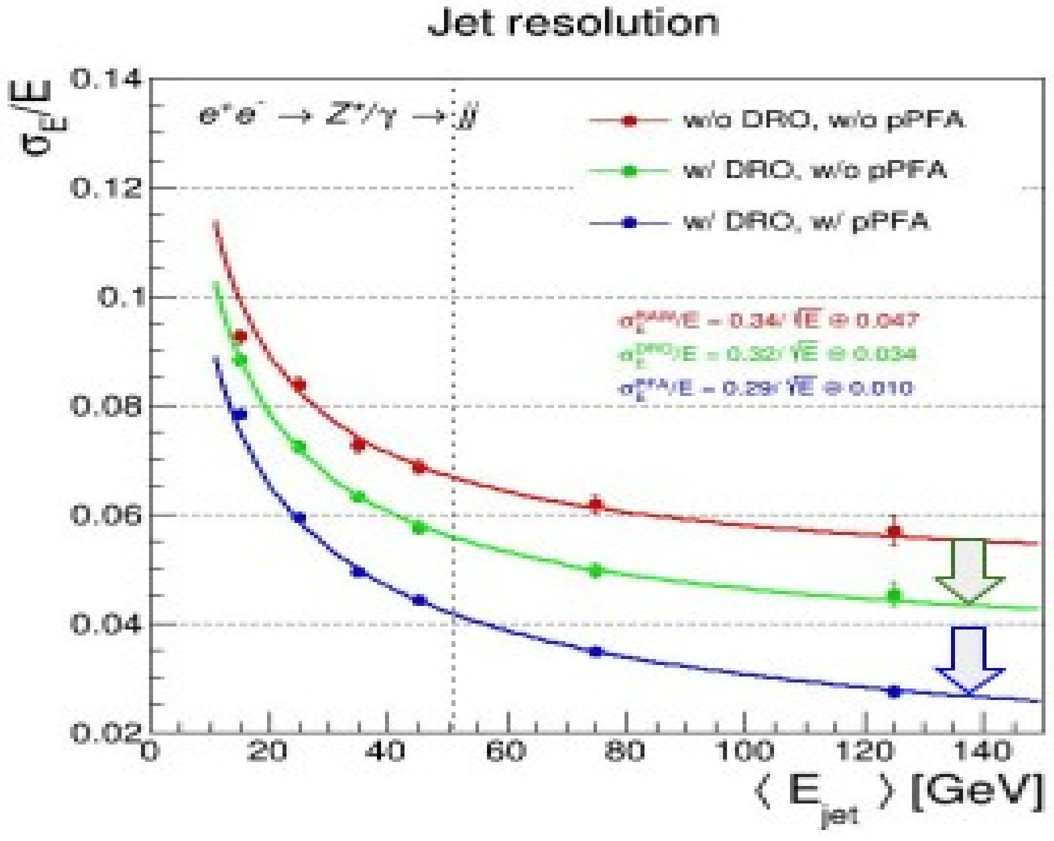
Ongoing efforts within US Calvision, IDEA and Crystal Clear collaborations

- Proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPMs)
- Ongoing simulation effort in DD4HEP and FCC software + DR-PFA developments



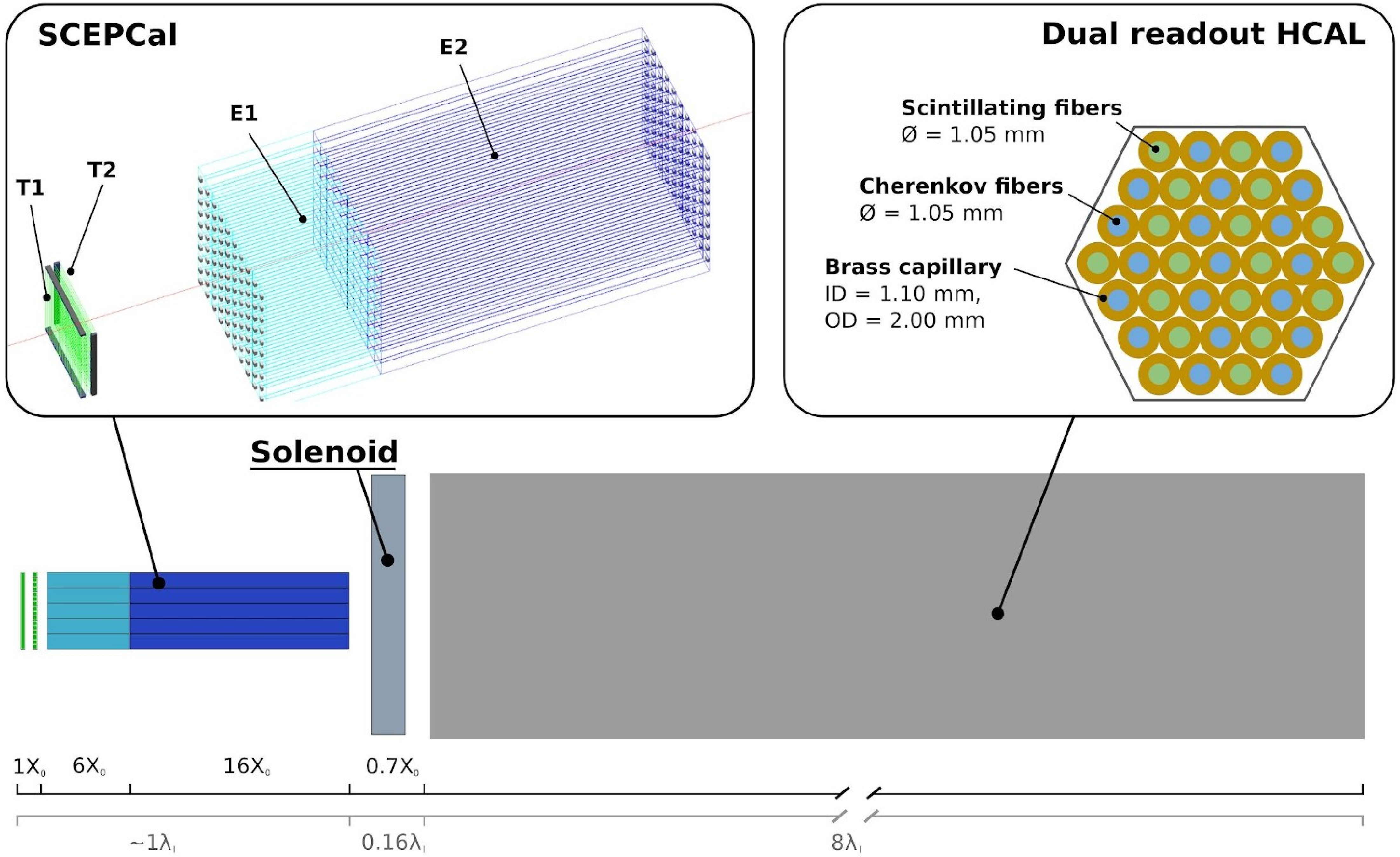
New perspectives on segmented crystal calorimeters for future colliders, 2020 *JINST* 15 P11005

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



Crystal option (IDEA++)

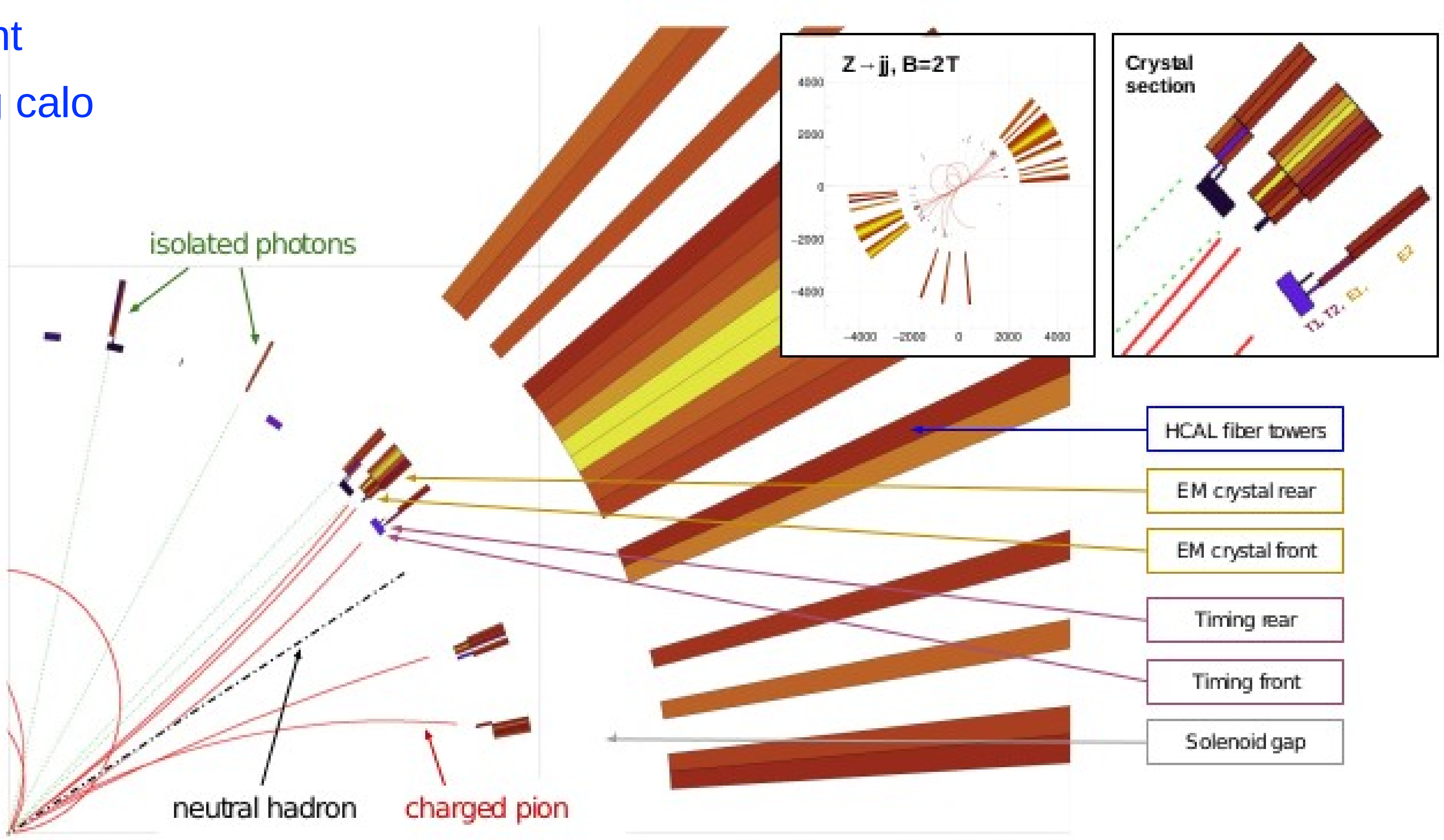
- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% / \sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$



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



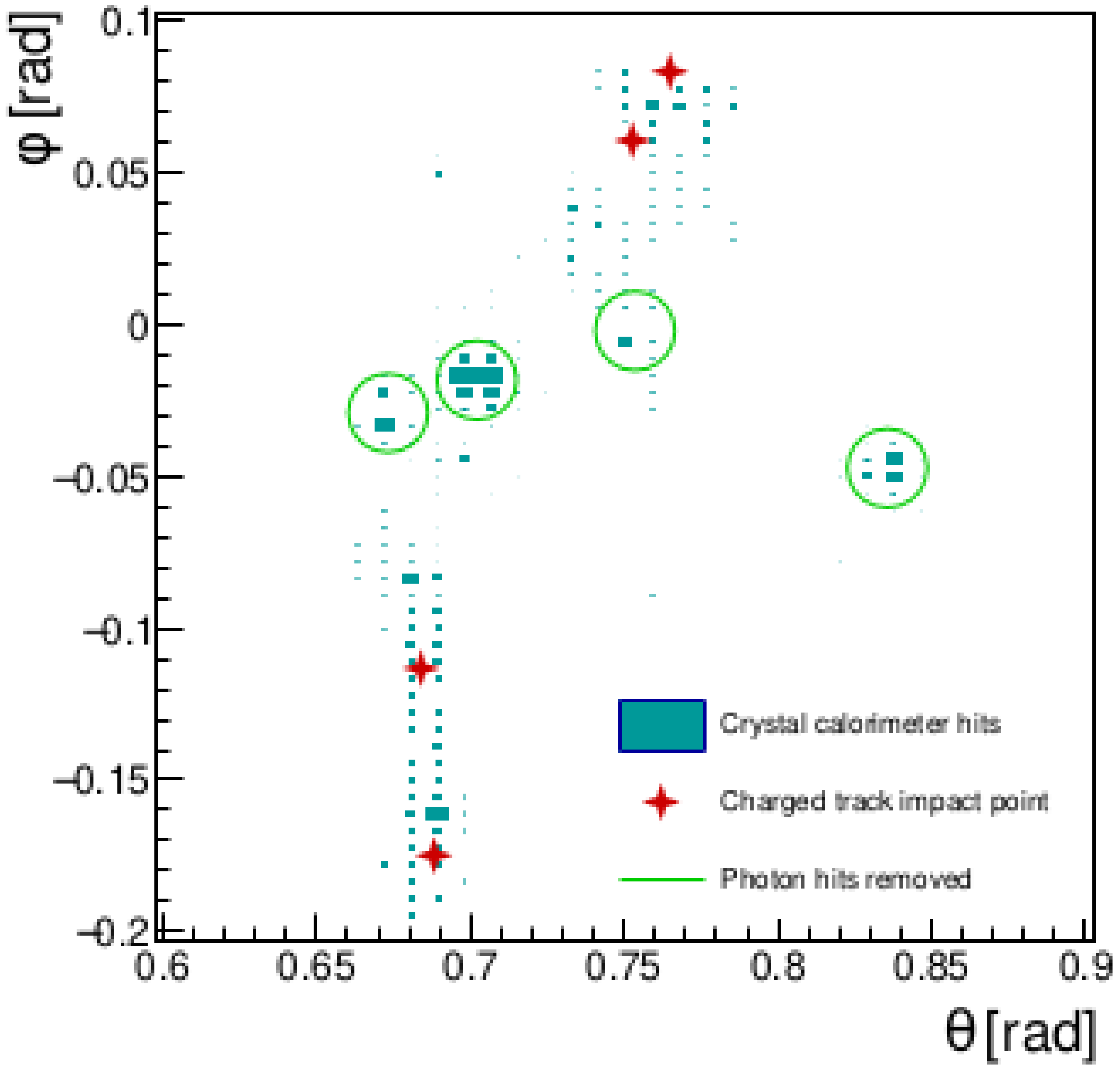
IDEA++ dual-readout-PFA

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)



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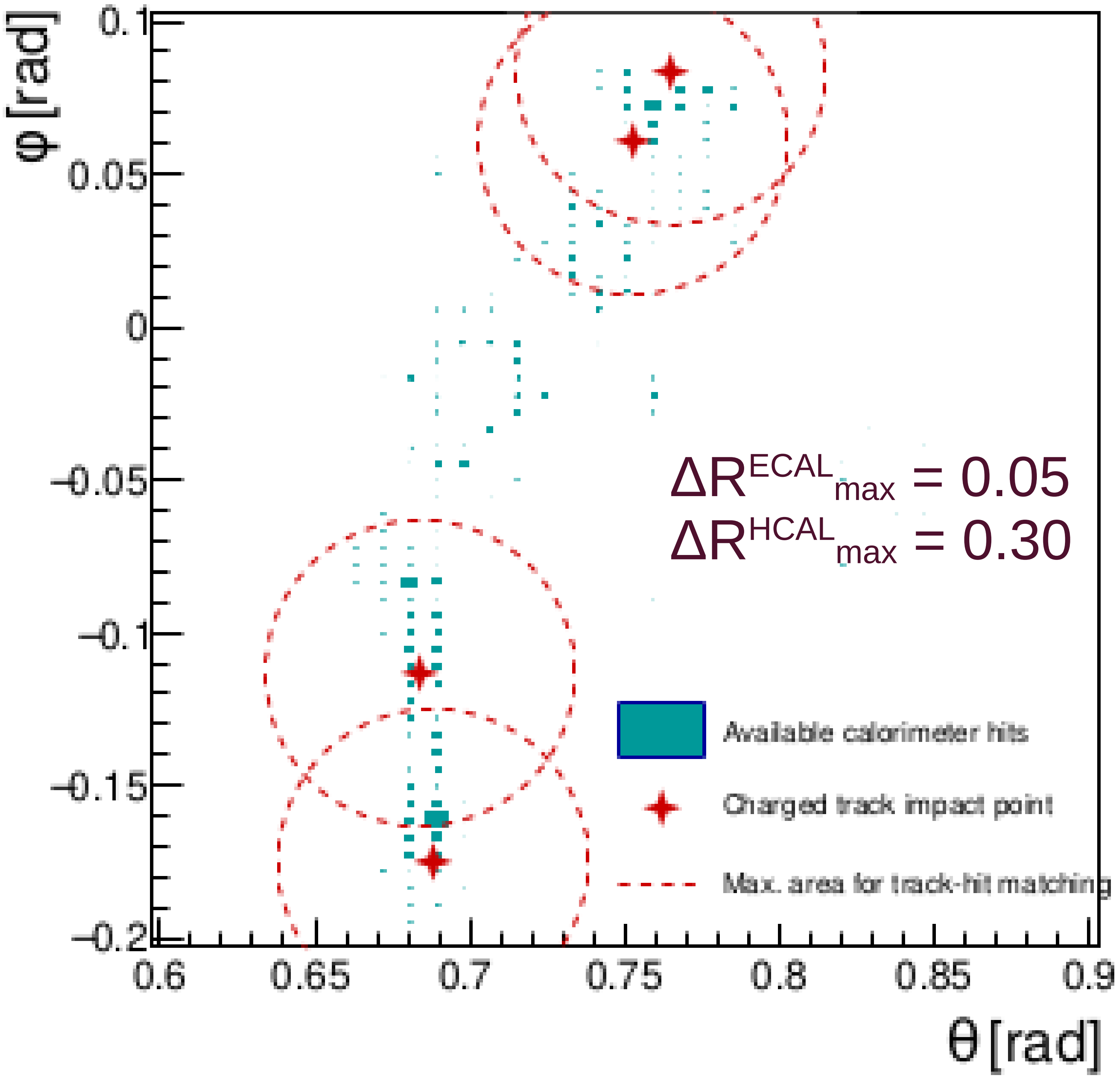
$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

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



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

IDEA++ dual-readout-PFA

Geant4 simulation of Z → jj events:

- magnetic field ON but NO tracker
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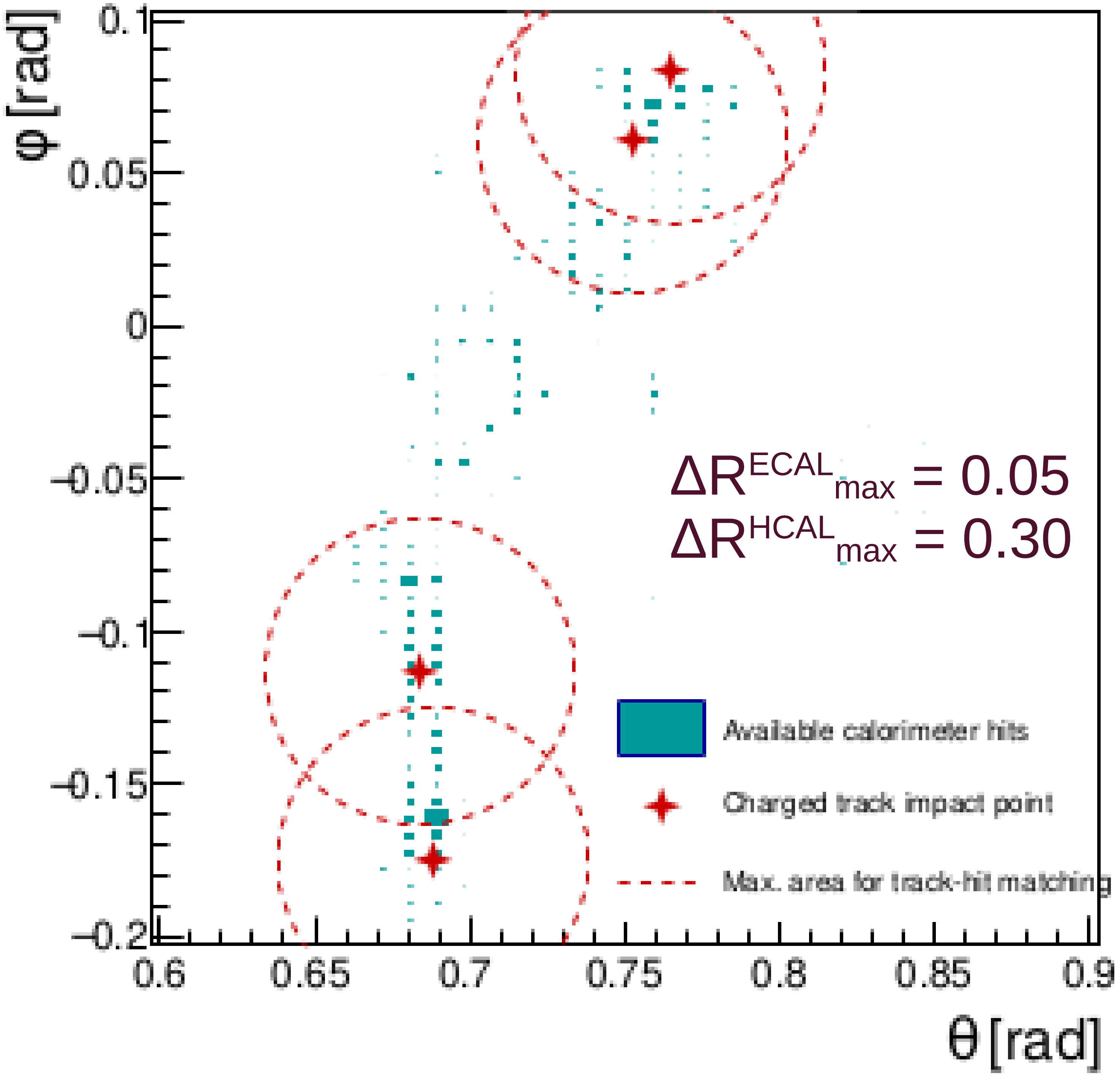
$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- 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:

- magnetic field ON but NO tracker
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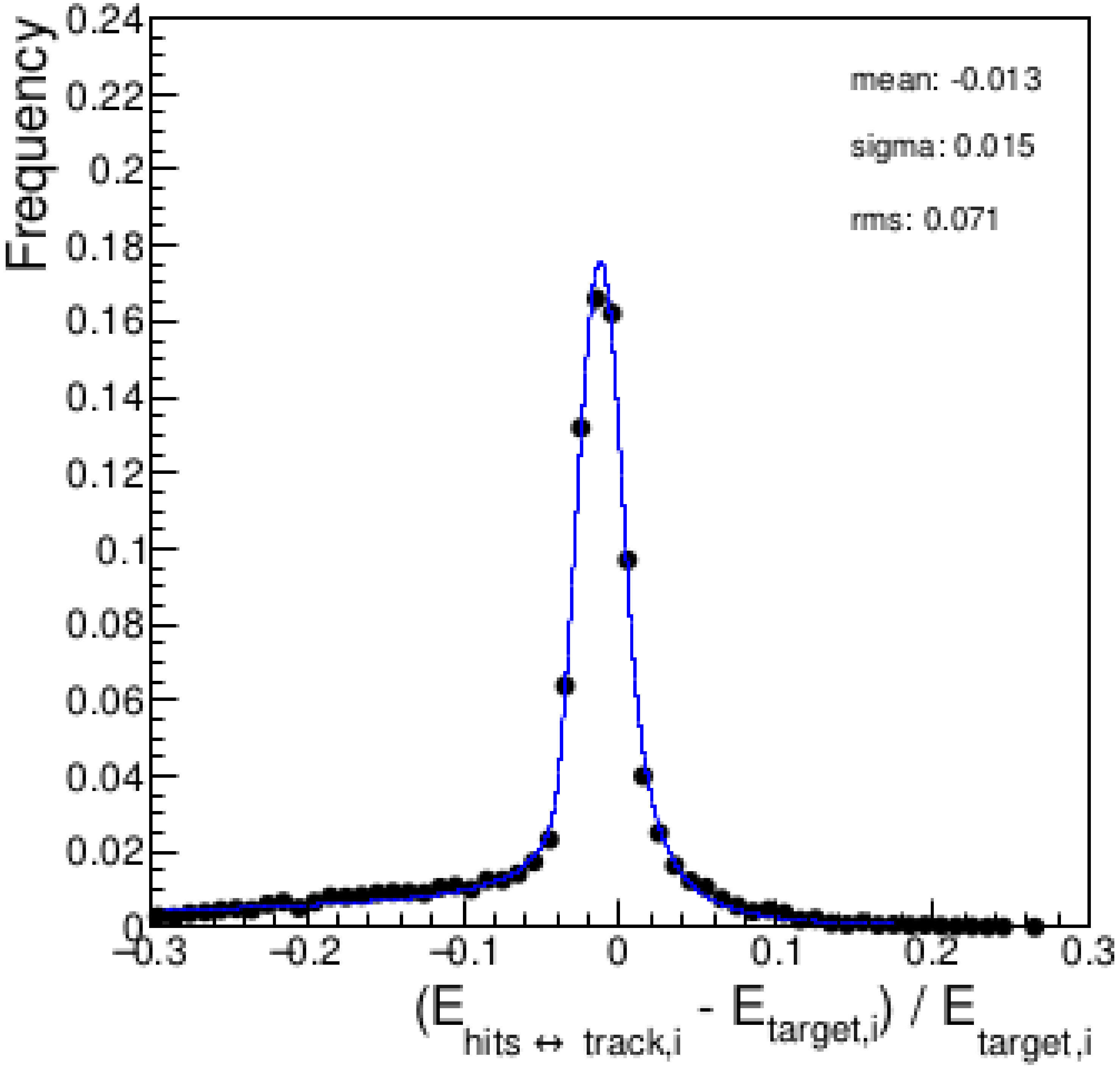
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

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

- 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)



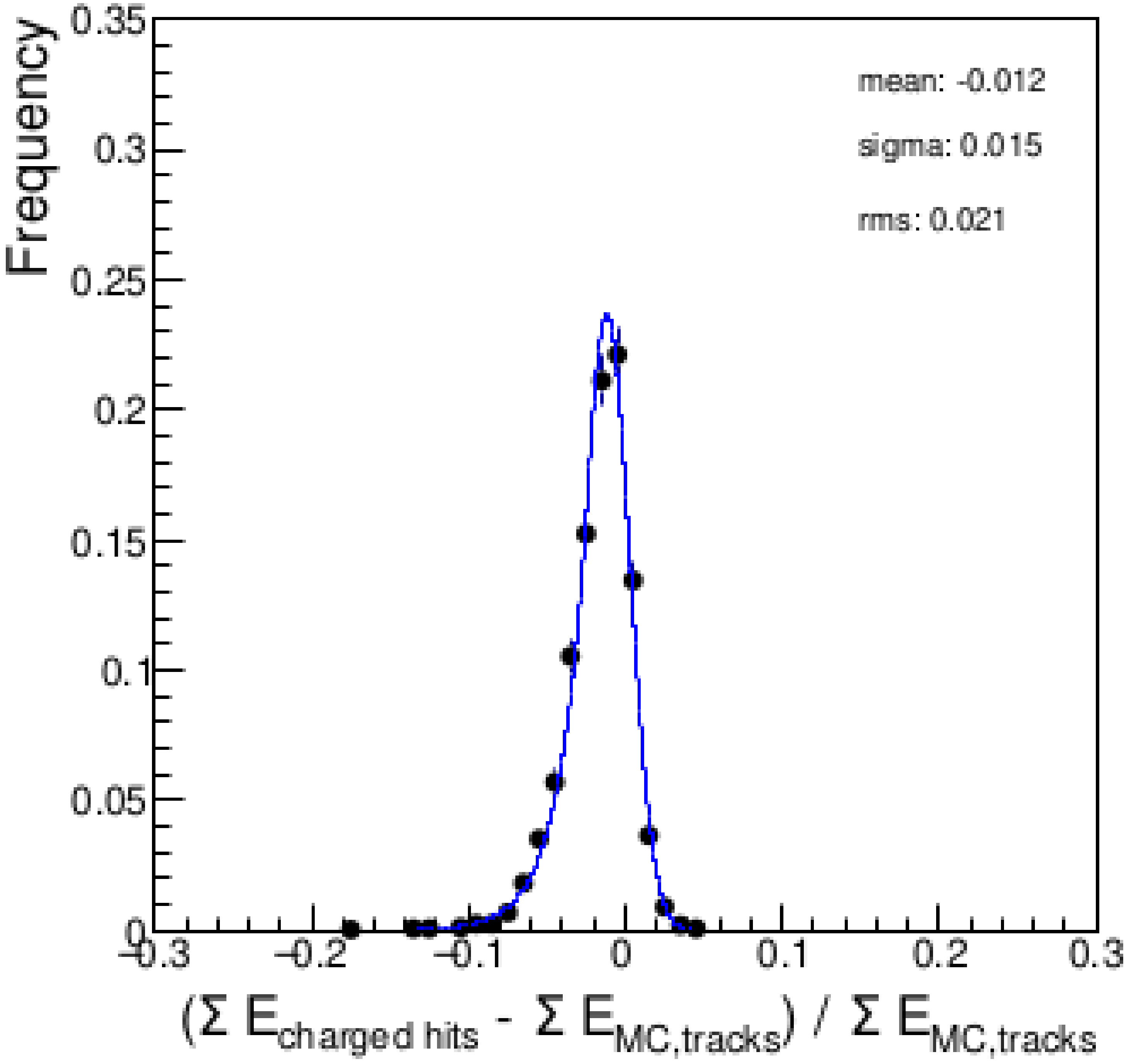
IDEA++ dual-readout-PFA

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

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

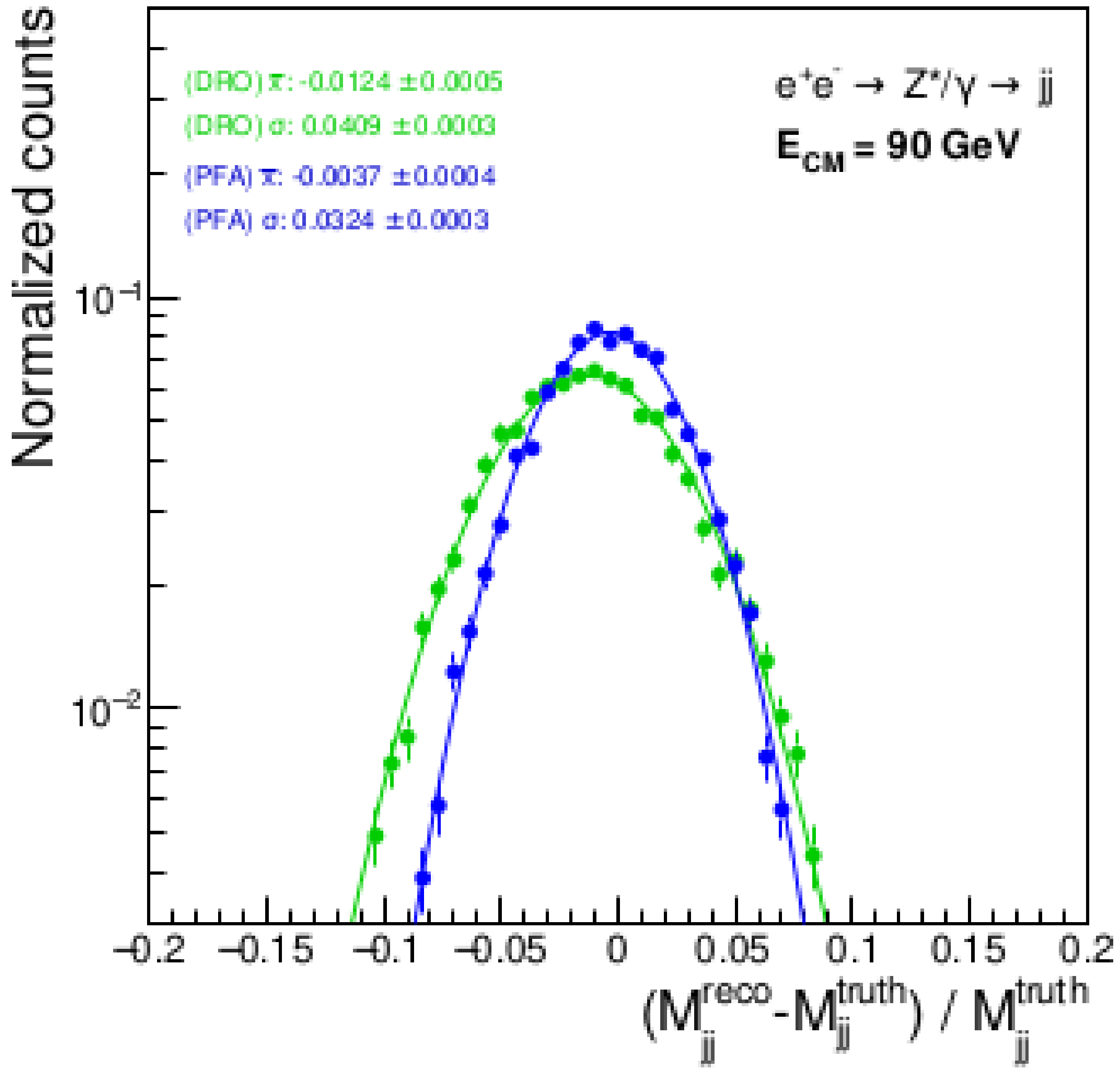
- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone(s)
- compare with E_{target}(track)
- if “good” agreement remove hits and track

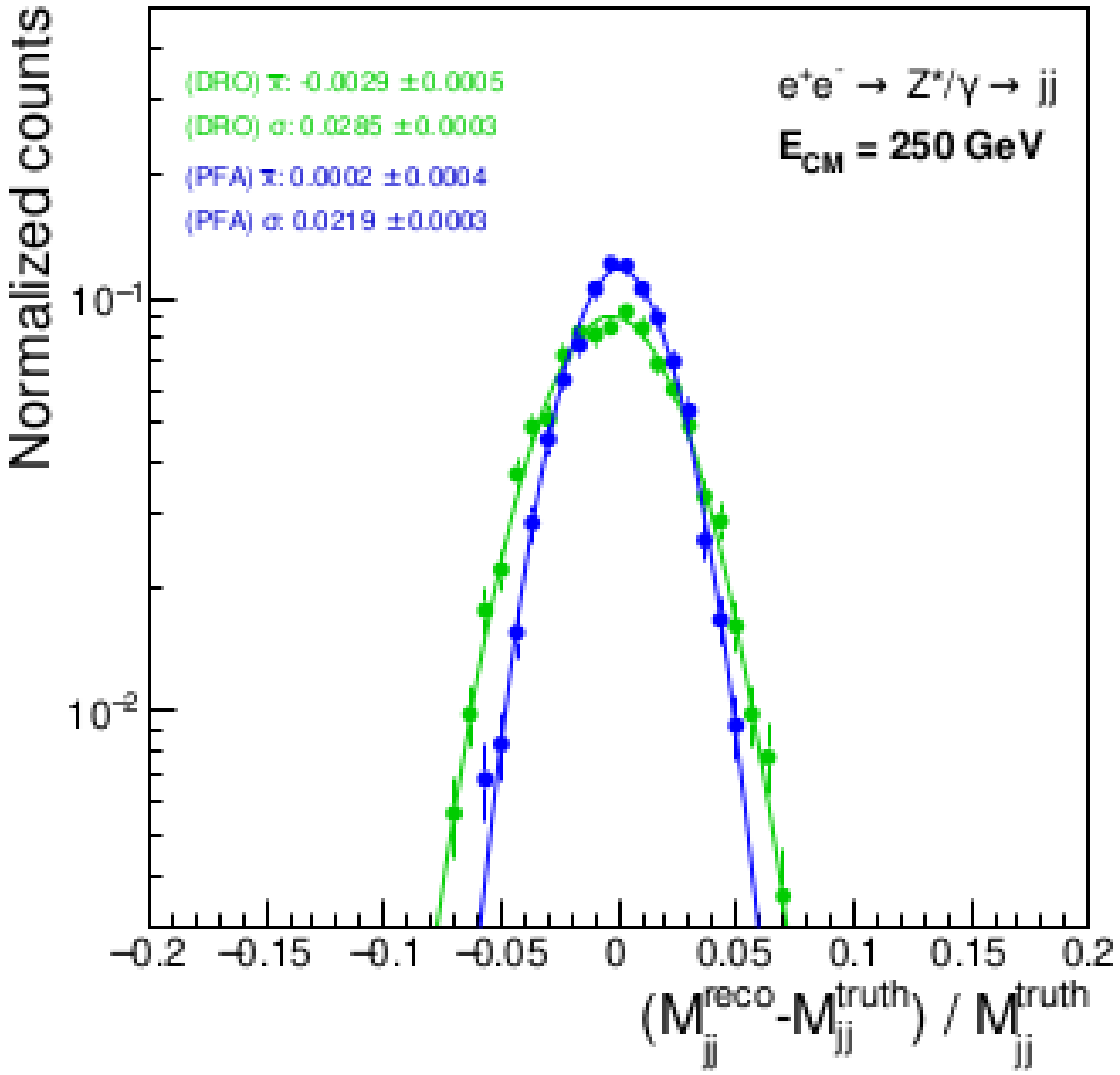


IDEA++ dual-readout-PFA

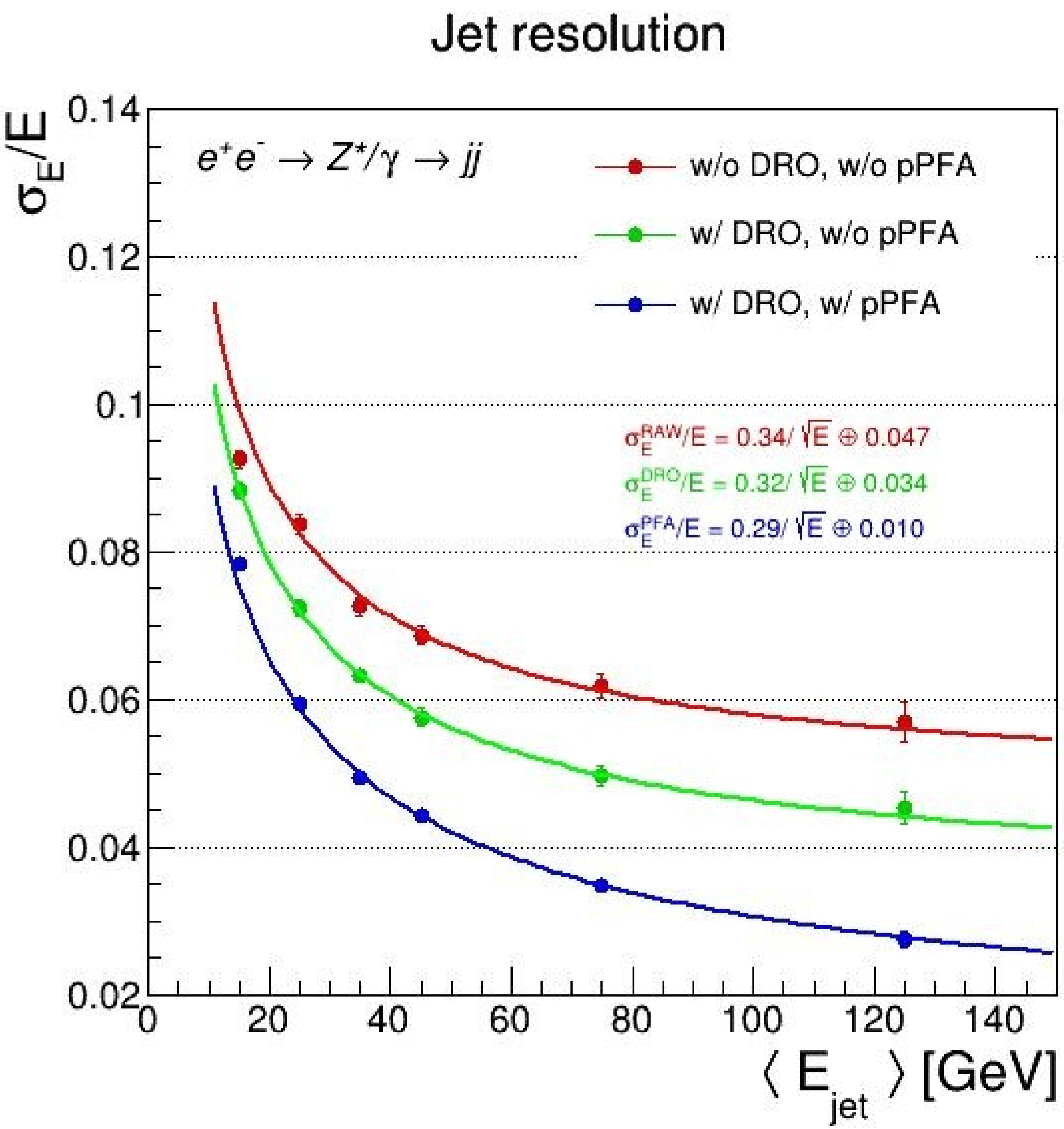
... continue

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





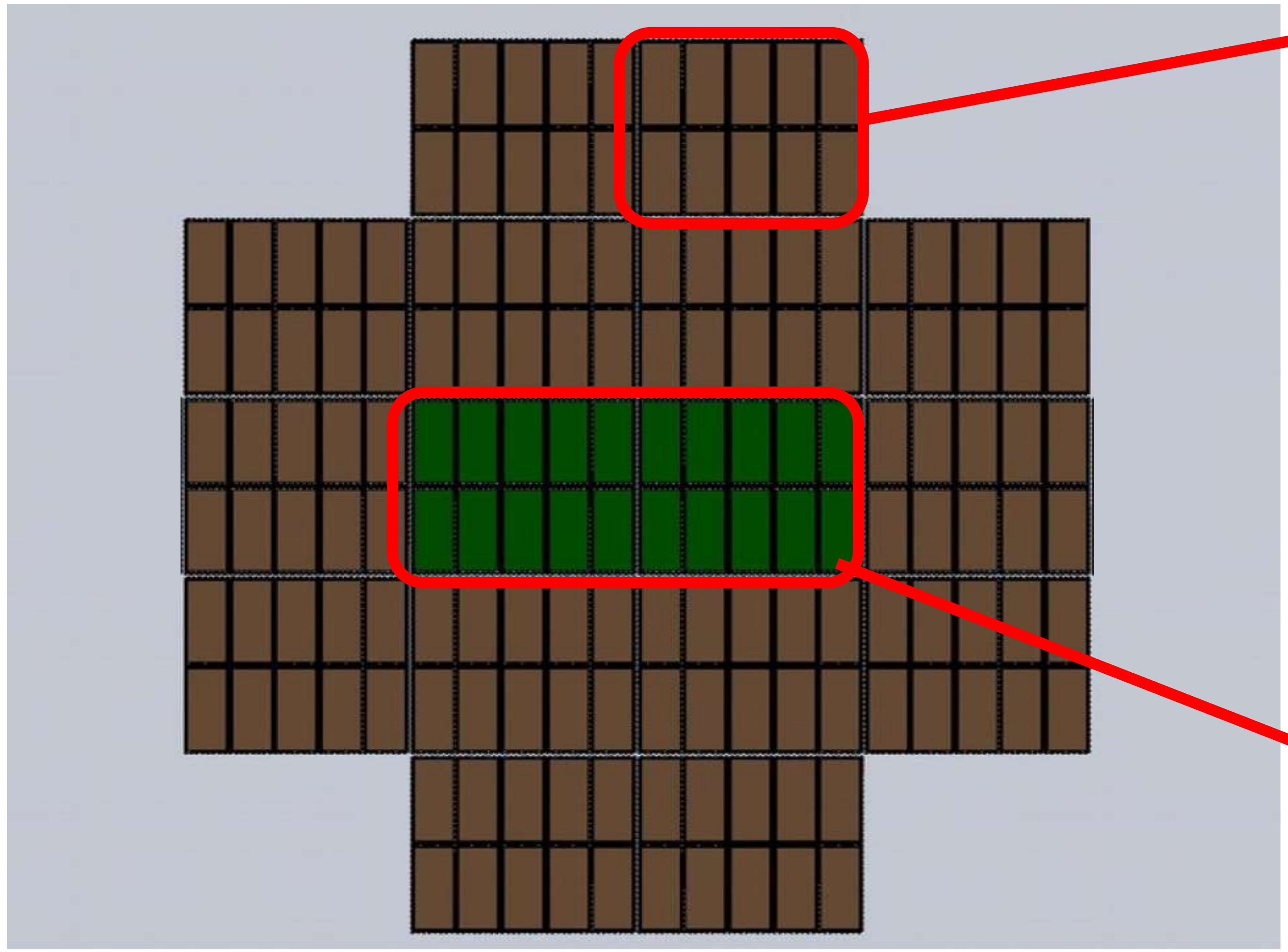
finally ...


Jet resolution
σ_E/E
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]
$e^+e^- \rightarrow Z^*/\gamma \rightarrow jj$
w/o DRO, w/o pPFA
w/ DRO, w/o pPFA
w/ DRO, w/ pPFA
$\sigma_E^{RAW}/E = 0.34/\sqrt{E} \oplus 0.047$
$\sigma_E^{DRO}/E = 0.32/\sqrt{E} \oplus 0.034$
$\sigma_E^{PFA}/E = 0.29/\sqrt{E} \oplus 0.010$

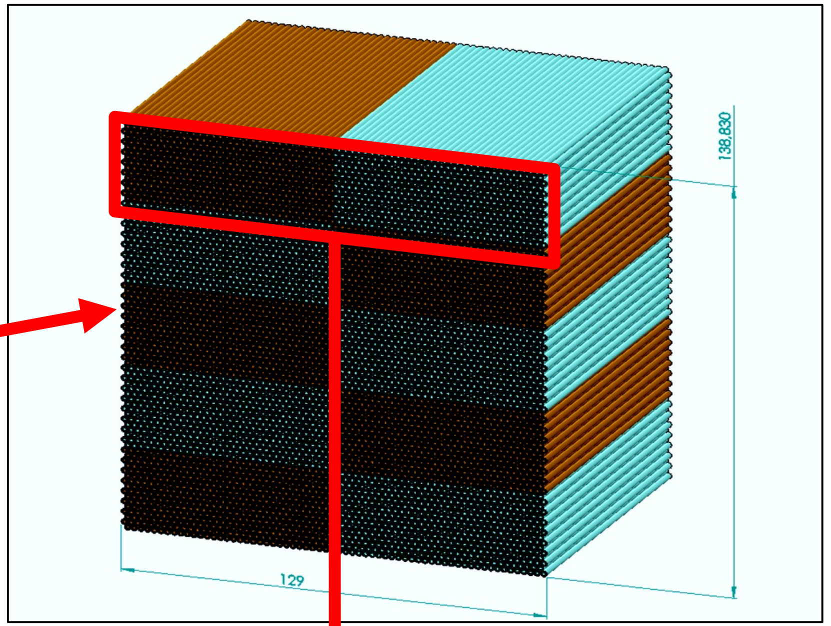
HiDRa – Highly granular Dual Readout demonstrator

Hadronic-size prototype:

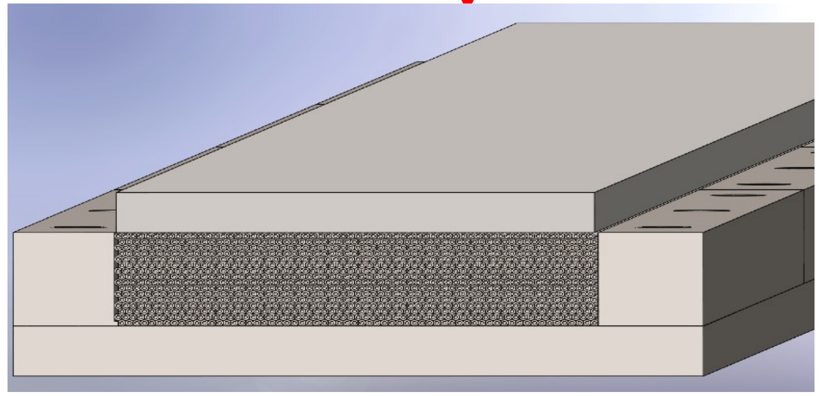
16 modules w/ highly granular core



~ 65 × 65 × 250 cm^3



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

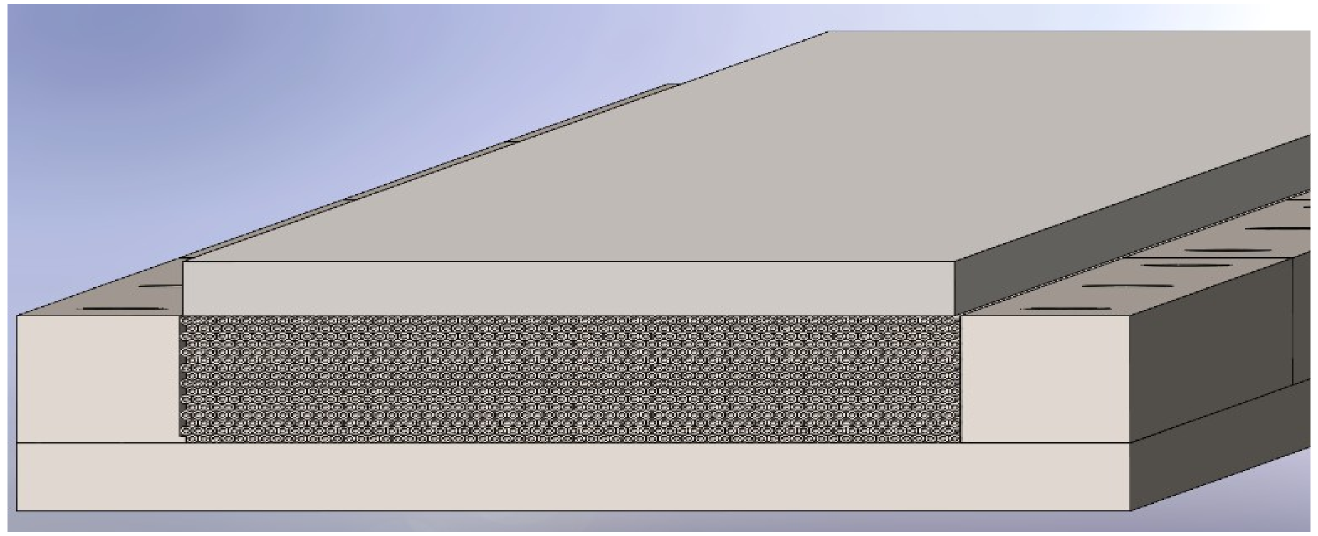


1 MiniModule:
64 × 16 = 1024 fibres in total
512 S + 512 C

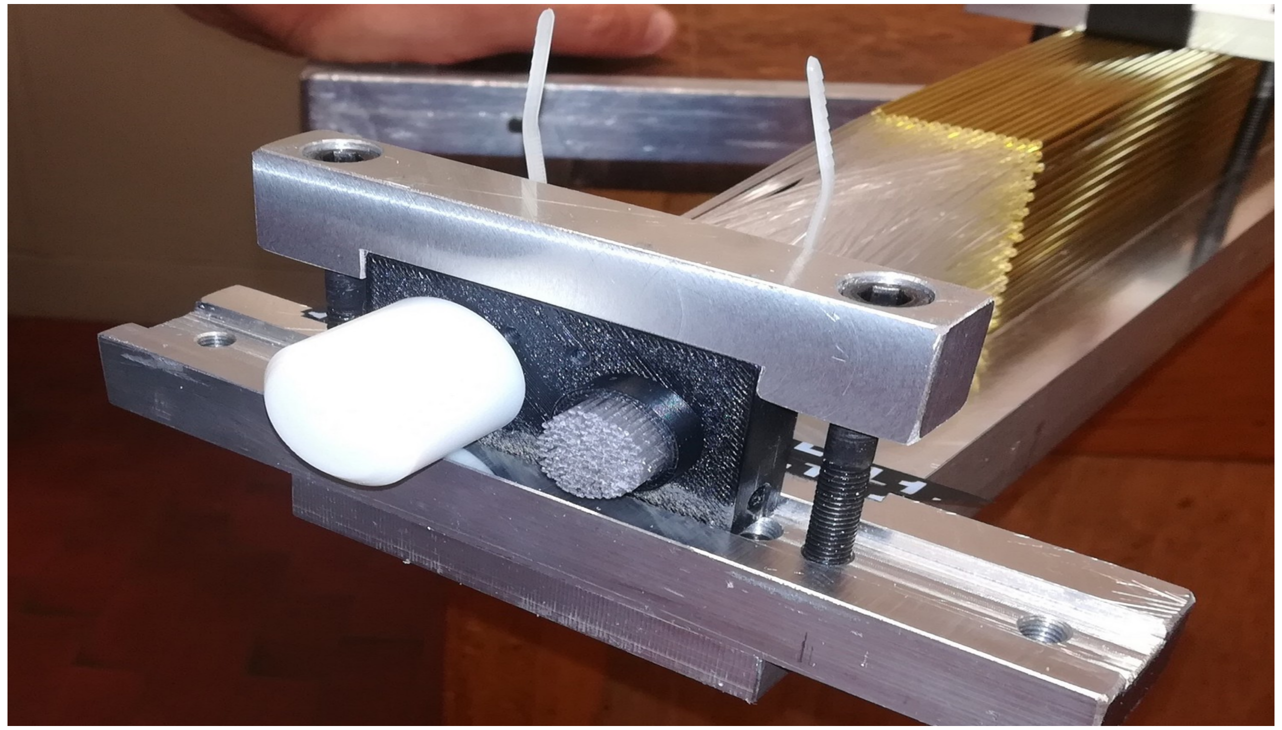
highly granular core:

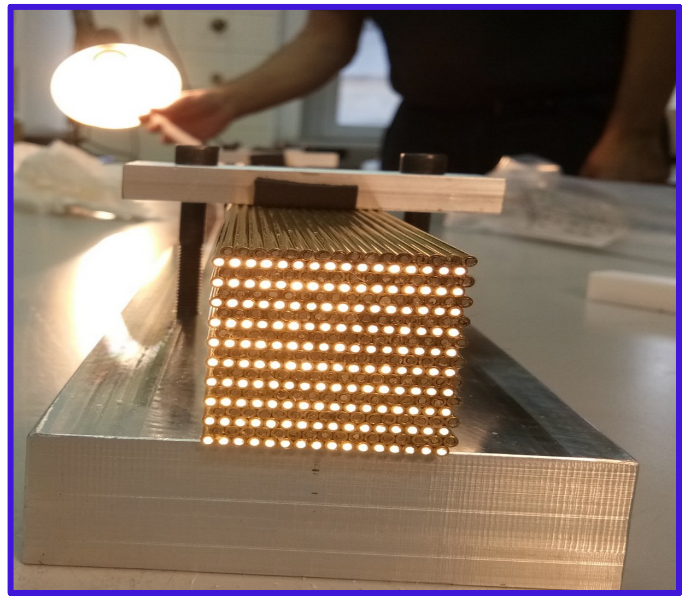
10240 fibres to be read out with SiPMs

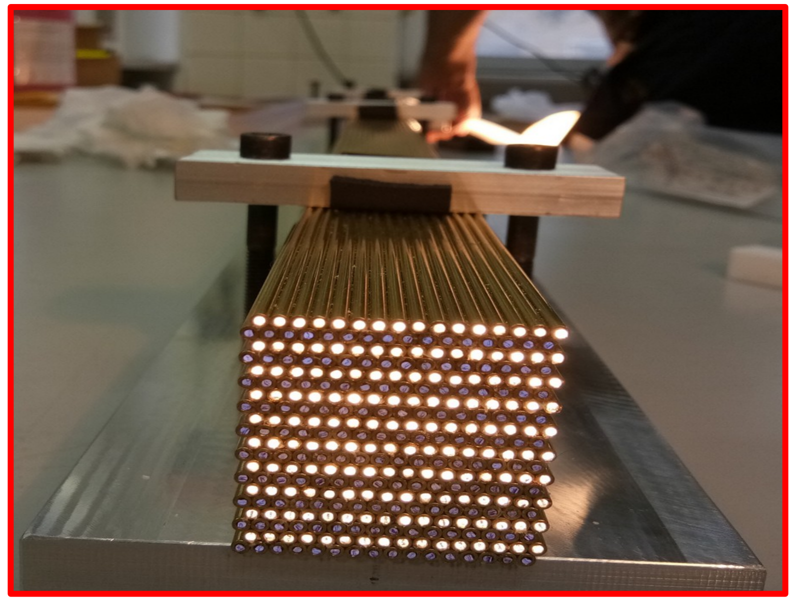
Present design



- C and S fibres positioned per raw
- Fibre separation at calorimeter rear end
- Grouping for interfacing to PMTs





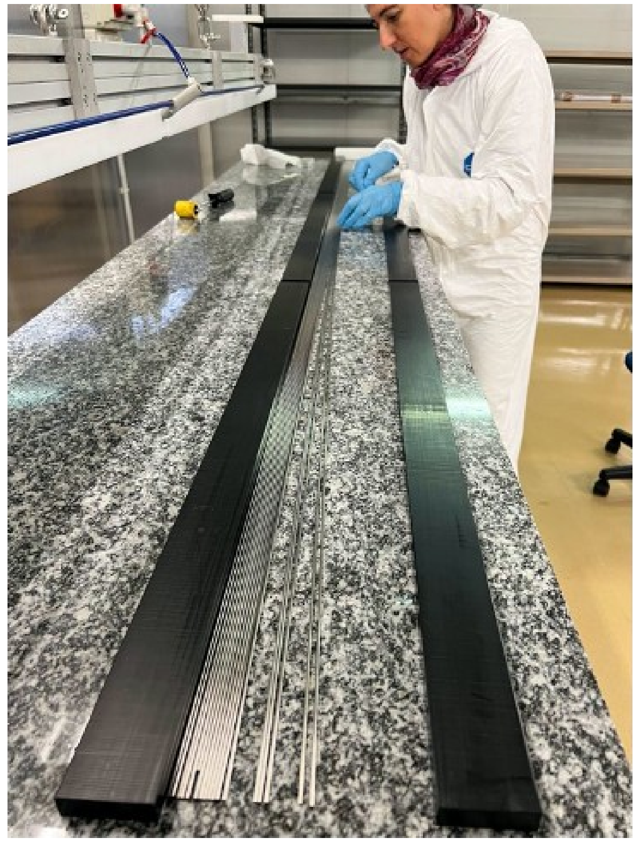


scintillating fibres

Cherenkov fibres

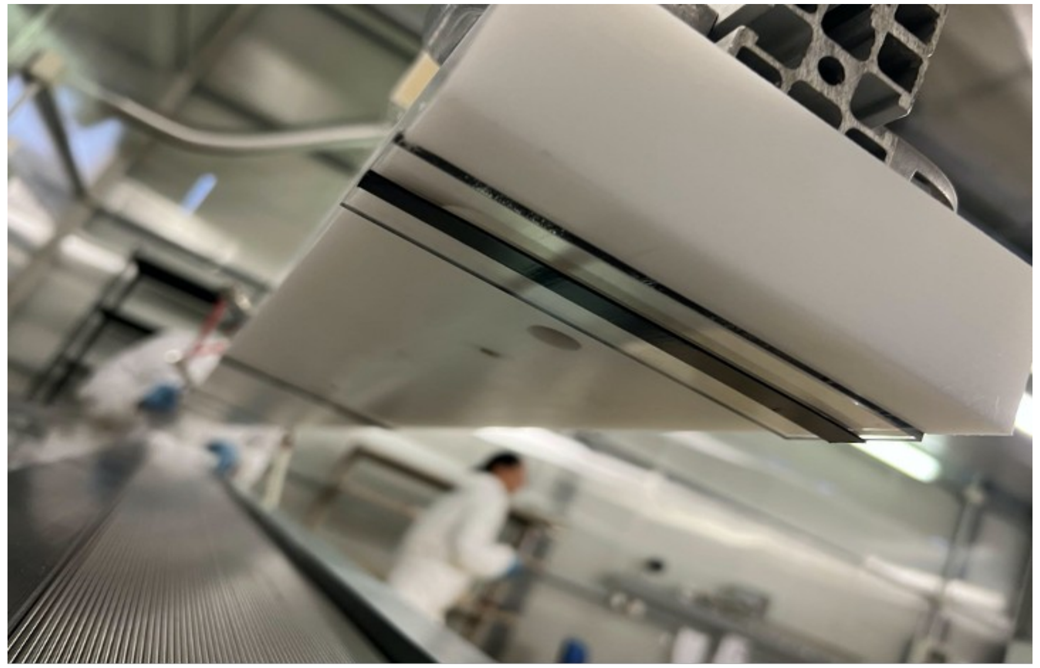
Fibre disposal and grouping (pictures from previous prototype)

Construction technique



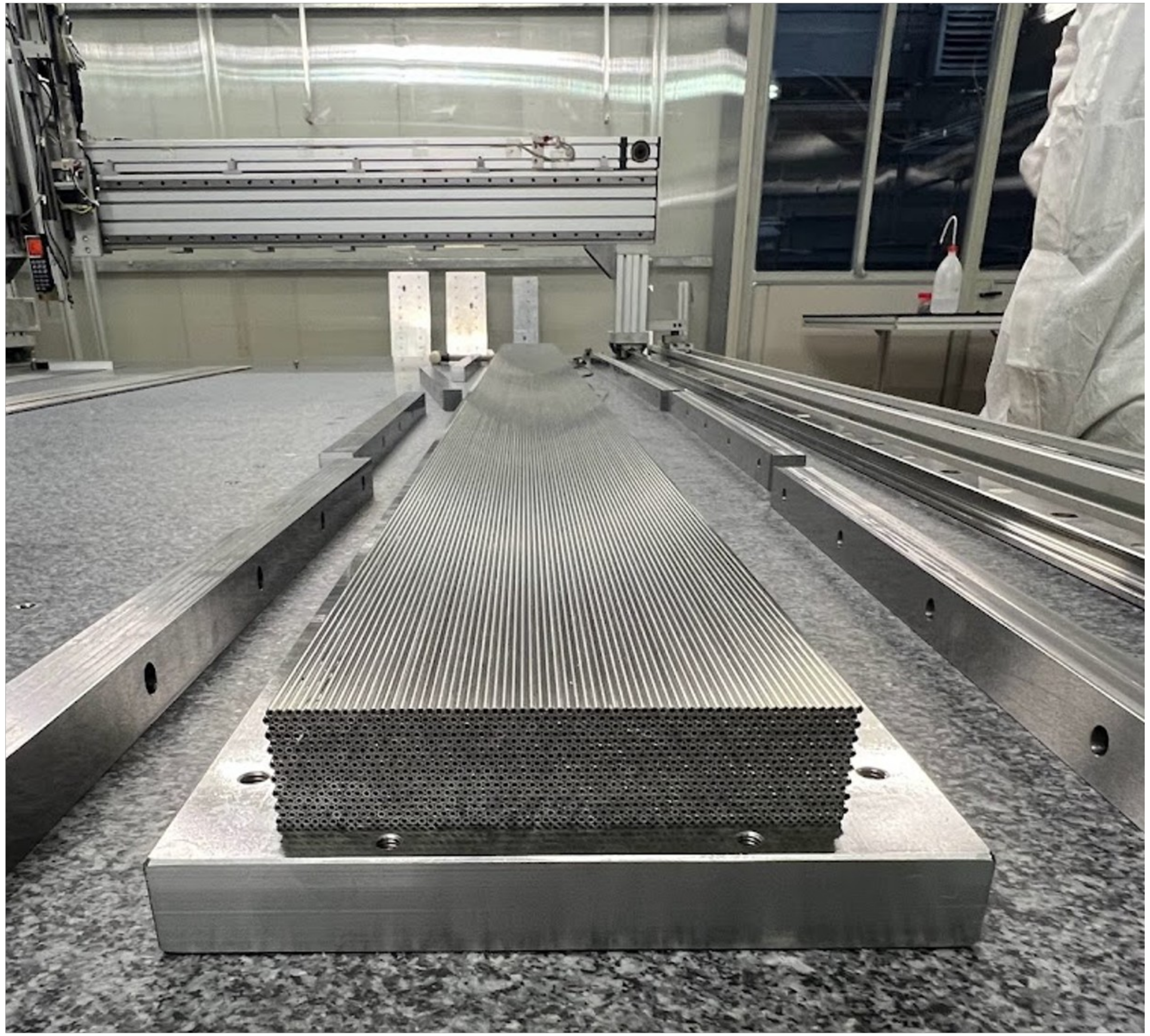
tube aligned
in reference tool

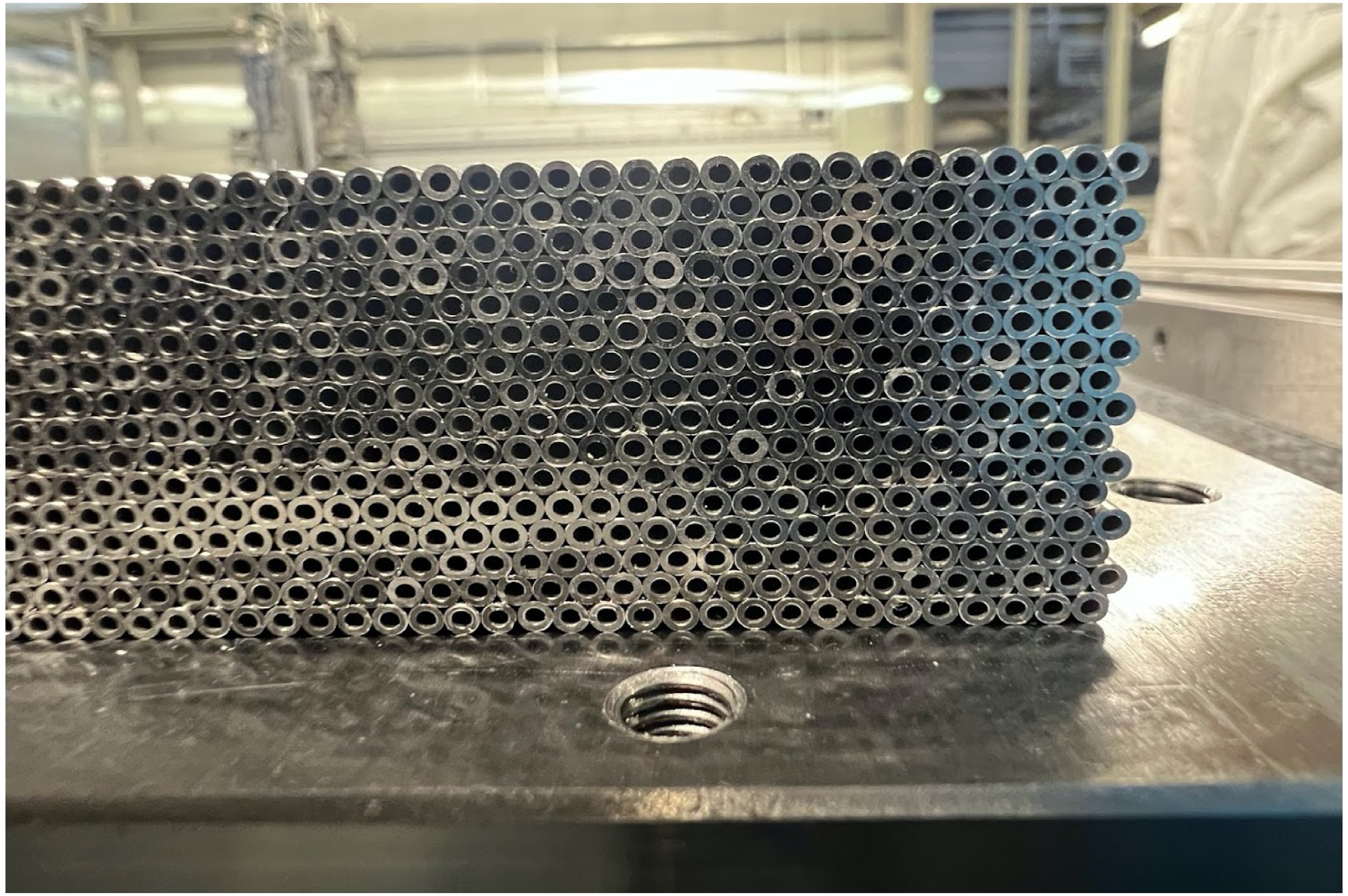
Stiffback-like technique for tube handling, gluing and positioning



Vacuum + double-sided tape for tube handling

Minimodule 0





Module handling and DQ

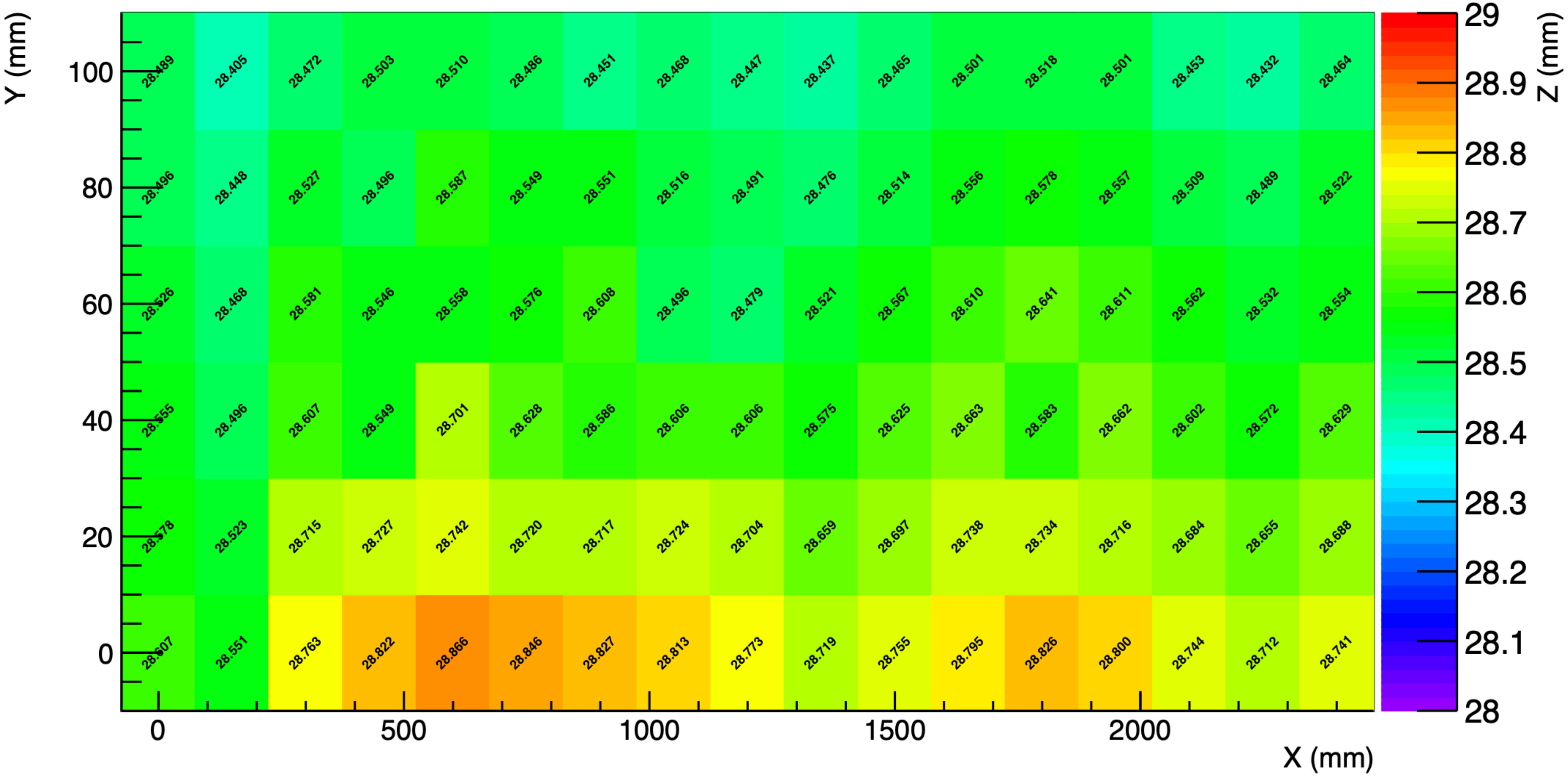
Same stiffback used
for module handling by
adding extra vacuum tool

Semi-automatic system
for planarity QAQC

Minimodule-0 QAQC

tube OD:
2.026 mm

h_nom:
28.351 mm



28.489	28.405	28.472	28.503	28.510	28.486	28.451	28.468	28.447	28.437	28.465	28.501	28.518	28.501	28.453	28.432	28.464
28.496	28.448	28.527	28.496	28.587	28.549	28.551	28.516	28.491	28.476	28.514	28.556	28.578	28.557	28.509	28.489	28.522
28.526	28.468	28.581	28.546	28.558	28.576	28.608	28.496	28.479	28.521	28.567	28.610	28.641	28.611	28.562	28.532	28.554
28.555	28.496	28.607	28.549	28.701	28.628	28.586	28.606	28.606	28.575	28.625	28.663	28.583	28.662	28.602	28.572	28.629
28.578	28.523	28.715	28.727	28.742	28.720	28.717	28.724	28.704	28.659	28.697	28.738	28.734	28.716	28.684	28.655	28.688
28.607	28.551	28.763	28.822	28.866	28.846	28.827	28.813	28.773	28.719	28.755	28.795	28.826	28.800	28.744	28.712	28.741

Production scheme

- Day 0:
  - Preparation tubes and tooling
- Day 1:
  - Gluing of Minimodule N (~3h)
  - Preparation fibres for Minimodule N
- Day 2:
  - Preparation tubes for Minimodule N+1
  - Releasing Minimodule N
  - QAQC Minimodule N
- Day 3:
  - Gluing Minimodule N+1
  - Fibre insertion in Minimodule N
  - Preparation fibres for Minimodule N+1

1 FTE physicist
+ 1 FTE technician

Students in PCTO

Schedule (from available funds)

- Tubelet order ~ 3 week
- Delivery ~ 4 w production + 2 w import
- QAQC + cleaning ~ 4 w

→ **at least 3 months**

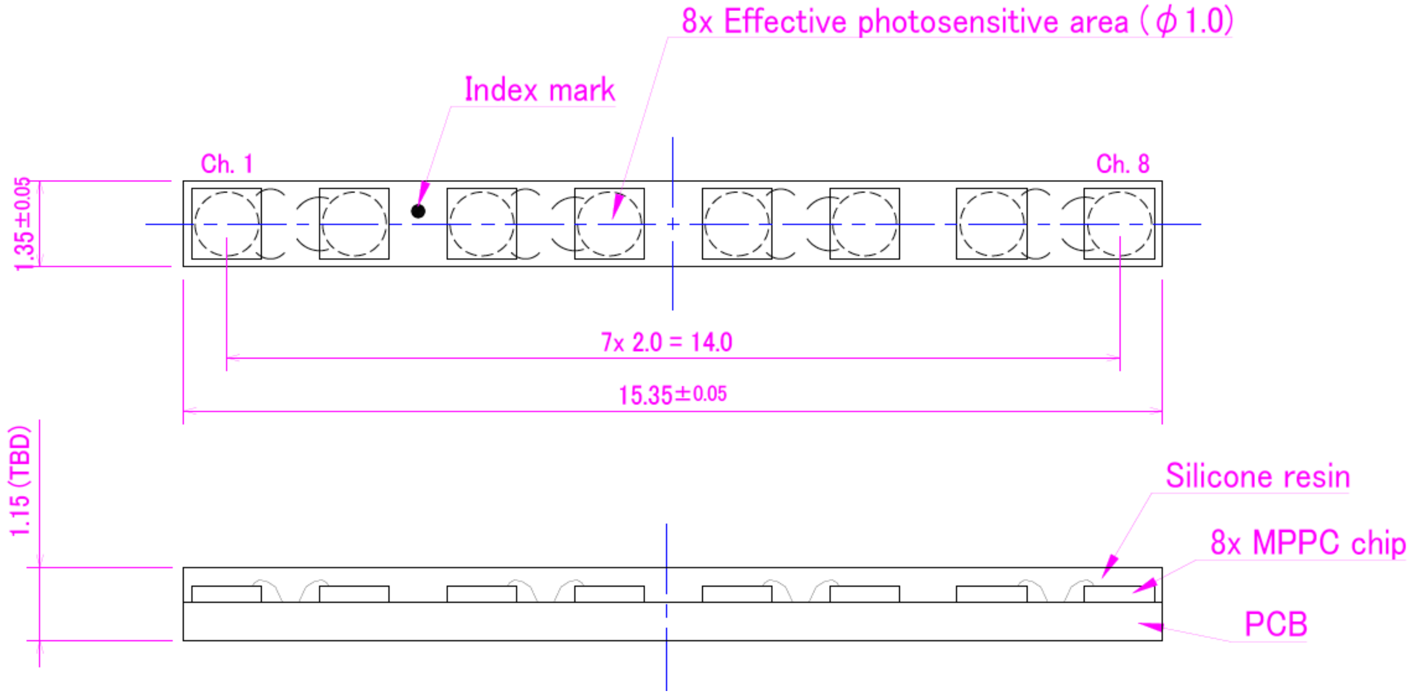
- Expected production speed
  - 5 minimodules in 2 weeks → 80 minimodules in 8 months
  - Includes:
    - absorber gluing
    - fibre insertion
    - fibre gluing and milling (for PMT coupling)

→ **~ one year in total**

SiPMs

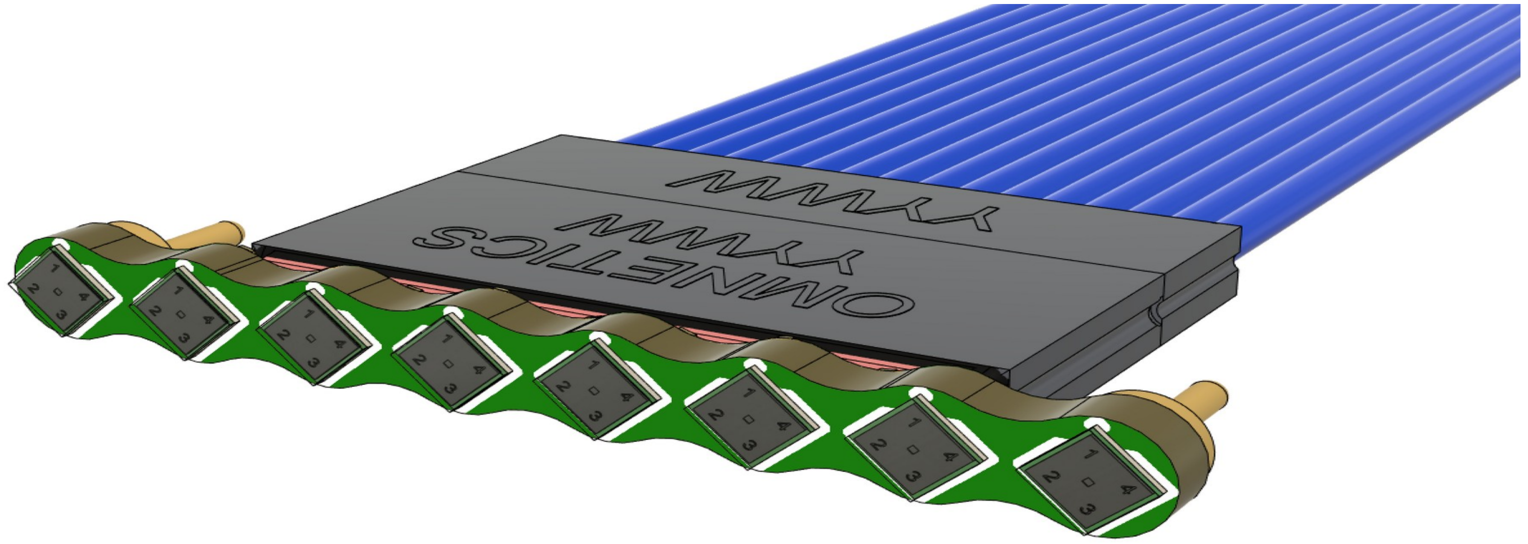
New solution by Hamamatsu:

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



Our present best fit:

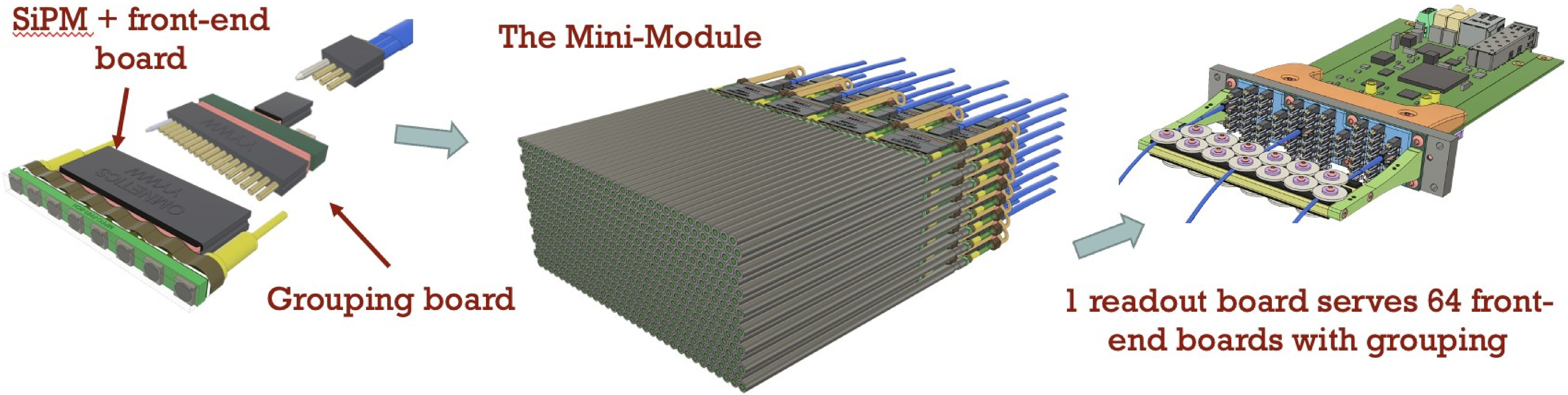
a) use 10 µm cell-size SiPMs for scintillating fibres
b) use 15 µm cell-size SiPMs for clear fibres



Got 10 boards per cell-size type for testing

Highly granular modules

- 10240 SiPMs → 1280 SiPM boards + 5% spare = 1344 SiPM boards
- 1344 front-end boards
- 1344 grouping boards (+ cables)
- 22 patch panels
- 20-22 readout boards (A5202)
- 2 data concentrators



Summary

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
→ high-granularity 3D information

em crystal option → boost em performance without spoiling hadronic one

High-granularity 3D information
→ powerful input for deep-learning algorithms and/or PFA
→ highly performing final-state identification capabilities

R&D activities ongoing in Europe, S. Korea and U.S. exploiting all directions

Hadronic-scale demonstrators under construction in both Europe and S. Korea

Objectives

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

Validate Geant4 shower modeling

Assess scalable solutions concerning construction and signal readout

Exploit DNN architectures for physics analysis

Assess performance in relevant benchmark physics channels

Advertising

If you are interested, please join CERN e-group:

idea-dualreadout@cern.ch

and (by-weekly) meetings with scheduling at:

https://indico.cern.ch/category/10684/

Backup

IDEA dual-readout group

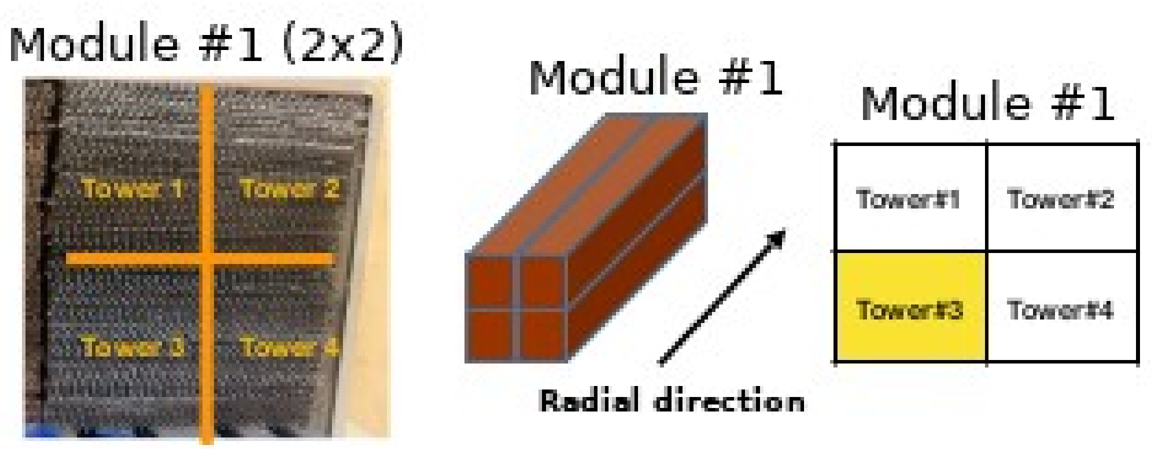
Three main activity pillars:

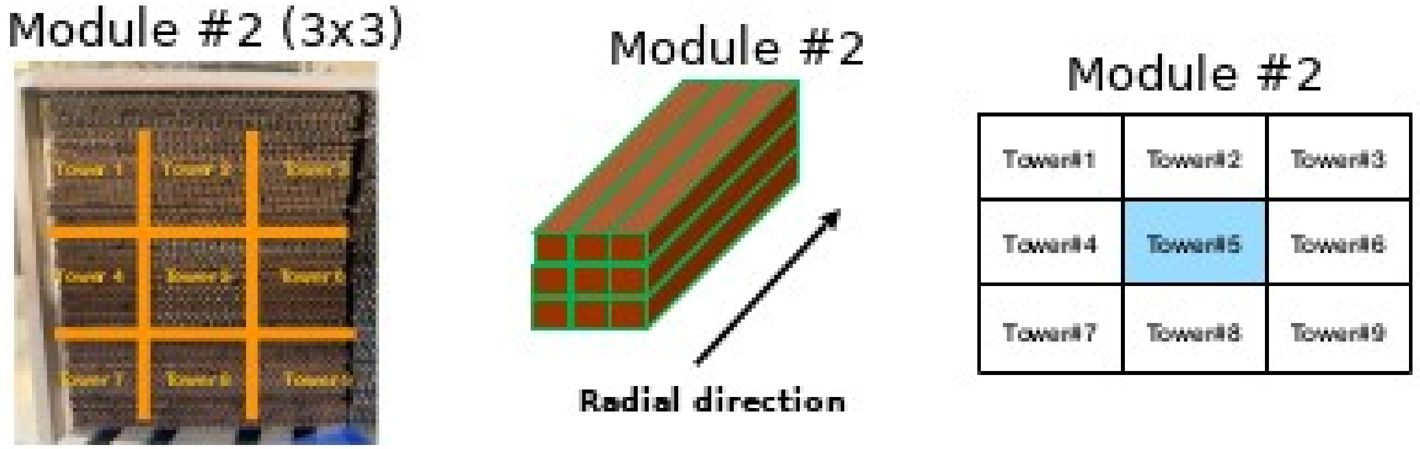
1) South Korea → projective fibre-sampling calorimeter

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

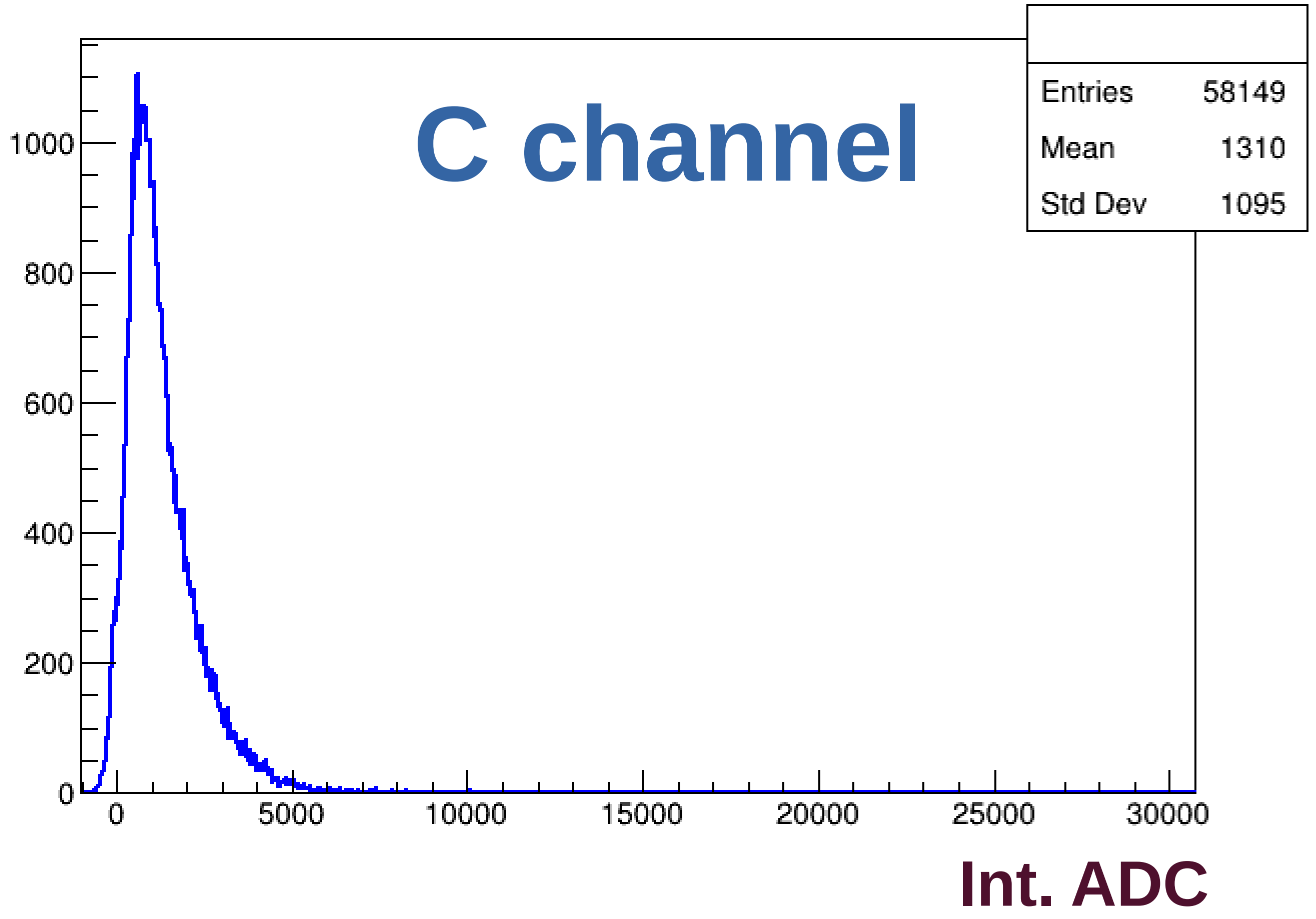
3) U.S. (Calvision project) → mainly (but not only) on crystal em calorimeter

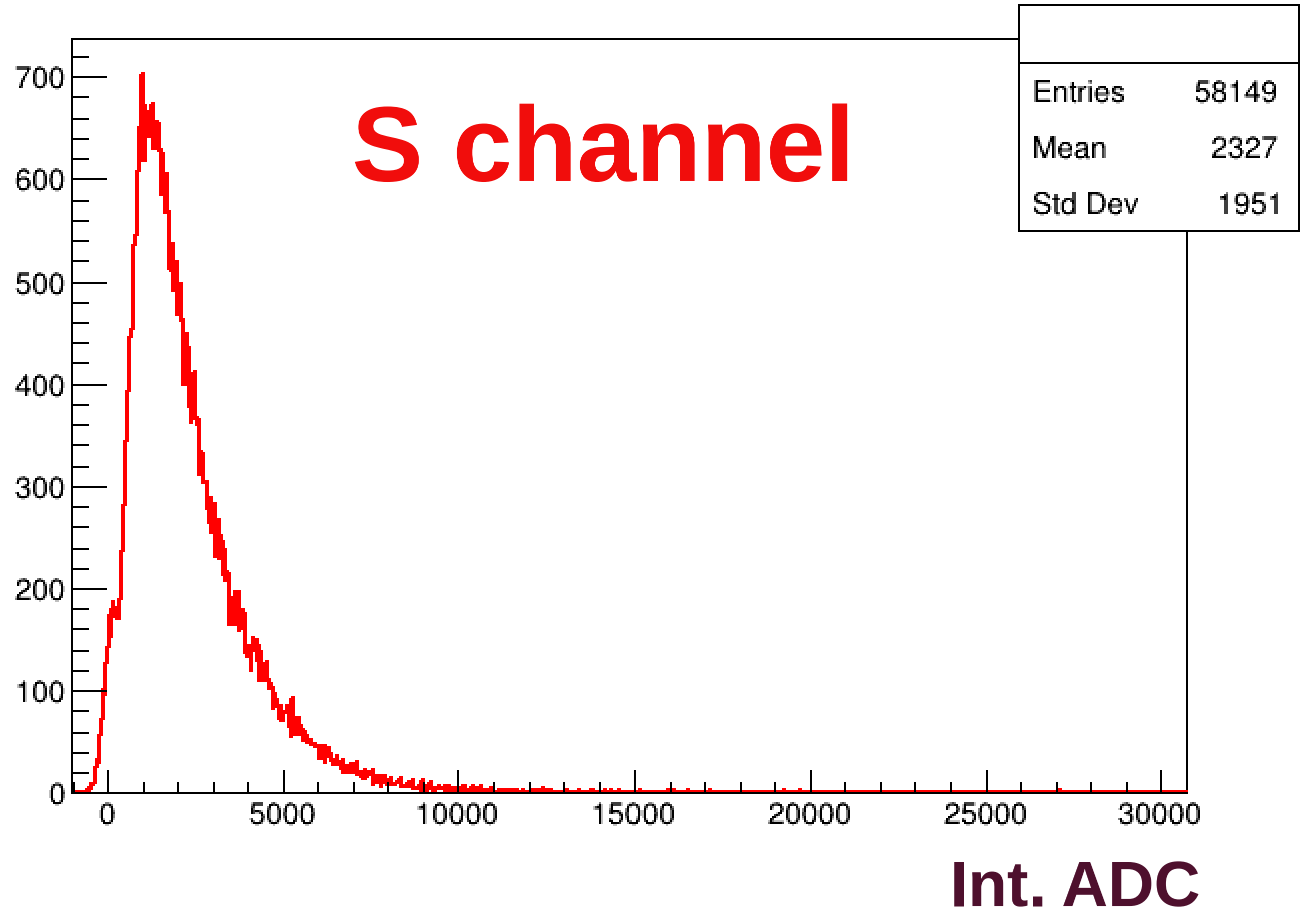
2022 Korean-prototype beam test





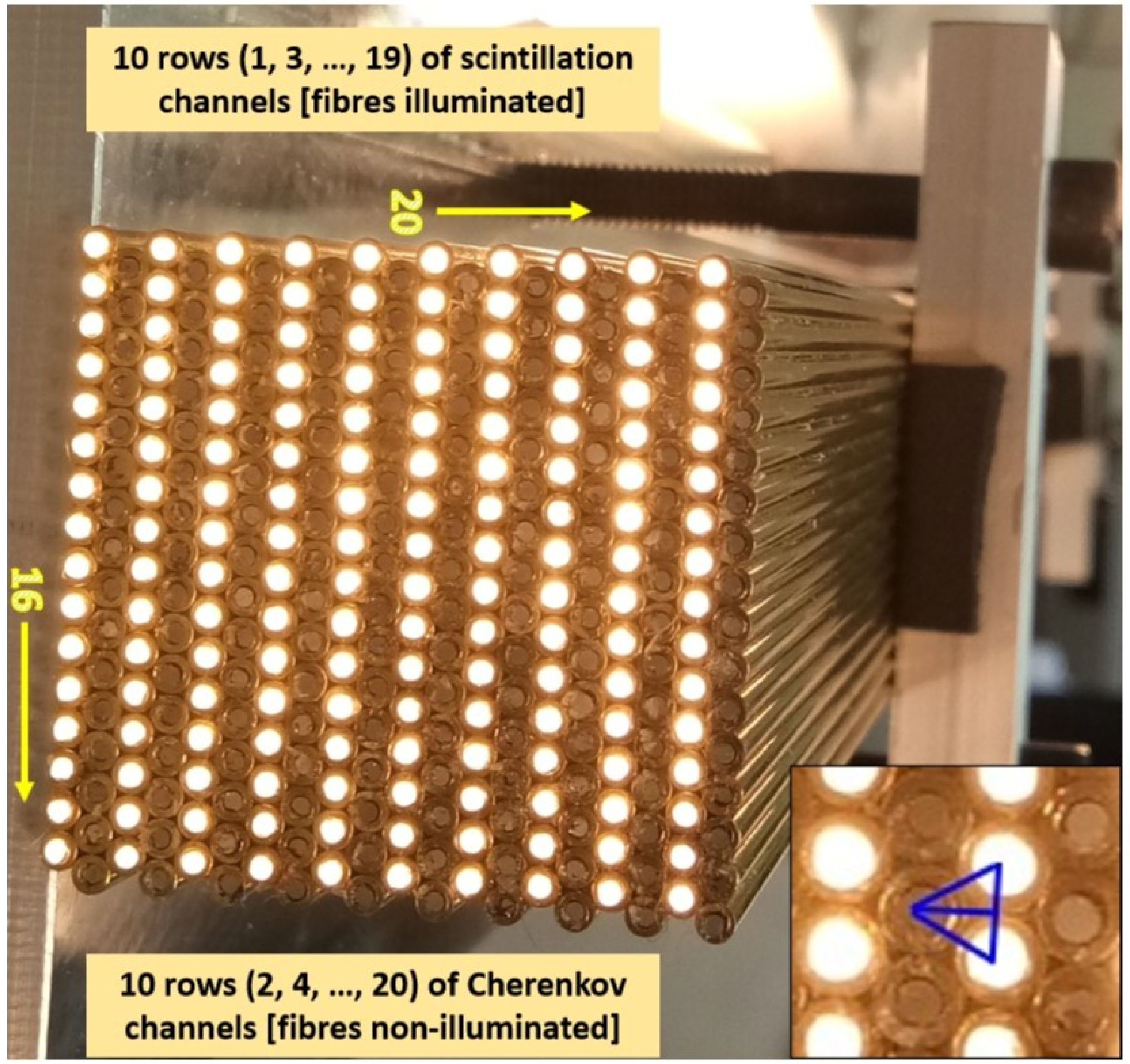
- Data analysis in progress



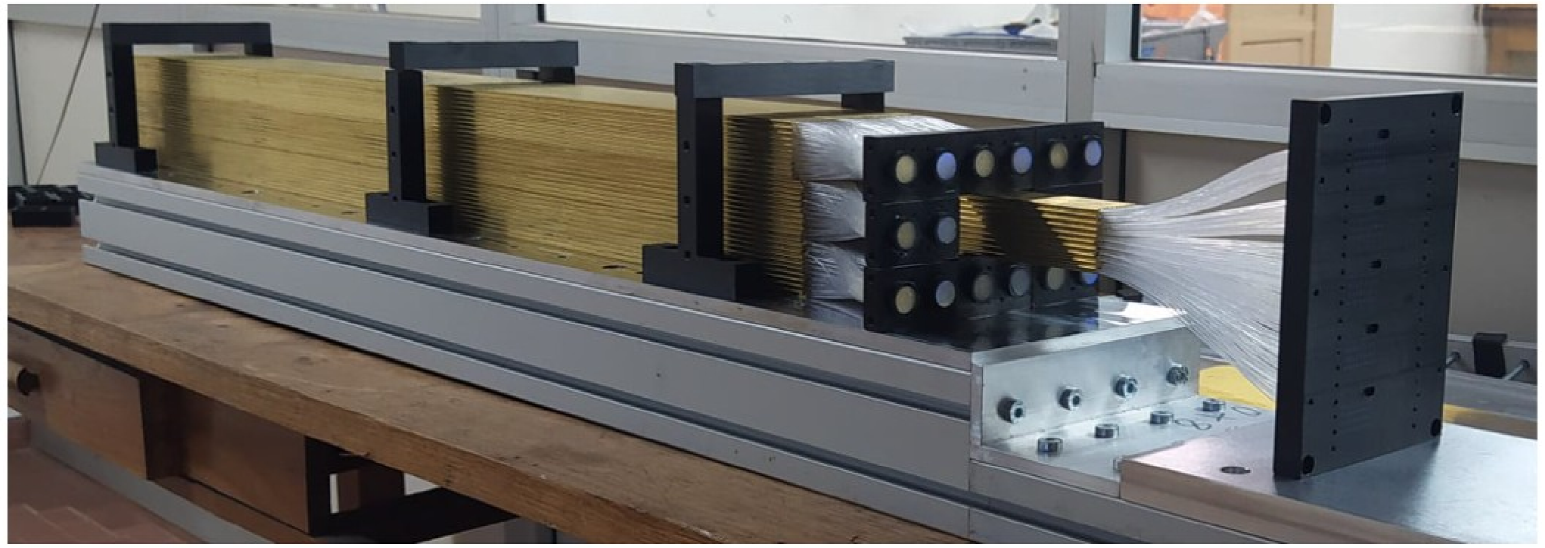


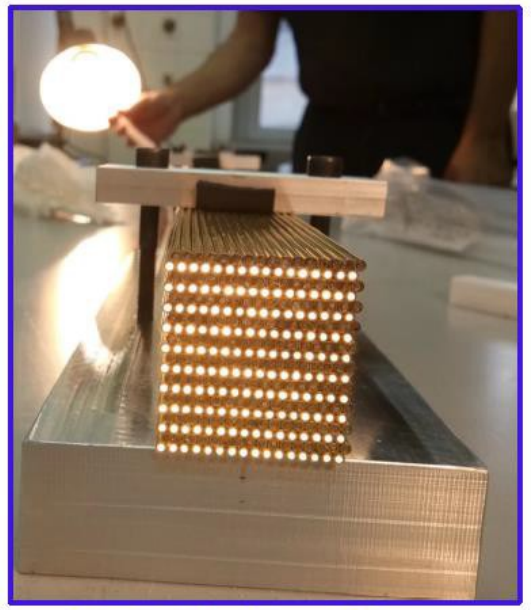
IDEA 2020 em-size bucatini prototype (EU)

Nine ~3.5×3.3 cm^2 towers

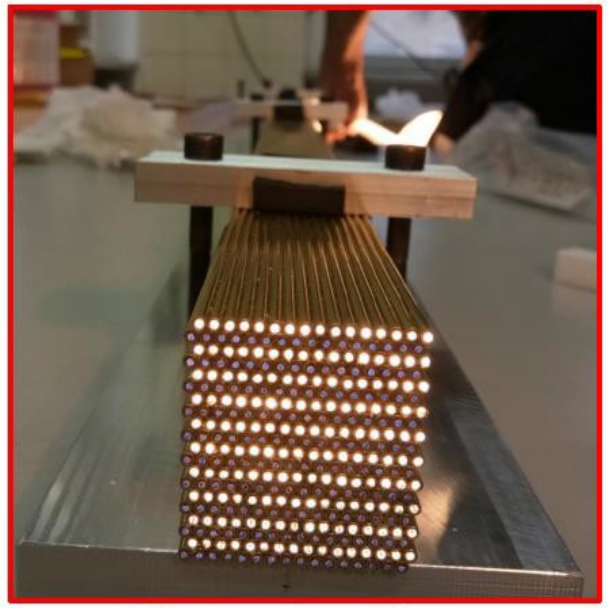


One tower (i.e. 360 fibres) w/ highly-granular (SiPM) readout





Scintillation fibers



Cherenkov fibers

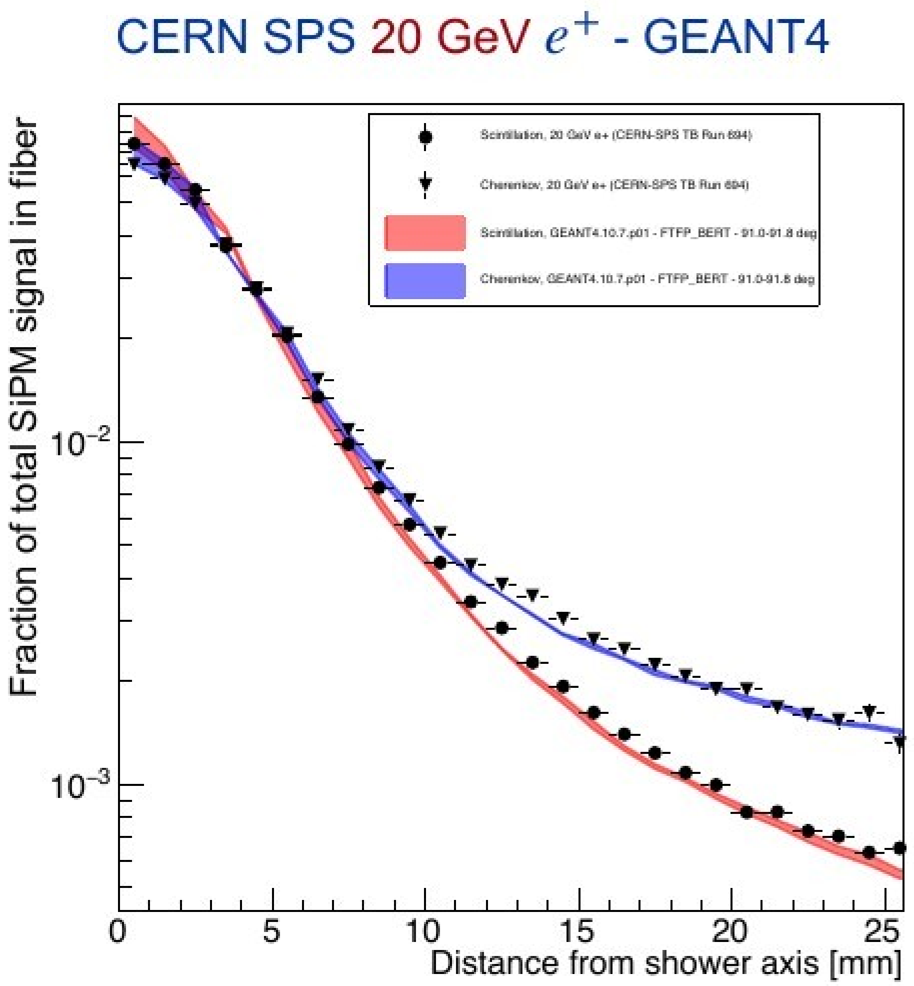
IDEA 2020 em-size bucatini prototype (EU)

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

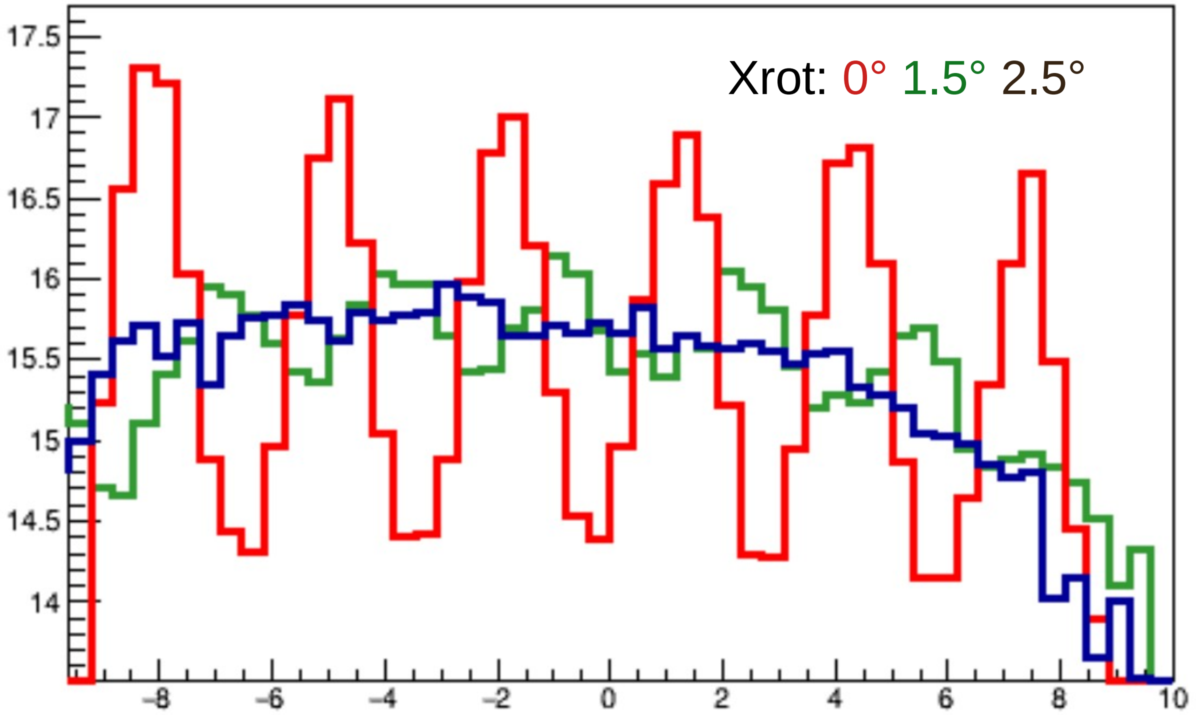
Data vs. Geant4 simulation

Lateral profiles extracted as average value for every x-bin

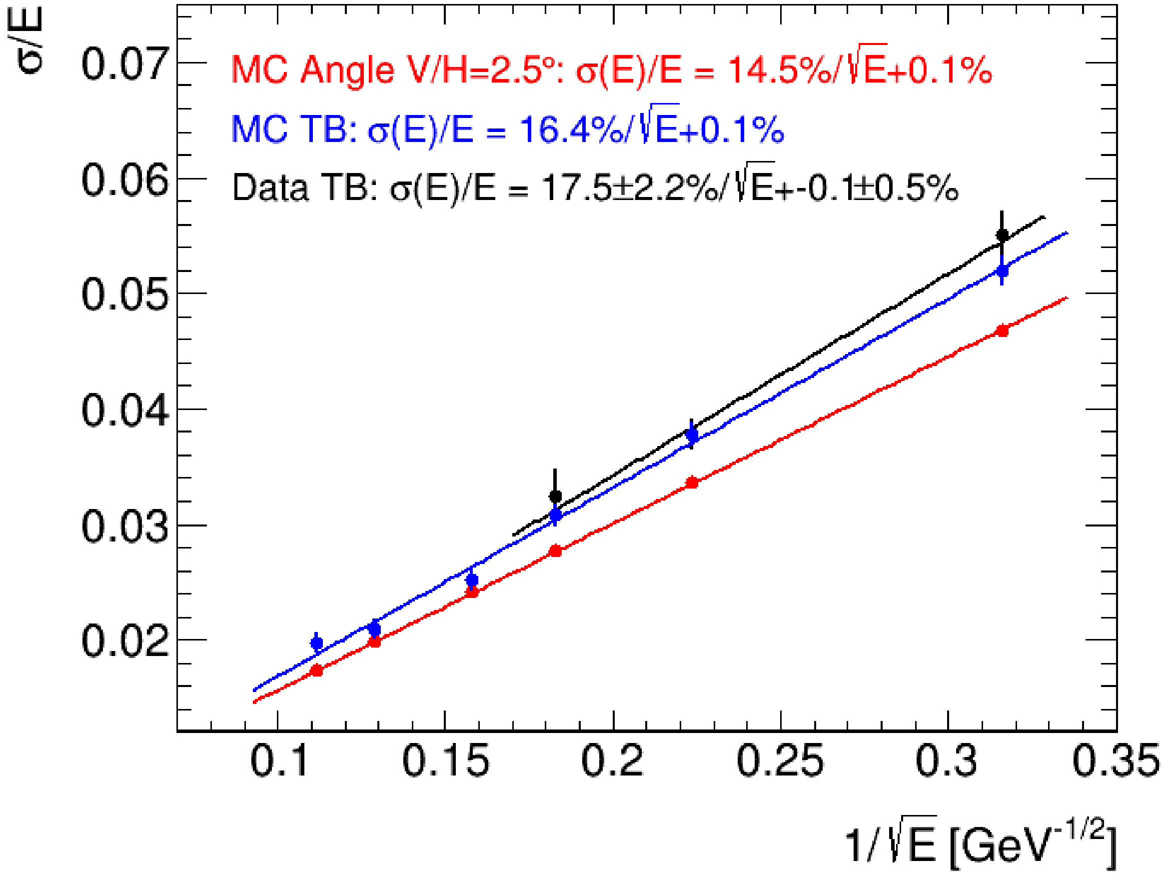


Other results

Angular dependence (from MC)



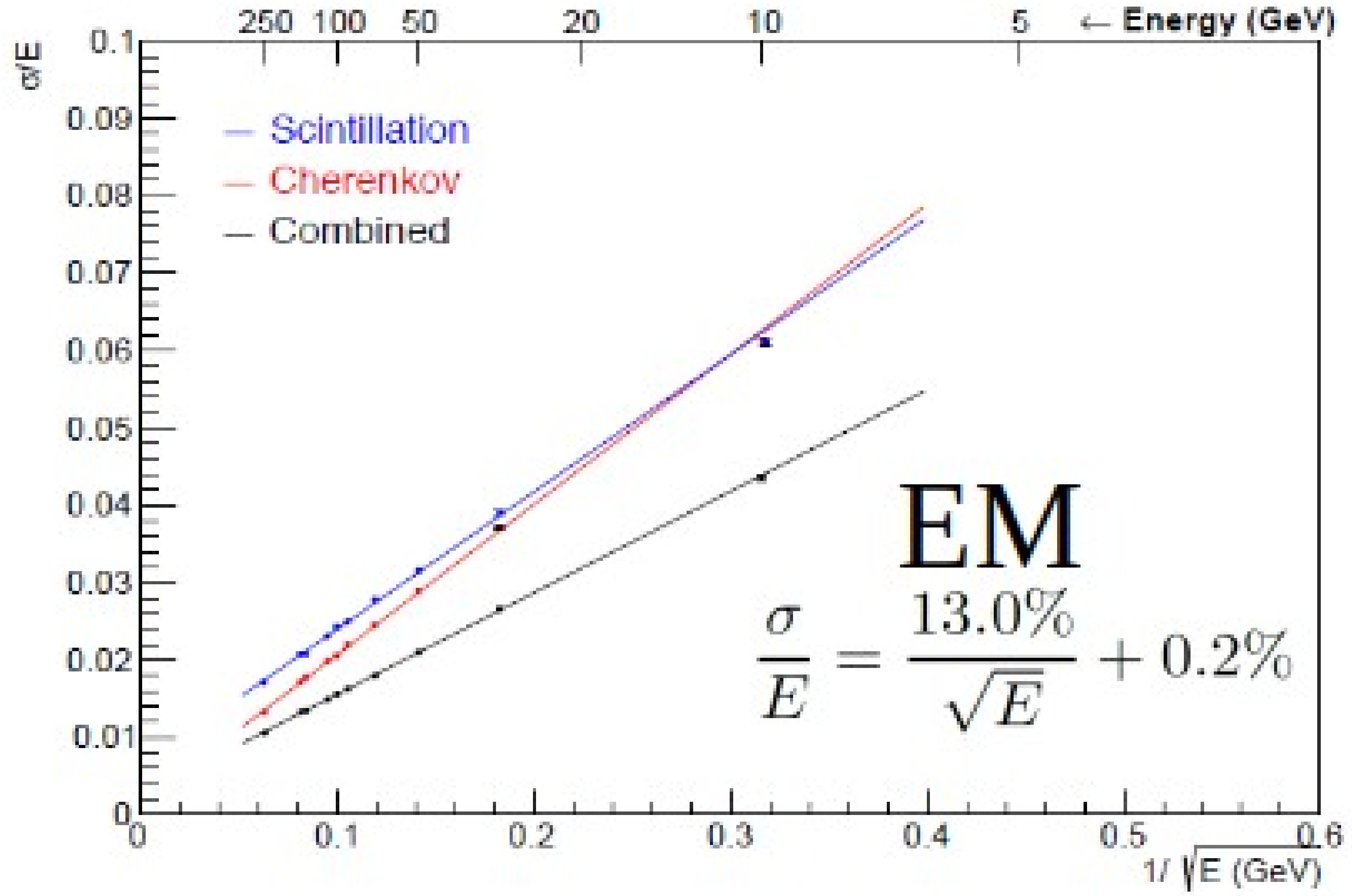
EM resolution

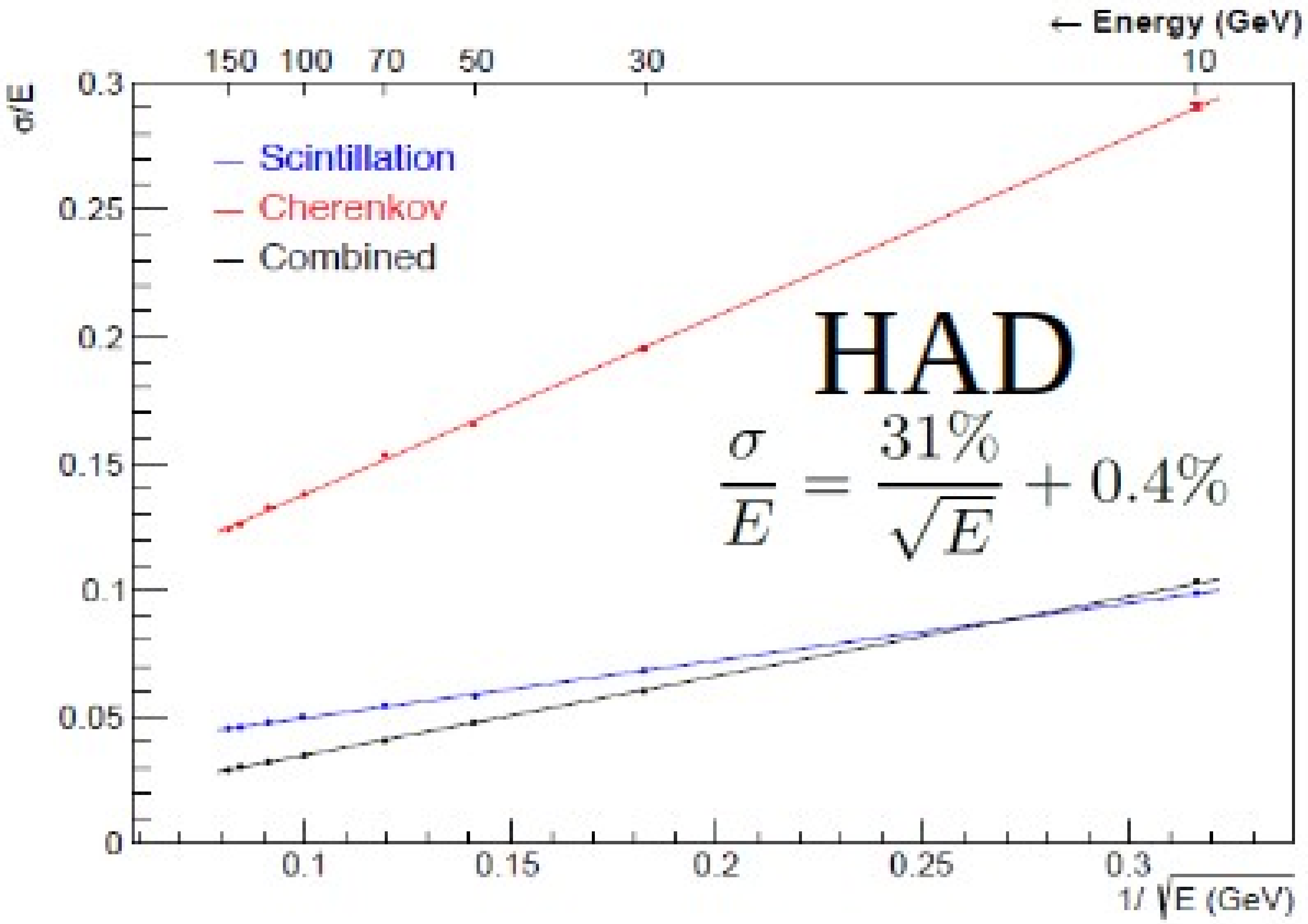


Need another beam test
Need beam purity
Need correct detector setup (angle, preshower)

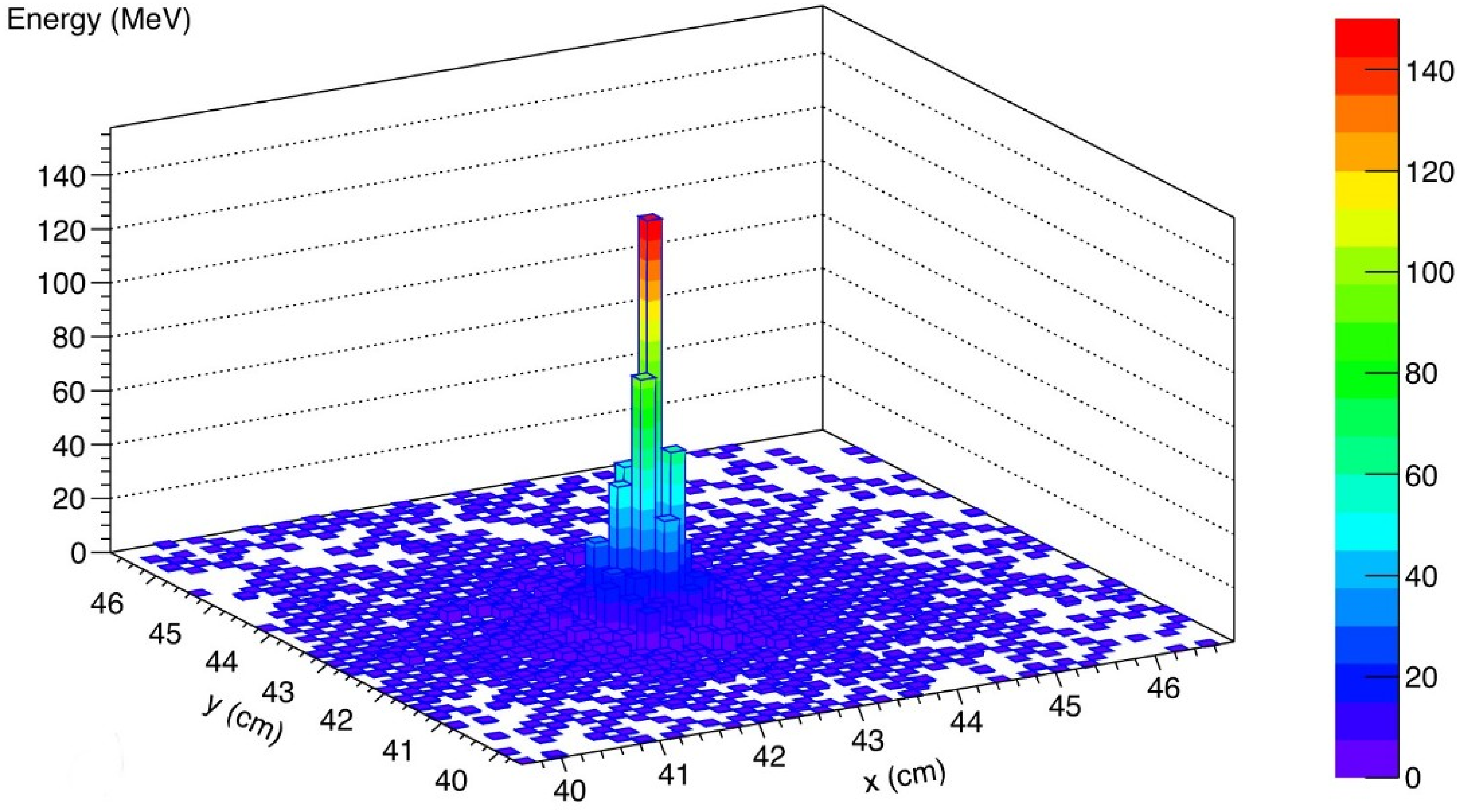
Geant4 simulation

- Good resolutions averaged over eta and phi

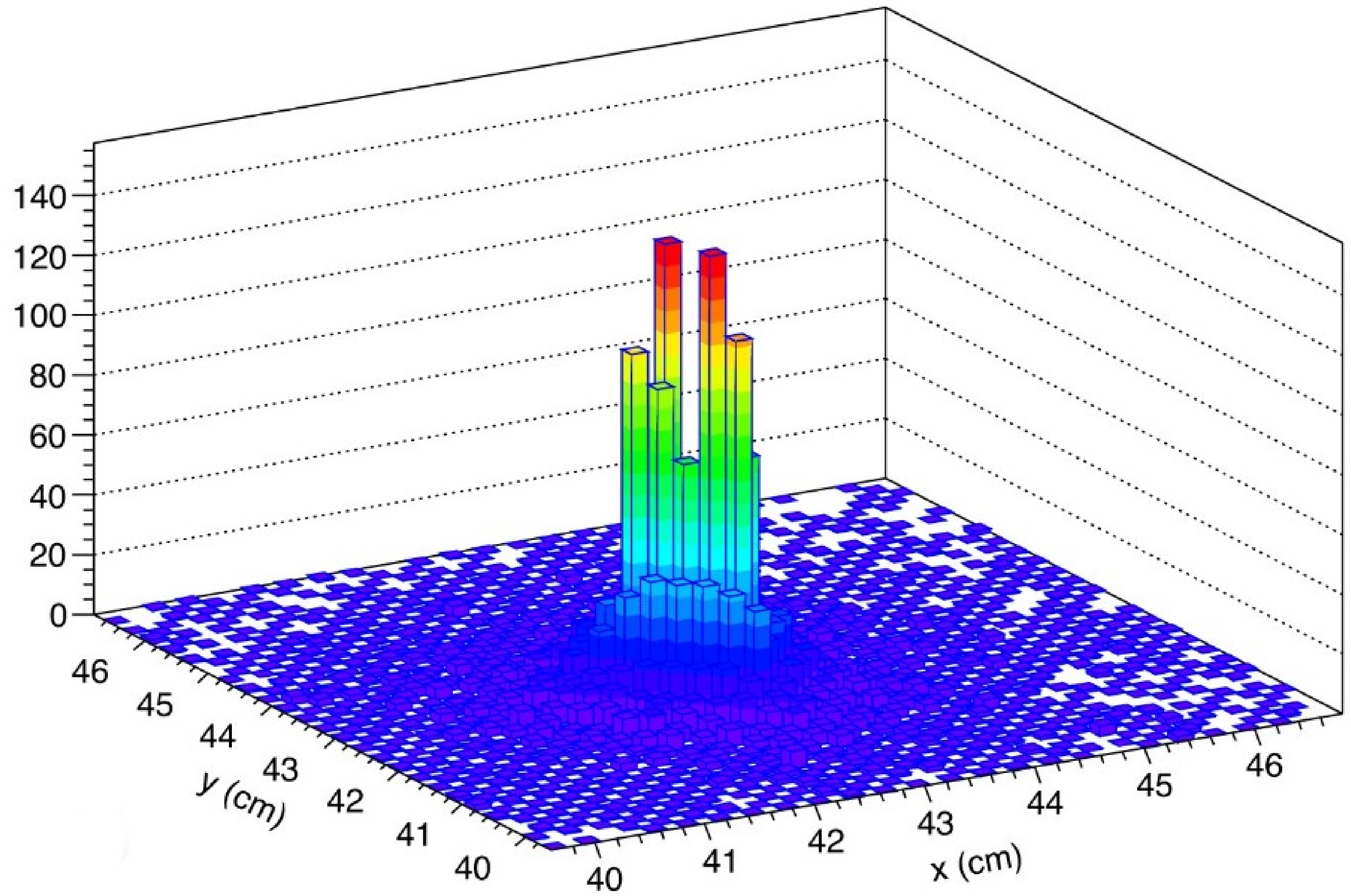




Event displays

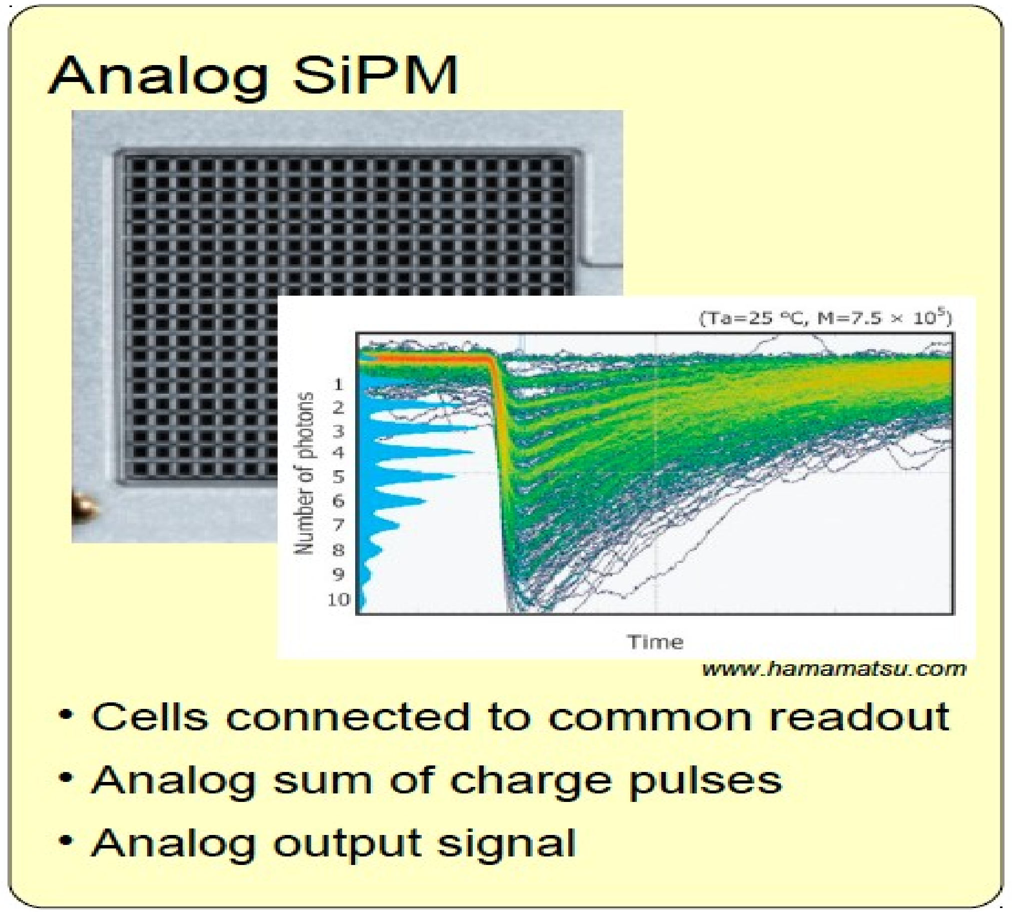


50 GeV e^-



100 GeV π^0

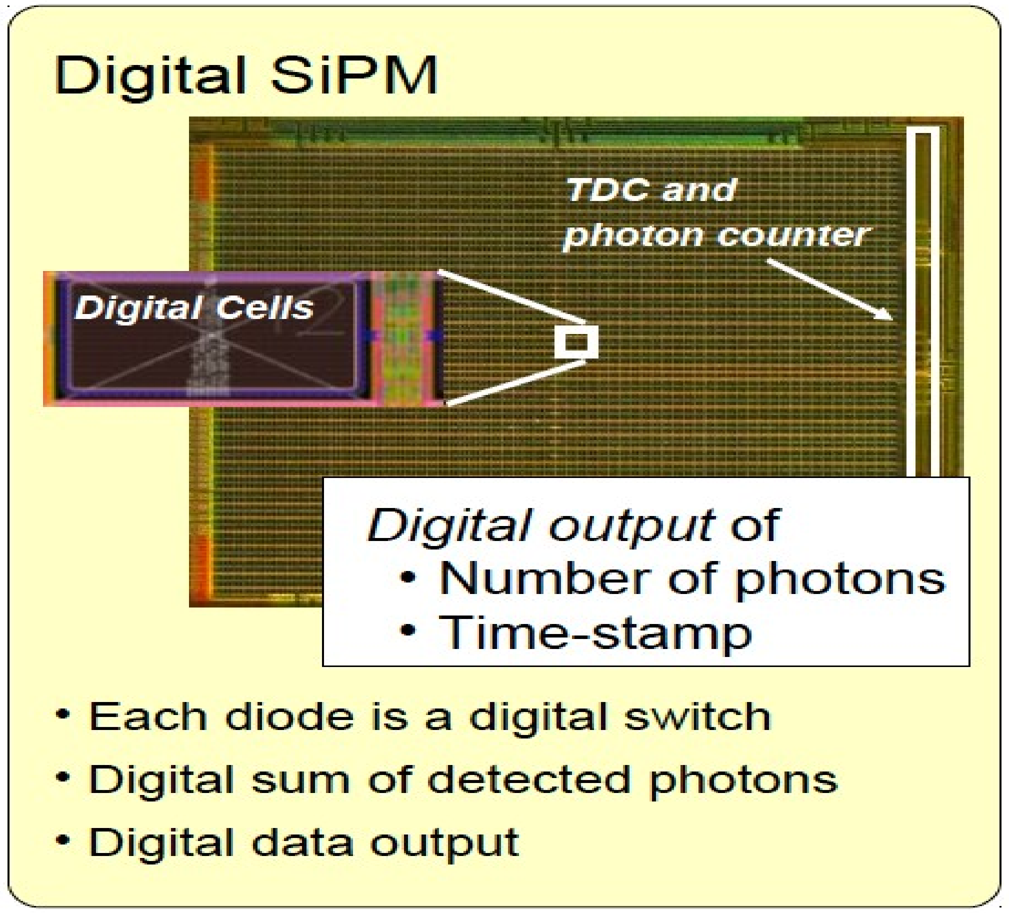
Alternative to SiPMs?



Analog SiPM

www.hamamatsu.com

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



Digital SiPM

Digital output of
- Number of photons
- Time-stamp

- 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

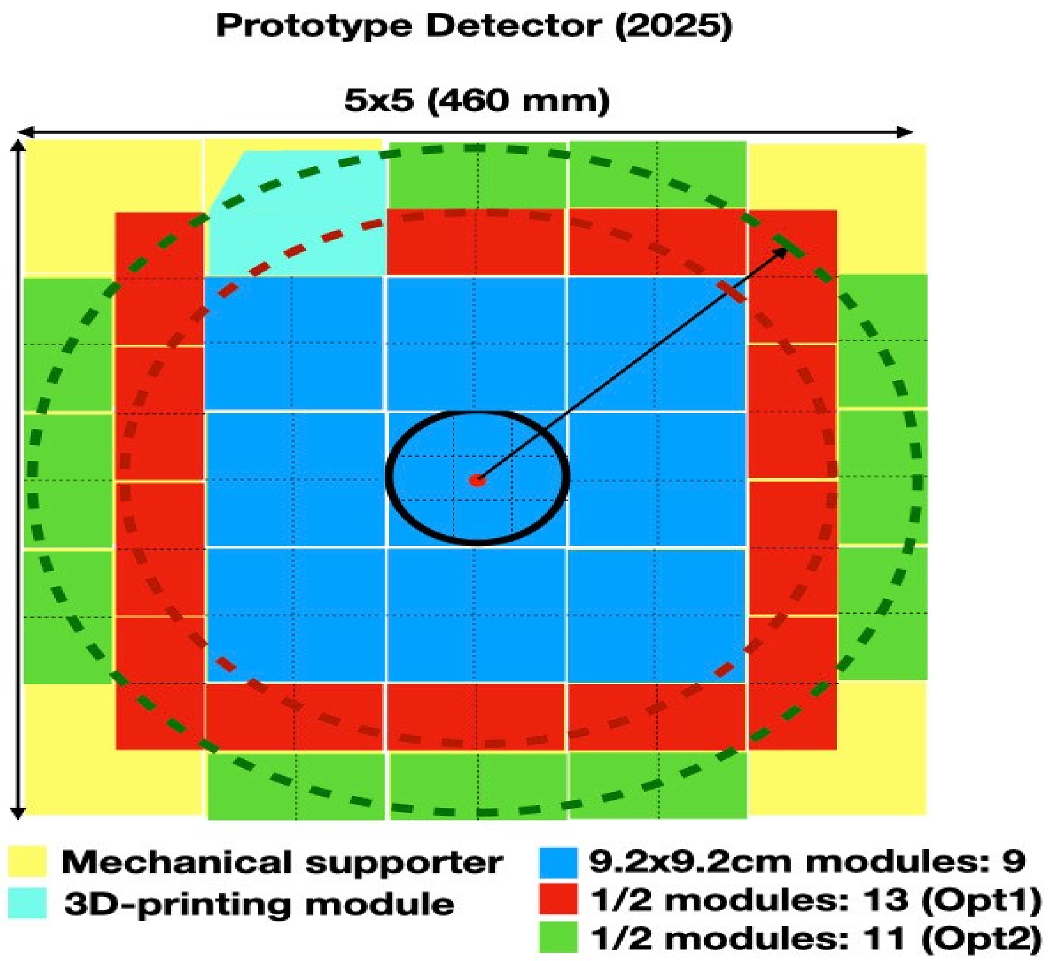
Requirements

	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

South Korea activities

Investigating:

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



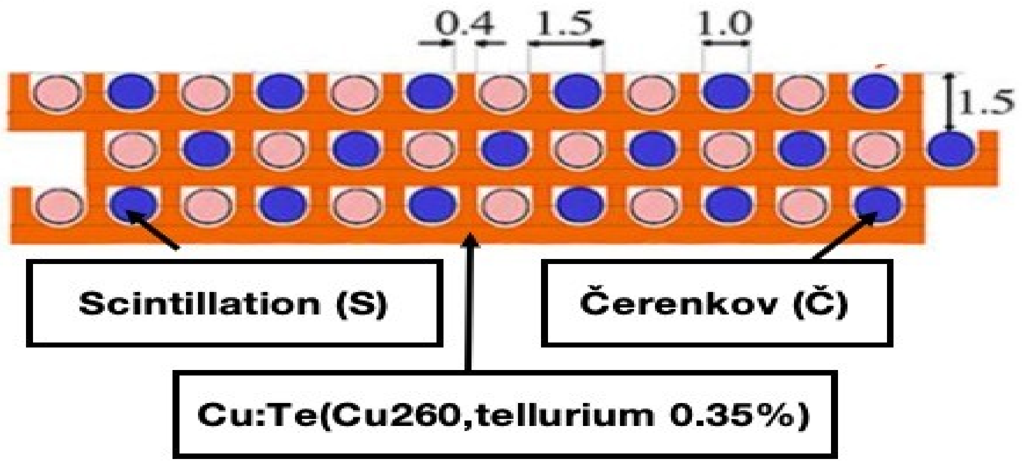
Absorber production:

- 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

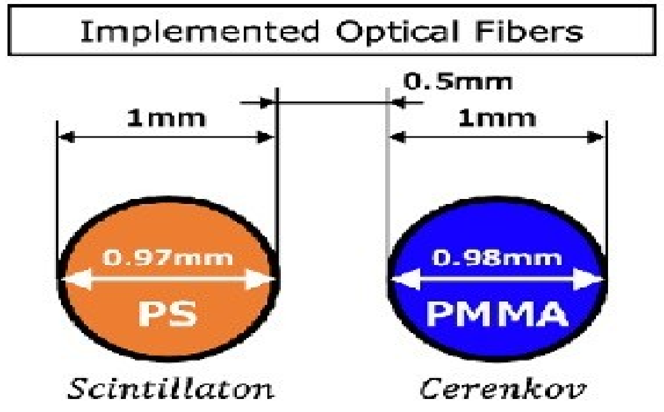
2 modules tested w/ beam in 2022

- **Copper Plate & Fibers**



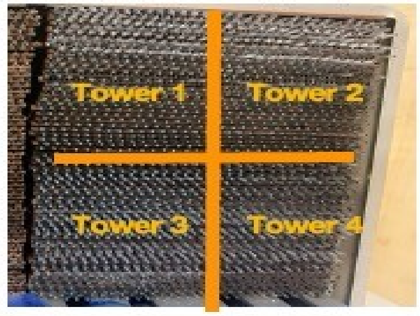
- **Copper plate (60)**
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

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

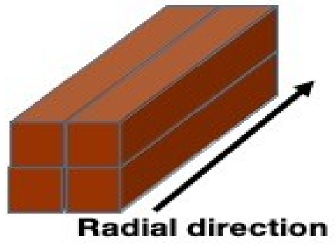


- **Configuration of Fibers & Readout detector for Test Beam**

Module #1 (2x2)



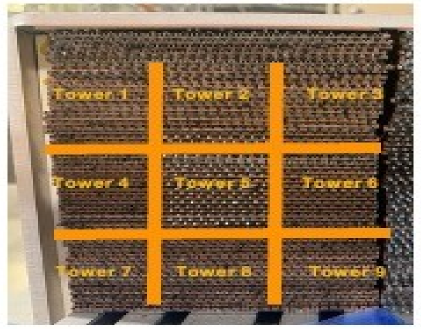
Module#1



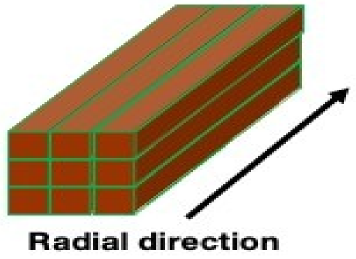
Module#1

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

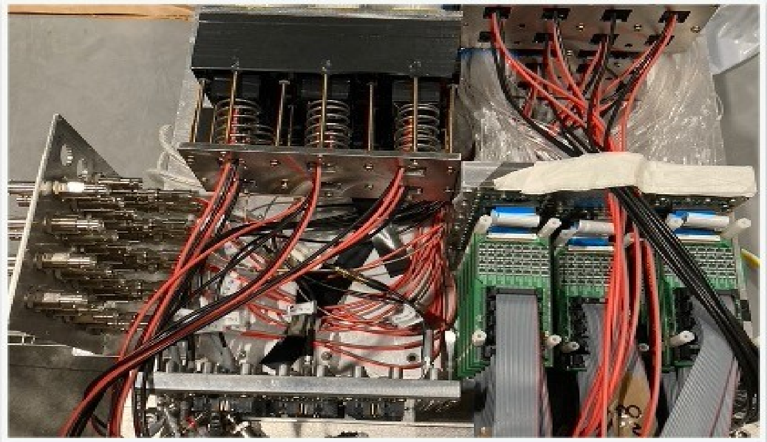
	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2 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 Efficinecy (Q.E.)**	**max. HV (V)**	**Rise time (ns)**	**Pulse width (ns)**	**photo**
PLANACON XP85012	53x53 mm²	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 mm²	35% at 420 nm	~7% at 550 nm	1000	2.2	11.9	0.75	
R11265-100 (new)	**23x23 mm²**	**~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 mm²)	~15% at 400 nm	~17% at 550 nm	$V_{\text{breaking Down}}$ + 5 V	~1.75x10⁵	~2x10¹⁰/sec as incident photons	16675	31 % (0.524 mm²)
fiber (Φ1 mm)	0.785 mm²						~7745 (effectively)	

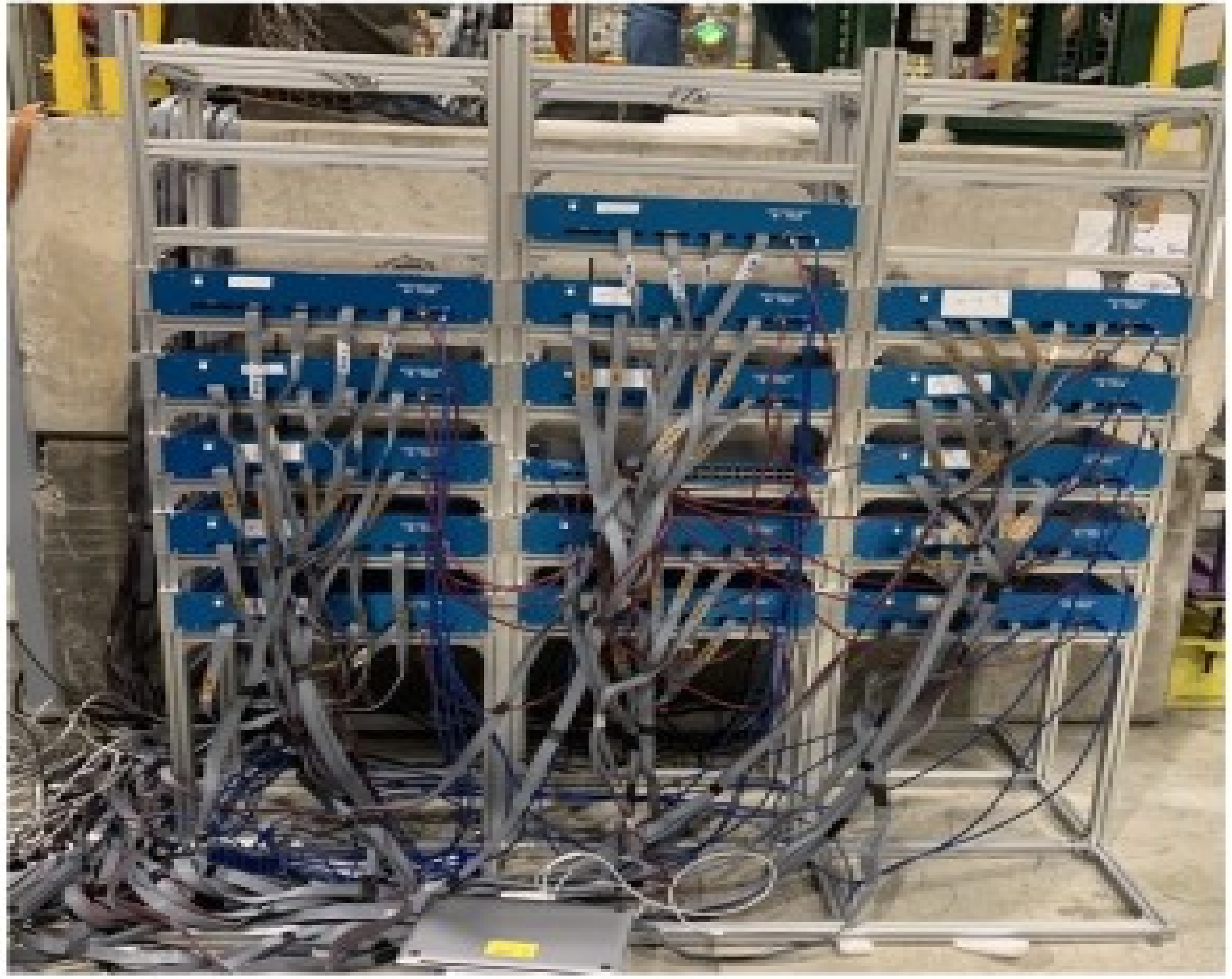
DAQ system

- 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

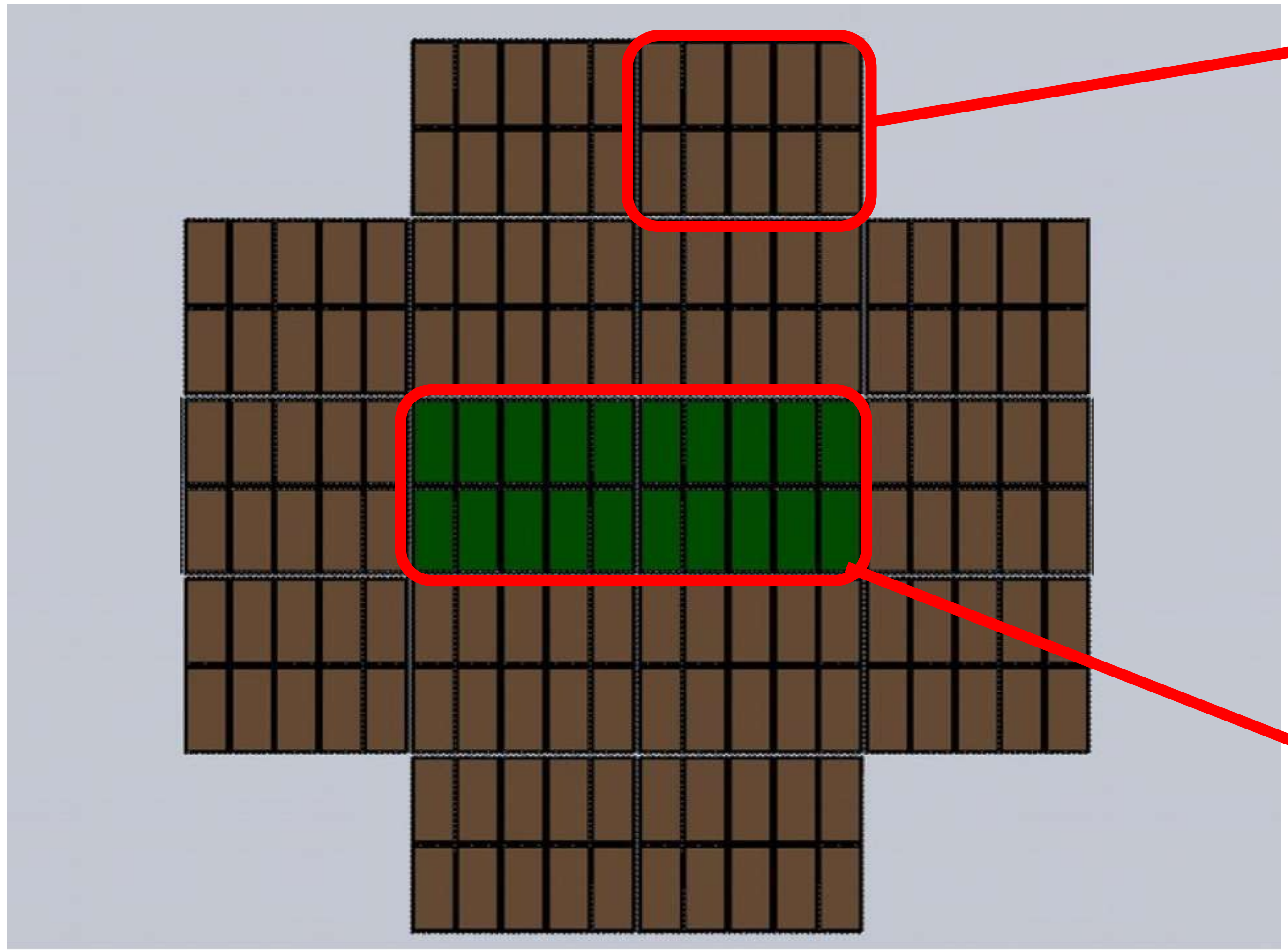
- All boards connected with PC using USB3 line



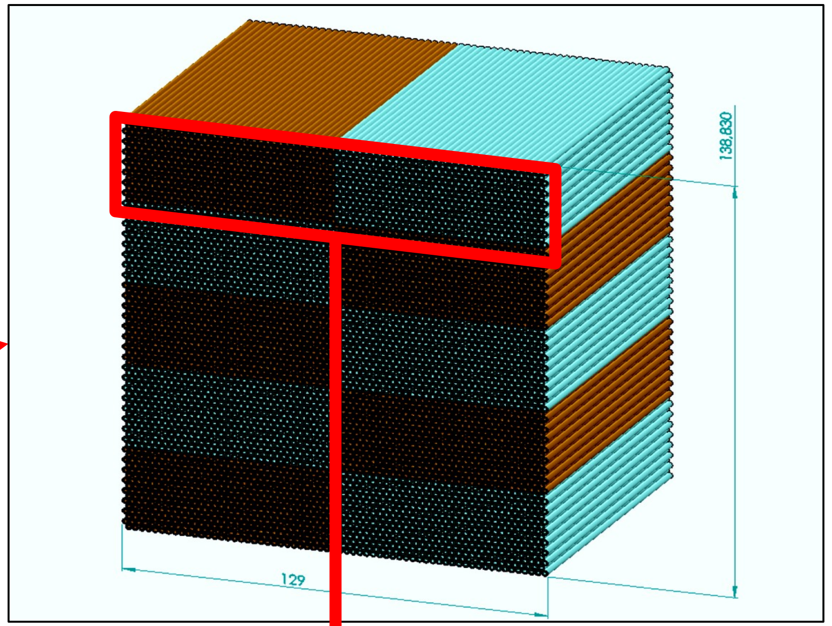
HiDRa – Highly granular Dual-Readout demonstrator (INFN)

Hadronic-size prototype:

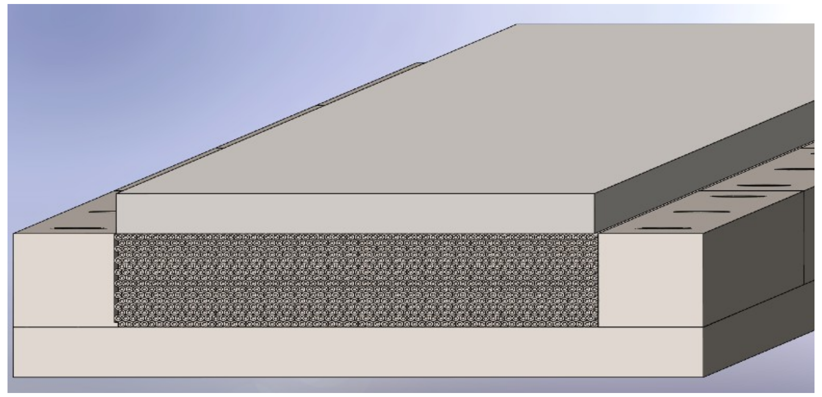
16 modules w/ highly granular core



HiDRa



1 Module:
5 MMs
~ 13 × 13 cm^2



1 MiniModule:

64 × 16 =
1024 fibres in total

512 S + 512 C

highly granular core:

1024 fibres to be readout with SiPMs

Capillary tube parameters

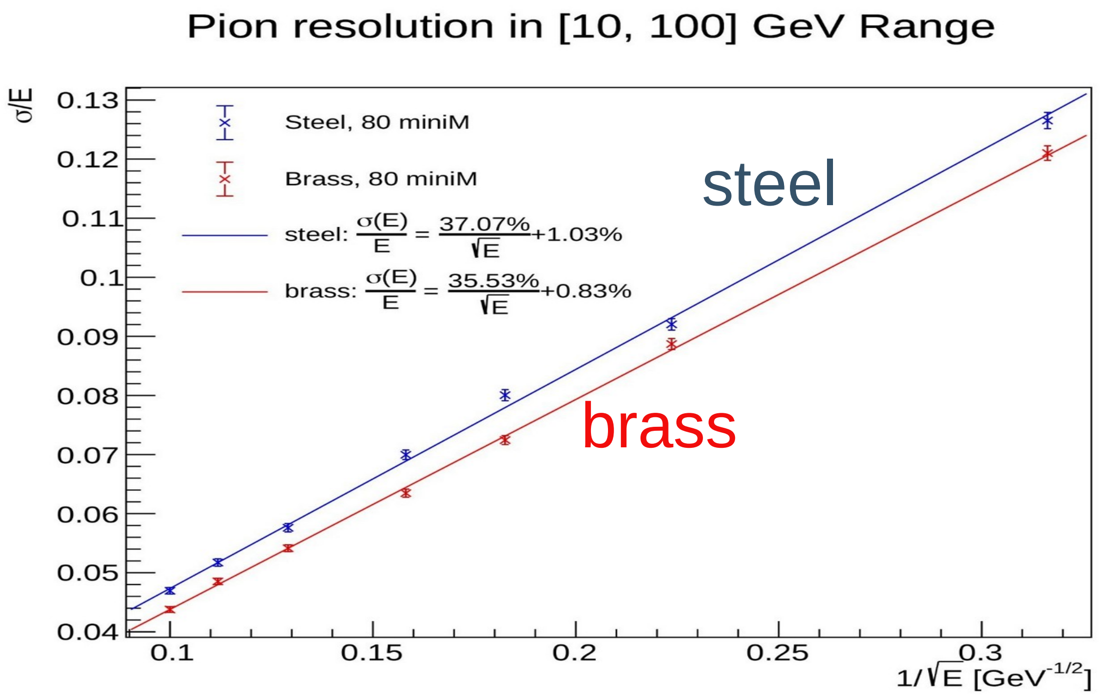
- Dimensions:
  - External diameter: 2 (± 0.050) mm ⟸ from SiPM dimensions
  - Internal diameter: 1.1 (-0 +0.1) mm ⟸ from fibre dimensions
  - Length: 2.5 m ⟸ from containment studies

→ 3% sampling fraction

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

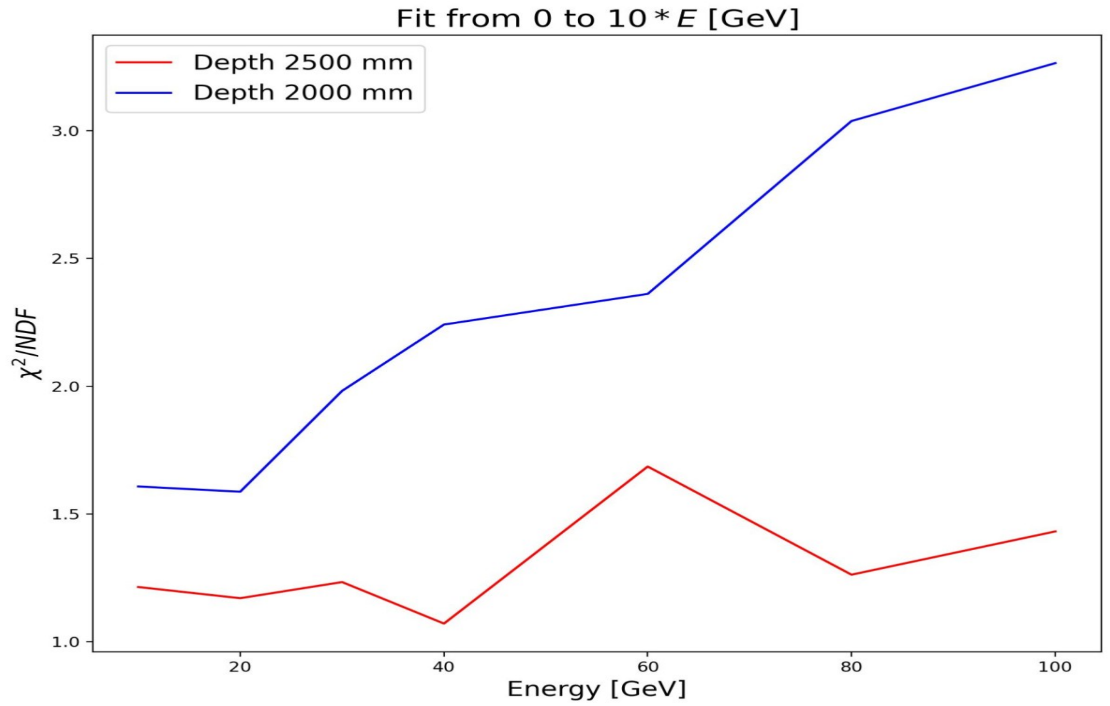
Geant4 simulations

Absorber choice

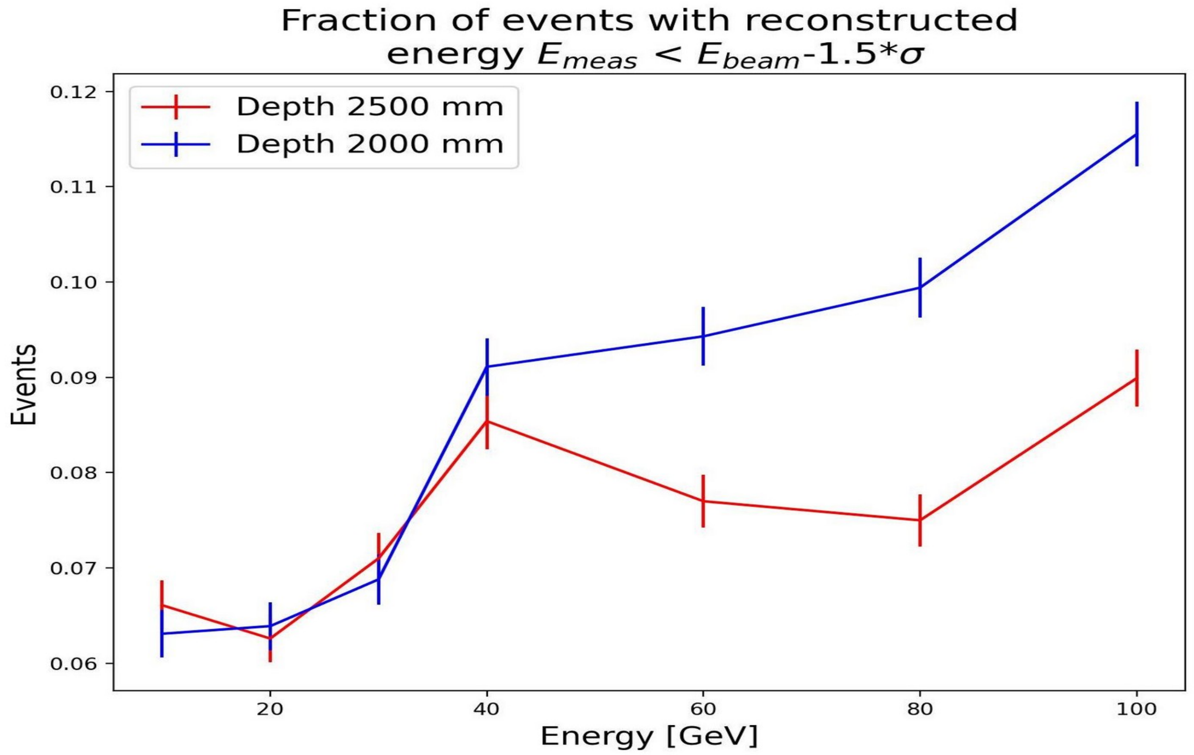


Calorimeter depth

χ2 / ndof



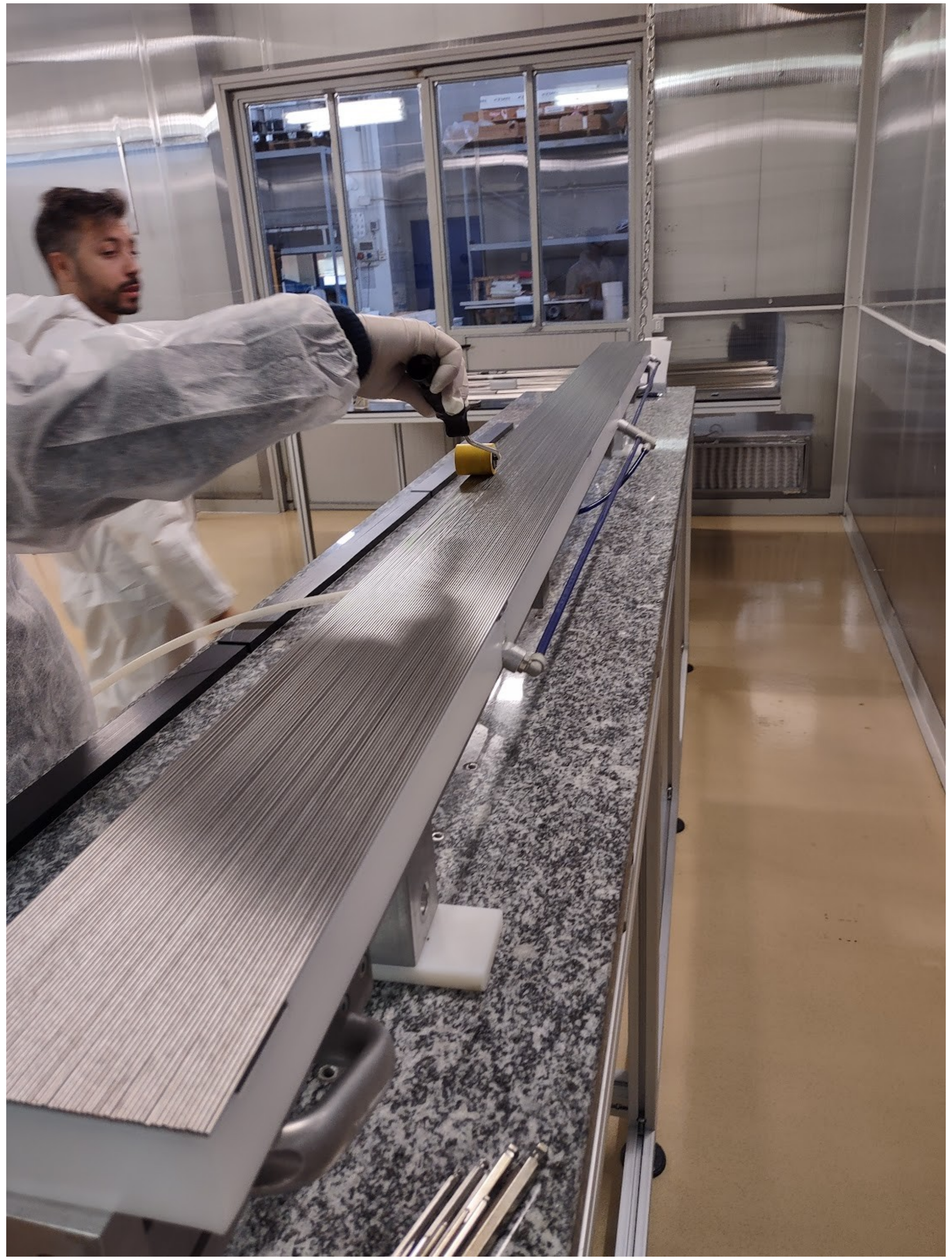
Low-energy tails

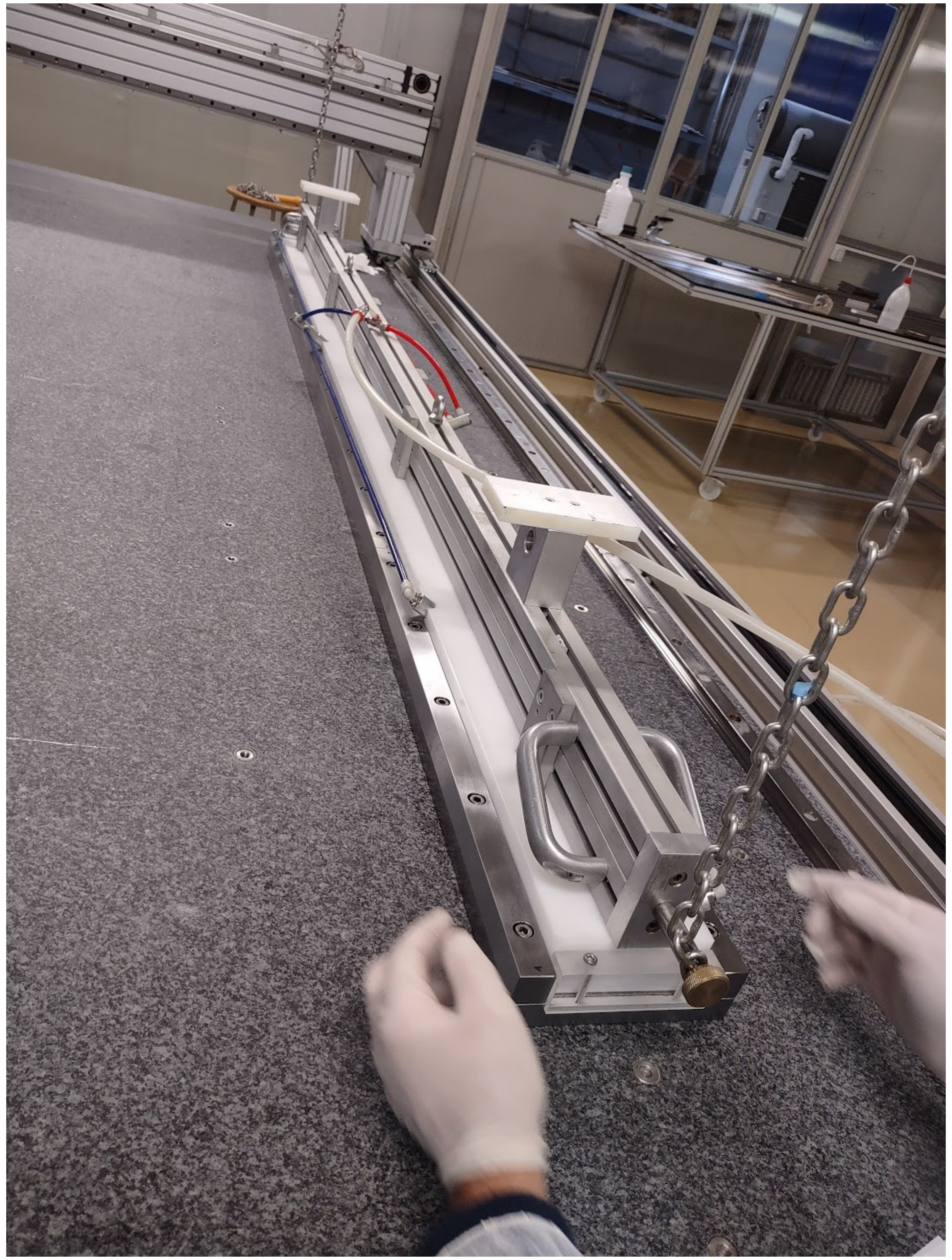


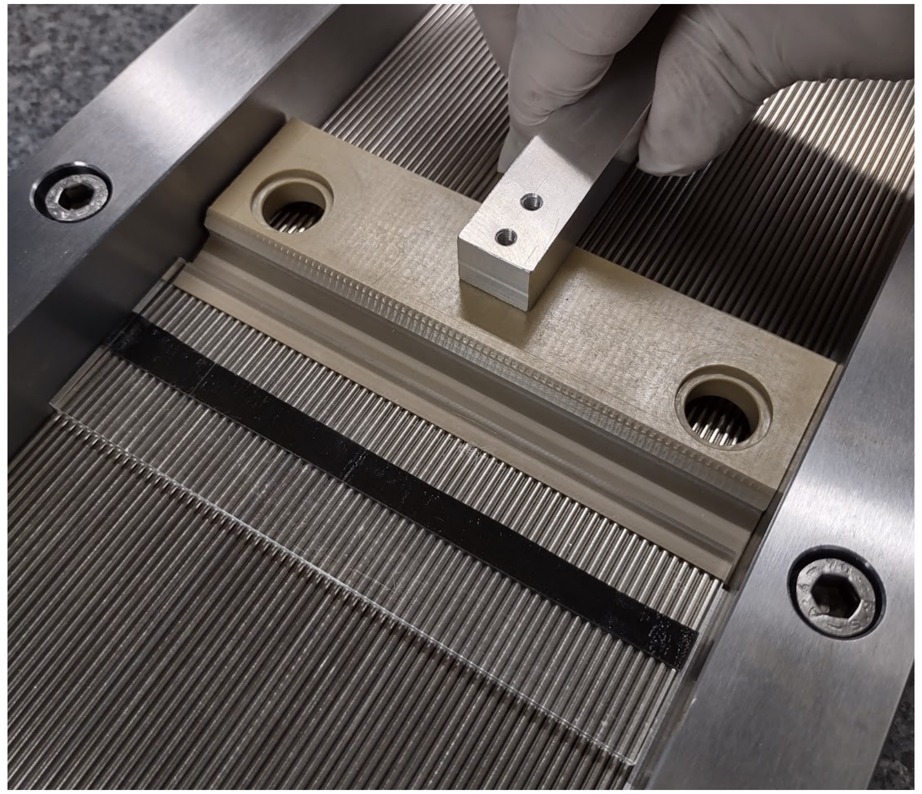
Capillary QA/QC

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

Tube gluing

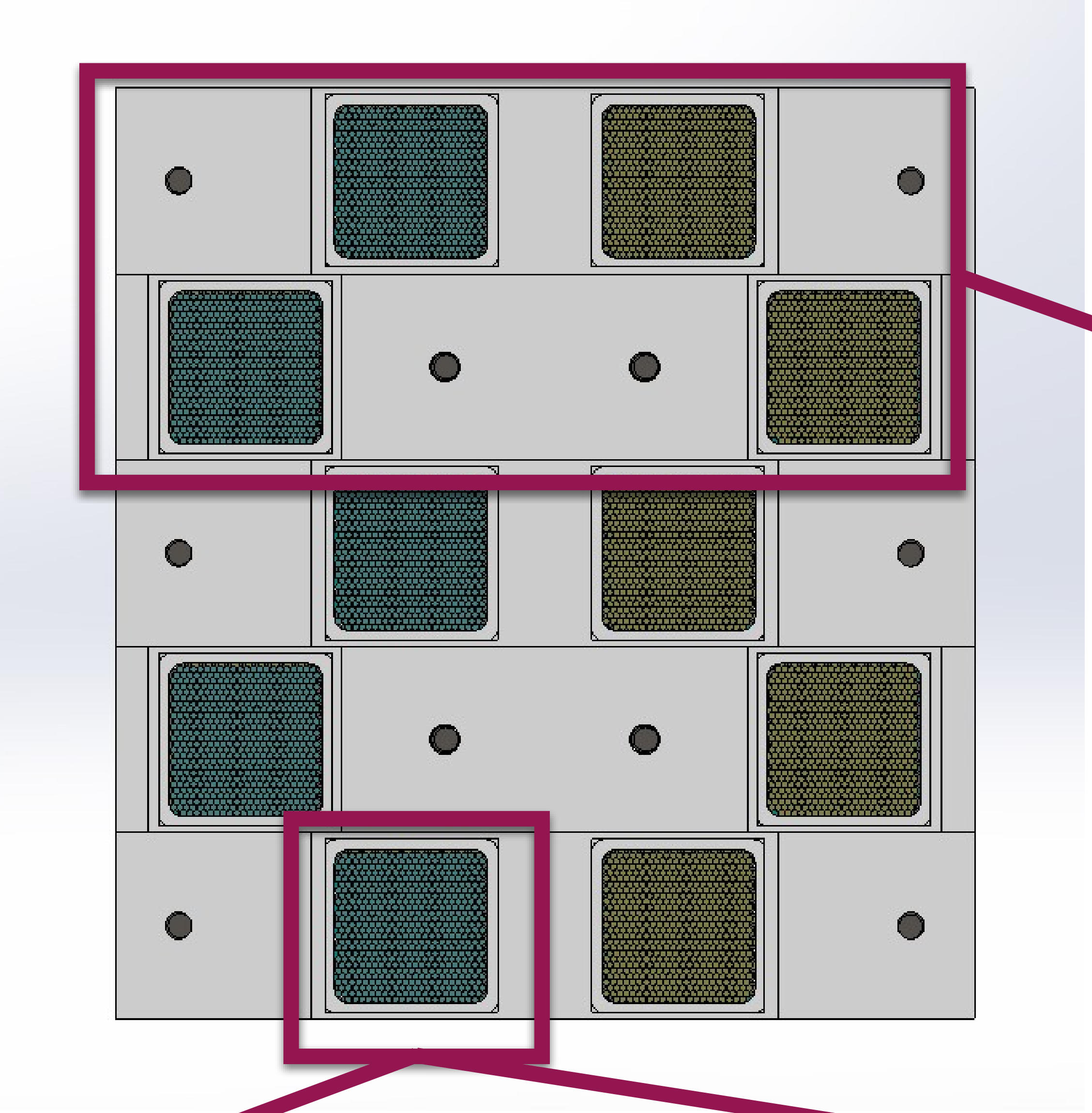




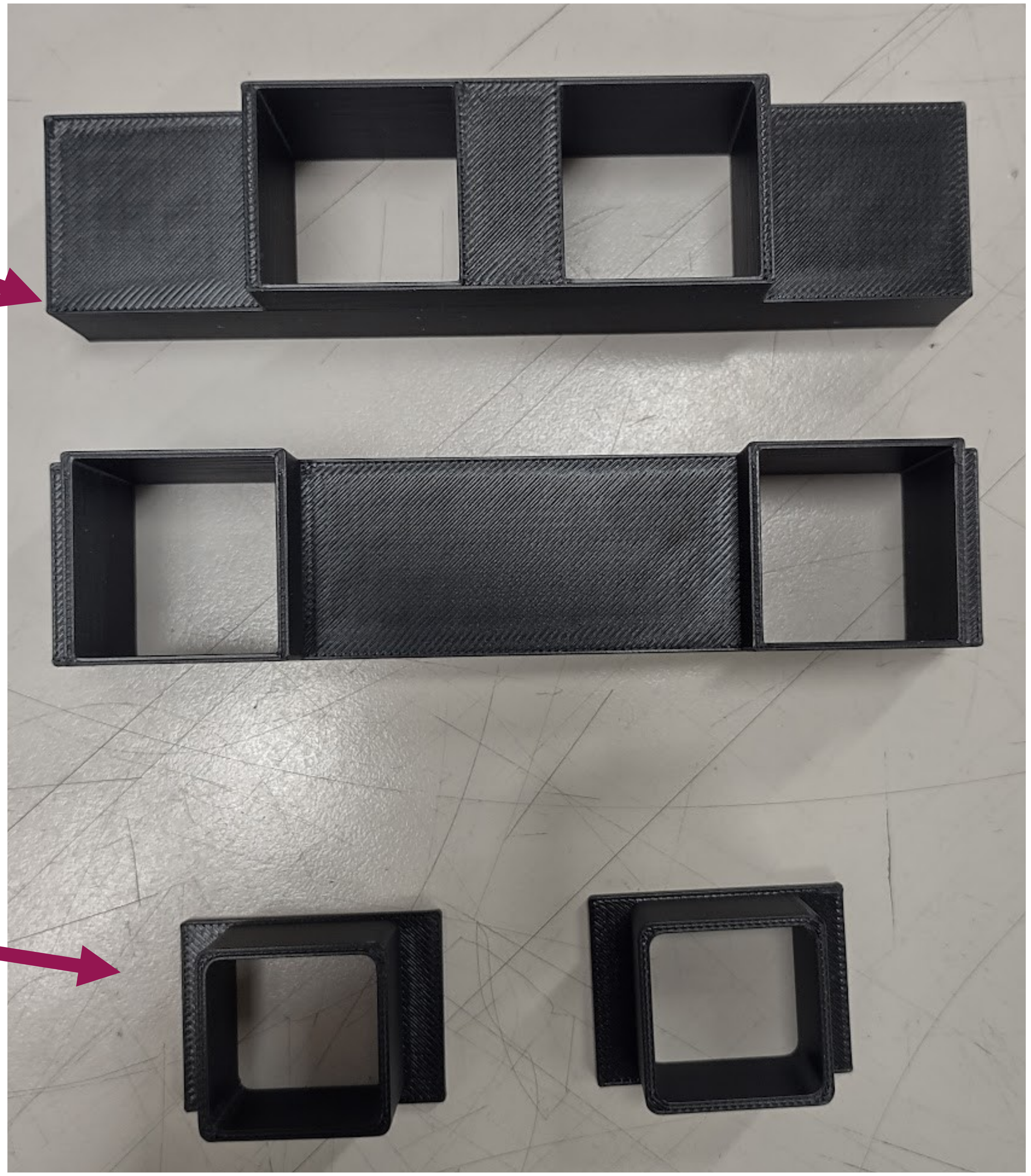


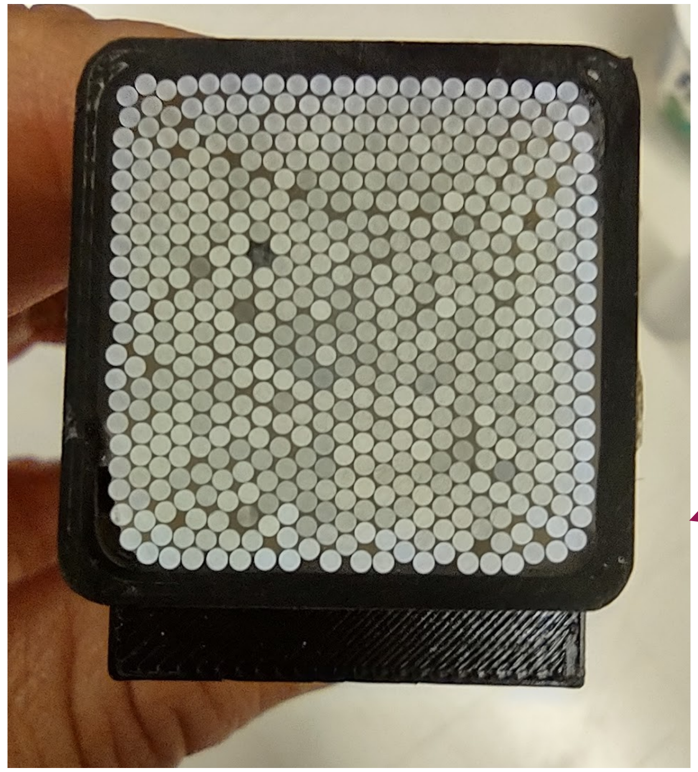
Stiffback-like technique for tube handling, gluing and positioning

PMT readout: fibre grouping

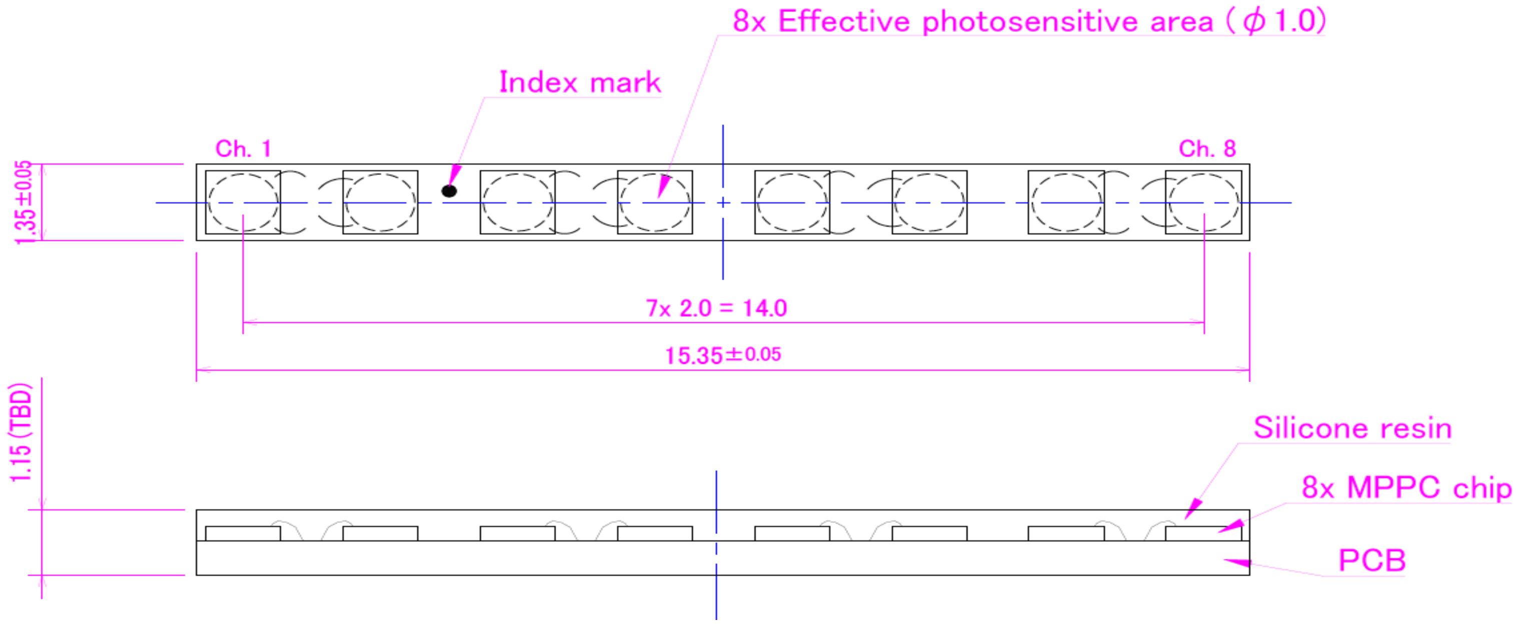


3D-printed fibre and PMT holders

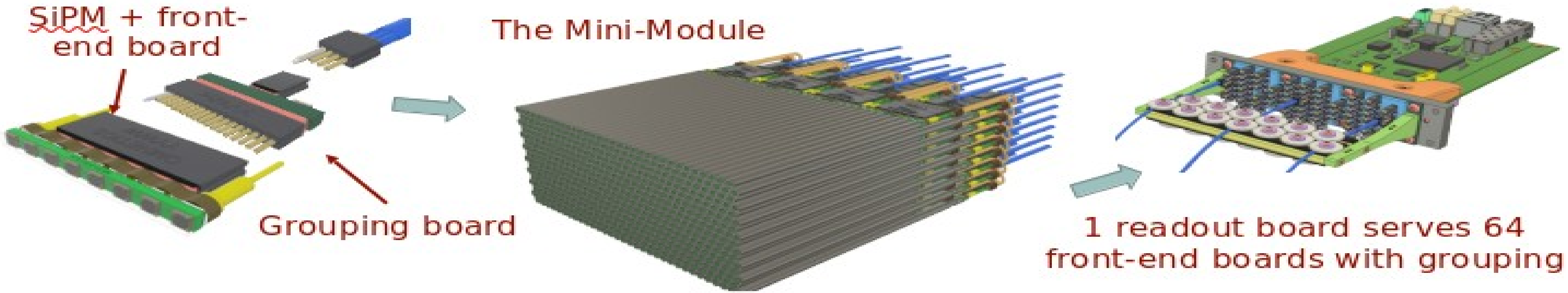




SiPM integration and readout



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

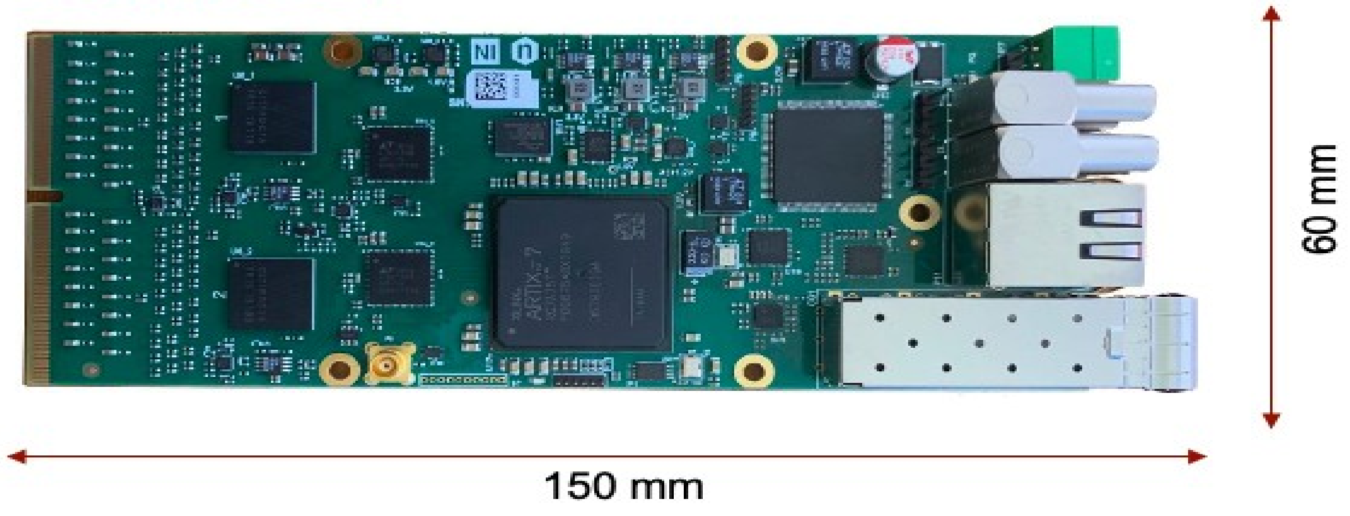


- Each SiPM bar operated at same voltage (V_{bd}<0.15V)
- Signals from 8 SiPMs summed up in grouping board

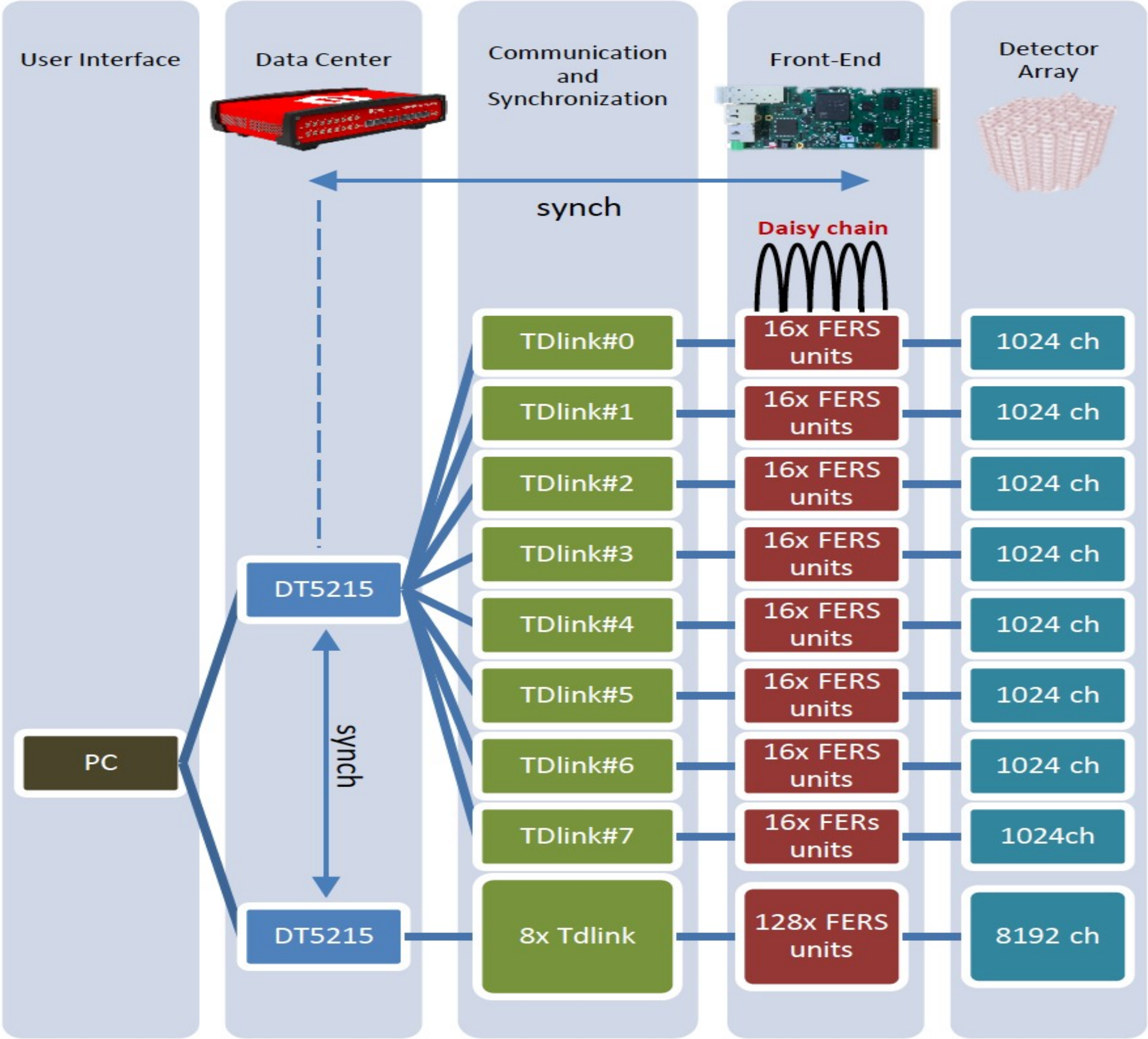
SiPM integration and readout

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

FERS: A5202



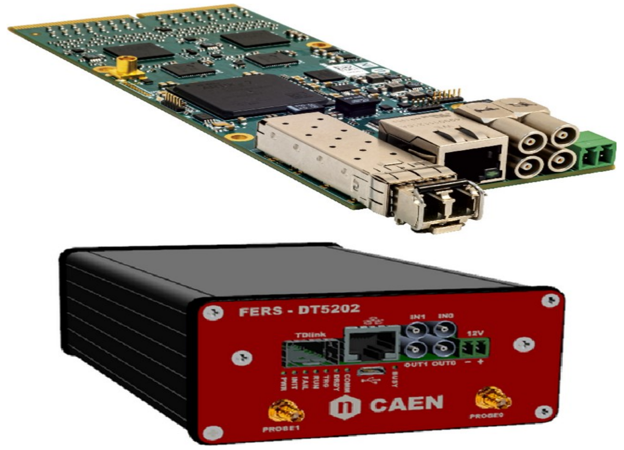
- 64 channels on two Citiroc1A
- Signal preamplification, shaping and integration
- HV power supply with temperature compensation
- Two 12-bit ADCs for charge measurement
- 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 high-resolution TDCs (LSB = 50 ps)
- Optical readout interface (6.25 Gbit/s)



User Interface	Data Center	Communication and Synchronization	Front-End	Detector Array
		TDlink#0	16x FERS units	1024 ch
		TDlink#1	16x FERS units	1024 ch
		TDlink#2	16x FERS units	1024 ch
	DT5215	TDlink#3	16x FERS units	1024 ch
		TDlink#4	16x FERS units	1024 ch
		TDlink#5	16x FERS units	1024 ch
PC		TDlink#6	16x FERS units	1024 ch
		TDlink#7	16x FERs units	1024ch
	DT5215	8x Tdlink	128x FERS units	8192 ch

Data concentrator delivered in September

FERS readout integration in EUDAQ



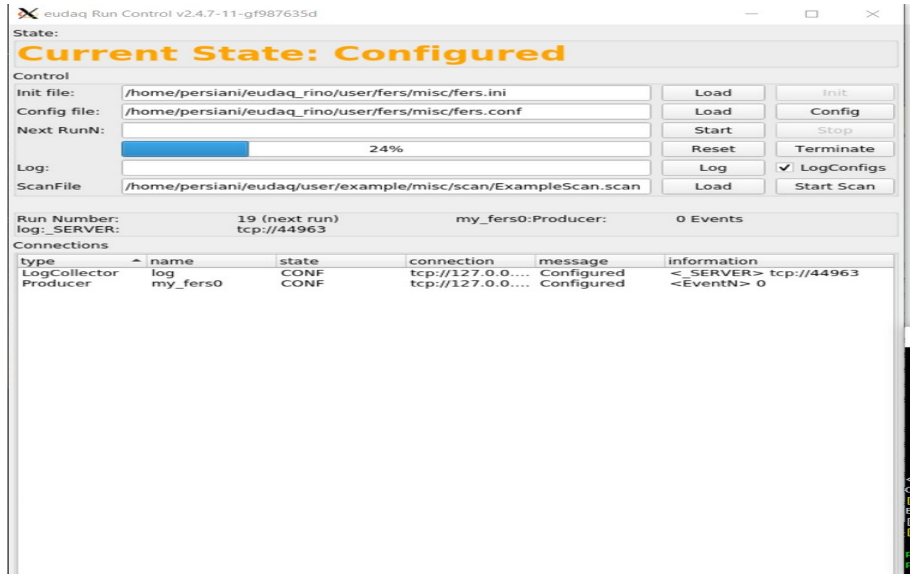
- Modular data acquisition framework, in C++
- Open source, compatible with different OSs
- Finite-State Machine implemented
- HW-specific parts decoupled from core software
- Raw data can be converted to LCIO format
- Many detector prototypes at DESY II Test Beam Facility integrated in EUDAQ
- EUDAQ 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



State:

Current State: Configured

Control

Init file: /home/persiani/eudaq_rino/user/fers/misc/fers.ini

Config file: /home/persiani/eudaq_rino/user/fers/misc/fers.conf

Next RunN:

24%

Log:

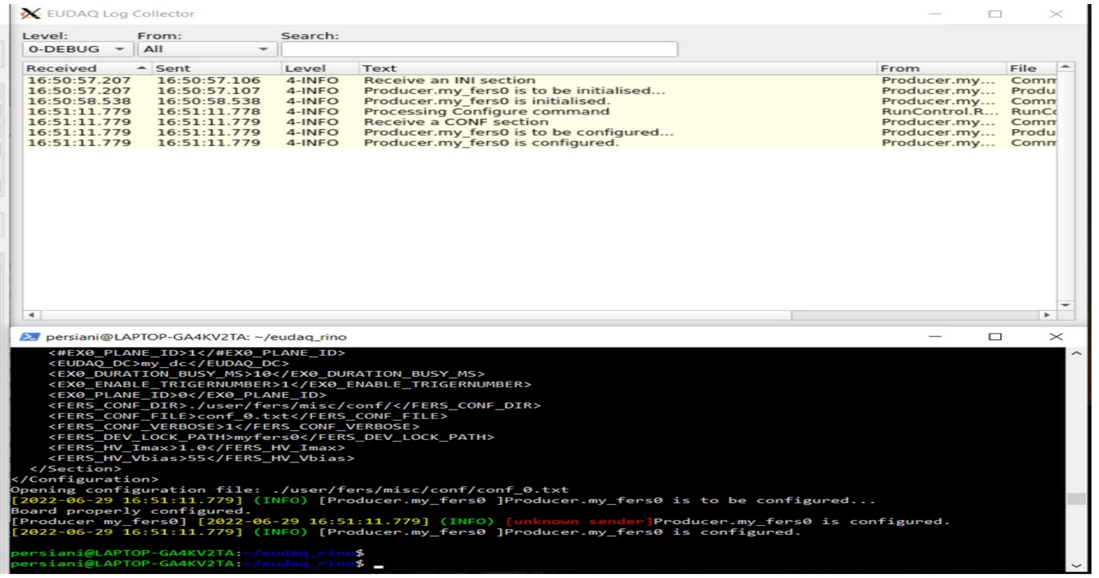
ScanFile /home/persiani/eudaq/user/example/misc/scan/ExampleScan.scan

Run Number: 19 (next run)
log:_SERVER: tcp://44963

my_fers0:Producer: 0 Events

Connections

type	name	state	connection	message	information
LogCollector	log	CONF	tcp://127.0.0....	Configured	<_SERVER> tcp://44963
Producer	my_fers0	CONF	tcp://127.0.0....	Configured	<EventN> 0

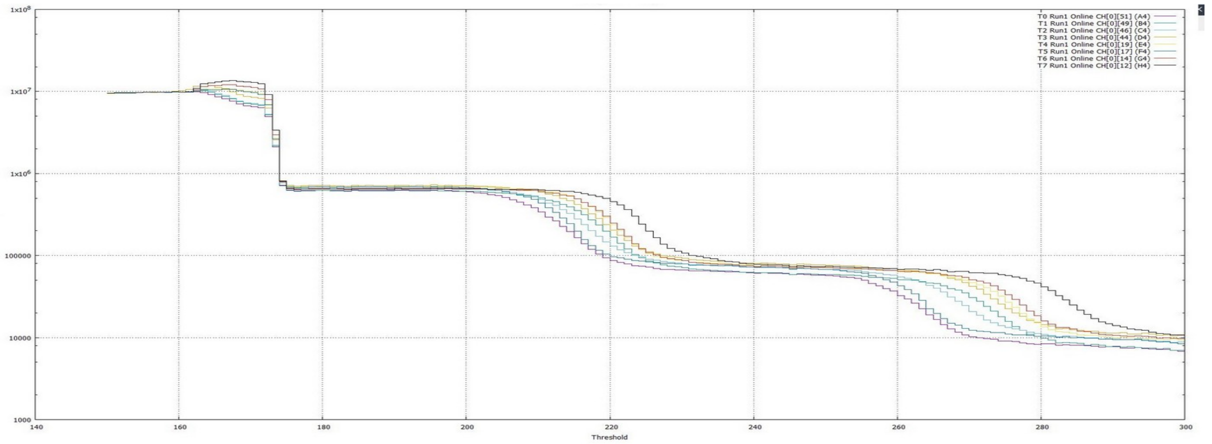


Level: 0-DEBUG
From: All
Search:

```
Received      Sent          Level   Text                                          From              File
16:50:57.207  16:50:57.106  4-INFO  Receive an INI section                        Producer.my...    Comm
16:50:57.207  16:50:57.107  4-INFO  Producer.my_fers0 is to be initialised...     Producer.my...    Produ
16:50:58.538  16:50:58.538  4-INFO  Producer.my_fers0 is initialised.             Producer.my...    Comm
16:51:11.779  16:51:11.778  4-INFO  Processing Configure command                  RunControl.R...   RunCo
16:51:11.779  16:51:11.779  4-INFO  Receive a CONF section                        Producer.my...    Comm
16:51:11.779  16:51:11.779  4-INFO  Producer.my_fers0 is to be configured...      Producer.my...    Produ
16:51:11.779  16:51:11.779  4-INFO  Producer.my_fers0 is configured.              Producer.my...    Comm
```

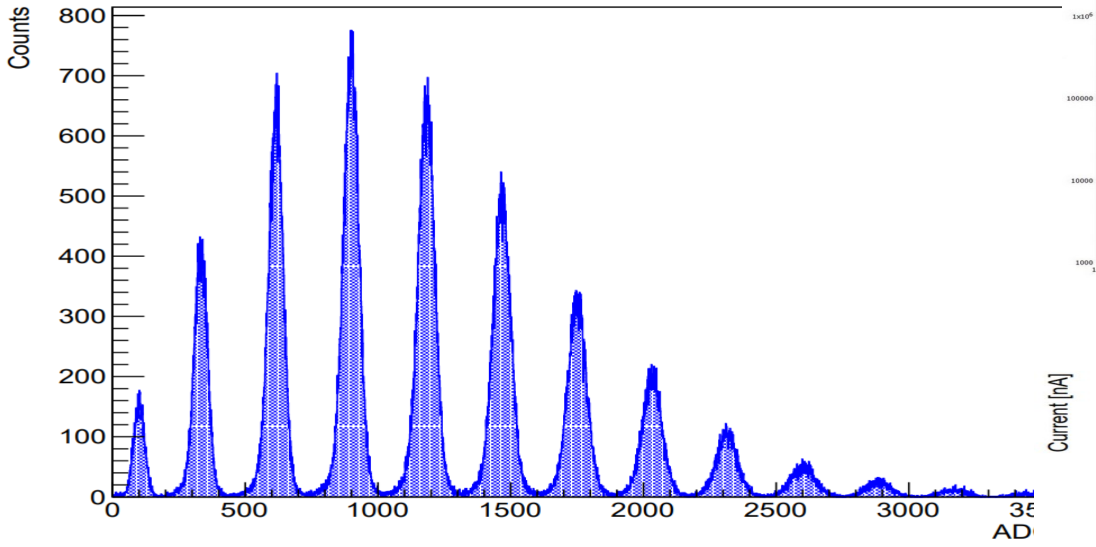
persiani@LAPTOP-GA4KV2TA: ~/eudaq_rino

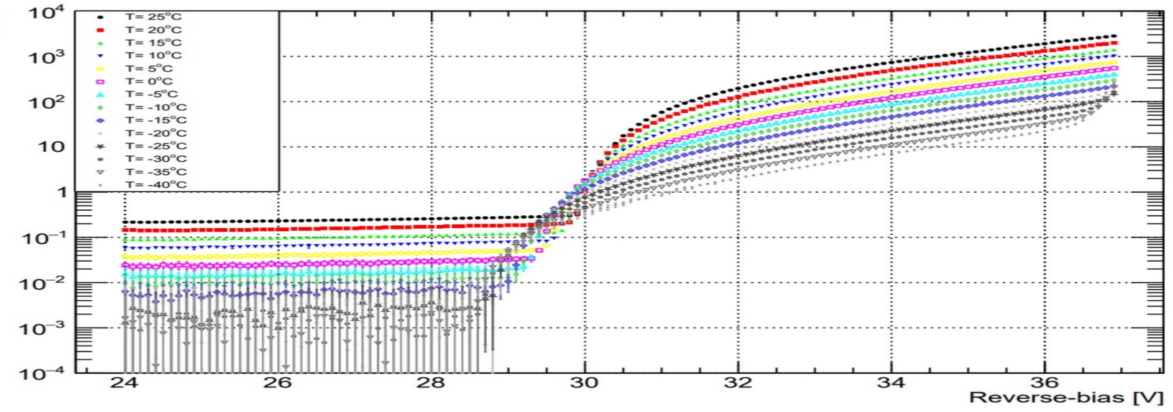
```
    <#EX0_PLANE_ID>1</#EX0_PLANE_ID>
    <EUDAQ_DC>my_dc</EUDAQ_DC>
    <EX0_DURATION_BUSY_MS>10</EX0_DURATION_BUSY_MS>
    <EX0_ENABLE_TRIGERNUMBER>1</EX0_ENABLE_TRIGERNUMBER>
    <EX0_PLANE_ID>0</EX0_PLANE_ID>
    <FERS_CONF_DIR>./user/fers/misc/conf/</FERS_CONF_DIR>
    <FERS_CONF_FILE>conf_0.txt</FERS_CONF_FILE>
    <FERS_CONF_VERBOSE>1</FERS_CONF_VERBOSE>
    <FERS_DEV_LOCK_PATH>myfers0</FERS_DEV_LOCK_PATH>
    <FERS_HV_Imax>1.0</FERS_HV_Imax>
    <FERS_HV_Vbias>55</FERS_HV_Vbias>
  </Section>
</Configuration>
Opening configuration file: ./user/fers/misc/conf/conf_0.txt
[2022-06-29 16:51:11.779] (INFO) [Producer.my_fers0 ]Producer.my_fers0 is to be configured...
Board properly configured.
[Producer my_fers0] [2022-06-29 16:51:11.779] (INFO) [unknown sender]Producer.my_fers0 is configured.
[2022-06-29 16:51:11.779] (INFO) [Producer.my_fers0 ]Producer.my_fers0 is configured.

persiani@LAPTOP-GA4KV2TA:~/eudaq_rino$
persiani@LAPTOP-GA4KV2TA:~/eudaq_rino$ _
```



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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