Dual Readout Method in Calorimetry

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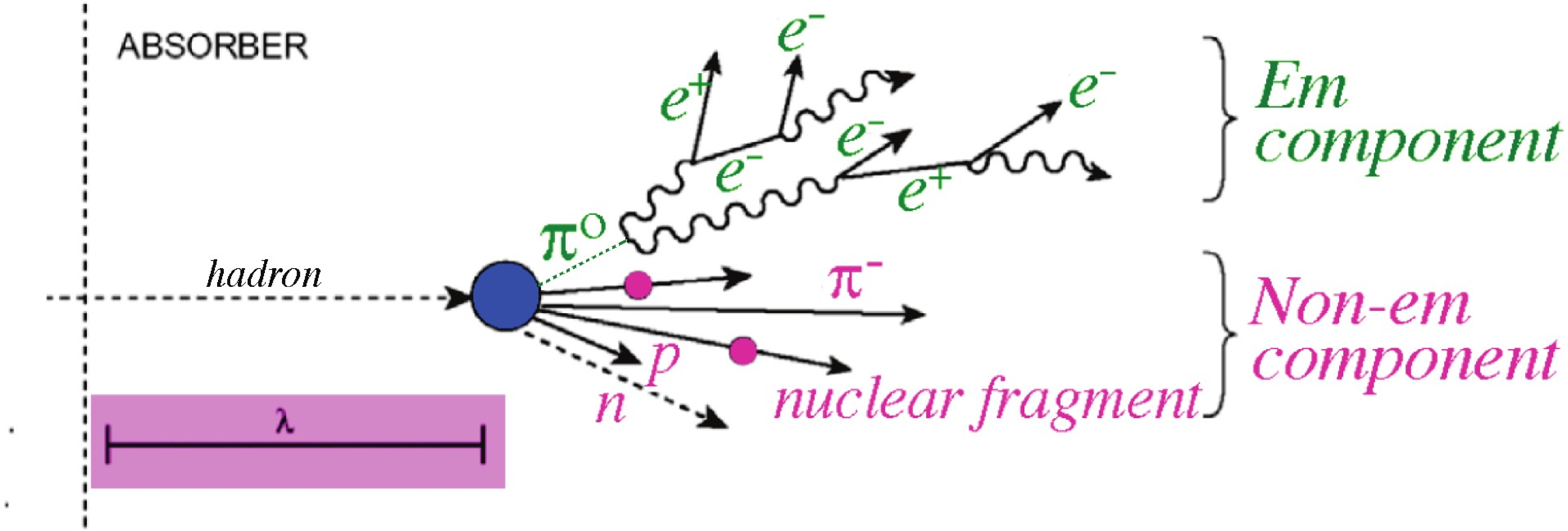
outline

1. Hadron calorimetry issues
2. Dual-readout calorimetry
3. Few DREAM/RD52 results
4. Dual readout goes granular (IDEA fibre calorimeter)
5. Exploit timing and DNNs
6. Crystal option (IDEA++) and pPFA
7. Next steps

1. Hadron calorimetry issues

hadron calorimetry

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



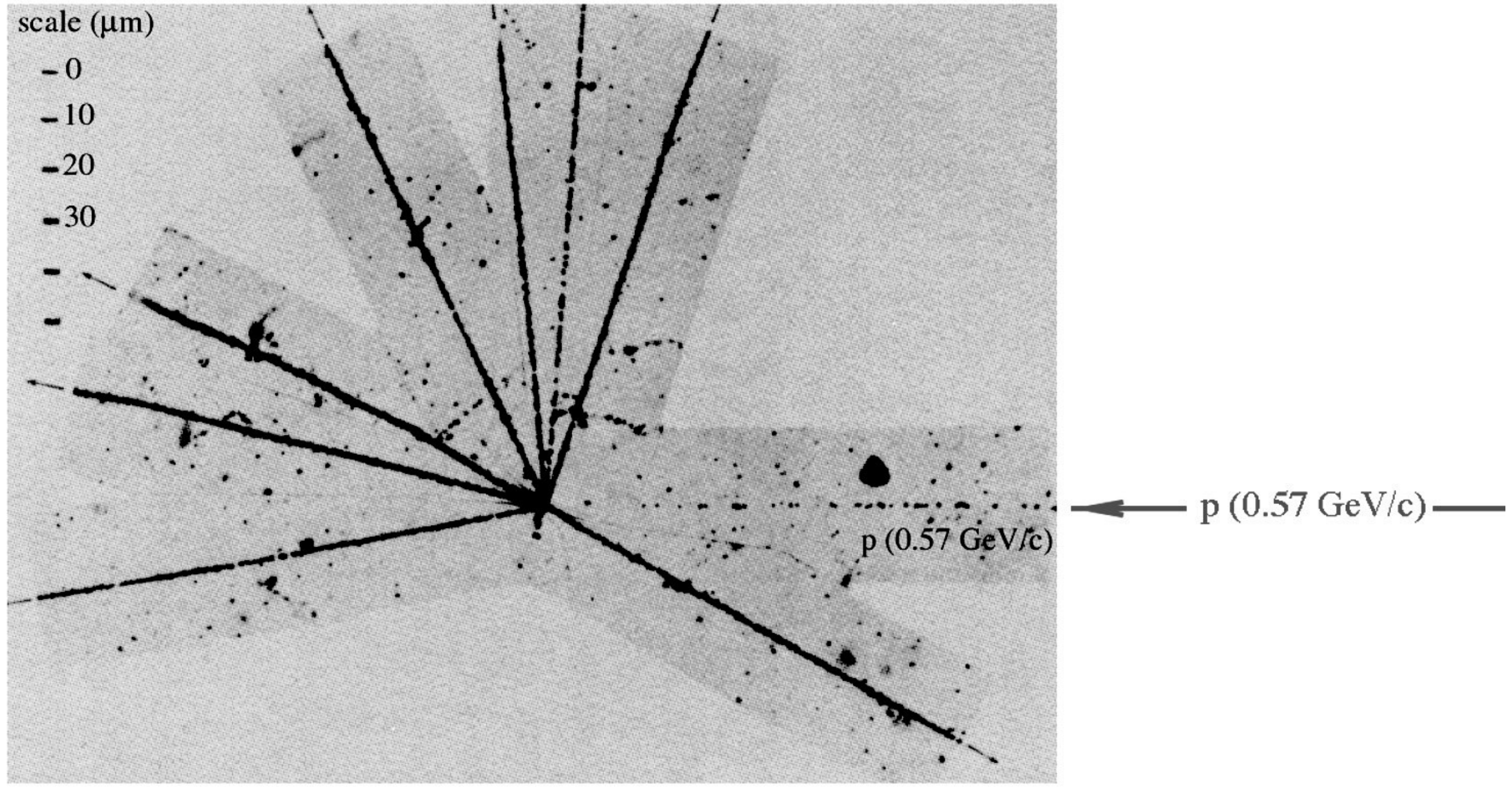
hadronic component: p, n, $\pi^{\pm}$, nuclear fission, … delayed photons, …

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

hadronic showers

- ***Electromagnetic (em) component***
  - electrons, photons

- ***Hadronic (non-em) component***
  - charged mesons $\pi^{\pm}$, $K^{\pm}$ [~ 20%]
  - nuclear fragments, p [~ 25%]
  - neutrons, soft γ's [~ 15%]
  - break-up of nuclei ("invisible") [~ 40%]



average values … issue: fluctuations!

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

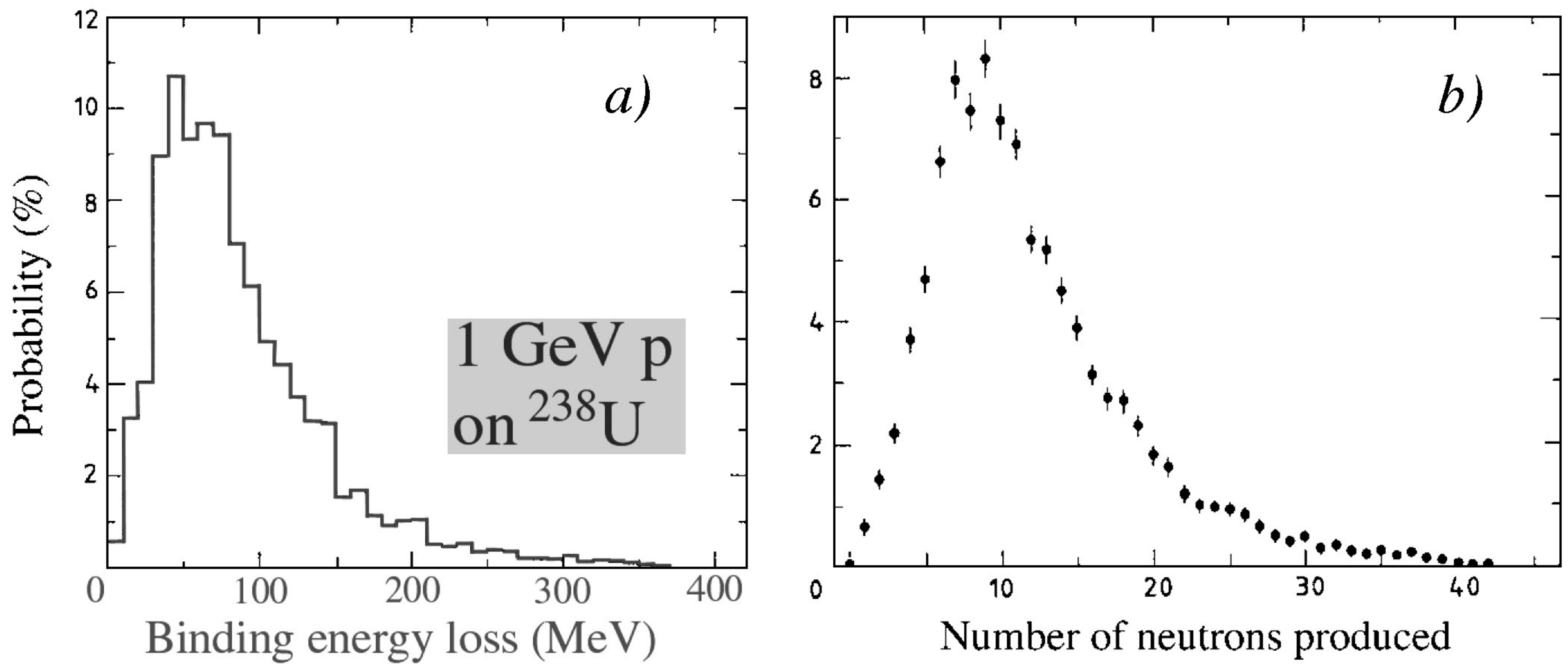
invisible energy

- ✦ 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)



Wigmans, NIM A259, 389

em fraction f_{em}

Shower energy fraction mainly carried by π^0 (but also η) mesons
For shower initiated by charged pions:

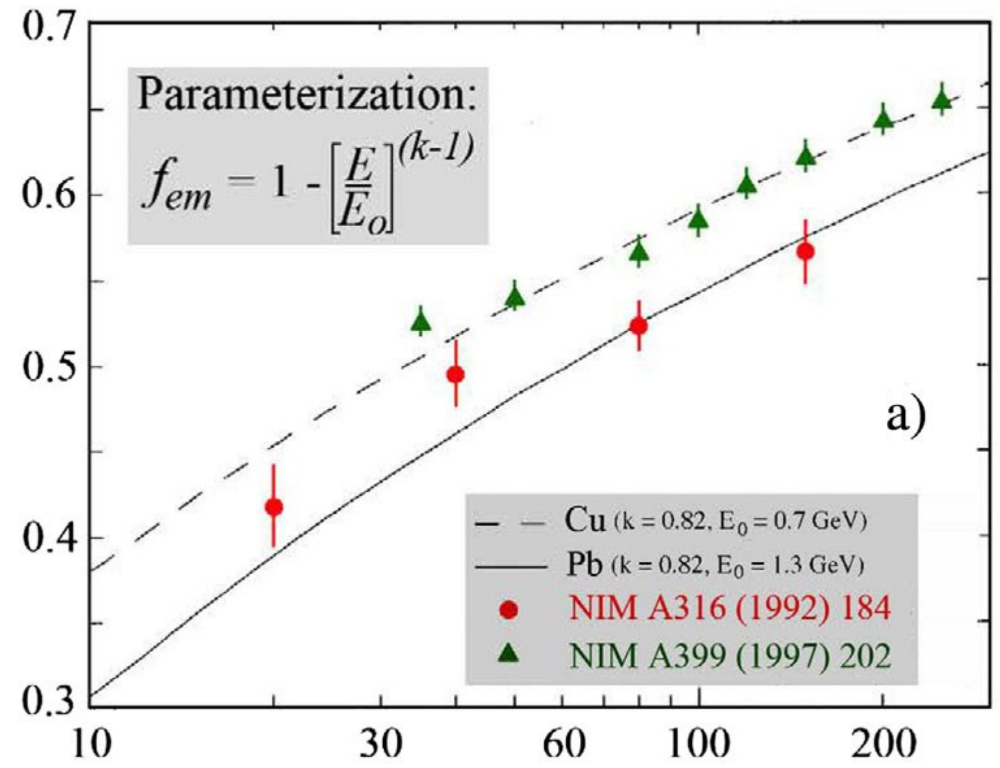
$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

E_0: average energy for single π^0 production, $k \approx 0.8 < \sim 1$

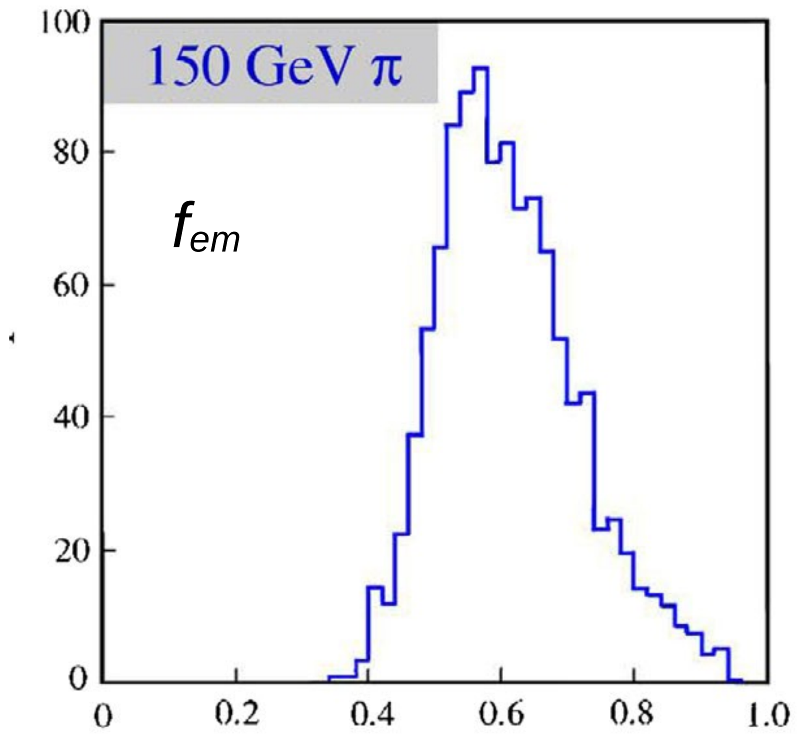
$\langle f_{em} \rangle$ large and energy dependent

fluctuations in f_{em} large and non-poissonian

< f_{em}> vs. pion energy



GeV



DOI: 10.1103/RevModPhys.90.025002

detector response

Response:

detected signal per unit energy deposit

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

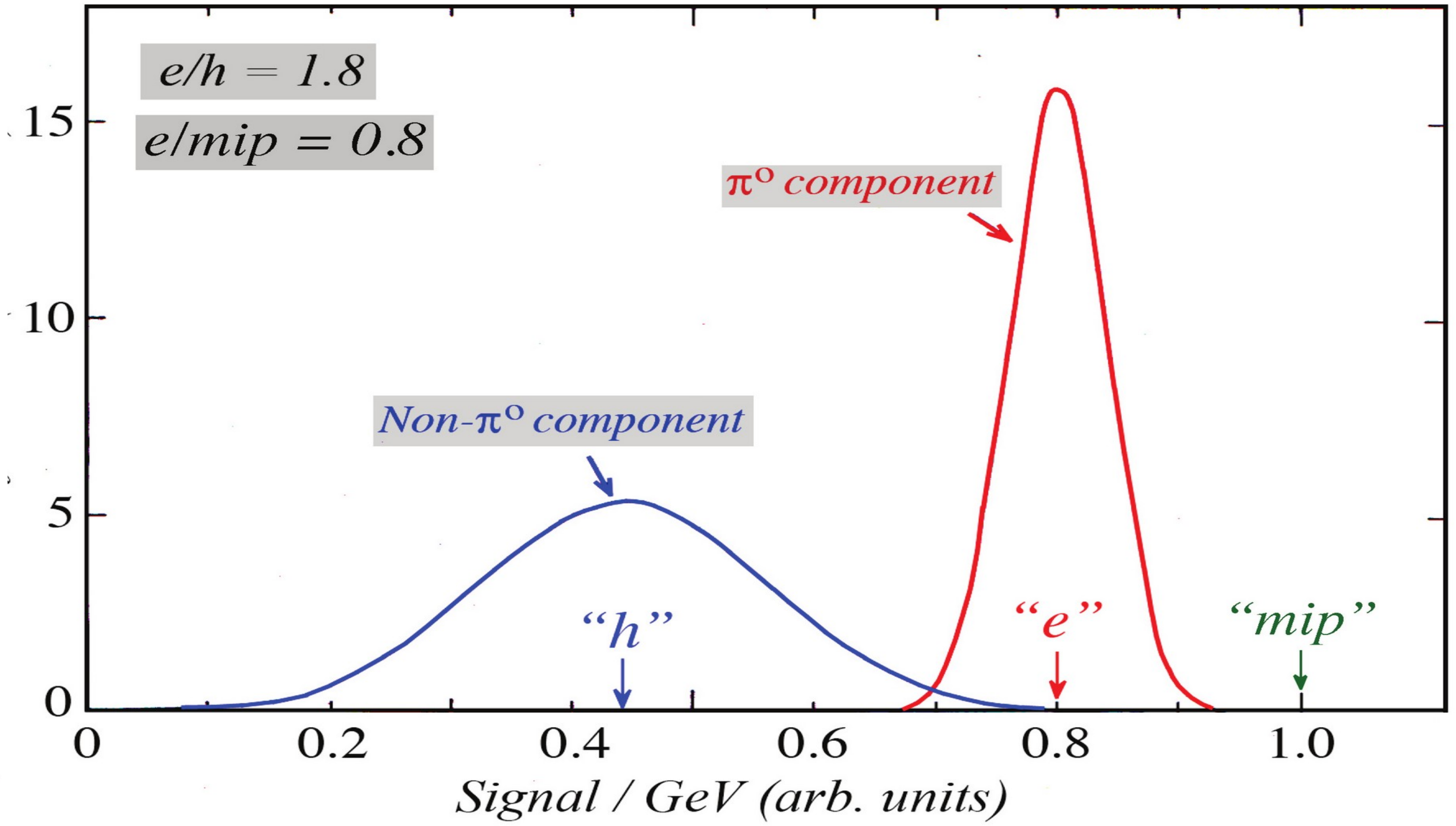
Hadronic showers:

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

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

response to hadronic showers

Response to protons ?

Average signal for protons: $S_p = e \cdot \langle f_{em}(p) \rangle \cdot E + h \cdot (1 - \langle f_{em}(p) \rangle) \cdot E$

$\rightarrow$ Response: $R_p = S_p / E \equiv p, \quad \langle f_{em}(p) \rangle \equiv f_p = f_p(E)$

$\rightarrow$ $p = e \cdot f_p + h \cdot (1 - f_p) = h \cdot (1 + f_p \cdot (e/h - 1))$

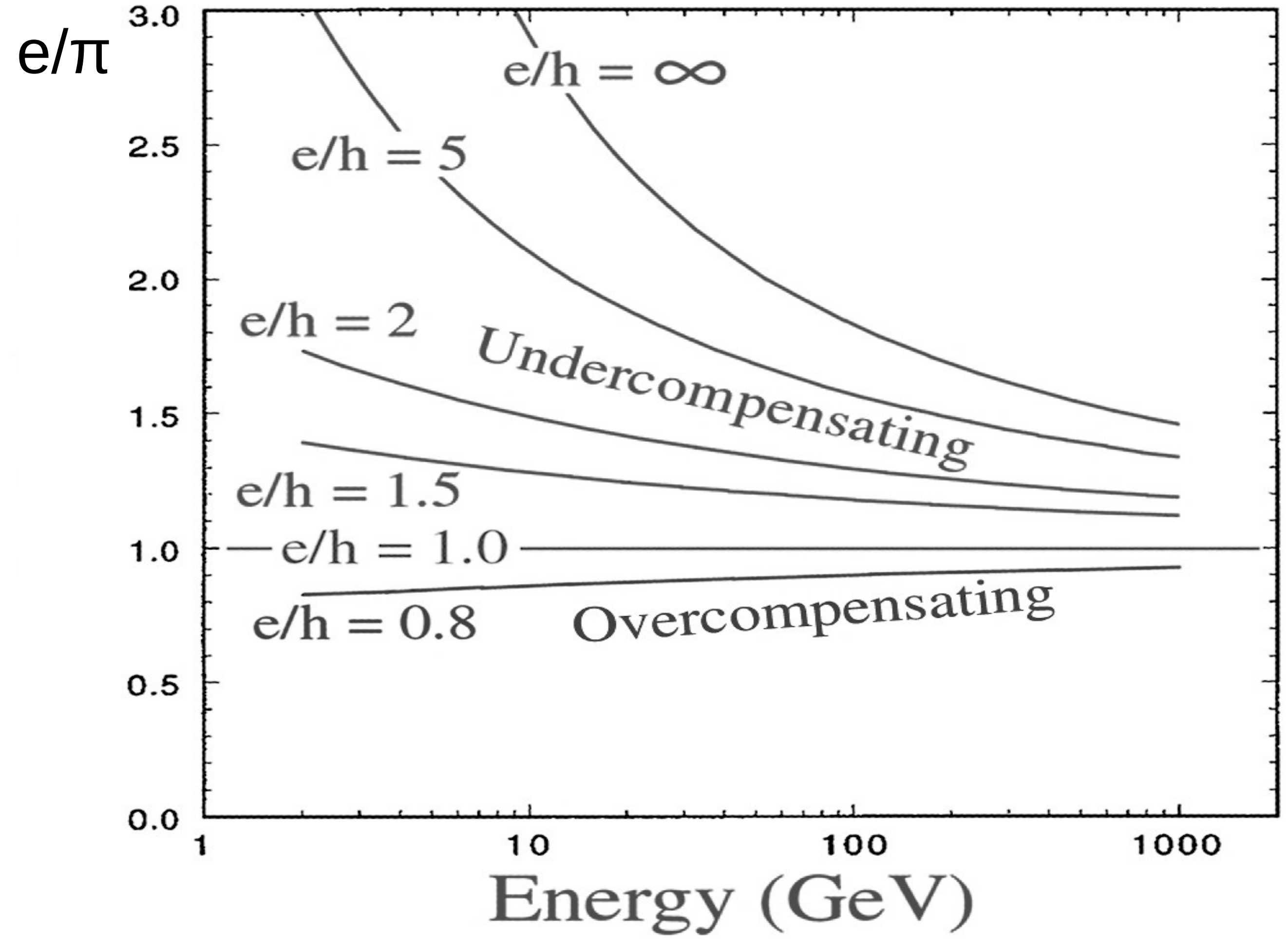
$e/p = e/h \, / \, (1 + f_p \cdot (e/h - 1))$ $\rightarrow$ do we have a problem ?

e/π ratio

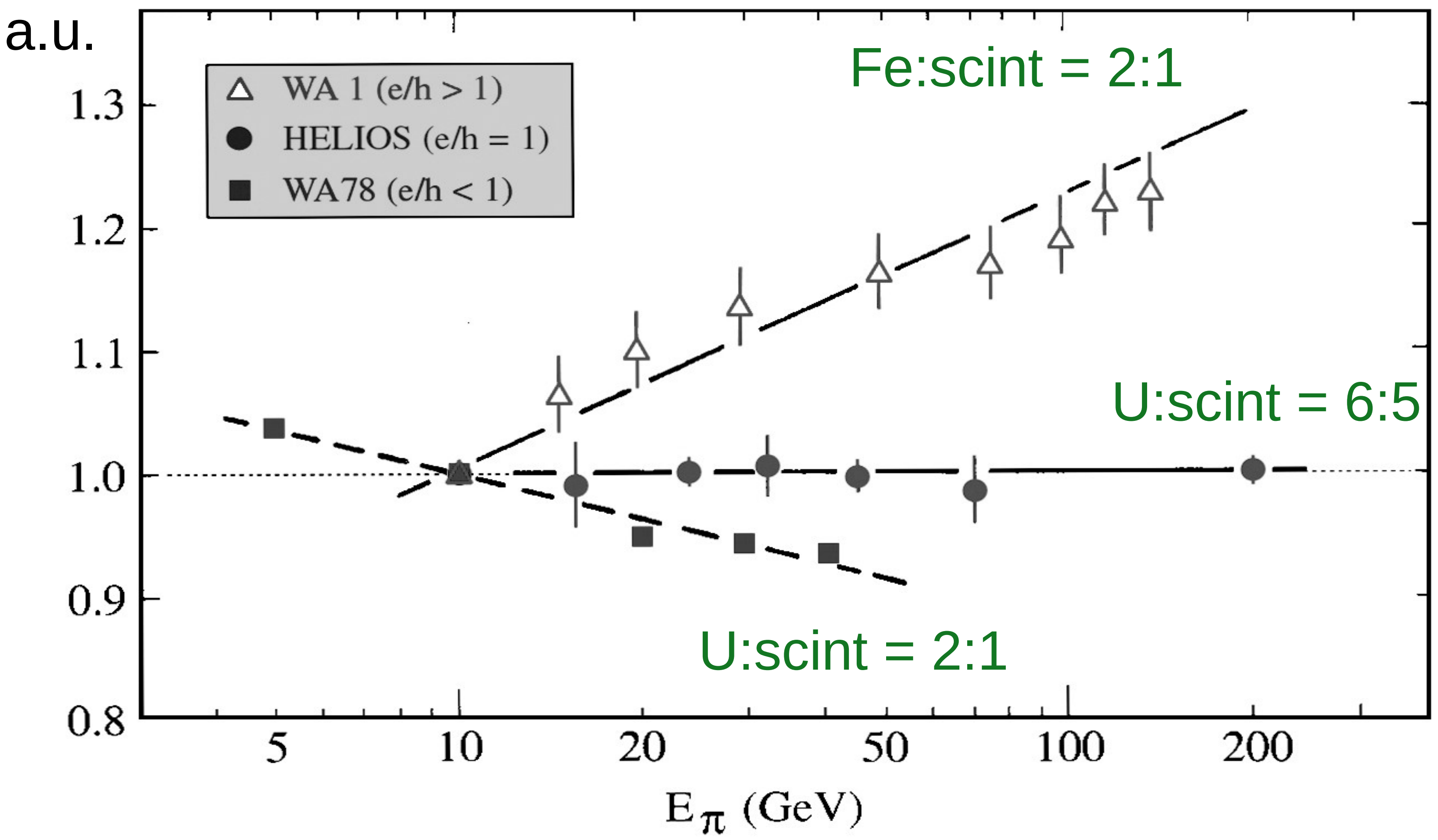
As well, calorimeter response to charged pions: π

$e/\pi = e/h \,/\, (\, 1 + f_\pi \cdot (\, e/h - 1\,)\,)$ $\qquad f_\pi \equiv \langle f_{em}(\pi) \rangle \neq f_p$

e/π as function of E



Response to π as function of E



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 → spoil em performance

→ tune active / passive material ratio

e/mip ratio

mip : minimum ionising particle → only ionisation

dE/dx (mip) :

lead ~ 12.6 MeV/cm → 7 MeV/X_0
copper ~ 12.7 MeV/cm → 18 MeV/X_0
(PMMA ~ 2.3 MeV/cm → 78 MeV/X_0)

Moreover in high-Z absorbers :

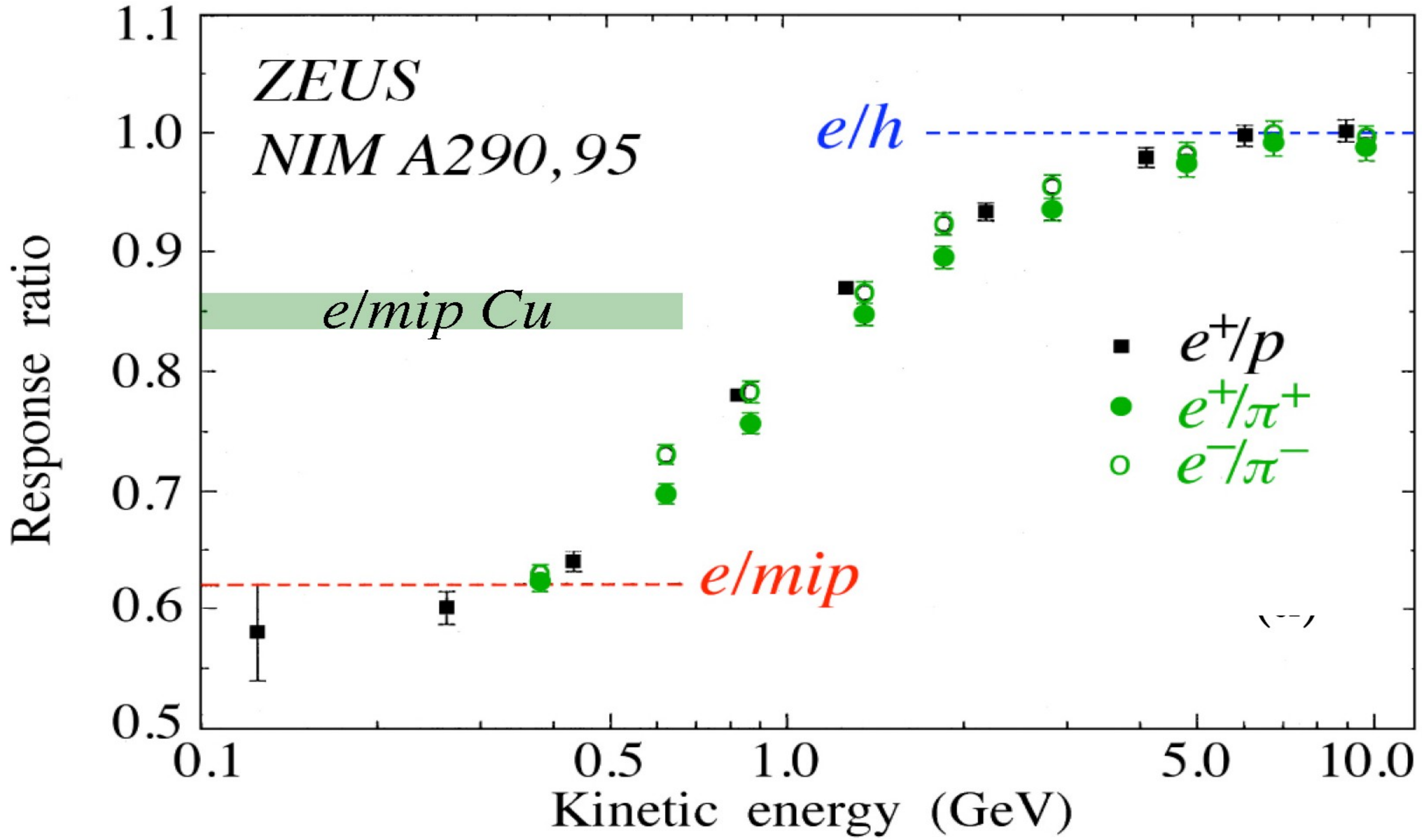
Z^5 dependence of photoelectric effect → most soft-γ interact in absorber

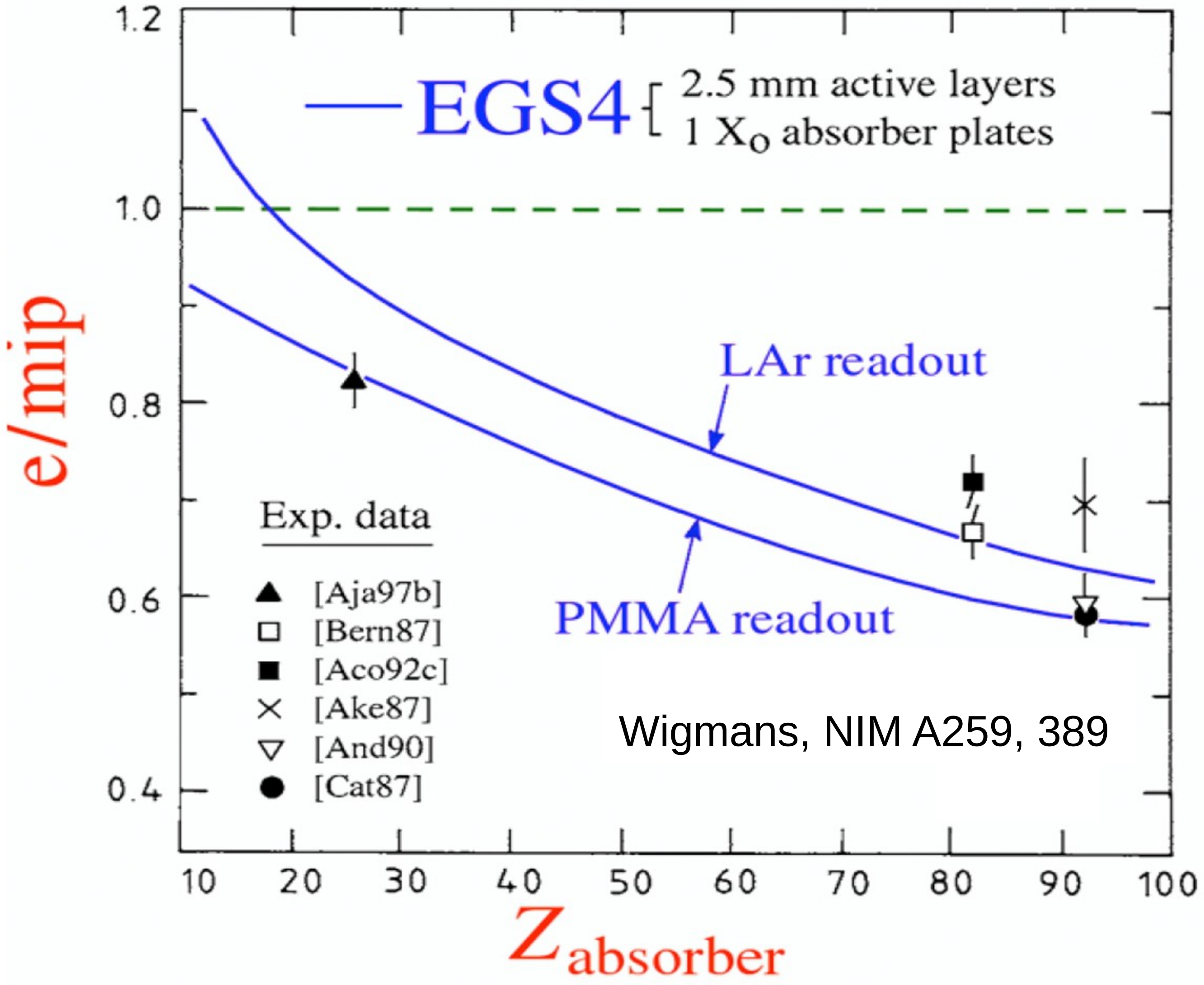
photoelectrons have very short range → contribute to signal only close to boundaries

→ response to em showers suppressed wrt. mips

e/mip ratio

Low-energy response (compensating calorimeter!)





Non-linearity at low energy with high-Z absorbers (U, Pb)

Mitigated with low-Z absorbers (Cu)

Relevant for jet detection … should we really care about ?

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

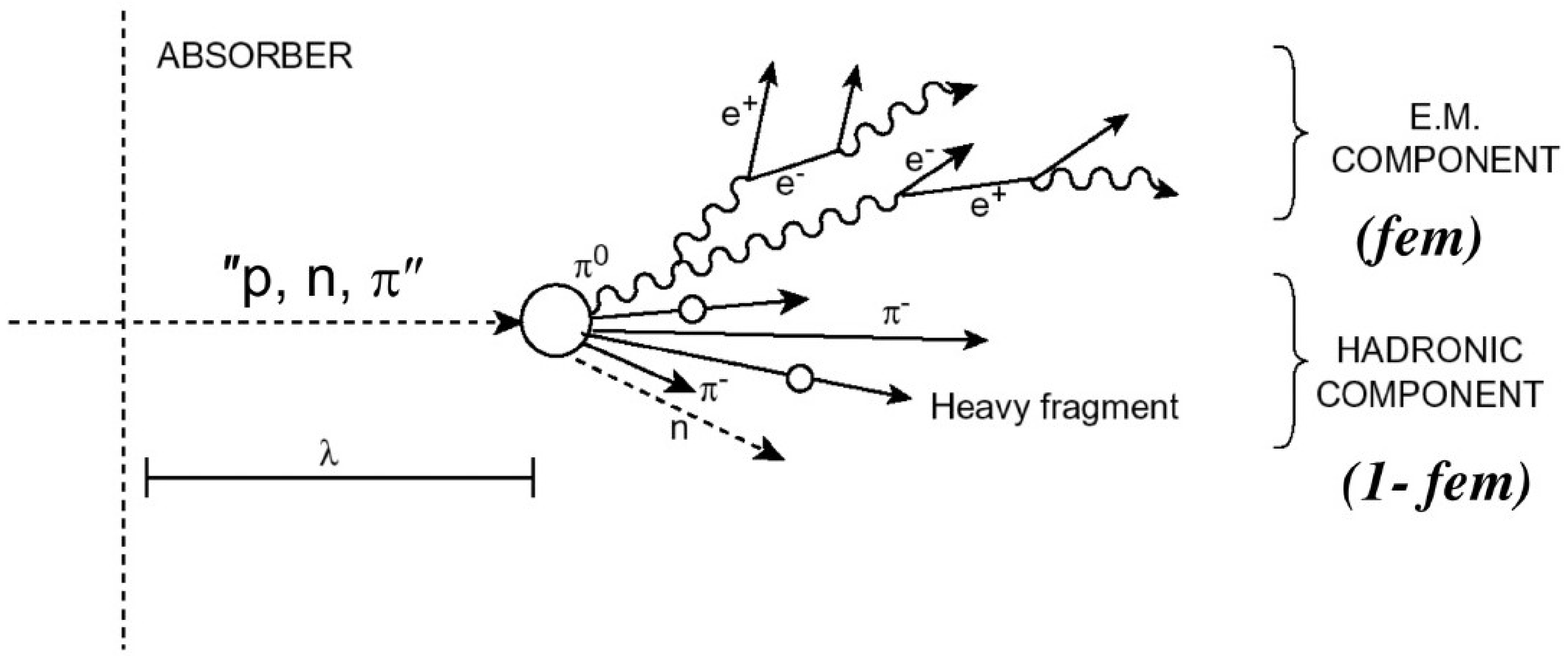
    ⇒ small sampling fraction (~3%) ⇒ poor em resolution
  - good em resolution ⇒ high sampling fraction (100% crystals, 20% LAr)

    ⇒ large non compensation ⇒ poor jet resolution

2. 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

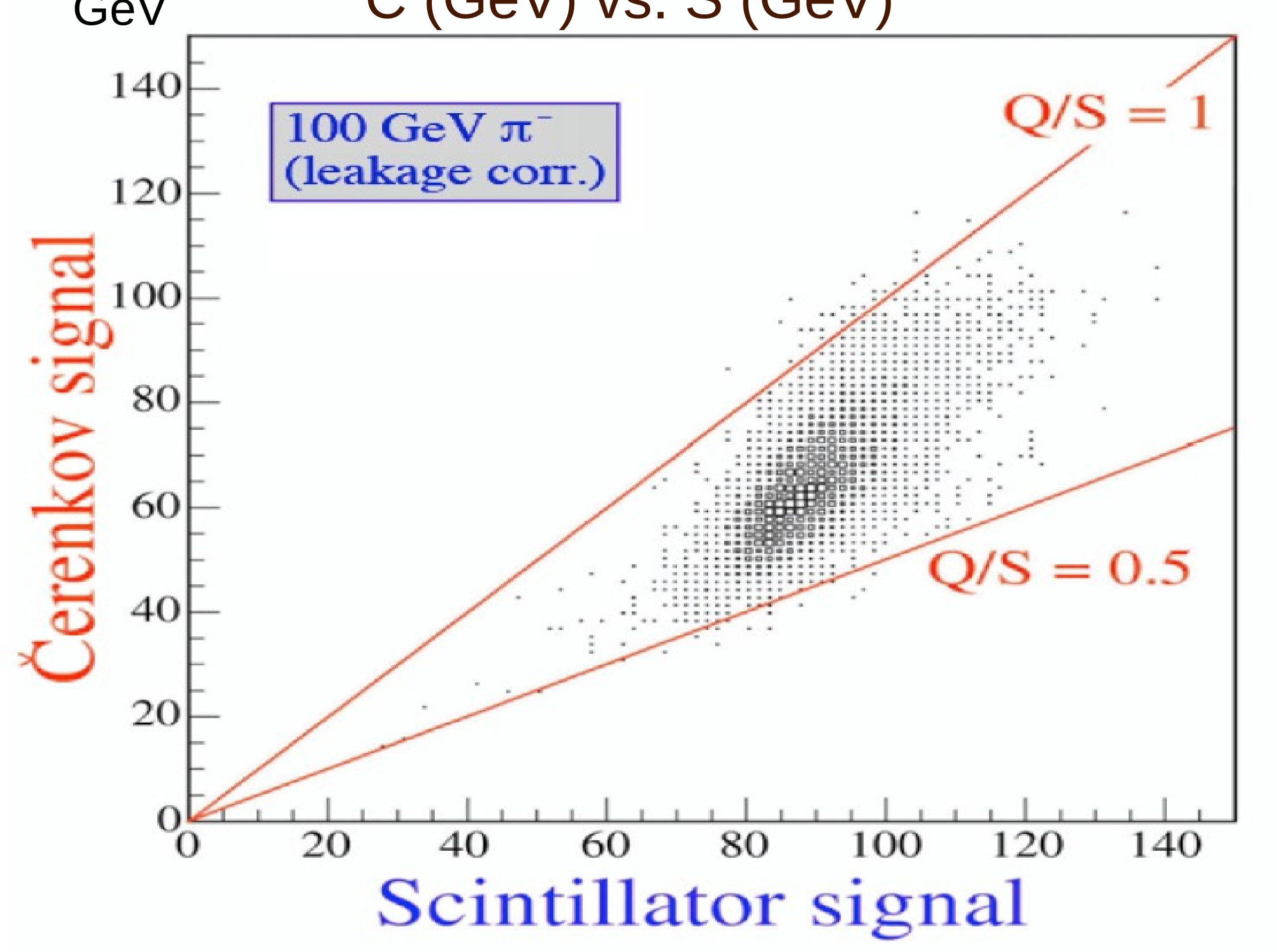
$s = (h/e)_S$, $c = (h/e)_C$: detector-specific constants

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

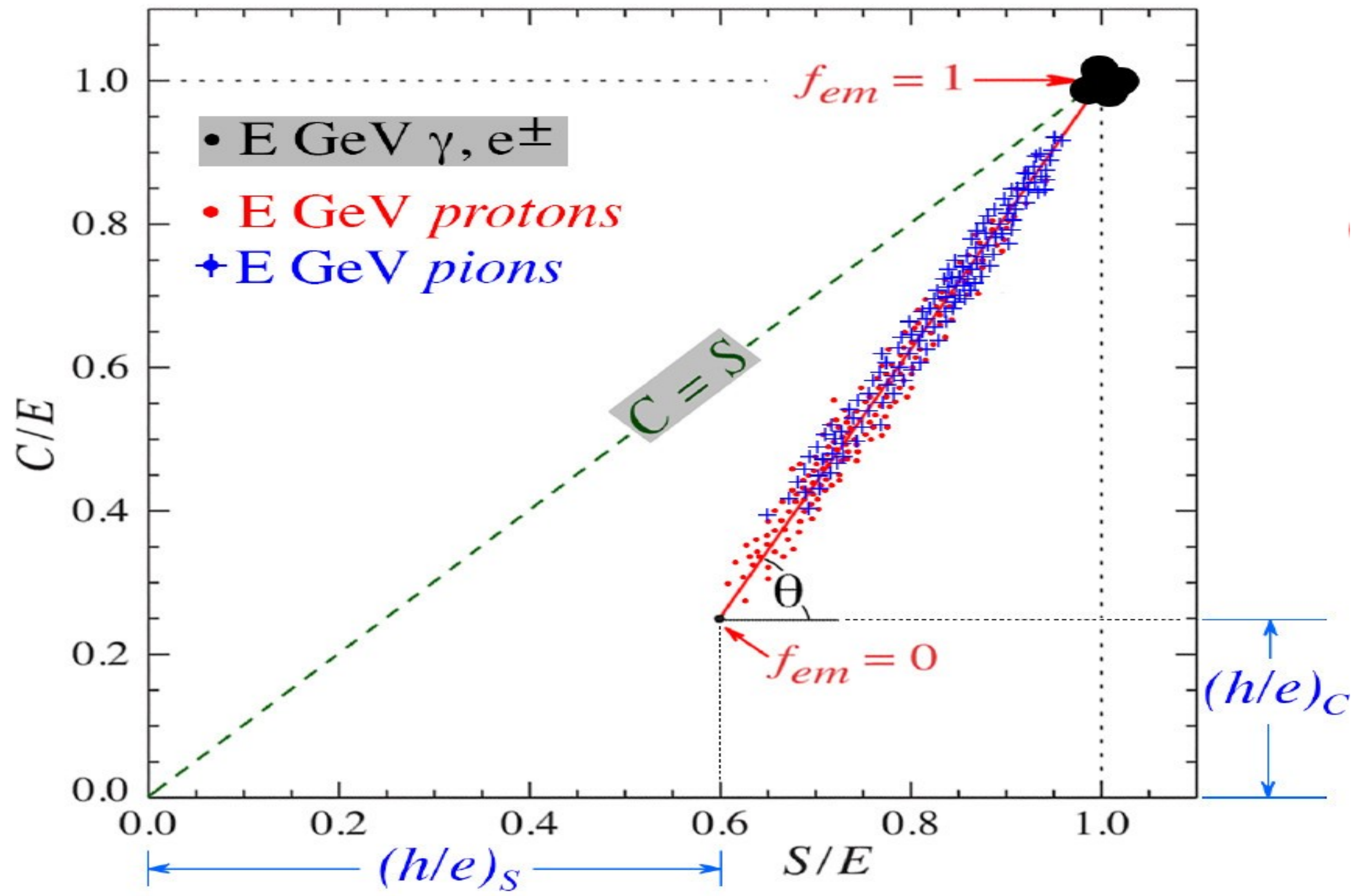
E measured at em energy scale

applying dual-readout formulae

GeV C (GeV) vs. S (GeV)



C/E vs. S/E



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

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

θ, χ independent of both:

- i) energy (!)
- ii) type of hadron (!!)

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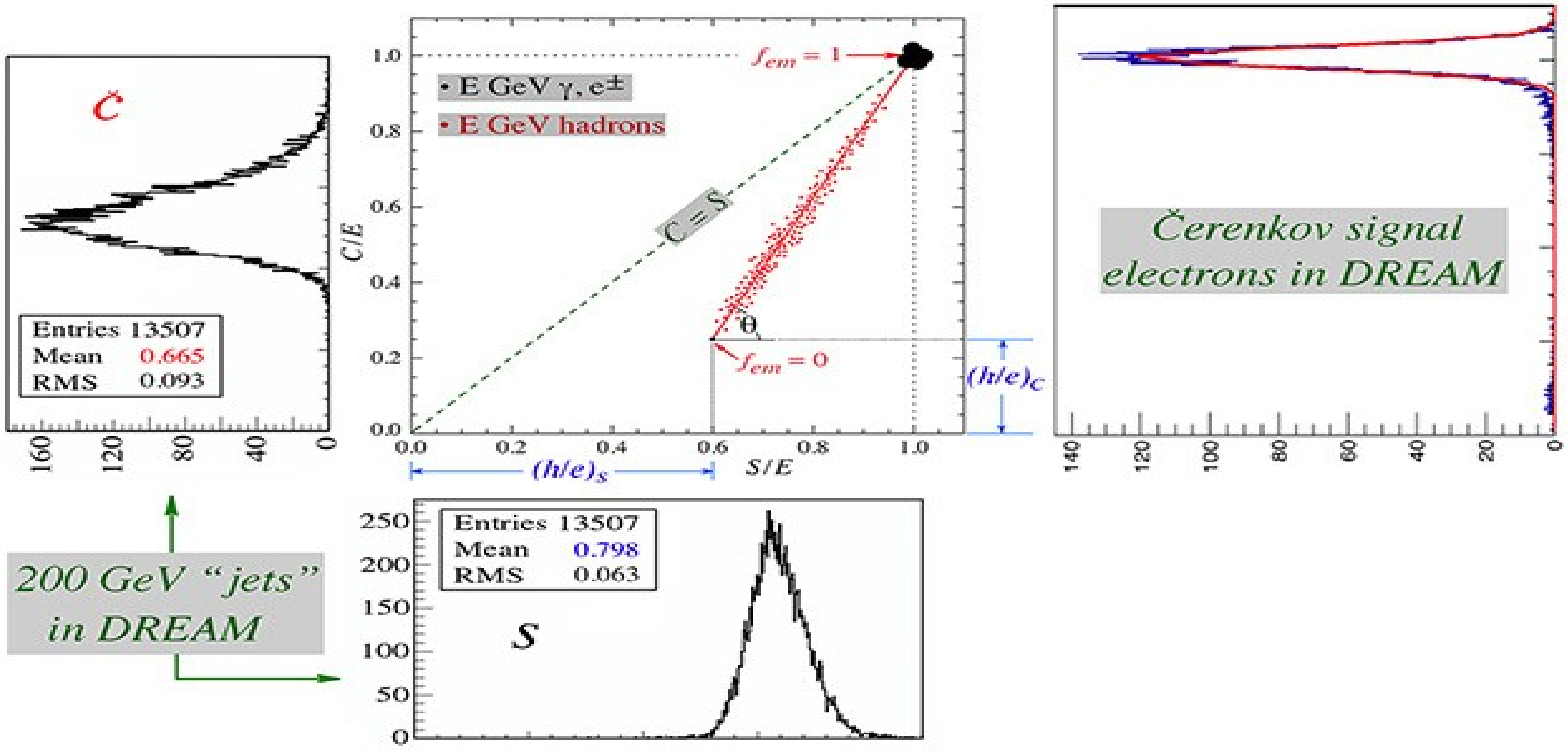
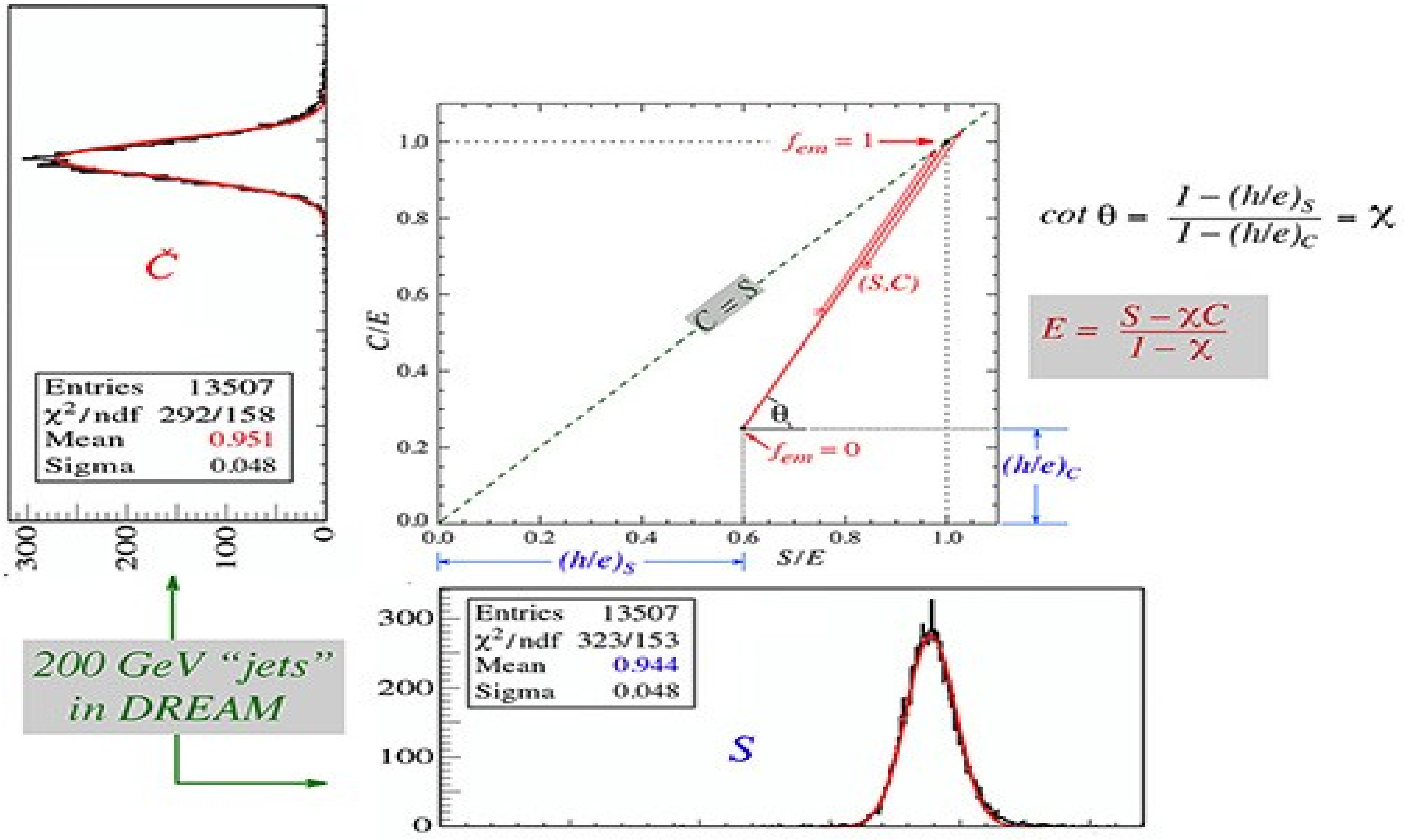
$$E = \frac{S-\chi C}{1-\chi}$$

is universally valid

before dual-readout correction

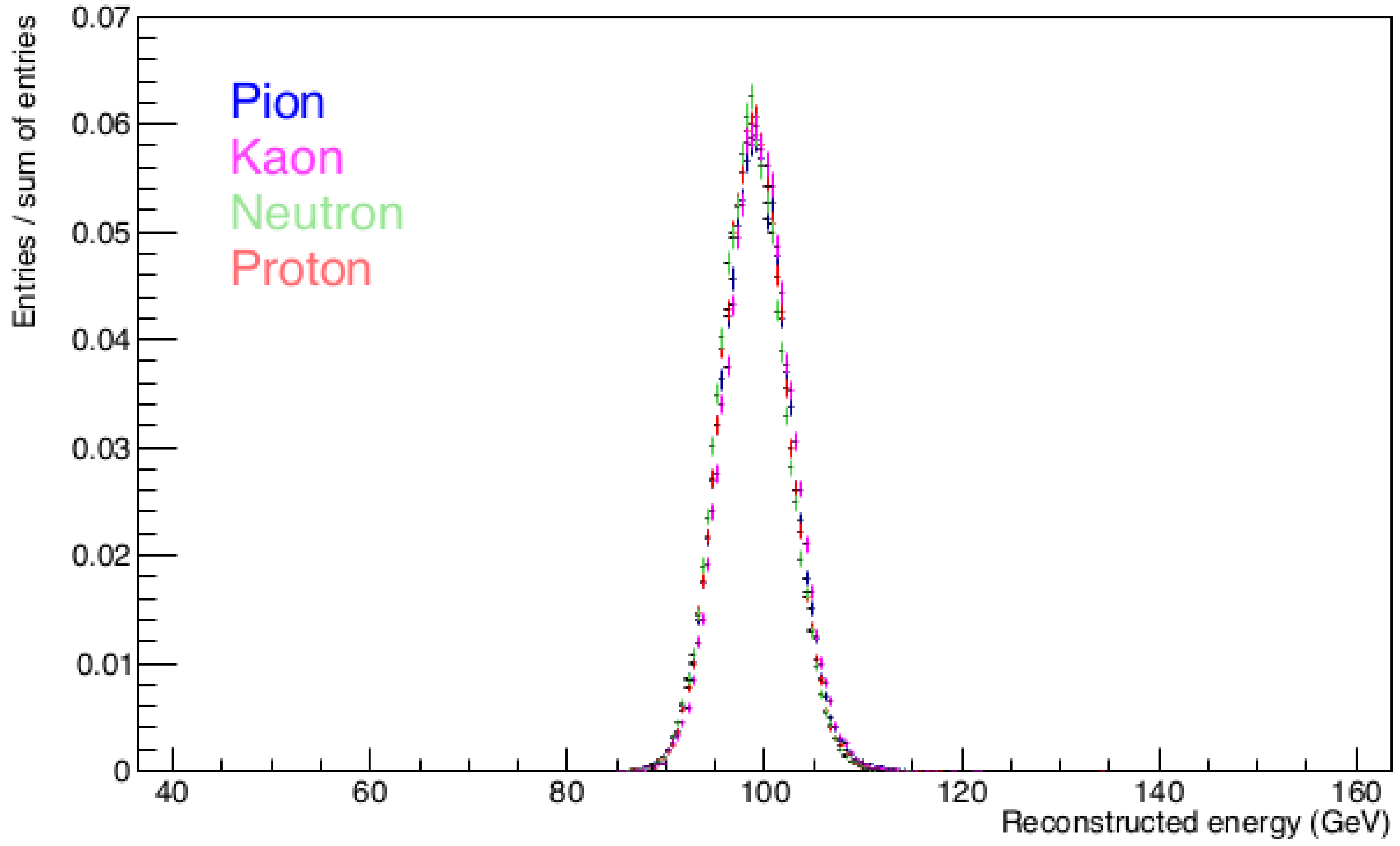


after dual-readout correction

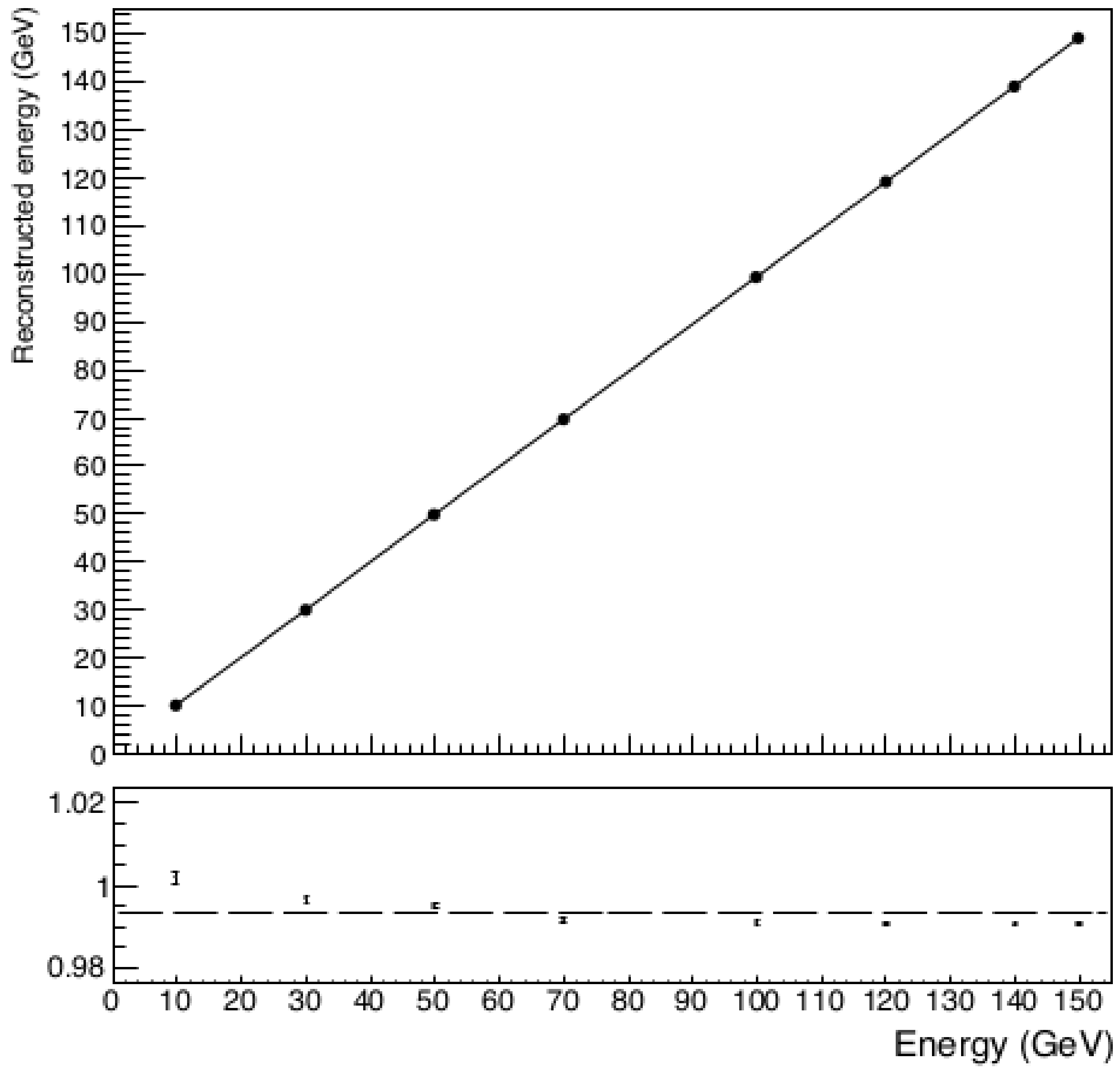


Geant4 simulations

100 GeV hadrons



10-150 GeV π^-



f_{em}

$C/S = [\ f_{em} + s \times (1 - f_{em})\ ] / [\ f_{em} + c \times (1 - f_{em})\ ]$

→ C/S depends only on f_{em} so that

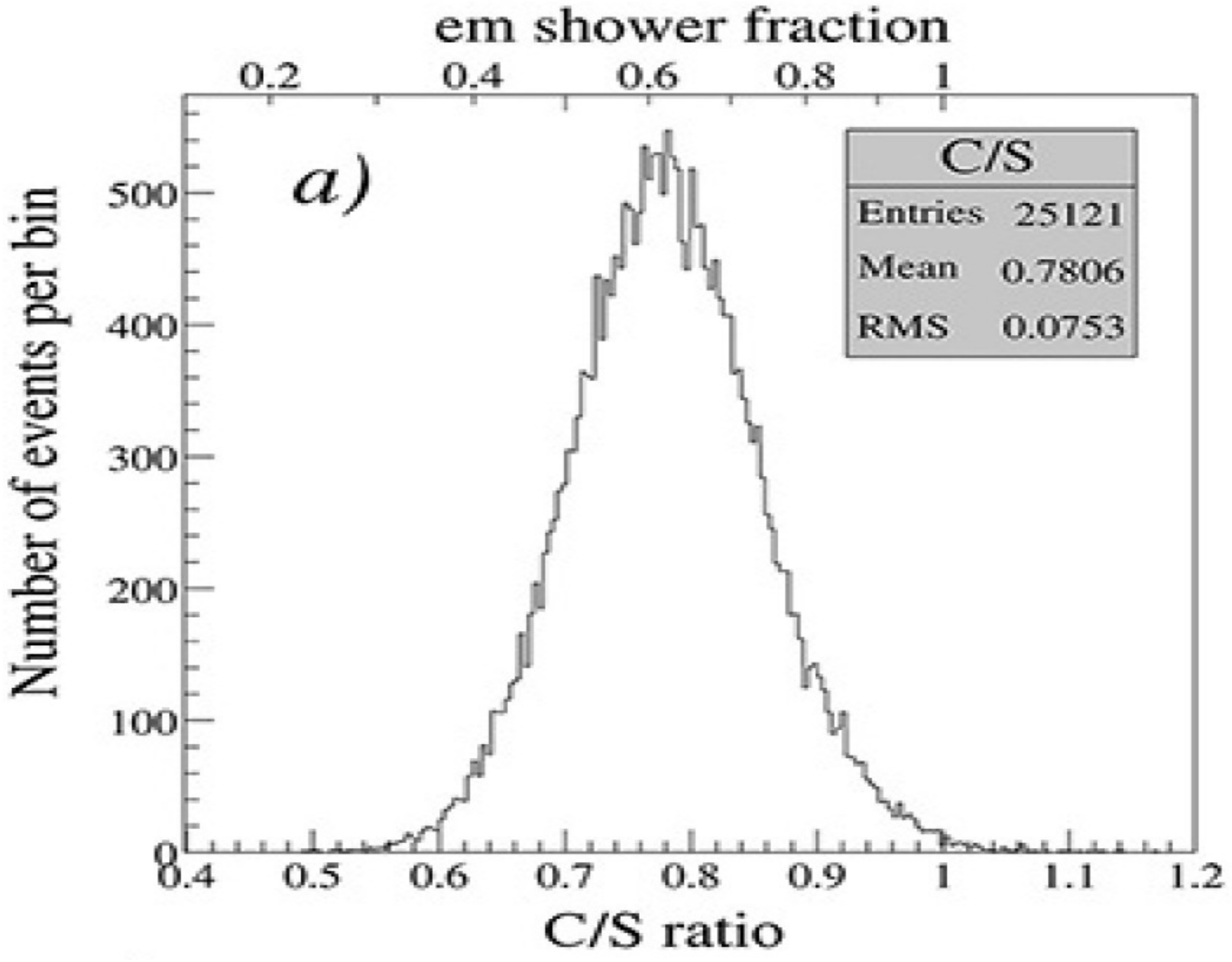
$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$

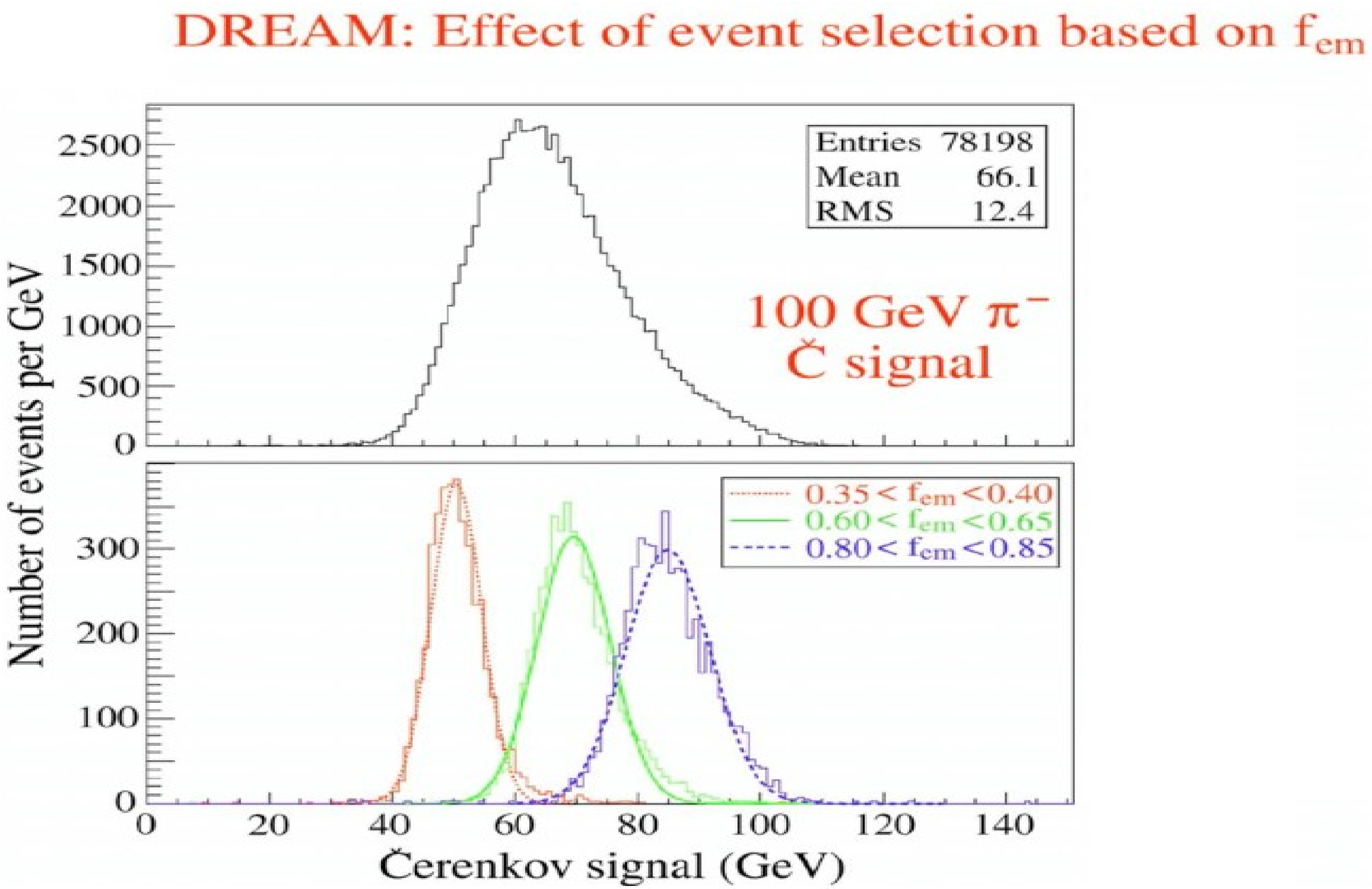
→ f_{em} depends only on C/S → can use C/S to select f_{em} subsamples

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

[or extracted e.g. by fitting <C/E> as function of E]

f_{em} fluctuations





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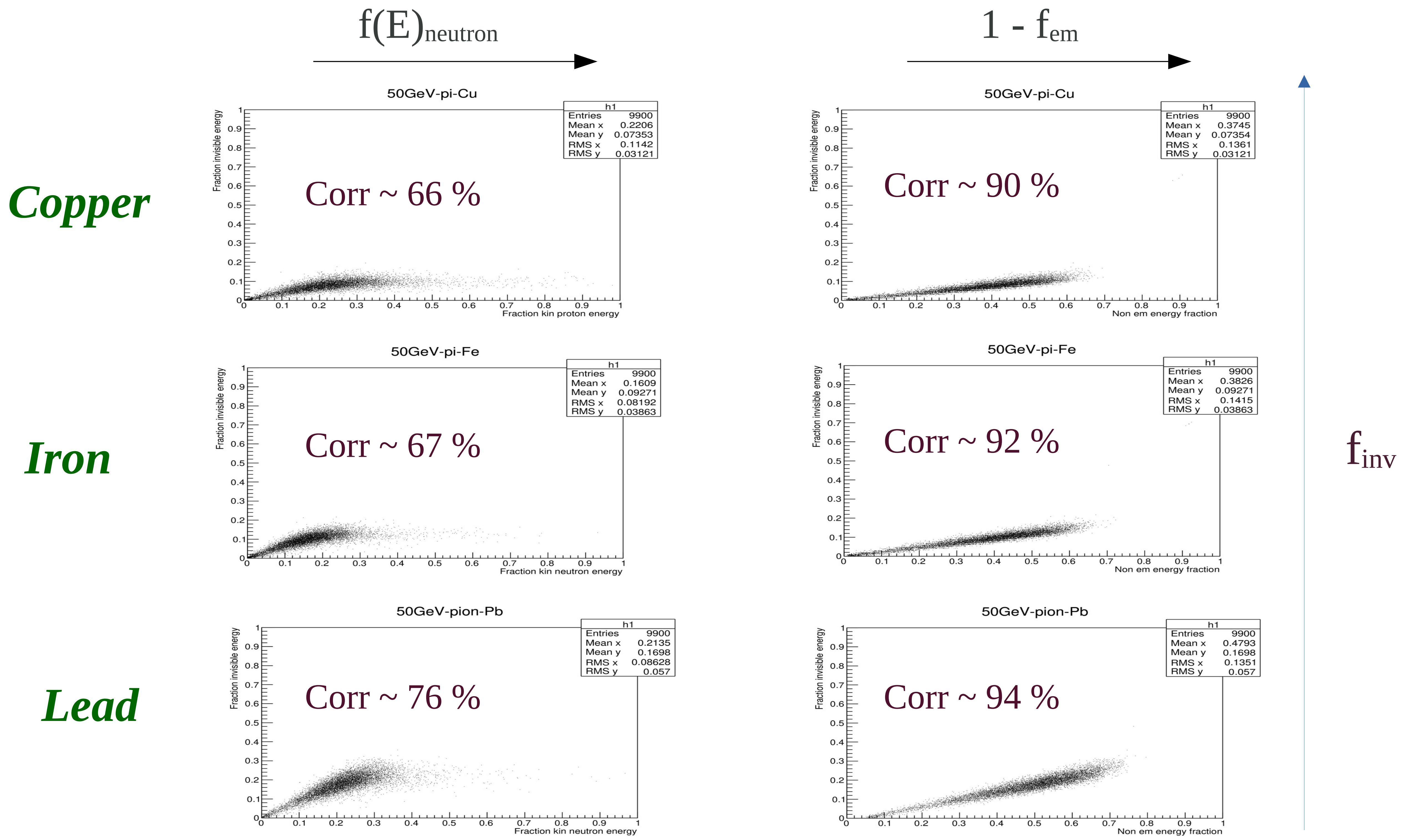
invisible energy fraction – Geant4 simulations



back to 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

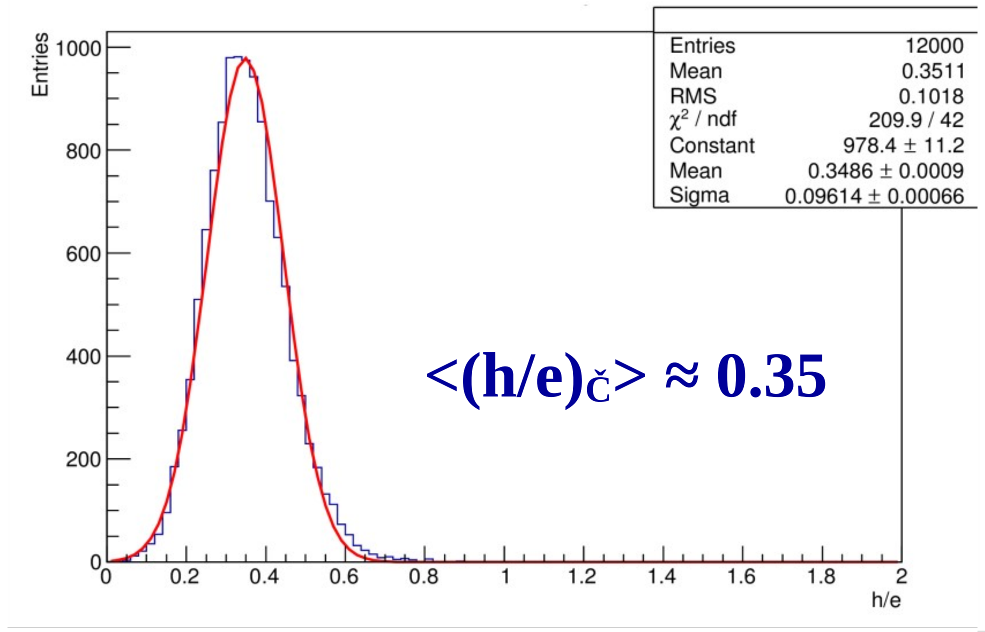
(1-f_{em}) can be reconstructed within (unknown) constant factor (>) O(1)

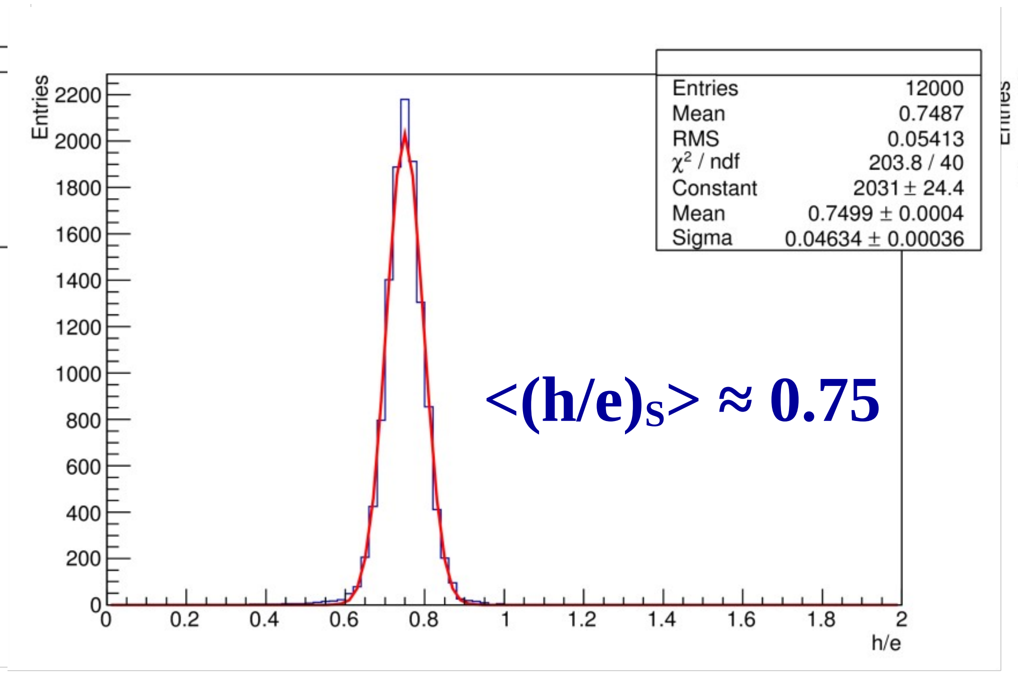
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \frac{E - S}{E - C}$$

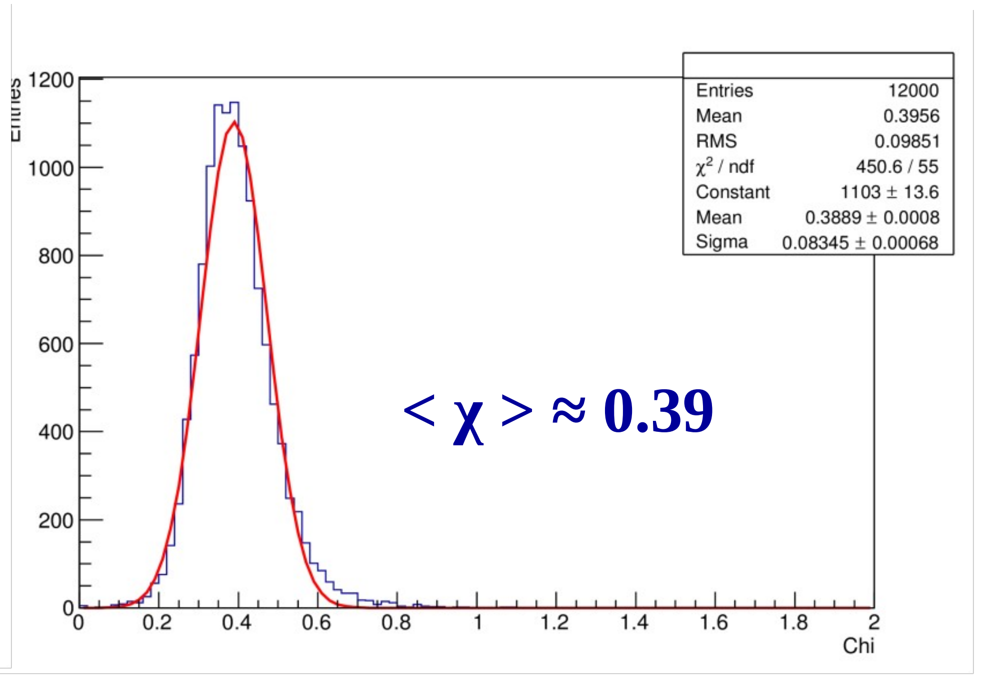
$$if \quad \left(\frac{h}{e}\right)_S > \left(\frac{h}{e}\right)_C \Rightarrow \chi < 1$$

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

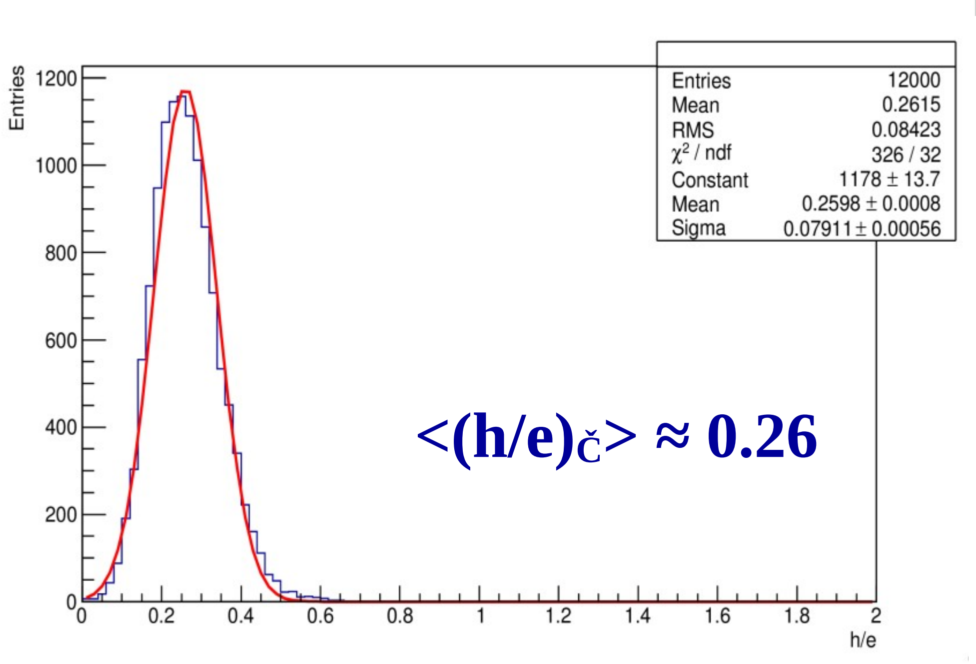
Geant4 simulations – (h/e) and χ factors

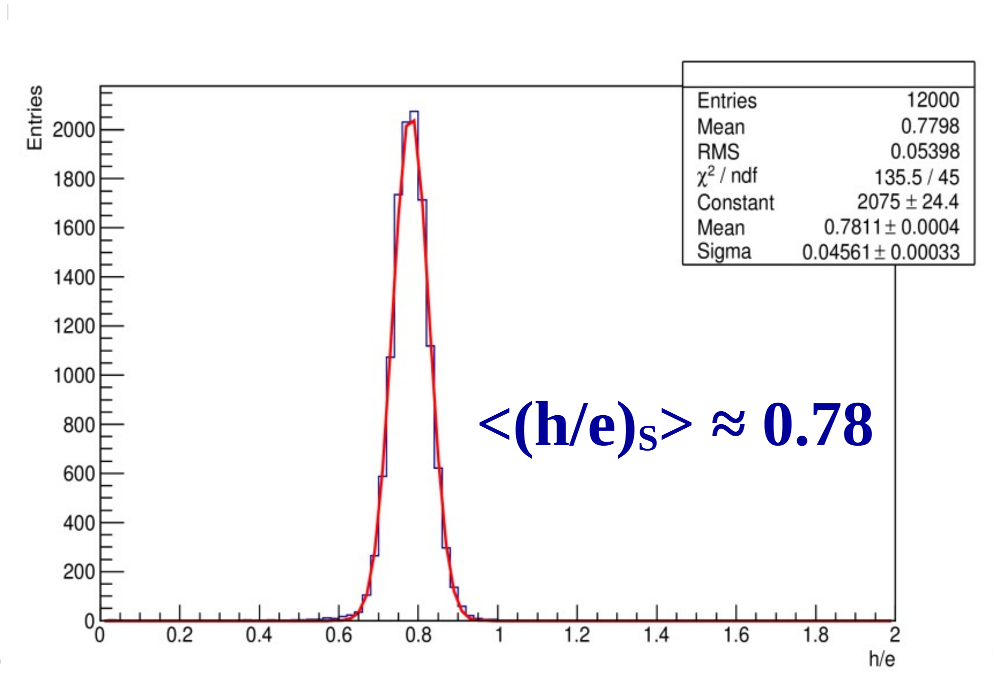


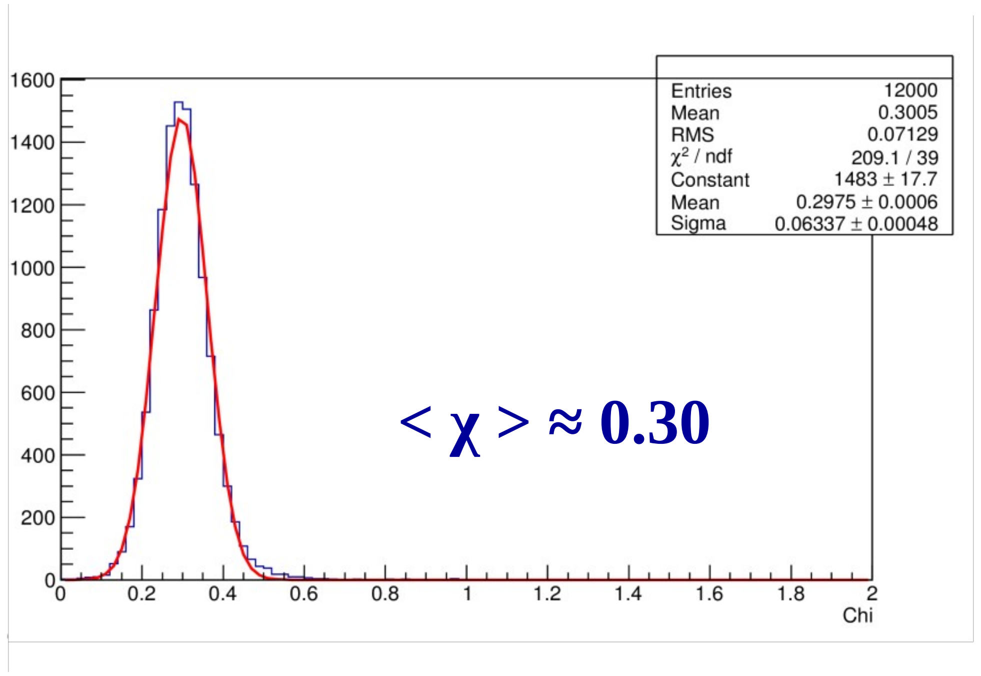




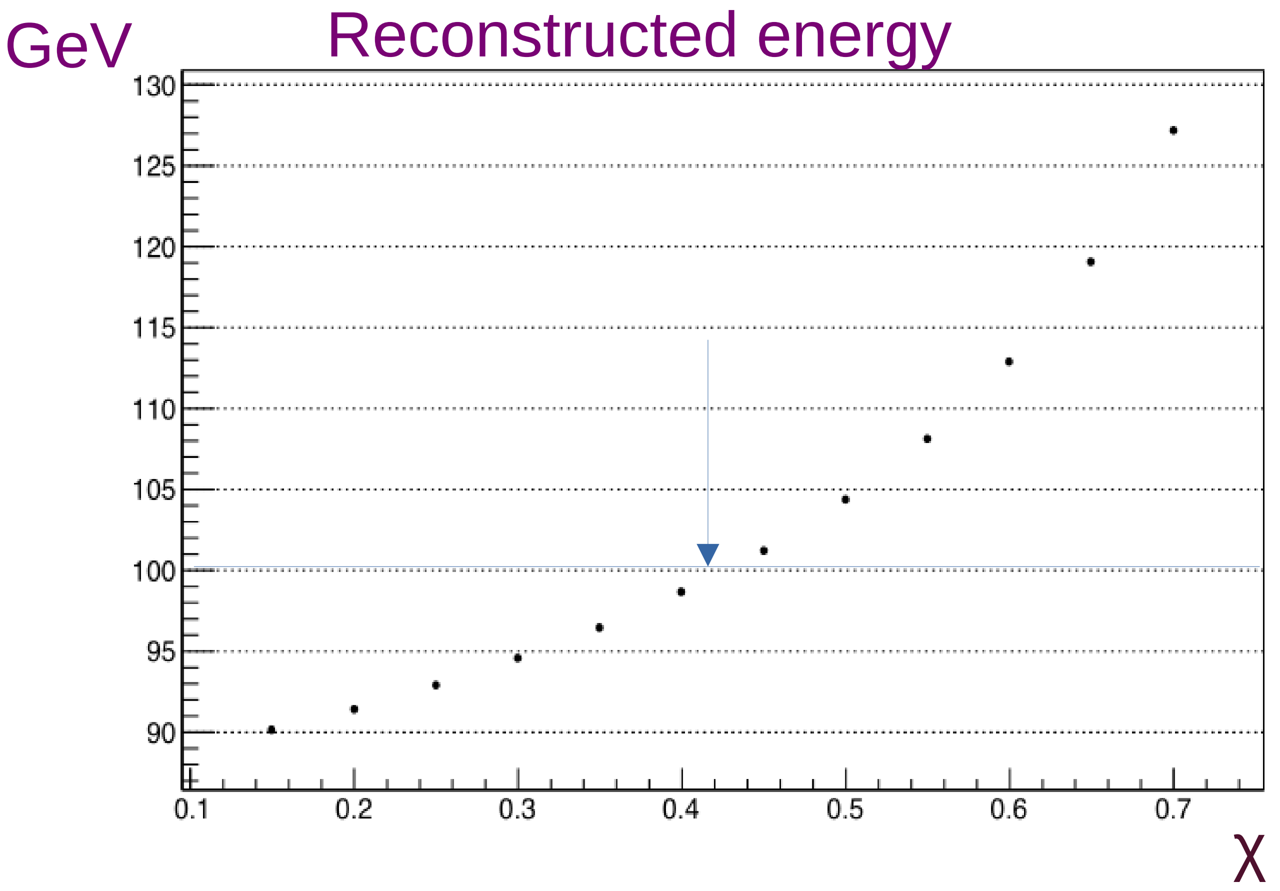
80 GeV protons in Copper ↑ & Lead ↓

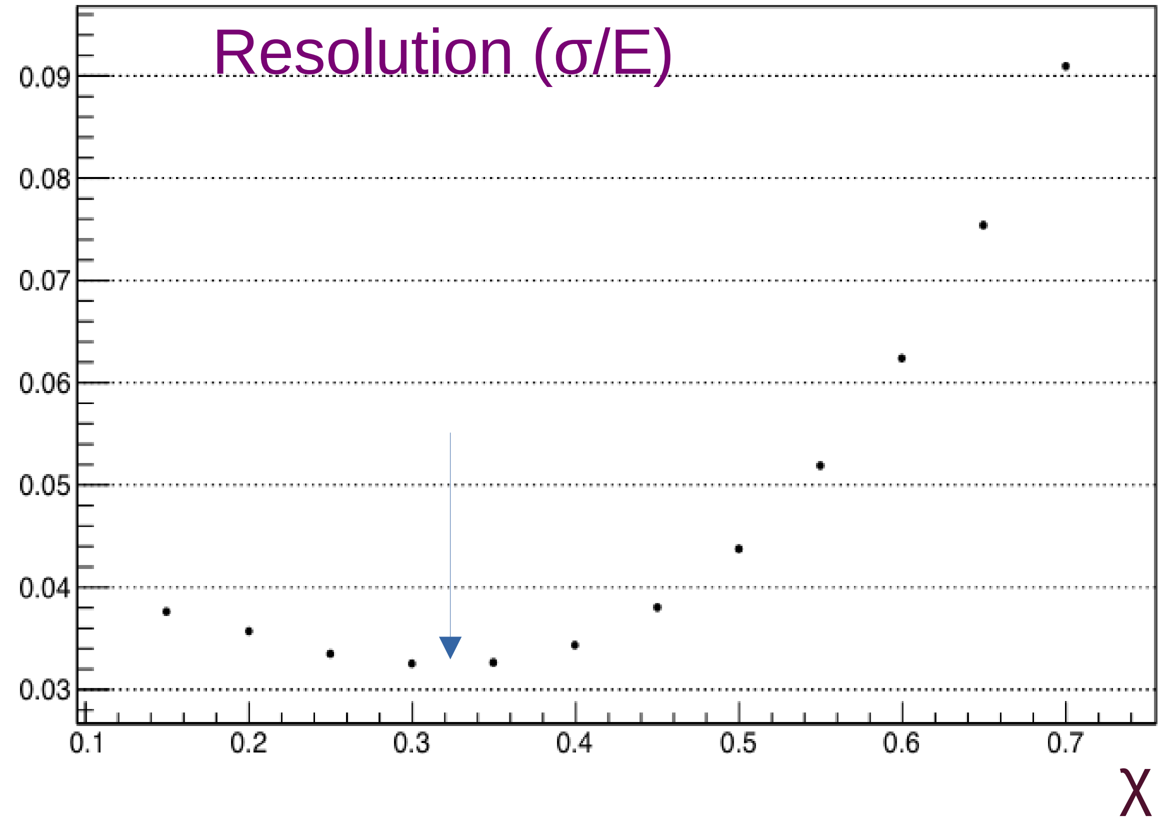




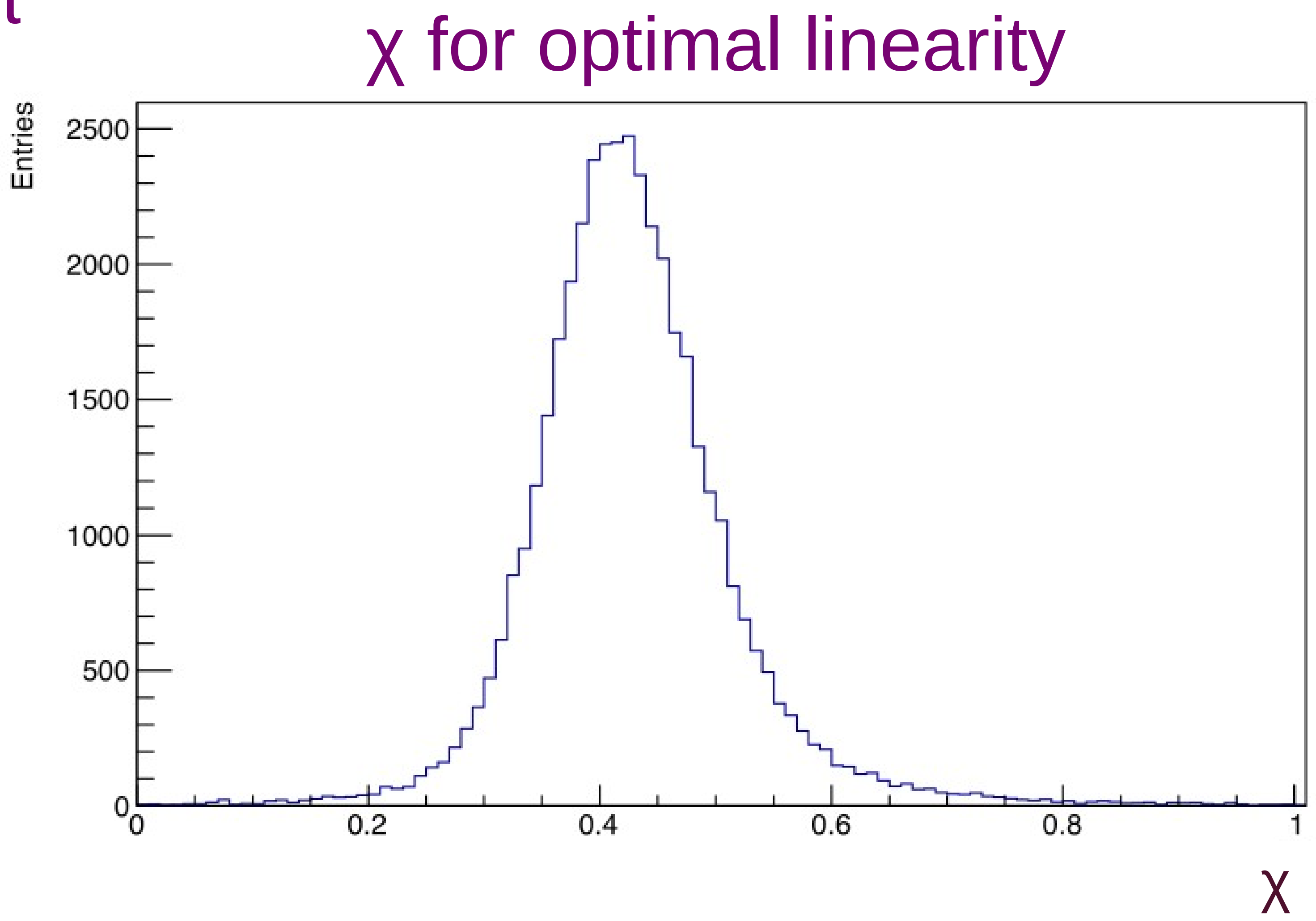


Geant4 simulations – χ scan





100 GeV π^-



Can't optimise both !

Target should be linearity

f_{em} (really f_h) estimation

Independently for S and C signals, you can easily get:

$\eta_x \equiv (h/e)_x$

$$f_h \stackrel{\text{def}}{=} (1 - f_{em}) = \frac{1 - S/E}{1 - \eta_S} = \frac{1 - S/E}{\chi \cdot (1 - \eta_C)} = \frac{1 - C/E}{1 - \eta_C}$$

f_h can be estimated event-by-event within scale factor ≈ 1
(since $\eta_C << 1$)

(h/e) estimation (?)

Up to few hundreds GeV, <f_h> as function of E, should be fairly well described by:

$$<f_h(E)> \;\approx\; (E/E_0)^{m-1} \qquad \text{for } E > E_0$$

where mainly (?) m should depend on absorber, E_0 on particle type

Two-parameter fit to:

$$1 - <C/E> \approx (1 - \eta_C) \times (E/E_0)^{m-1} = \lambda \times E^{m-1}$$

$$\lambda \equiv (1 - \eta_C) \times E_0^{1-m}$$

to be checked with M.C. and (hopefully) validated with some TB data ...

Some more input/assumptions (?):

$$m \in [0.80,\; 0.87] \quad \Rightarrow \quad 1 - m \in [0.13,\; 0.20] \ll 1$$

$$E_0(\pi) \;\; [\; E_0(p) \;] \approx 1 \text{ GeV } [\; 2.6 \text{ GeV} \;]$$

with pion data, since $E_0^{1-m}(\pi) \approx 1 \quad \Rightarrow \quad \lambda(\pi) \approx 1 - \eta_C$

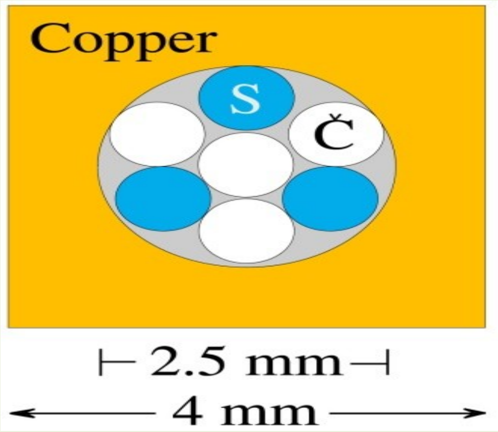
then with proton [kaon, ...] data $\quad \Rightarrow \quad E_0(p) \; [\; E_0(K), \; ... \;]$

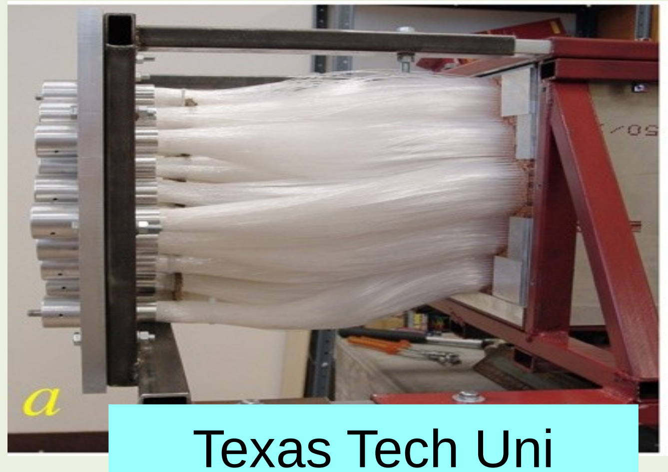
3. Few DREAM/RD52 results

DREAM/RD52 dual-readout spaghetti prototypes

2003
DREAM

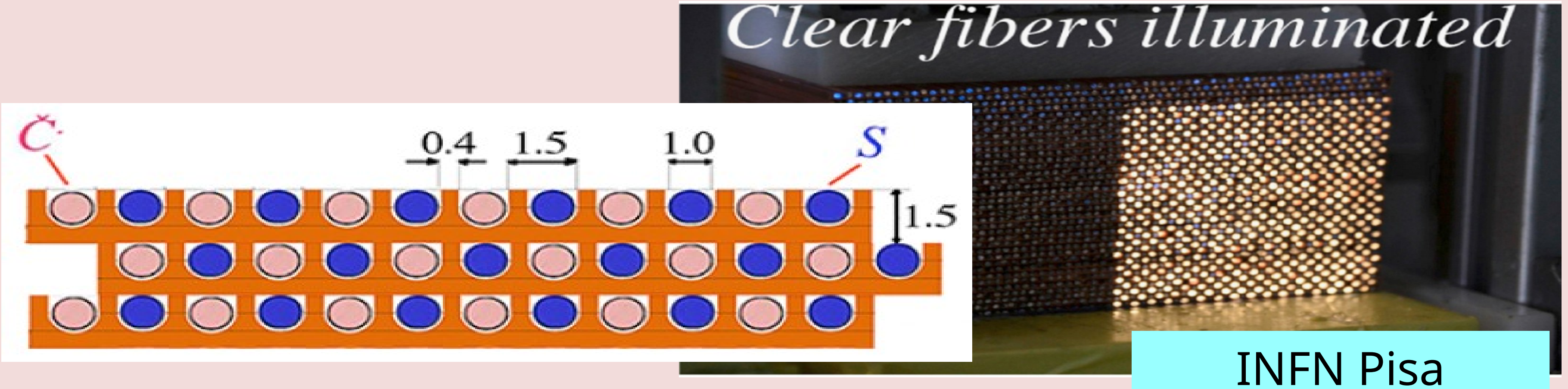
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}





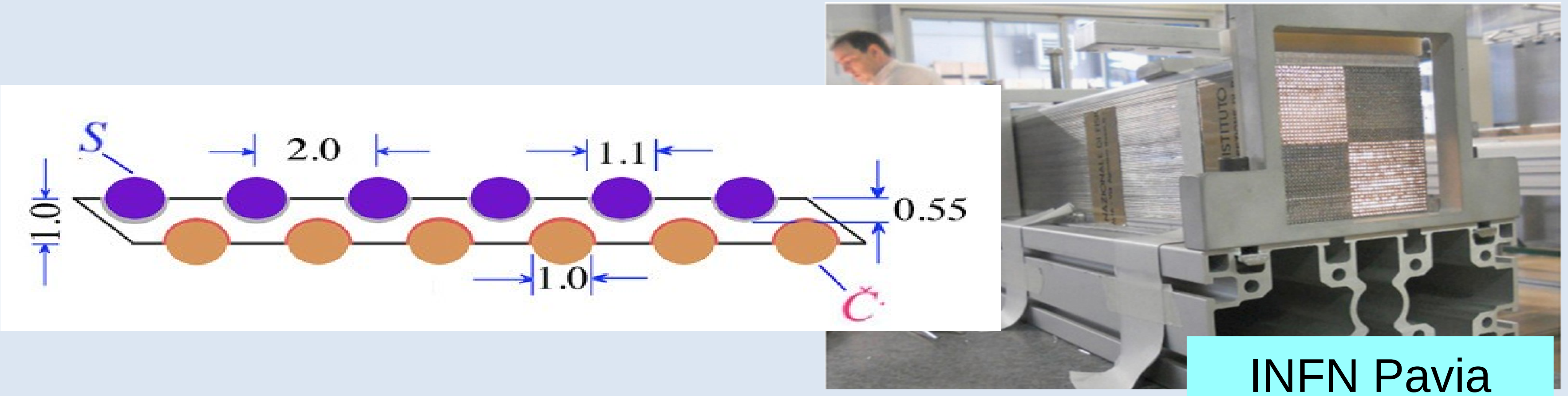
2012
RD52

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

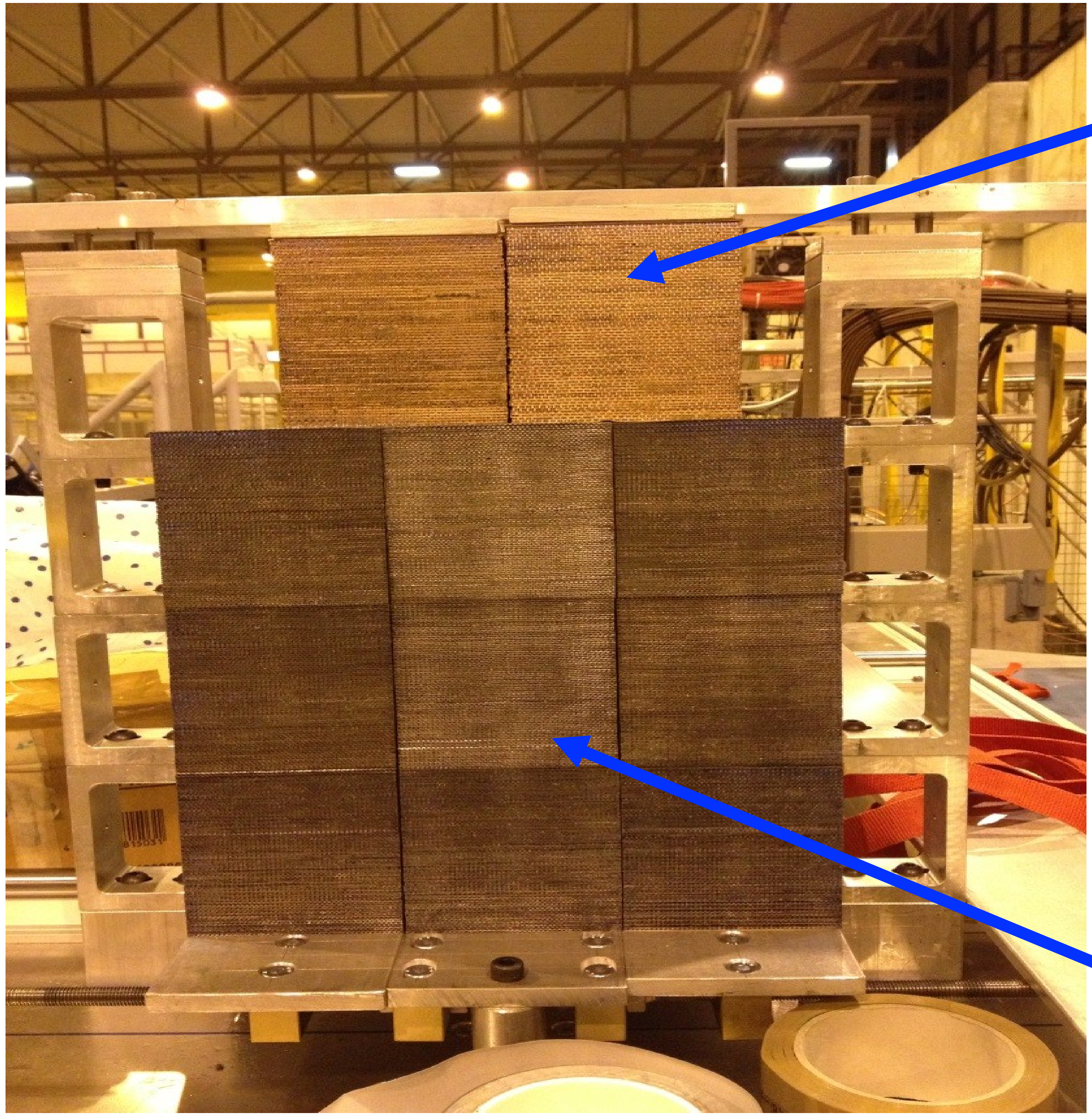


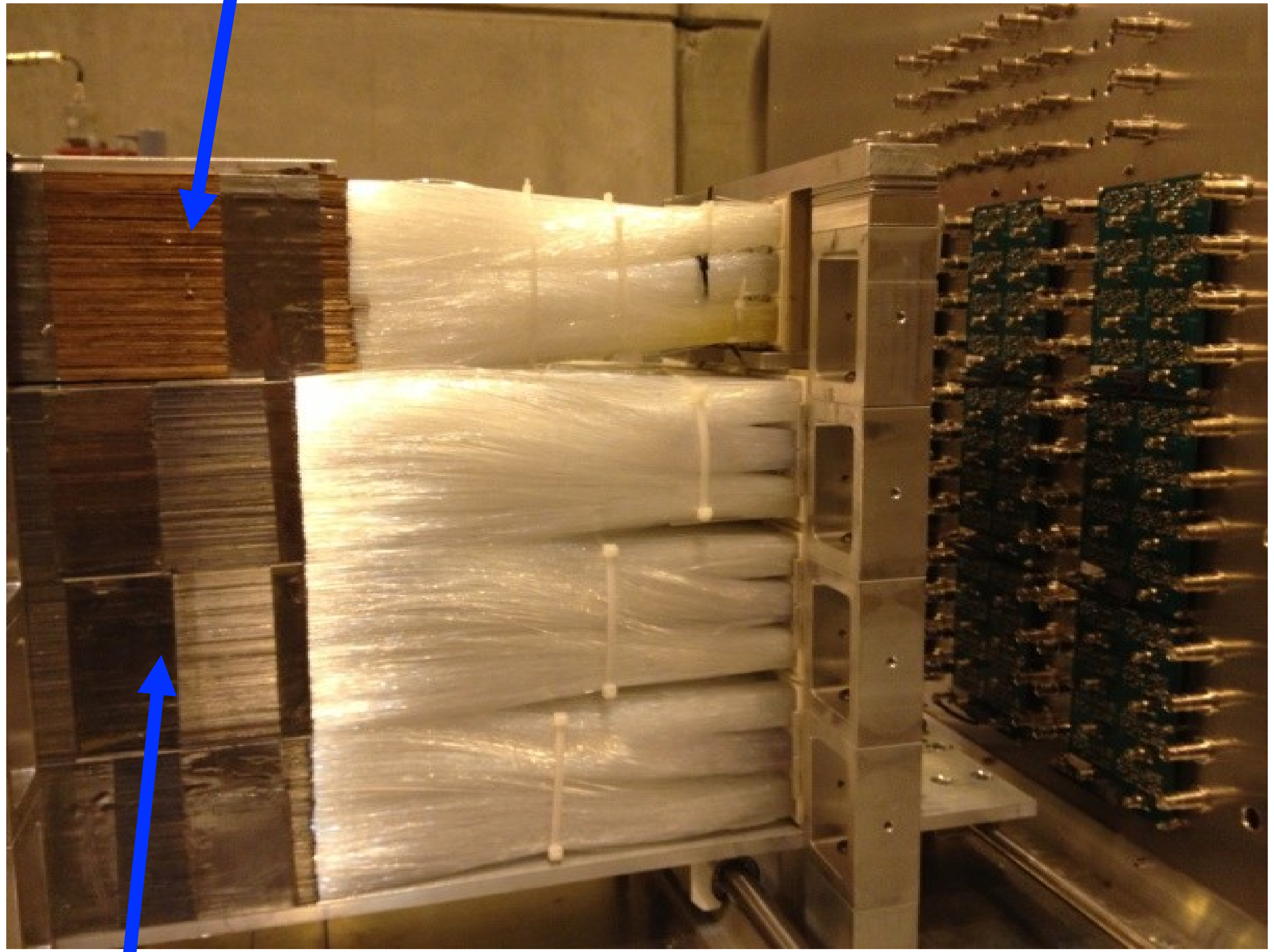
2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



RD52 dual-readout spaghetti prototypes

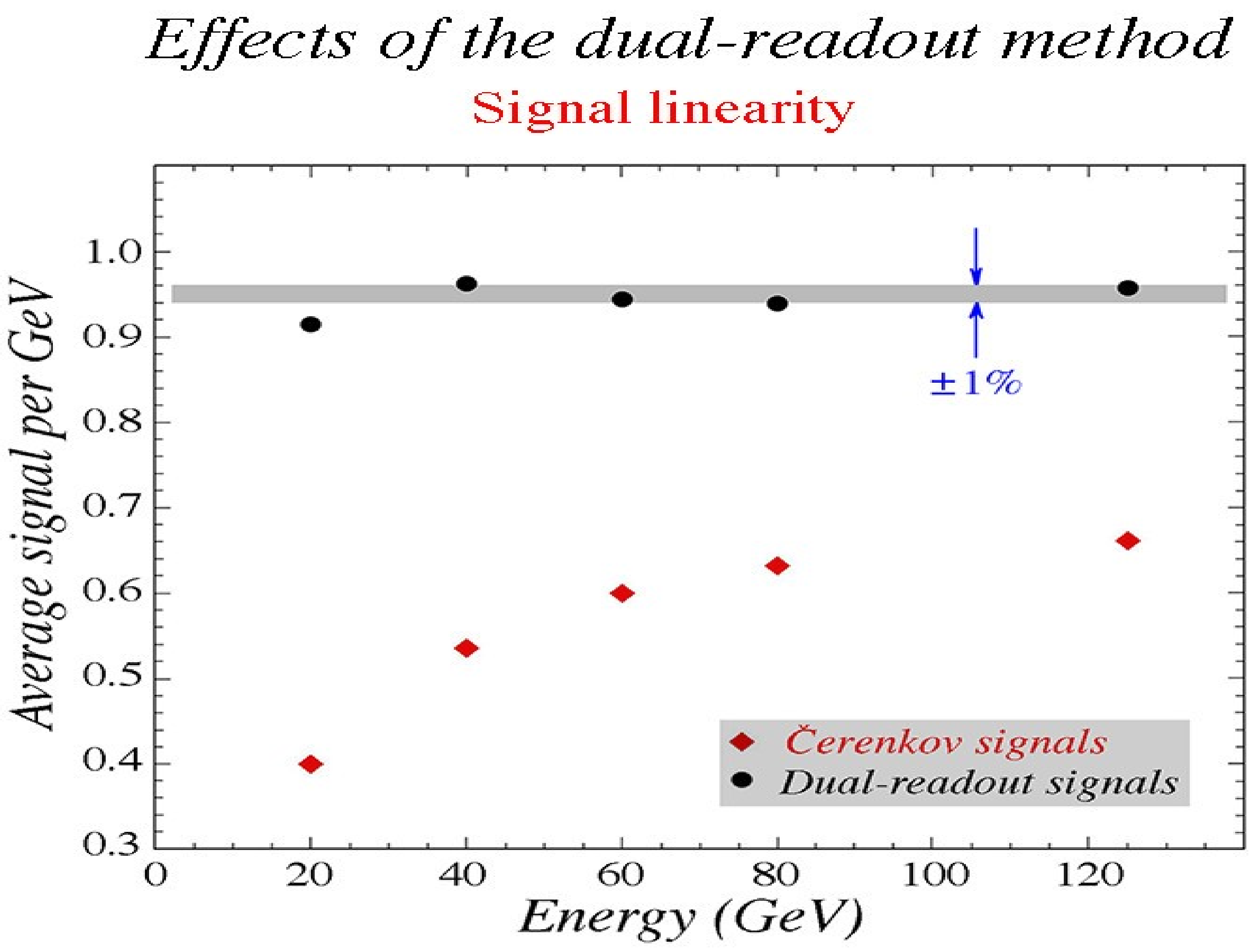




2 Cu modules

3×3 lead matrix

dual-readout at work (1)



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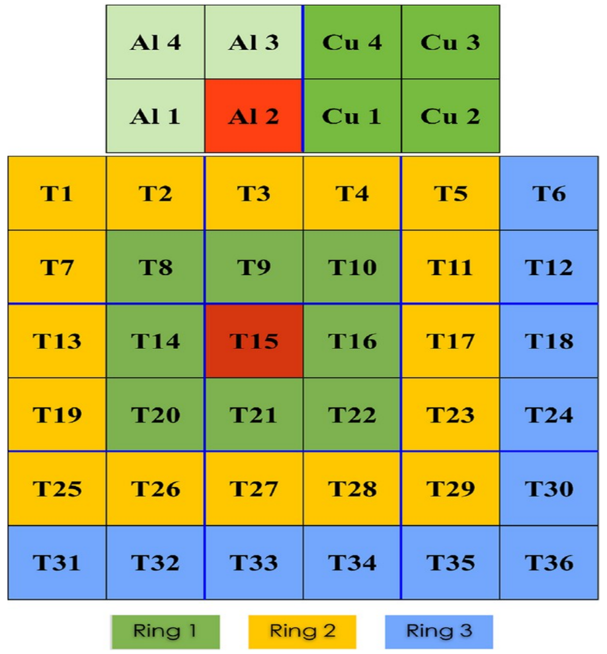
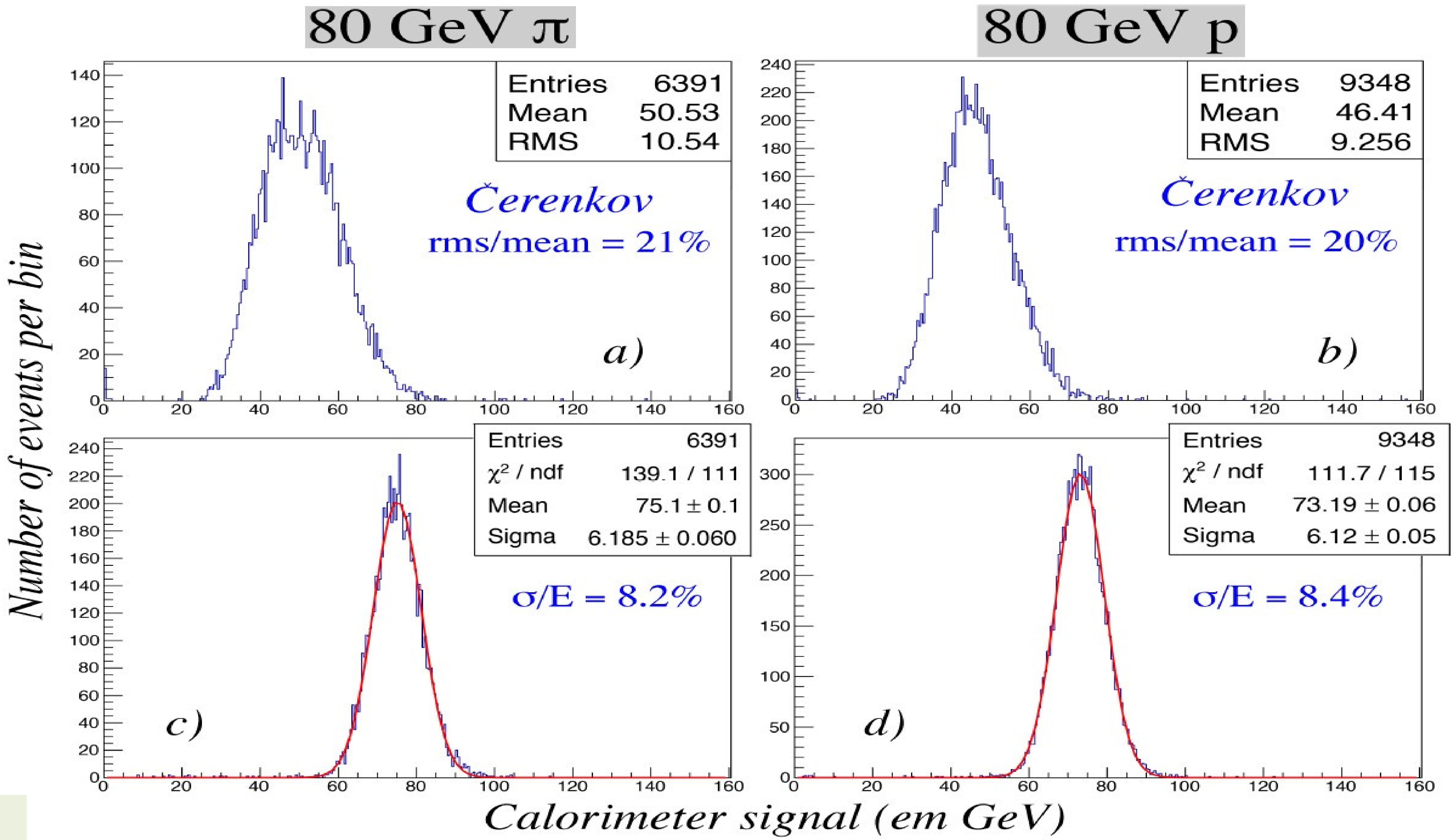
dual-readout at work (2)





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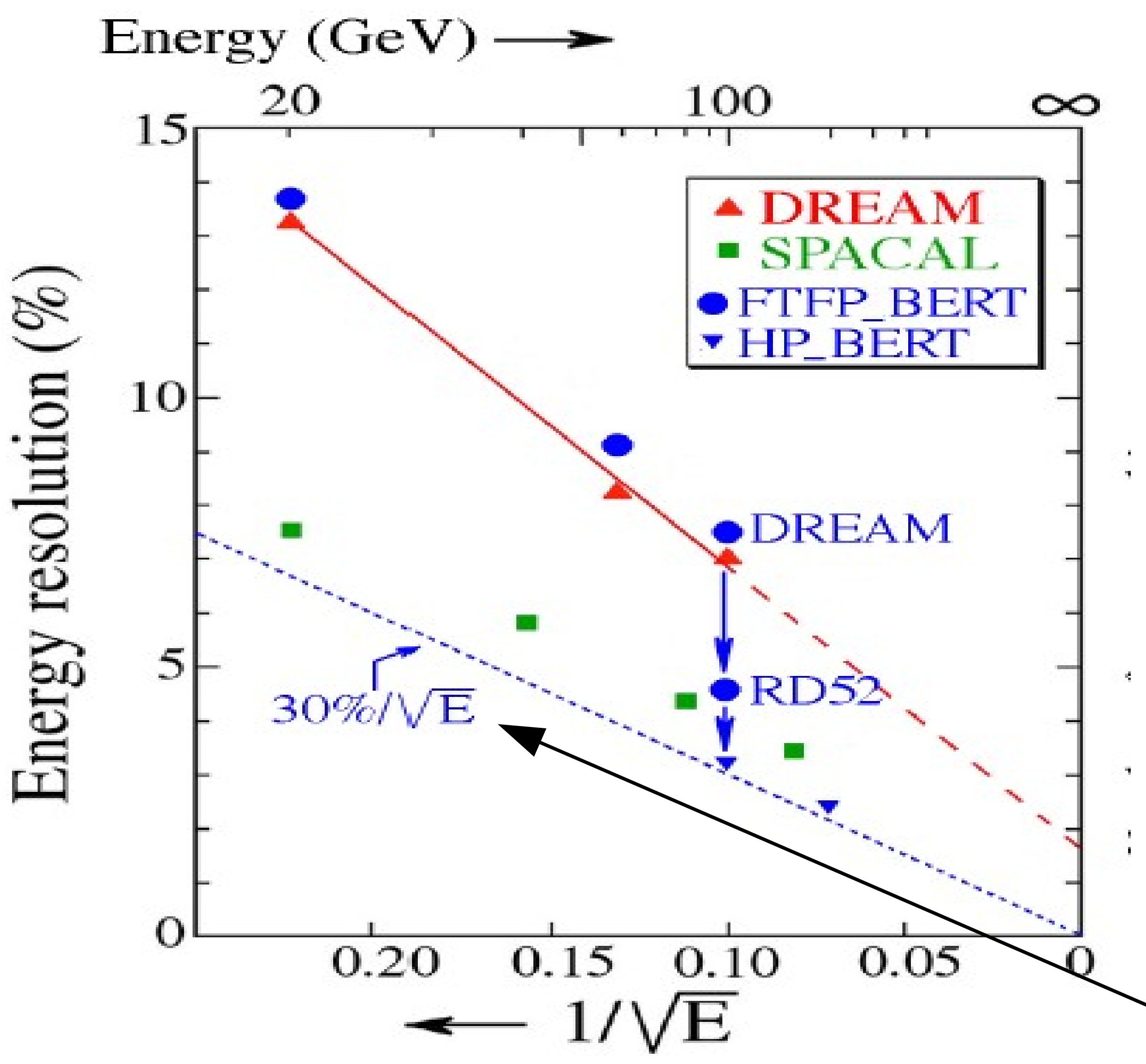
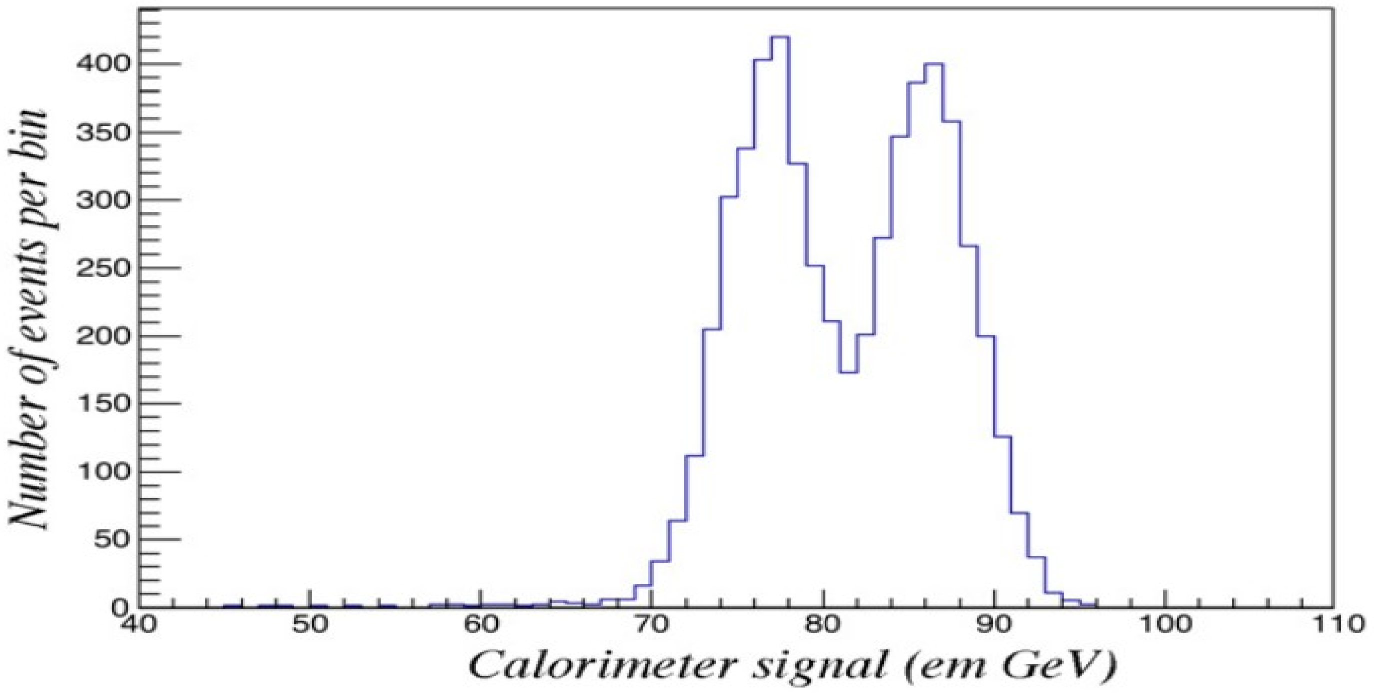
RD52 expected hadronic performance

Hadronic Resolution



W/Z separation



Geant4 simulations

NIM A 824 (2016) 721

particle ID (electron/hadron discrimination)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

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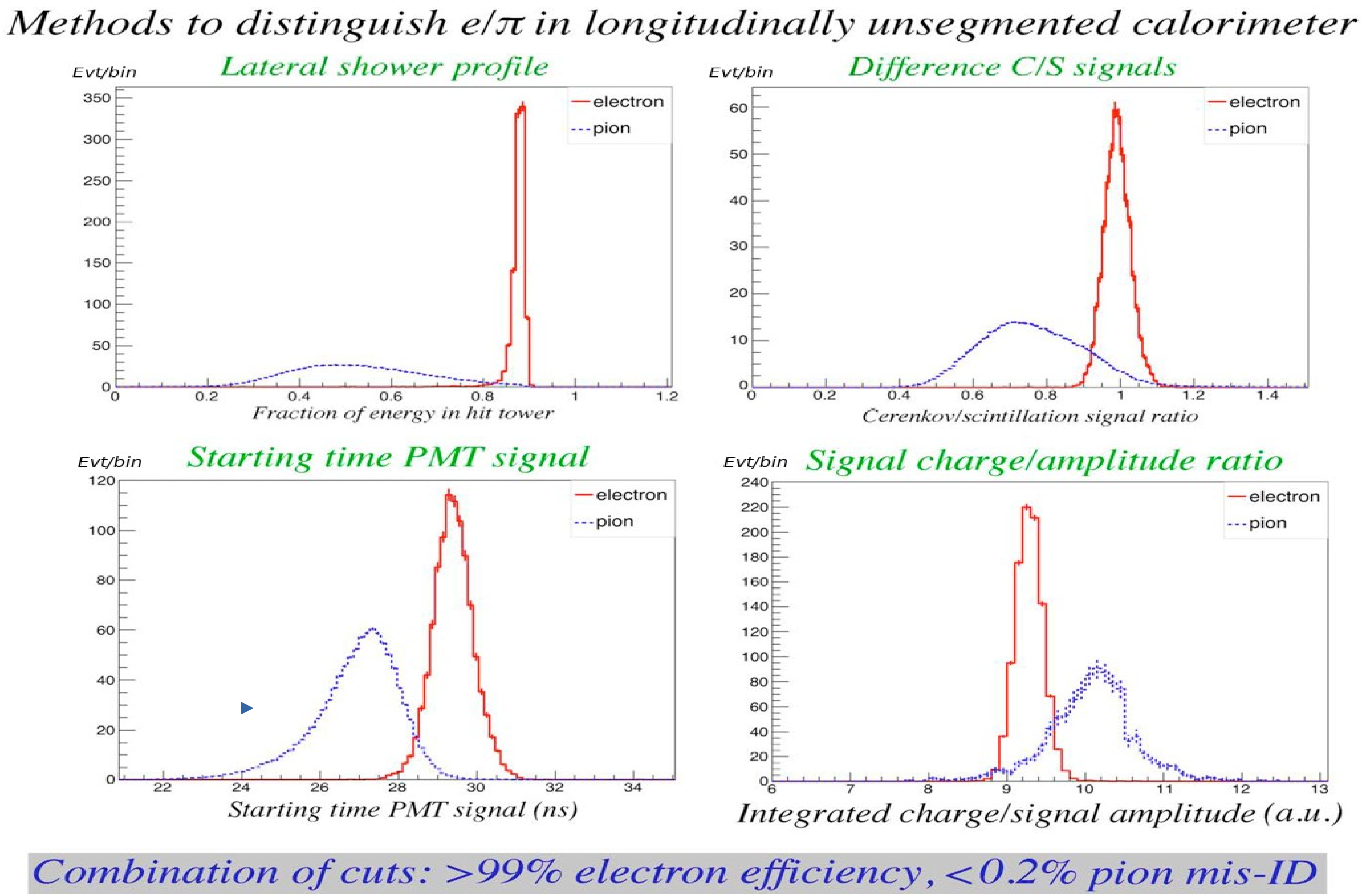
time-of-arrival distribution
measured w/ TDC



4. Dual readout goes granular (IDEA fibre calorimeter)

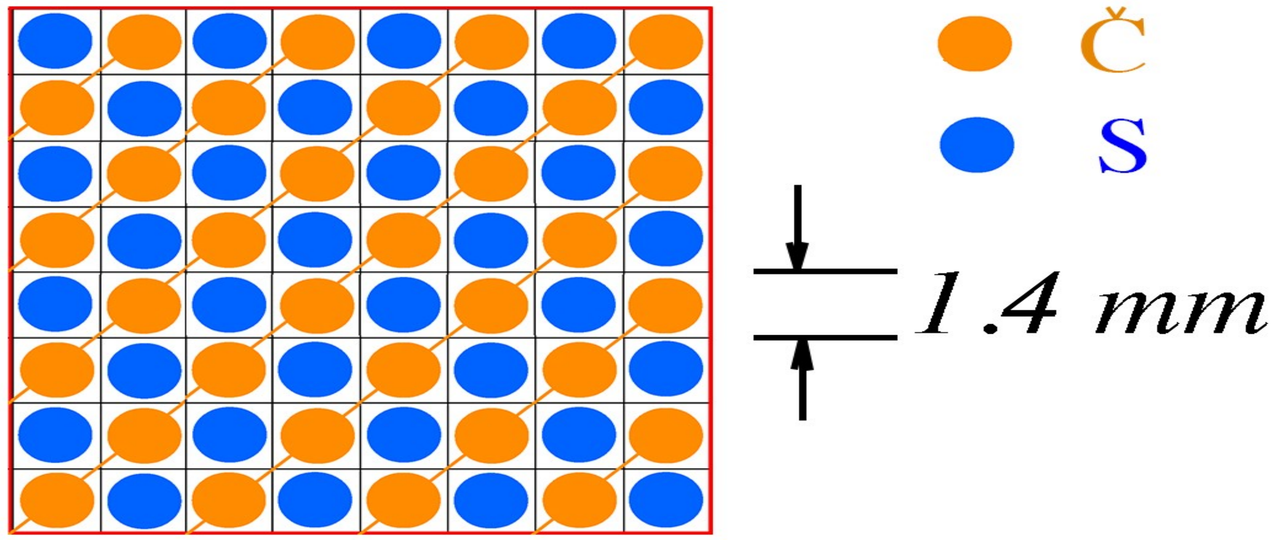
RD52 SiPM module

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

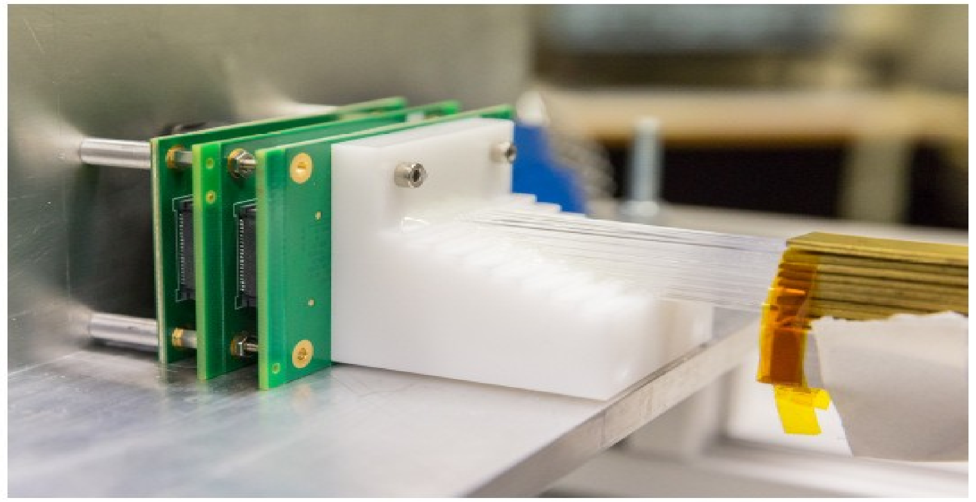
32 (S) + 32 (Č) fibres
X_0 ~ 29 mm
R_M ~ 31 mm

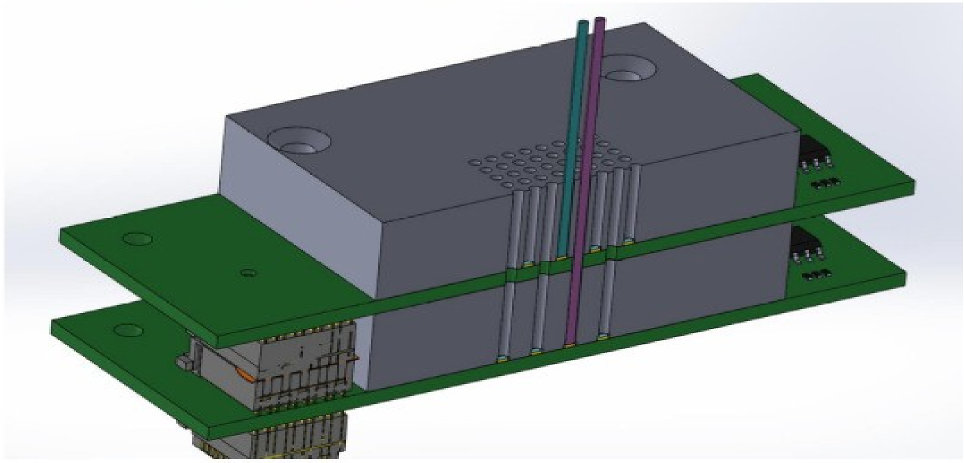
~ $(0.4\ R_M)^2 \times 39\ X_0$

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



Light sensors (SiPM)

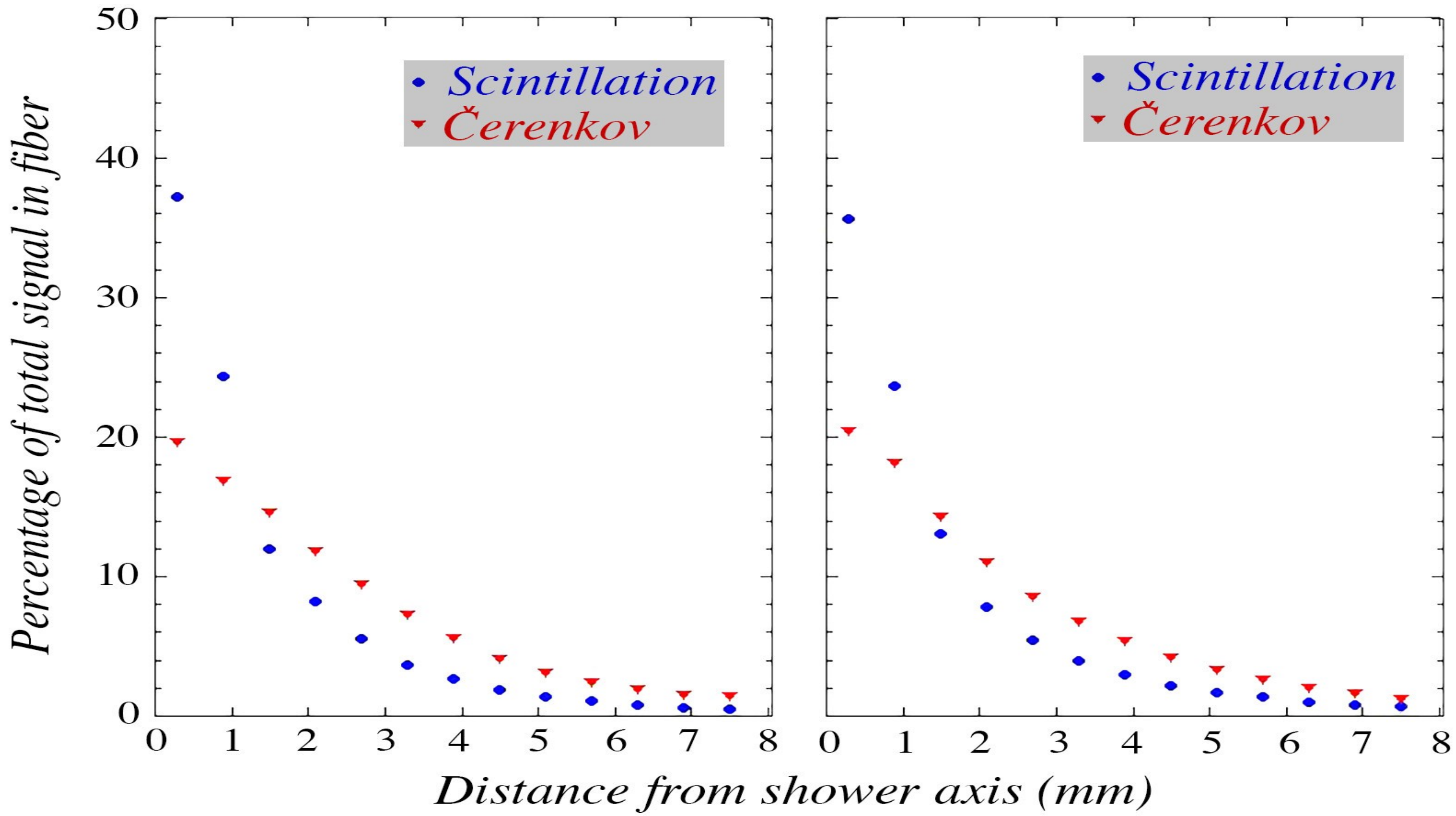




lateral shower profile w/ SiPMs

10 / 40 GeV e^-

$\theta, \Phi = 0°$



em shower very narrow:

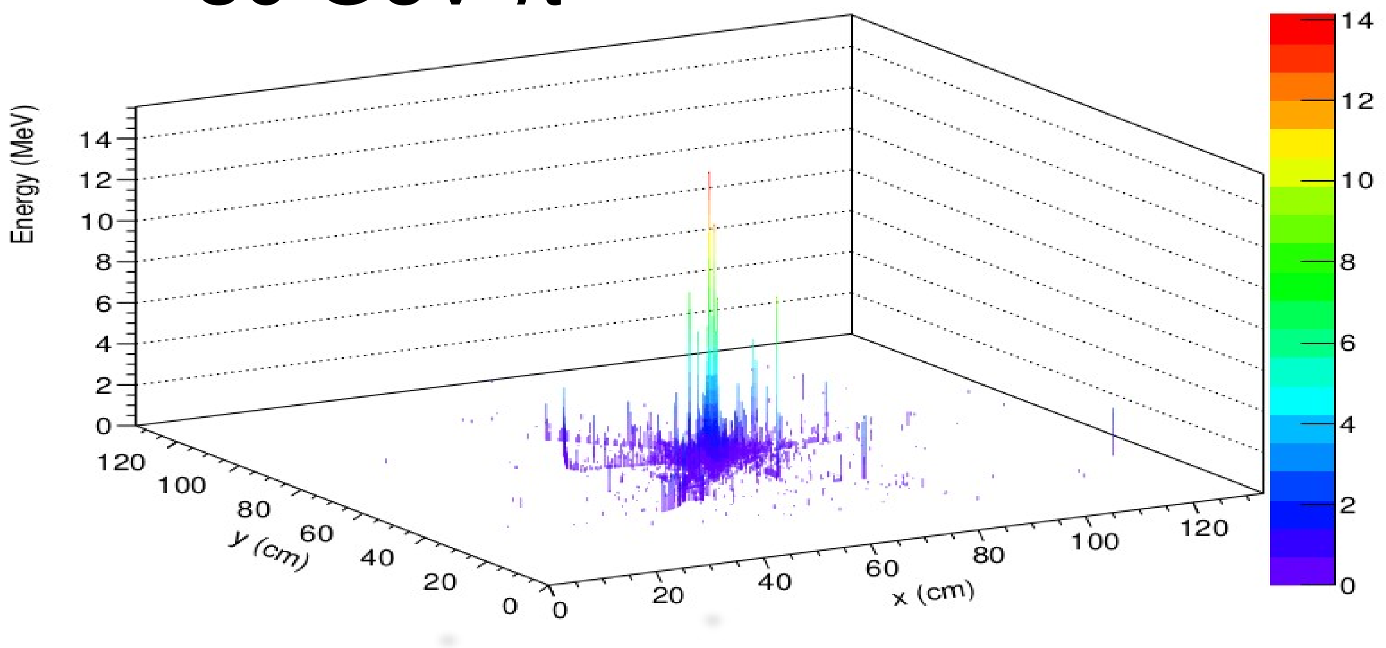
~10% (~50%) within ~1 (~10) mm from shower axis

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

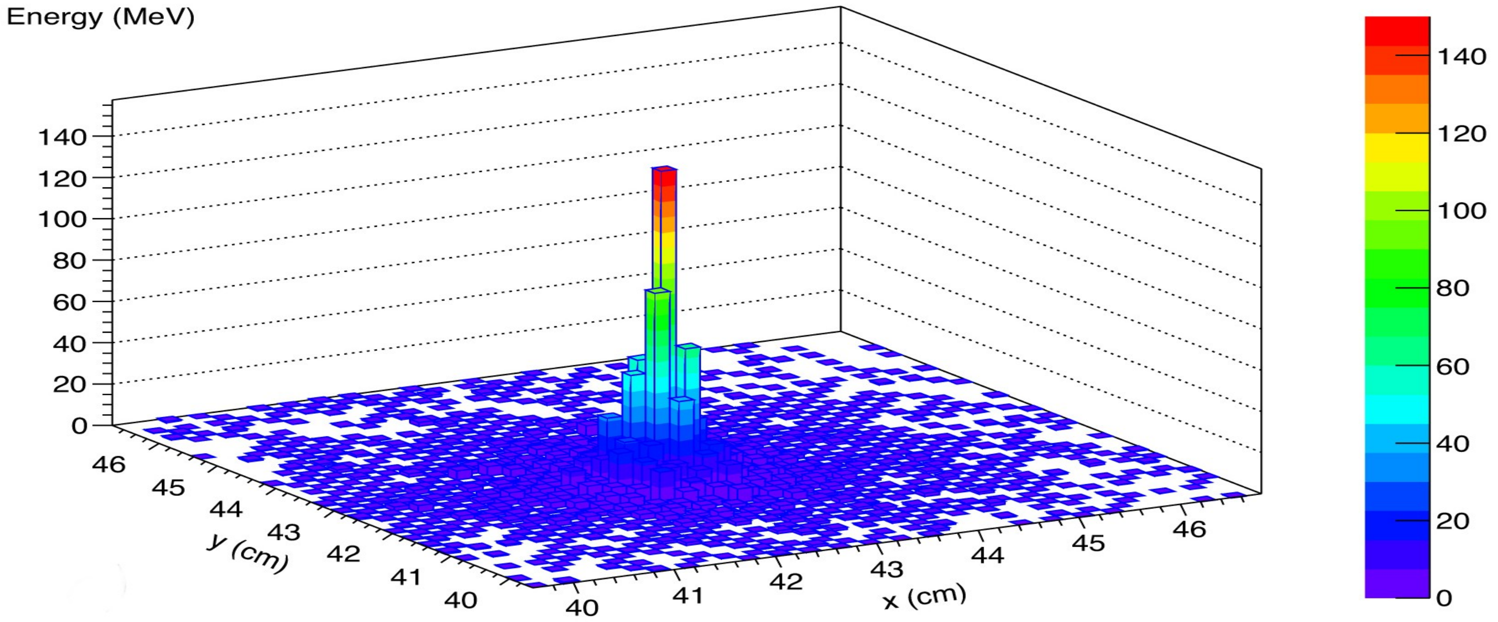
2D fibre imaging

Geant4 single-particle simulations

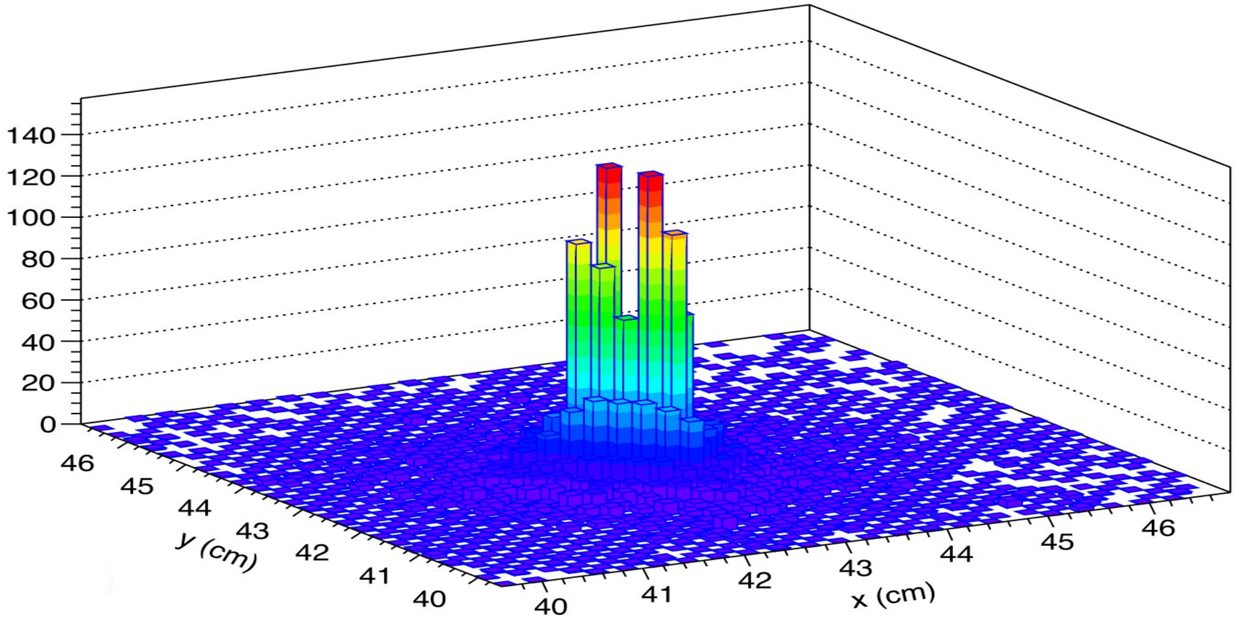
80 GeV π^-



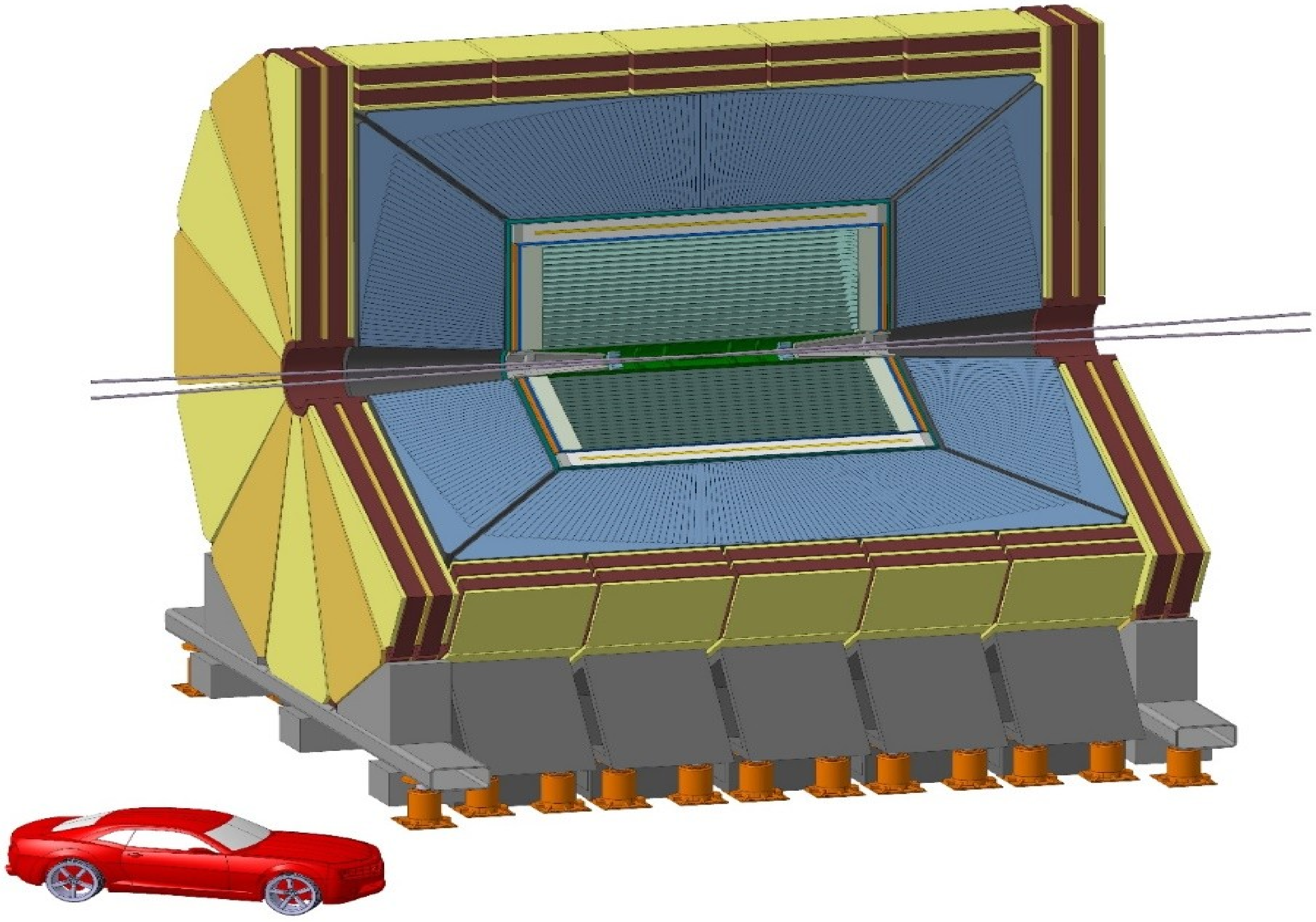
50 GeV e^-



100 GeV π^0

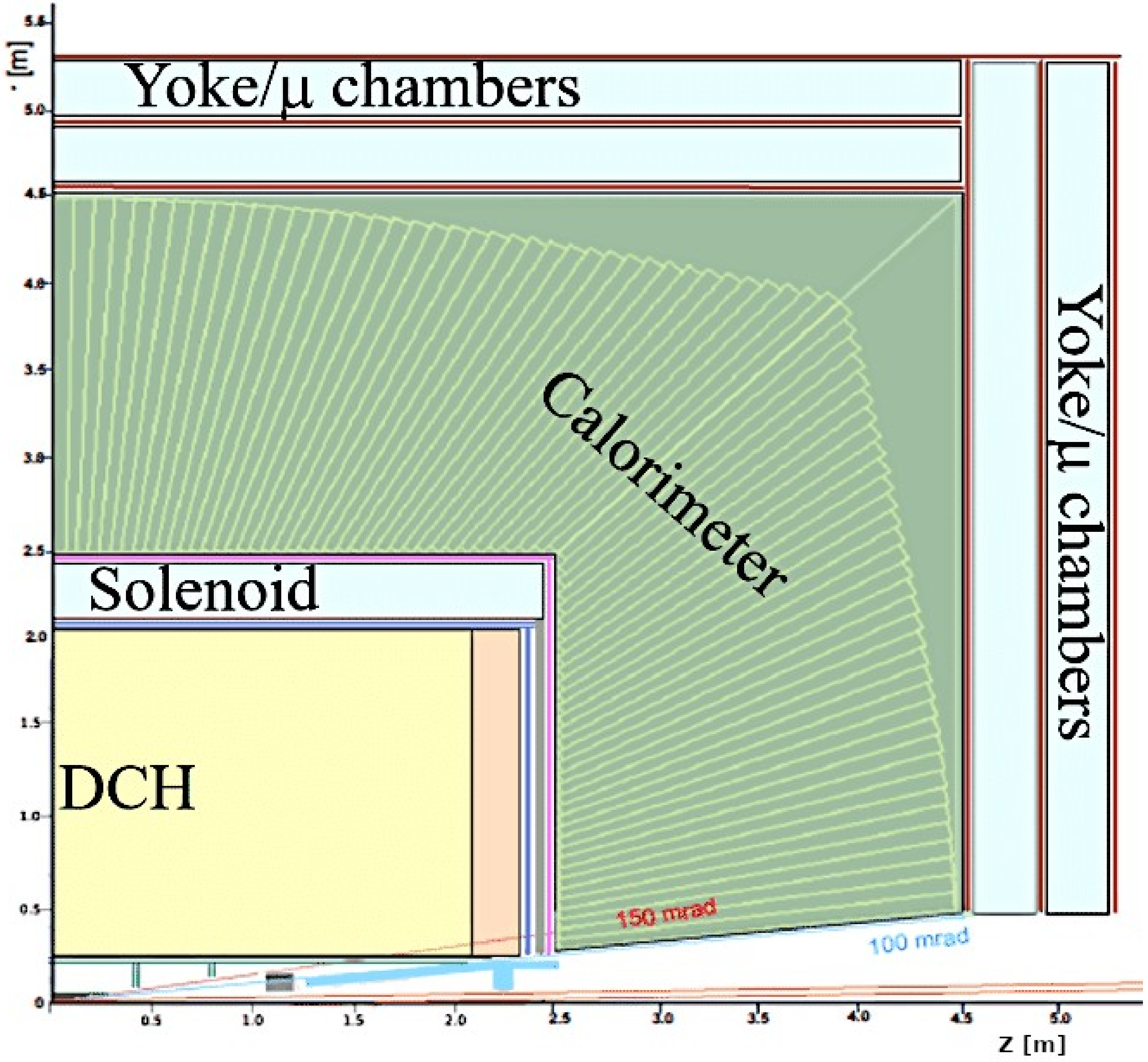


IDEA: Innovative Detector for e+e- Accelerators



IDEA baseline concept

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



IDEA dual-readout calorimetry group

Three main activity pillars:

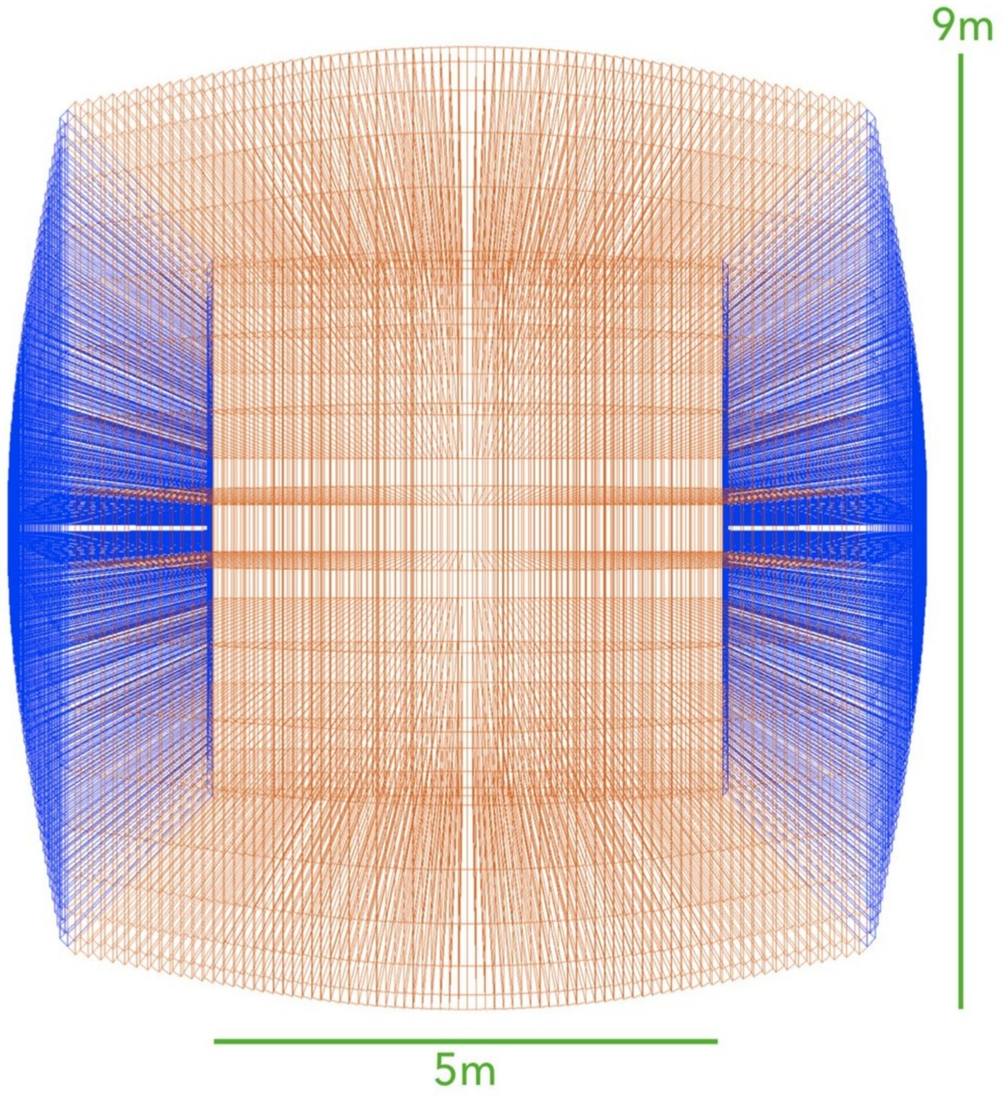
1. Europa: INFN, Sussex University → mainly (but not only) fibre-sampling calorimetry

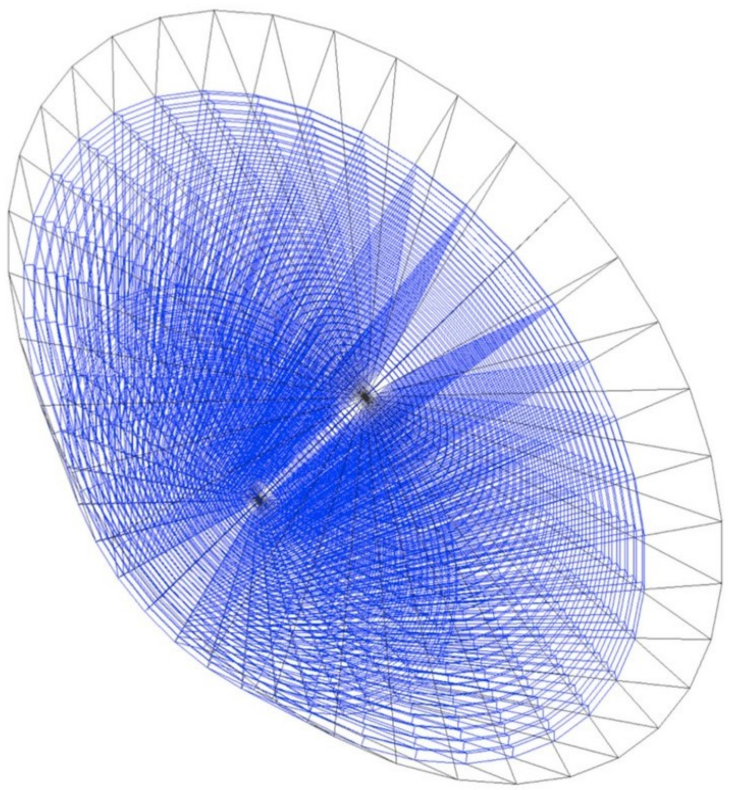
2. Korea → projective fibre-sampling calorimetry

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

keywords: dual readout, high granularity & timing

IDEA all-fibre DR calorimeter option



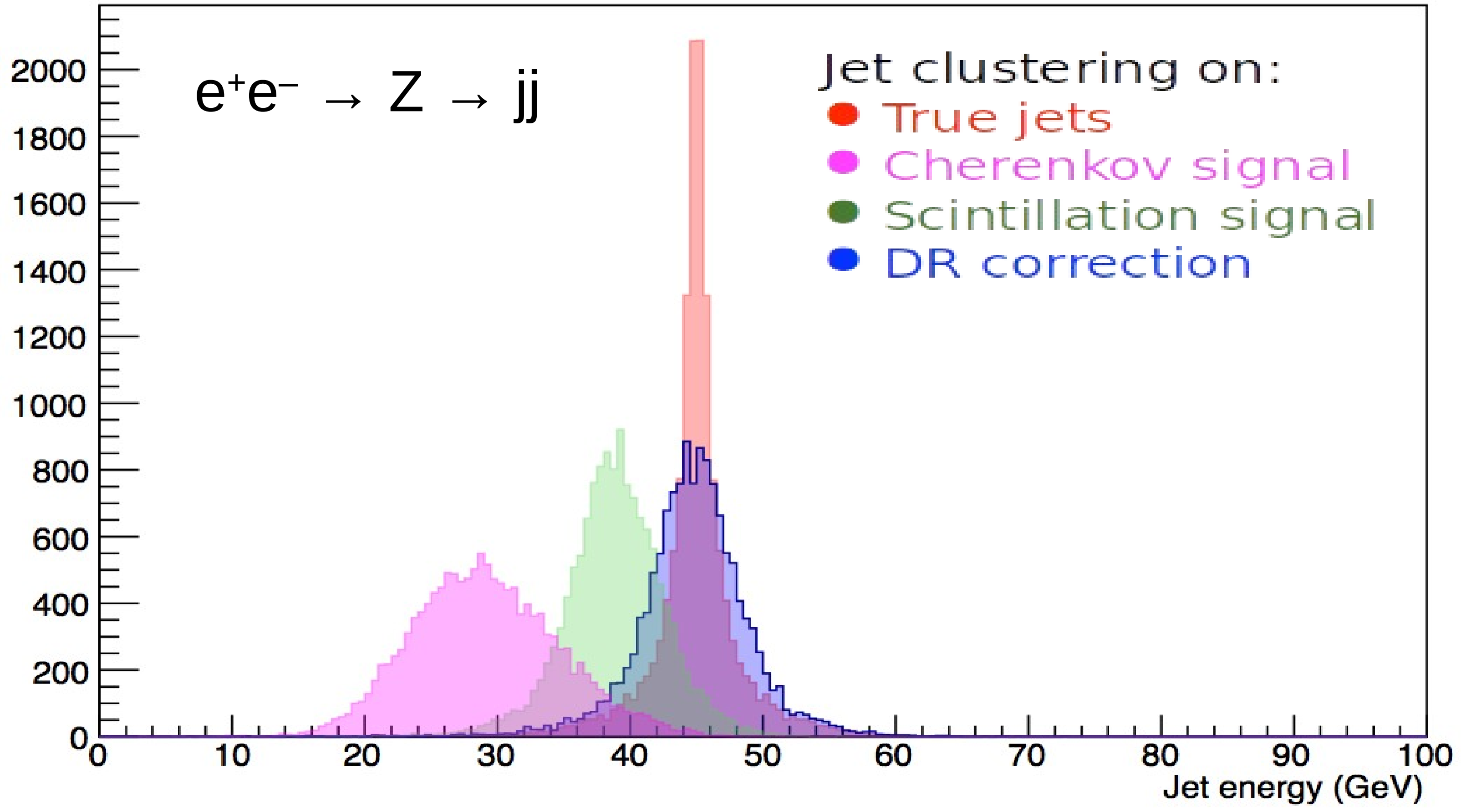


- DR fibre calorimeter
  - O(100 M) fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
    - ϑ coverage: $|\vartheta| > 100$ mrad
- G4 simulation available
  - tuned to RD52 TB data

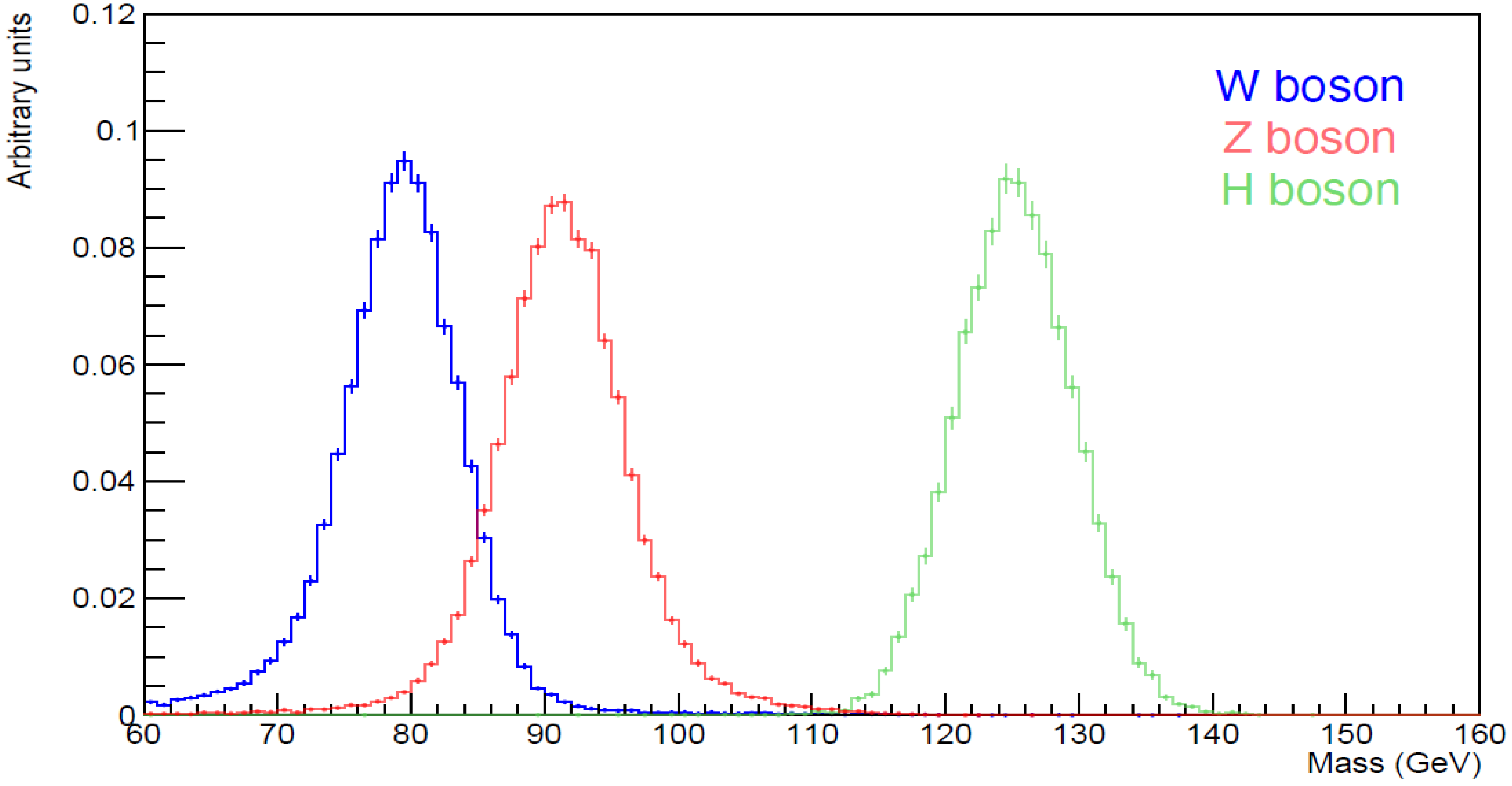
Geant4 simulations

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

Single jet resolution @ 45 GeV

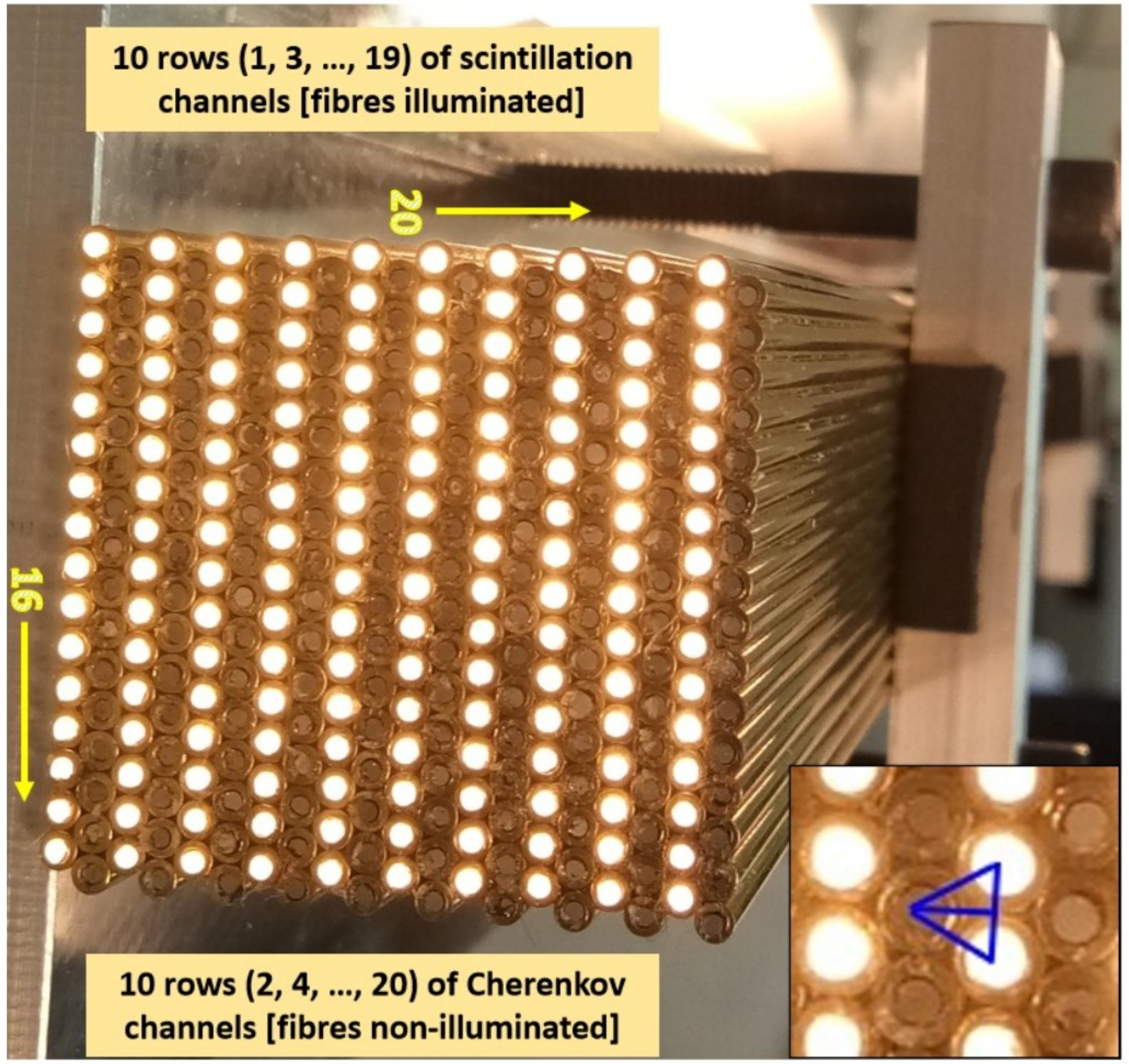


W/Z/H → jj invariant mass

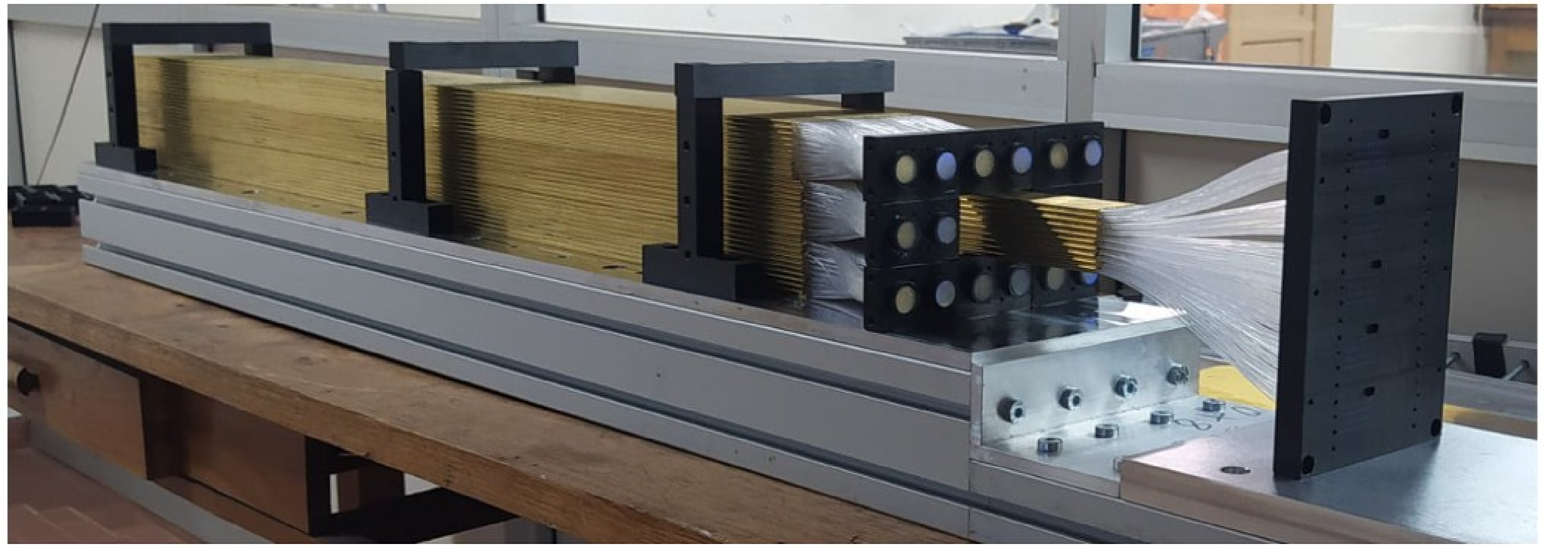


IDEA 2020 em-size bucatini prototype (EU)

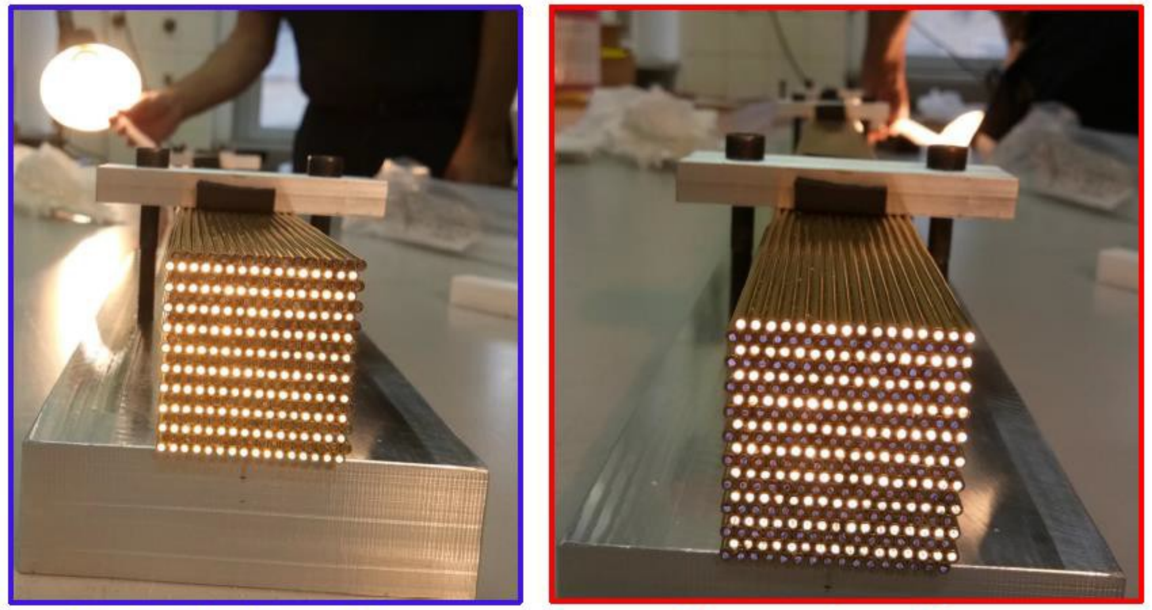
Nine ~3.5×3.3 cm^2 towers made of capillary brass tubes



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

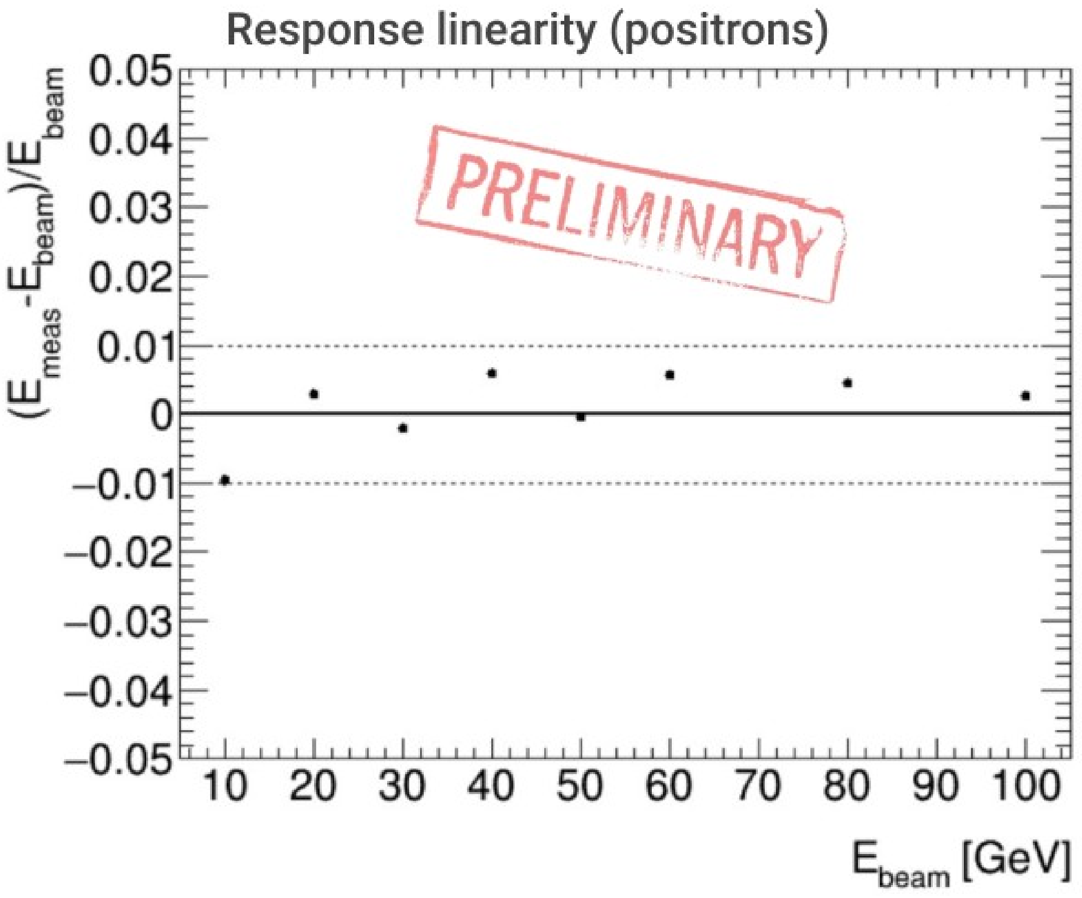


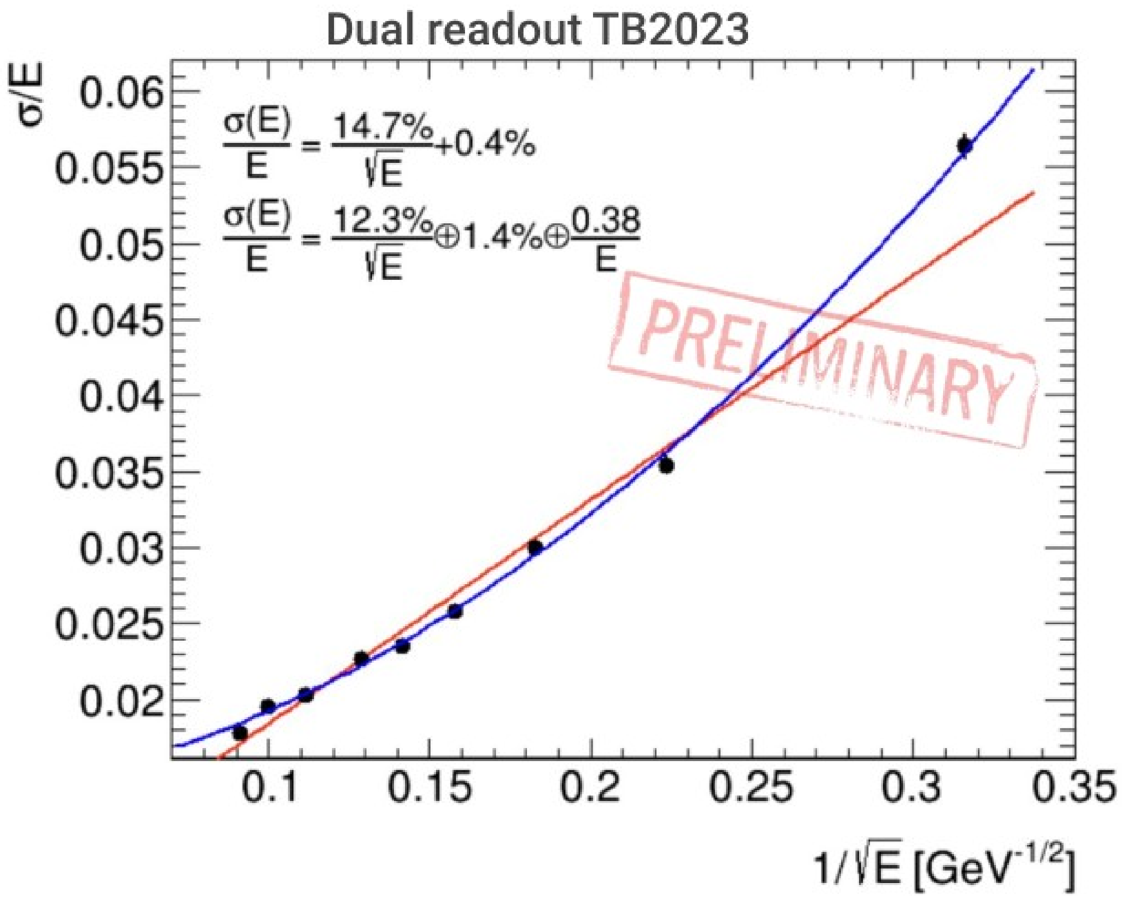
Eight (surrounding) towers read out with PMTs



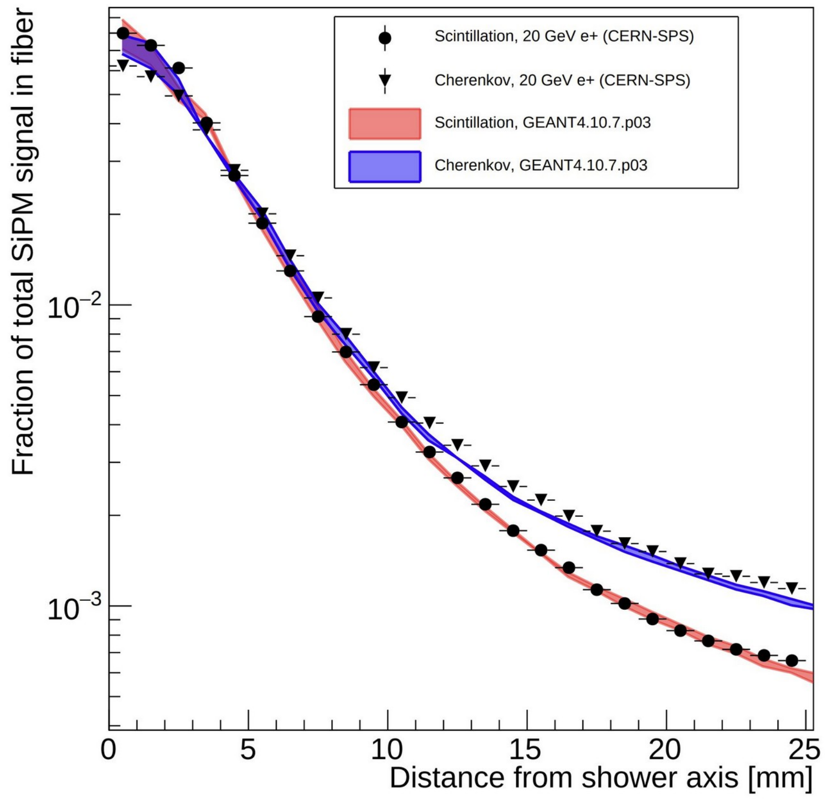
Scintillation fibers   Cherenkov fibers

Few testbeam results





Lateral shower profile (2021 TB)



5. Exploiting timing and DNNs

τ-decay tagging w/ DNNs

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

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

Simulation of both detector and SiPM response

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

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

NN implementation

Two DNN architecture variants studied:

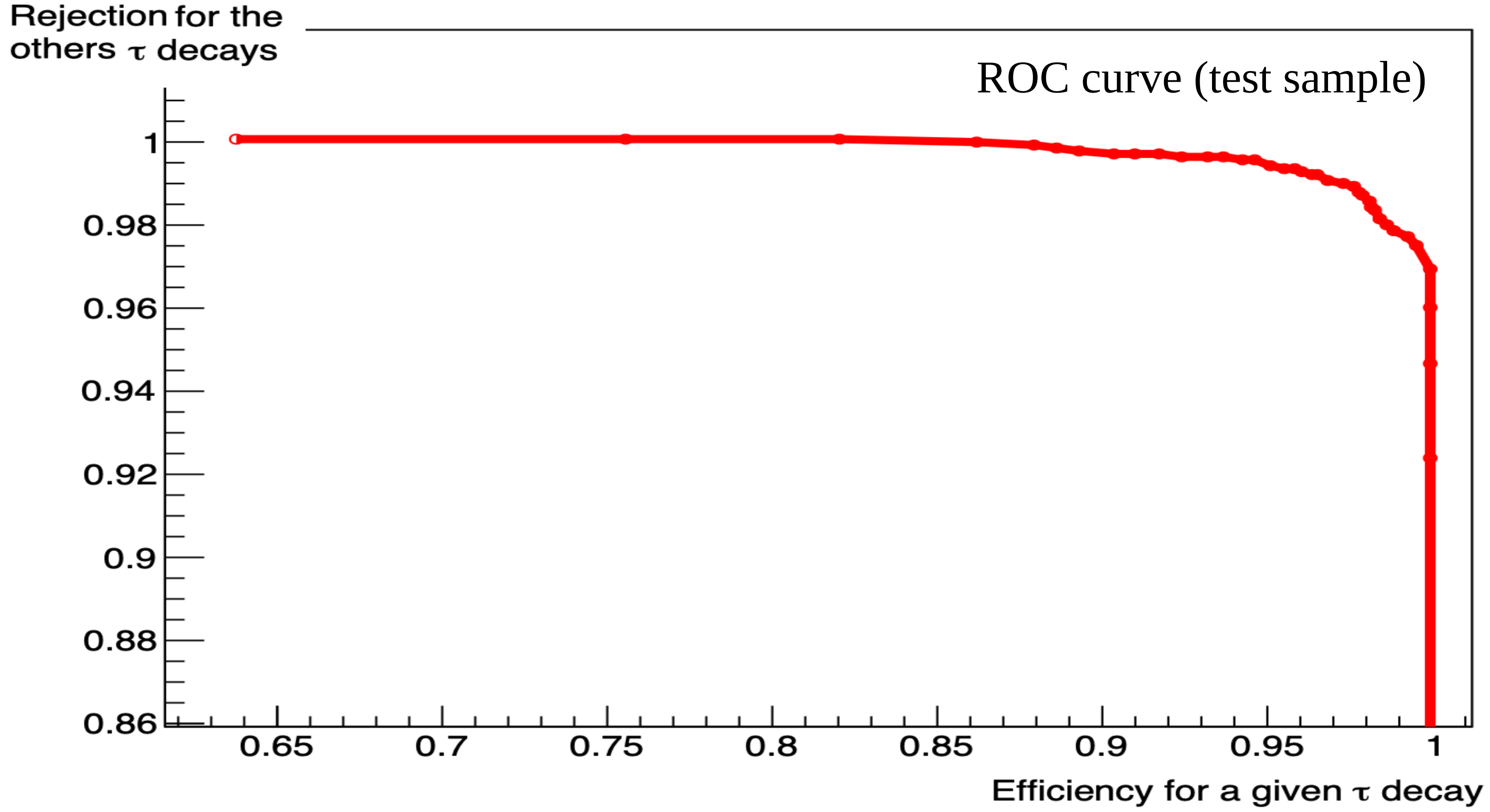
- VGG-11 like (VGG = Visual Geometry Group, Oxford Un.)
- Dynamic Graph CNN (DGCNN)

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

Training set: 6 BR × 2000 evts

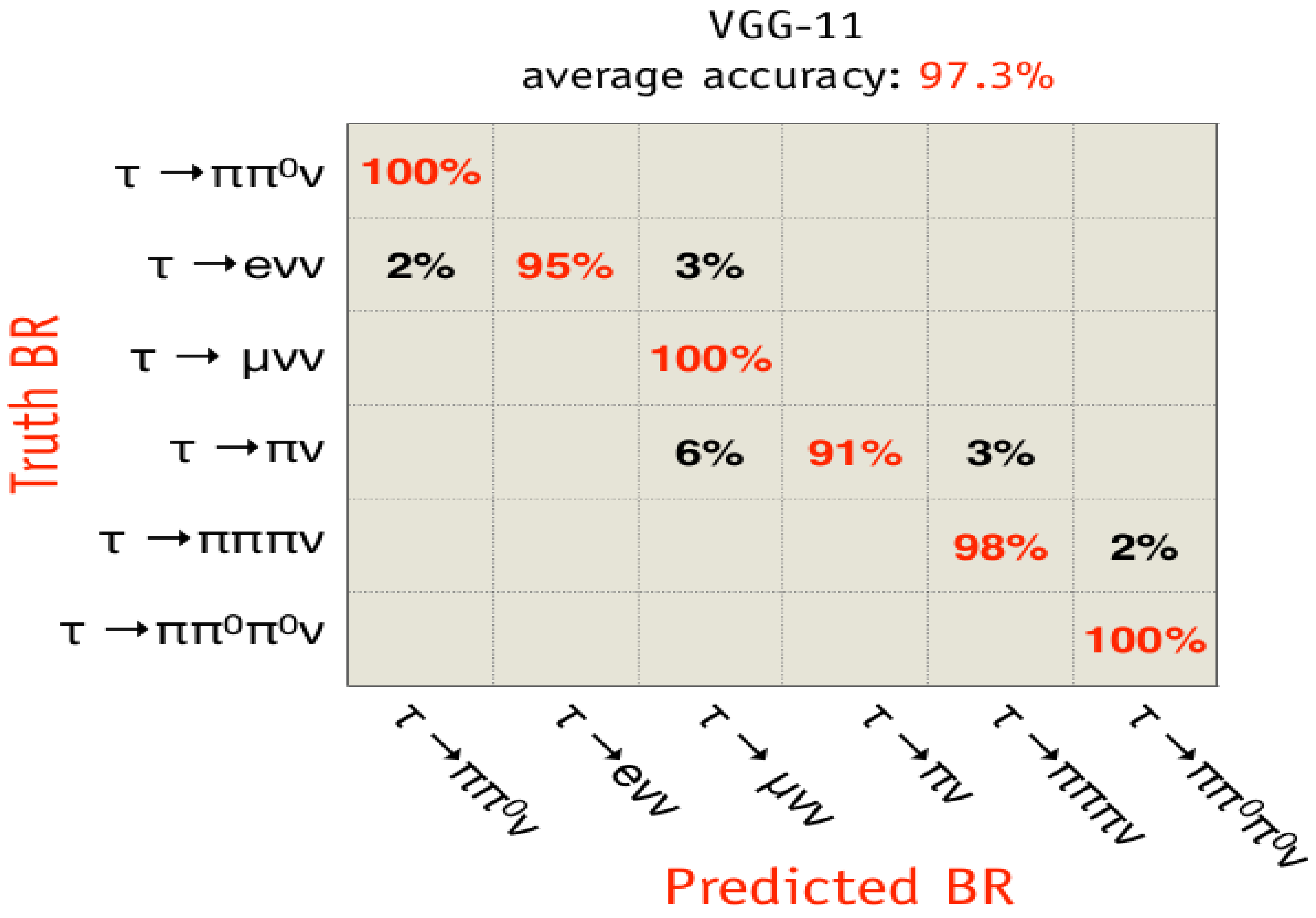
$\tau \to \pi\pi^0\nu$
$\tau \to \mu\nu\nu$
$\tau \to e\nu\nu$
$\tau \to \pi\nu$
$\tau \to \pi\pi\pi\nu$
$\tau \to \pi\pi^0\pi^0\nu$

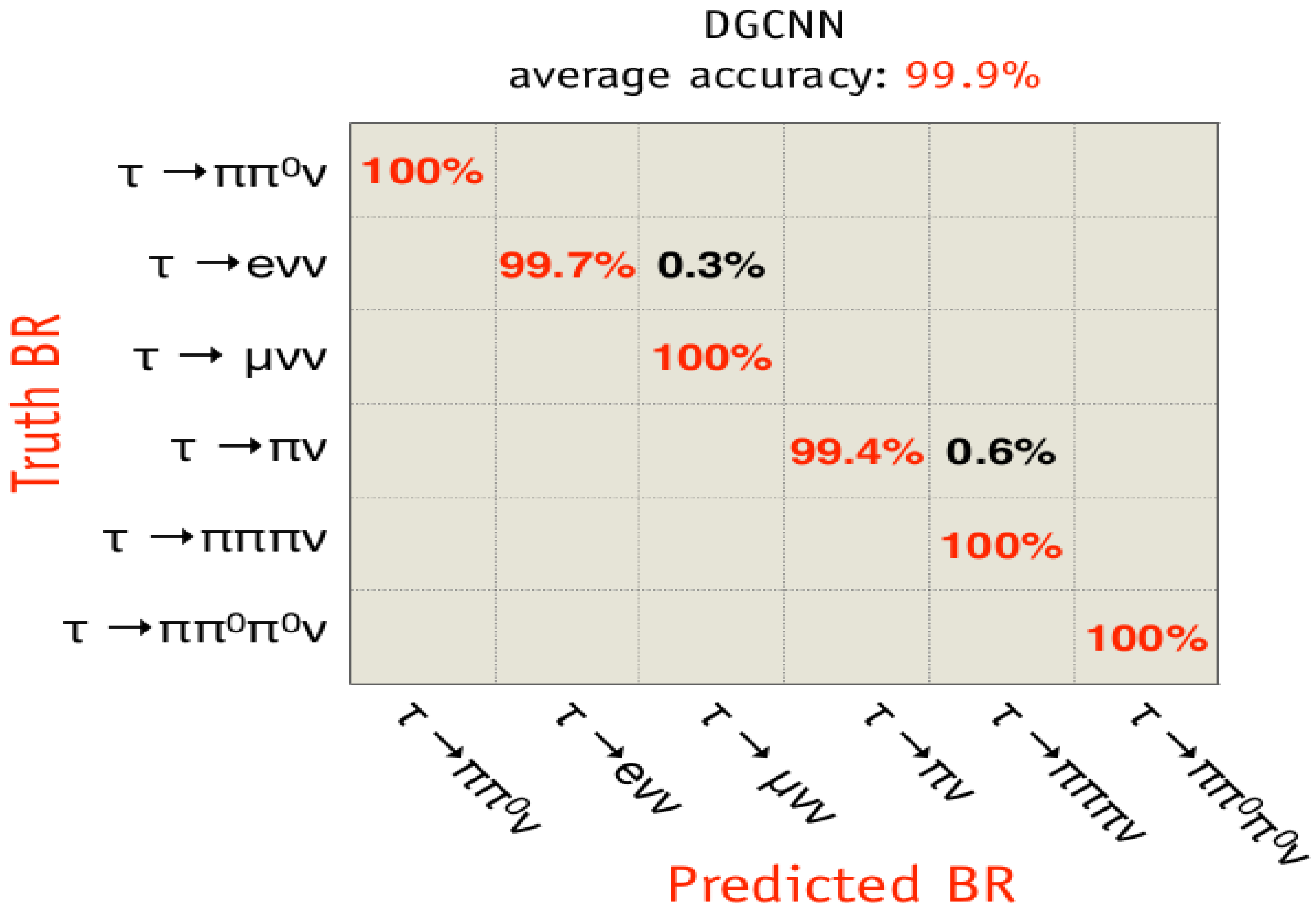
VGG example



NN performance

Confusion matrix on test set





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

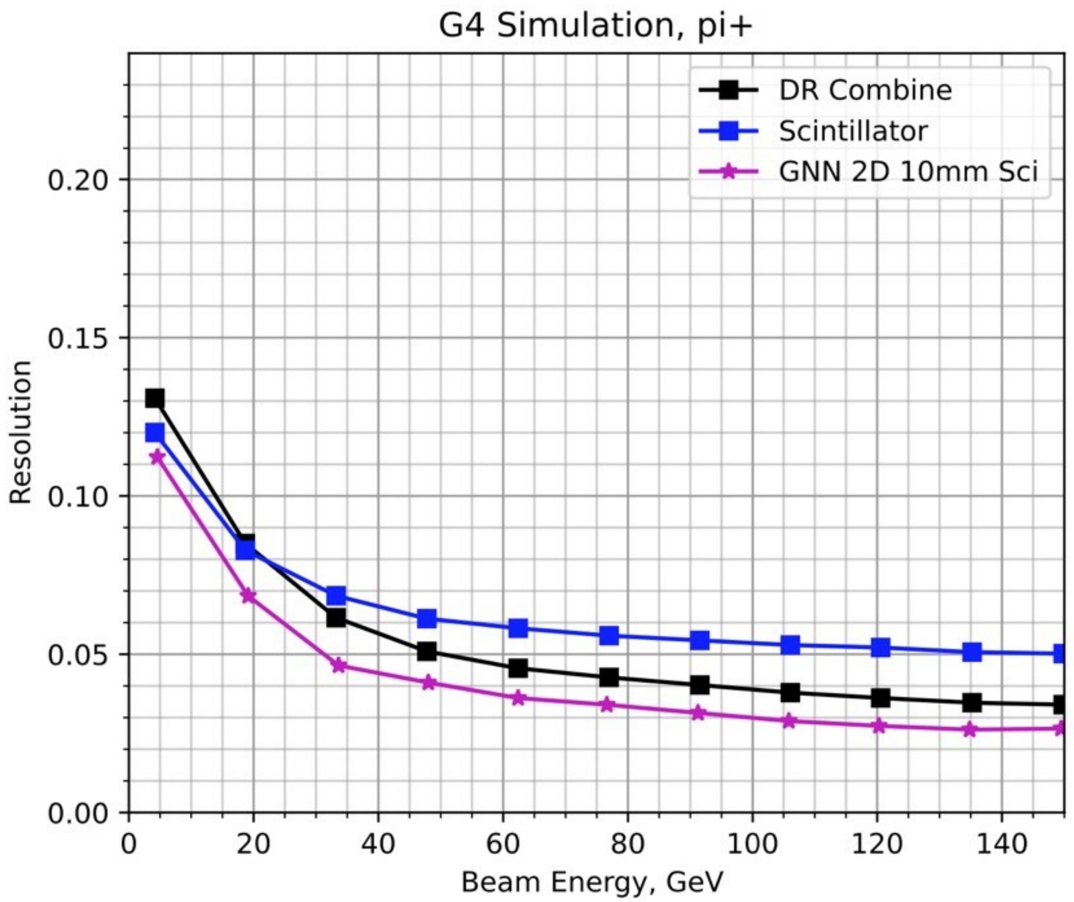
Preliminary results
No optimisation

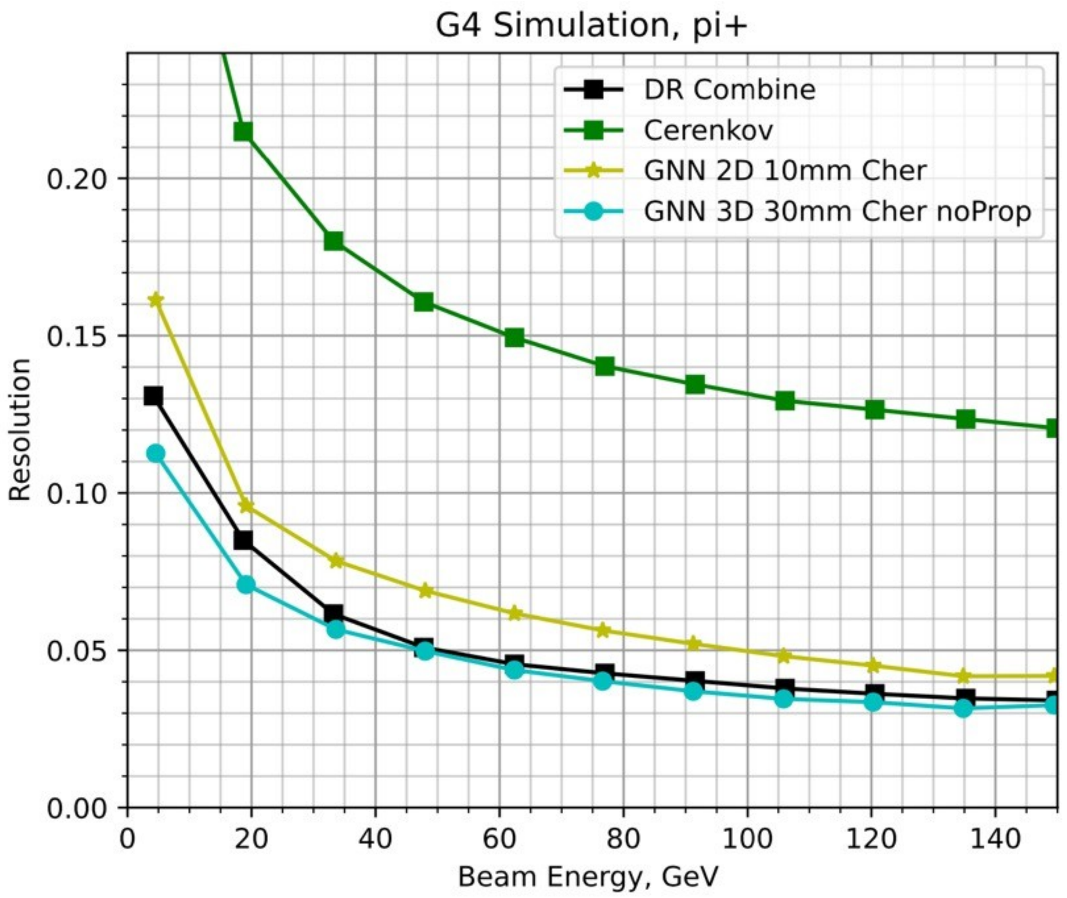
Cu absorber (2 m deep)

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

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

3D imaging fibre DR calorimeter coupled to Graph DNN





longitudinal segmentation w/ timing (U.S.)

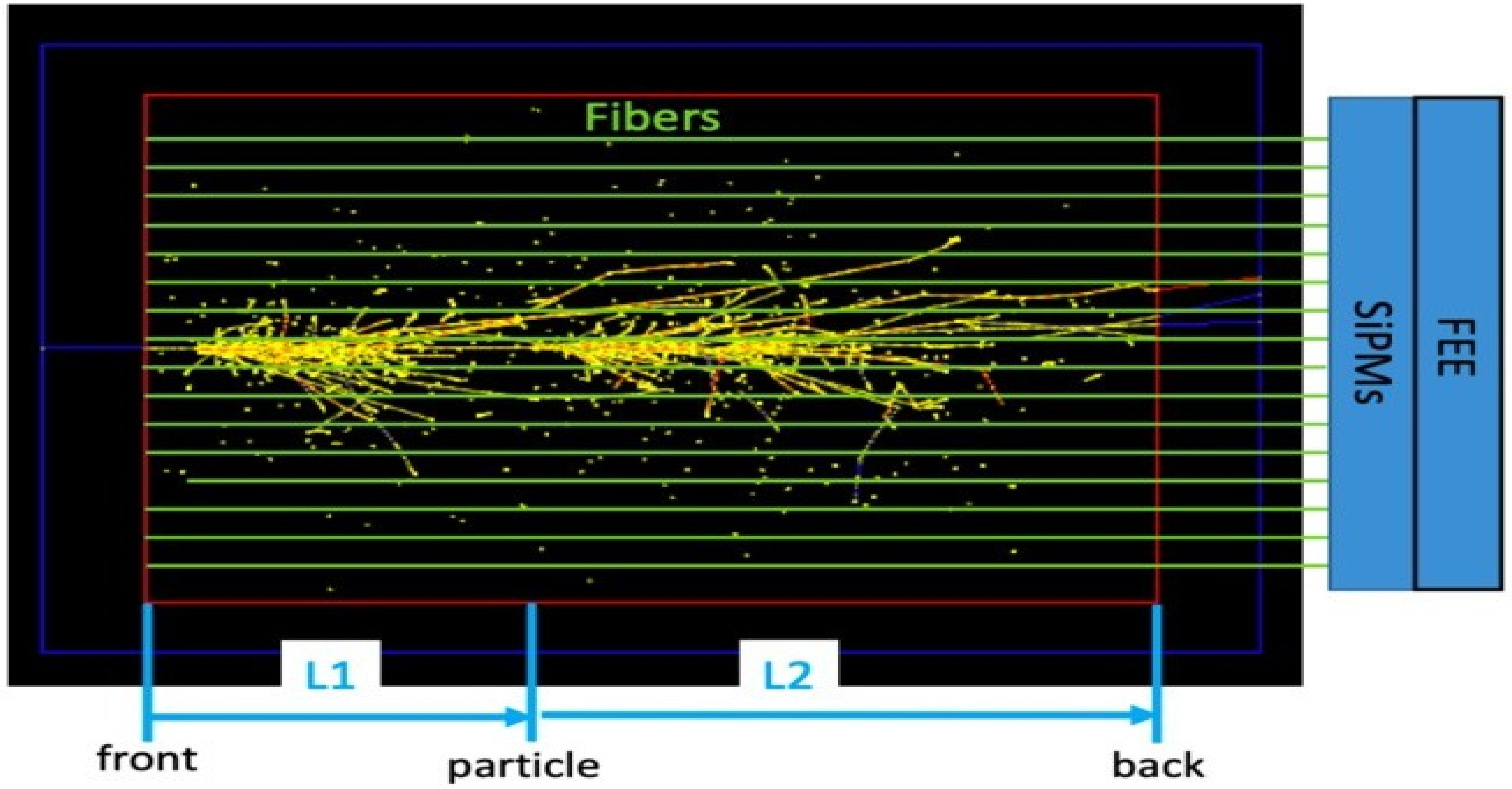


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

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

@ 100 GeV

only Cherenkov fibres

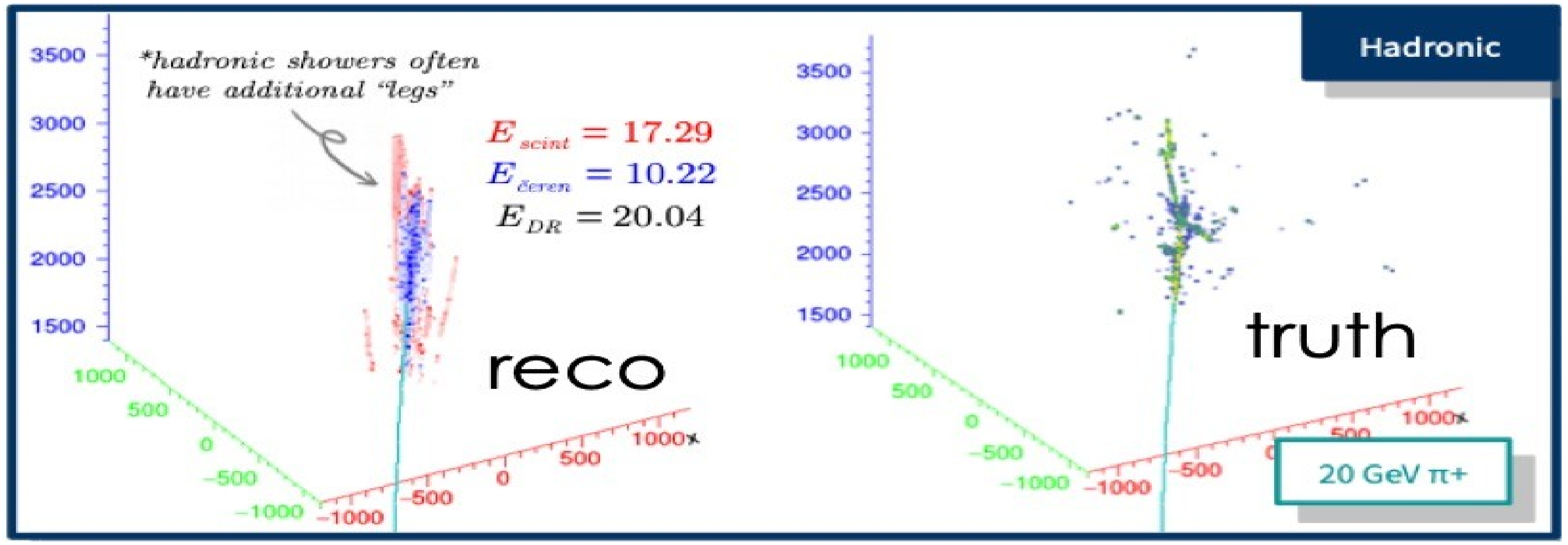
longitudinal segmentation w/ timing (Korea)

Full SiPM signal sampled at 10 GHz

FFT used to mitigate exponential tail

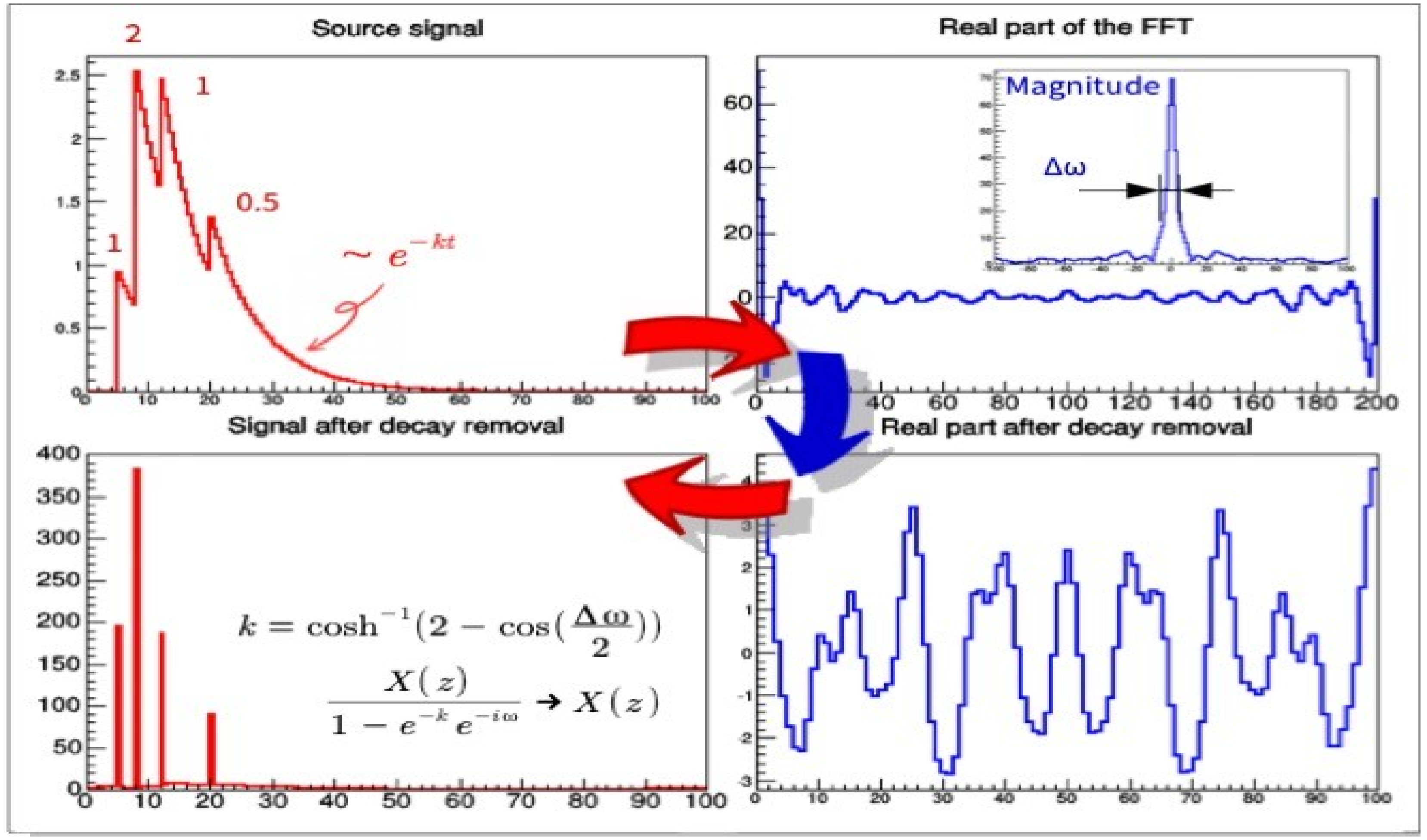
Unlocks full longitudinal information about energy deposit

Combined with DR information
allows in-shower cluster identification



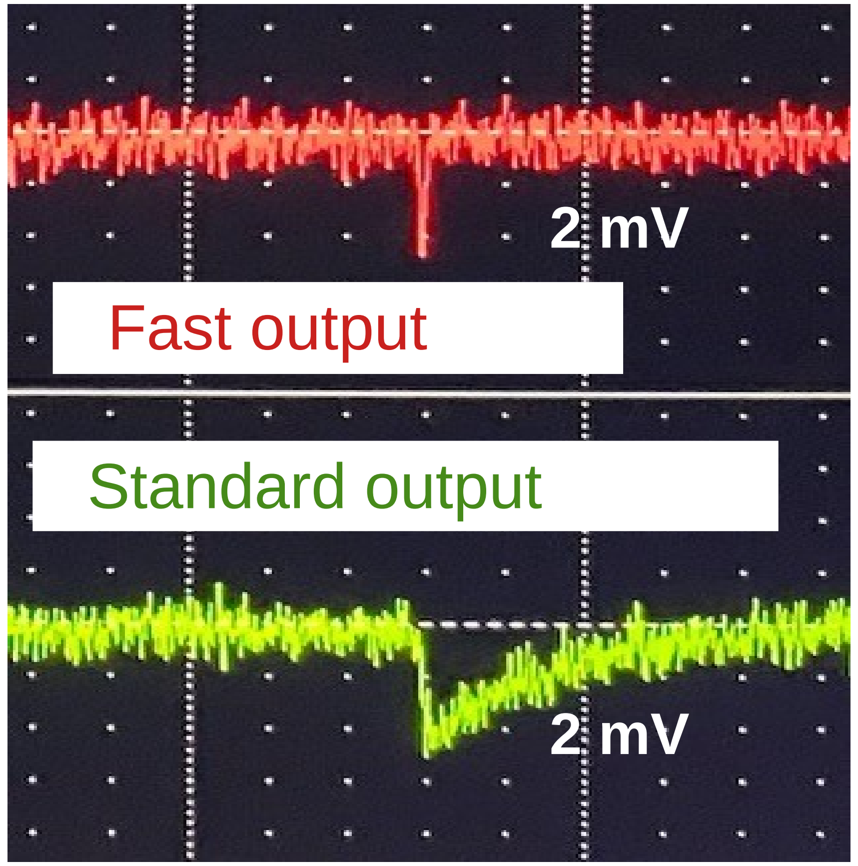
Time domain

Frequency domain

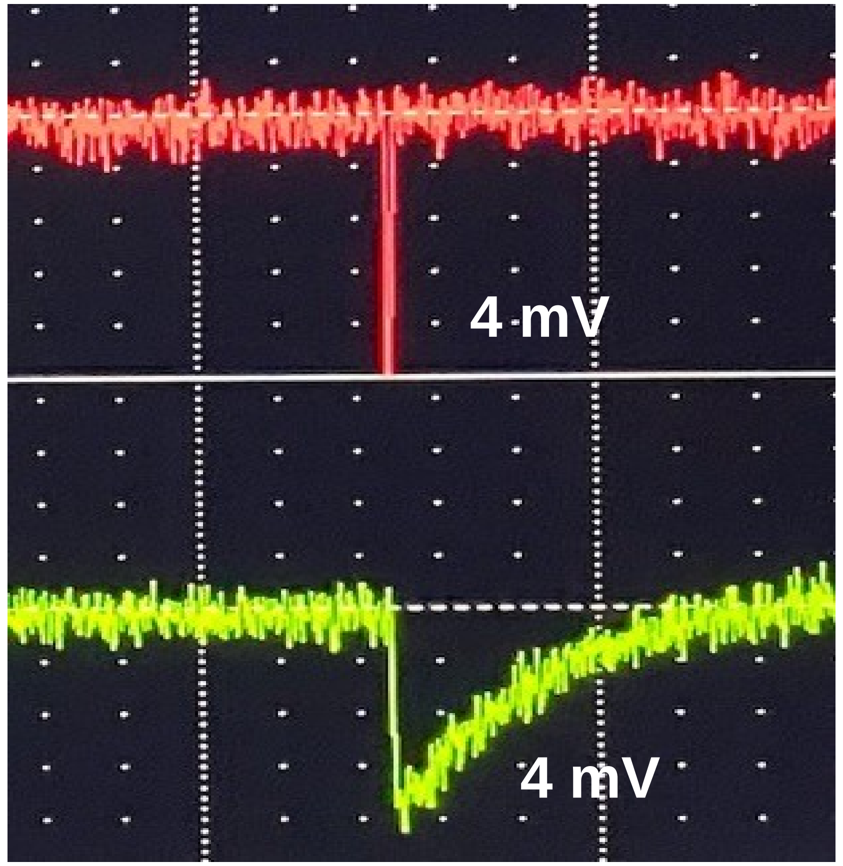


waveform digitisation (U.S.)

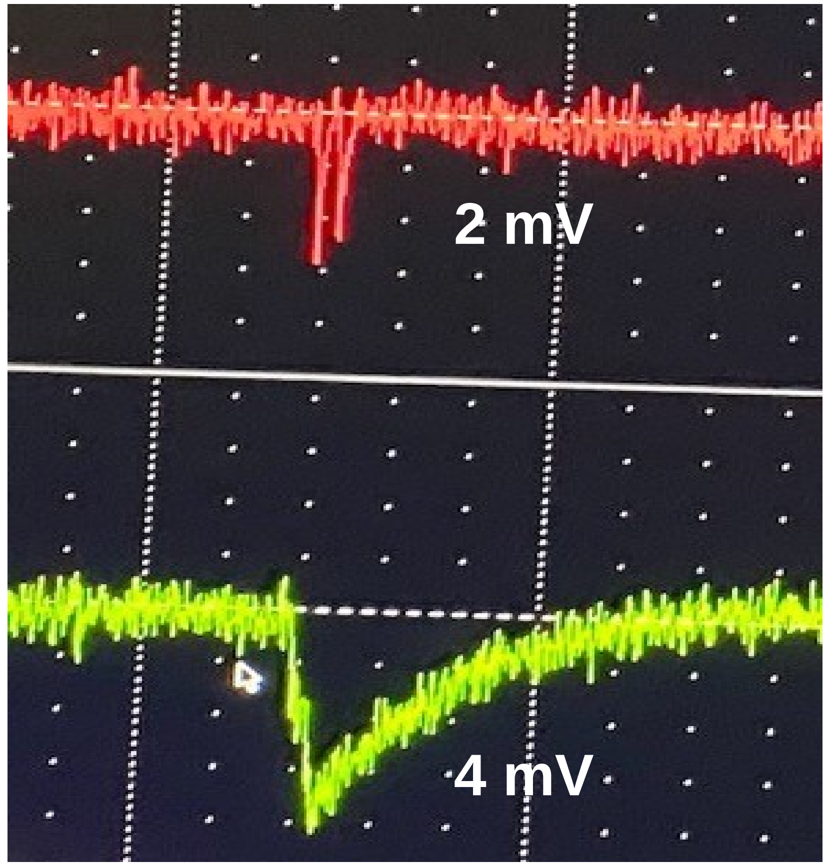
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard outputs



One-photon event



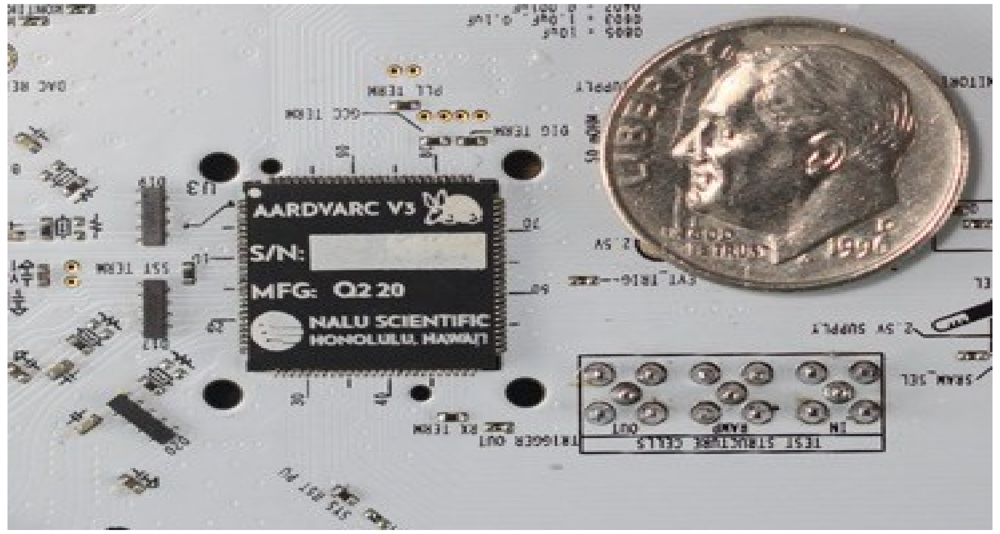
Two-photon event
(simultaneous)



Two-photon event
(5 ns apart)

NALU Scientific
AARDVARC v3

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

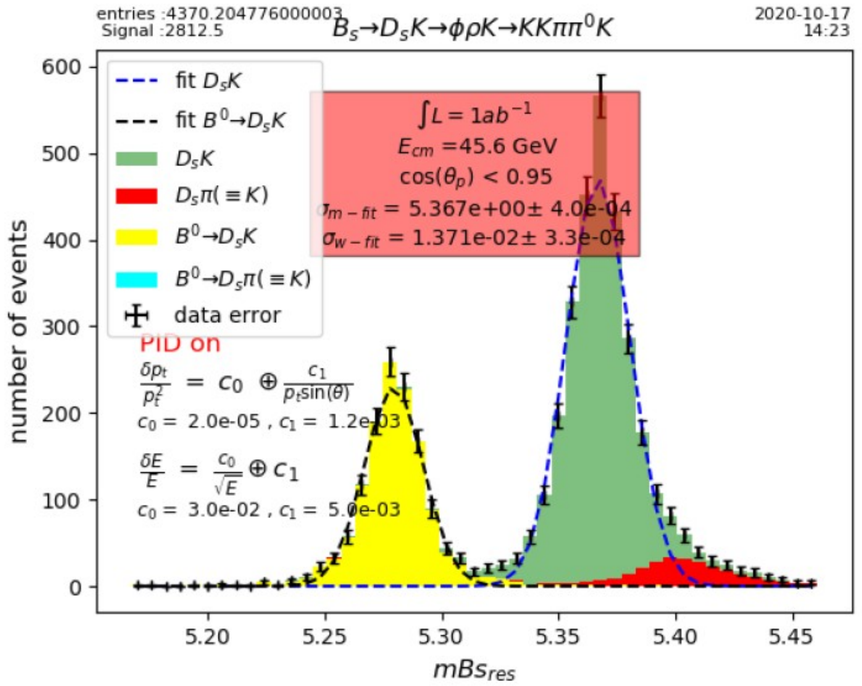


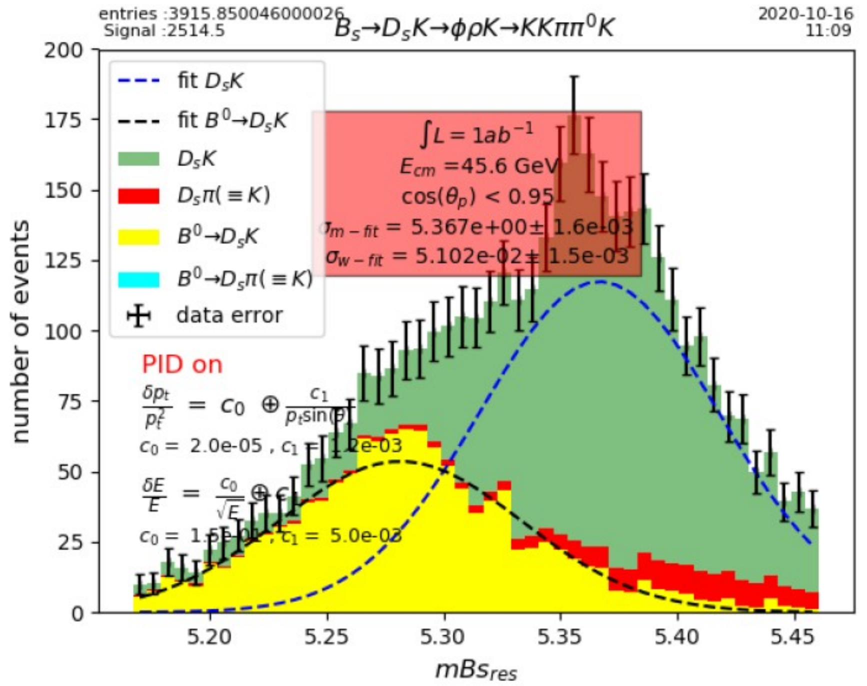
6. Crystal option (IDEA++) and pPFA

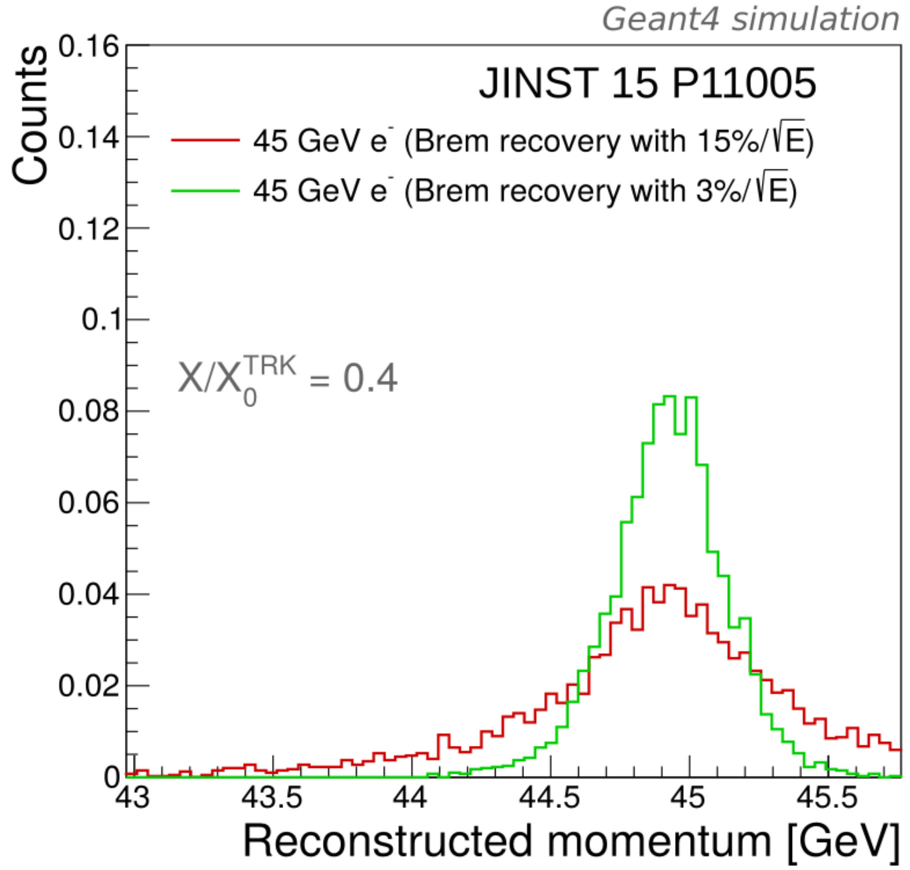
high EM energy resolution @ FCC-ee

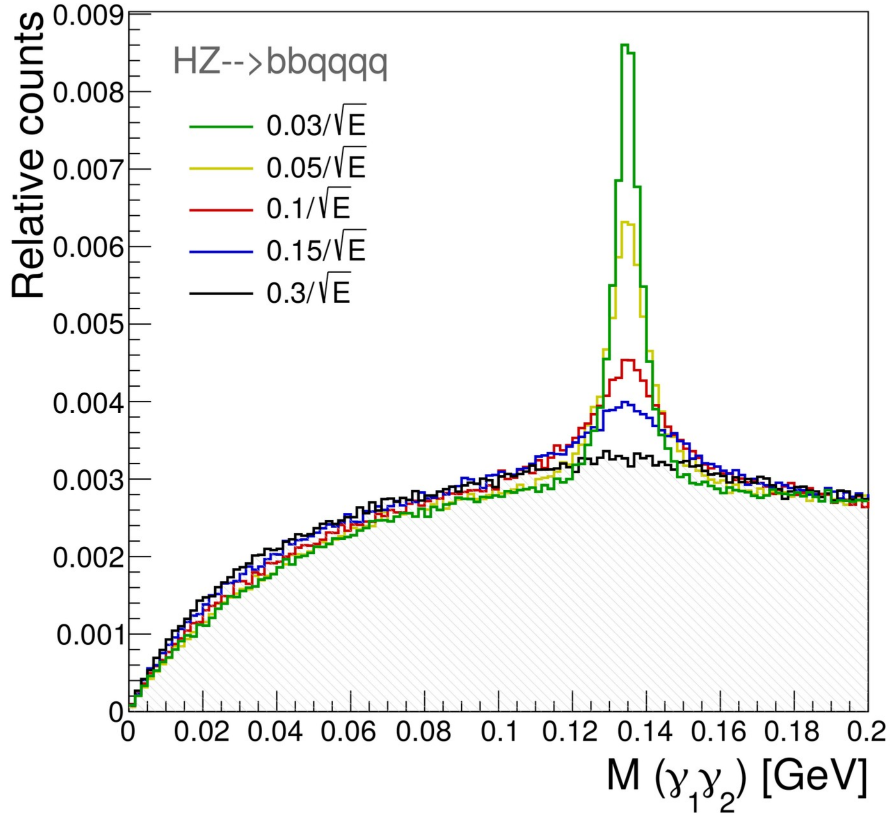
3%/√E EM energy resolution → improve event reconstruction and expand landscape for physics studies @ e^+e^- colliders

- CP violation studies with B_s decay to final states with low energy photons
- Clustering of π^0's photons to improve performance of jet clustering algorithms
- Improve resolution of recoil-mass signal from Z→ee decays (recovering brems photons)





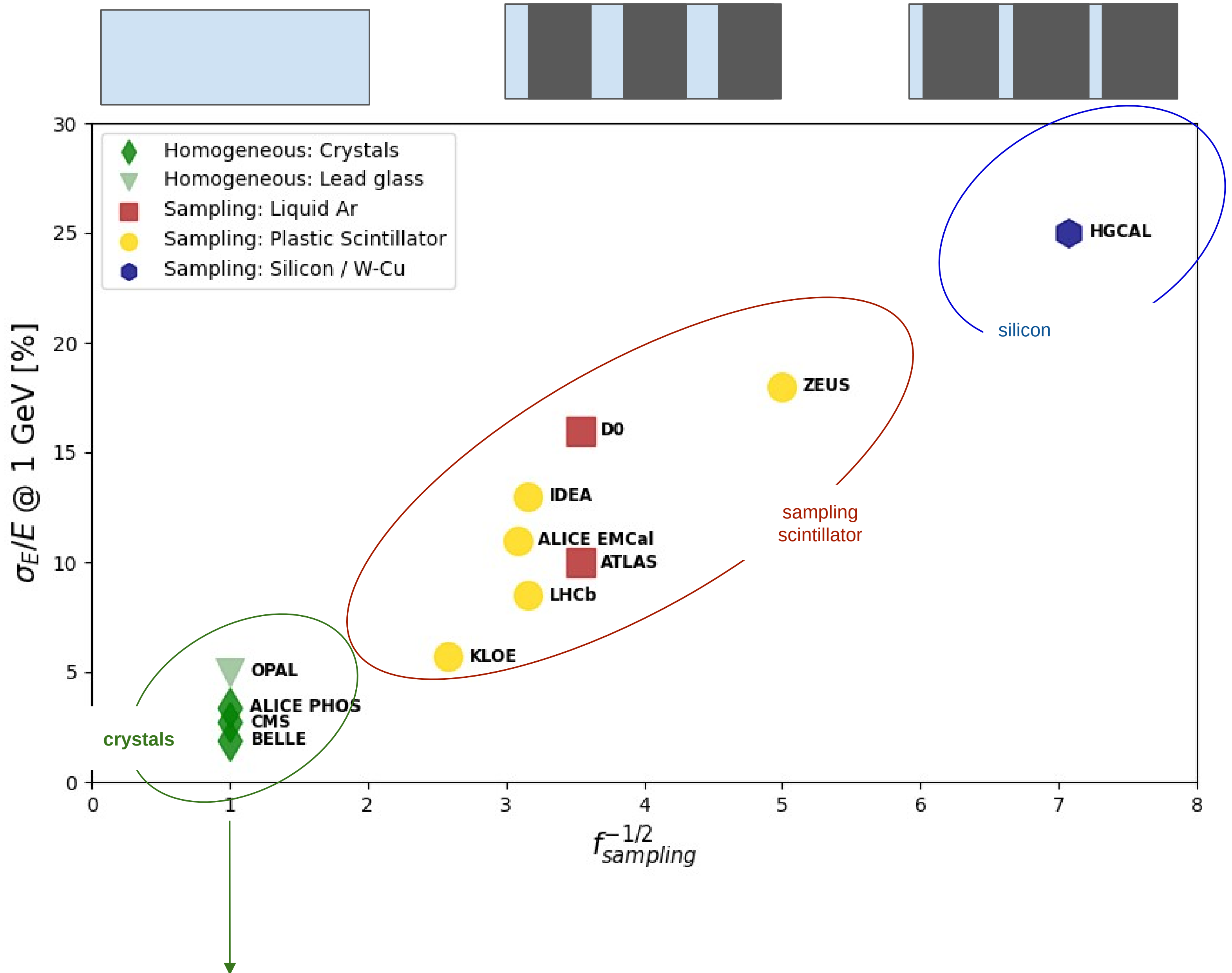




homogeneous crystal calorimetry

- Long history in pushing frontier of high EM resolution
- Only way to get 1-3%/√(E) energy resolution for photons (and thus π^0's)
- No stringent requirements on radiation tolerance and pileup @ future e^+e^- Higgs factorier → can exploit best possible precision of event reconstruction

A sample of existing and future calorimeters



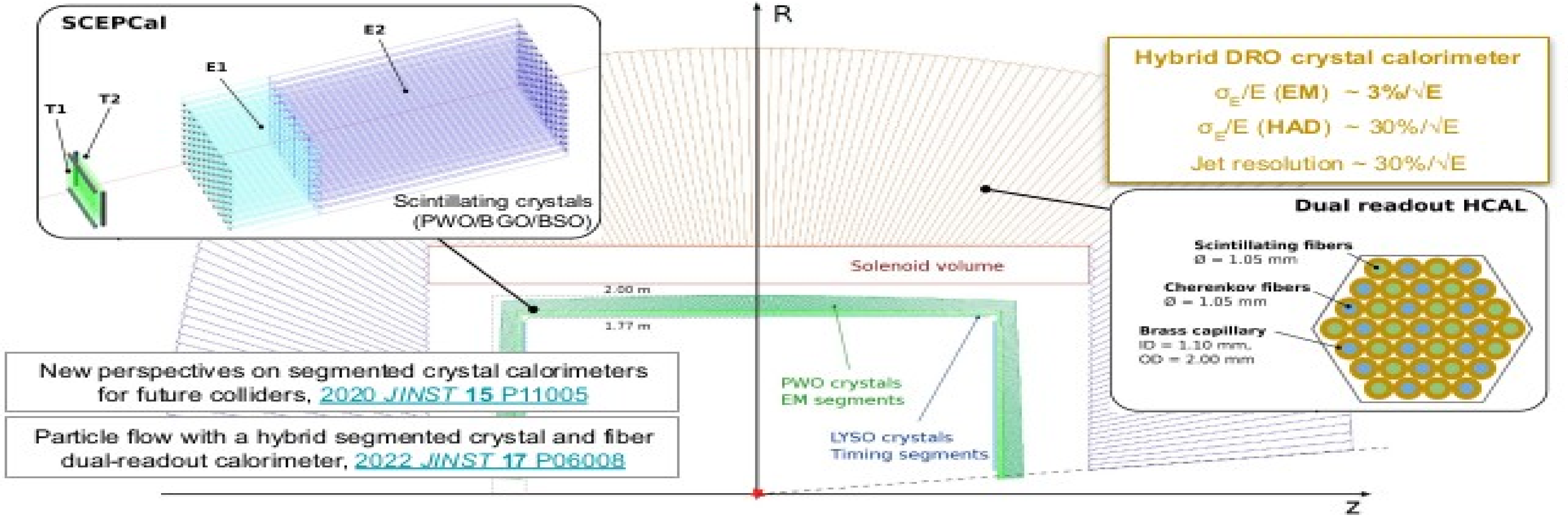
Entire EM shower sampled, large light signals produced

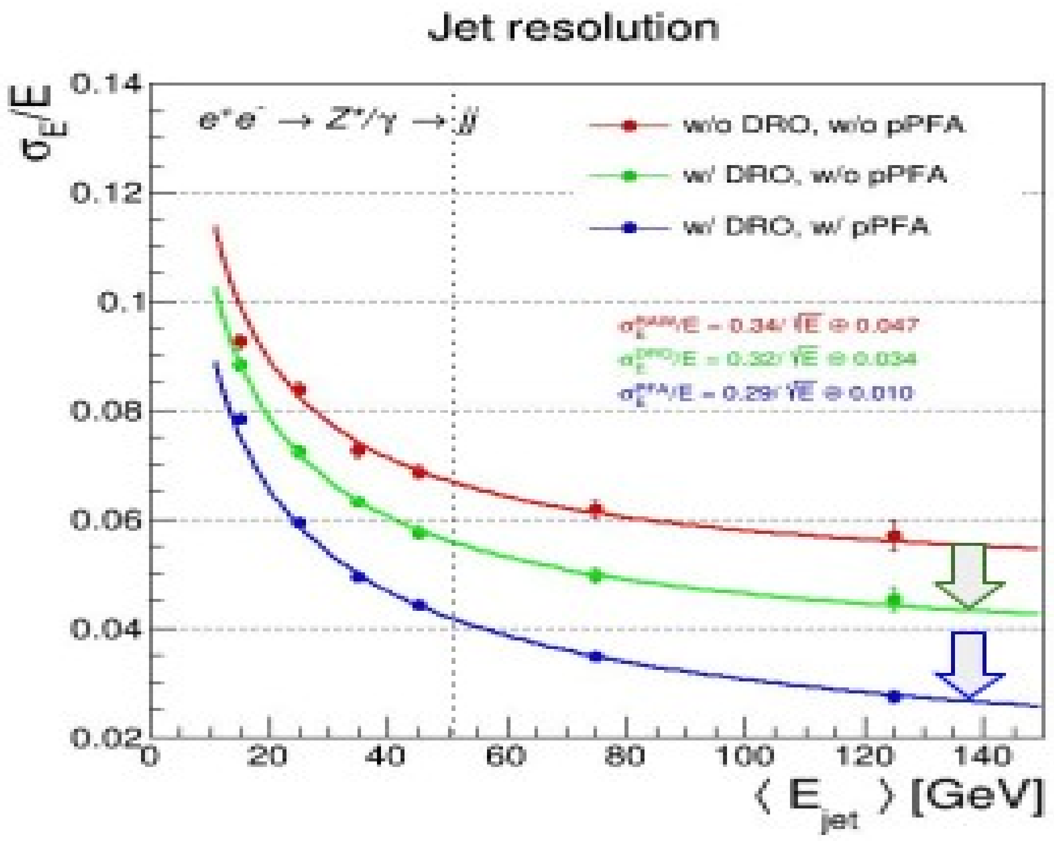
dual-readout crystal option (IDEA++)

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

ongoing joint efforts within US Calvision, IDEA and Crystal Clear collaborations

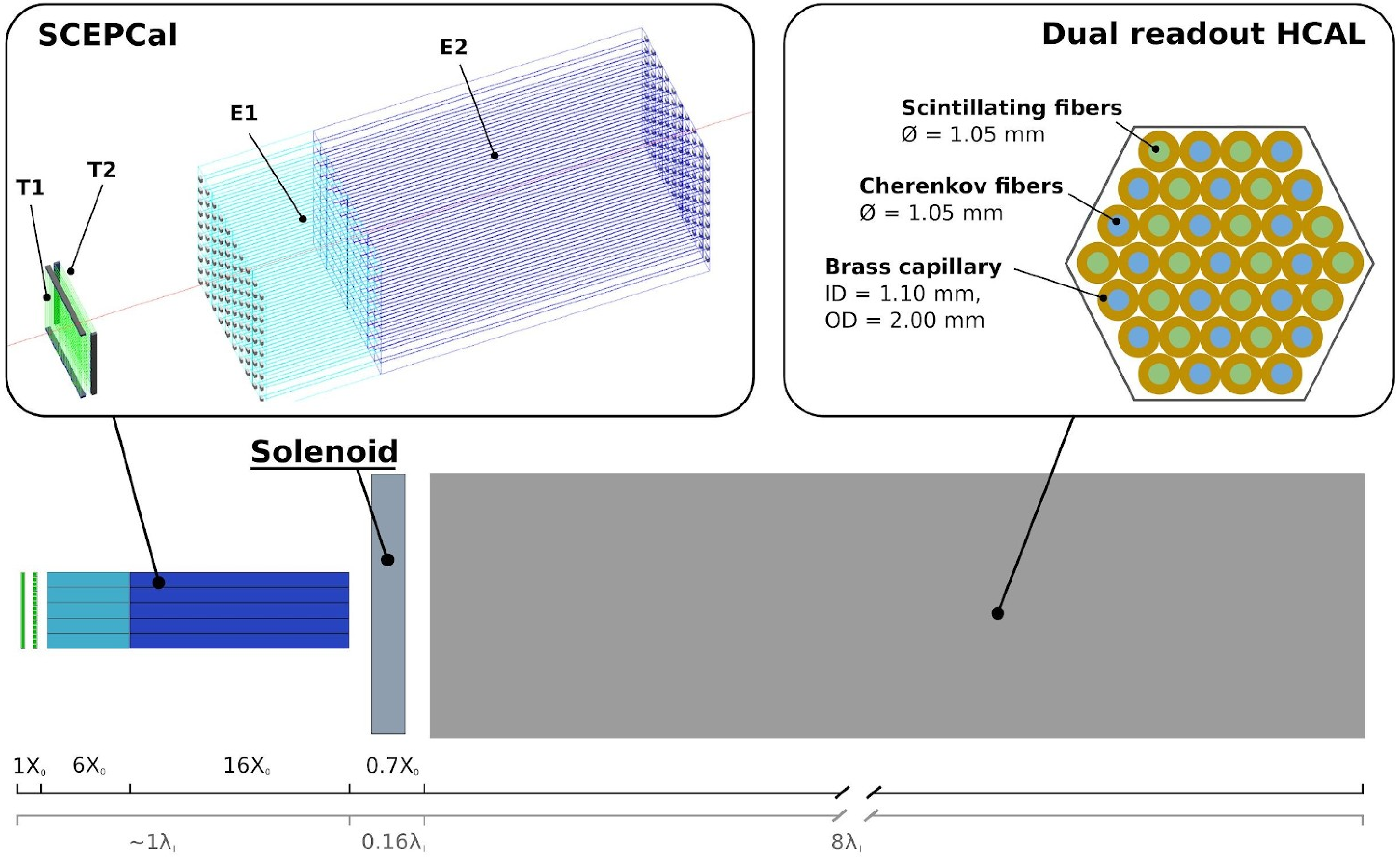
- proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPM readout)
- ongoing simulation effort in DD4HEP and FCC software + DR-pPFA developments





dual-readout crystal option (IDEA++)

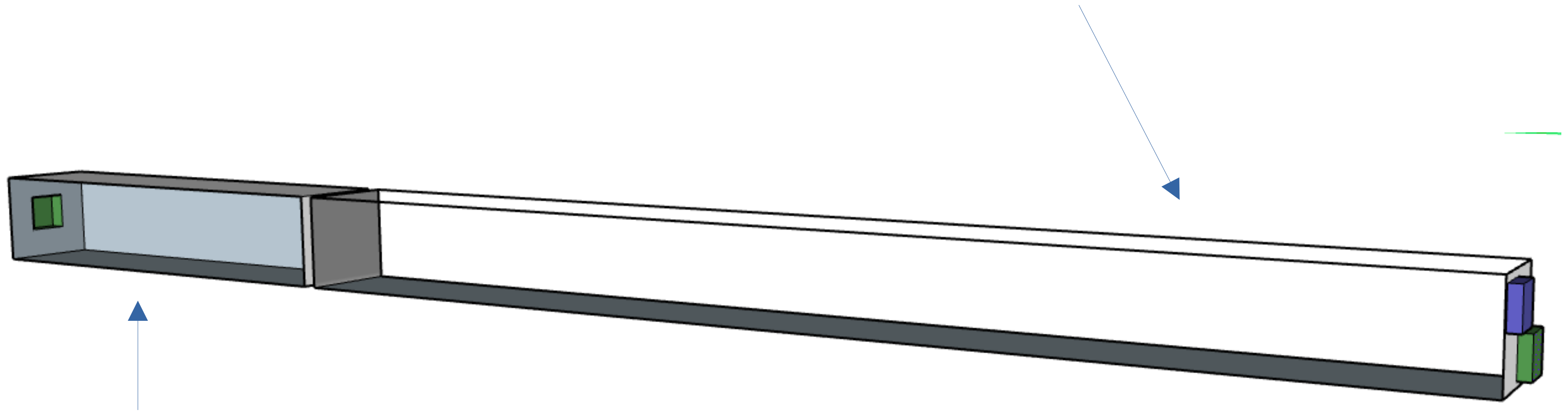
- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% /\sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$



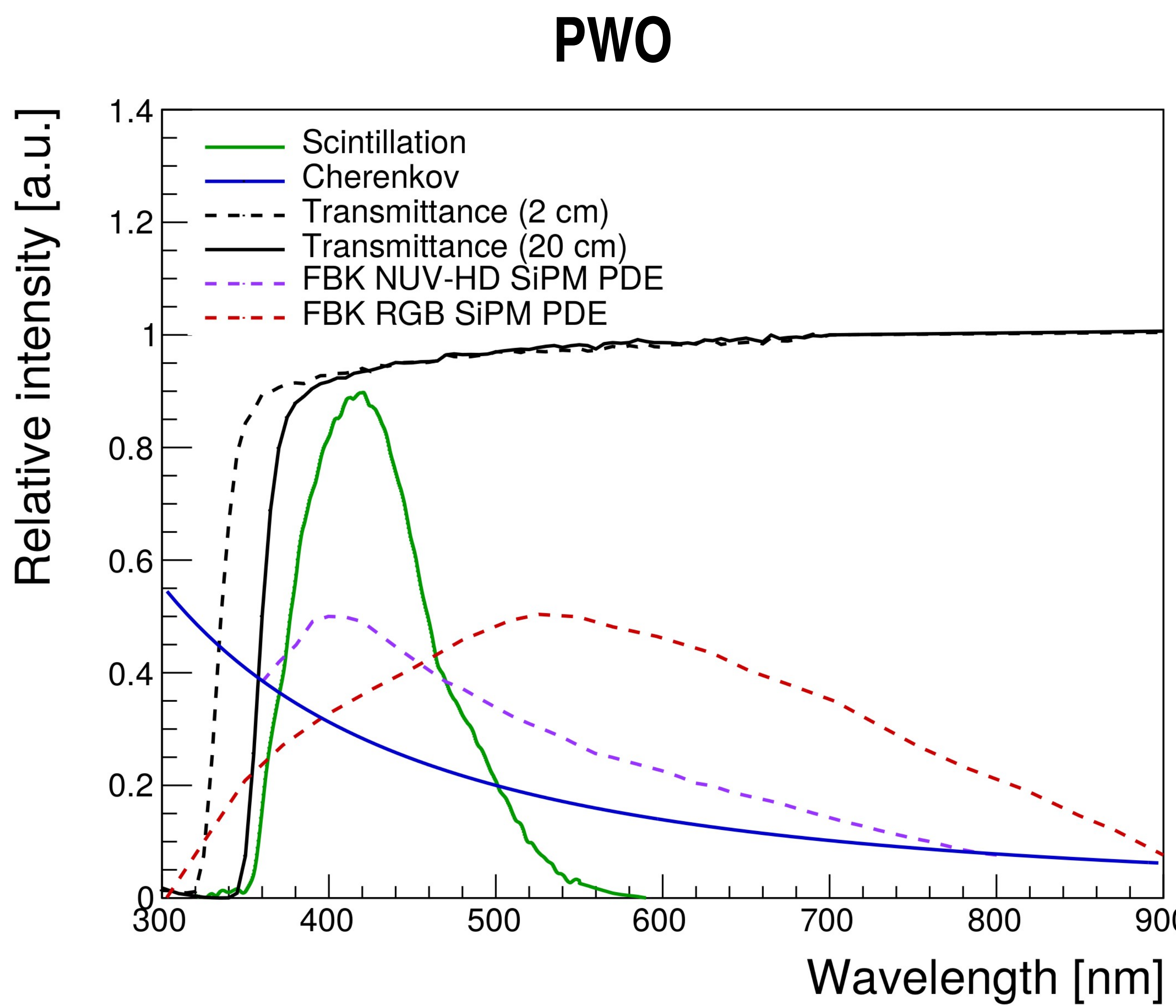
dual-readout in crystals

- Simultaneous readout of scintillation and Cherenkov light from same active element with dedicated SiPMs and wavelength filters

Rear crystal ECAL segment: two 4x4 mm² SiPMs with optical filters optimised for scintillation and Cherenkov detection

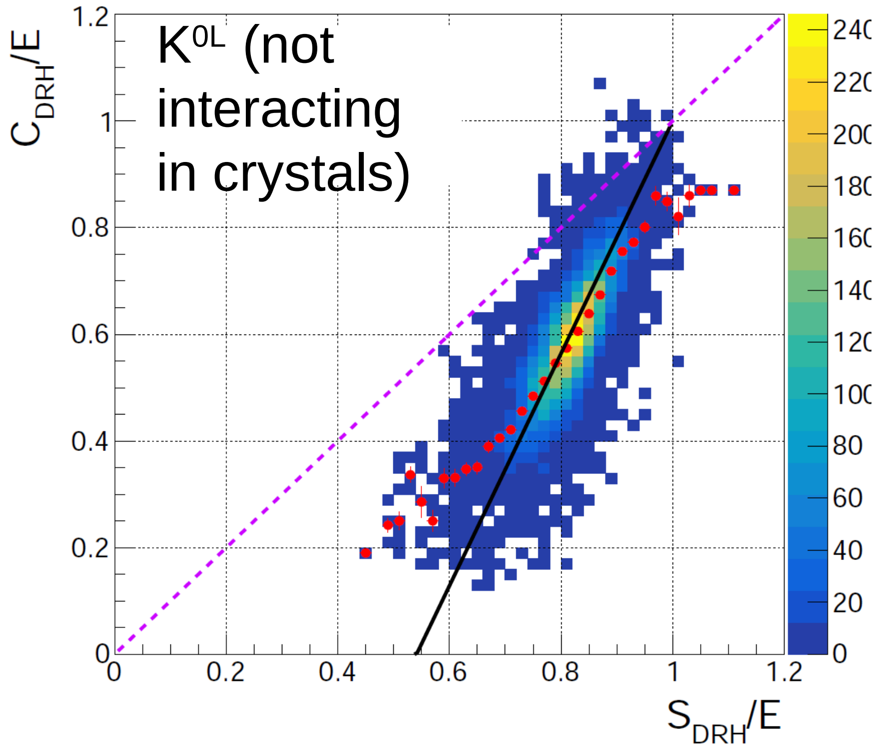


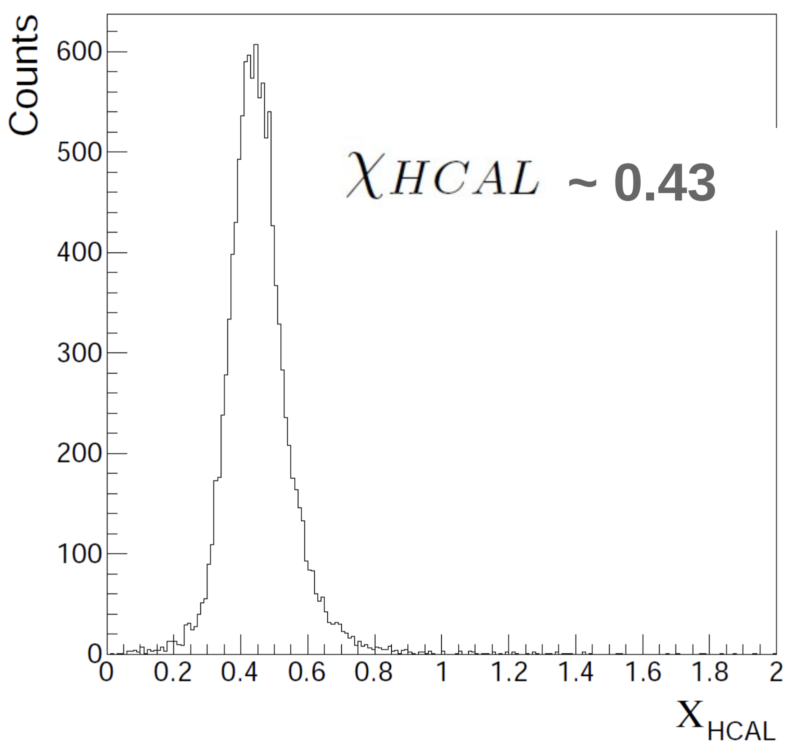
Front crystal ECAL segment: single 5x5 mm² SiPM per crystal optimised for scintillation light detection



dual-readout method in hybrid system

1. Independently evaluate χ-factors for crystal and fibre sections
2. Independenlty apply DRO correction on energy deposits for crystal and fibre sections
3. Add up corrected energy from both sections





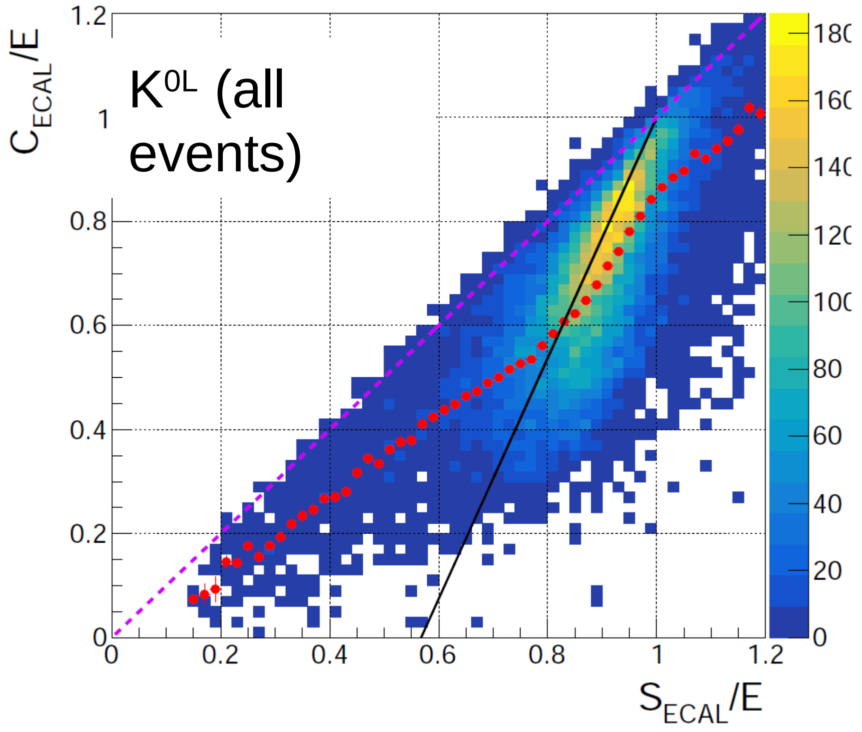
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

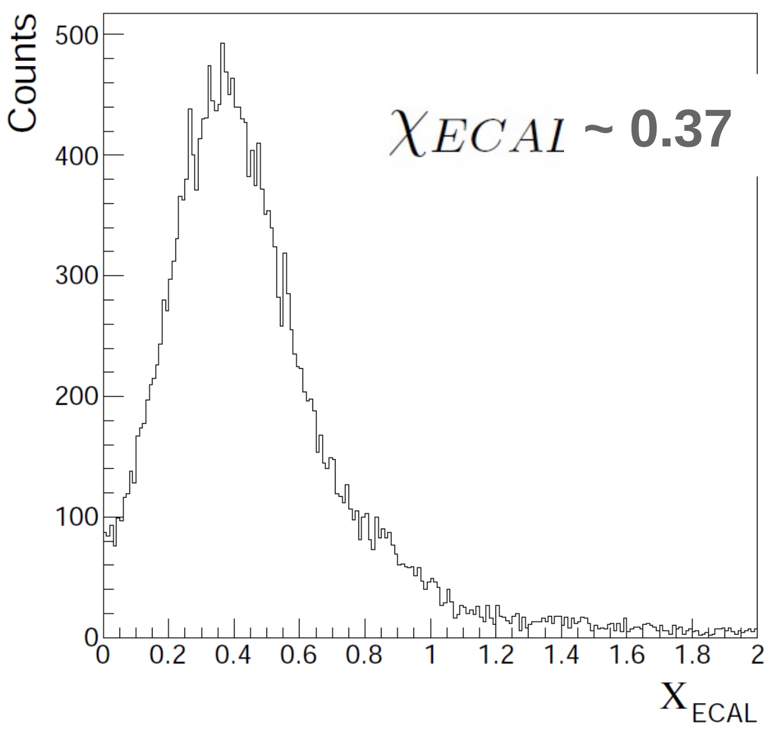
$$\chi_{ECAL} = \frac{1-(h/e)_s^{ECAL}}{1-(h/e)_c^{ECAL}}$$

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1-\chi_{HCAL}}$$

$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1-\chi_{ECAL}}$$

$$E_{total} = E_{HCAL} + E_{ECAL}$$



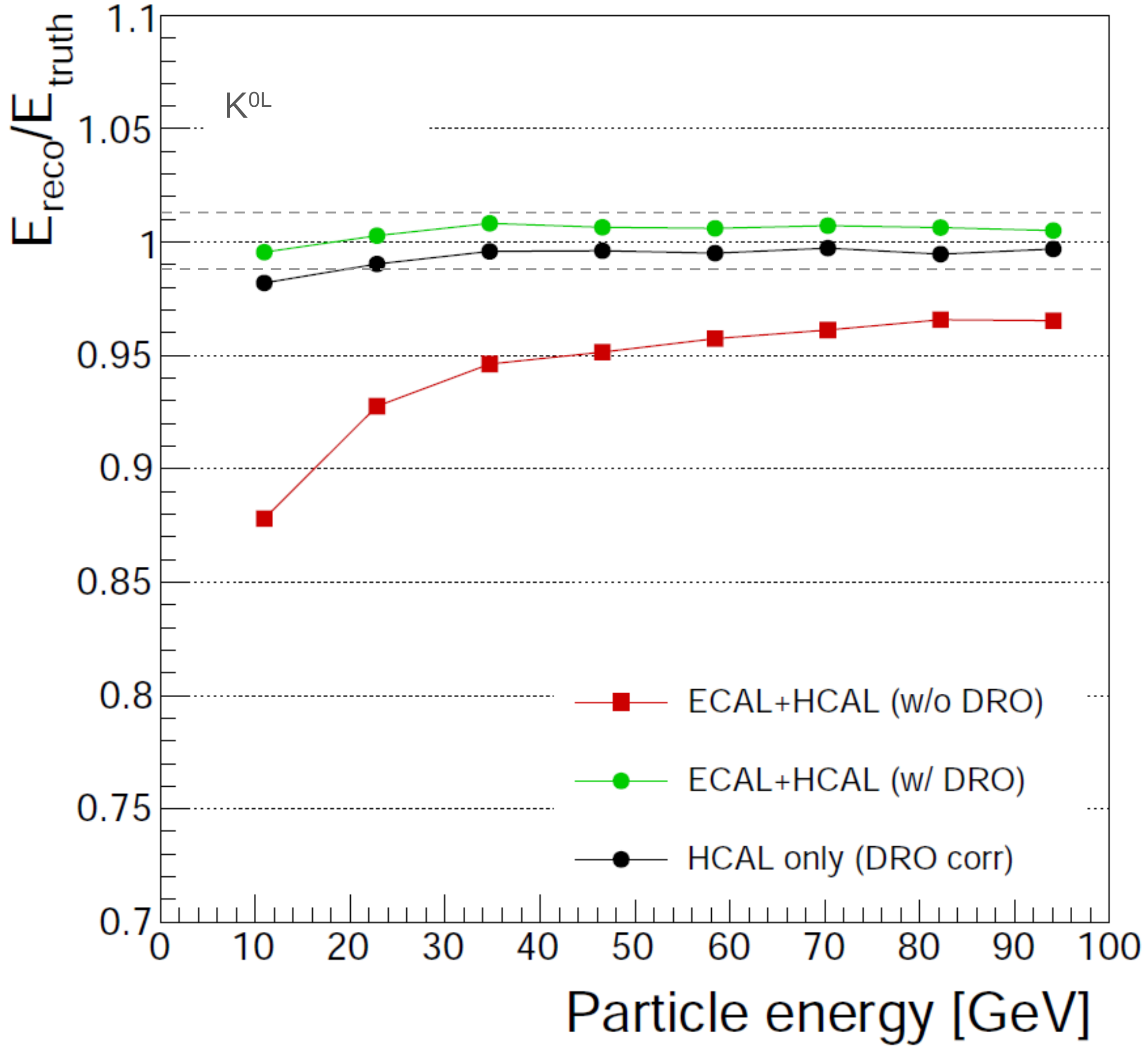


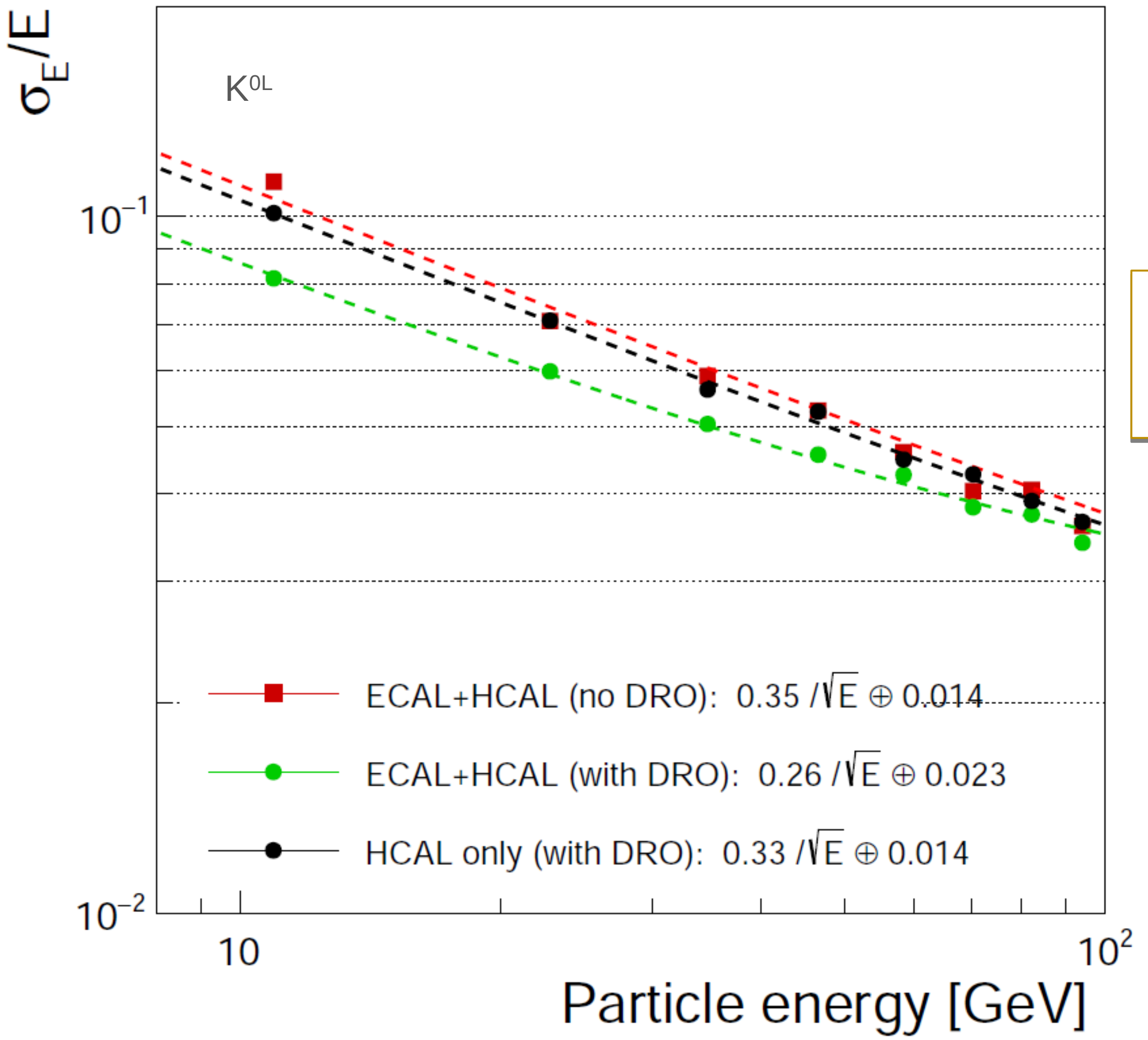
light yields (assumptions)

- ECAL (crystal section): 2000 (scintillation) and 160 (Cherenkov) p.e./GeV
- HCAL (fibre section): 400 (S) and 100 (C) p.e./GeV

Energy resolution for neutral hadrons

- **Dual-readout method confirms applicability to hybrid calorimeter system**
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to fibre-only IDEA calorimeter





σ_E/E_{HAD} ~ 27%/√E ⊕ 2%

DR-oriented PF approach (DR-pPFA)

- Different optimisation of PF algorithm required for coarsely segmented calorimeter
- Q: Could better energy linearity and resolution offset coarser longitudinal segmentation?

	High granularity Si/W ECAL and scintillator based HCAL	Fiber-based dual-readout calorimeter	Hybrid crystal and dual-readout calorimeter
N. of longitudinal layers	> 40	1	5
ECAL cell cross-section HCAL cell cross-section	25–100 mm^2 100–900 mm^2	2–144 mm^2	100 mm^2 400–2500 mm^2
EM energy resolution HAD energy resolution	$15 - 25\%/\sqrt{E}$ $45 - 55\%/\sqrt{E}$	$10 - 15\%/\sqrt{E}$ $25 - 30\%/\sqrt{E}$	$\approx 3\%/\sqrt{E}$ $\approx 25 - 30\%/\sqrt{E}$

Moderate longitudinal segmentation (helpful to identify and measure π^0 jet component)

Highest energy resolution and linearity

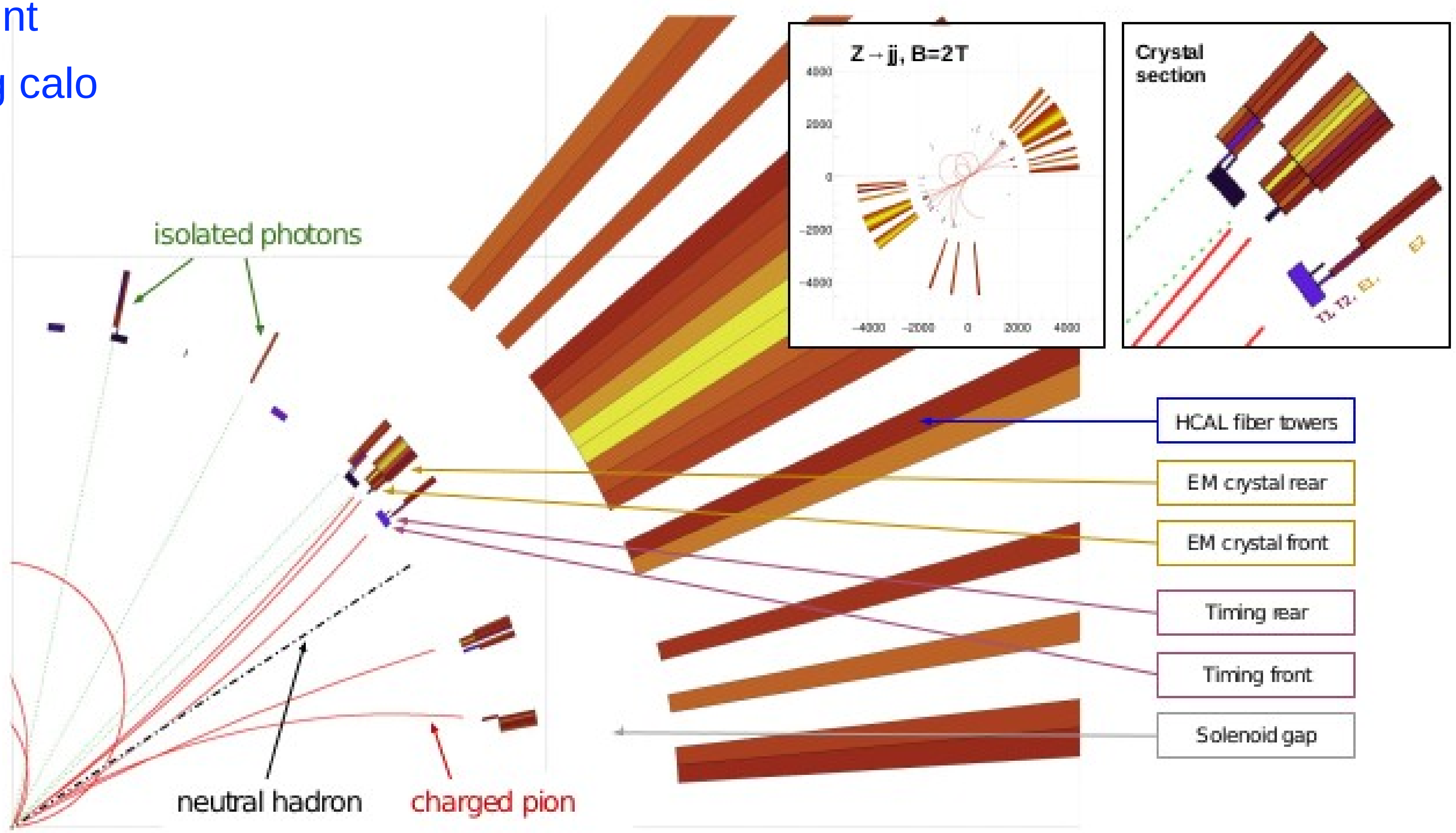
Highest longitudinal segmentation

Highest transverse segmentation: full potential (e.g. using neural networks) yet to be explored

https://doi.org/10.1088/1748-0221/17/06/P06008

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



jet reconstruction → IDEA++ DR-pPFA

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)

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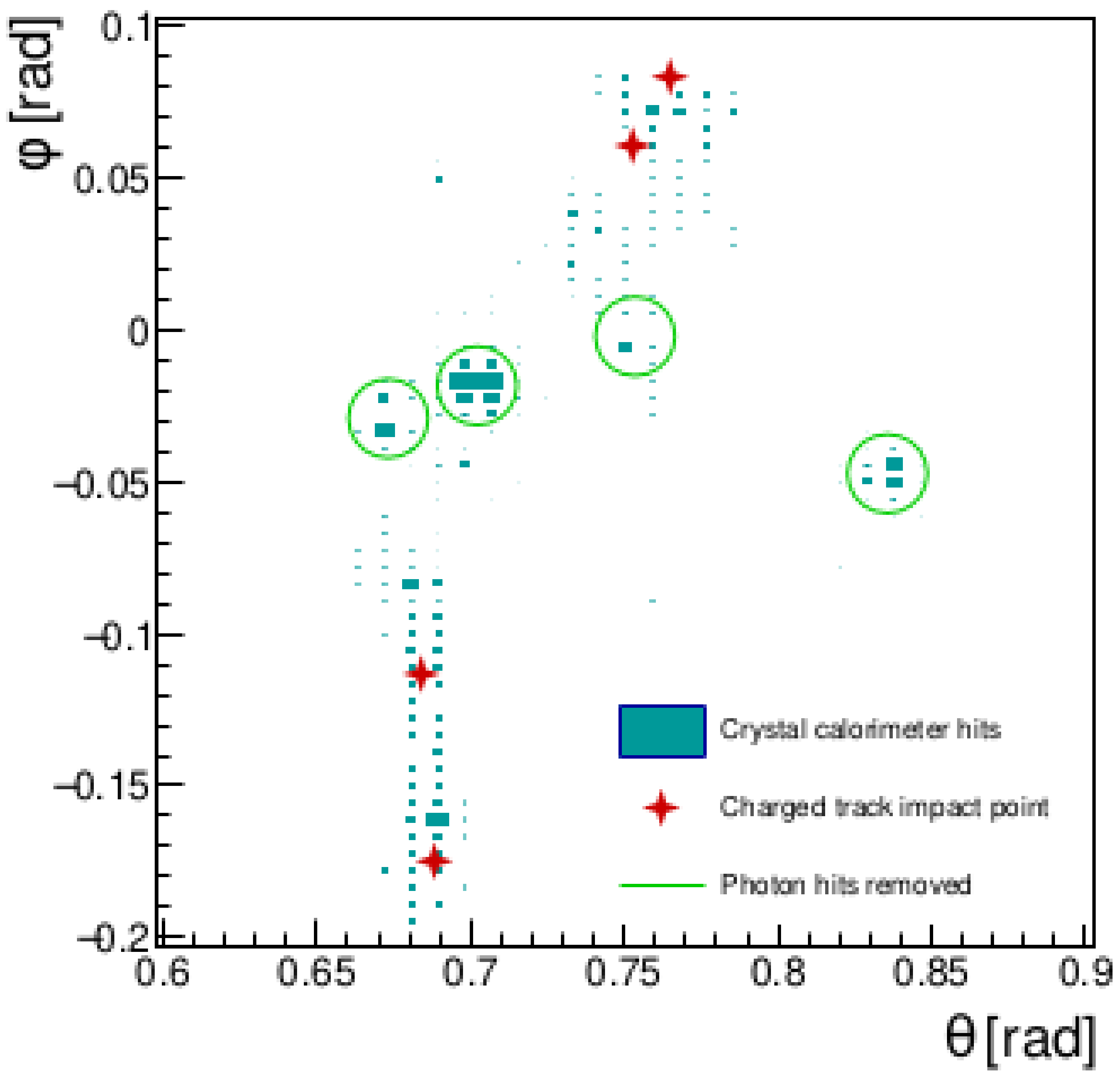

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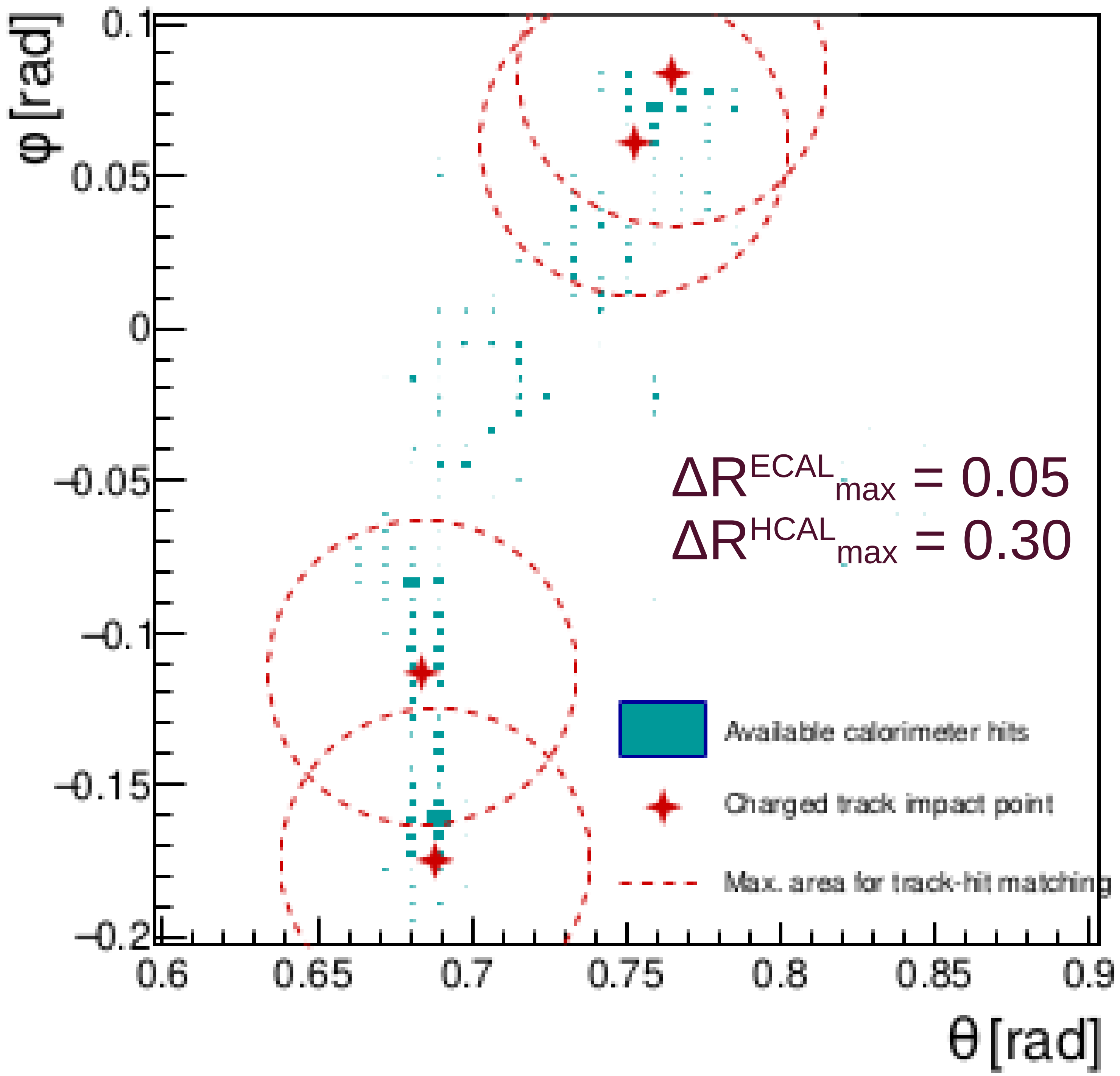

$\Delta R^{ECAL}_{max} = 0.05$
$\Delta R^{HCAL}_{max} = 0.30$

jet reconstruction → IDEA++ DR-pPFA

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- for each track, rank calo hits by distance
- collect hits in cone(s)

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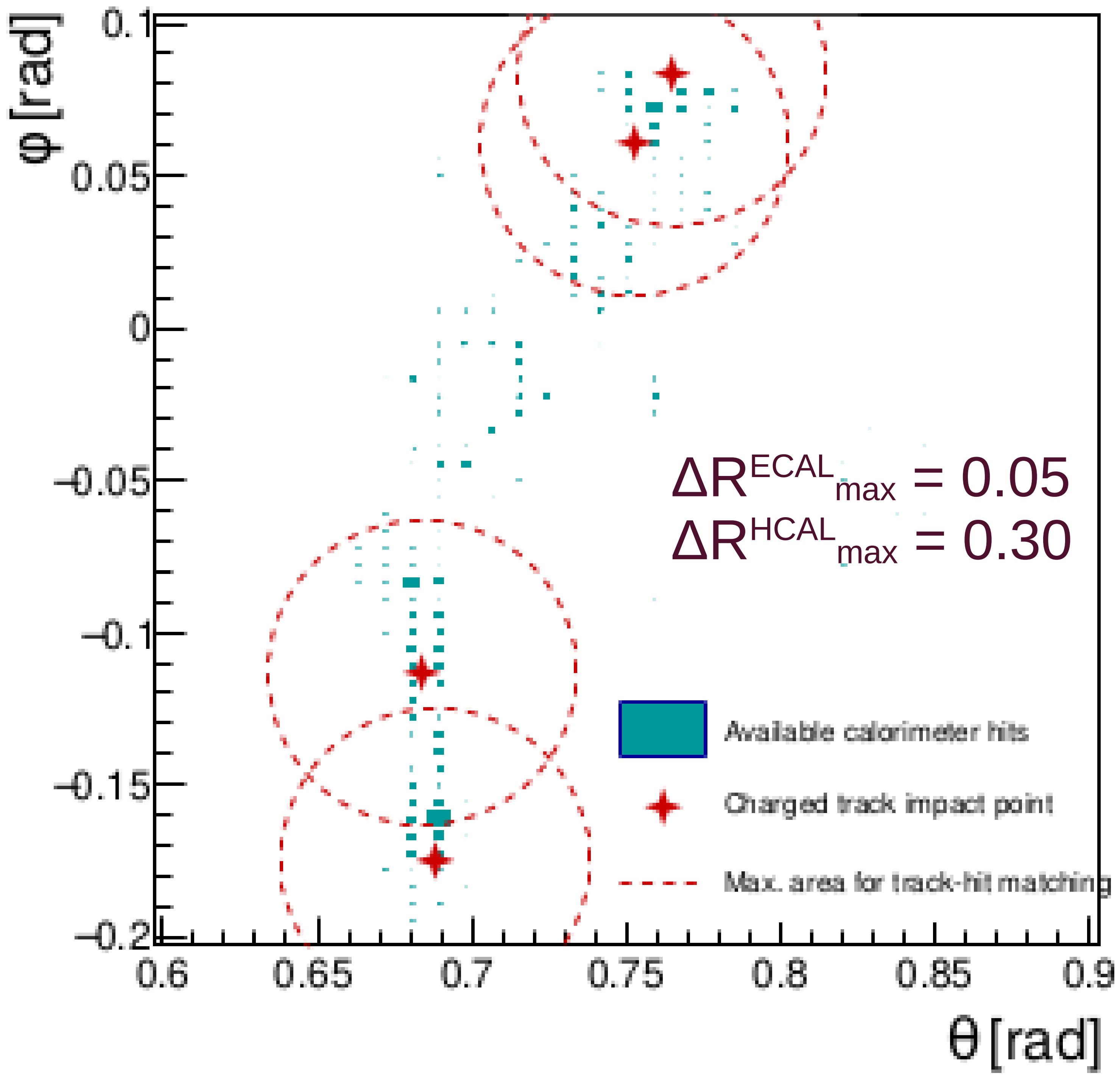

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- compare with E_{target}(track)

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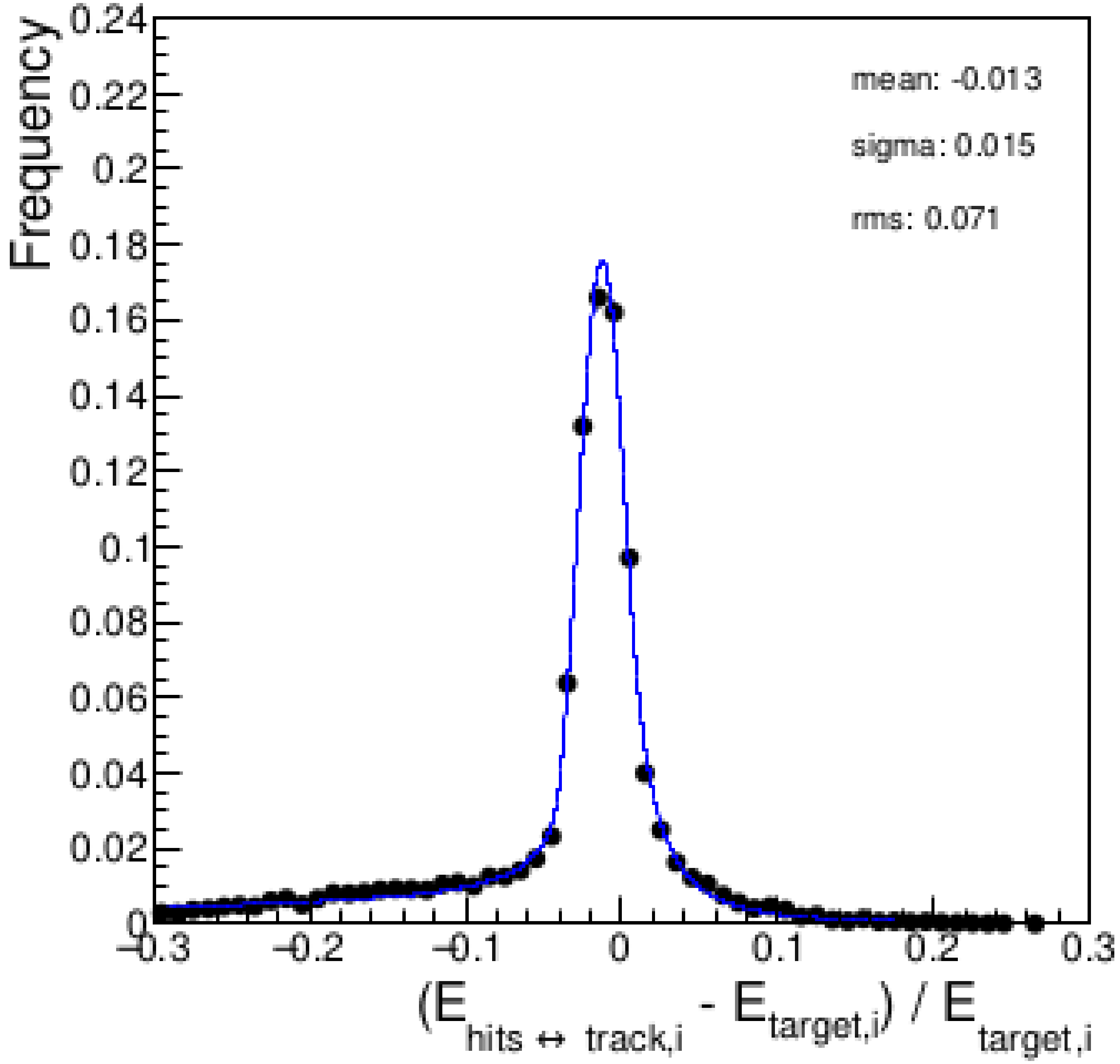


jet reconstruction → IDEA++ DR-pPFA

Geant4 simulation of $Z \rightarrow jj$ events:

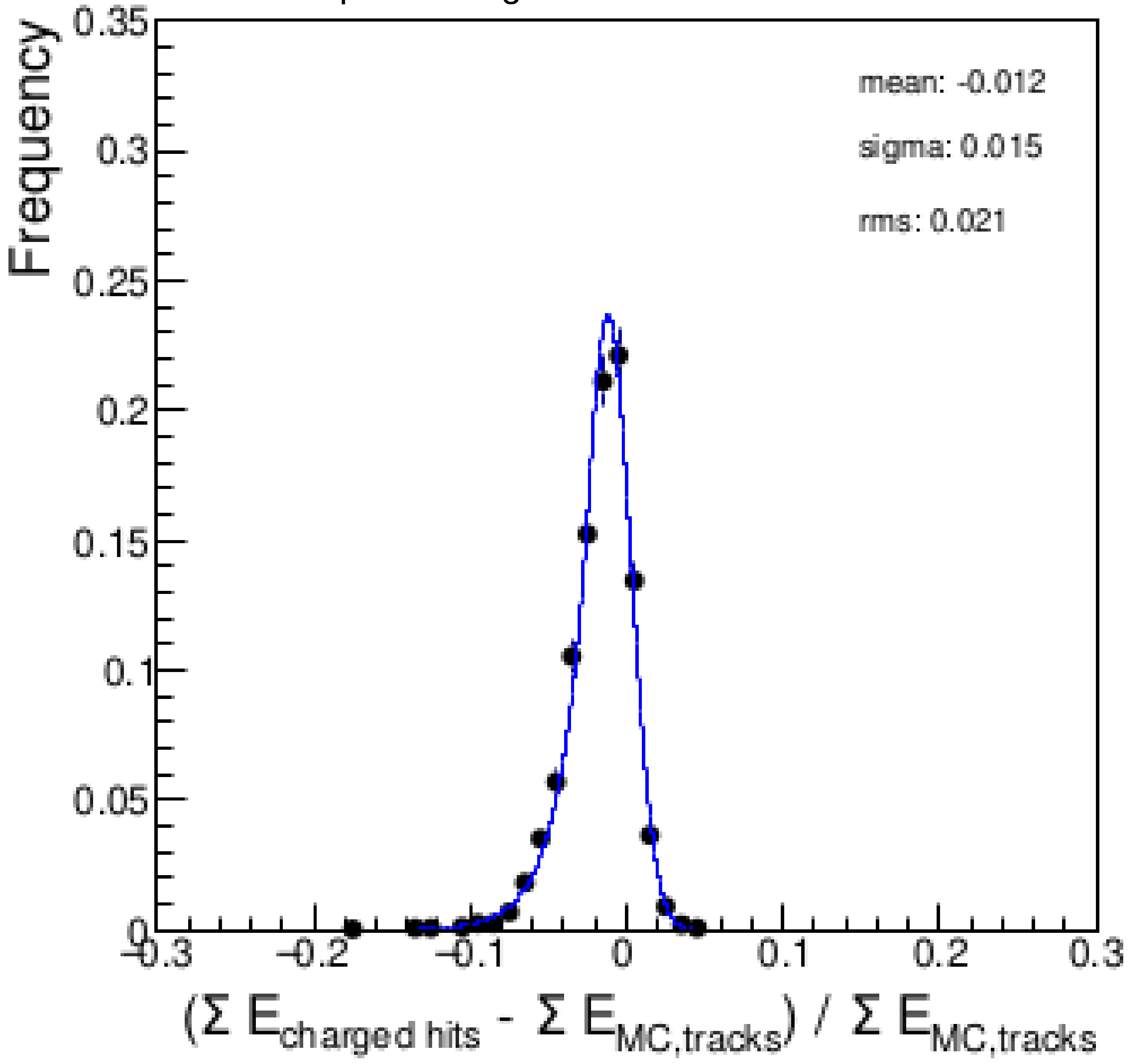
- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track, extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

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

- 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 replace them with track

Please note: dual-readout is used to correct energy of clustered calorimeter hits and improve track-hit matching

https://doi.org/10.1088/1748-0221/17/06/P06008



jet clustering

https://doi.org/10.1088/1748-0221/17/06/P06008

- Jet clustering algorithm* fed with collection of
  - all photon hits
  - tracks of
    - charged particles not reaching calorimeter
    - tracks swapped with calorimeter hits in previous step
  - All other calorimeter hits (both ECAL and HCAL) not been swapped out
- As result, 4-momentum vectors are clustered into two jets
- Jet energy ("non-swapped hadron" component) is corrected with DRO**

$$E_{jet} = C_{PFA} \cdot \left[\sum E_{hits,\gamma} + \sum E_{tracks} + \sum E_{hits,leftover,DRO} \right]$$

**FASTJET package: generalized k_T algorithm with R=2π and number of jets fixed to 2*

***dual-readout used here to correct energy of calorimeter hits with no match to tracks (e.g. neutral hadrons)*

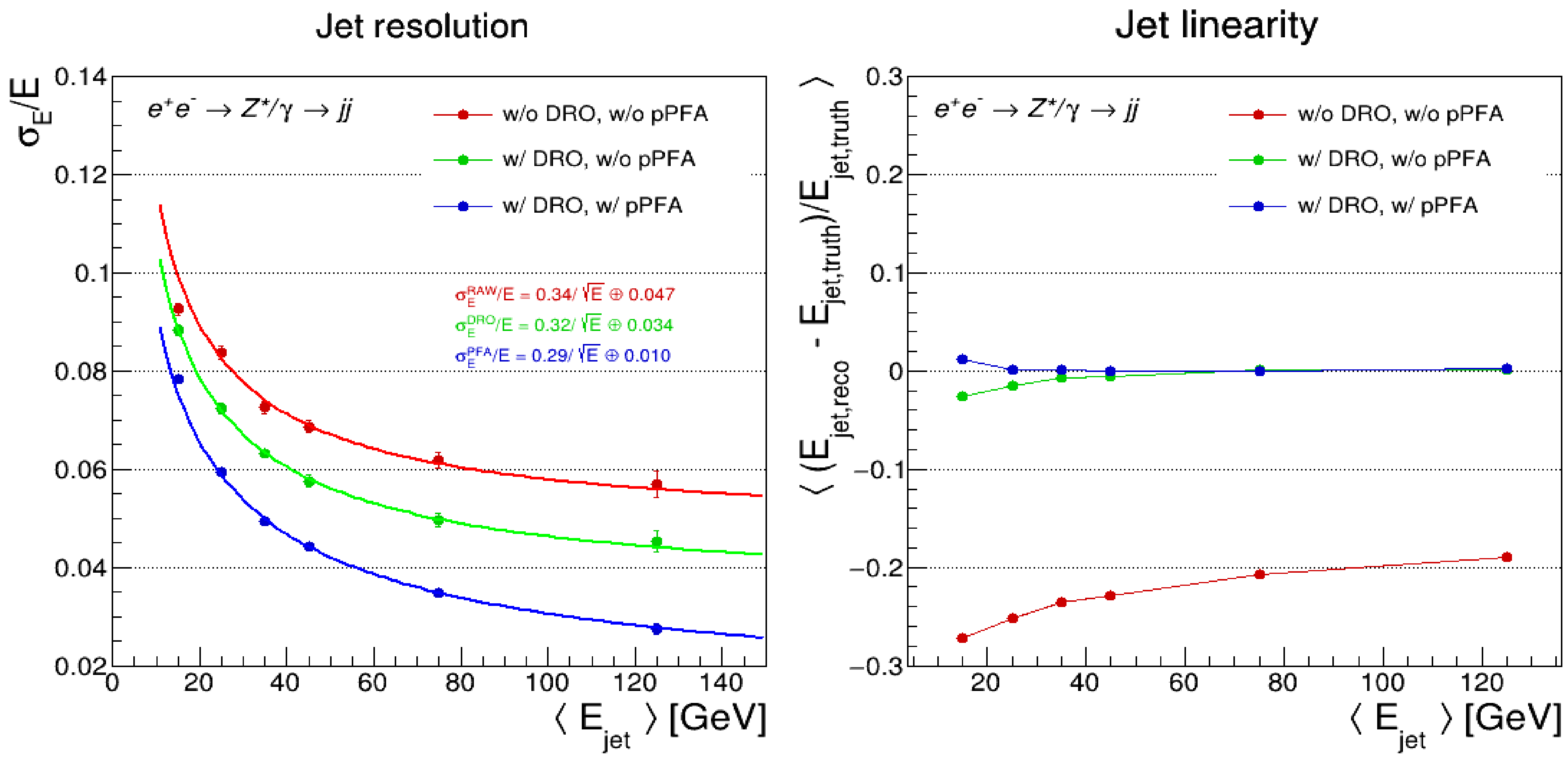
jet energy resolution w/ and w/o DR-pPFA

https://doi.org/10.1088/1748-0221/17/06/P06008

Resolution and linearity as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ events (at different centre-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA

More details in: 2022 JINST 17 P06008

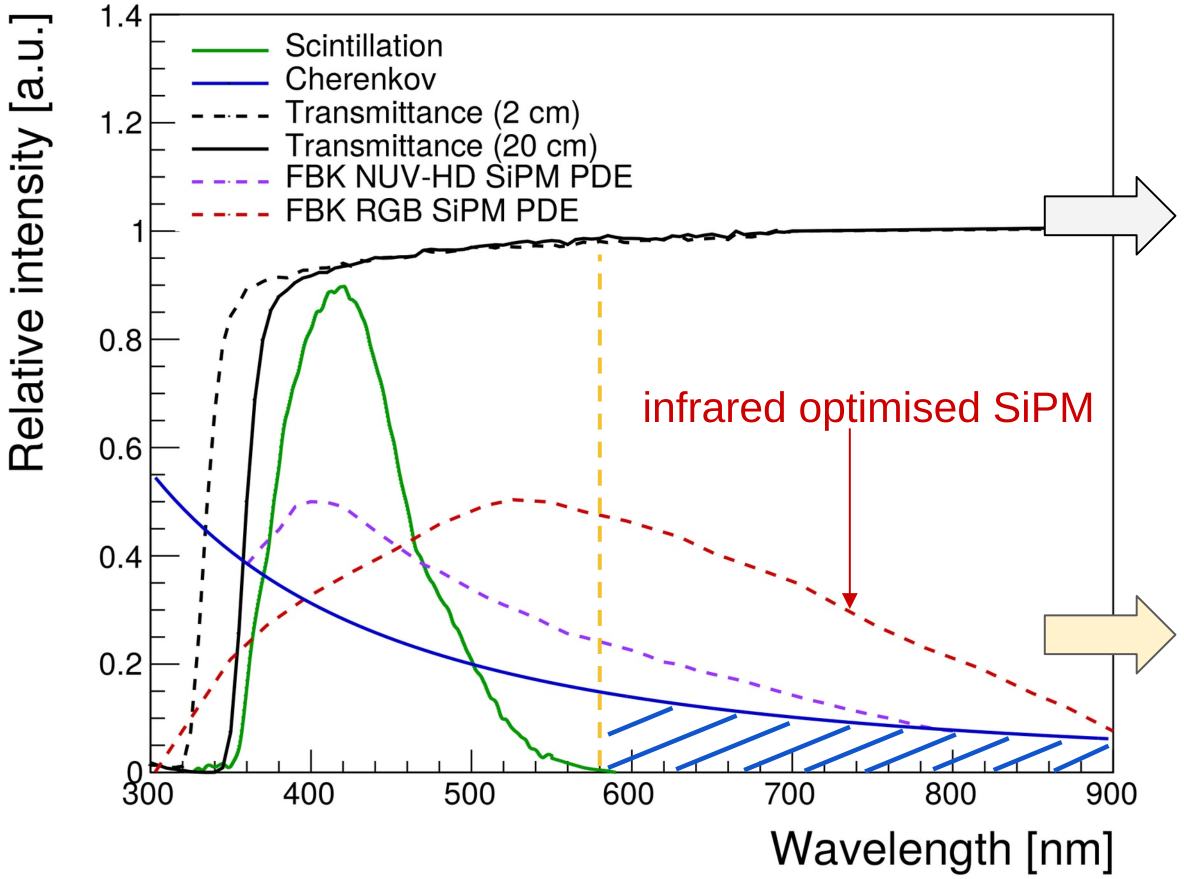


Sensible improvement in jet energy resolution using dual-readout information combined with PF approach → 3-4% for energies above 50 GeV

dual-readout challenge w/ crystals

- Light yield and purity of S and C signals - likely - key discriminant between crystal options
- Different strategies exploitable for different scintillators

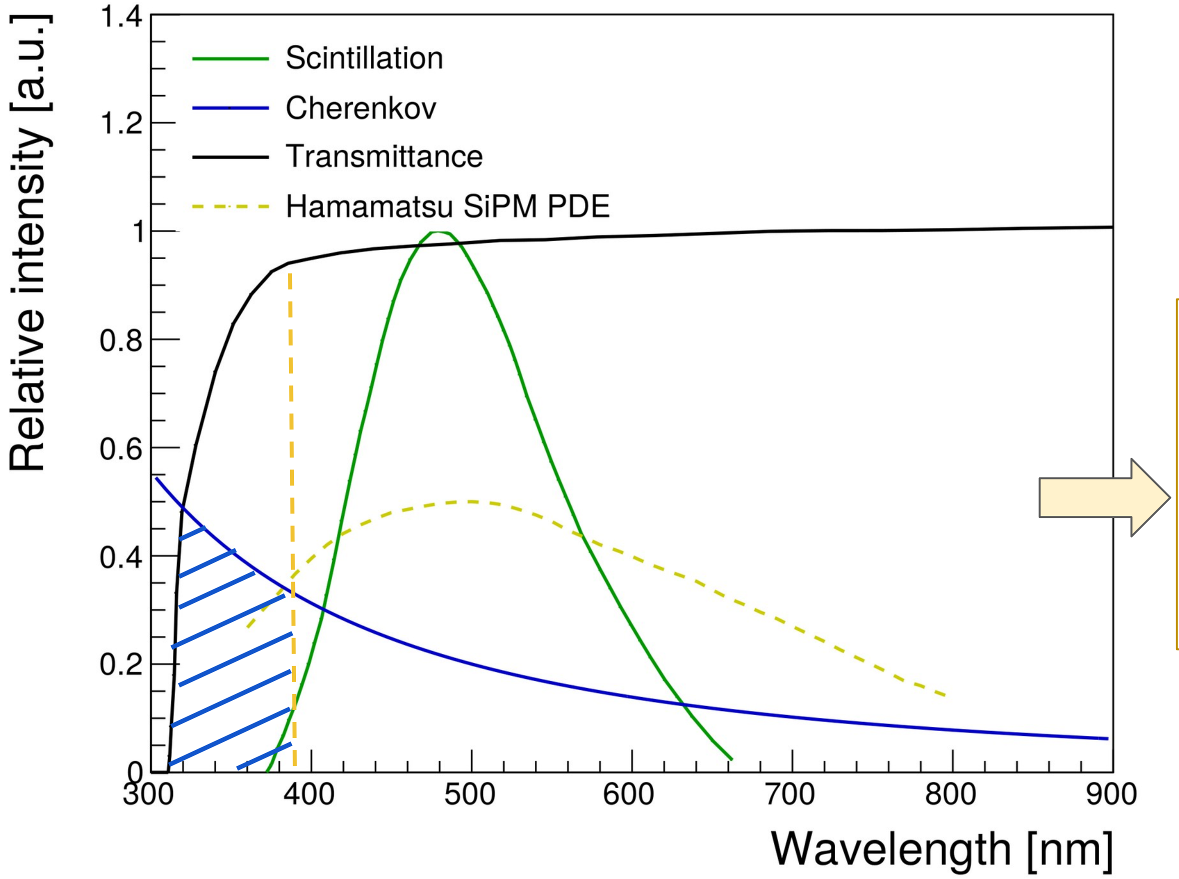
PWO



Estimated:
>2000 pe/GeV for scintillation photons
>100 pe/GeV for Cherenkov photons

Cherenkov photons above scintillation peak much less affected by self-absorption

BGO / BSO



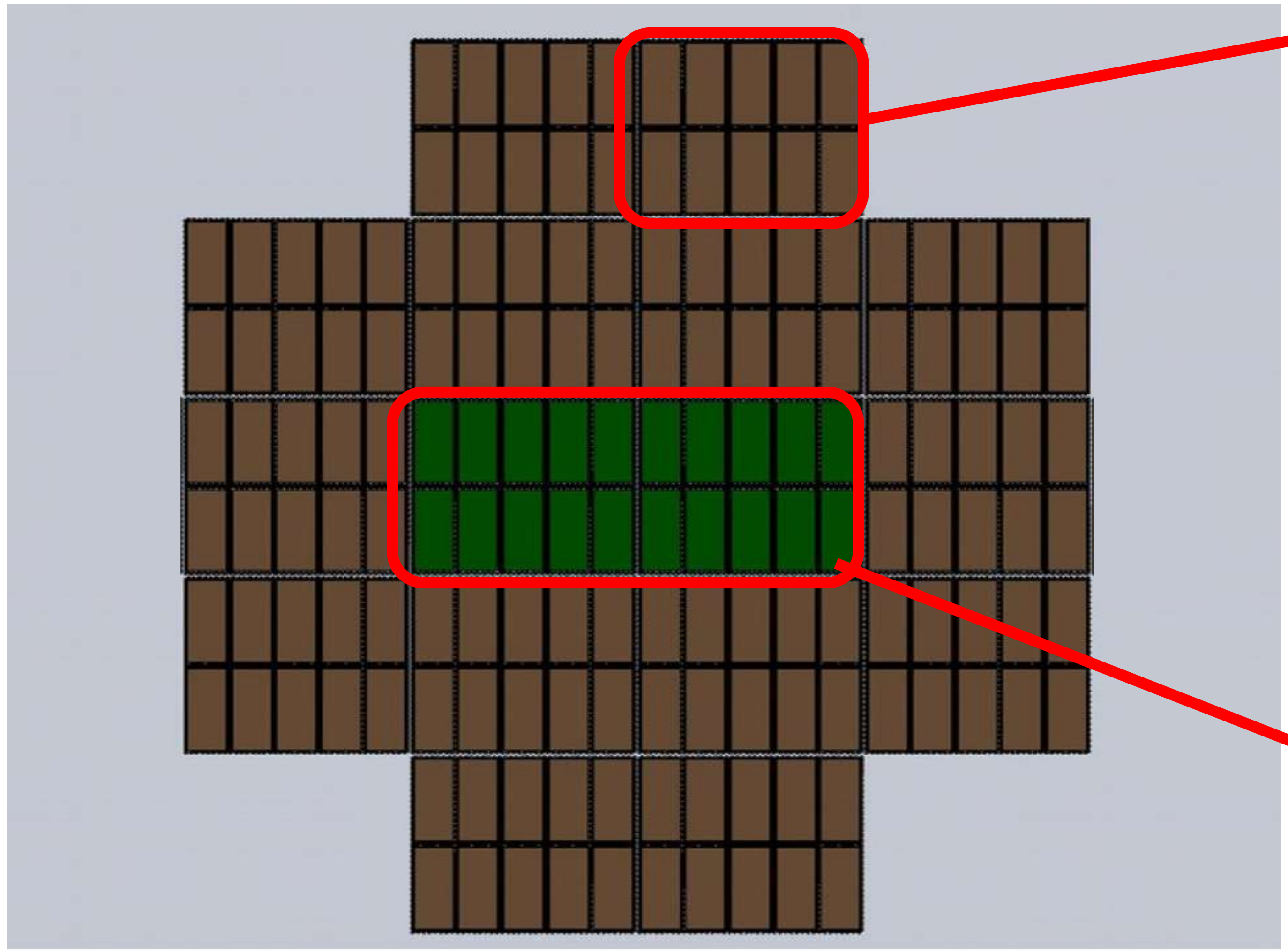
Larger Stokes shift, i.e. wider range of transparency for 'Cherenkov UV' photons

Hadronic-containment prototype

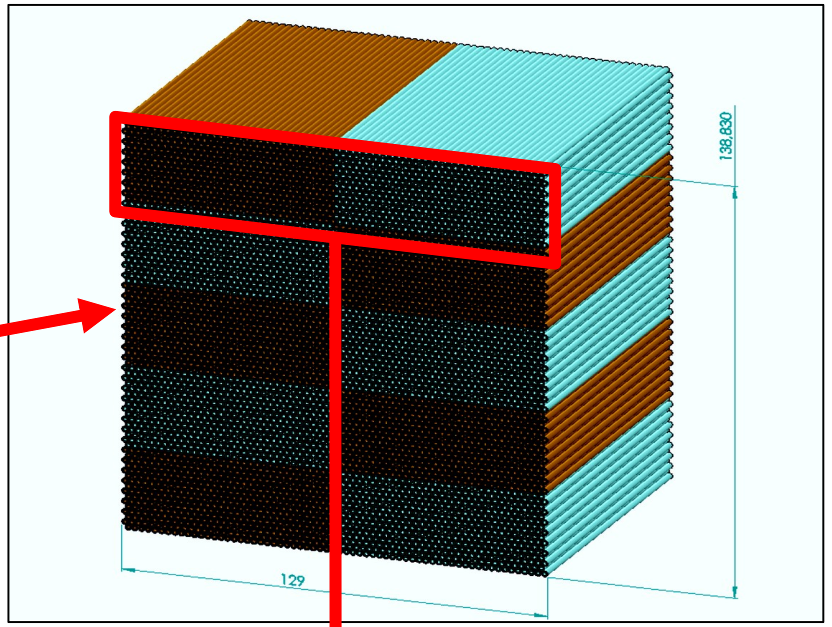
HiDRa – Highly granular Dual Readout demonstrator

Hadronic-size prototype:

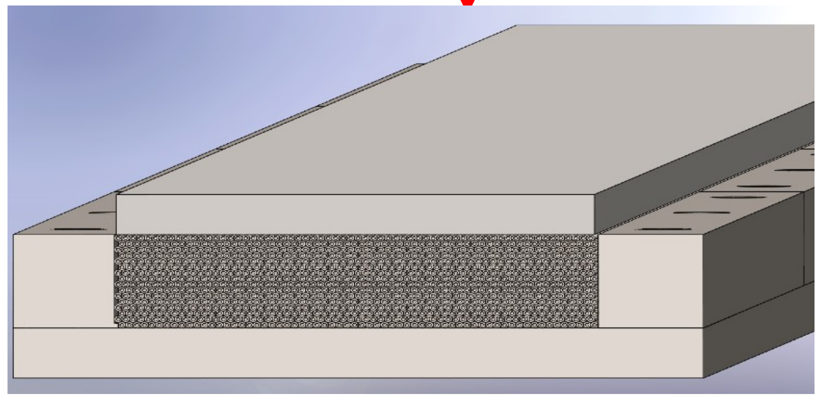
16 modules w/ highly granular core



~ 65 × 65 × 250 cm^3



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

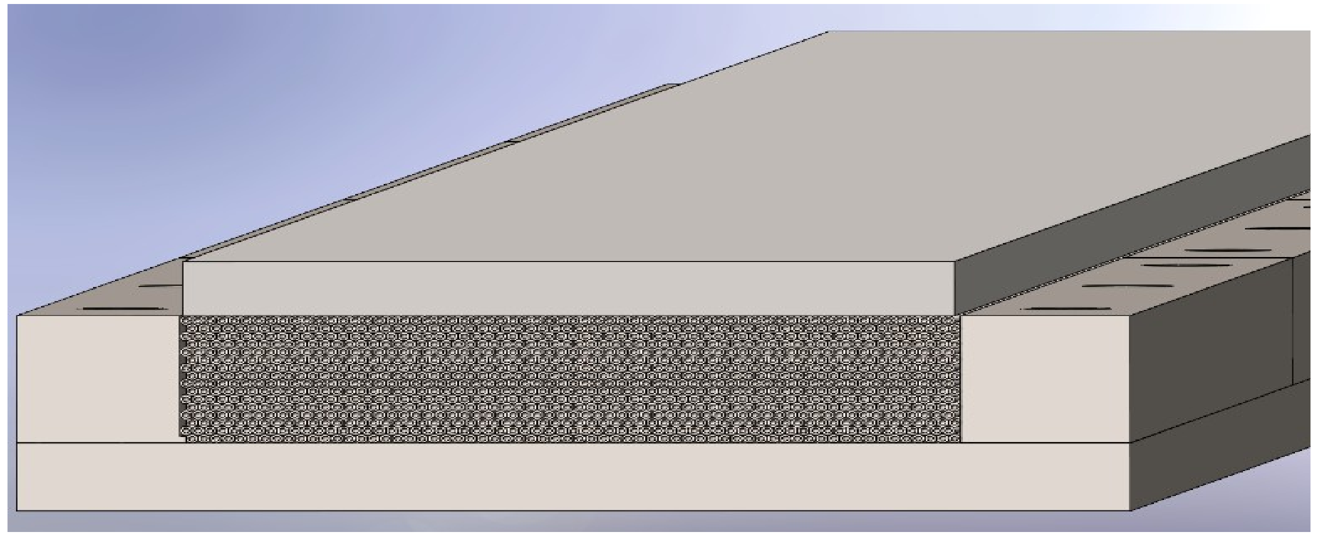


1 MiniModule:
64 × 16 = 1024 fibres in total
512 S + 512 C

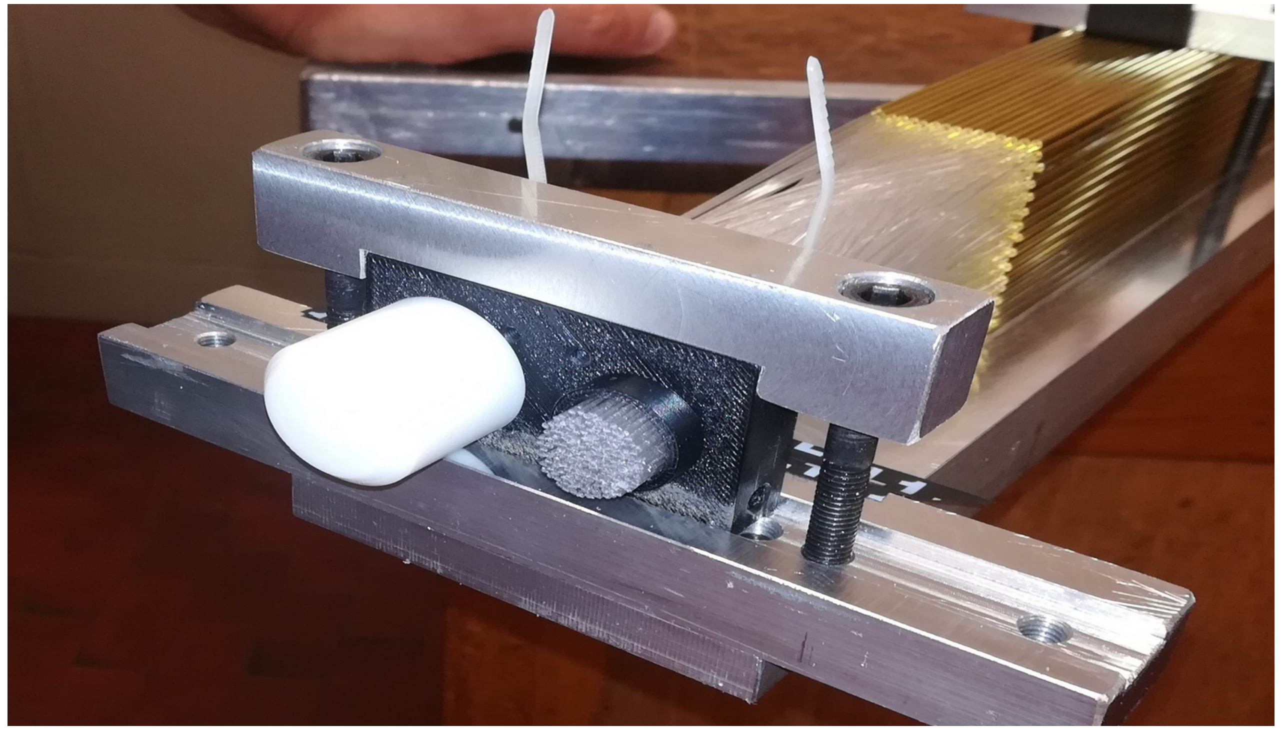
highly granular core:

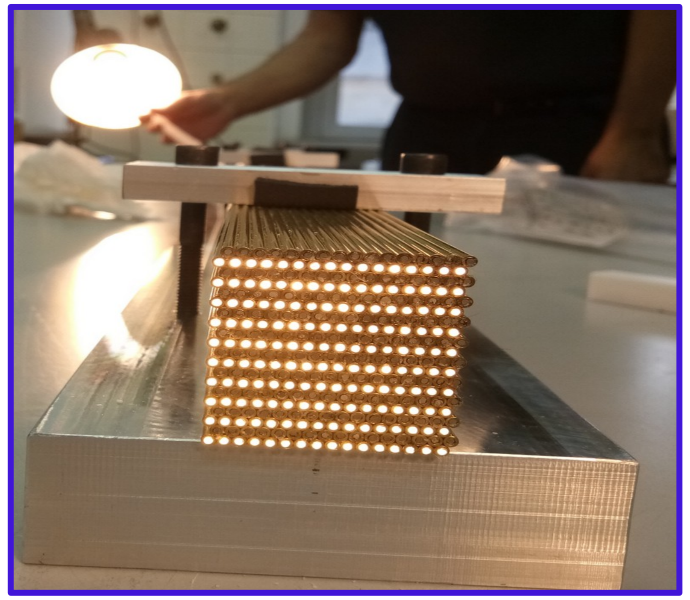
10240 fibres to be read out with SiPMs

Work in progress

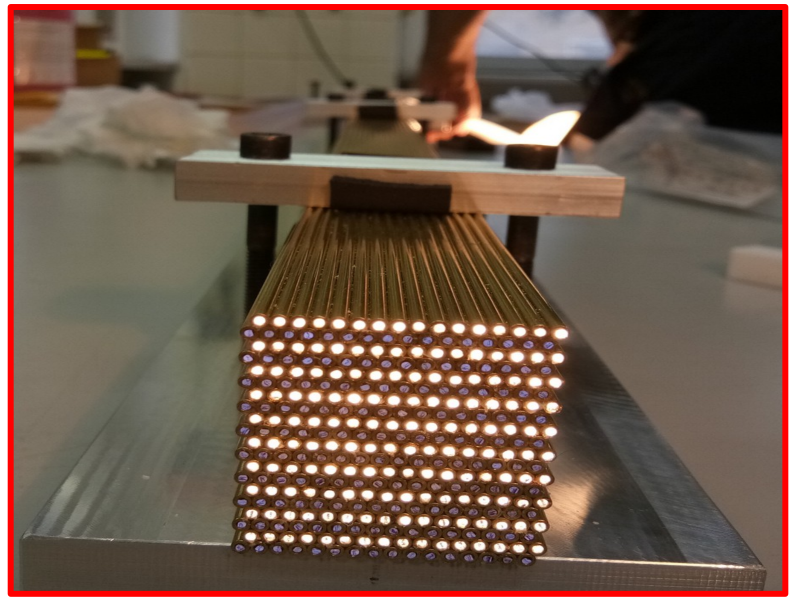


- Stainless steel capillary tubes w/ 2 mm diameter
- C and S fibres positioned per raw
- Fibre separation at calorimeter rear end
- Fibre grouping for PMT coupling





scintillating fibres



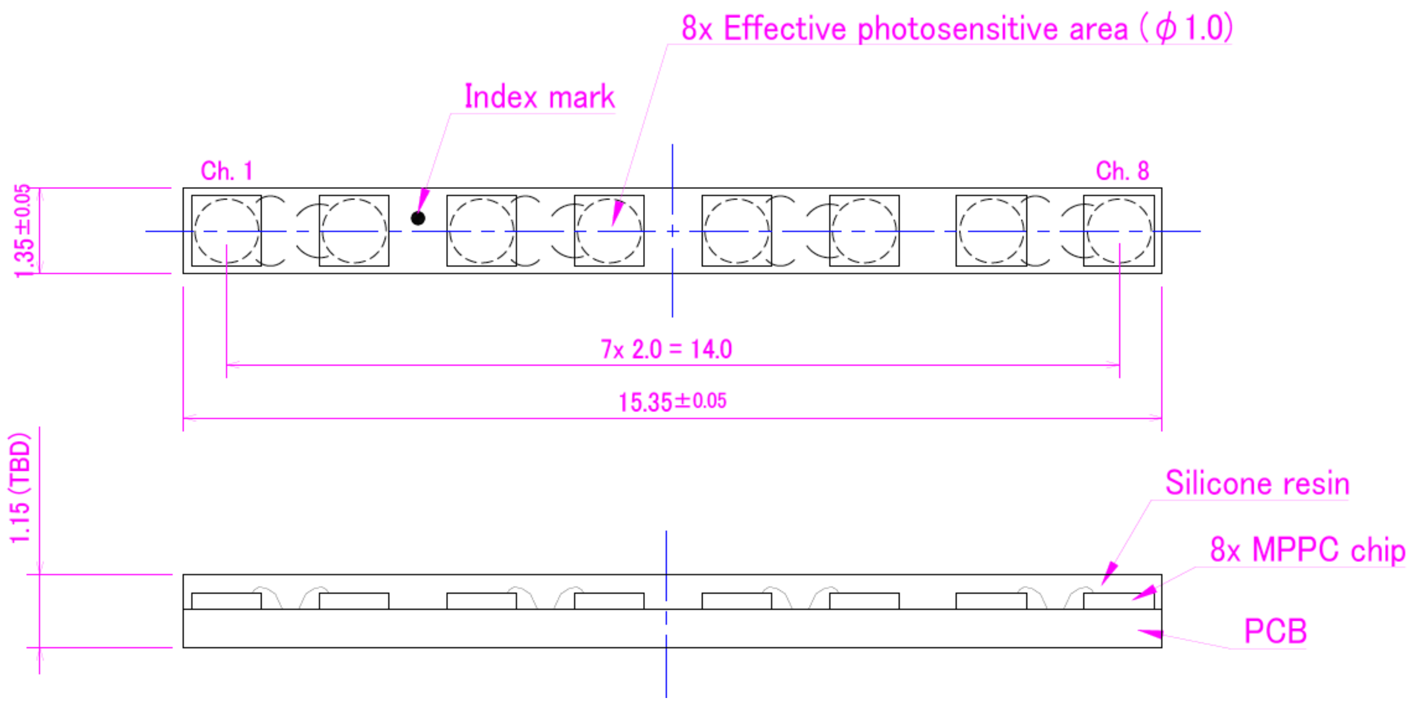
Cherenkov fibres

Fibre disposal and grouping (pictures from 2020 brass prototype)

SiPMs for HiDRa

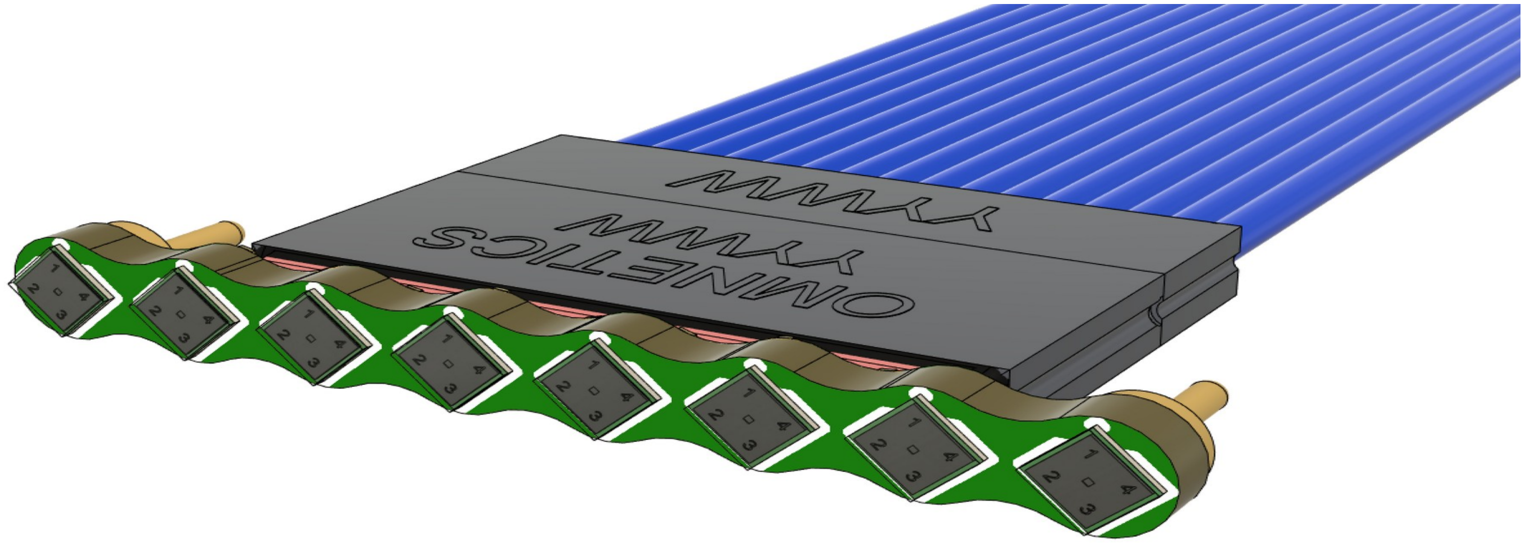
New solution by Hamamatsu:

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



Our present best fit:

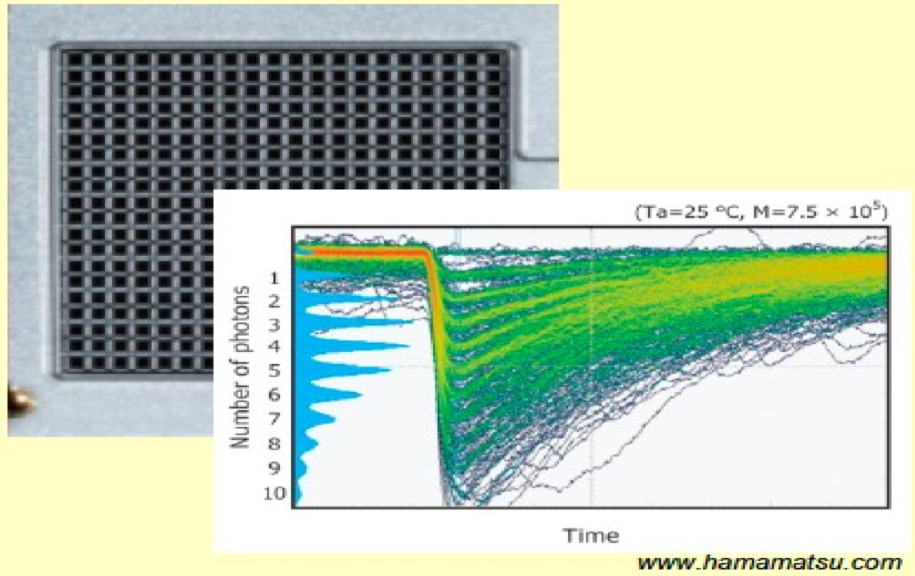
a) use 10 μm cell-size SiPMs for scintillating fibres
b) use 15 μm cell-size SiPMs for clear fibres



Testing 10 boards per cell-size type

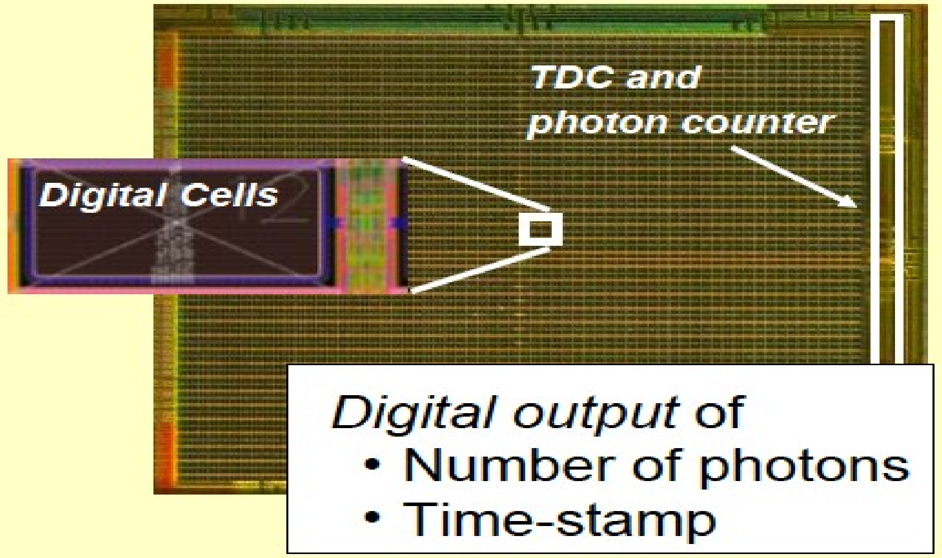
Alternative photosensors

Analog SiPM



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

Digital SiPM



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

digital SiPMs (dSiPMs)

no need for analogue-signal post-processing

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

Conclusions

Growing interest for dual-readout calorimetry
(other activities ongoing on dual- and also triple-readout calorimeters)

IDEA fibre calorimeter: dual-readout + single-fibre light sensors (SiPM) + timing
→ highly granular 3D information

Dual-readout crystal option → may boost em performance without spoiling hadronic one

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

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

Hadronic-scale demonstrators under construction

Targets

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

Validate Geant4 shower modeling

Assess scalable solutions concerning construction and signal readout/handling

Exploit DNN architectures for physics analysis

Assess performance in relevant benchmark physics channels

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

Further lectures

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