FCC-ee:
R&D on Calorimetry for the IDEA Detector

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INFN Pavia

First FCC Italy Workshop
March 22nd, 2022

** on behalf of the IDEA Dual-Readout Group*

calorimetry @ FCC-ee

"Probe Higgs and EWK physics with unparelleled precision"

→ high energy resolution: mainly driven by Higgs physics

→ high spatial resolution: mainly driven by τ and HF physics

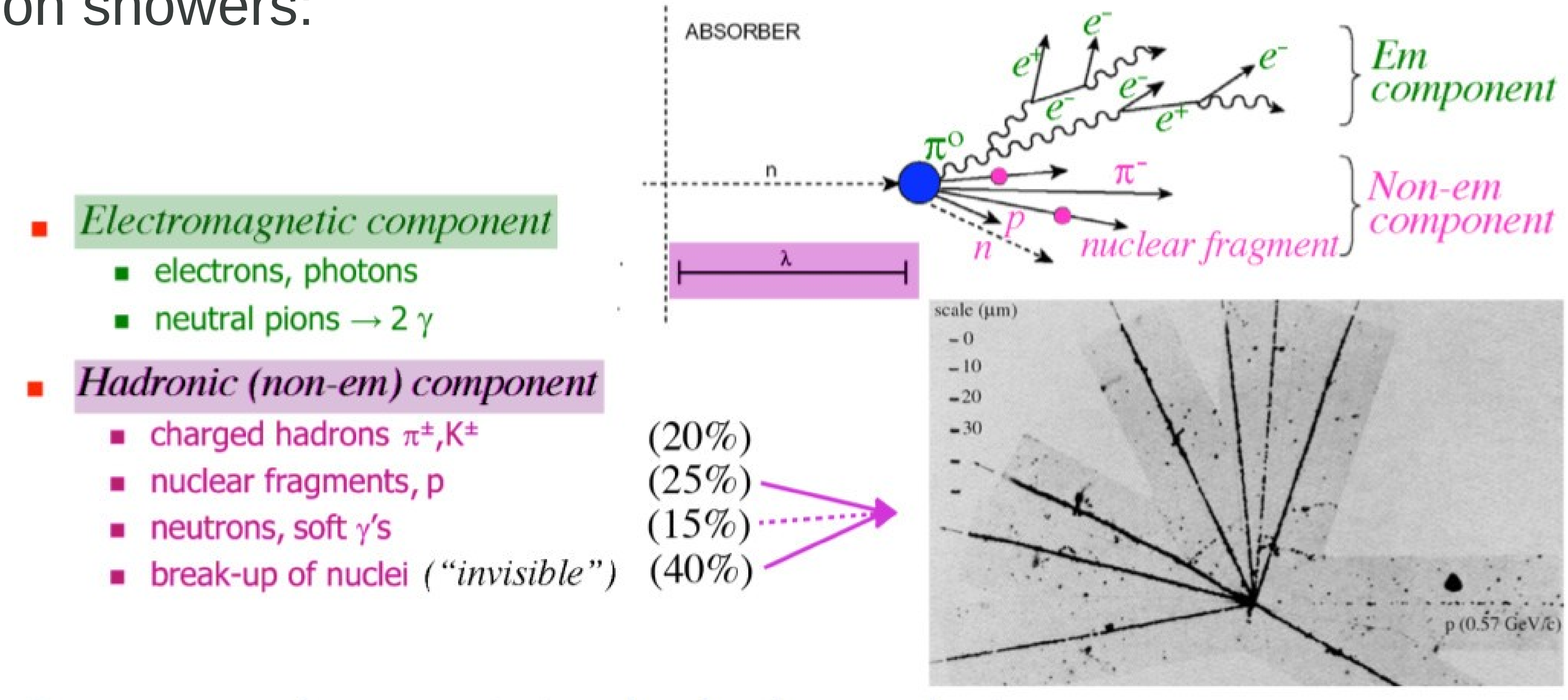
Two approaches:

CLD: Particle Flow → optimise granularity

IDEA: Dual Readout → optimise hadronic resolution

dual readout in a nutshell

Hadron showers:



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

→ large non-Gaussian fluctuations among em and non-em shower components

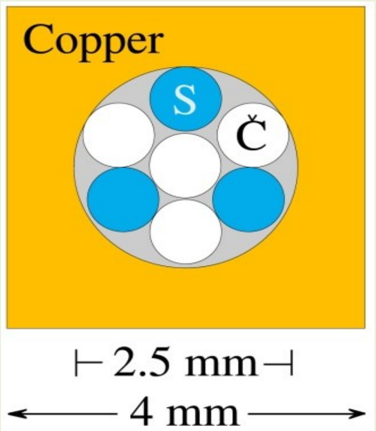
Dual readout:

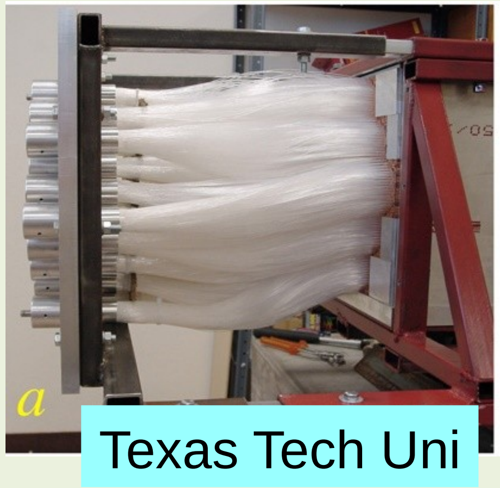
compensate event-by-event fluctuations through two independent shower-detection processes (e.g. Cherenkov and scintillation light production)

fibre-sampling prototypes (PMT readout)

2003
DREAM

Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%

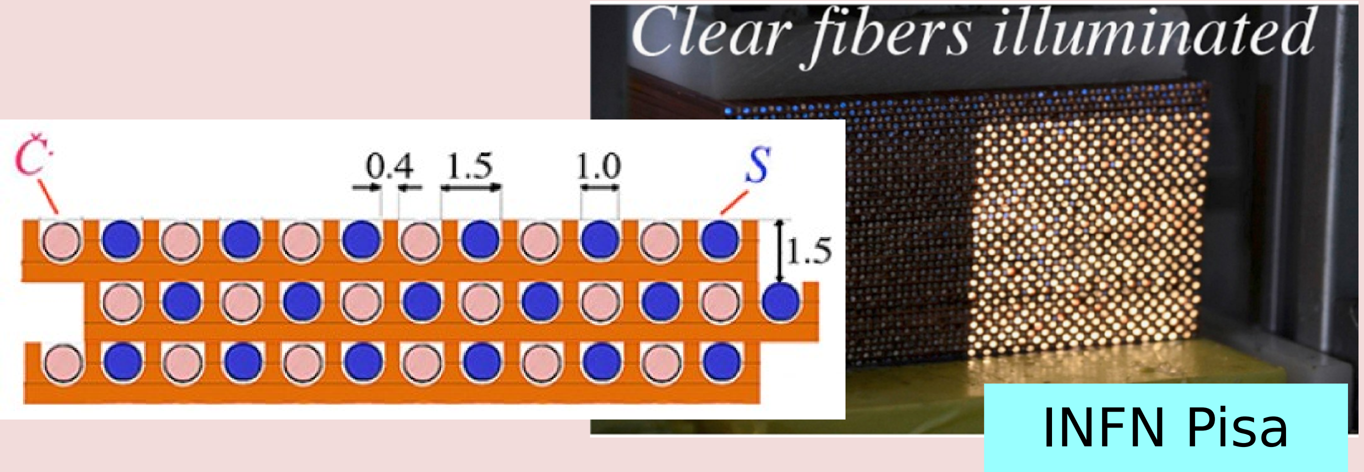




Texas Tech Uni

2012
RD52

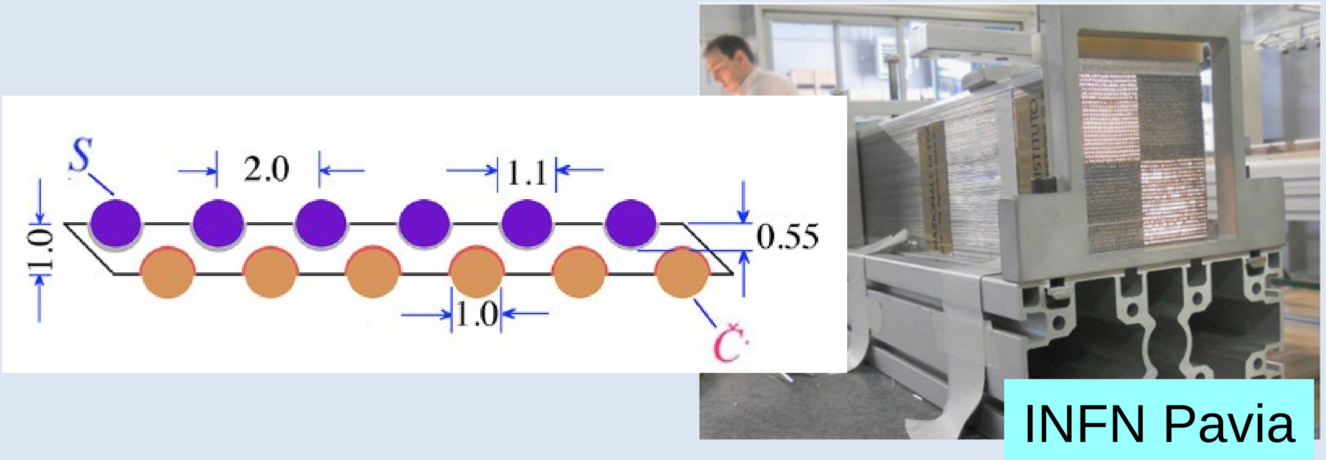
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

2012
RD52

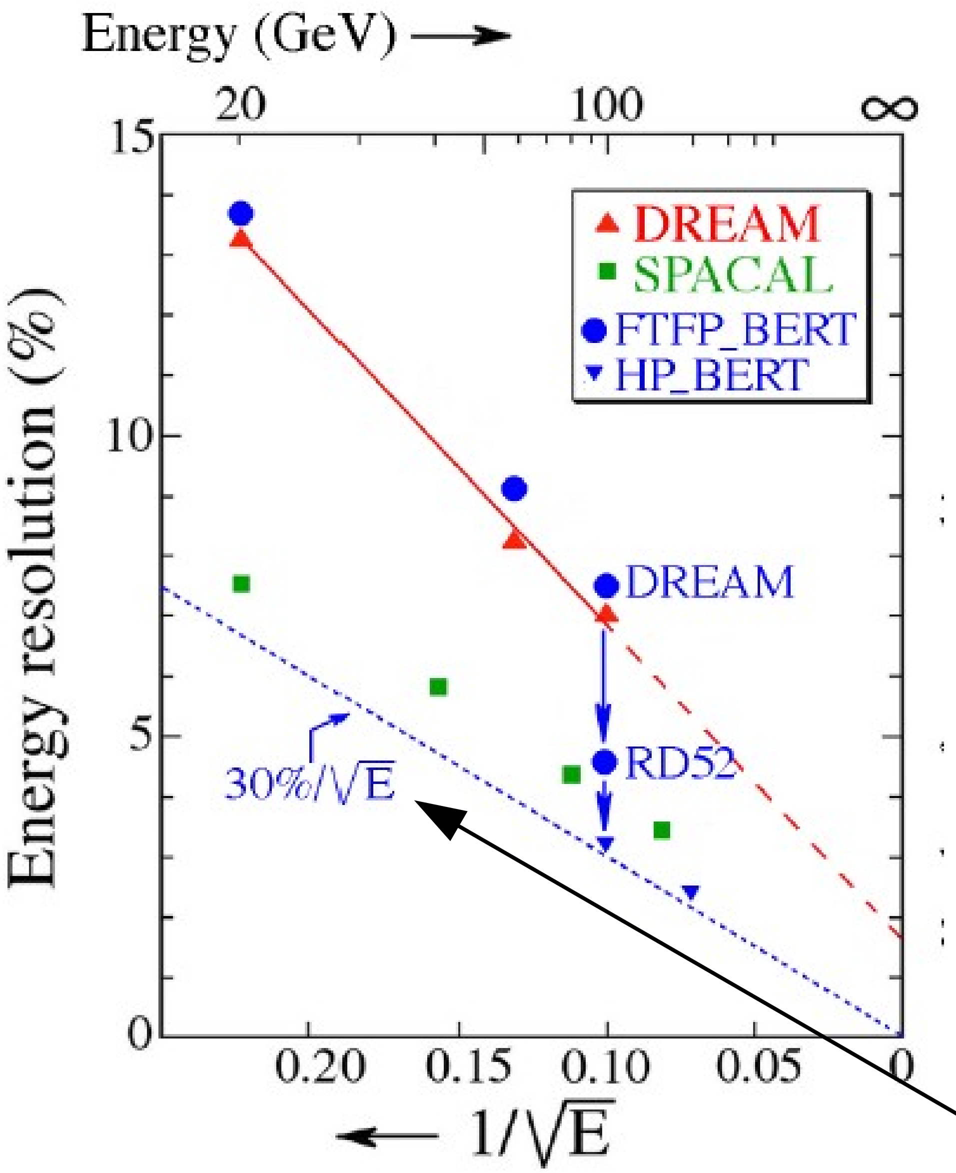
Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



INFN Pavia

RD52 hadronic performance

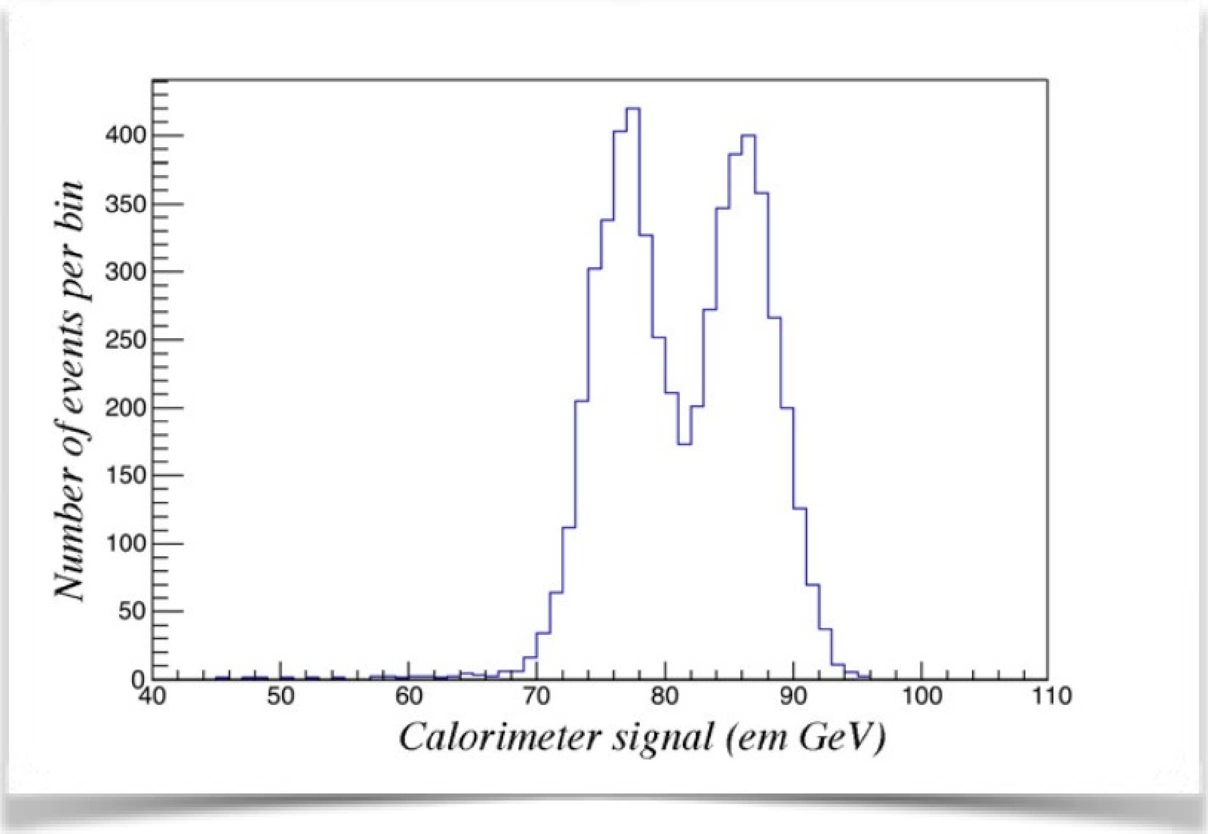
Hadronic Resolution



NIM A 824 (2016) 721

W/Z separation

[H → WW / H → ZZ separation]



Geant4 Simulations

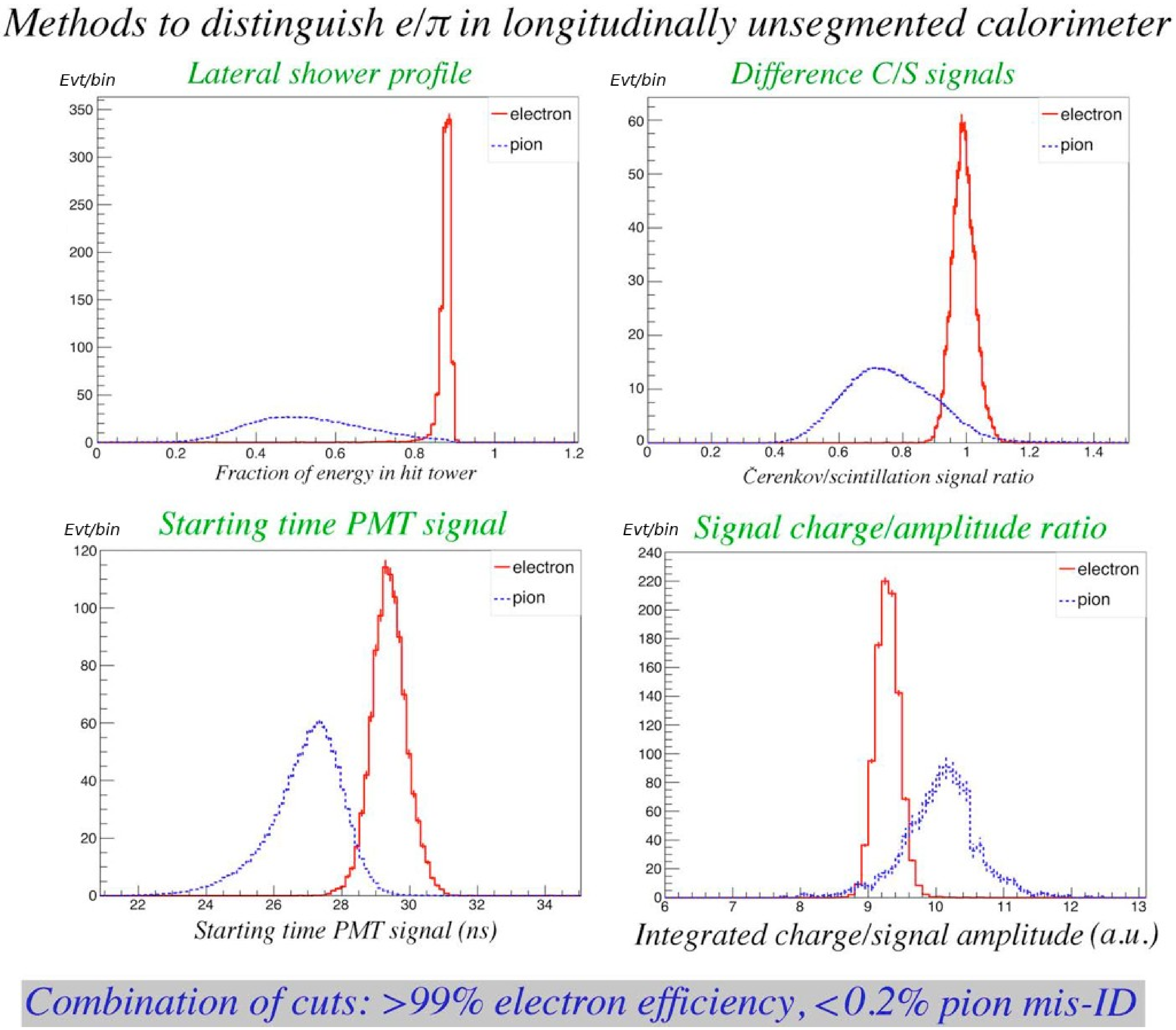
RD52 particle ID (electron/hadron separation)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

NIM A 735 (2014) 120



Methods to distinguish e/π in longitudinally unsegmented calorimeter

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

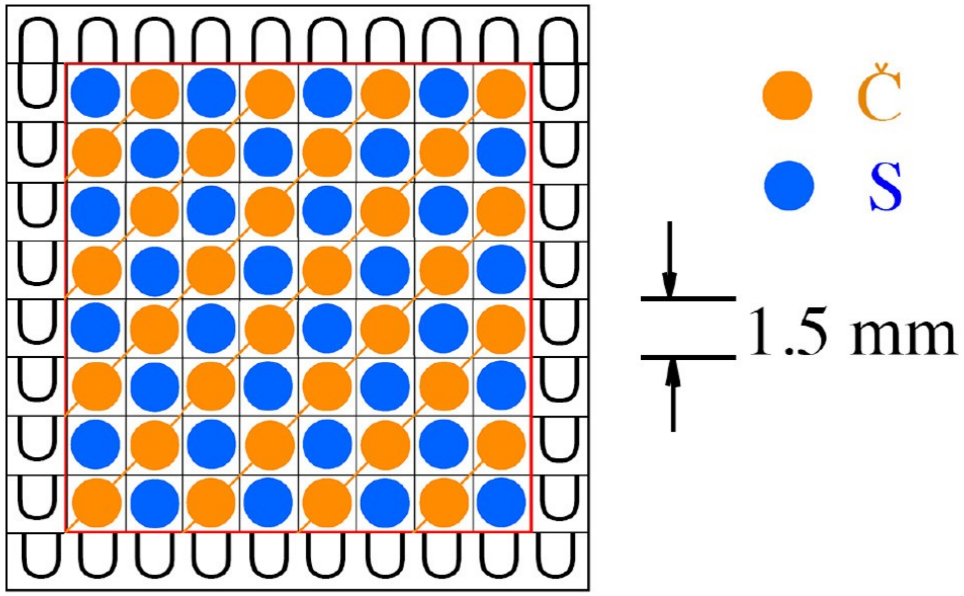
highly granular prototype (RD52)

Brass module, dimensions: ~ 112 cm long, 12 x 12 mm²

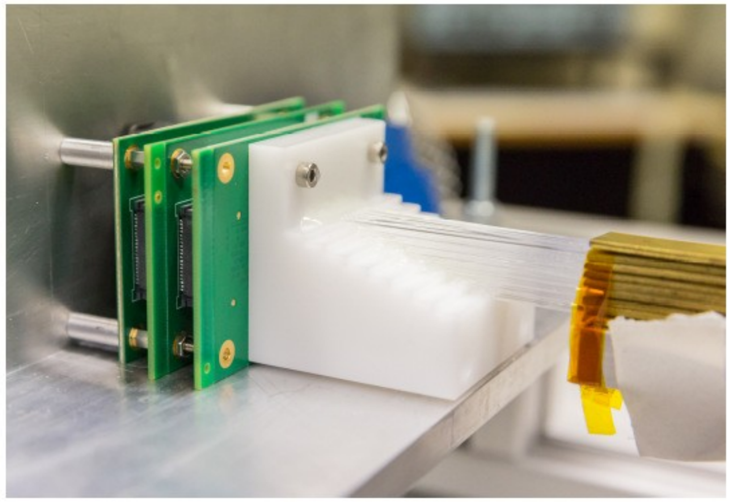
32 (S) + 32 (Č) fibres
X_0 ~ 29 mm
R_M ~ 31 mm

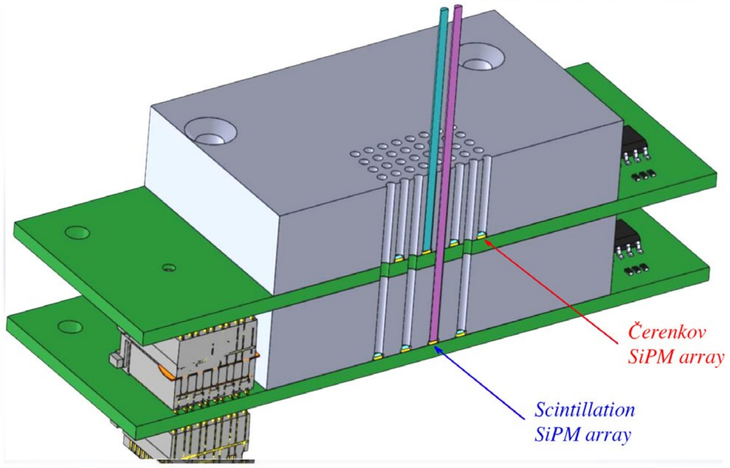
~ $(0.4\ R_M)^2 \times 39\ X_0$

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



Light sensors (SiPM)





NIM A 899 (2018) 52

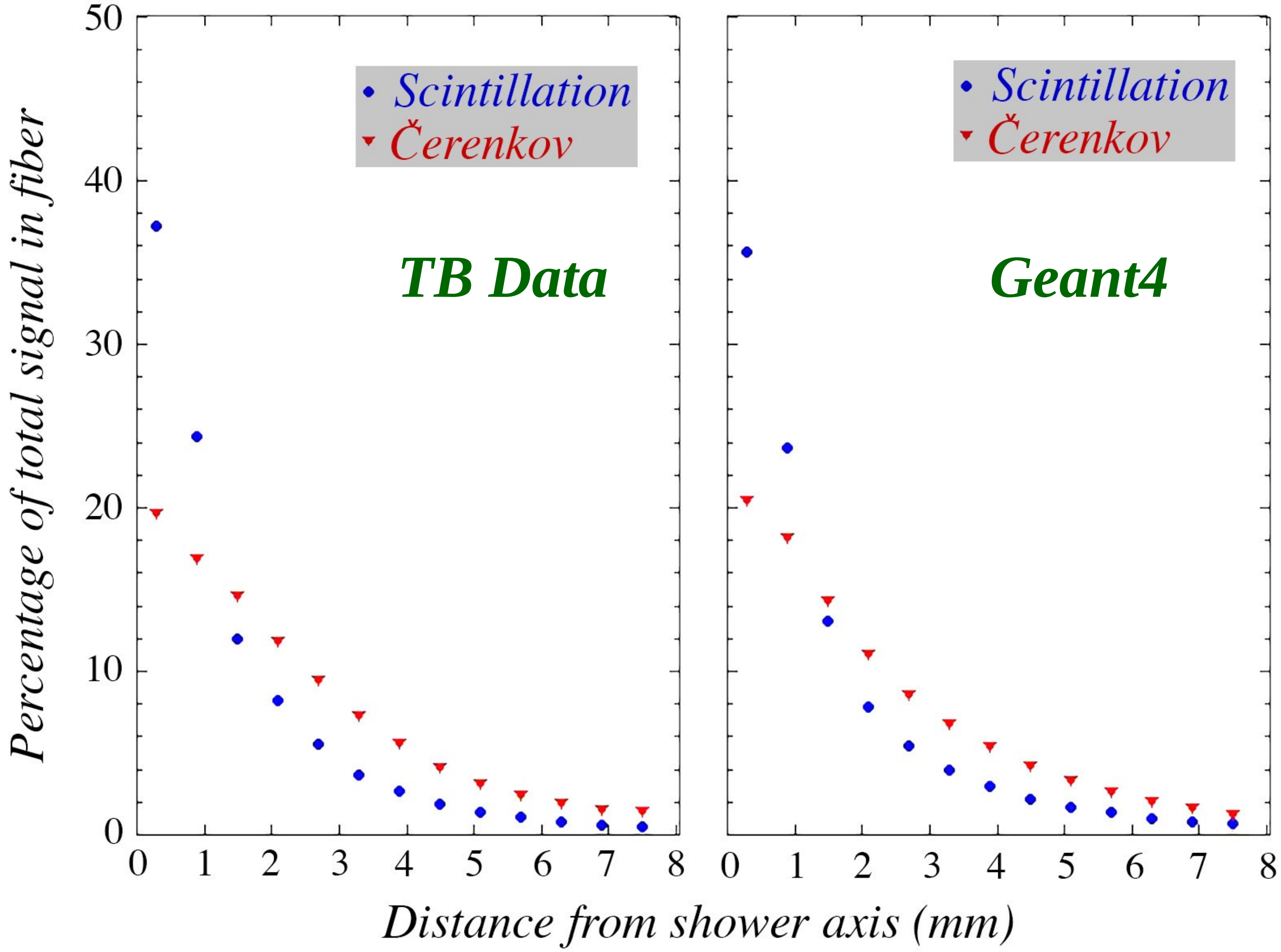
lateral shower profile w/ SiPM

NIM A 899 (2018) 52

10 / 40 GeV e^-

θ, Φ = 0°

Percentage of total signal in fibre

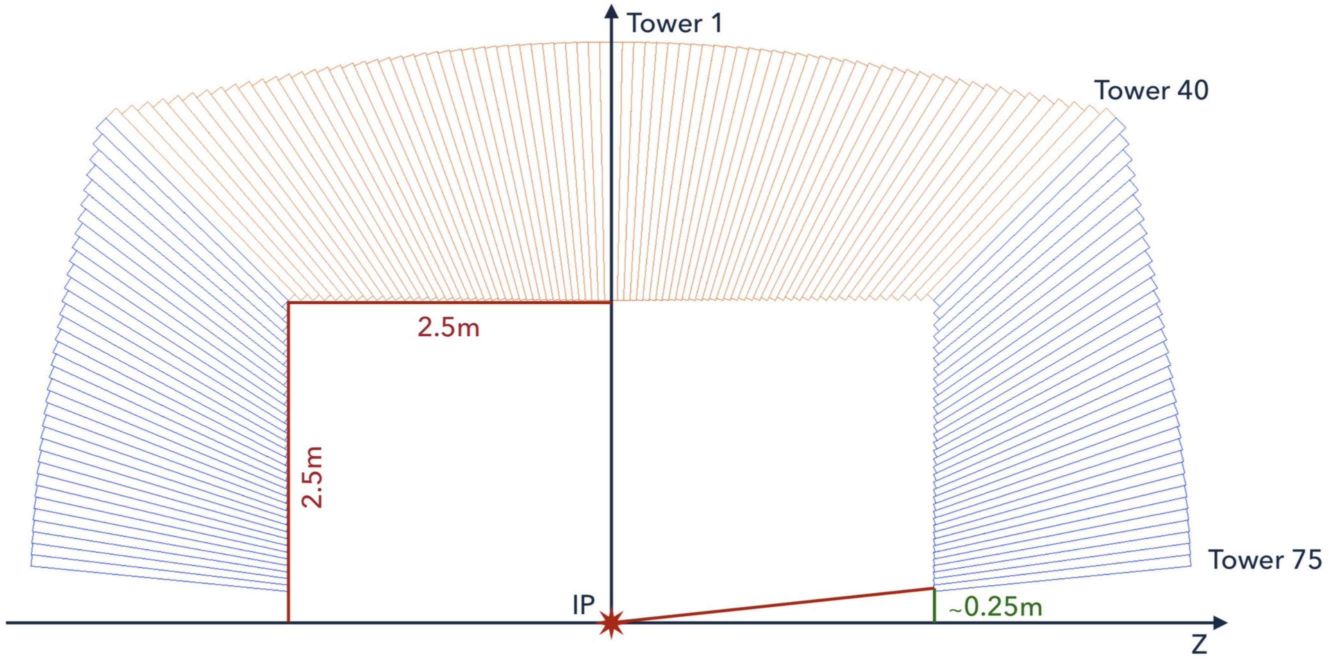


em shower are very narrow:

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

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

IDEA (full simulations)

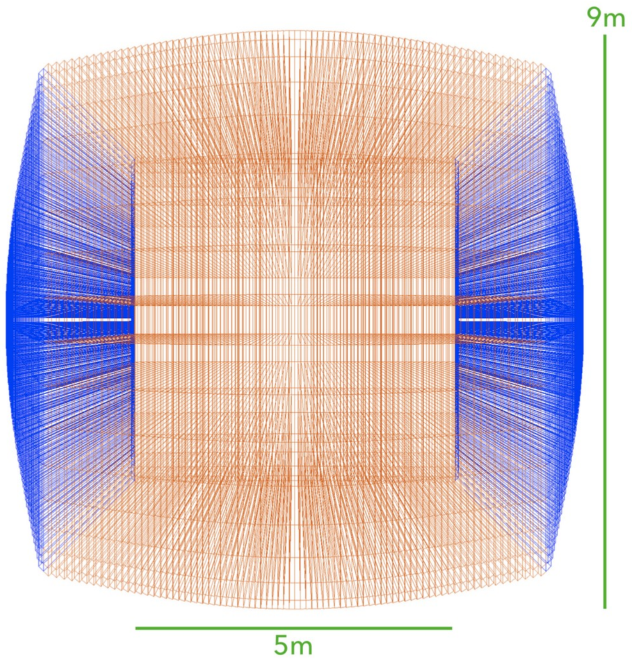


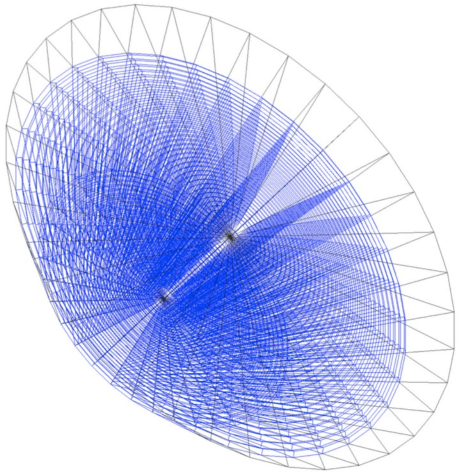
Baseline option

Cu absorber

1 mm fibres

1.5 mm pitch





75 projective towers
× 36 slices

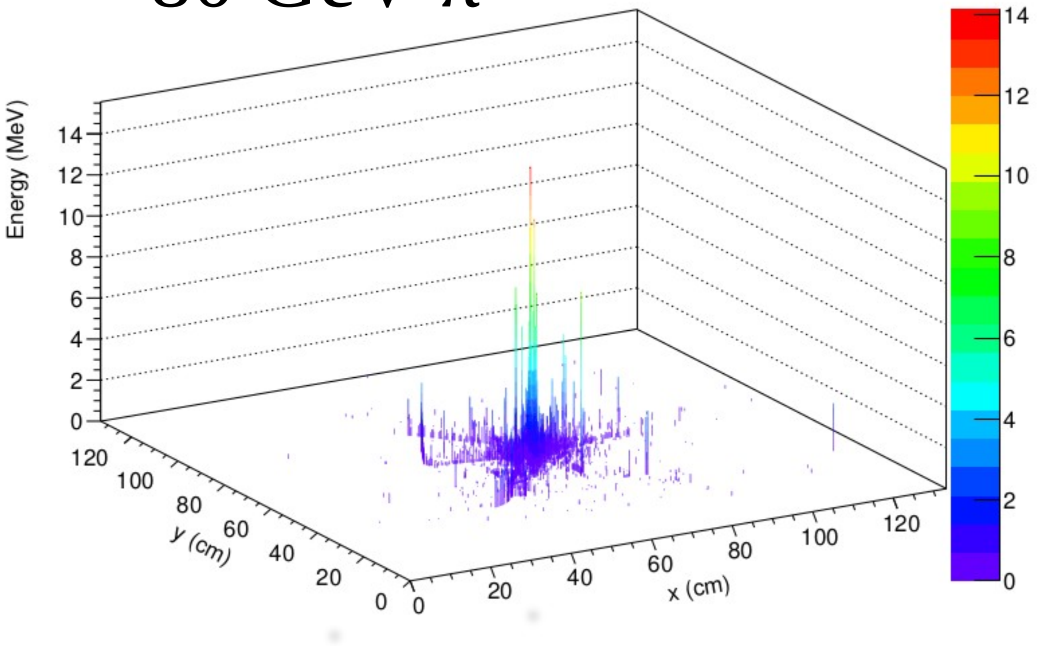
Δθ = 1.125°

Δφ = 10°

~130 M fibres

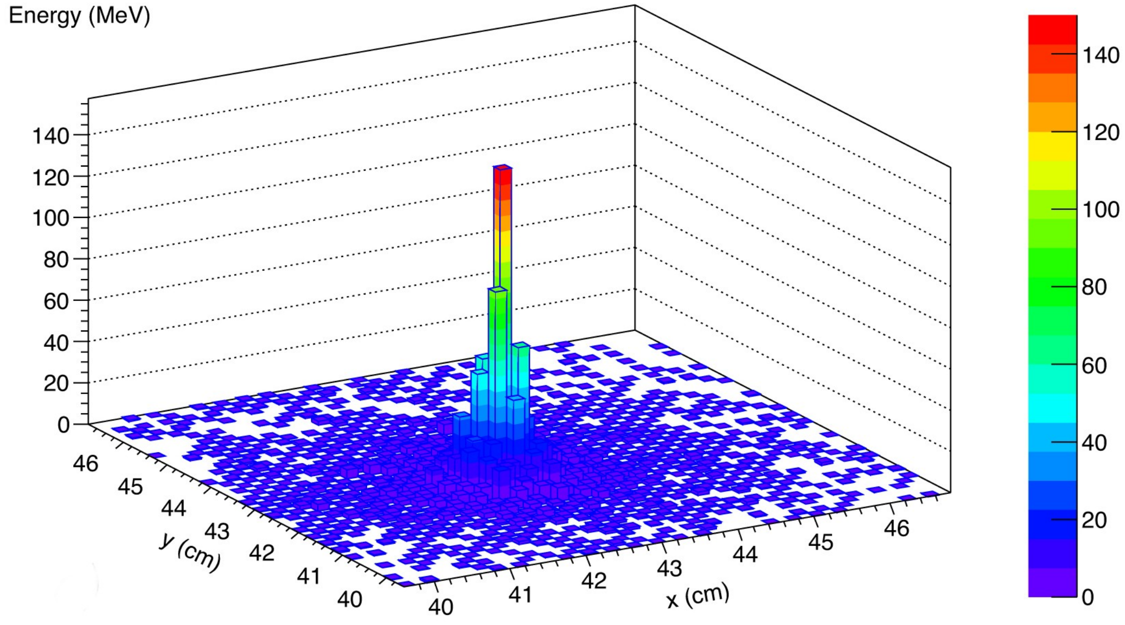
shower 2D-imaging

80 GeV π^-

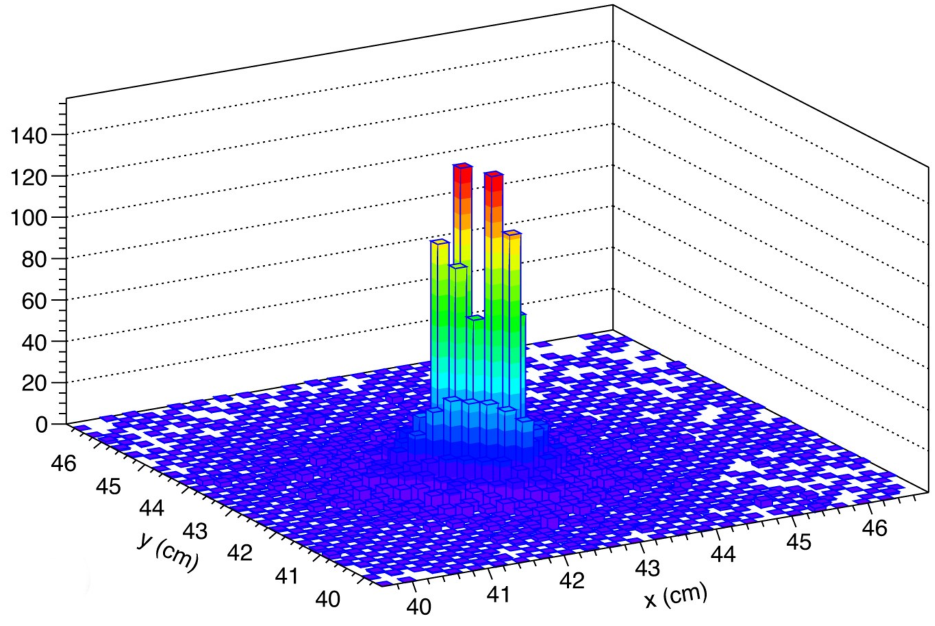


Geant4 single-particle simulations

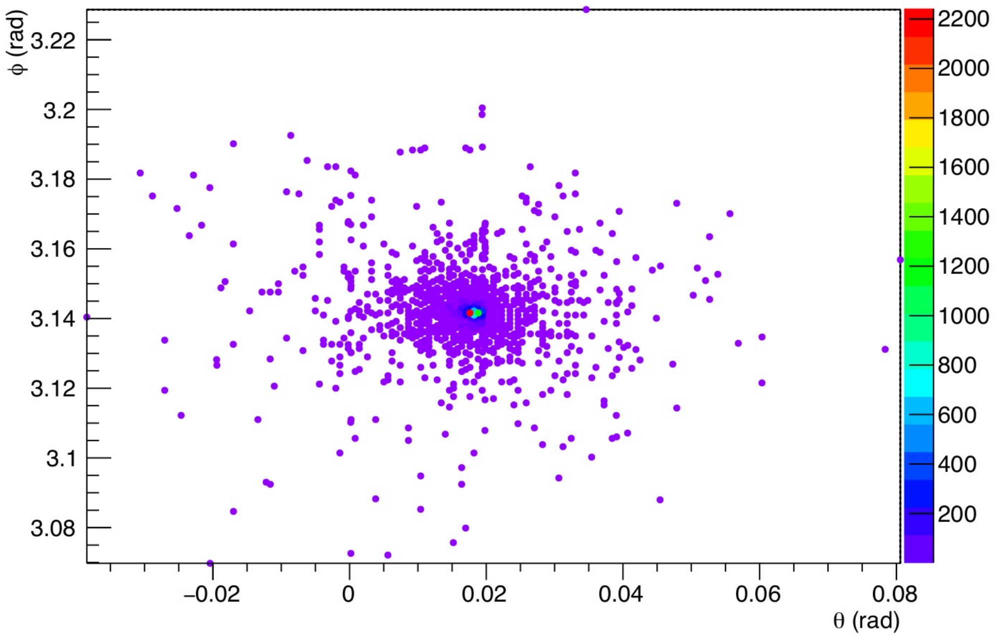
50 GeV e^-

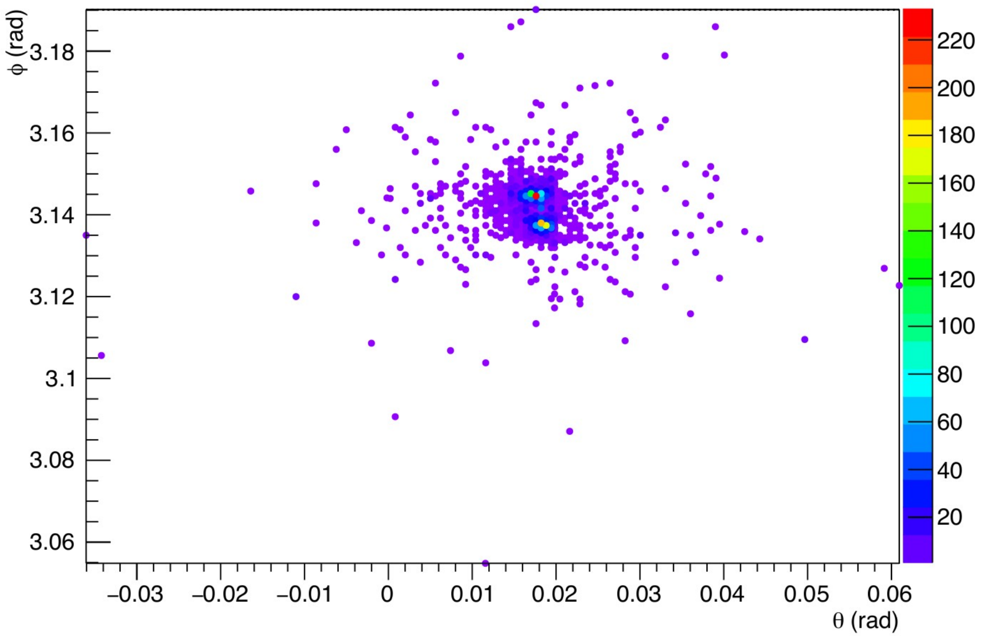


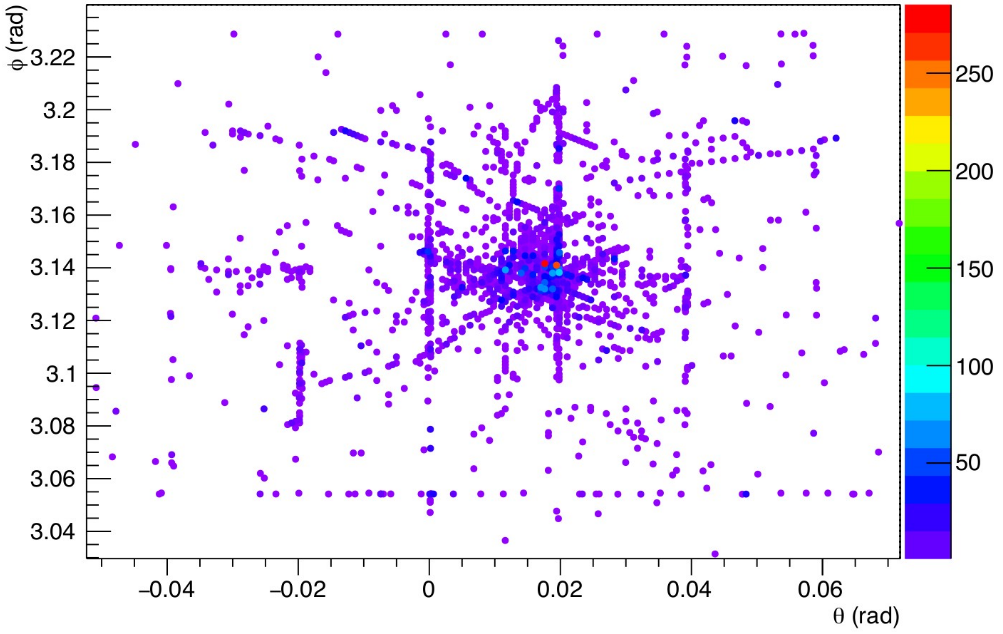
100 GeV π^0



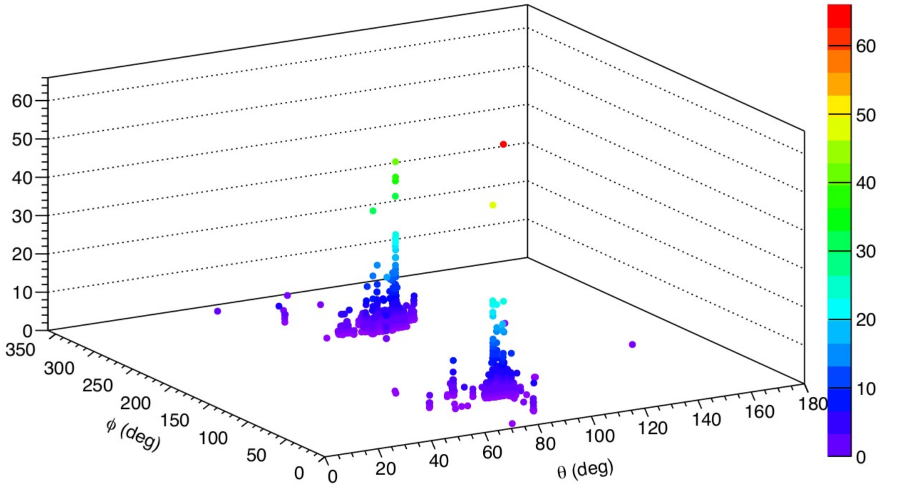
events @ full granularity


e- 40 GeV


π^0 40 GeV


π^- 40 GeV

Di-jet



3-leg international proto-collaboration

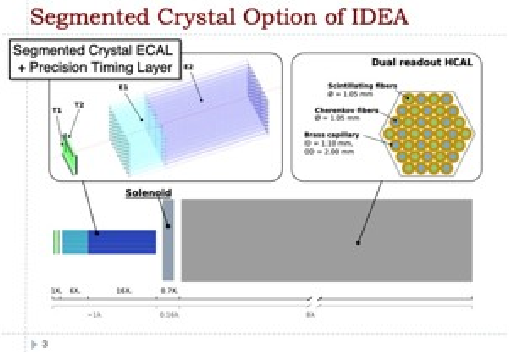
Prof. Hyonsuk Jo (KNU)
Prof. Jason Lee (UoS)
Prof. Sehwook Lee (KNU)
Prof. Hwidong Yoo (YU)

Prof. Rong-Shyang Lu

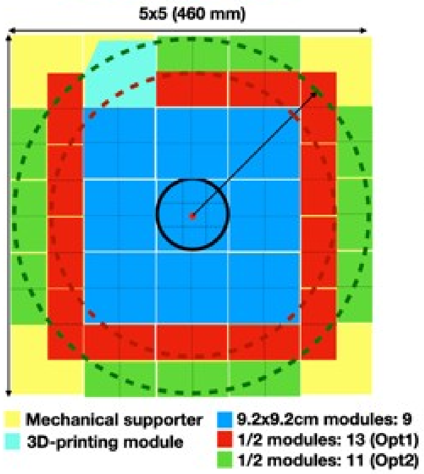
Prof. Chia Ming Kuo

Taiwan

3. Crystal option


Segmented Crystal Option of IDEA

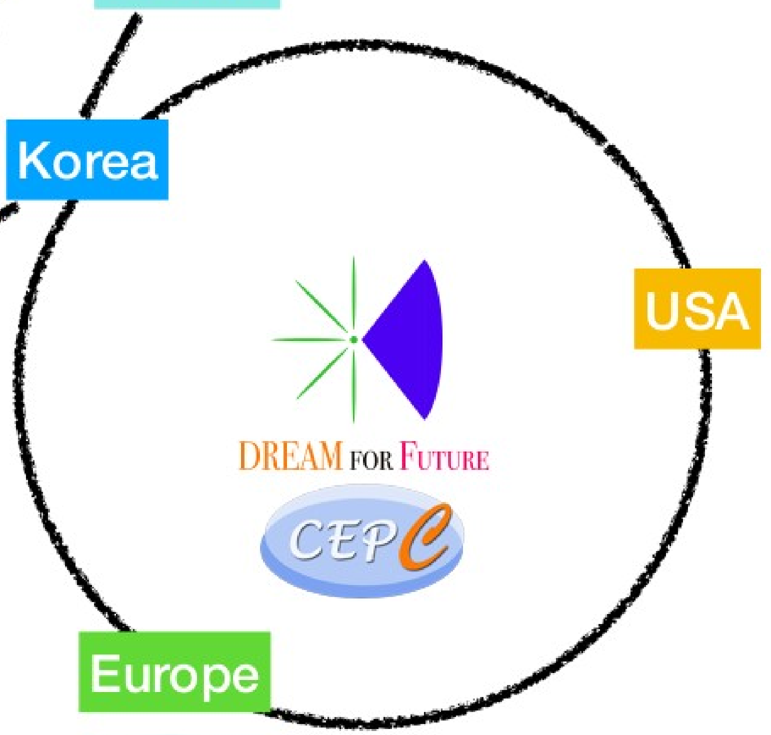
2. Full-size prototype detector



🟨 Mechanical supporter
🟦 3D-printing module
🟦 9.2x9.2cm modules: 9
🟥 1/2 modules: 13 (Opt1)
🟩 1/2 modules: 11 (Opt2)

Japan

Prof. Yuji Enari
(Active from 2021)



Prof. Sarah Eno

Prof. Chris Tully

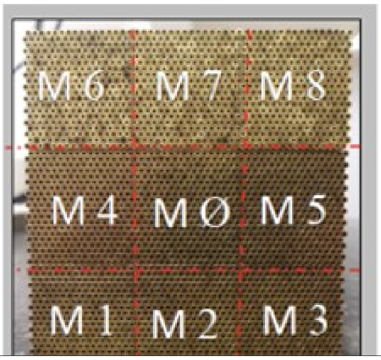
Prof. Richard Wigmans

Prof. John Hauptman

Prof. Paolo Giacomelli (Bologna)
Prof. Romualdo Santoro (Insubria)
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)

Prof. Iacopo Vivarelli

1. Bucatini prototype



International collaboration forms
- **Regular meeting**
- **Compensated R&D options**
- **Combine efforts**

+ Texas Tech Prof. Nural Akchurin

+ UTFSM Valparaiso Prof. Edson Carquin Lopez

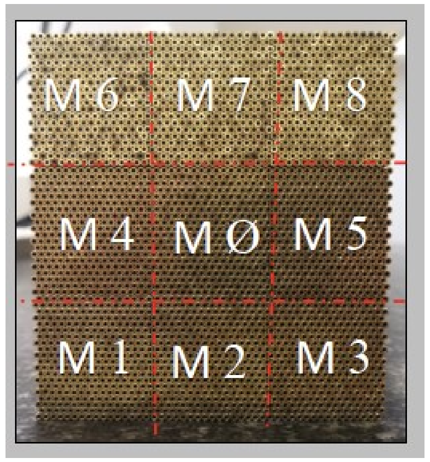
2021 (highly granular) modular prototype

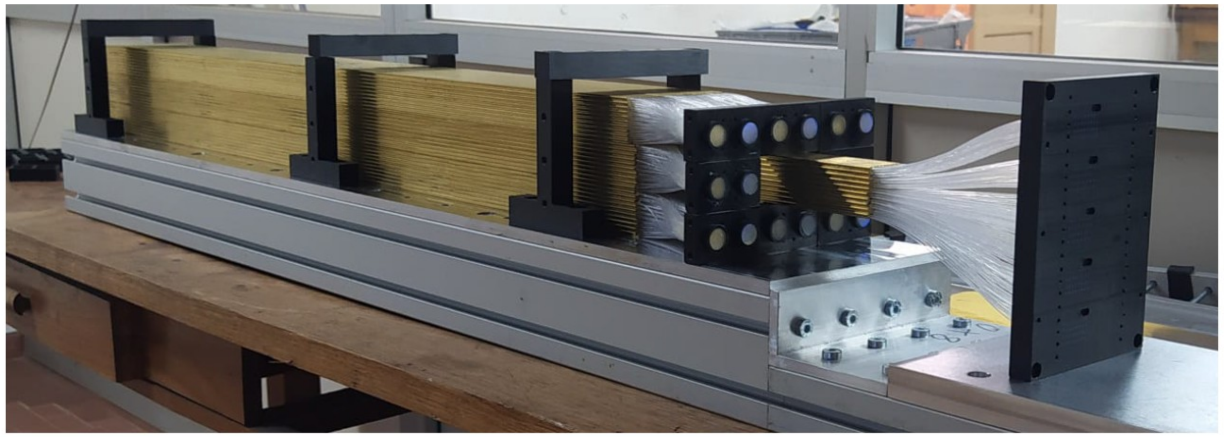
- 9 modules (M0-M8) each one made of 16×20 (2-mm Ø) brass capillary tubes (bucatini prototype)
  - M0 with “high-granularity” readout (SiPMs)
  - M1-M8 with “low-granularity” readout (PMTs)

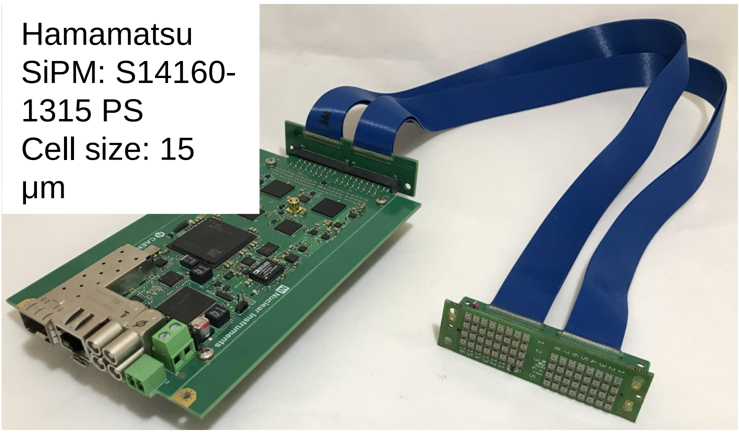
- alternate rows of scintillating and Čerenkov fibres

- total dimensions of ~ 10×10×100 cm^3 (“electromagnetic containment”)

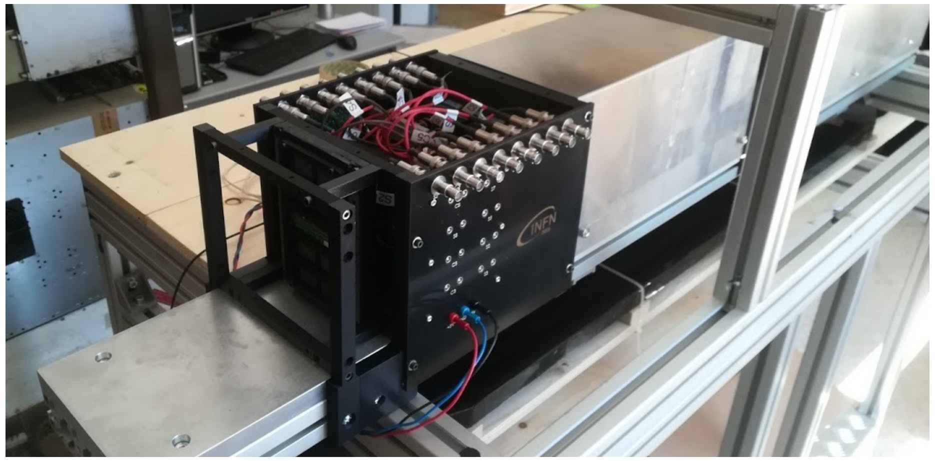
- tested with DESY and SPS beams







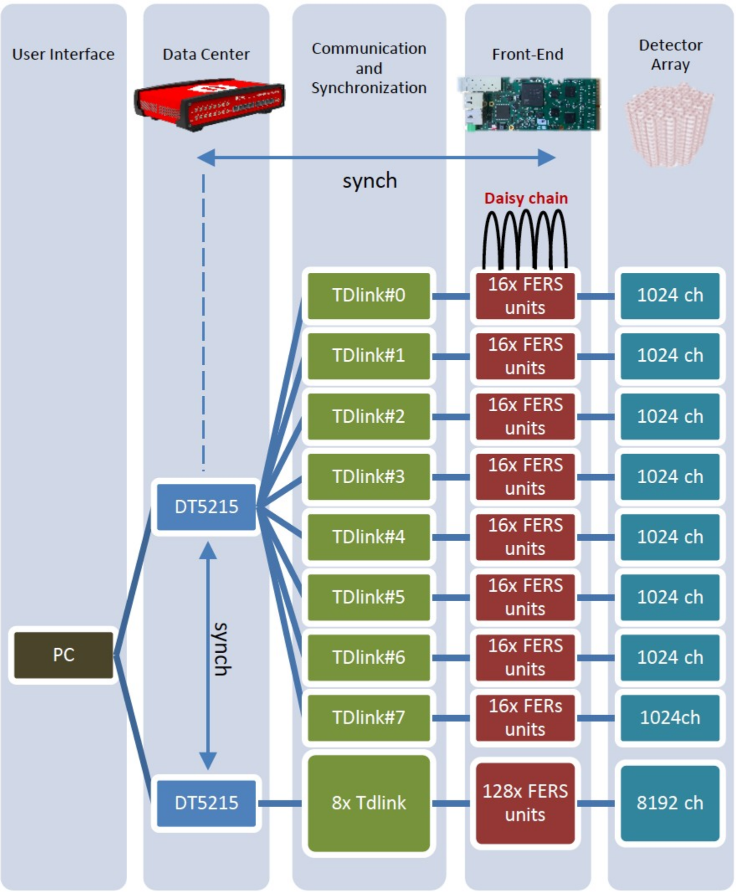
Hamamatsu SiPM: S14160-1315 PS
Cell size: 15 µm



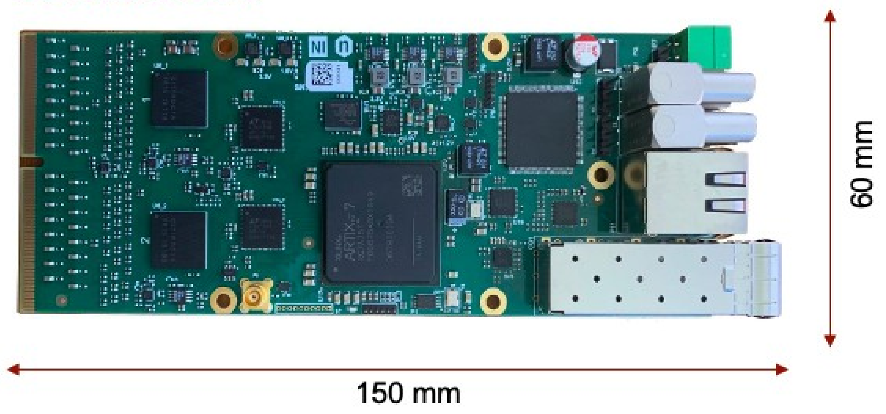
2021-prototype readout system

PMTs read out with QDC (V792AC) and TDC (V775N) CAEN modules

Highly granular module read out with FERS-5200 CAEN system using five A5202 readout boards → *in perspective, should we look for custom solution?*



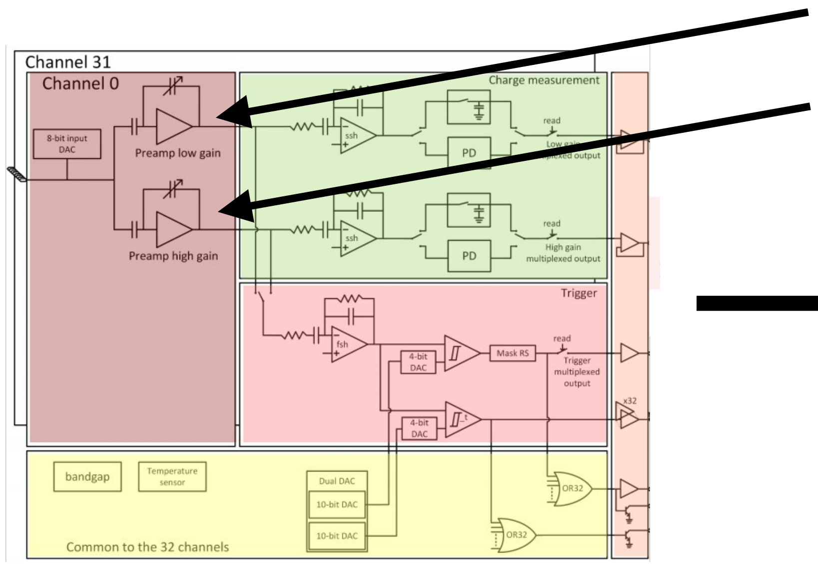
FERS: A5202



- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout (6.25 Gbit/s)

SiPM readout w/ Citiroc 1A

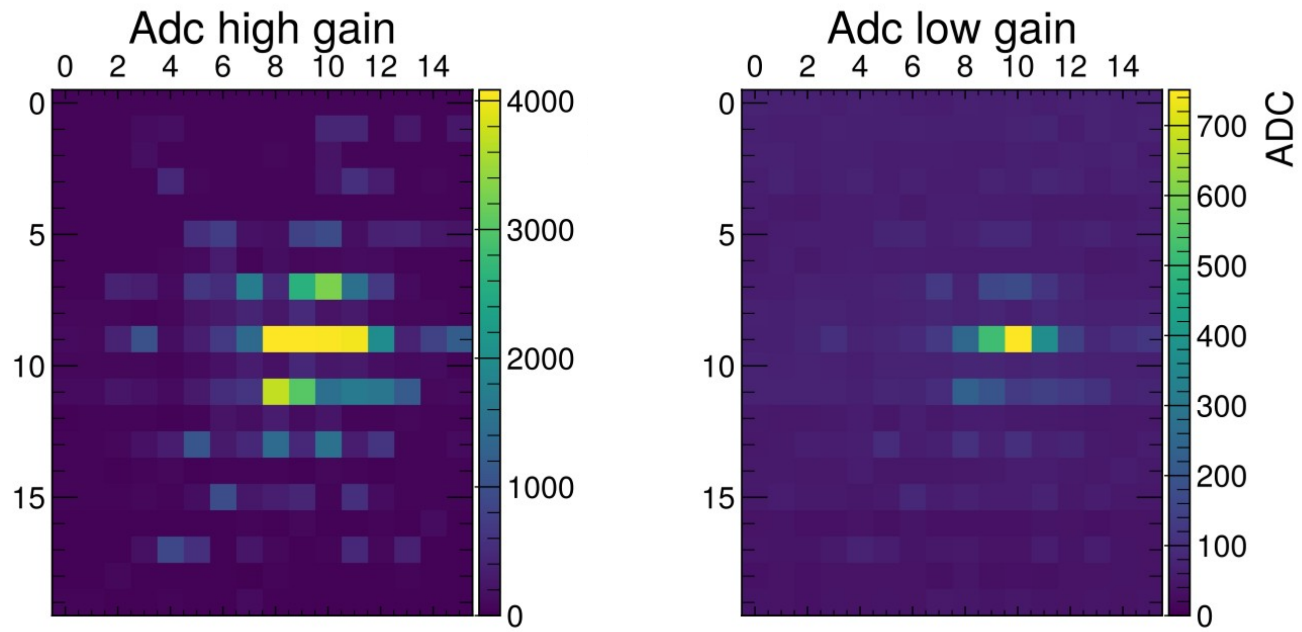
CITIROC 1A: block diagram

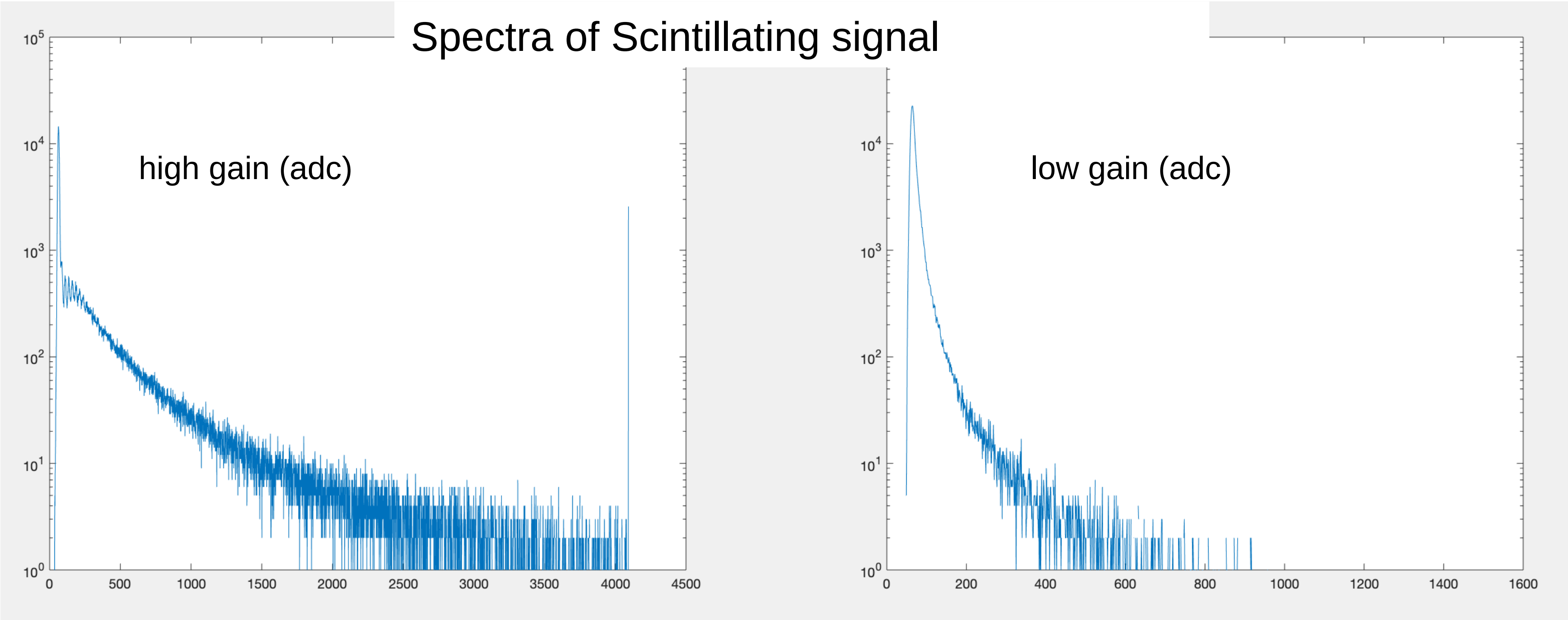


low-gain preamp

high-gain preamp

6 GeV beam centred on central tower (M0)




Spectra of Scintillating signal

high-gain channel sensitive to single photoelectrons (measure pedestal and ΔPP)

→ use high-gain channel to cross-calibrate low-gain channel in photoelectrons

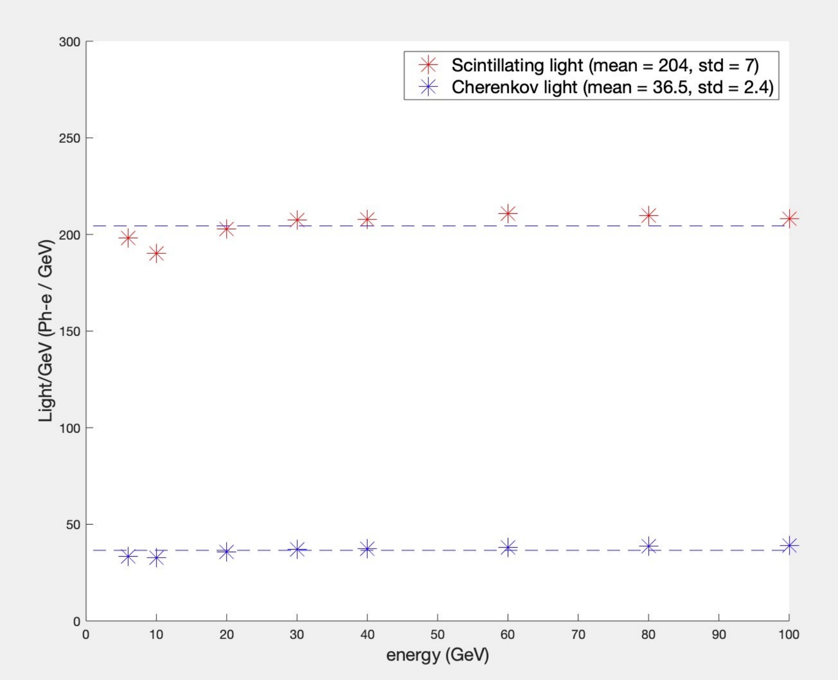
preliminary results

All SiPM signals converted to ph-e and separately summed up for Čerenkov and scintillation light

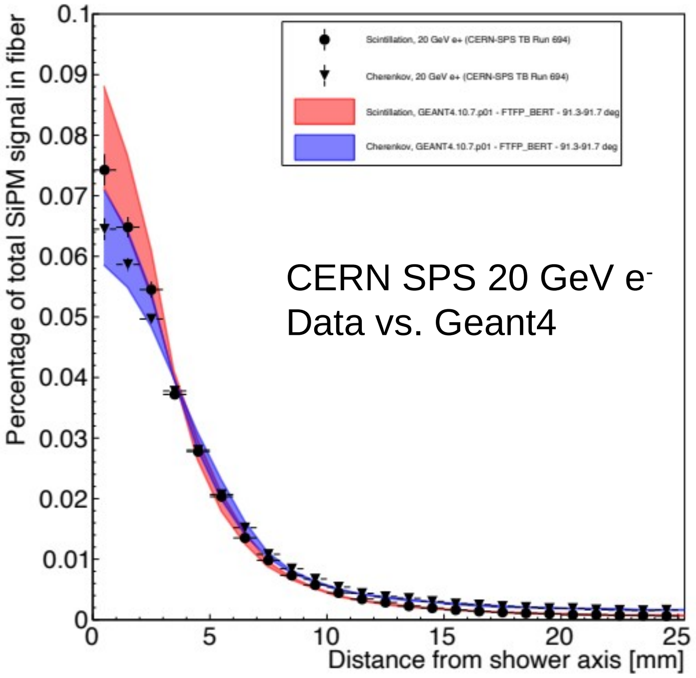
Light yield (ph-e / GeV)

yellow filter on scintillating fibres

no filter on Čerenkov fibres



shower profile

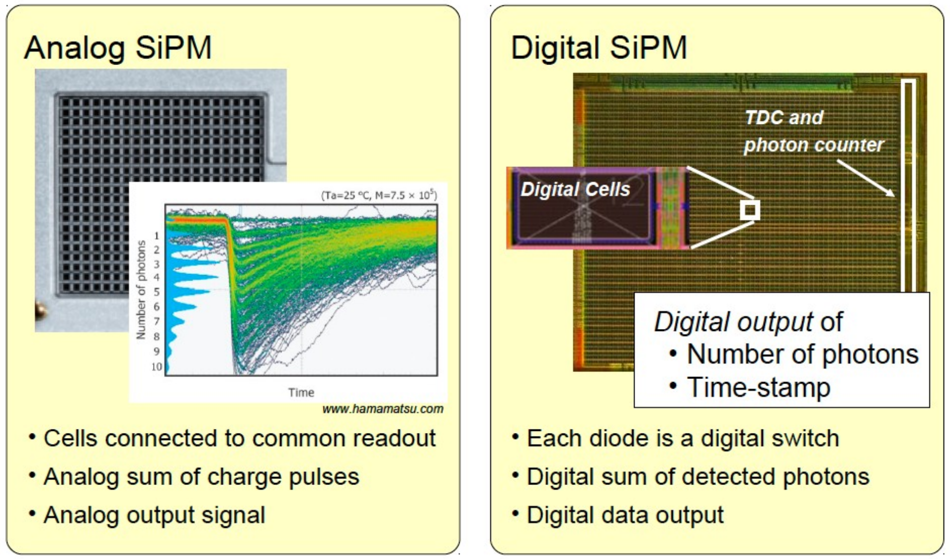


Data - Geant4 comparison at 20 GeV

- Non negligible dependence of shower shape on impinging angle
- Good agreement when including a ±0.2° systematics on impinging angle
  - Both shower “core” and “tails” properly reconstructed
- Sensible differences between scintillation and Čerenkov signals at any energy scale

very perspective R&D?

Do you really want to be analogue?



Analog SiPM

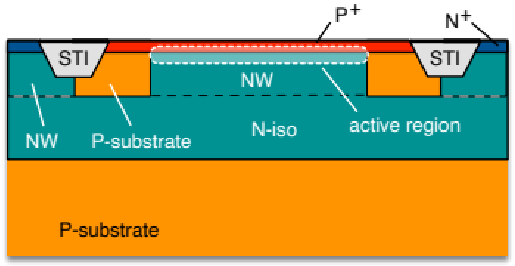
- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM

Digital output of
- Number of photons
- Time-stamp

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

https://indico.gsi.de/event/2099/contributions/6718/attachments/5430/6692/DIRC2013_Philips_Haemisch.pdf



L. Ratti et al, Front. Phys., 14 January 2021 https://doi.org/10.3389/fphy.2020.607319

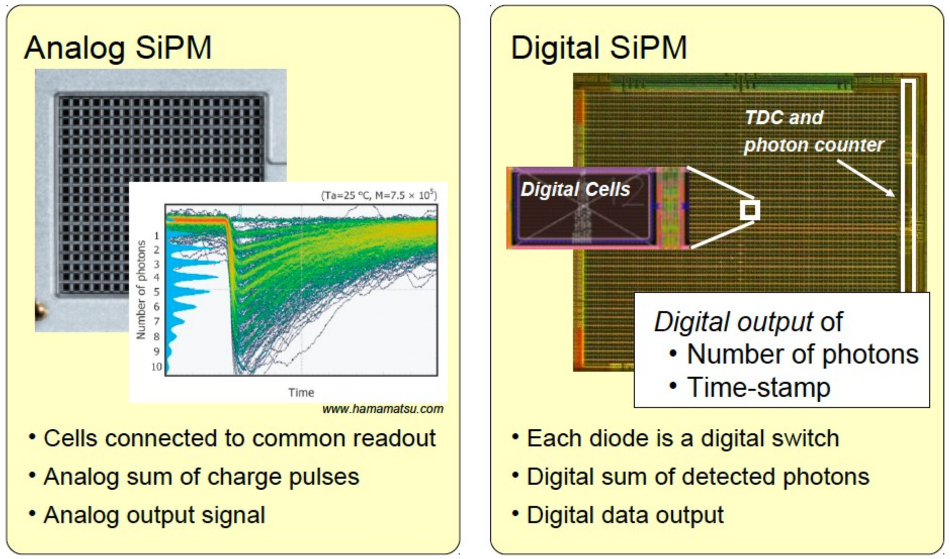
digital SiPM (dSiPM): CMOS monolithic sensor and digitiser

→ no need for analogue signal post-processing

directly provide # of fired pixels, ToA, possibly ToT

very perspective R&D?

Do you really want to be analogue?



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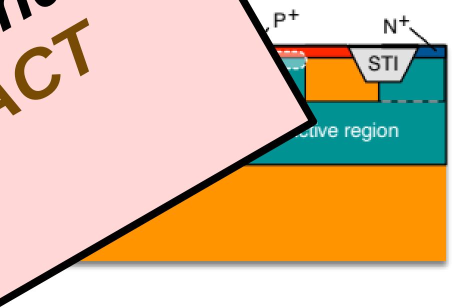


Ratti et al, Front. Phys., 14 January 2021
https://doi.org/10.3389/fphy.2020.607319

strategic R&D but … not yet specifically funded
[window opportunity inside the ATTRACT RandomPower project]

digital **monolithic sensor and digitiser**

→ r analogue signal post-processing

directly provide # of fired pixels, ToA, possibly ToT

HiDRa

High-resolution highly granular Dual-Readout demonstrator

INFN – CSN V call with a 3-year (2022-2024) program

Goals: build a highly granular “hadronic containment” prototype in order to:

1) design and validate a scalable construction technique

2) design and validate a scalable readout architecture based on SiPMs

3) assess hadronic performance

4) validate Geant4 hadronic shower simulation models

5) assess longitudinal shower position measurements through timing

6) exploit DNN algorithms in final-state identification and reconstruction

[INFN divisions of Bologna, Catania, Milano, Pavia, Pisa, Roma, TiFPA,
with the collaboration of the University of Sussex
and UTFSM of Valparaiso]

the project

1) size: ~ 65×65×250 cm^3

2) # of channels: ~80k tubes & fibres

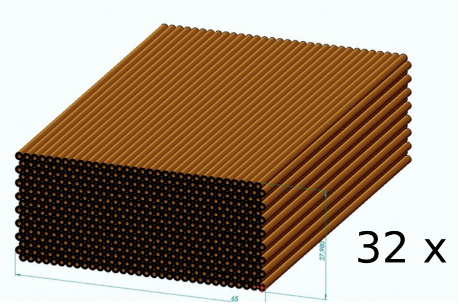
3) highly granular core (~10k fibres to be read out with SiPMs)

4) scalable design

The challenge

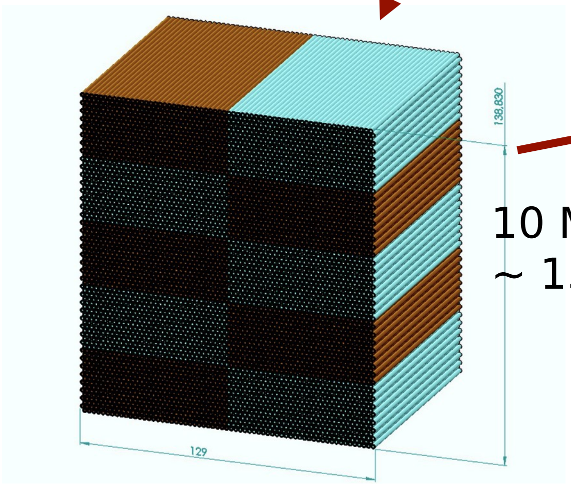
10240 SiPMs to be read out, on detector back side

The Mini-Module

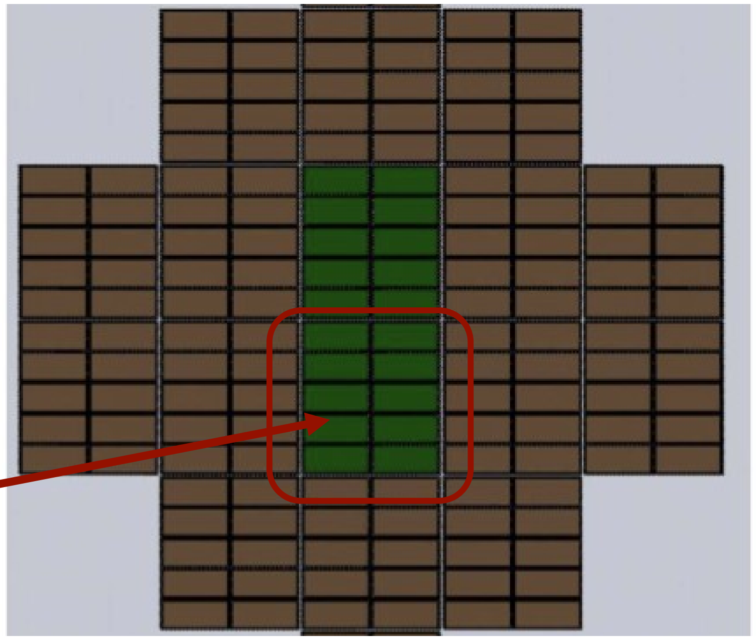


32 x 16 capillaries

The Module



10 Mini-modules
~ 13 x 13 x 250 cm^3



- 16 modules in total
  - 2 central modules equipped with SiPMs
  - 14 modules equipped with PMTs

mechanics – 2022 program

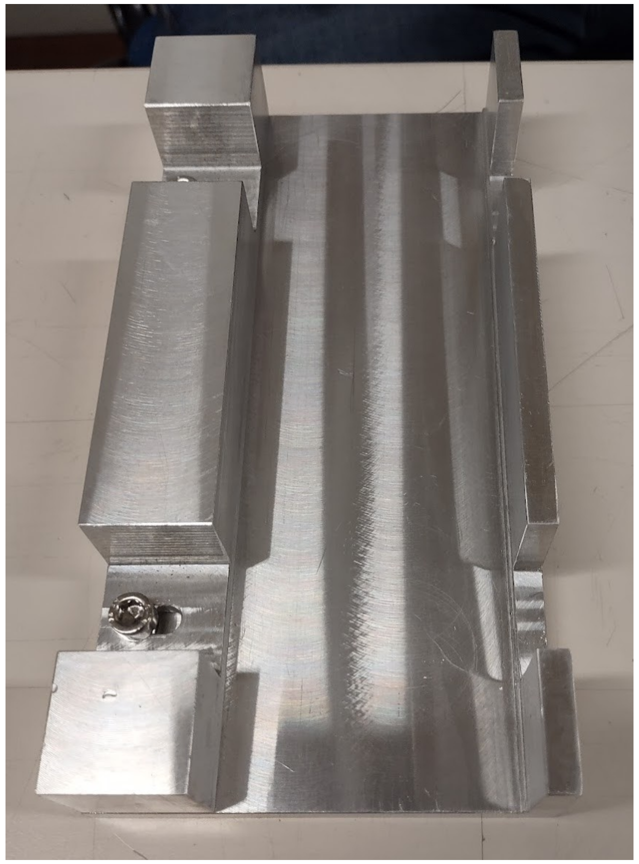
a) 1 × 20-cm-long minimodule → study assembly technique and tools

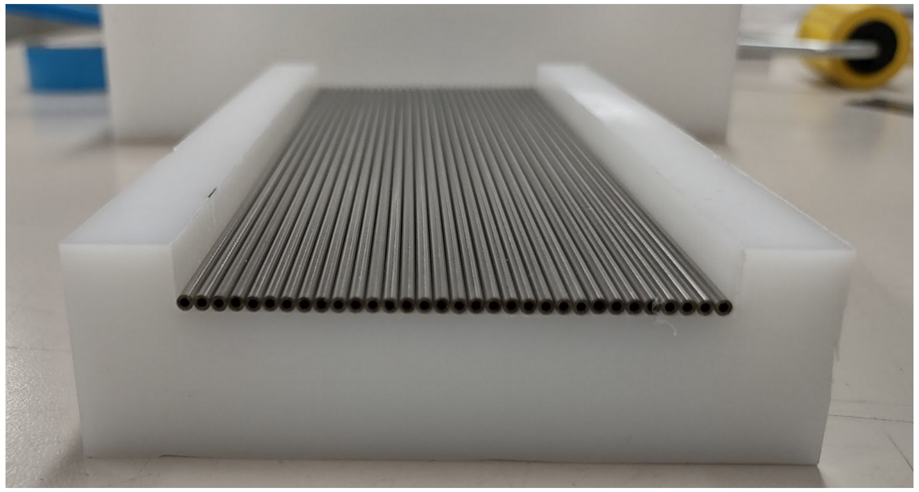
b) 1 x 250-cm-long minimodule → scale up technique and tools

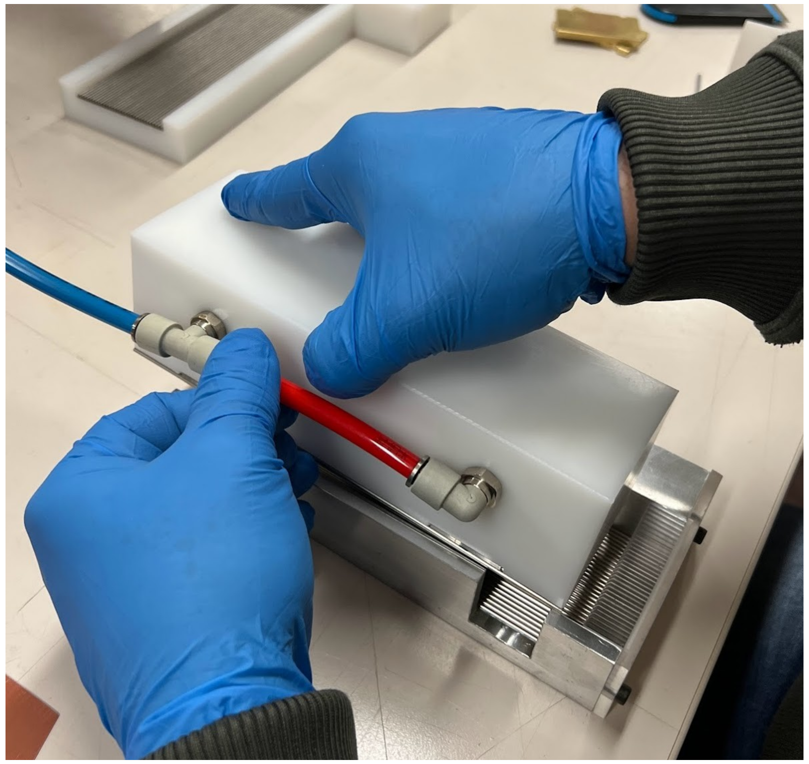
c) 2nd 250-cm-long minimodule → verify mechanical coupling, study fibre grouping for PMT readout

20-cm-long minimodule: pretty good quality of capillary tubes → simplify tooling

1) tooling designed and built
2) six layers glued and measured

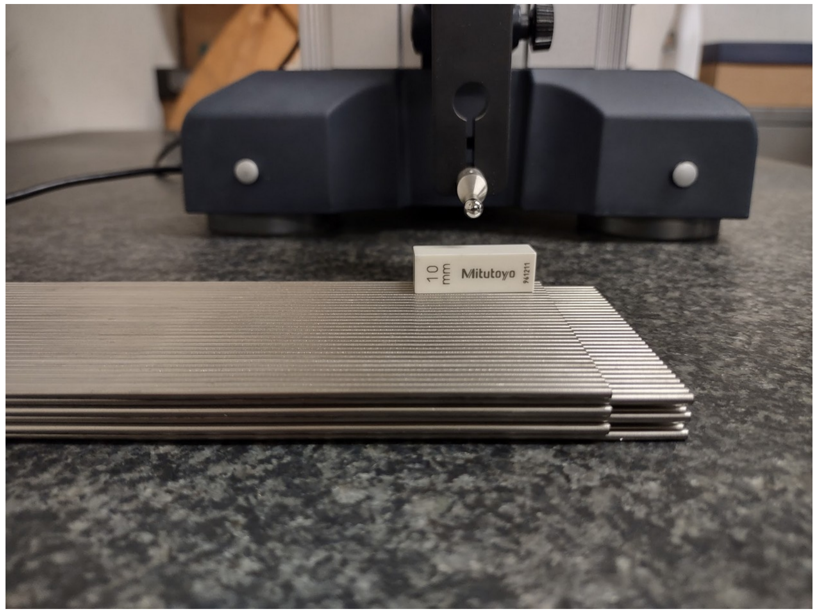






INFN PAVIA

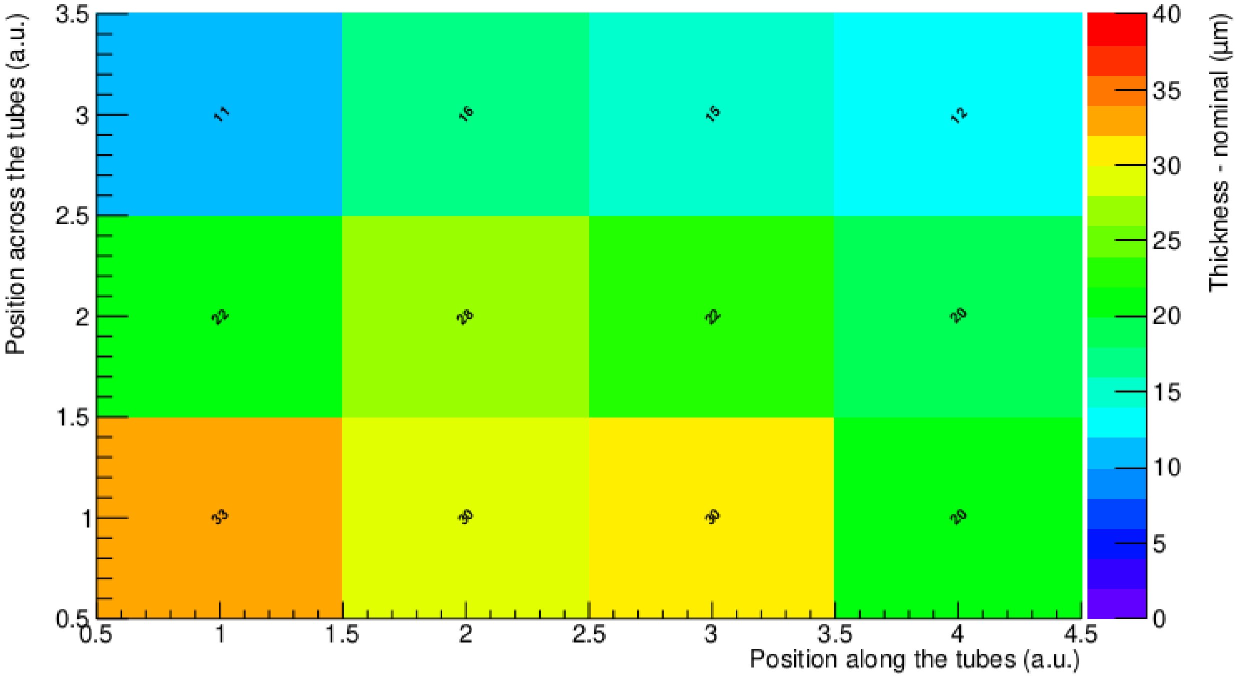
20-cm-long minimodule



measured overall dimensions and geometry
(thickness, width on both sides)

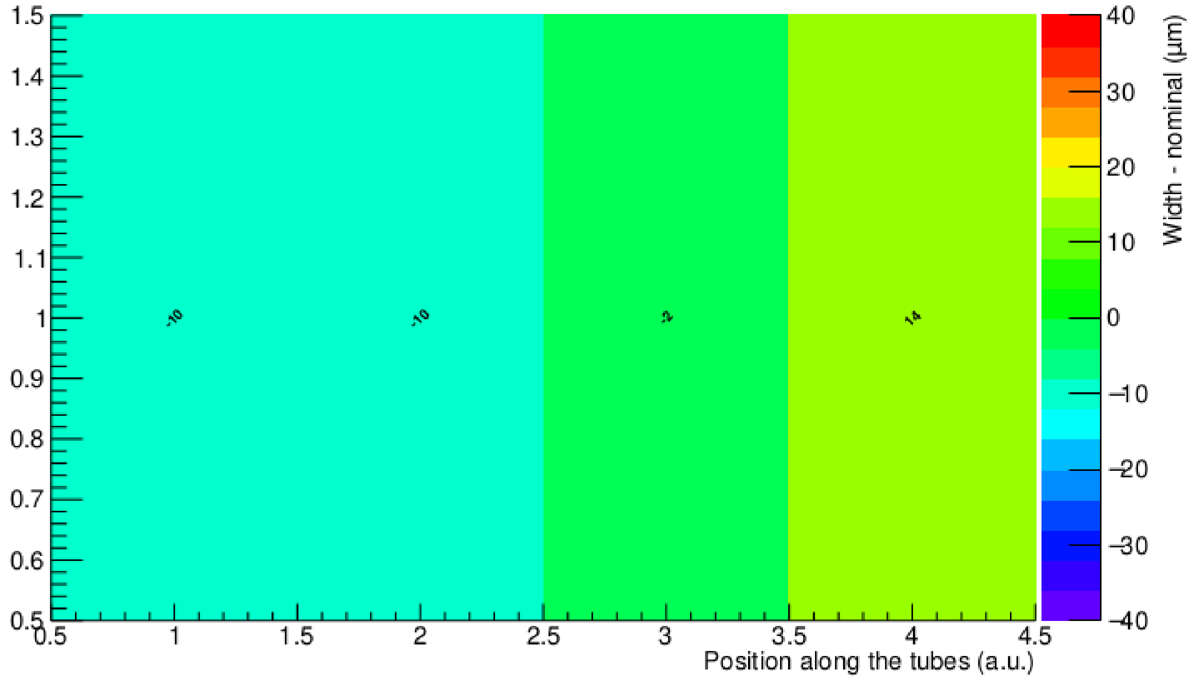
bending = 12 μm
torsion = 10 μm

module thickness



11 μm < all values < 33 μm

module width



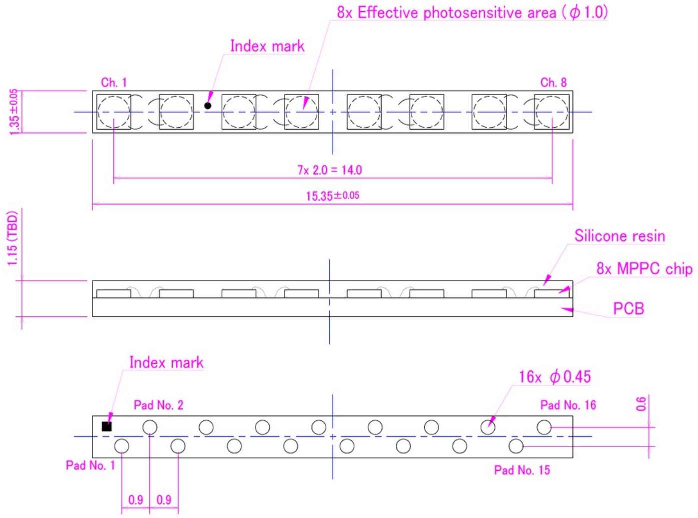
|all values| < 14 μm

front-end elx (grouping)

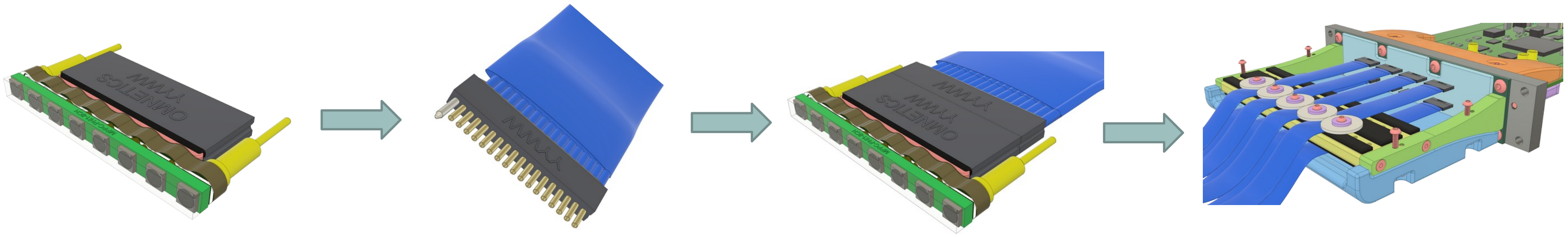
Requirements:

- individually qualify each SiPM
- reduce number of readout channels
  - → 8-SiPM signal grouping for readout
  - → linearity needs to be guaranteed

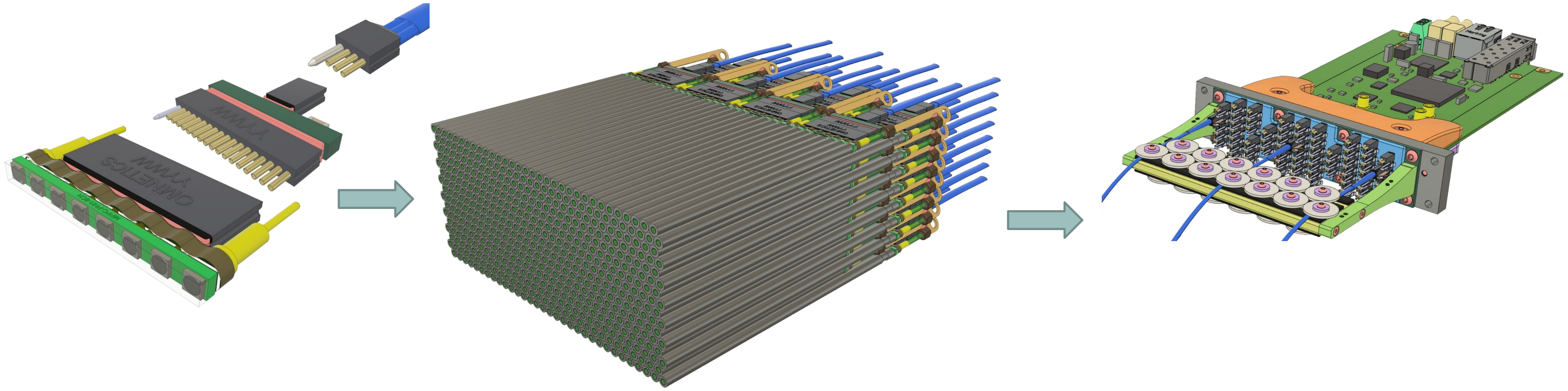
8-SiPM module from Hamamatsu



a) Commissioning: 1 front-end board → 8 readout channels



b) Operation: 1 front-end board → 1 readout channel



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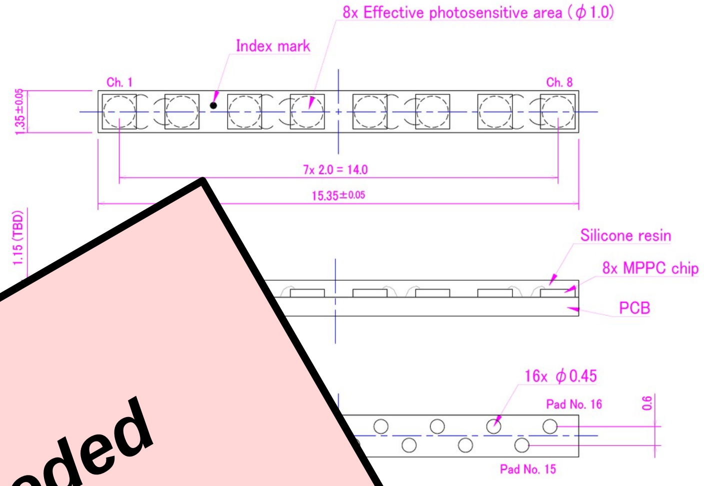
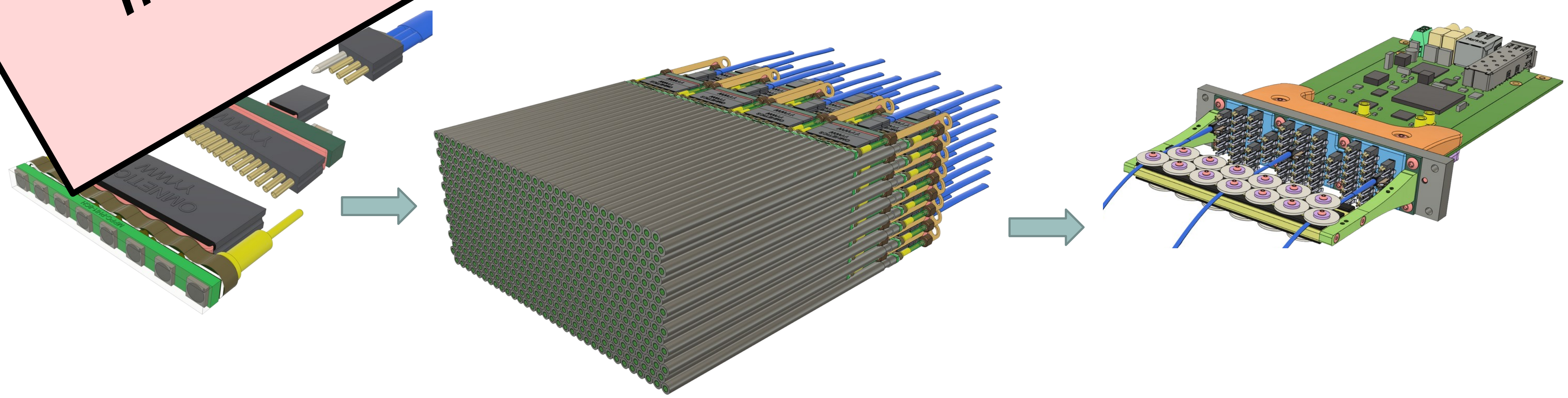


a) Commissioning: 1 front-end board → 8 re

have initial design but more R&D needed

b) Operation: 1 adout channel



readout system

Two possible ways:

charge integration (baseline)
waveform sampling (alternative to be studied)

both presently targeting commercial implementations (by CAEN) of “SiPM-customised” chips (produced by Weeroc and by Nalu Scientific)

Q: would be worthwhile to invest on R&D in this context?

dual-readout crystal option

Segmentations optimised for particle ID and PFA

SiPM readout for contained cost and power budget

T1&T2 timing layers

LYSO:Ce crystals (~1 X_0)

σ_t ~ 20 ps

More details in: 2020 JINST 15 P11005

E1&E2 ECAL layers

PWO crystals

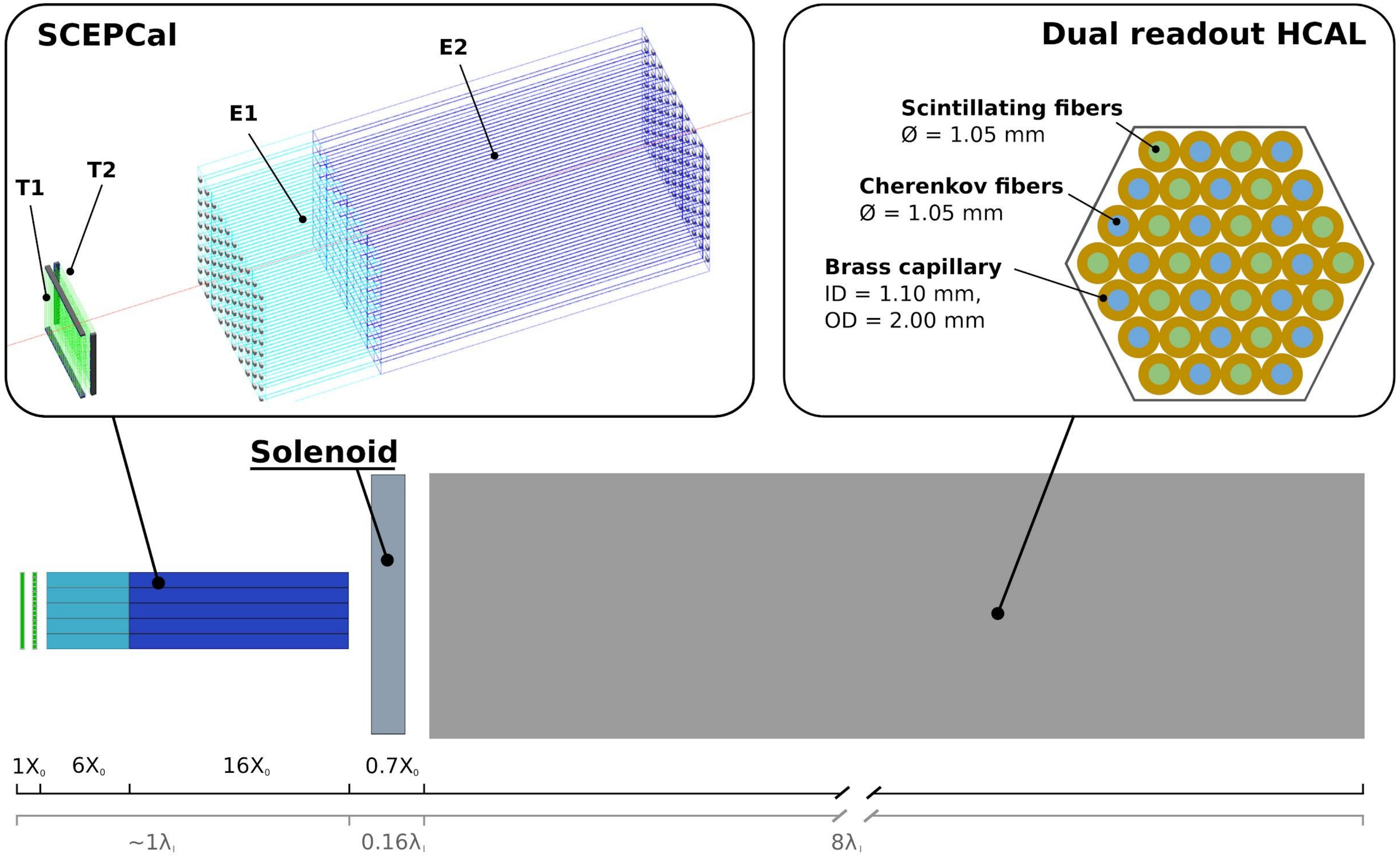
~6 X_0 + ~16

σ_{EM}/E ~ 3%/√E

Ultra-thin (~0.7 X_0) solenoid

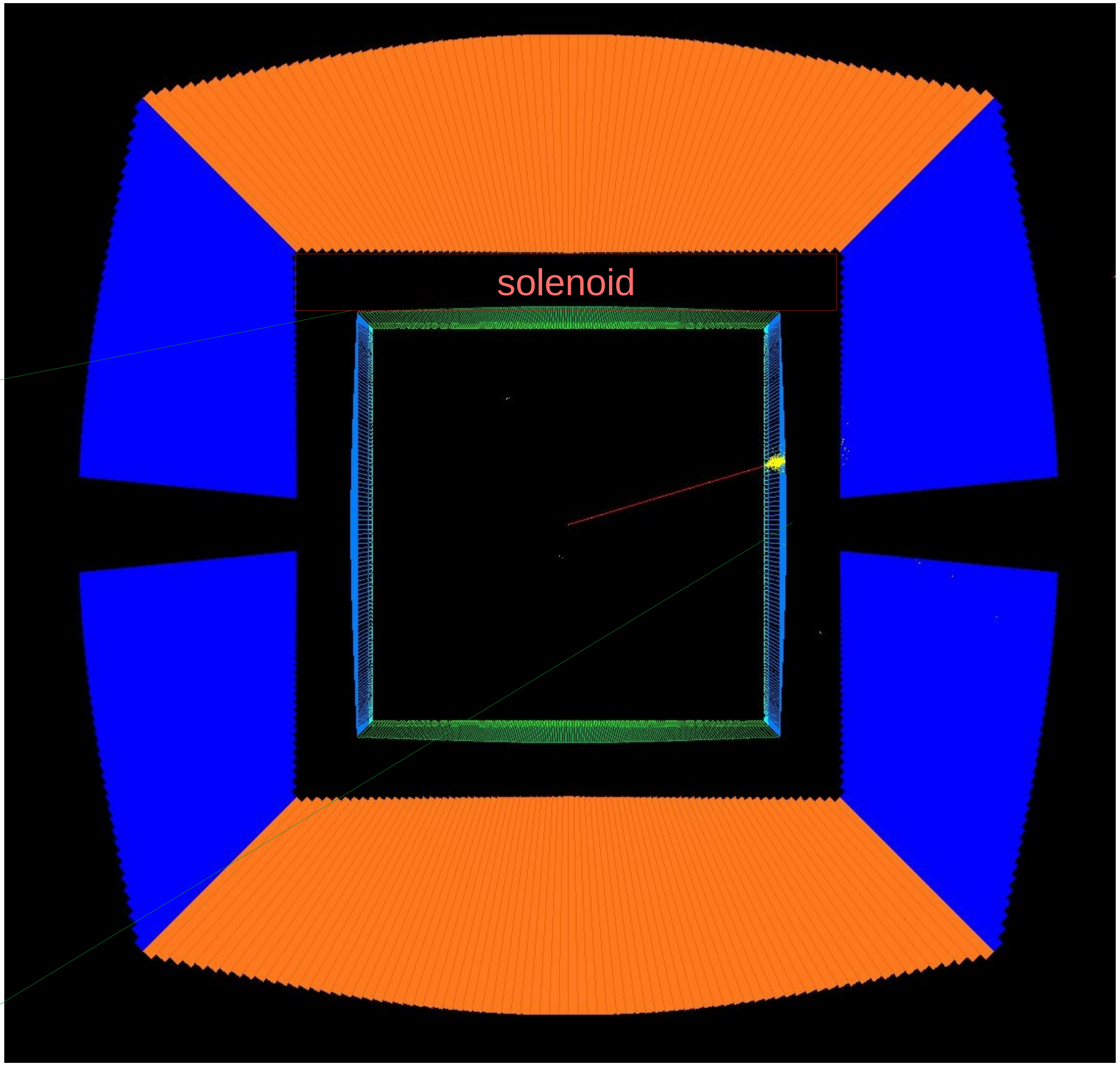
HCAL layer

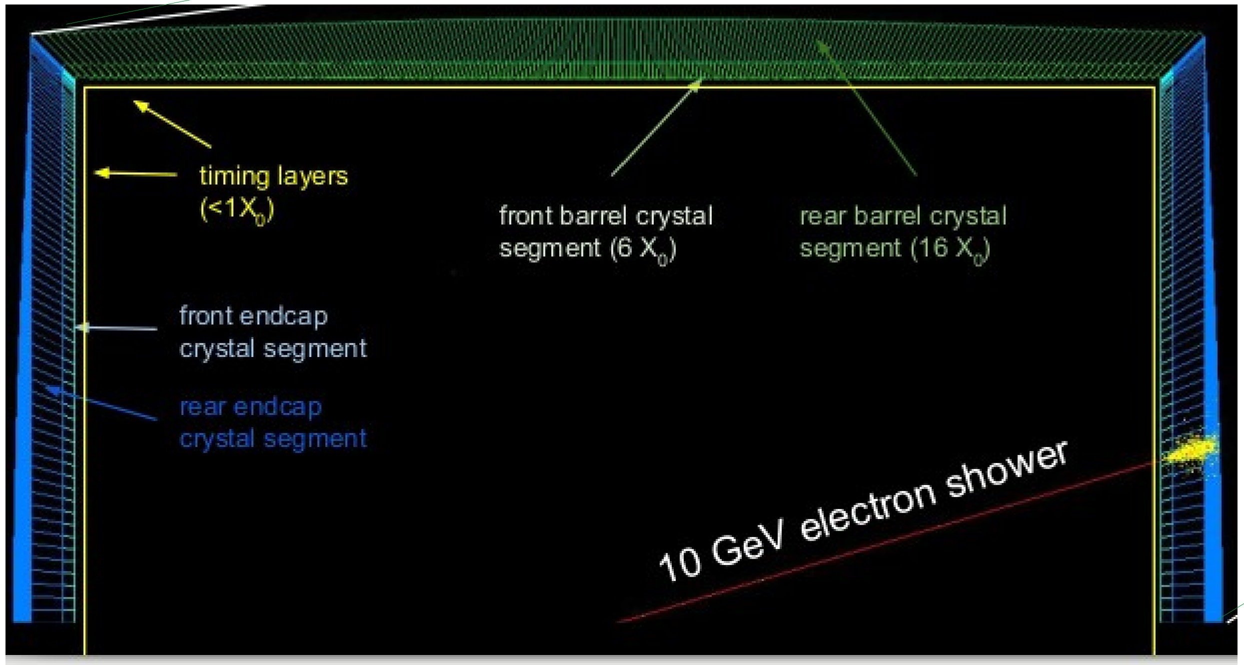
σ_{HAD}/E ~ 26%/√E



integration in Geant4 IDEA simulation

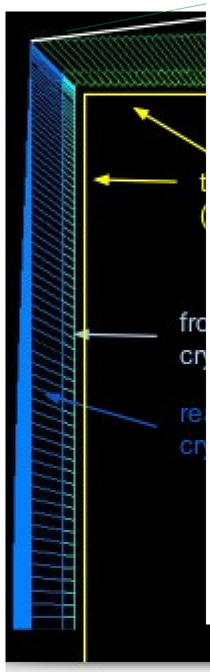
- Barrel crystal section inside solenoid volume
- Granularity:
  1x1 cm^2 PWO segmented crystals
- Radial envelope:
  ~1.8-2.0 m
- ECAL readout channels:
  ~1.8 M (including DR)

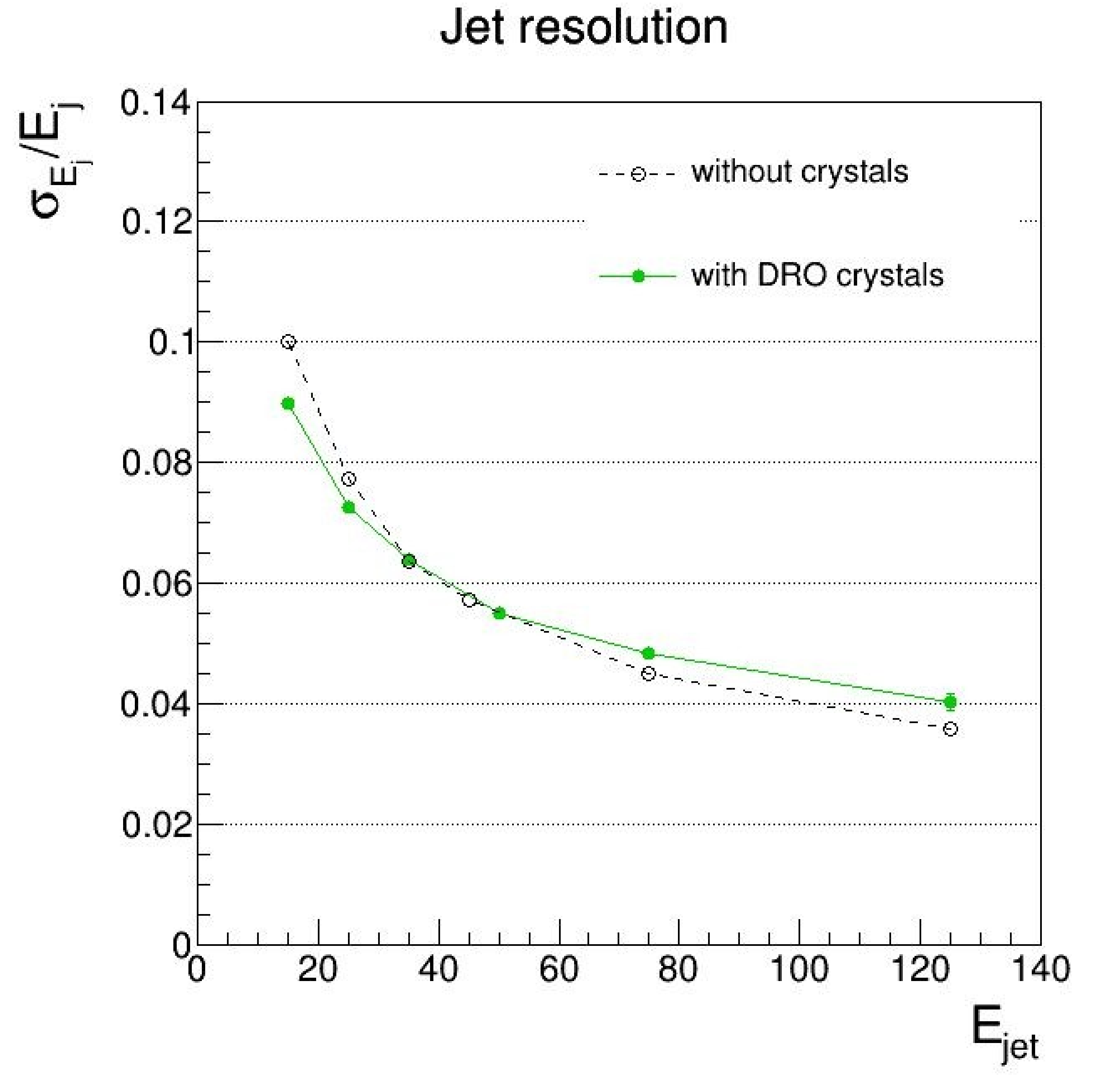


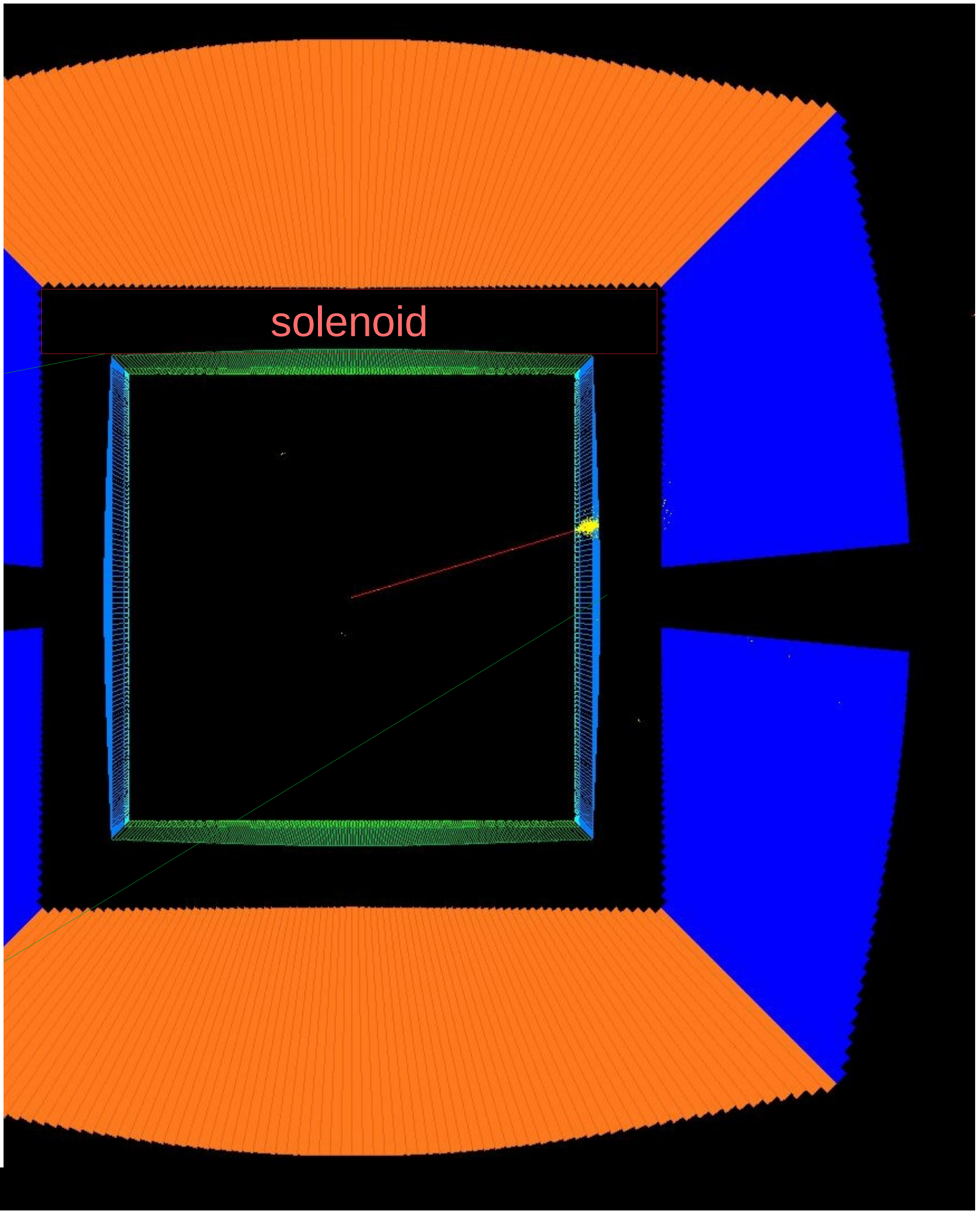


integration in Geant4 IDEA simulation

- Barrel crystal section inside solenoid volume
- Gra
- Rad
- ECA







integration in Geant4 IDEA simulation

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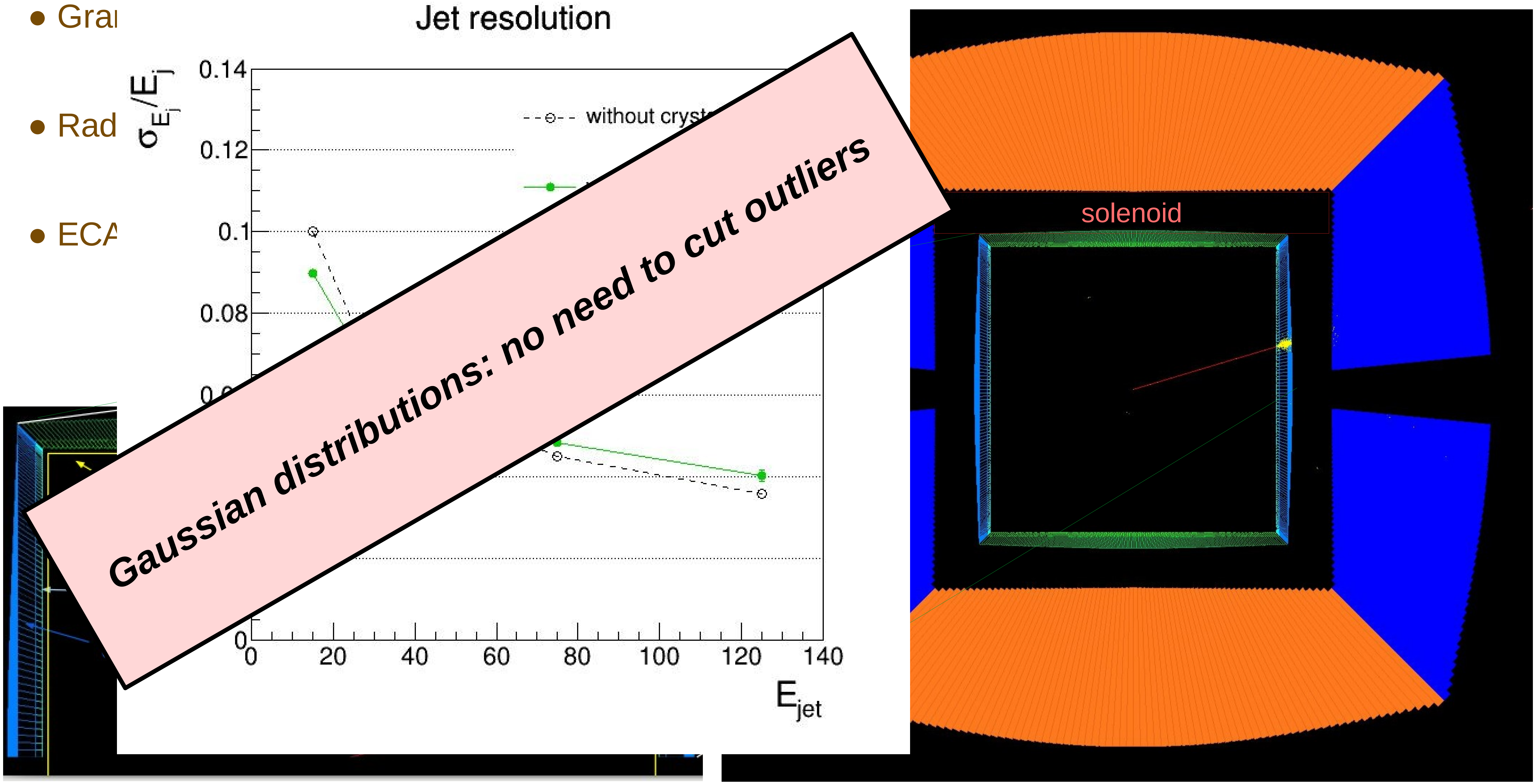
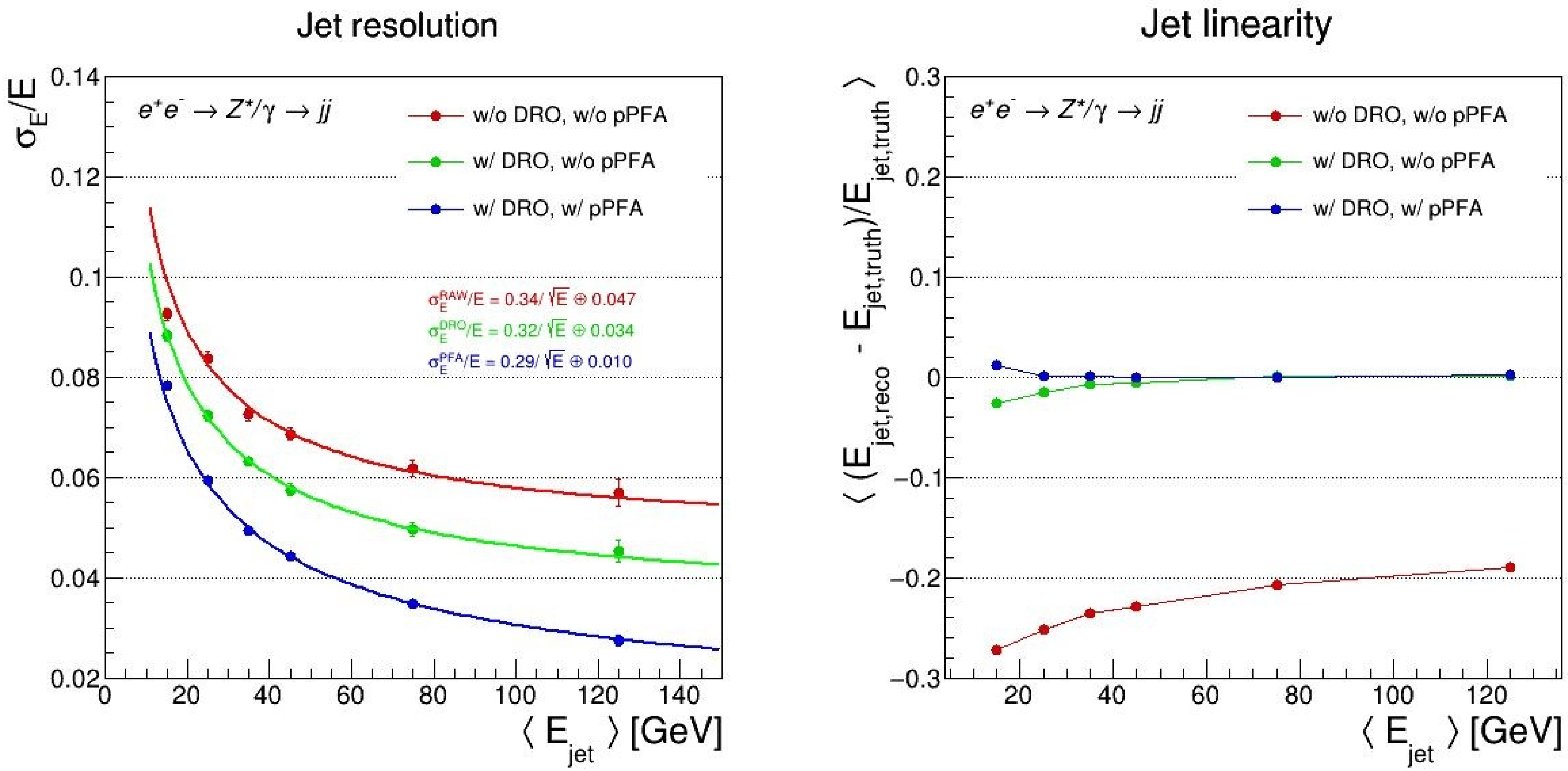


Gaussian distributions: no need to cut outliers

dual-readout particle flow algorithm

Jet resolution: with and without DR / pPFA



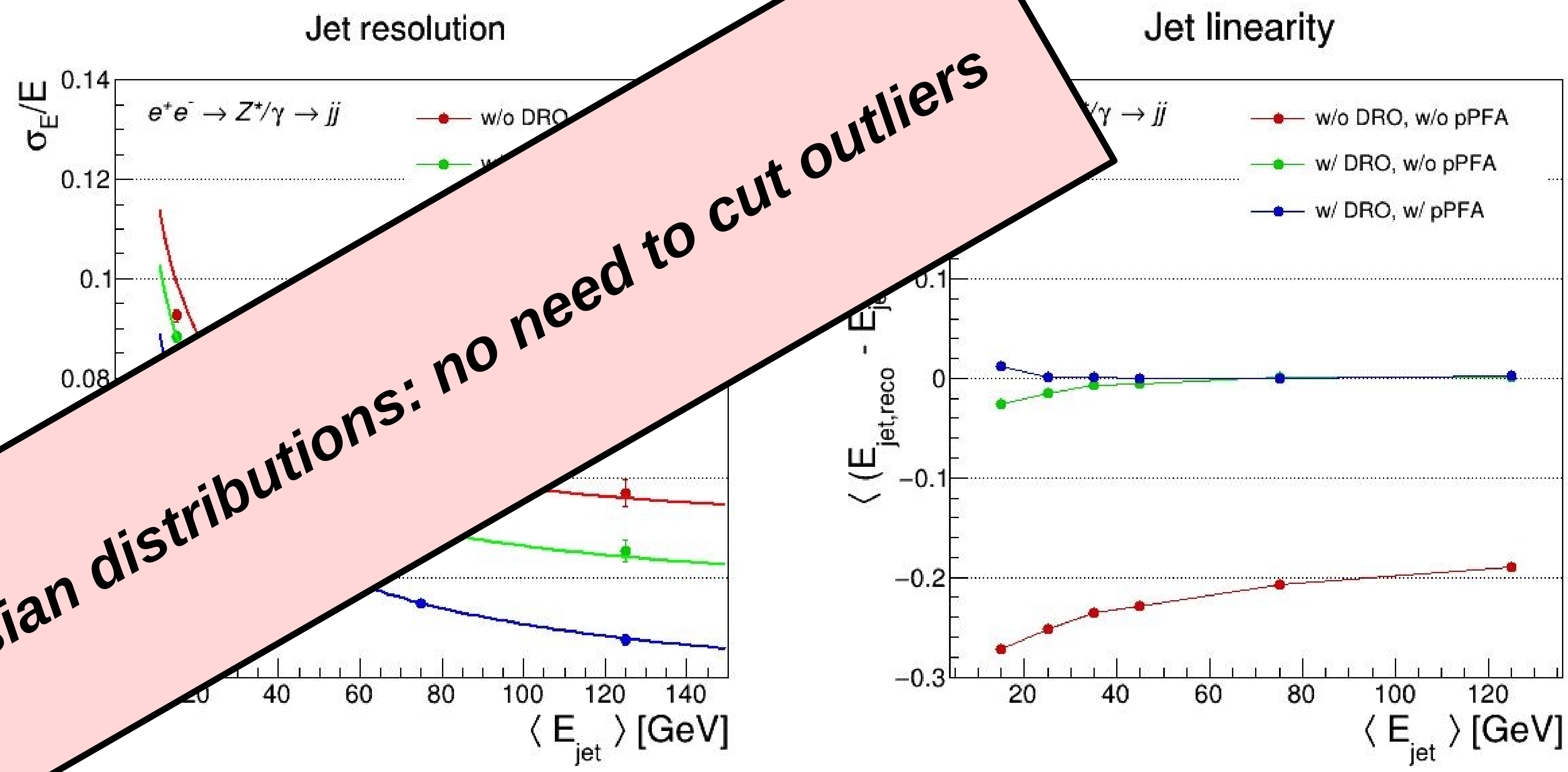
sensible improvement using DR information combined with a PFA approach

→ 3-4% for jet energies above 50 GeV

More details in: arXiV 2202.0.1474 (Feb 2022)

dual-readout particle flow algorithm

Jet resolution: with and without DR / pPFA



Gaussian distributions: no need to cut outliers

sensible improvement using DR information combined with a PFA approach

→ 3-4% for jet energies above 50 GeV

More details in: arXiV 2202.0.1474 (Feb 2022)

crystal proposal(s)

Funding request presented by a bunch of U.S. universities (P.I. prof. Sarah Eno)
Maryland, Princeton, Texas Tech, Virginia, Michigan, Purdue

and labs
MIT, Fermilab, Caltech

for building a dual-readout crystal prototype detector over next few years

→ quite large R&D program covering all aspects

→ got initial seed, more funding request submitted

→ Snowmass white paper submitted

PRIN “young” funding proposal under preparation (P.I. dr. Marco Lucchini, Milano Bicocca)

Simulation efforts ongoing to:

optimise ECAL+HCAL detector concept and integration
→ study impact of granularity and of timing information

optimise DR-PFA algorithm

projective geometry

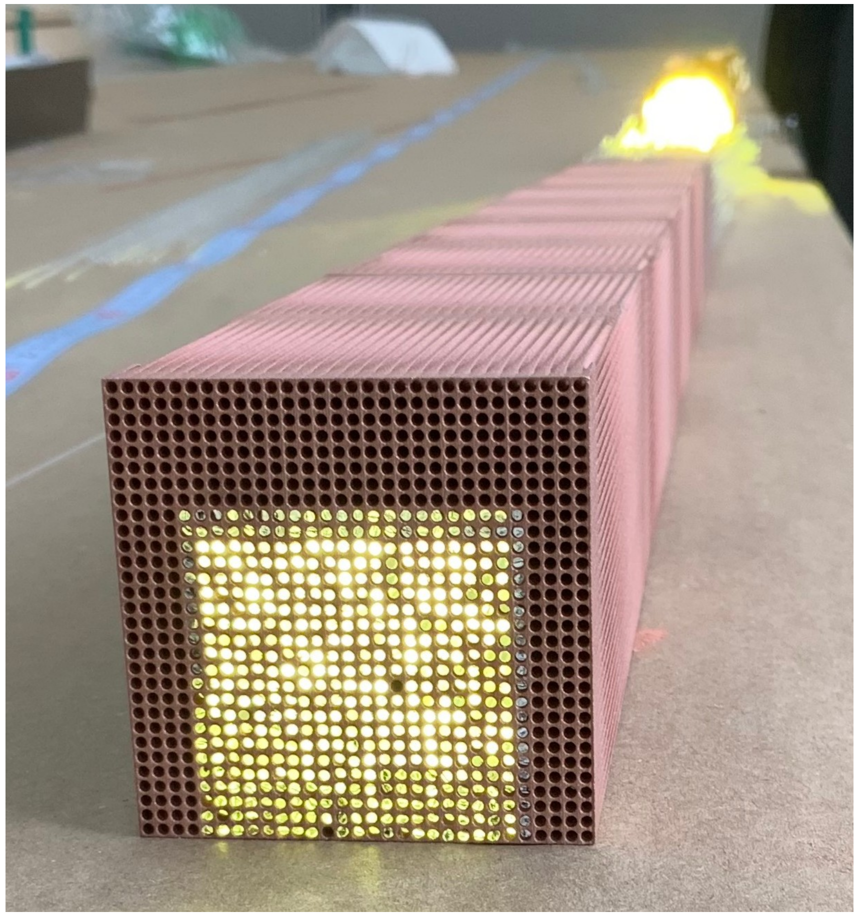
Significant funding obtained by a bunch of Korean universities (P.I. prof. Hwidong Yoo)

R&D presently focused on:

- copper/brass forming (all available options being considered, included 3D printing)
- readout system with waveform sampling (CAEN V1742 digitiser)
  → testbeam with refurbished RD52 modules under preparation
- simulation and deep-learning algorithms

3D-printed prototype

quite impressive but at present by far too costly



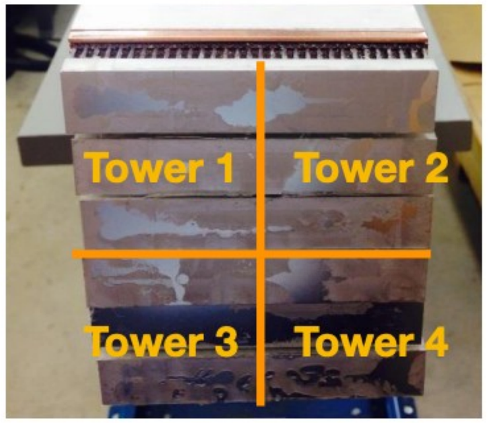
Korean planning

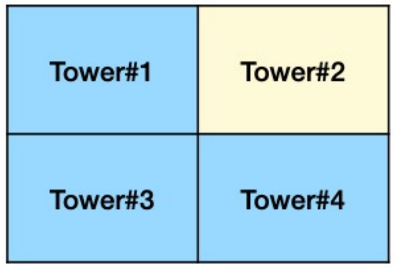
plate-based (+ possibly 3D-printed) prototype

short-term plan

mid-term plan

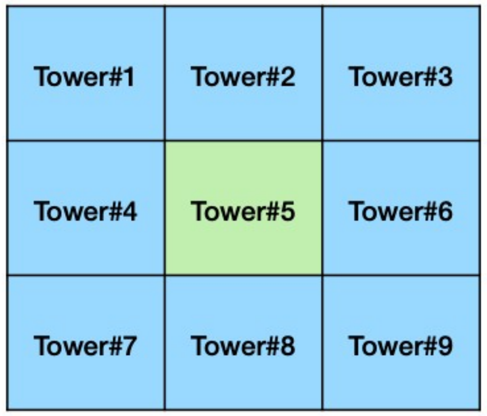
Module #1 (2x2)



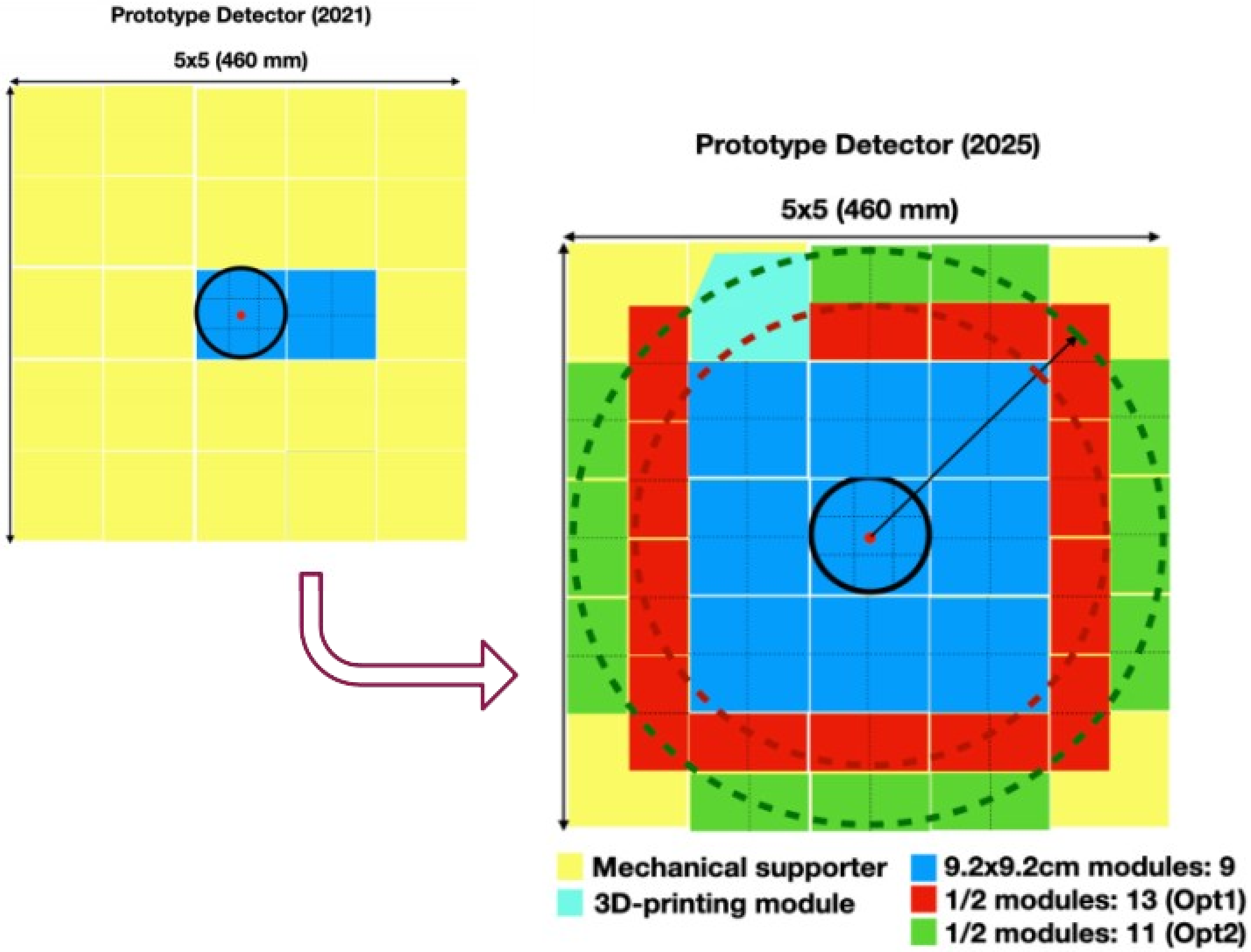


Tower#1	Tower#2
Tower#3	Tower#4

Module #2 (3x3)



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



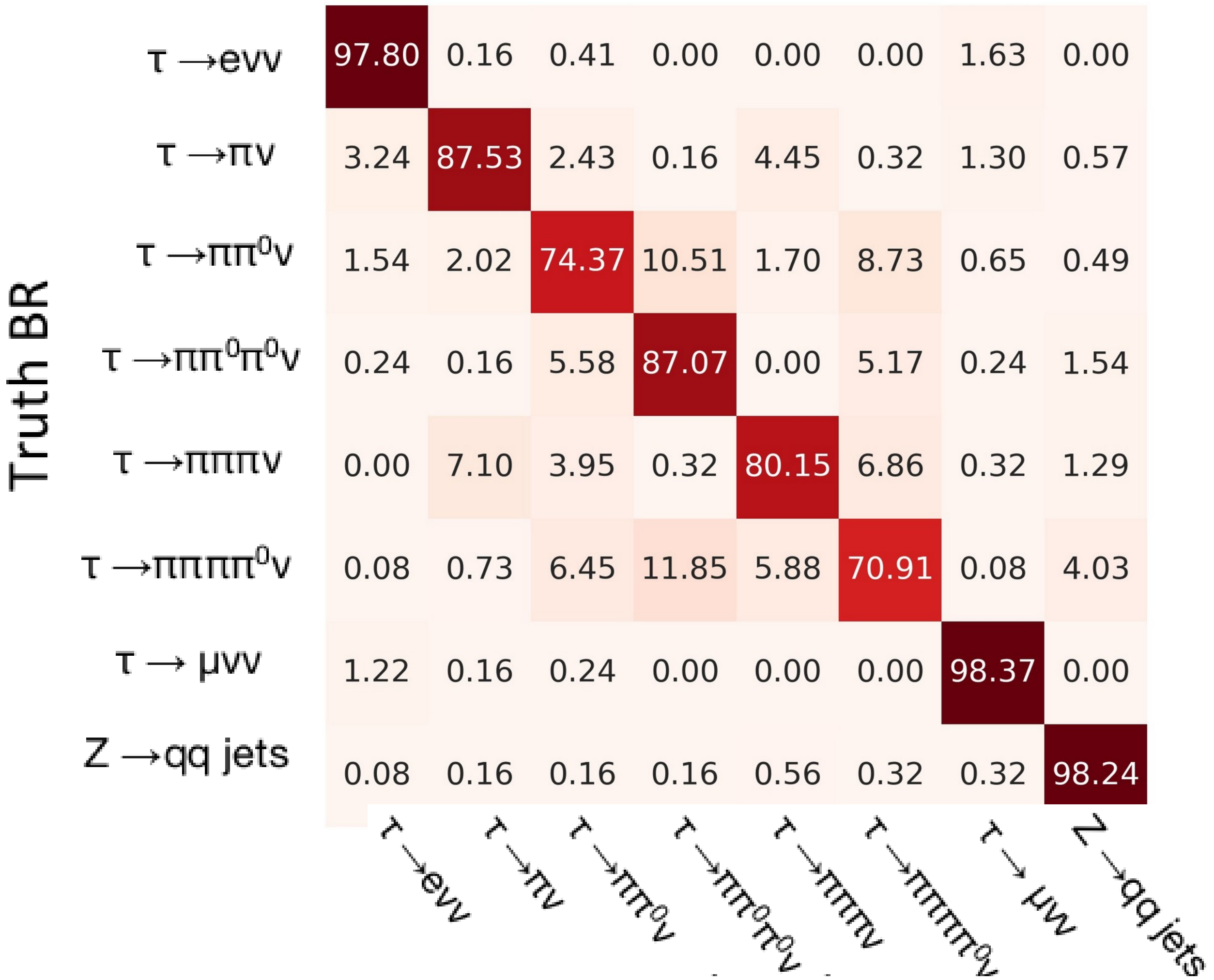
→ building more and more modules (2022-25)

deep-learning algorithms

τ-decay case study

Dynamic Graph CNN (DGCNN) architecture with realistic SiPM input

- calorimeter signals only -



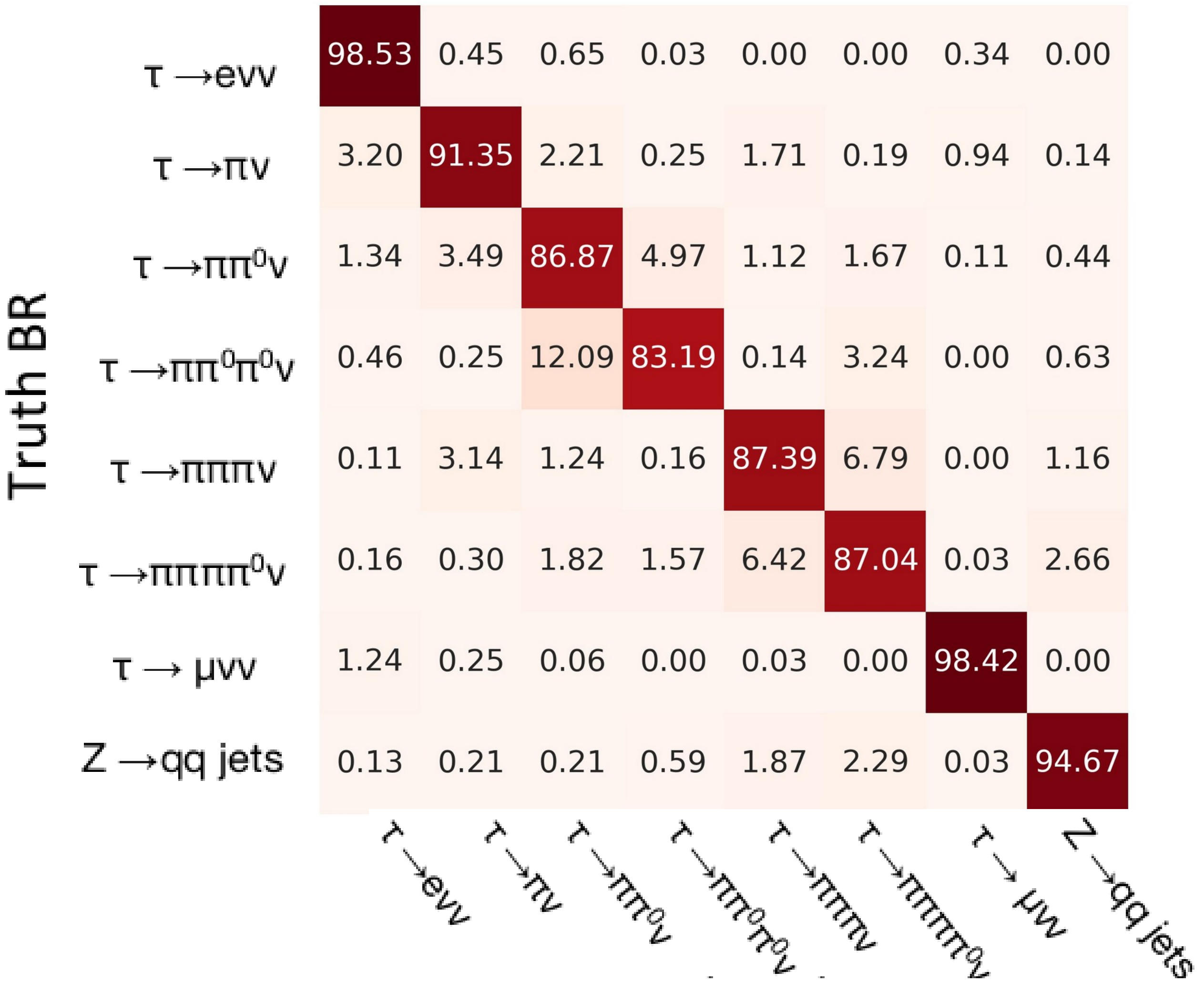
Truth BR

	$\tau \rightarrow e\nu\nu$	$\tau \rightarrow \pi\nu$	$\tau \rightarrow \pi\pi^0\nu$	$\tau \rightarrow \pi\pi^0\pi^0\nu$	$\tau \rightarrow \pi\pi\pi\nu$	$\tau \rightarrow \pi\pi\pi\pi^0\nu$	$\tau \rightarrow \mu\nu\nu$	$Z \rightarrow qq$ jets
$\tau \rightarrow e\nu\nu$	97.80	0.16	0.41	0.00	0.00	0.00	1.63	0.00
$\tau \rightarrow \pi\nu$	3.24	87.53	2.43	0.16	4.45	0.32	1.30	0.57
$\tau \rightarrow \pi\pi^0\nu$	1.54	2.02	74.37	10.51	1.70	8.73	0.65	0.49
$\tau \rightarrow \pi\pi^0\pi^0\nu$	0.24	0.16	5.58	87.07	0.00	5.17	0.24	1.54
$\tau \rightarrow \pi\pi\pi\nu$	0.00	7.10	3.95	0.32	80.15	6.86	0.32	1.29
$\tau \rightarrow \pi\pi\pi\pi^0\nu$	0.08	0.73	6.45	11.85	5.88	70.91	0.08	4.03
$\tau \rightarrow \mu\nu\nu$	1.22	0.16	0.24	0.00	0.00	0.00	98.37	0.00
$Z \rightarrow qq$ jets	0.08	0.16	0.16	0.16	0.56	0.32	0.32	98.24

Predicted BR

(B=0 and no solenoid material)

Accuracy: 86.8%



Truth BR

	$\tau \rightarrow e\nu\nu$	$\tau \rightarrow \pi\nu$	$\tau \rightarrow \pi\pi^0\nu$	$\tau \rightarrow \pi\pi^0\pi^0\nu$	$\tau \rightarrow \pi\pi\pi\nu$	$\tau \rightarrow \pi\pi\pi\pi^0\nu$	$\tau \rightarrow \mu\nu\nu$	$Z \rightarrow qq$ jets
$\tau \rightarrow e\nu\nu$	98.53	0.45	0.65	0.03	0.00	0.00	0.34	0.00
$\tau \rightarrow \pi\nu$	3.20	91.35	2.21	0.25	1.71	0.19	0.94	0.14
$\tau \rightarrow \pi\pi^0\nu$	1.34	3.49	86.87	4.97	1.12	1.67	0.11	0.44
$\tau \rightarrow \pi\pi^0\pi^0\nu$	0.46	0.25	12.09	83.19	0.14	3.24	0.00	0.63
$\tau \rightarrow \pi\pi\pi\nu$	0.11	3.14	1.24	0.16	87.39	6.79	0.00	1.16
$\tau \rightarrow \pi\pi\pi\pi^0\nu$	0.16	0.30	1.82	1.57	6.42	87.04	0.03	2.66
$\tau \rightarrow \mu\nu\nu$	1.24	0.25	0.06	0.00	0.03	0.00	98.42	0.00
$Z \rightarrow qq$ jets	0.13	0.21	0.21	0.59	1.87	2.29	0.03	94.67

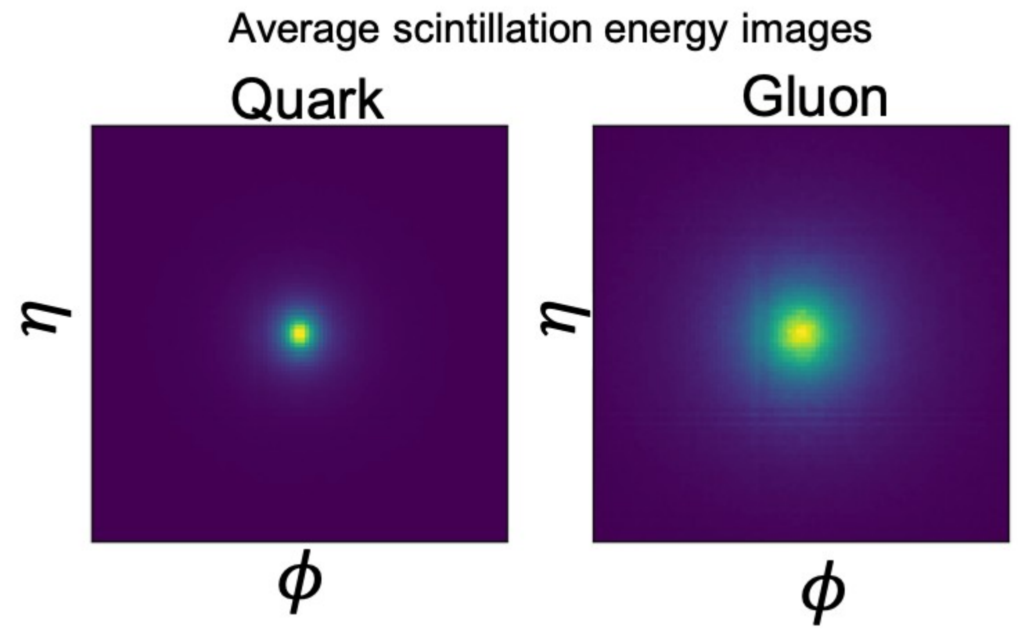
Predicted BR

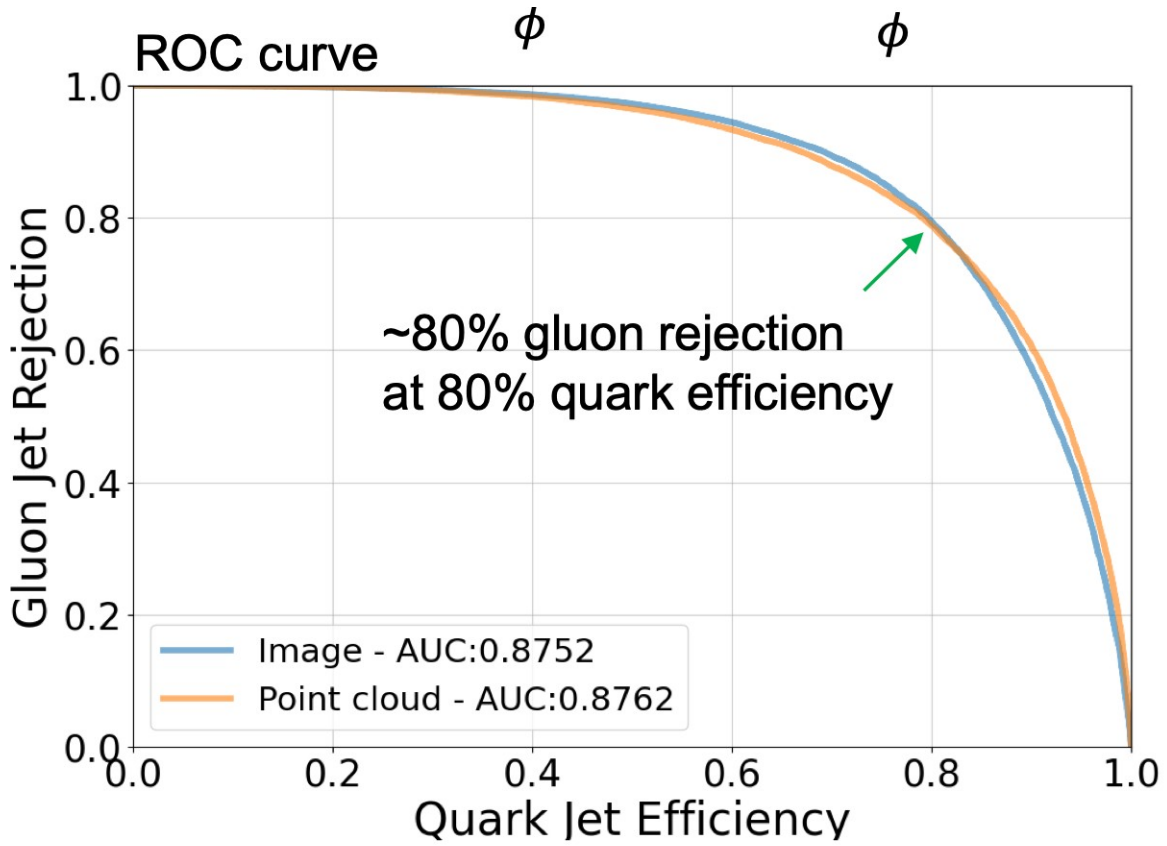
(B field and material)

Accuracy: 90.8%

last but not least … very preliminary

quark/gluon jet identification:





~80% gluon rejection
at 80% quark efficiency

summary

(highly granular fibre-sampling) dual-readout calorimetry solid candidate for future Higgs/EWK factories

“top-of-the-art” performance in most – or likely all – physics channels predicted when crystal EM section included

many technical “stand-alone” questions (on mechanics, sensors, elx) still open

detector integration (still missing engineered design) open issue as well

→ works ongoing (or planned to go) in many places

→ many of them hopefully cleared during next 3-4 years

job offers

Many interesting activities lacking manpower!

If you are interested, please join group:

idea-dualreadout@cern.ch

and (by-weekly) meetings which schedule is at:

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

Backup

dual-readout math

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

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

f_{em} = electromagnetic shower fraction

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

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

dual-readout formulae

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

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

measurable event by event, if χ is known

→ *(1-f_{em}) can be reconstructed within an unknown constant factor*

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

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

χ measurable if E is known