A Dual Readout Calorimeter for FCC-ee ?

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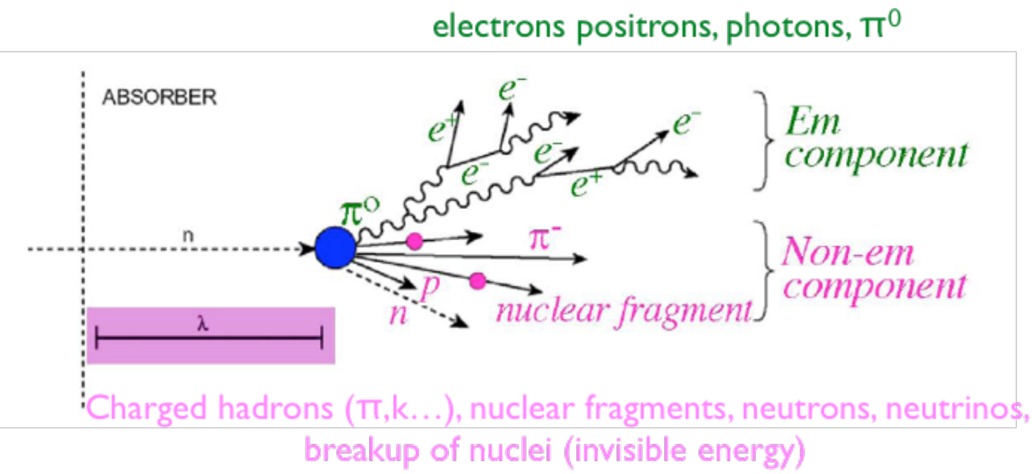
on behalf of the IDEA Dual-Readout Calorimeter Collaboration

January, 21st 2021

Dual-readout in a nutshell



Cherenkov light (C)	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light (S)	measure dE/dx

Measure the electromagnetic fraction event by event to equalize the response off-line

- **Compensation** achieved without construction constraints
- **Calibration** of a hadron calorimeter just with electrons
- **High resolution** EM and HAD calorimetry

Dual-readout in a nutshell

Simultaneous measurement on event-by-event basis of em fraction of hadron showers

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

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

e/h ratios ($c = (h/e)_c$ and $s = (h/e)_s$ for either Cherenkov or scintillation structure) can be measured

Θ and χ are independent of both energy and particle type

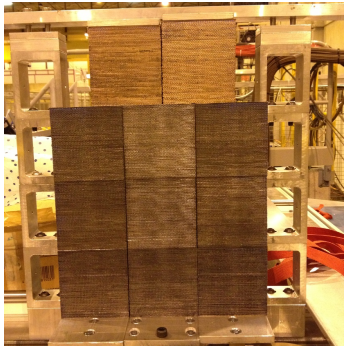
It is possible to evaluate $f = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$ and $E = \dfrac{S - \chi C}{1 - \chi}$

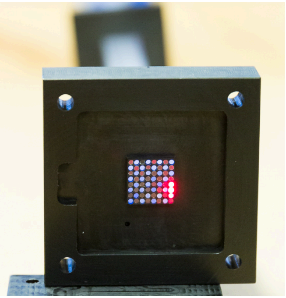
Dual-readout @work

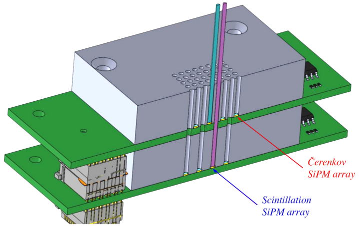
This research activity has been carried on by the RD52 experiment @CERN
http://www.phys.ttu.edu/~dream/index.html

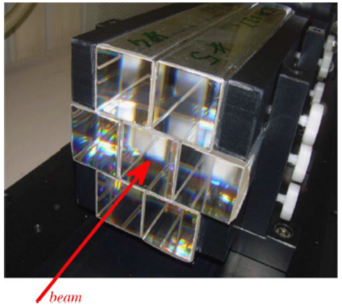
Sampling Calorimeter
Two types of fibers, either sensitive to Cherenkov and Scintillation Separated by construction

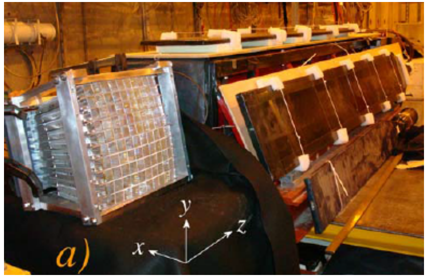
Homogeneous Calorimeter
Possibility to solve sampling fluctuation problem. Need to separate C and S light.





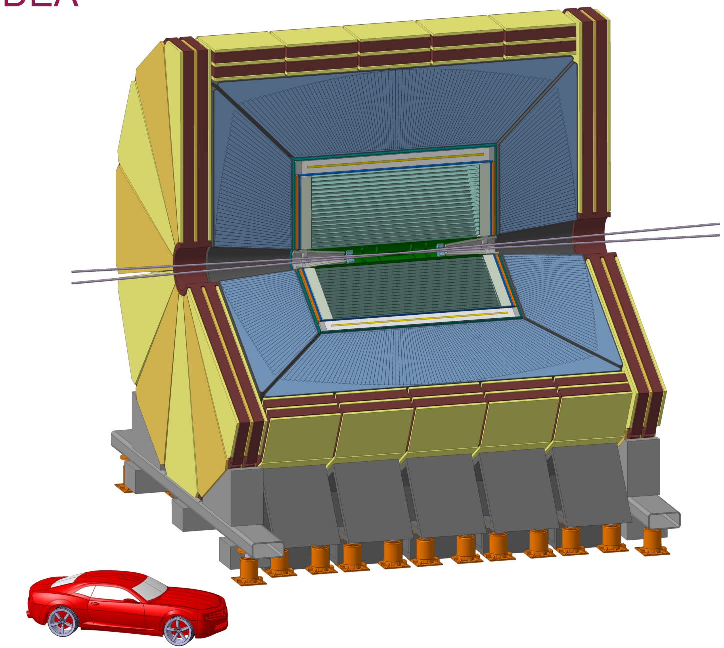






Dual-readout calorimeter: international collaboration

IDEA



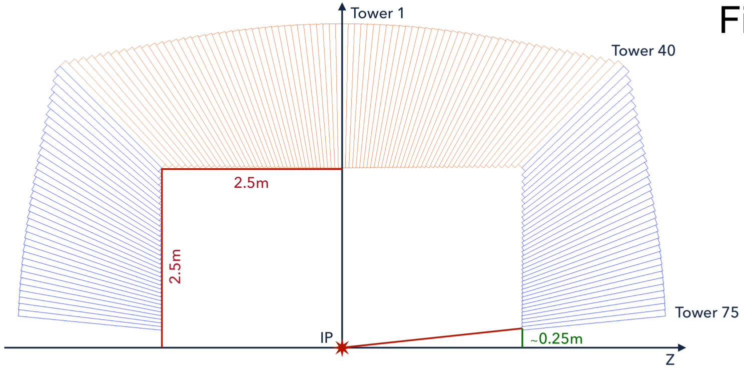
Innovative Detector for Electron-positron Accelerators

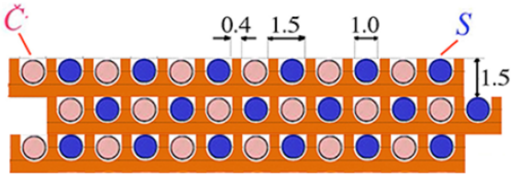
- Included in FCC and CepC CDRs
- Growing international collaboration in
  - **Europe**: **Croatia** (RBI), **UK** (Univ. of Sussex), **Italy** (INFN-BO, INFN-CT, INFN-PI, INFN-PV, Univ. of Insubria)
  - **Asia: Korea** (Kyungpook Univ., Seoul Univ., Univ.of Seoul, Yonsei Univ.)
  - **USA:** Iowa State Univ., Texas Tech Univ., Univ. of Meryland, Univ. of Princeton

idea-dualreadout@cern.ch

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

Simulations for performance studies



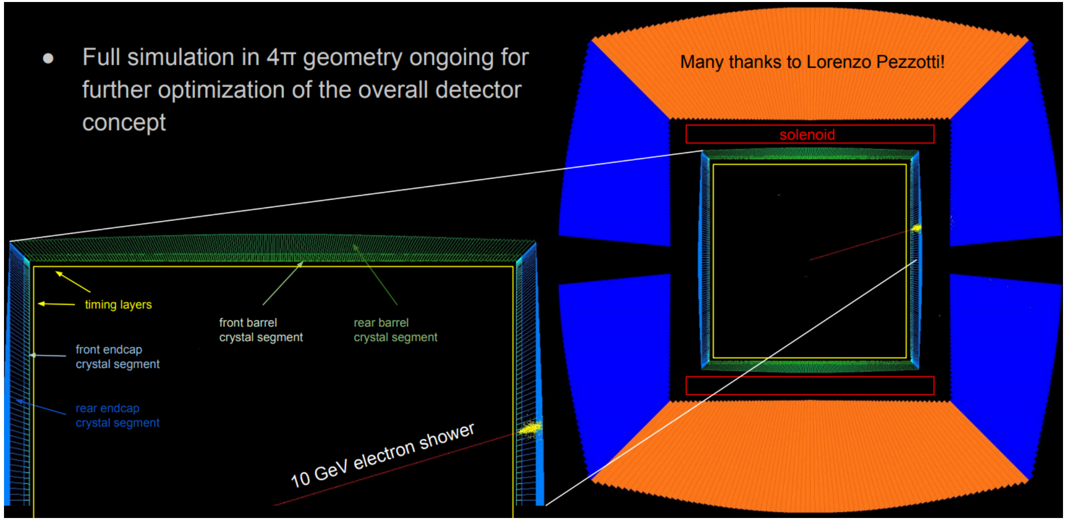


75 projective elements x 36 slices
Copper + scintillating and Cherenkov fibers
Read out the single fiber: 130 M channels

Fiber DR calorimeter

G4 standalone simulation

Fiber+crystal options



Large number of performance & phys studies
See "additional slide"

W/Z/H 2-jets final states

Jet reconstruction:

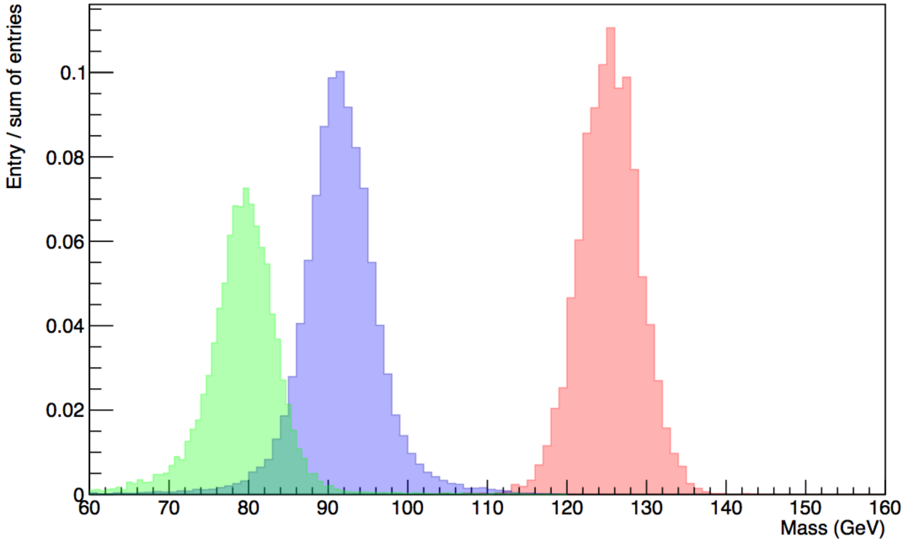
Jet generated with PYTHIA8, tuned to LEP measurement
Propagated in GEANT4 calorimeter
    Obtain C and S response + (θ,ϕ) of the tower
    Get jet 4-momenta
Clustering with FASTJET (Duhram kt algorithm)

$$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$$

$$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$$

$$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$$

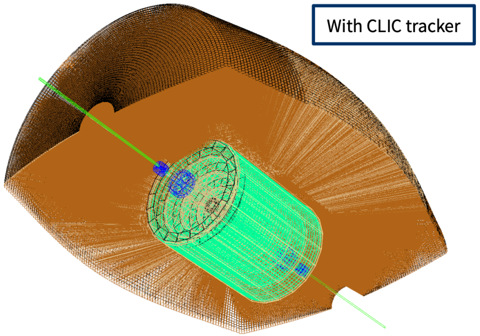
PYTHIA8 + GEANT4 + FASTJET



4-jet final state studies on-going

Simulations for performance studies

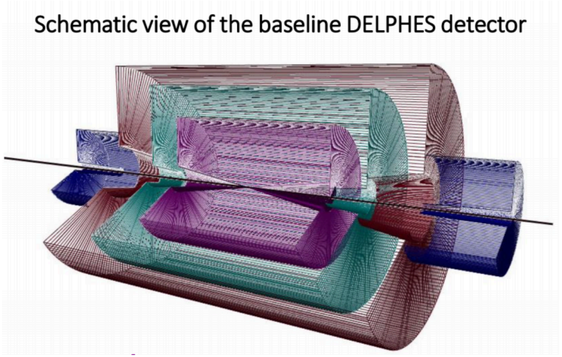
DD4HEP simulation



Fiber DR calorimeter

Fiber+crystal options moving to DD4HEP too

DELPHES fast simulation

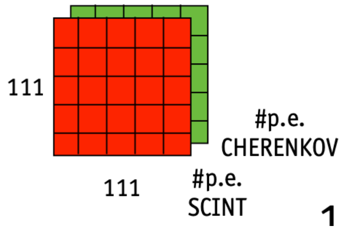


https://indico.cern.ch/event/971970/contributions/4172118/attachments/2173583/3670428/DIOLAITI-presentation2021.pdf

Machine-Learning approach

Reconstruct and identify particle is under development with promising results.

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	$\tau \to \pi\pi\pi\pi^0\nu$
2	7	Z →qq jets



DNN models:

- VGG-like CNN with 3D and 2D convolutions: jet/tau representation 2-channel 111x111 mesh
- DGCNN: jet/tau representation: 2D point-cloud of fbres coordinates + #p.e. as features

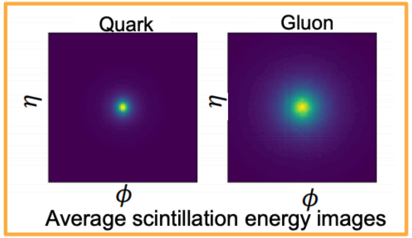
Truth BR \ Predicted BR	$\tau \to \mu\nu\nu$	$\tau \to e\nu\nu$	$\tau \to \pi\nu$	$\tau \to \pi\pi^0\nu$	$\tau \to \pi\pi^0\pi^0\nu$	$\tau \to \pi\pi\pi\nu$	$\tau \to \pi\pi\pi\pi^0\nu$	Z →qq jets
$\tau \to \mu\nu\nu$	97%	2%	1%					
$\tau \to e\nu\nu$	1%	97%	1%	1%				
$\tau \to \pi\nu$	1%	3%	87%	4%	1%	2%		1%
$\tau \to \pi\pi^0\nu$		1%	5%	76%	13%	1%	3%	1%
$\tau \to \pi\pi^0\pi^0\nu$				7%	88%		4%	1%
$\tau \to \pi\pi\pi\nu$			5%	2%		75%	15%	2%
$\tau \to \pi\pi\pi\pi^0\nu$			1%	1%	4%	8%	81%	5%
Z →qq jets					1%	1%	2%	96%

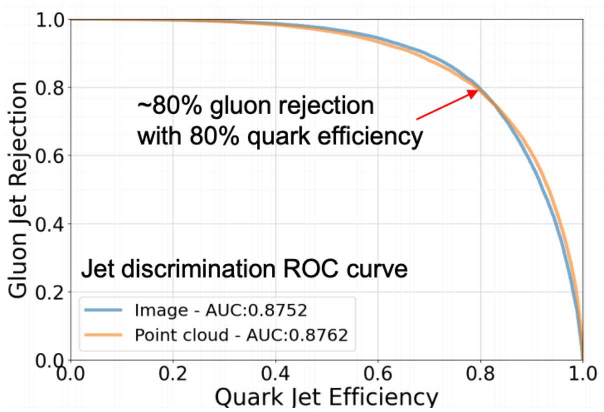
Predicted BR

(B field and material)

average accuracy: **87%**

CNN model



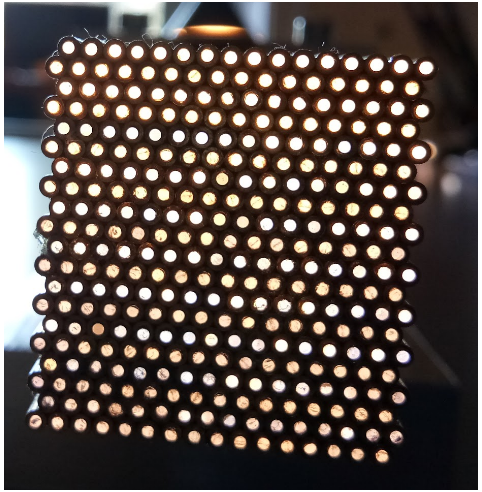


Fiber calorimeters developments

On the path toward the experiment scale:

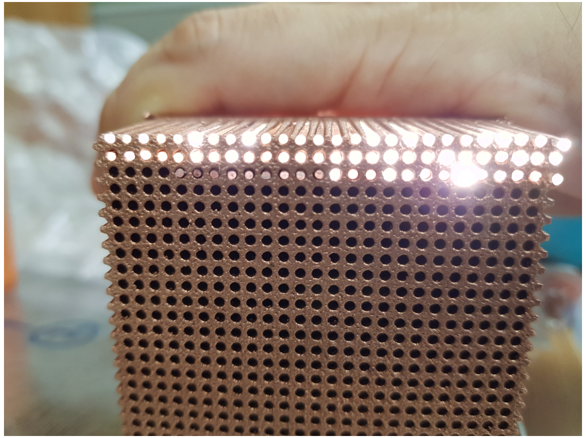
- Hadronic full-containment prototype
- Scalable techology for both mechanical construction and Readout (SiPM based)

Capillary-tubes calorimeter

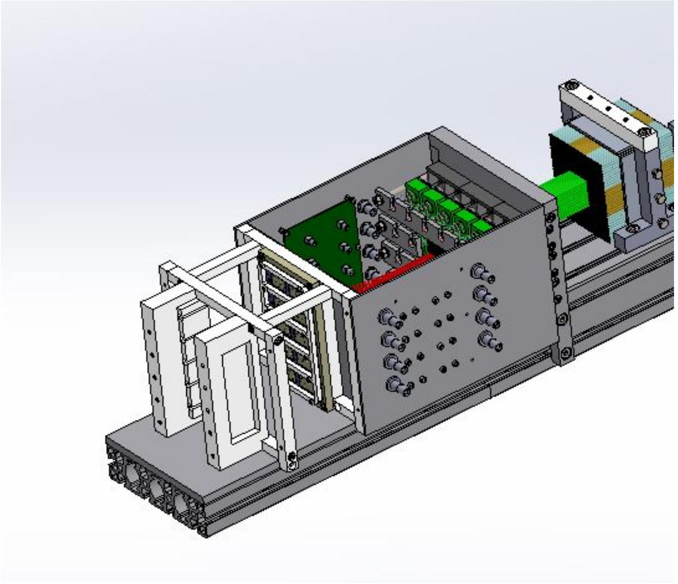


Plates-absorber calorimeter

3D-printing matrix calorimeter



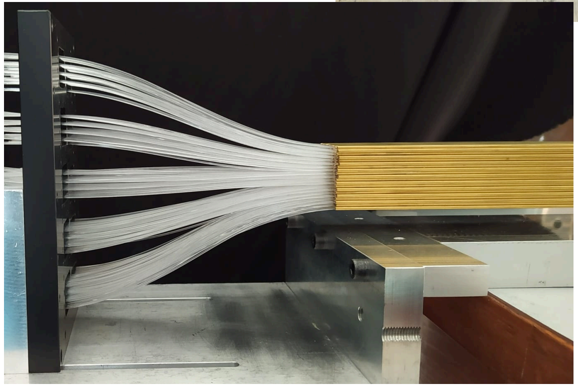
Capillary-tubes based prototype



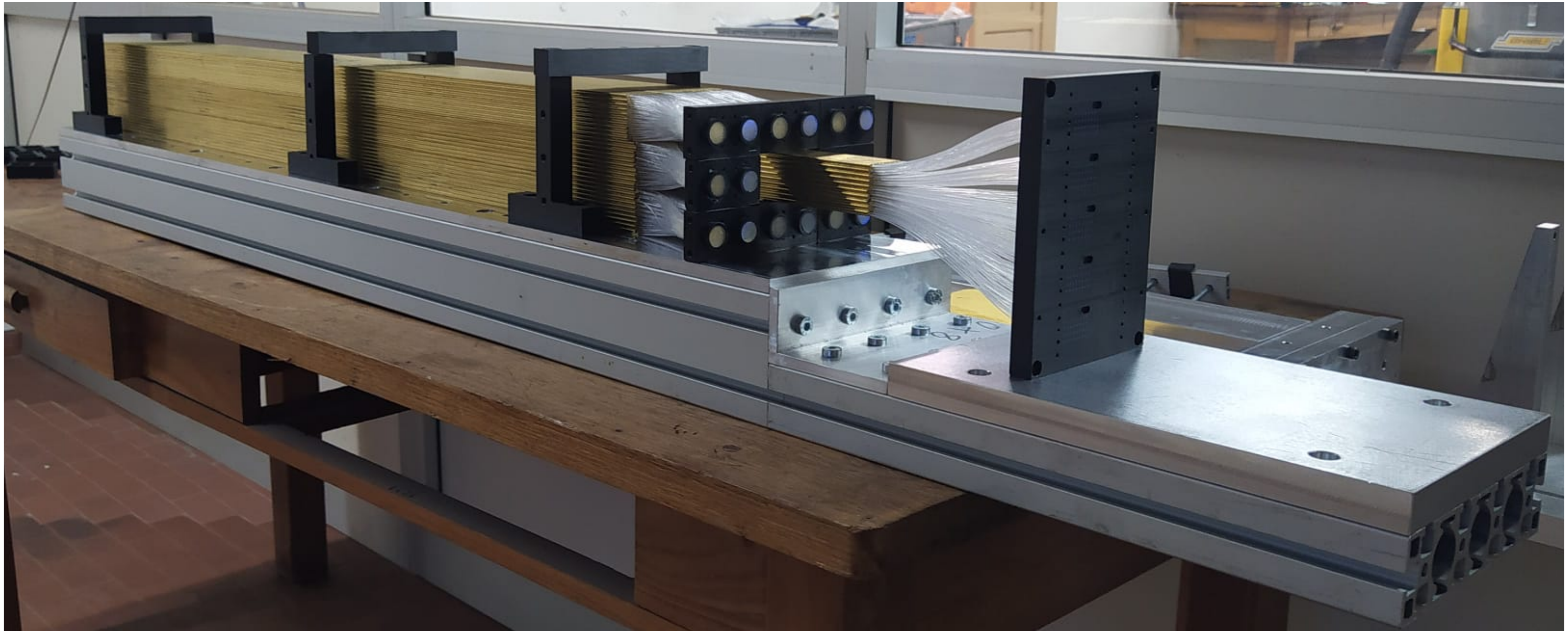
10x10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S)

Capillary:
2mm outer diameter, 1mm inner diameter
Material: brass CuZn37

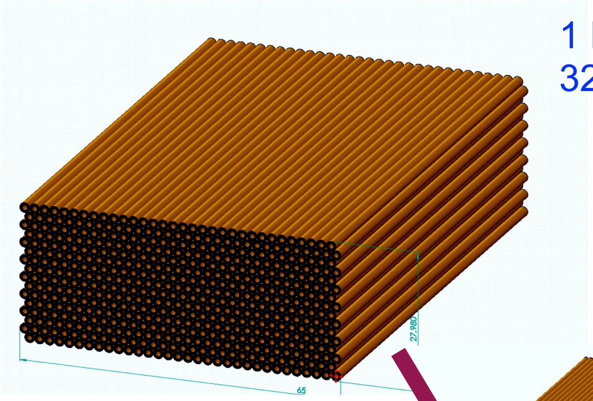
Readout:
- 1 central tower readout by SiPMs
- 8 surrounding towers readout by PMTs (à la RD_52)



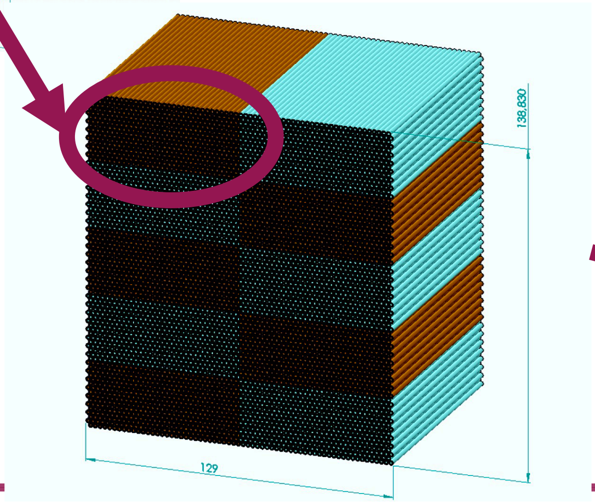
Capillary-tube based Prototype



Capillary-tubes based calo



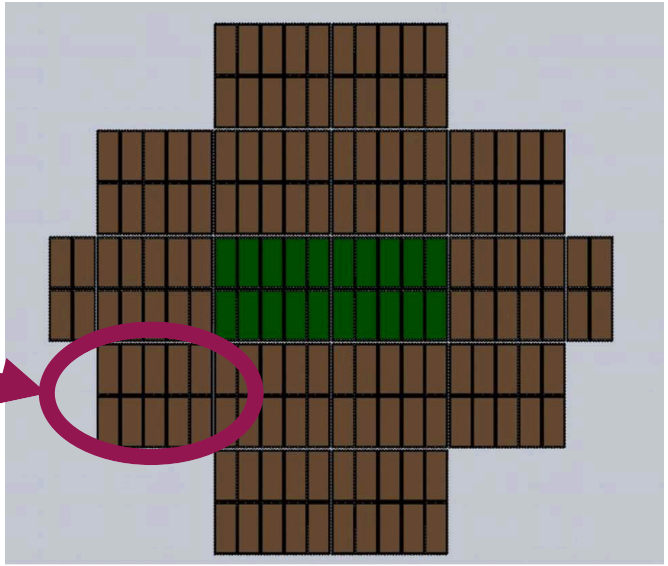
1 Mini-Module (MM):
32 x 16 channel (512 ch)



1 Module:
2 x 5 MMs
→ 10 FEE boards
(8-channel grouping)
~ 13 x13 x 200 cm^3

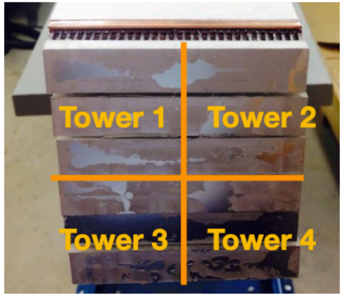
17 modules, ~ 65 x 65 x 200 cm^3

- 2 central modules with SiPMs
  → ~ 10 k SiPMs, ~ 20 FEE boards
- all others with PMTs
  → ~ 150 PMTs



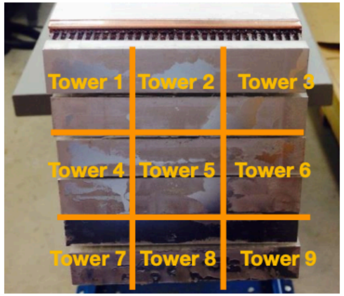
Plates-based (+3D printing) calo

Module #1 (2x2)

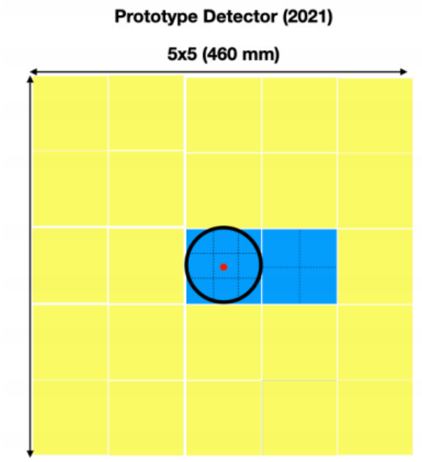


Tower#1	Tower#2
Tower#3	Tower#4

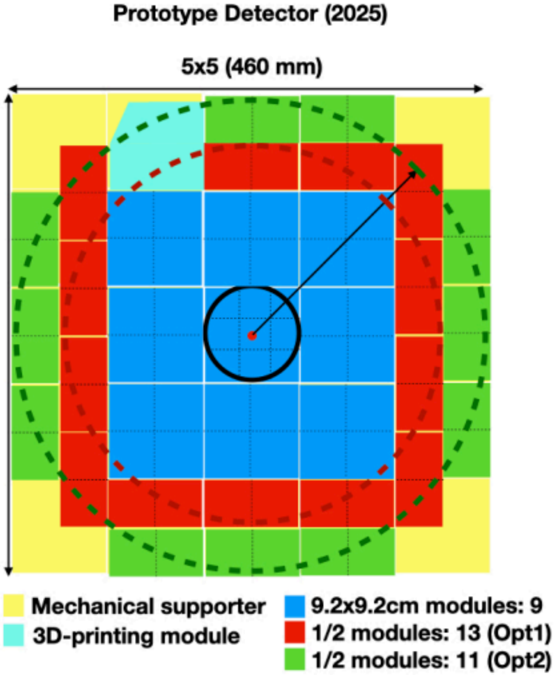
Module #2 (3x3)



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



Building more
and more module
2022-2025



SiPM - FEE-boards

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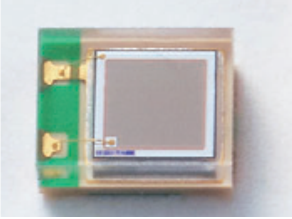
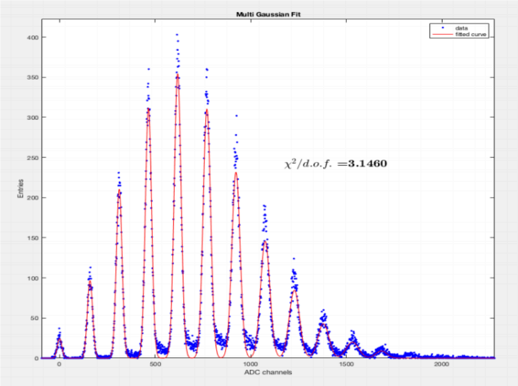
Sensor: S14160-1315PS
Cell size $=15\mu m$
Vbias = 42 (≈ 4 V over breakdown)
Signal amplification: 40dB
Measured Xtalk = 2%





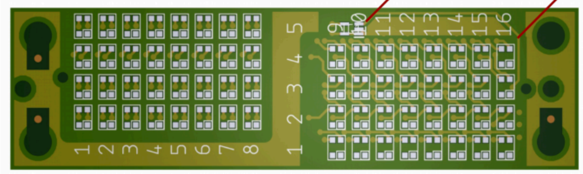
TB like

Toward experiment

Front view

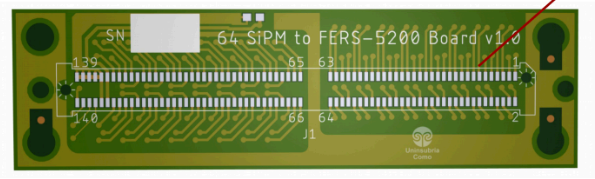
Temperature sensor

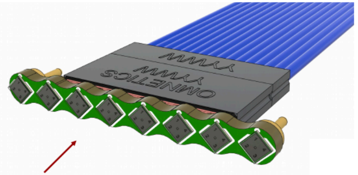
SiPM footprints



Connector footprints

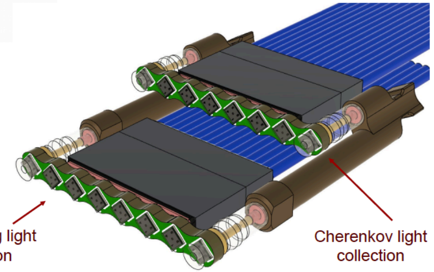
Back view





FEE-board + SiPMs
Segmentation optimised to exploit grouping

Pair of FEE-boards joint together with clips



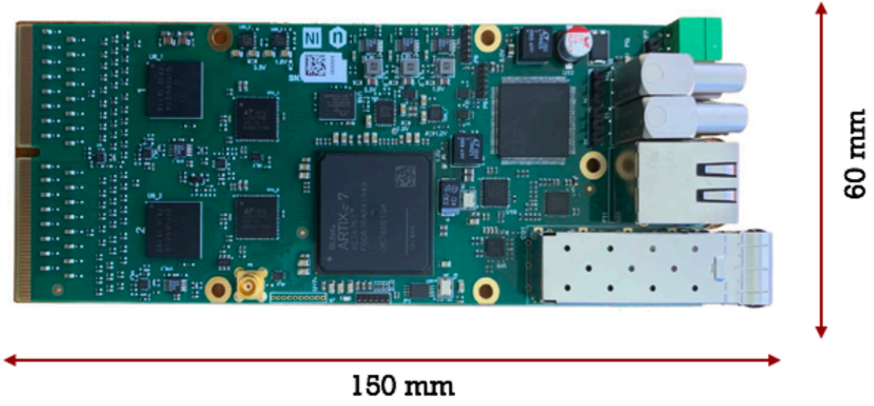
Scintillating light collection

Cherenkov light collection

SiPM cell size is one of the crucial parameter to cope with saturation (linearity) in Scintillation channel

SiPM Readout

FERS: A5202



The basic principle

- 2 Citiroc1A (64 ch)
- Timing with a TDC implemented into the FPGA (≈ 0.5 ns)
- 2 ADC to measure the charge
- 1 HV power supply (20 – 100V) with temperature compensation
- Interface for readout

SiPM Readout (2)

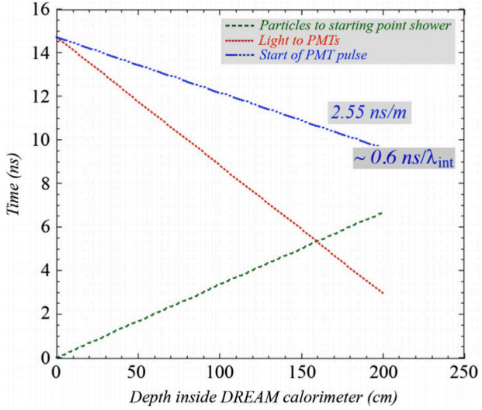
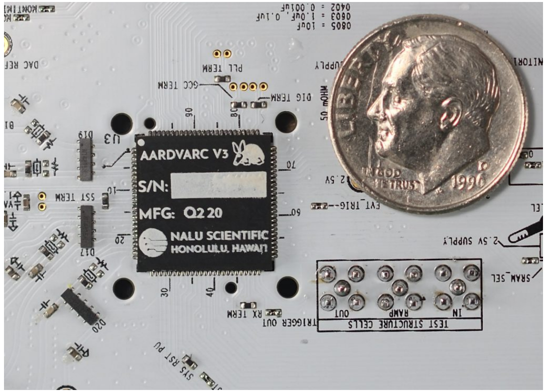


Fig. 8. Dependence of the starting time of the PMT signals on the average depth (*z*) inside the calorimeter where the light is produced (the dash-dotted line). This time is measured with respect to the moment the particles entered the calorimeter. Also shown are the time it takes the particles to travel to *z* (the dashed line) and the time it takes the light to travel from *z* to the PMT (the dotted line).

FEATURES	AARDVARC V3 [1]
SAMPLE BUFFER	32 k
CHANNEL	4-8 CHANNEL
BANDWIDTH	2 GHZ ANALOG
TIMING RESOLUTION	4-8 ps
SAMPLE RATE	10-14 GSa/s

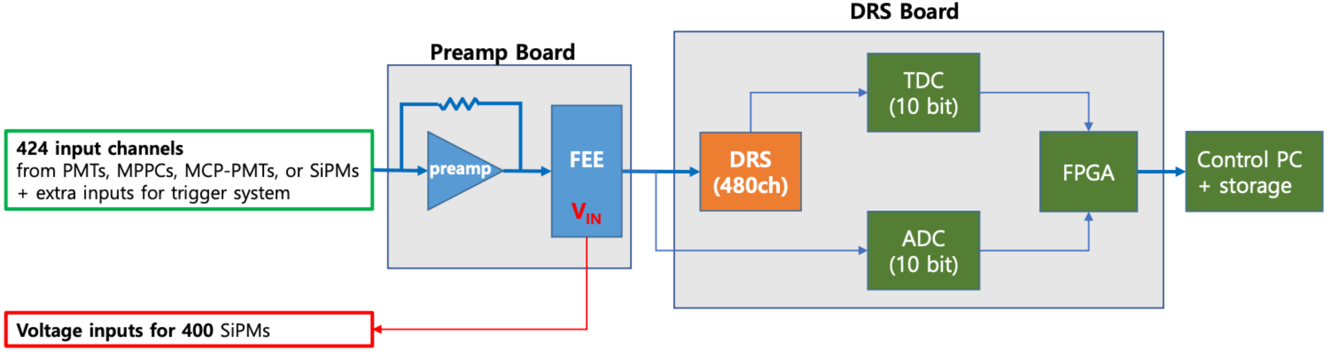


Timing information is a key element for PID in a longitudinally unsegmented fiber calorimeter

Recently developed Waveform Digitizer by NALU Scientific under evaluation

SiPM readout (3)

DAQ scheme



Trigger mode	Contents
Fast DAQ mode **(digitized data)**	Data format: **ADC peak value at time value** on the threshold Memory: DRAM Data size: 8 Bytes per channel (256 or 2^8 Bytes/32ch) Control bus: USB3 (expectation speed ~1 GBps) **Trigger rate: ~25 kHz** (when 15 DRS boards are controlled by a single DAQ pc with USB3 communication)
Waveform mode **(digitized data + waveform)**	Data format: **ADC peak value at time value** on the threshold + **waveform data** during gate open Memory: two RAM (one for ADC peak value and another one for waveform data) Data size: 2048 Bytes per channel (2^{16} Bytes/32ch) Control bus: USB3 (expectation speed ~1 GBps) **Trigger rate: ~0.1 kHz** (when 15 DRS boards are controlled by a single DAQ pc with USB3 communication)
Bin event mode	DAQ mode for taking data during periods in between beam spills

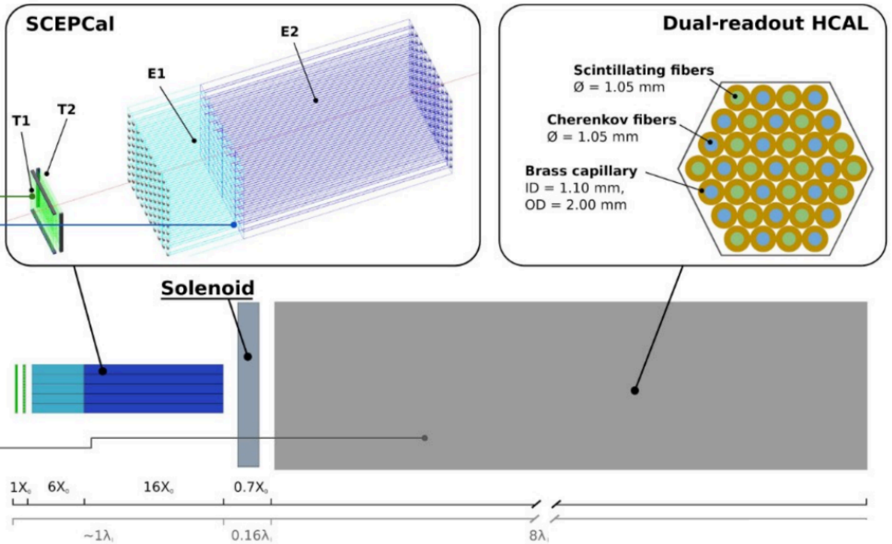
7

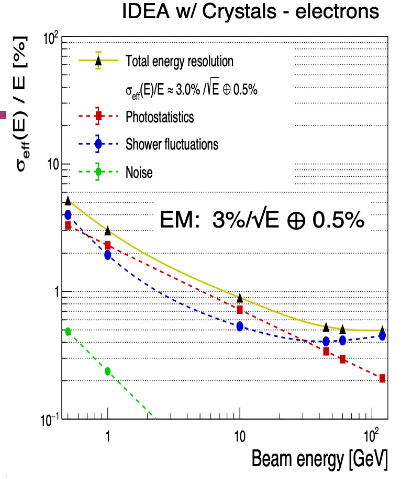
Crystal calorimeter option

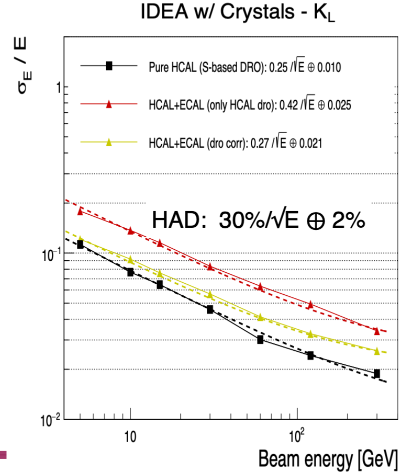
Layout overview

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$
  - Scintillating and quartz fibers inserted in brass capillaries
  - (similar to prototypes in







Outlook

- Many funding requests ongoing
  - S. Korea: large founding over ~5 years (APPROVED)
  - AIDA innova: mainly Post-doc positions (APPROVED)
  - Submitting PRIN at Italian MUR
  - Submitting INFN call CSN5: ~ 900k€ over three years (next summer)

- SNOWMASS Process
  - https://snowmass21.org/instrumentation/calorimetry#submitted_loi
  - Large number of LoI submitted

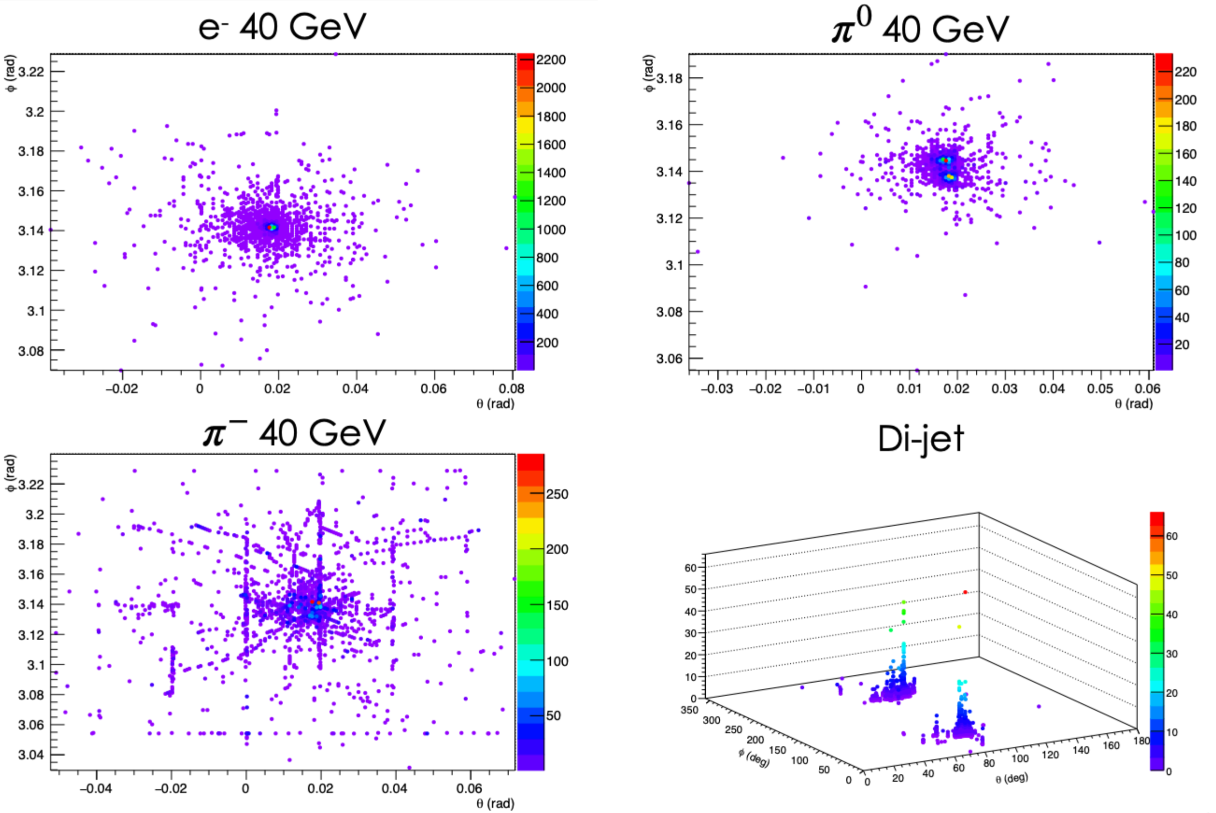
Outlook

INFN
Istituto Nazionale di Fisica Nucleare

- Very wide range of activities ongoing
  - Simulation, ML approach for reco, performance studies, physics studies …
  - Development in both the calorimeter construction technique and readout…
    - These activities mostly affected by covid-19 spread.
    - Foreseen TB @Desy postponed from Nov. 2020 to Feb. 2021, to be understood
- Collaboration is open to new groups interested in this detector technology

Additional Material

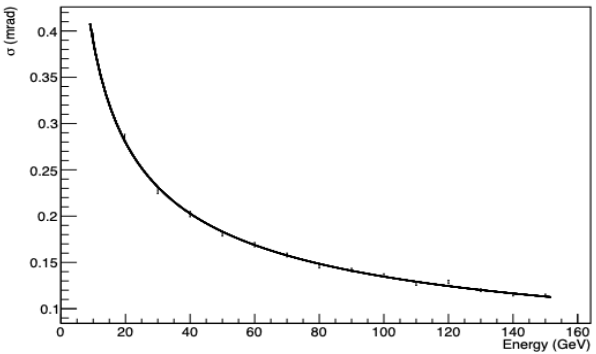
How events looks like (full granularity)



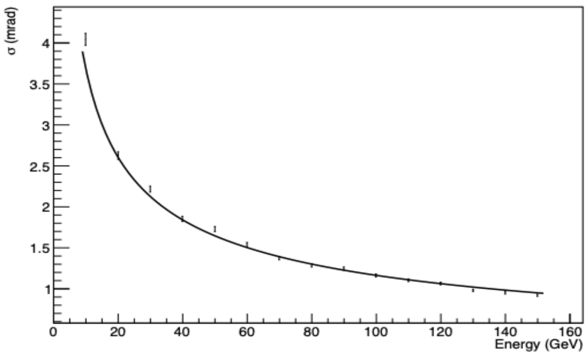
Angular resolution

Resolving angles

An excellent angular/position resolution is obtained by calculating the energy weighted barycenter. An example for the θ angle (mrad) combining the two signals:



$$e^- : \sigma(mrad) = \frac{1.17}{\sqrt{E\ (\mathrm{GeV})}} + 0.017$$

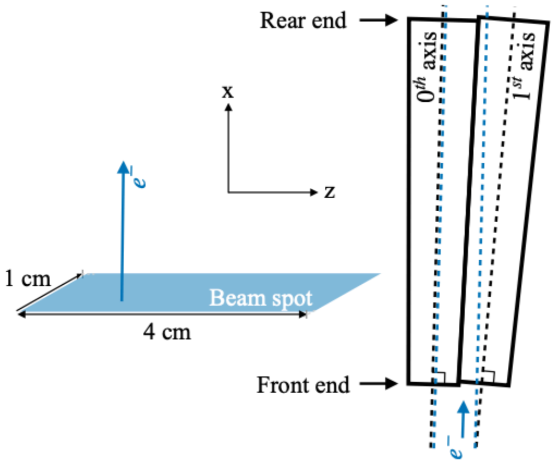


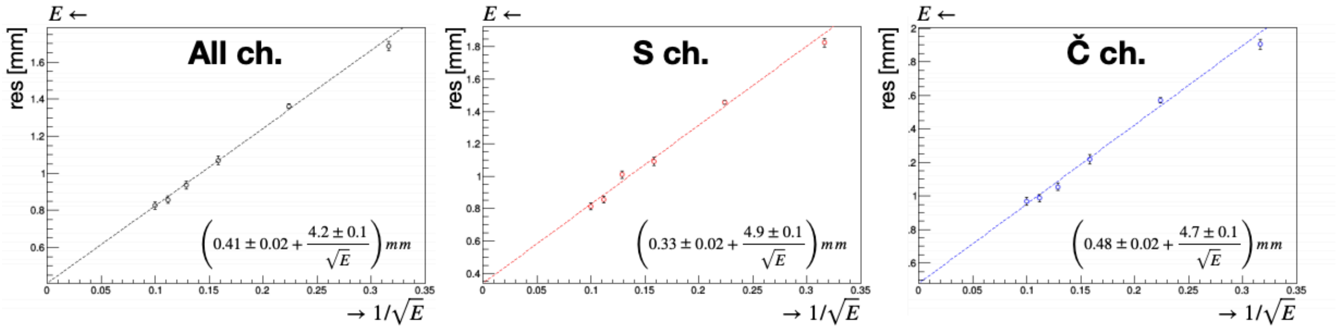
$$\pi^- : \sigma(mrad) = \frac{11.6}{\sqrt{E\ (\mathrm{GeV})}}$$

Similar results obtained for the ϕ angle.

Position resolution

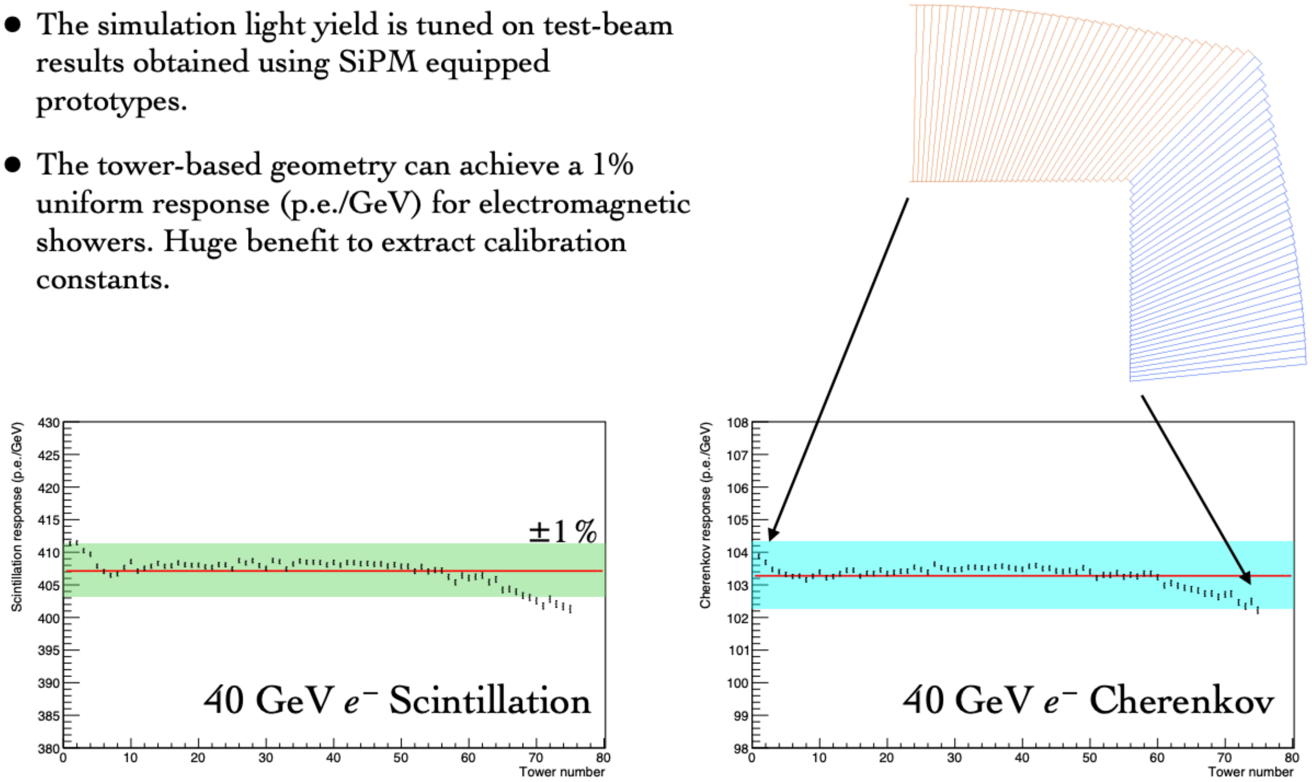
- Tested by e^- beams of 6 different energies
  - 10, 20, 40, 60, 80 and 100 GeV
- Position reconstructed by center of gravity of energies and compared with generated position
  - $\vec{x}_{reco} = \frac{\sum_i E_i \times \vec{x}_i}{\sum_i E_i}, i : \#SiPM$
- Preliminary position resolution:
  - $4.2\ \mathrm{mm}/\sqrt{E} + 0.4\ \mathrm{mm}$



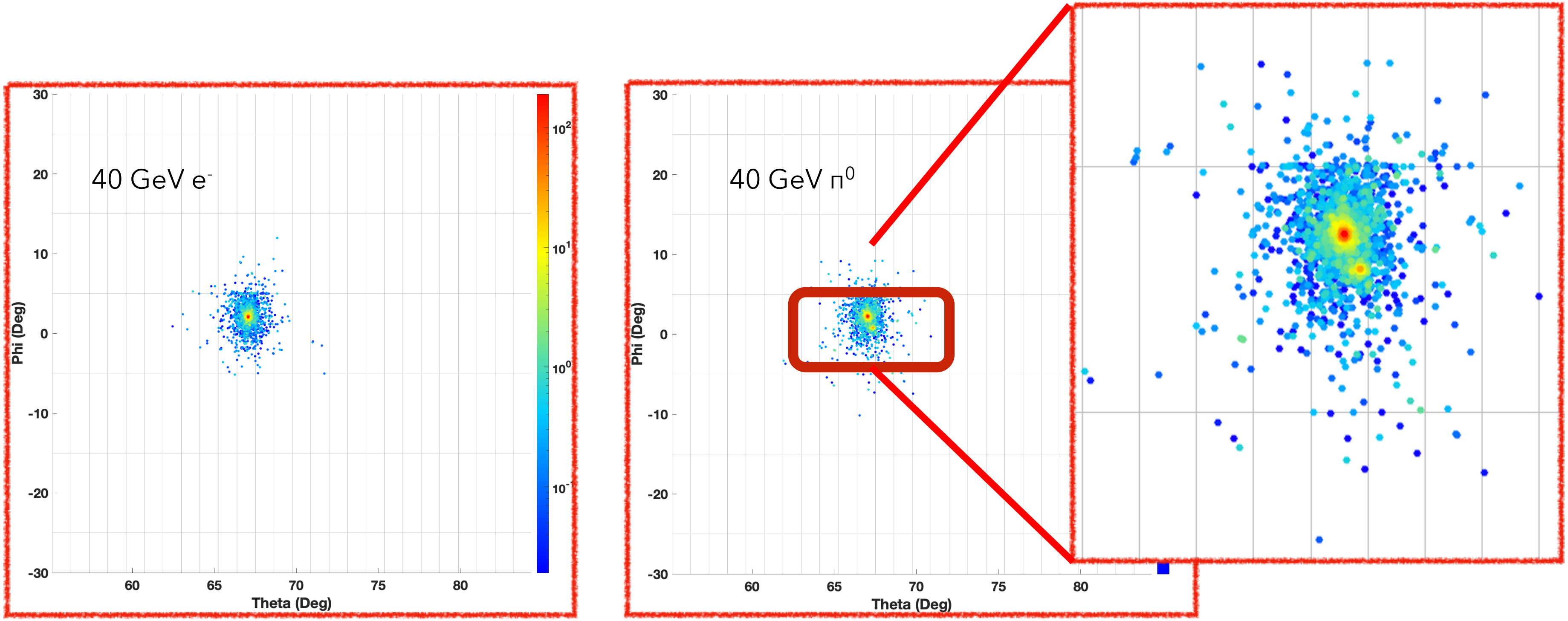


Response Uniformity

- The simulation light yield is tuned on test-beam results obtained using SiPM equipped prototypes.
- The tower-based geometry can achieve a 1% uniform response (p.e./GeV) for electromagnetic showers. Huge benefit to extract calibration constants.



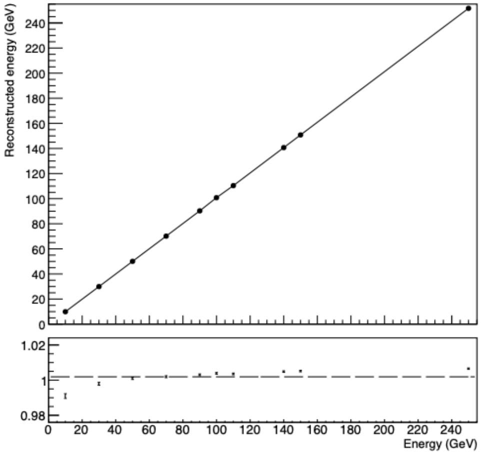
Di-photon performance

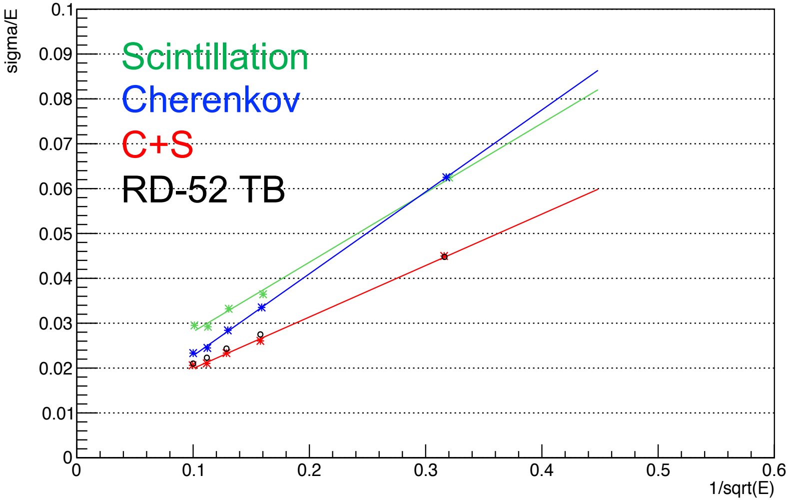


Electromagnetic performance

- An energy resolution for electromagnetic showers competitive with other sampling calorimeters was found:

$$\frac{\sigma}{E} = \frac{13\,\%}{\sqrt{E\,(\mathrm{GeV})}} + 0.2\,\%$$





- Providing an energy linearity of 1% and a uniform reconstructed energy of 0.5% over the whole detector physics acceptance.

Had. Performance: pion energy resolution

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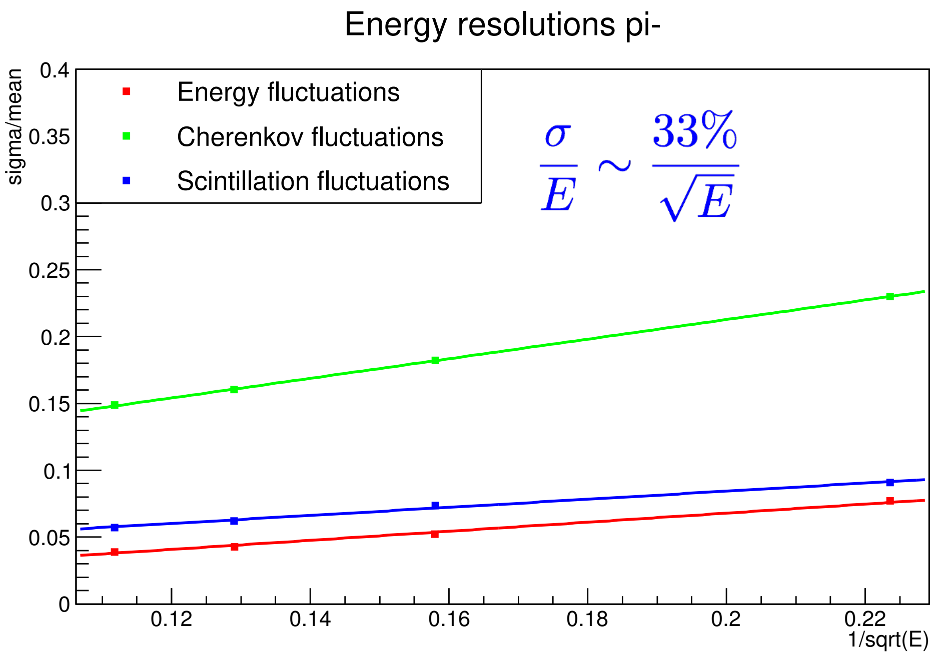
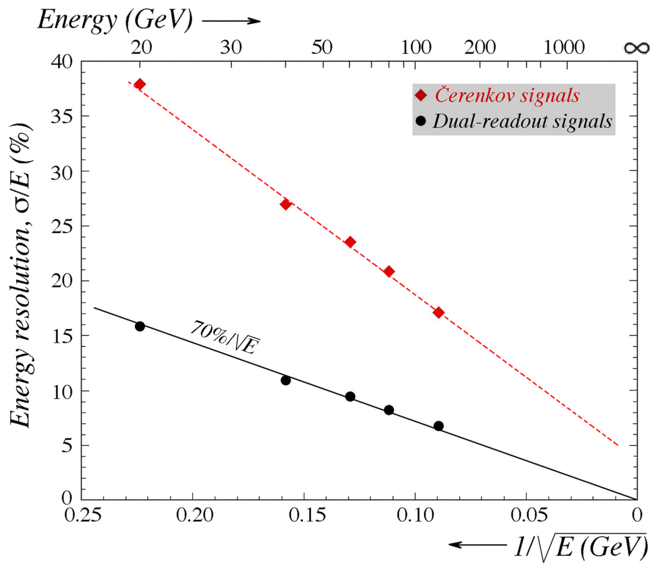


RD52 TB data - Lead-fibers module
NIMA 866, 76 (2016)

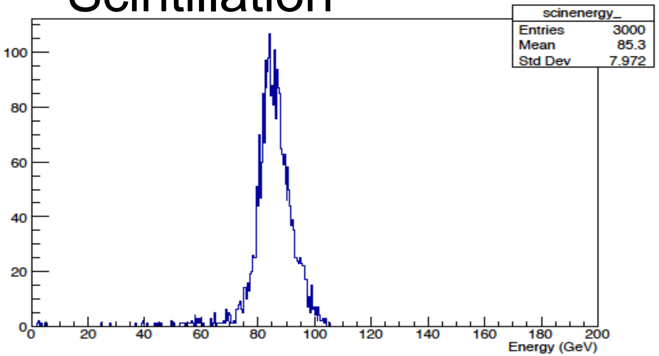


- 30x30 cm^2 lead/fibers module
- Containment ~ 90%
- not corrected for fiber attenuation length and lateral containment fluctuations

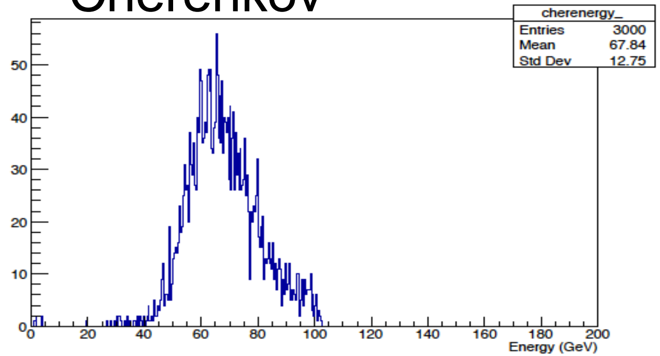
Had. Performance: pion energy resolution

Simulated 100 GeV π in IDEA calo
(FTFP-BERT phys list)

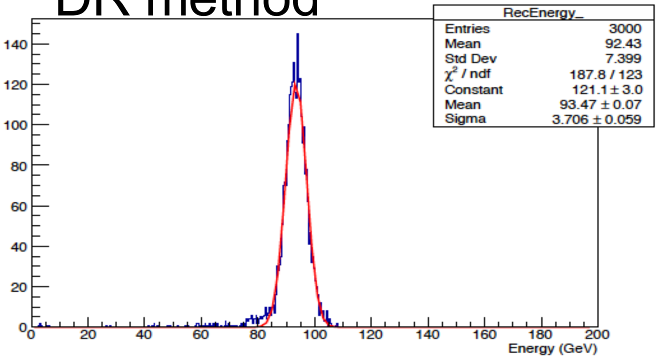
Scintillation

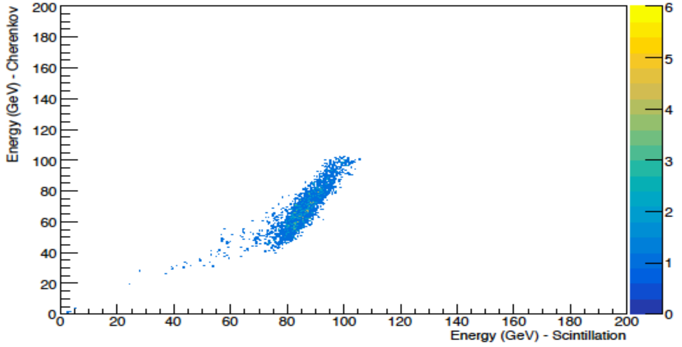


Cherenkov



DR method





Had. Performance: jet energy resolution

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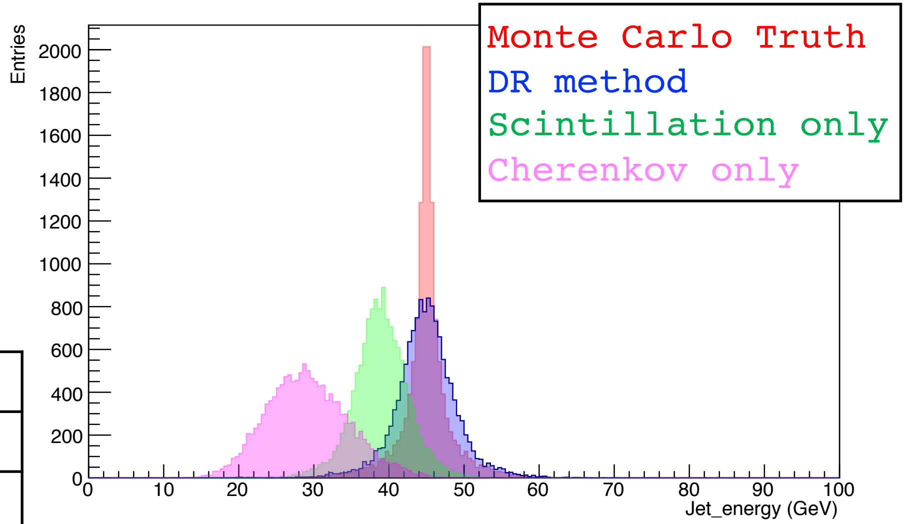
Jet reconstruction:

- ✦ Jet generated with PYTHIA8, tuned to LEP measurement
- ✦ Propagated in GEANT4 calorimeter
  - ✦ Obtain C and S response + (θ,φ) of the tower ➡️ get jet 4-momenta
- ✦ Clustering with FASTJET (Duhram kt algorithm)

	Average (GeV)	std
MC Truth	45.01	1.11
DR method	44.94	2.40
Scintillation	38.98	2.80
Cherenkov	29.37	5.30

$$e^+e^- \to q\bar{q}$$

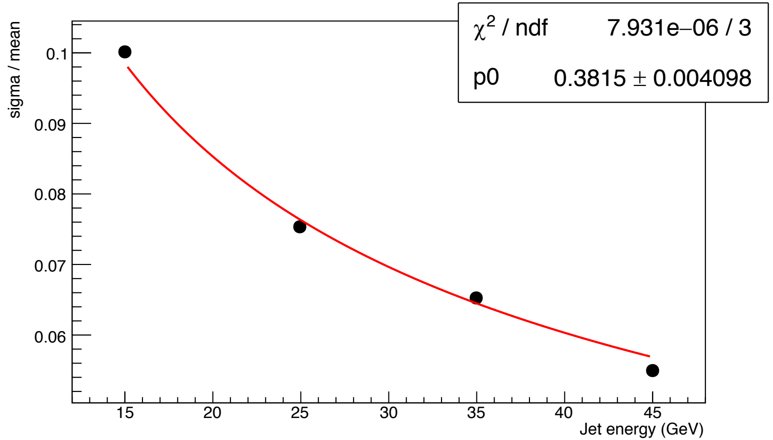
90 GeV center-of-mass



PYTHIA8 + GEANT4 + FASTJET

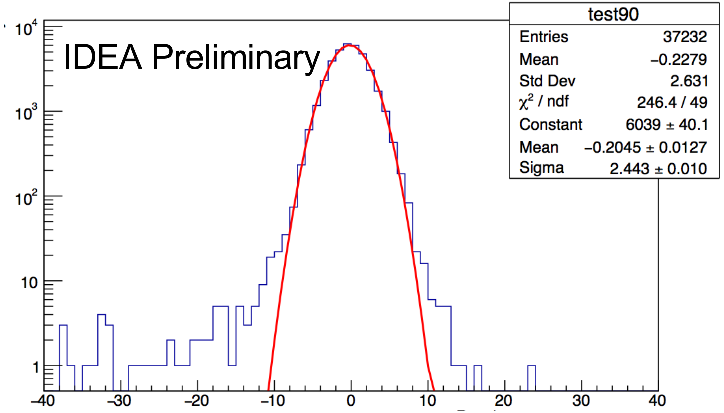
Had. Performance: jet energy resolution

PYTHIA8 + GEANT4 + FASTJET



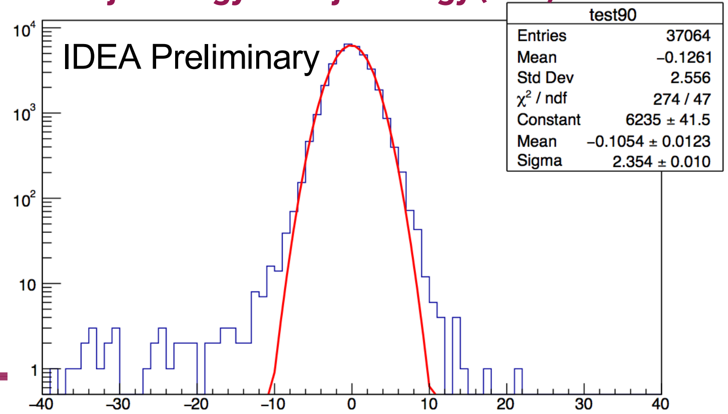
$$\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$$

Material Budget: 1 X_0 at 90°



Rec. jet energy - true jet energy (GeV)

No Material Budget

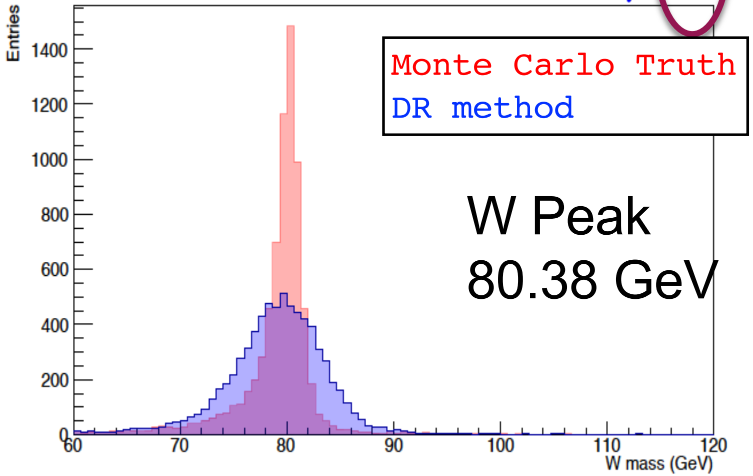


Rec. jet energy - true jet energy (GeV)

W and Z reconstruction

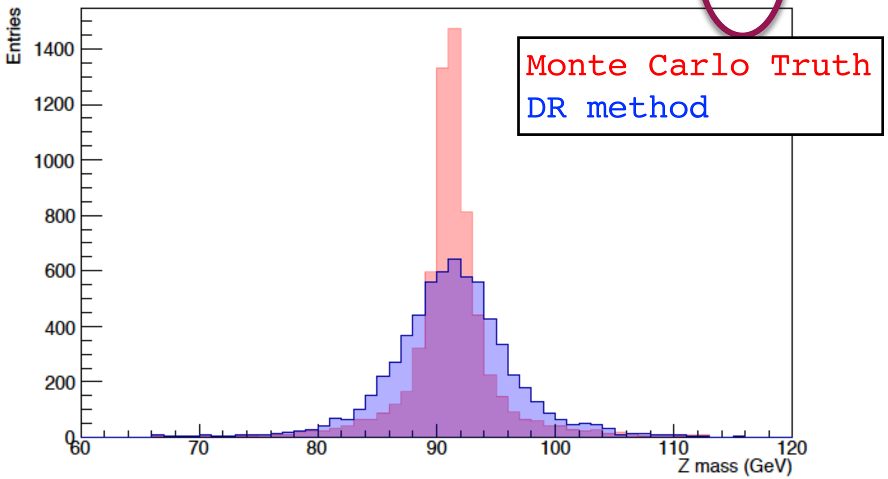
PYTHIA8 + GEANT4 + FASTJET

$$e^+e^- \rightarrow WW \rightarrow \mu\nu_\mu jj$$



W	Average (GeV)	std
MC Truth	79.3	4.2
DR method	79.14	5.1

$$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$$



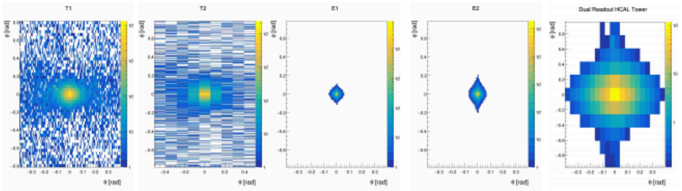
Z	Average (GeV)	std
MC Truth	91.24	4.32
DR method	91.32	5.43

CNN in crystal + fiber option

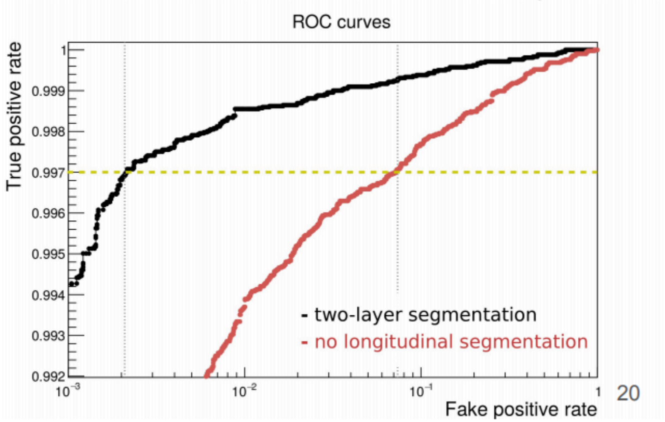
Exploiting segmentation for PID using CNNs

- Exploit the 5 calorimeter longitudinal layers:
  - For each layer the transverse segmentation combined with the additional information (e.g. dual readout and timing) can be treated as a colored image
  - Extract features from each image with convolutional filters
  - Combine features to identify particle patterns to achieve particle discrimination

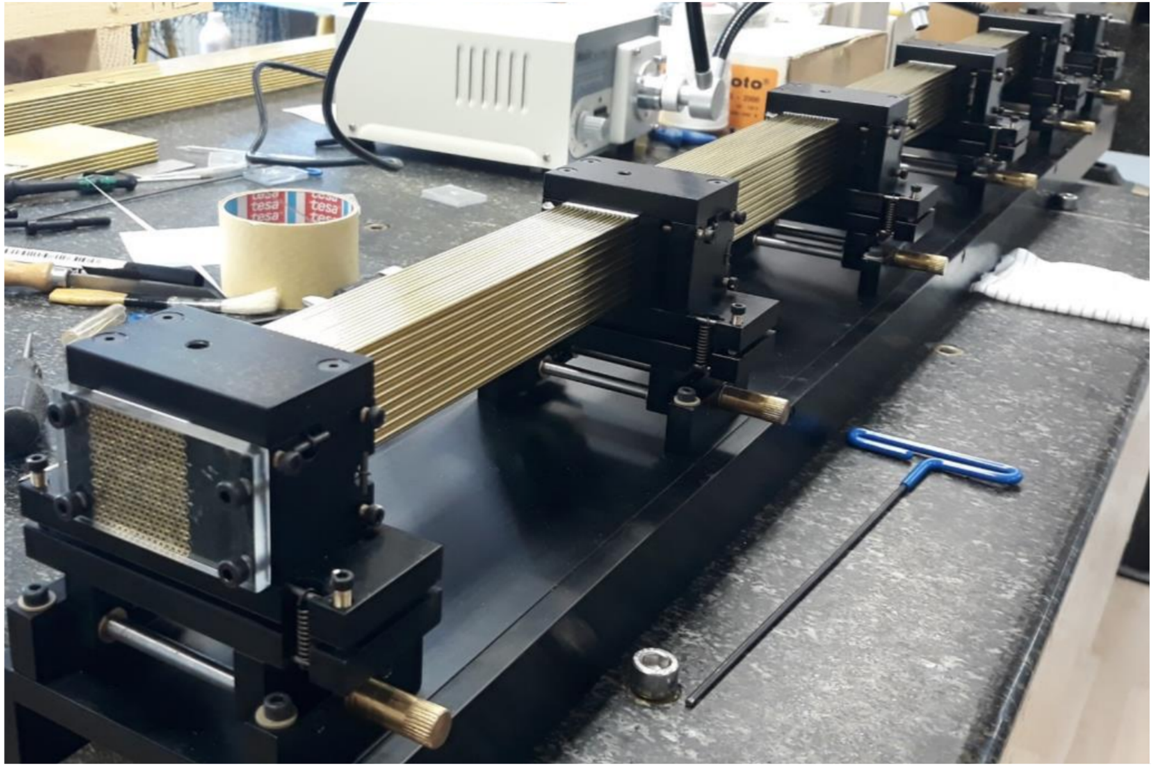
- Preliminary results: **longitudinal segmentation in the crystal EM section substantially reduces pion mis-identification rate**

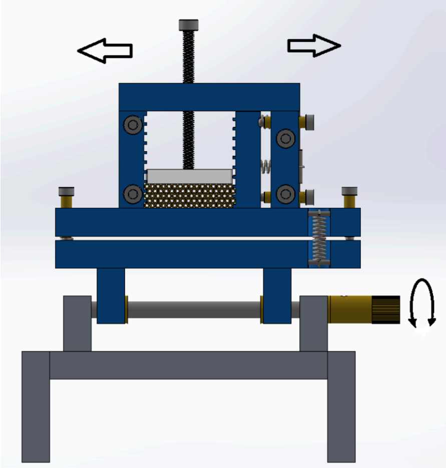


e^-/ π^- discrimination with ECAL only



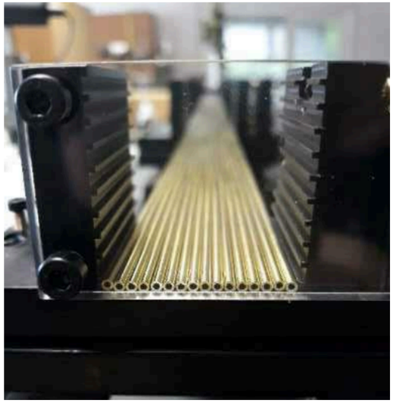
Assembly system

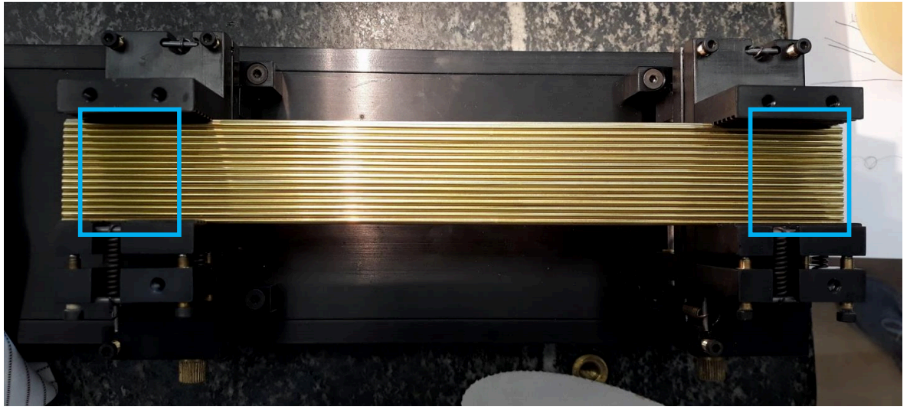




6 adjustable stands for packing capillaries to correct position. Alignment of stations through micrometric screws

Construction Method





- Capillaries are positioned layer by layer
- Dry run with all tubes for each tower (~3x3 cm^2) is performed and measurements are checked
- If all ok, capillaries removed and repositioned distributing glue at each layer
- Full tower left to cure overnight
- Measurement (external dimensions) done after removal from assembly stations

Fiber connection to PMTs

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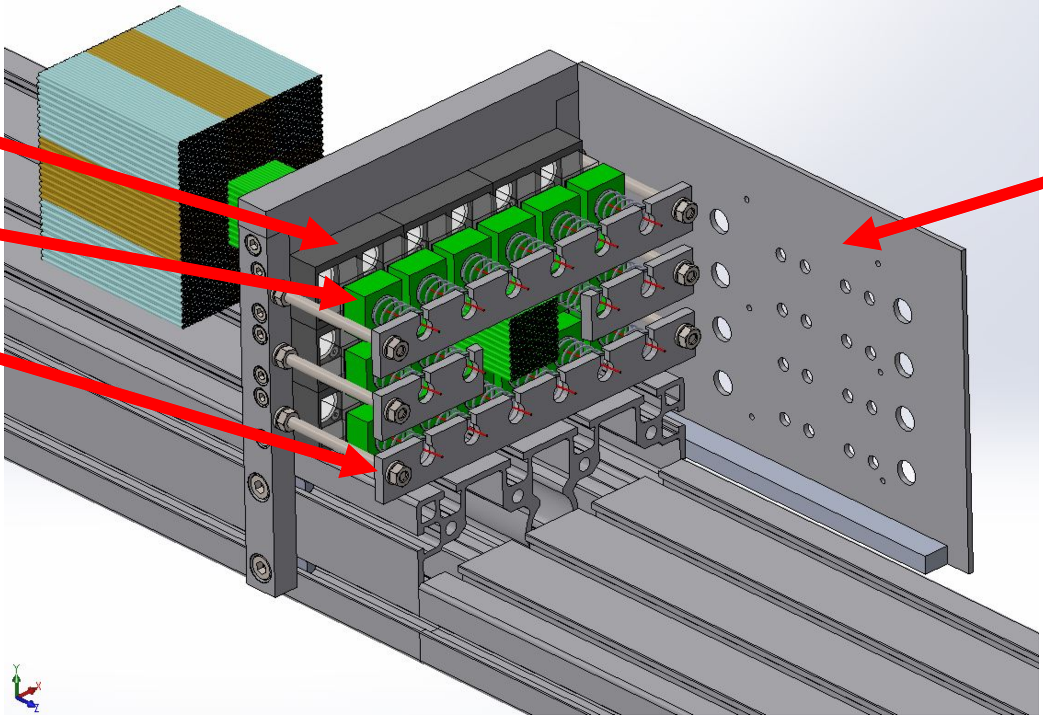
Fiber Holders

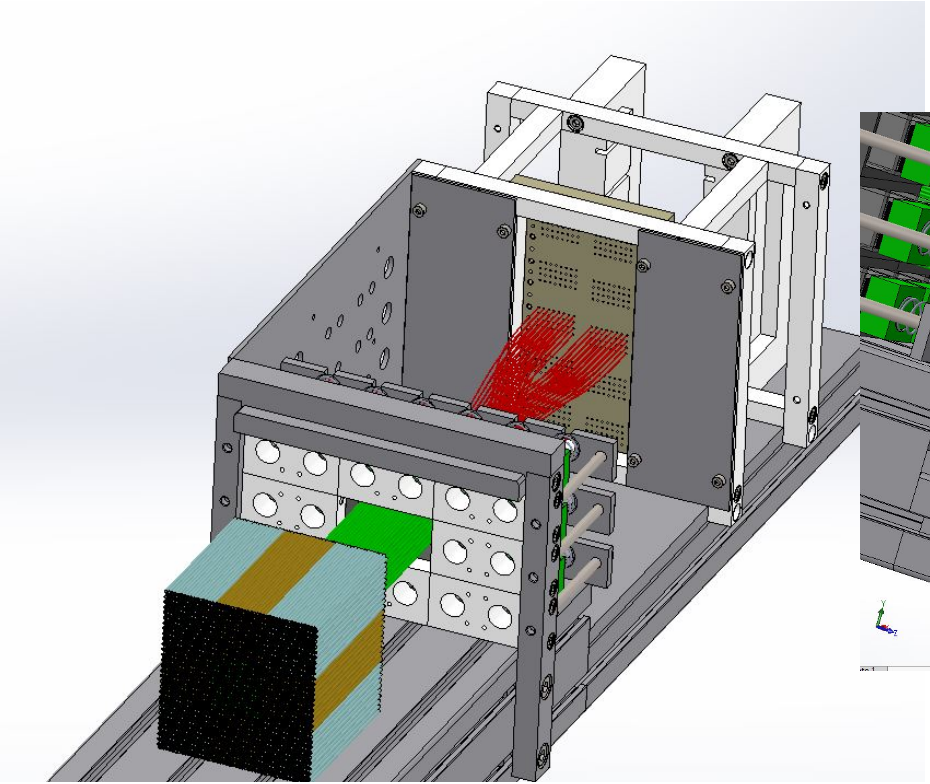
PMTs

PMT Holders



PMT Patch Pannel

Fiber connection to SiPMs



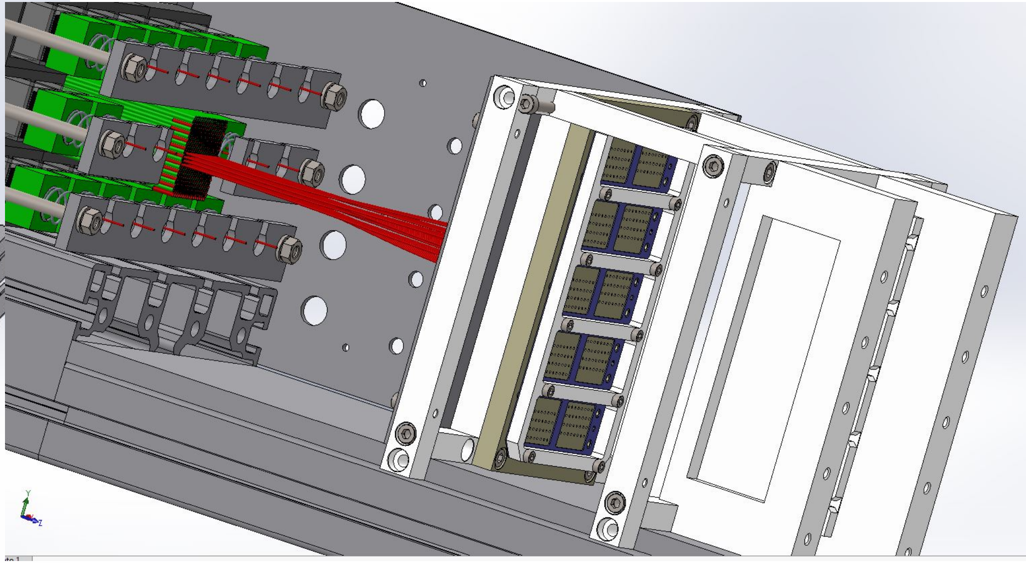
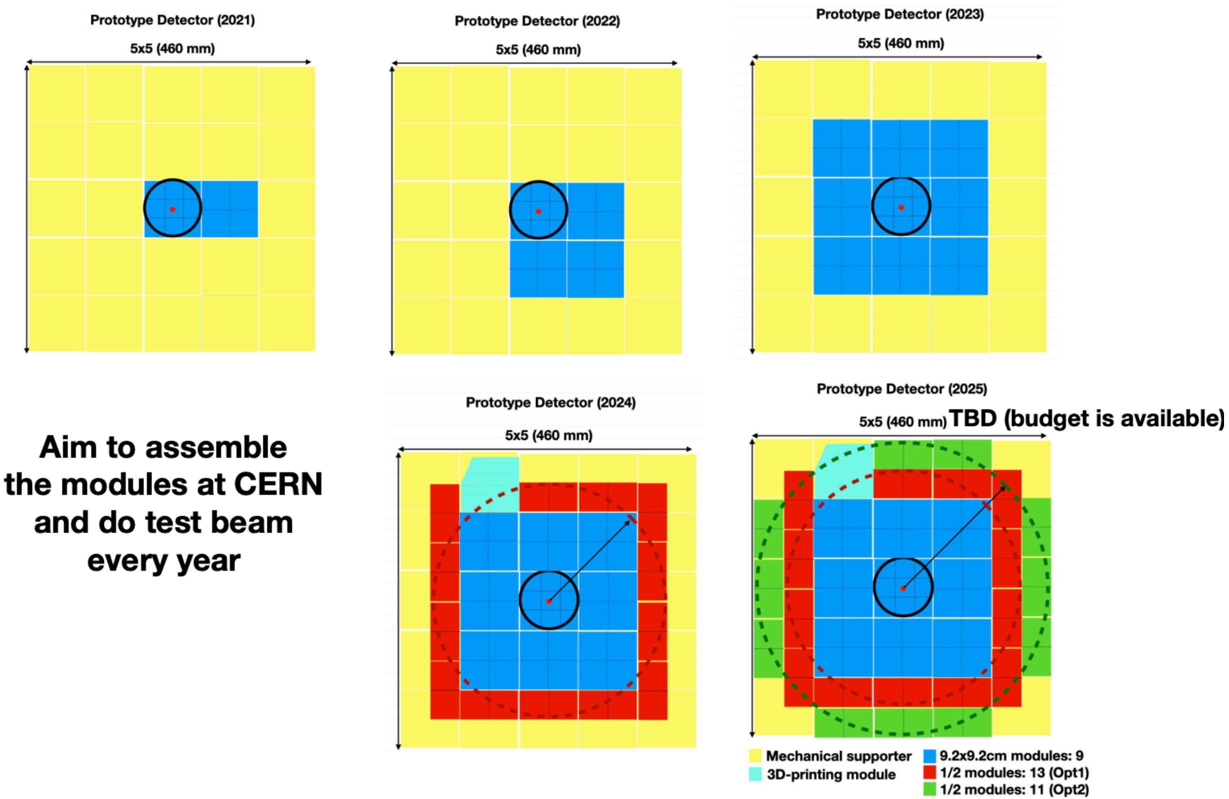


Plate-based prototype – roadmap to full containment



Aim to assemble the modules at CERN and do test beam every year

Plate-based prototype: fiber and readout config

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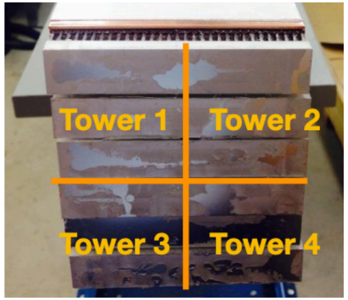
Module #1 (2x2)

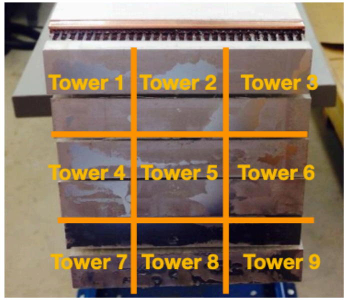


Tower#1	Tower#2
Tower#3	Tower#4

Combination of fibers for Module#1

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

Module #2 (3x3)



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

Combination of fibers for Module#2

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

Status of 3D-printing

- Ordered to Farsoon (China)
  - 10 different design of samples
  - 10 x 10 holes (front) and 11 x 11 holes (rear) with 1 cm height
- Quite impressive results with more accurate outcome
- Measured density: ~93%

	Samples	1	2	3	4	5	6	7	8	9	10
Diameter (mm)	Designed	1.0	1.1	1.2	1.1	1.0	1.3	1.1	1.2	1.2	1.1
	Outcome	0.9-0.95	0.9-0.95	1.0-1.05	0.8-0.85	0.8-0.85	1.1-1.15	0.9-0.95	1.0-1.05	1.0-1.05	0.9-0.95
Wall thickness (mm)	Designed	0.5	0.5	0.5	0.4	0.3	0.7	0.5	0.3	0.5	0.4
	Outcome	0.52	0.6	0.62	0.5	0.45	0.81	0.6	0.4	0.65	0.52

3D-printing samples