# Novel Brass Capillary Structure for the Dual Readout Calorimeter

## Dual-Readout Calorimeter for IDEA
## R&D Status and Plans

*Aneliya Karadzhinova-Ferrer*
Ruder Boskovic Institute, CDSE, *Zagreb, Croatia*

*On behalf of the IDEA detector concept group*

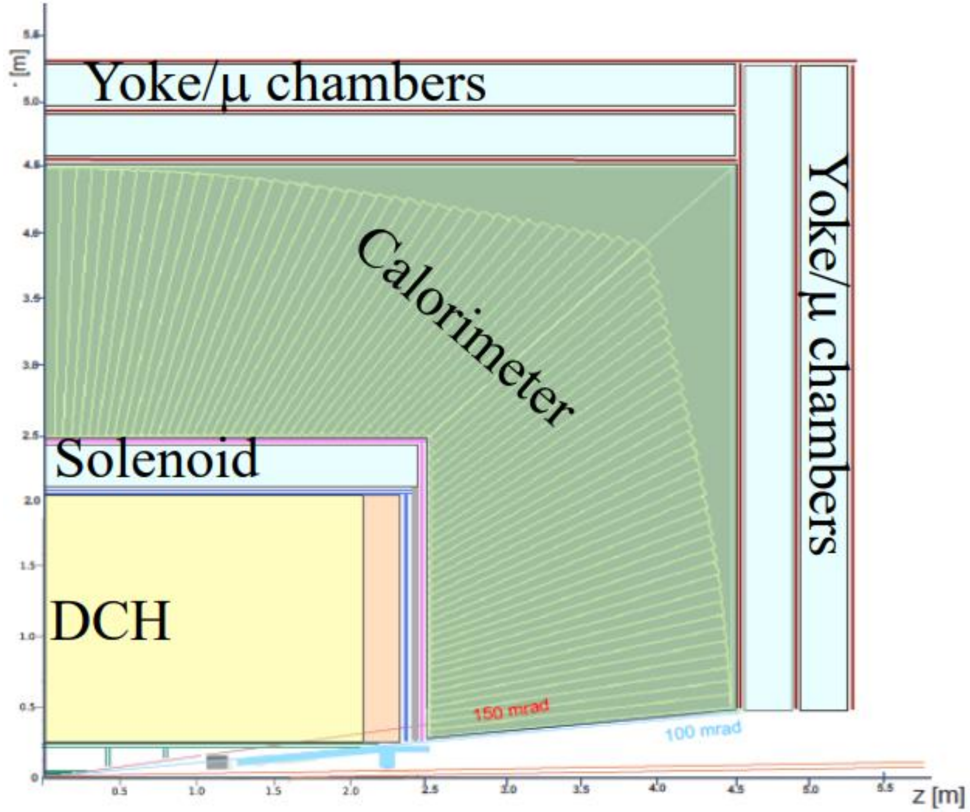
CDSE
Centar za detektore, senzore i elektroniku

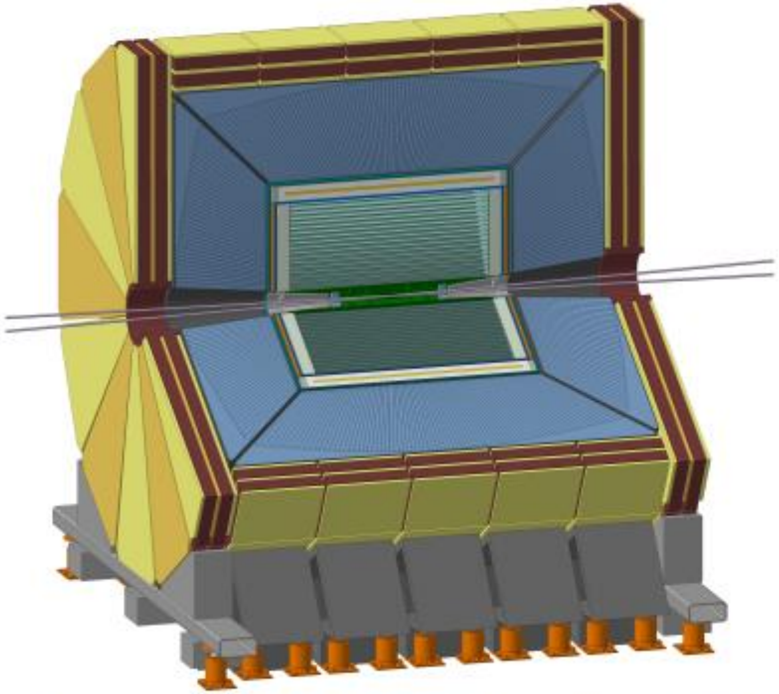
# The IDEA Detector concept

**Vertex:** 5 MAPS layers
r = 1.7-34 cm

**Drift Chamber:** 4 m long, r = 35-200 cm

**Outer Silicon Layers:** strips



* Iacopo Vivarelli talk at 4th FCC 2020
The IDEA detector

* Lorenzo Pezzotti talk at 4th FCC 2020
GEANT4 performance and analysis

**Superconducting solenoid coil:** 2 T, r ~ 2.1-2.4 m
$0.74\ X_0$, $0.16\ \lambda$ @ 90°

**Preshower:** μ-RWELL MPGD

**Dual-Readout Calorimeter:** 2 m

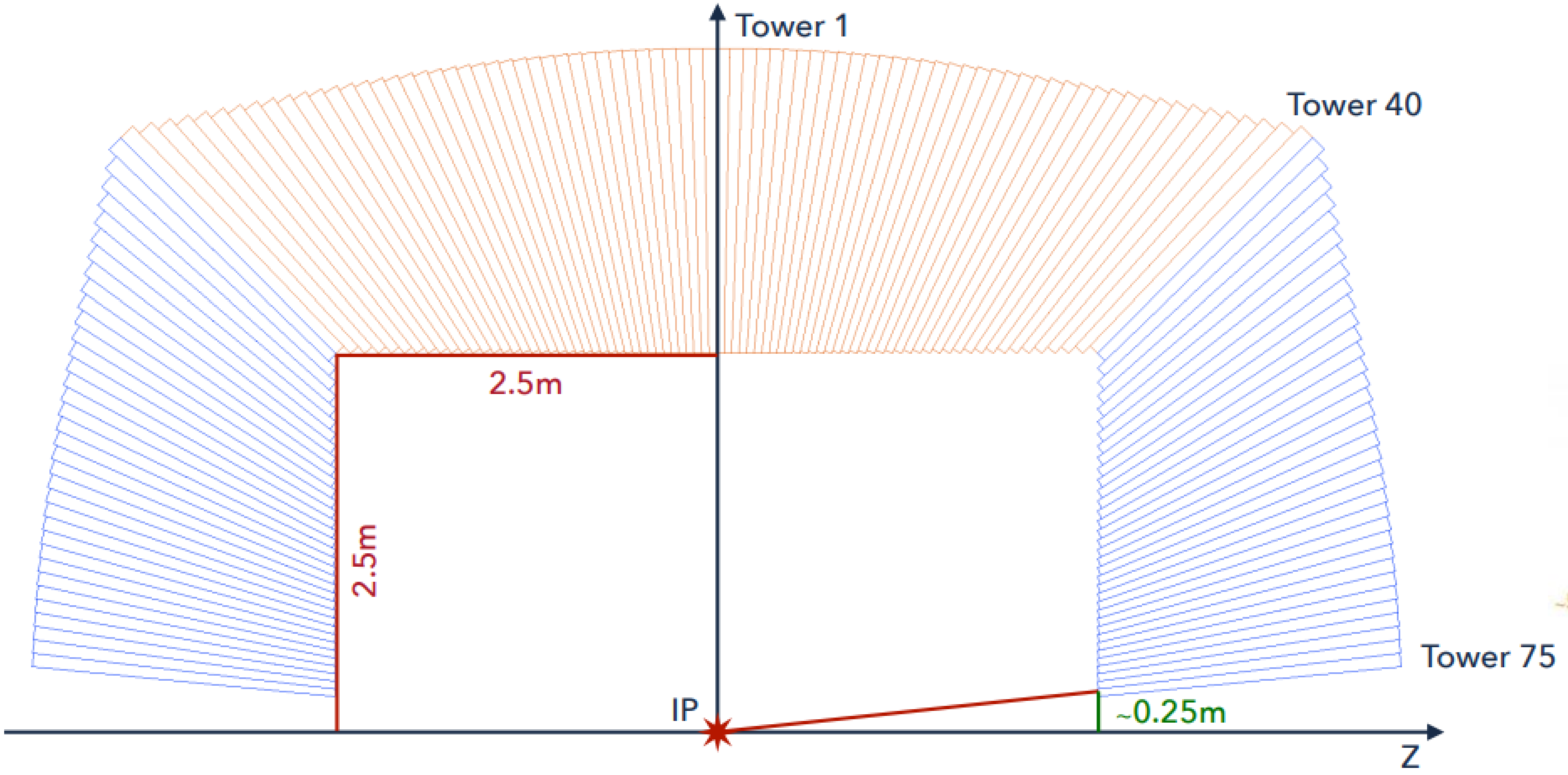
**Yoke + Muon chamber:** μ-RWELL MPGD

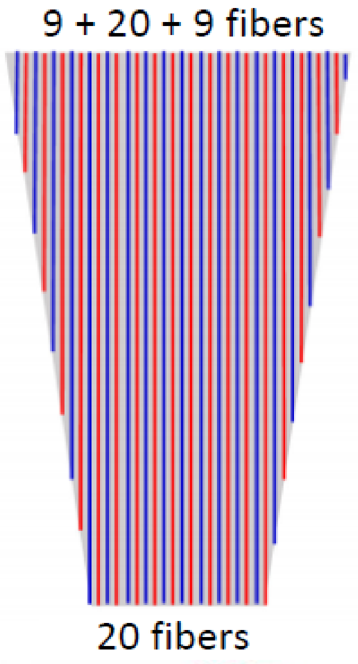
# The IDEA DR calorimeter

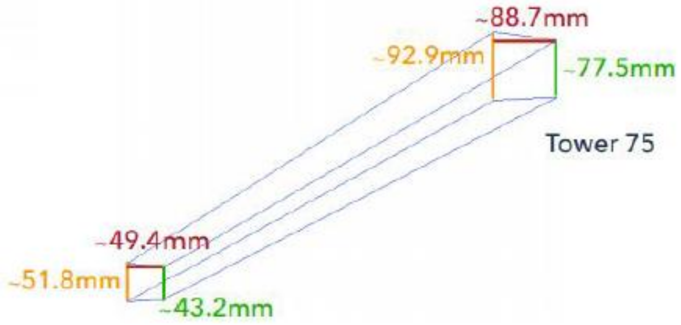
## Design of the fully projective fiber calorimeter

Tower segmentation: $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
Number of towers in barrel: 40 x 2 x 36 = 2880

Number of towers per endcap: 35 x 36 = 1260
Theta coverage up to ~0.100 rad




* Lorenzo Pezzotti talk at 4th FCC 2020
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# R&D strategy for the Dual-Readout Calorimeter

## Main objectives of the R&D plan for the next years

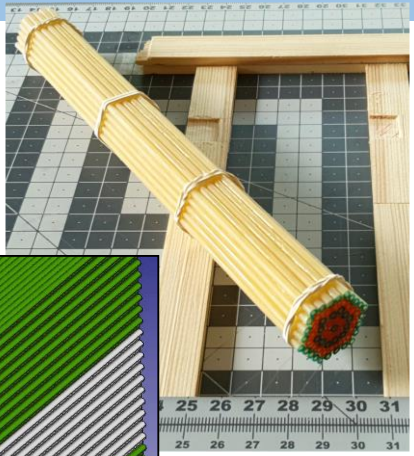
- Construction of an EM-size of a DR Calorimeter and evaluation of its performance
- Identifying and evaluating solutions at system level – Mechanics, Sensors, Readout scheme, Calibration
- Proof of concept of the dual-readout technique with respect to hadronic performance

## Execution in two steps

- Short-term plan – Construction and evaluation of a module with EM shower containment (10 x 10 x 100 $cm^3$) and a high-granularity core (3.5 x 3.2 x 100 $cm^3$) equipped with SiPMs

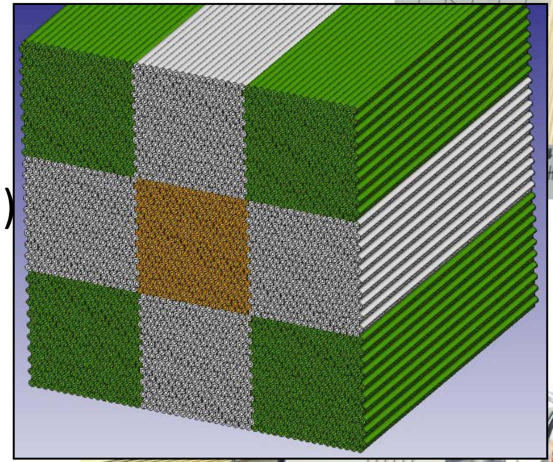
- Mid-term plan - design, construction and evaluation of a scalable system with hadronic shower containment, partially equipped with SiPM for cost/performance optimization

## The simulation input is crucial to define the requirements and to guide the R&D process in the correct direction



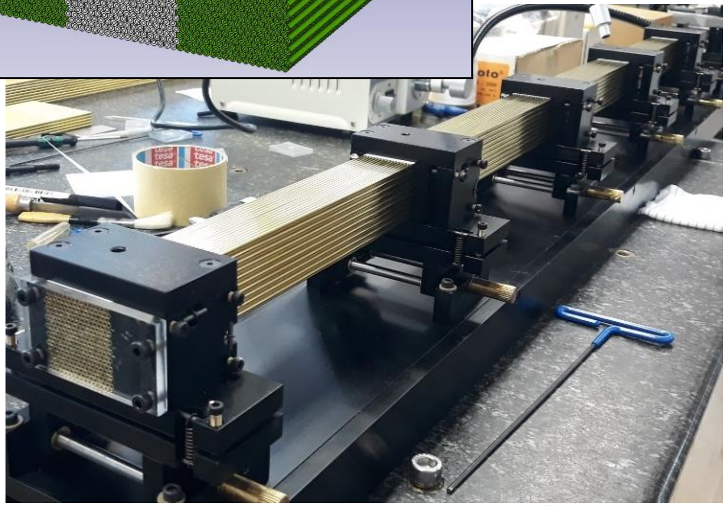
## Design requirements of EM prototype (10 x 10 x 100 $cm^3$)

- Brass Capillaries  with Outer diameter 2 mm and Inner diameter 1.1 mm
- 9 individual modules of 16 x 20 capillaries (160 Č & 160 Sc per module)
- Each capillary of the central module to be equipped with a SiPM (320 in total)
- The rests of the surrounding modules to be equipped with PMTs (2 per module)



## “Off the Shelf” capillaries

- Produced by Albion Alloys within the specifications OD 2.0 (+ 0.1 / - 0.0) mm, ID 1.1 (+ 0.1 / - 0.0) mm
- The requirement of the ID  comes from the outer diameter of the fibers, while the OD can be tuned



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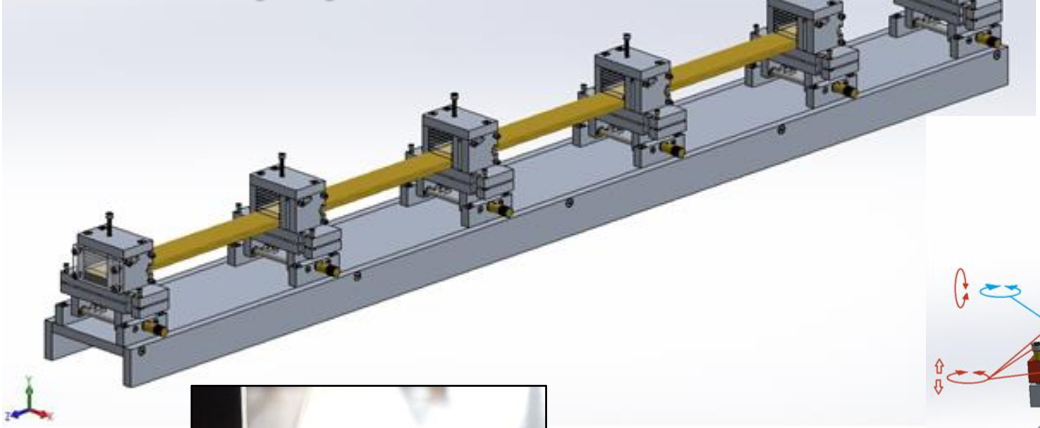
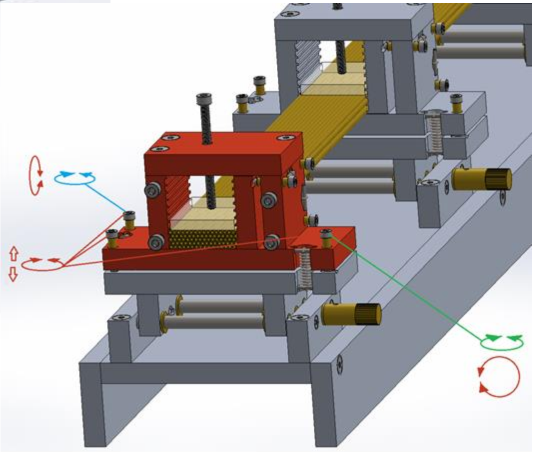
Grant Agreement No 669014

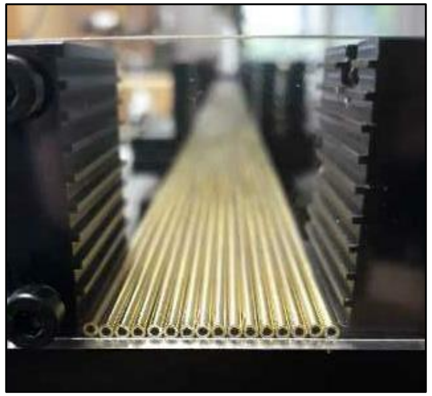
# R&D strategy for the Dual-Readout Calorimeter

## From idea to prototype for IDEA

### Assembly system







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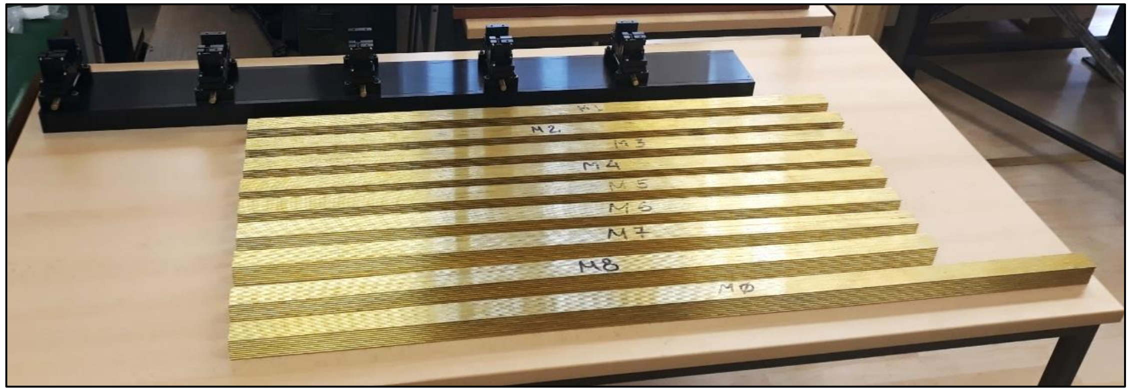
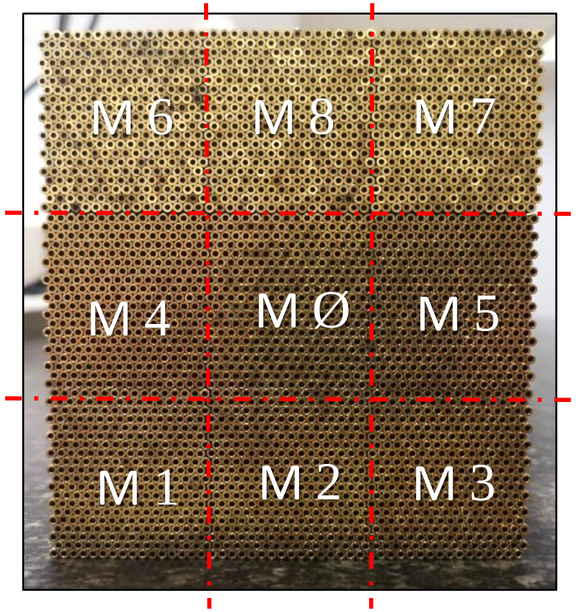




## EM tower prototype - Structure

- Time to produce a single module is ≈1.5 day (including epoxy curing time)
- The modules nicely fit close to each other
- The width and the height of the modules have a std of ~ 80 $\mu$m with a maximum difference < 200 $\mu$m





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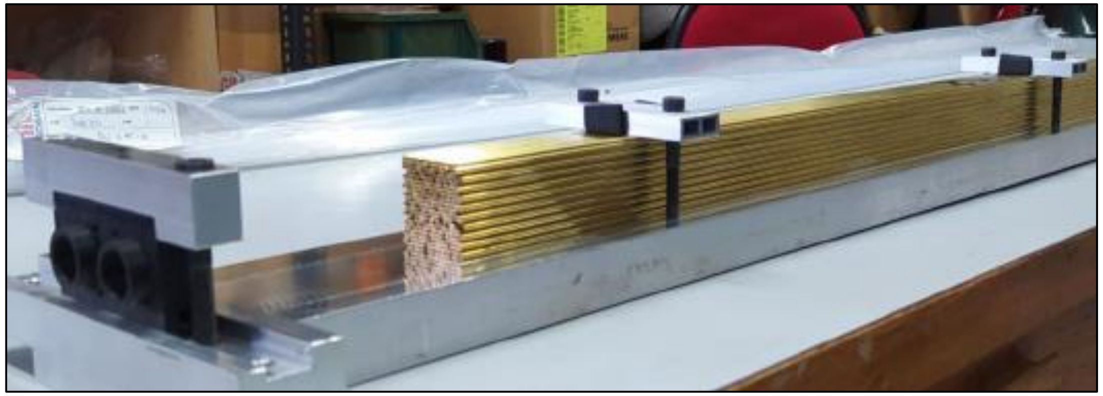
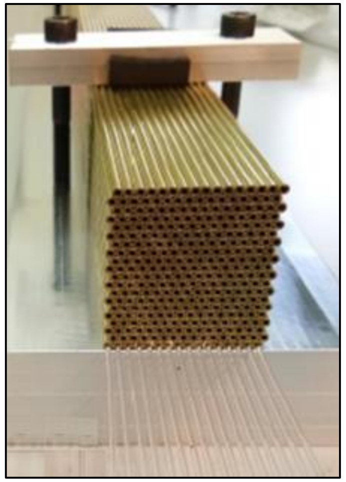
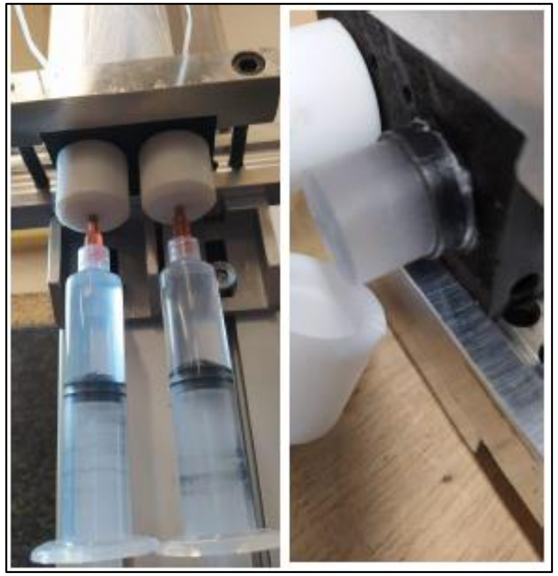
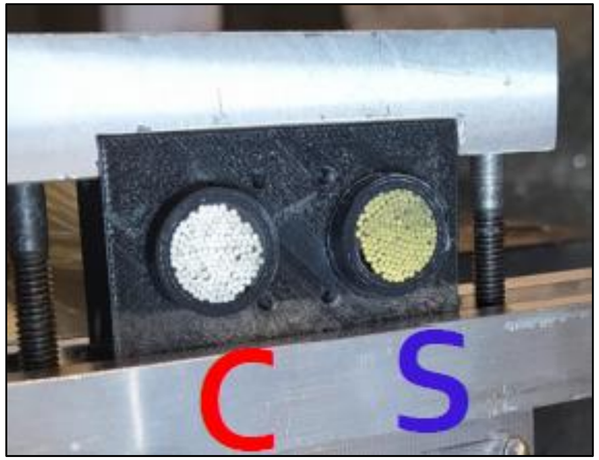
# R&D strategy for the Dual-Readout Calorimeter

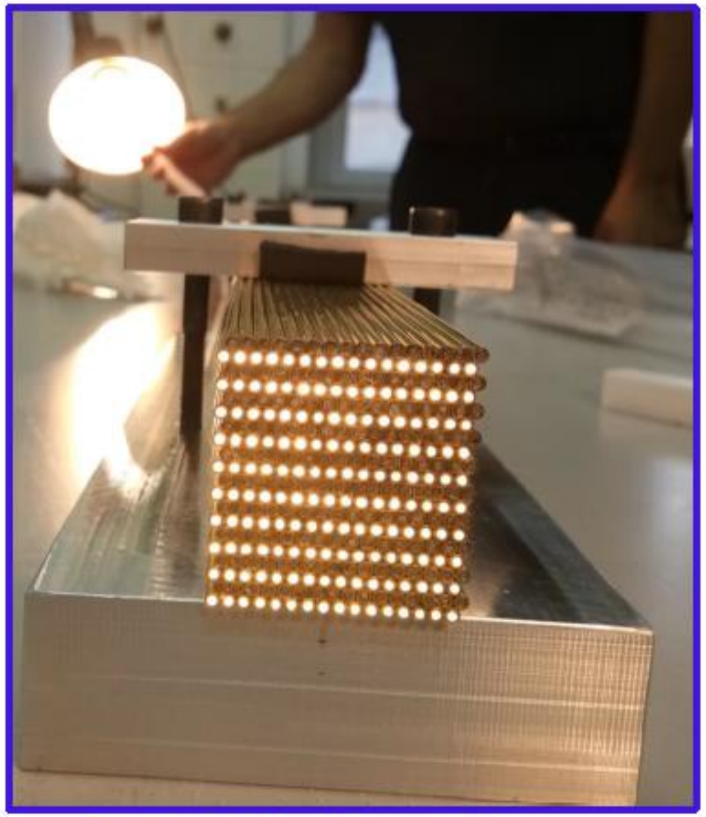
## From idea to prototype for IDEA



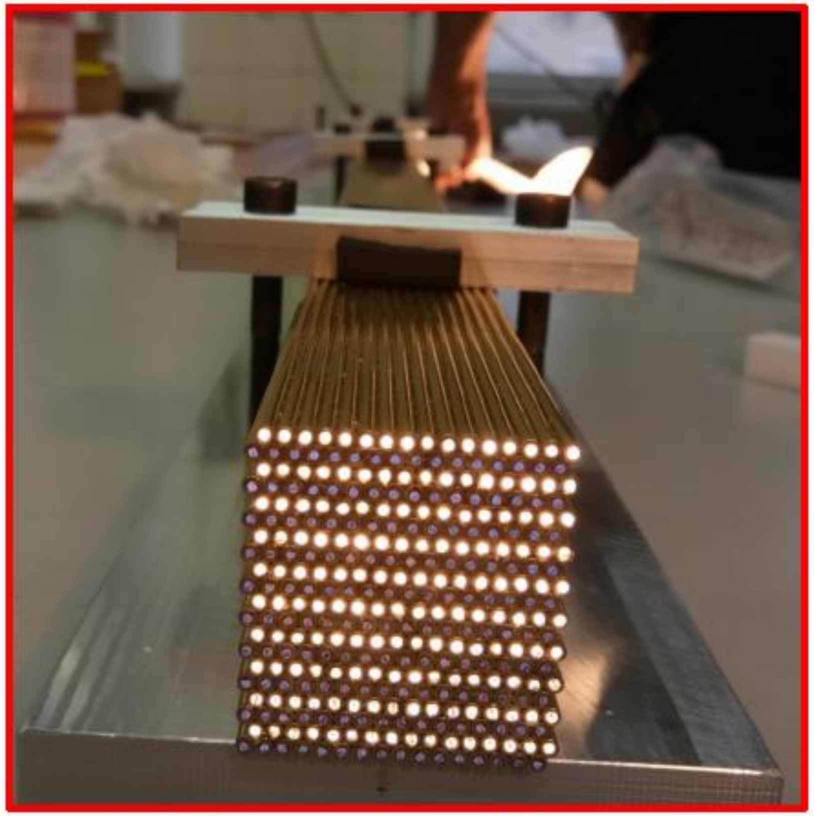








Scintillation fibers



Cherenkov fibers

## EM tower prototype – Fiber insertion

- Time to insert and mount 160 Č & 160 Sc fibers into single module -> 3-4 h
- Time for epoxy application -> 1 h
- Time for epoxy curing -> 24 h
- Time for milling -> 1 h

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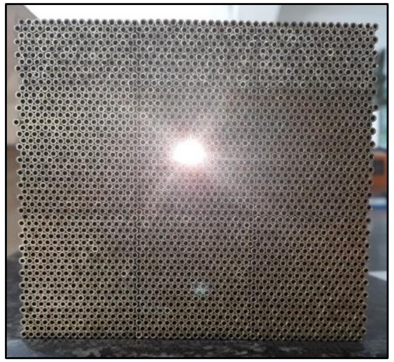
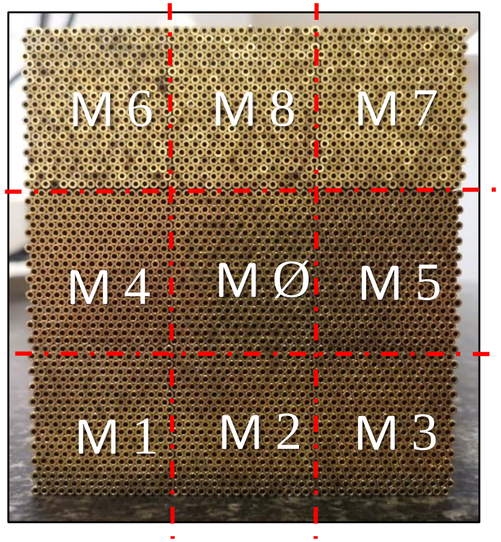
Total time ~ 1.5 days

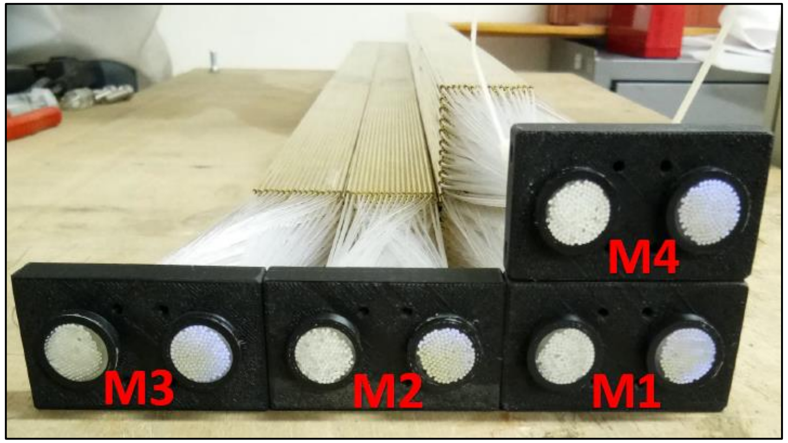
**Fibers illuminated from rear end**

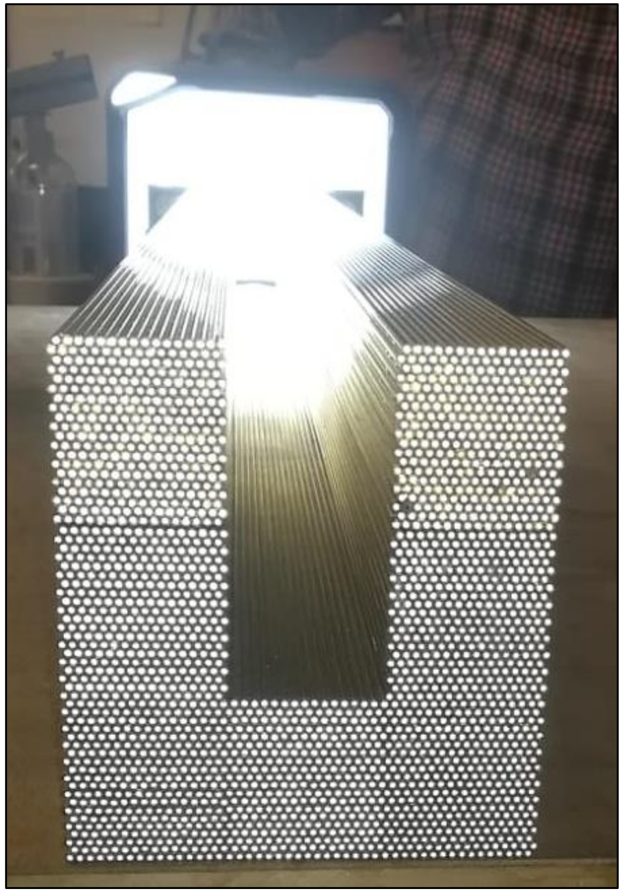
# R&D strategy for the Dual-Readout Calorimeter

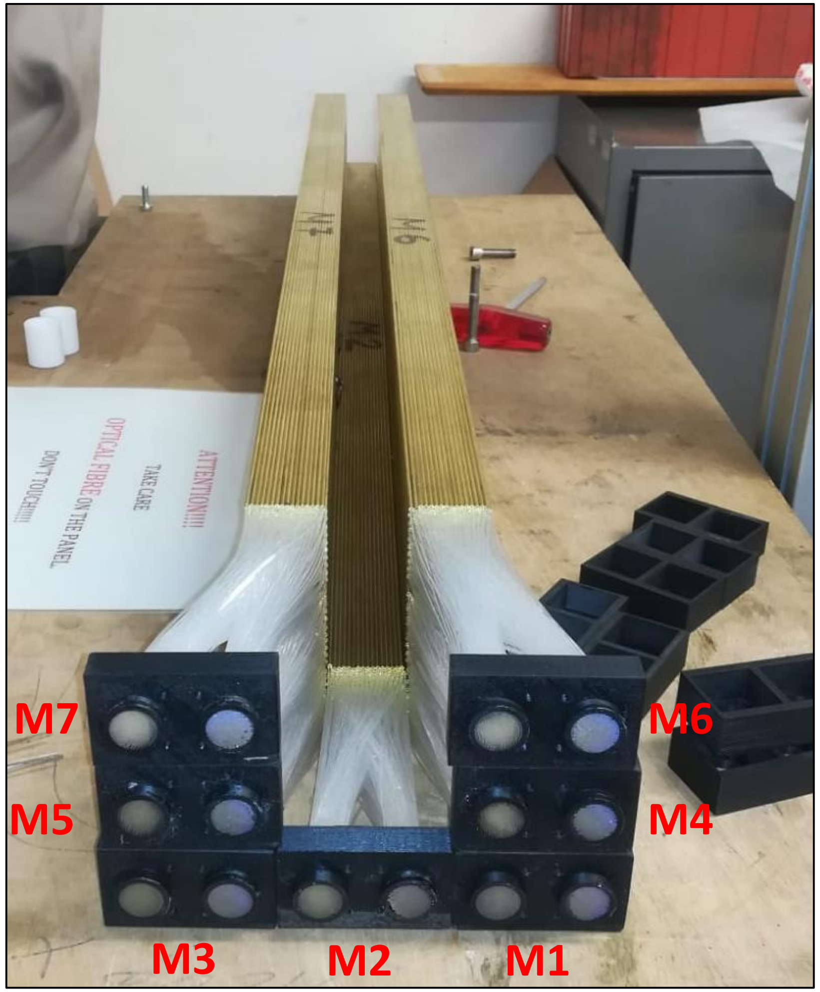
## From idea to prototype for IDEA





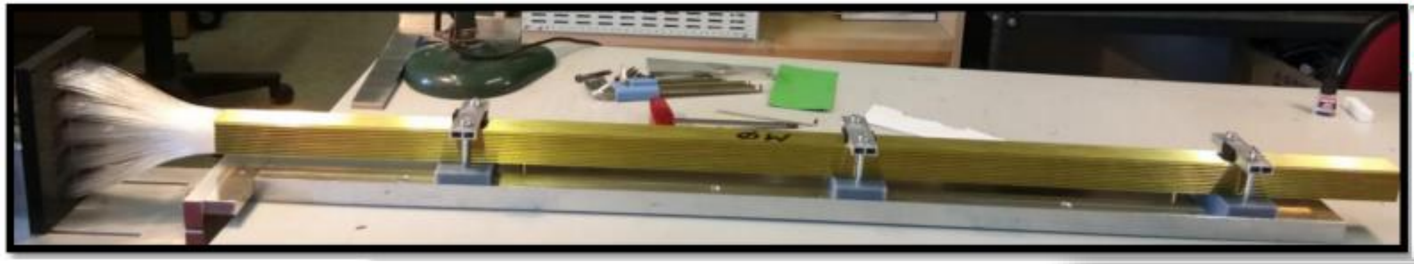





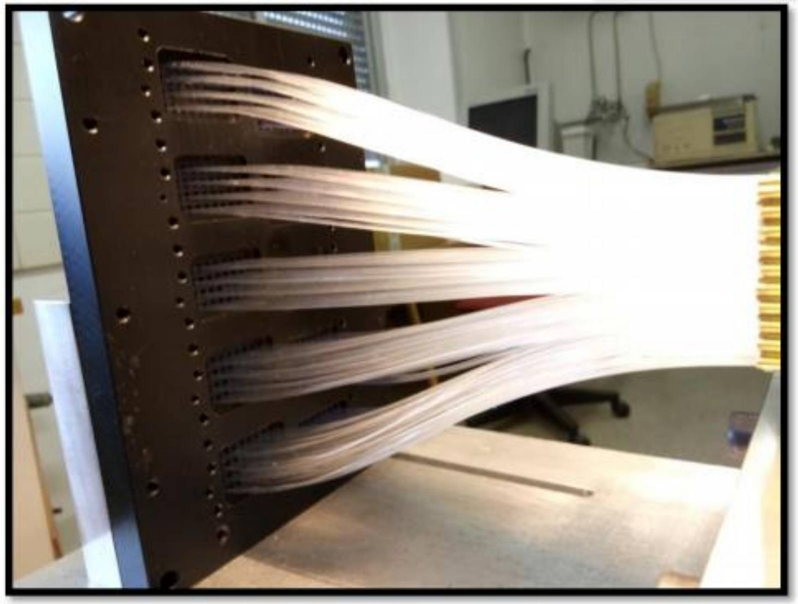
# R&D strategy for the Dual-Readout Calorimeter

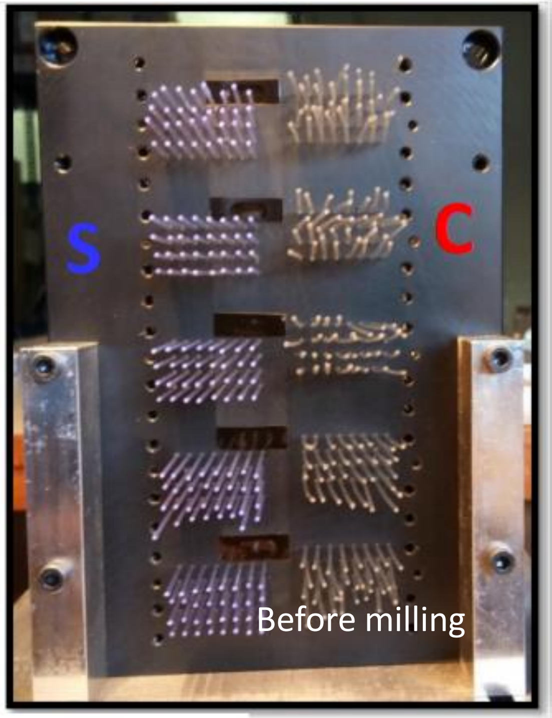
## From idea to prototype for IDEA

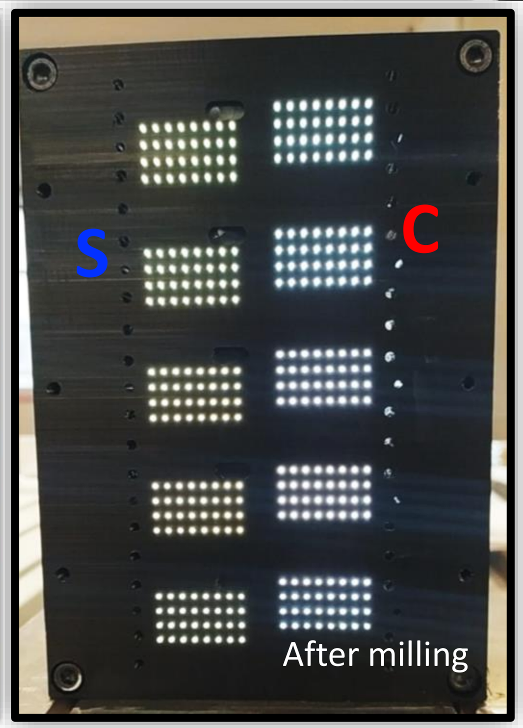
Central tower loaded with fibers



M0



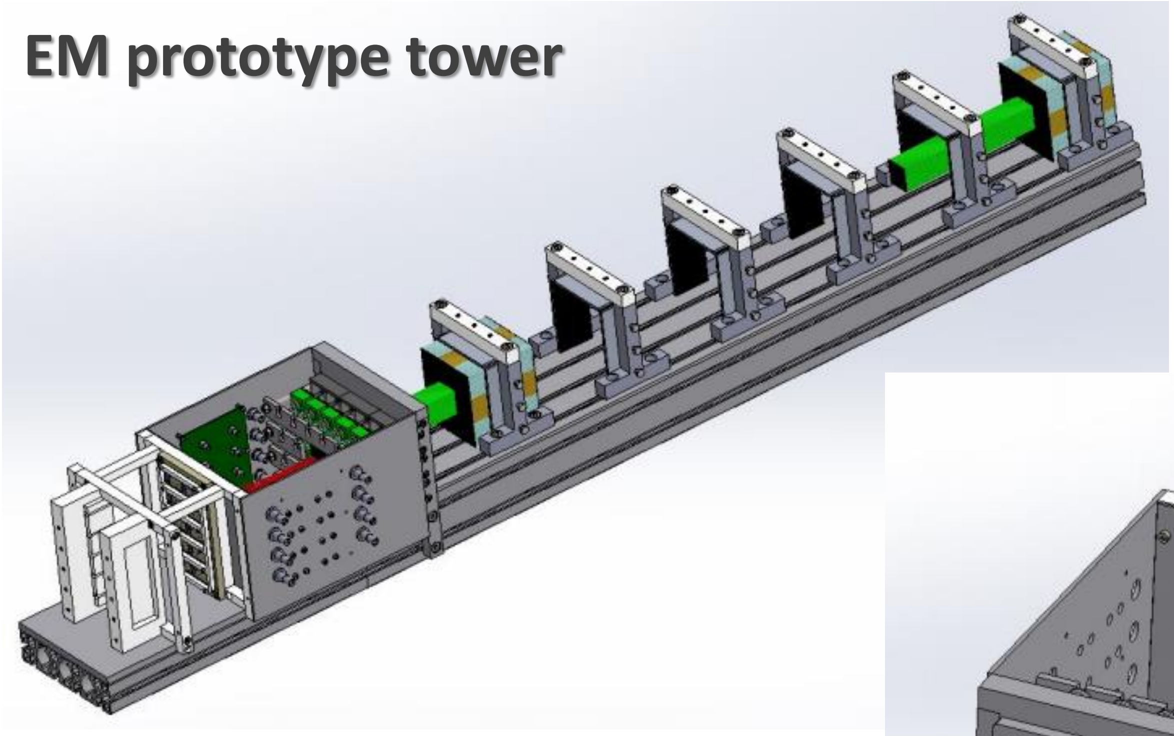


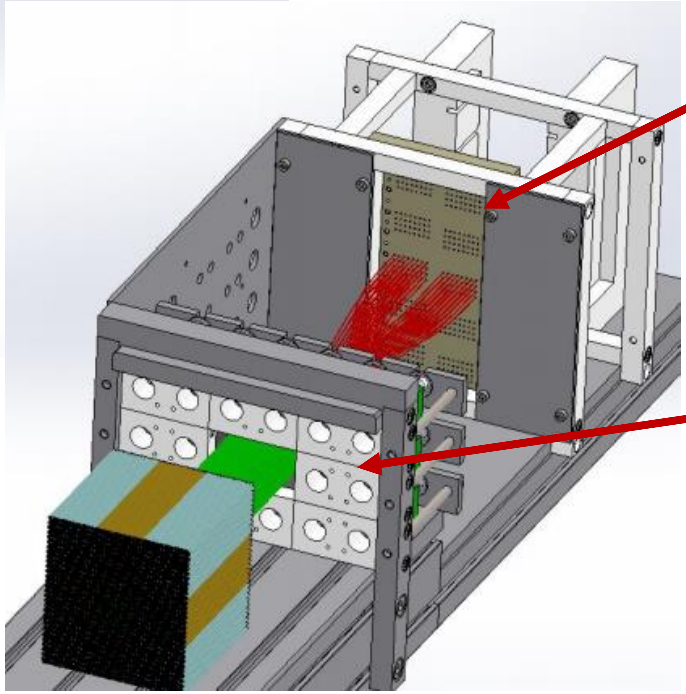



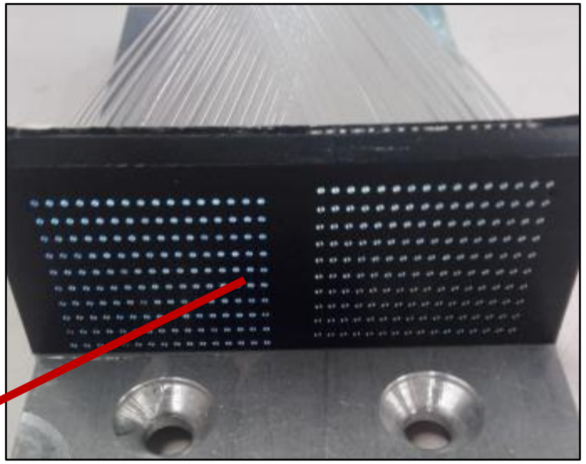

# R&D strategy for the Dual-Readout Calorimeter

## From idea to prototype for IDEA

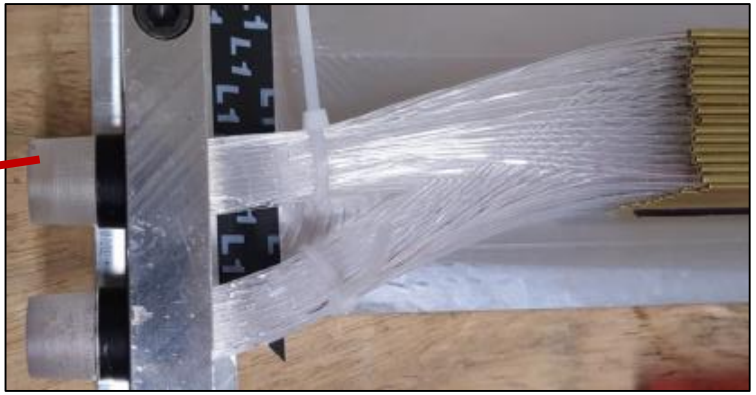
**EM prototype tower**







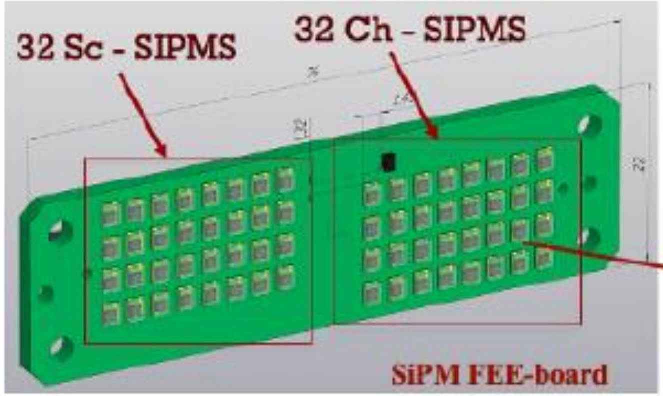
**Fiber grouping for SiPMs**

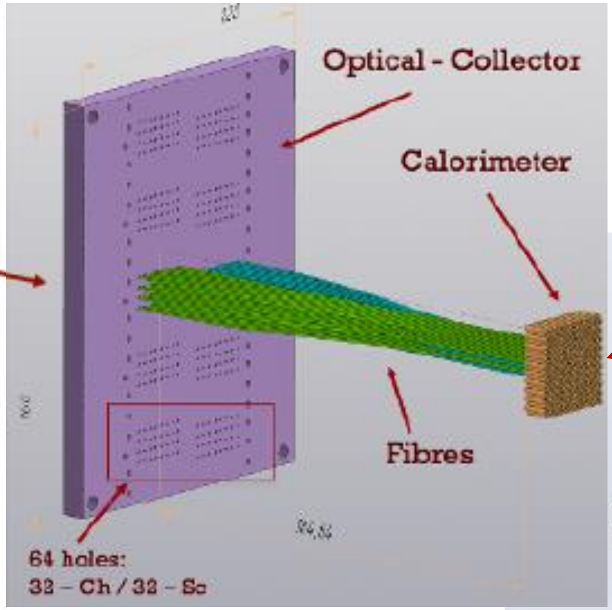


**Fiber grouping for PMTs**

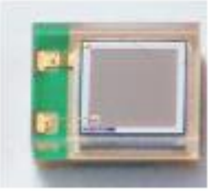
# R&D strategy for the Dual-Readout Calorimeter

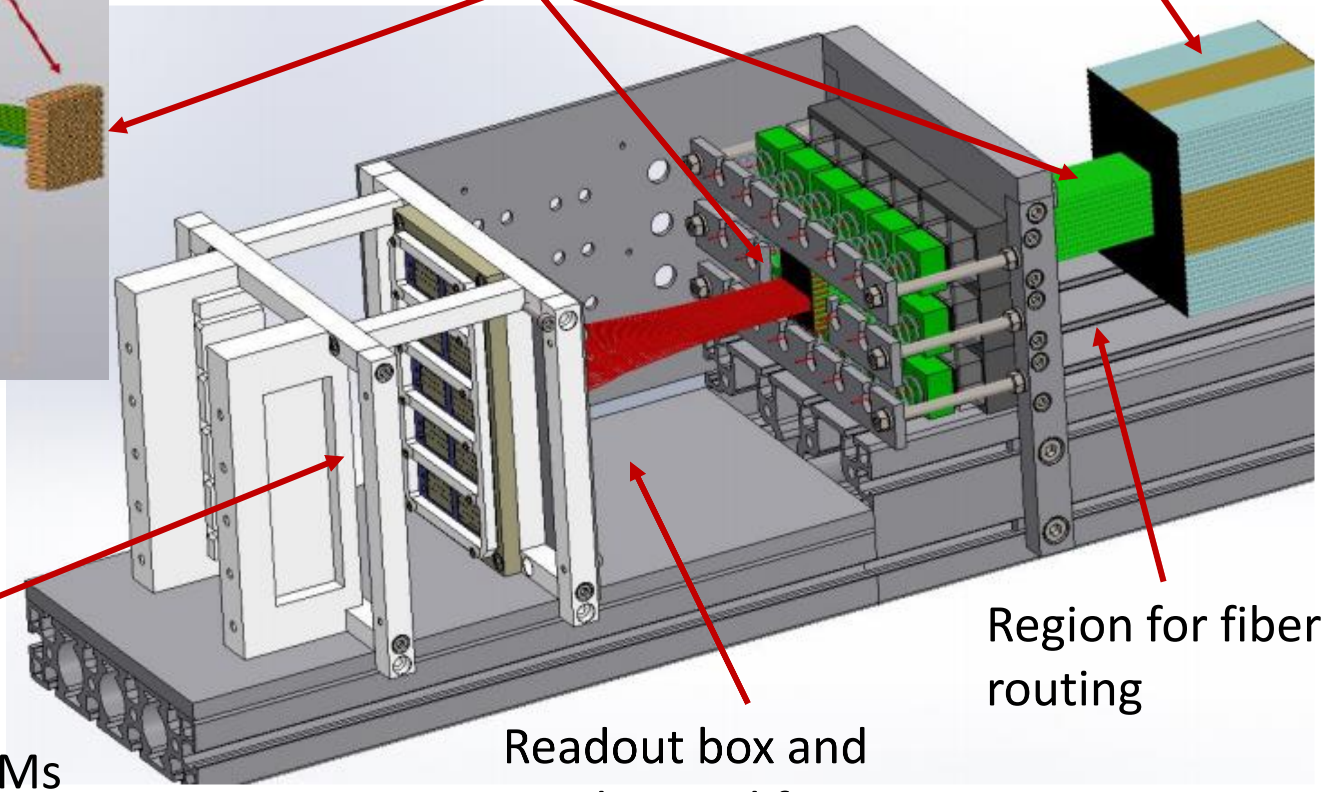
## From idea to prototype for IDEA



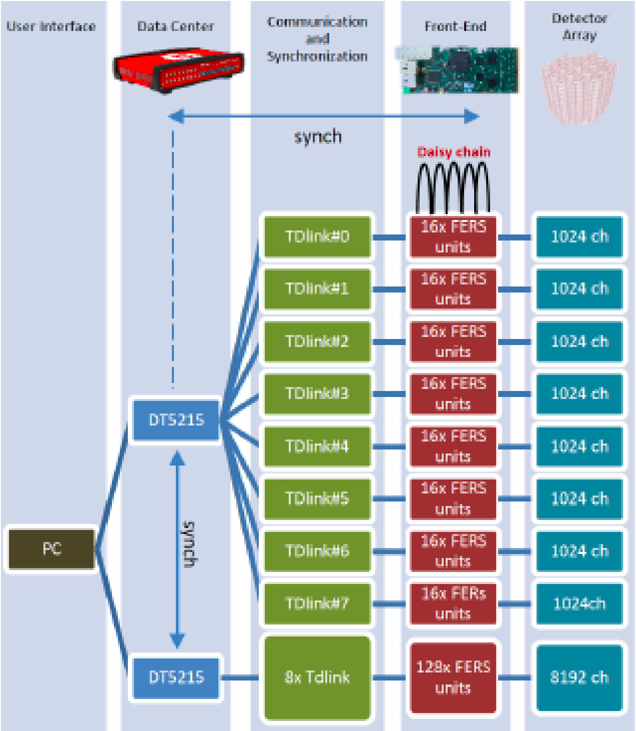

| S14160-1315PS | | |
|---|---|---|
| Effective Area | 1.3x1.3 | $mm^2$ |
| Cell pitch | 15 | $\mu m$ |
| Number of cells | 7296 | |
| Geometrical factor | 49 | % |
| Vbd | 38+-3 | V |
| Gain | $3.6*10^5$ | |
| PDE | 32 | % |
| Xtalk | <1 | % |
| DCR (Typical) | 120 | kHz |





## Readout scheme for EM prototype (10 x 10 x 100 $cm^3$)

- The readout of the PMTs will be based on Caen QDC (V862AC) and TDC (V775N) modules
- The readout of the highly granular module (320 SiPMs) will be based on the Caen FERS system (5200) using 5 readout boards (A5202)



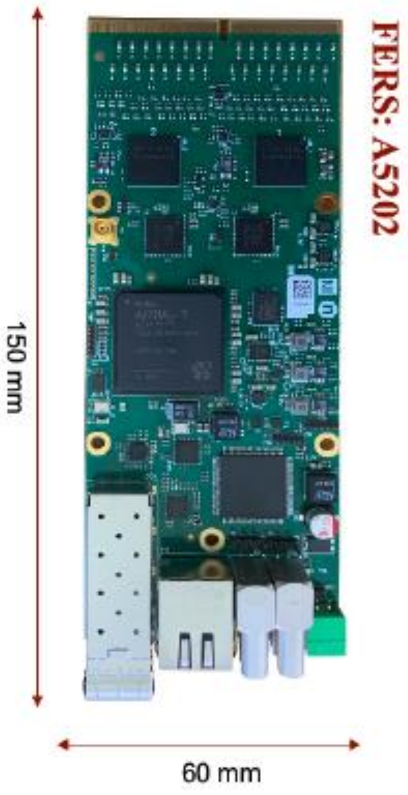


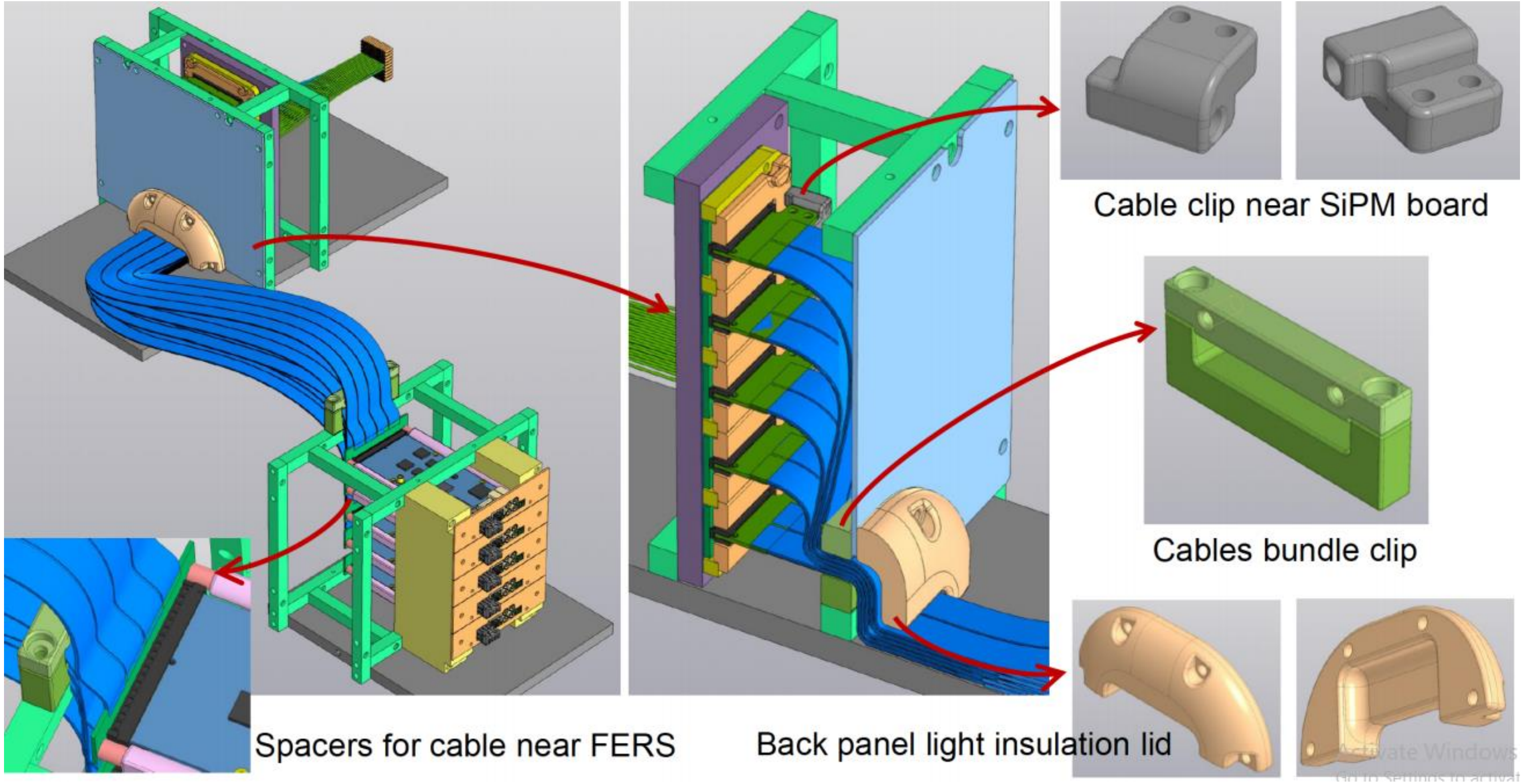
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 13-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (time resolution ≈ 200 ps)
- Optical link interface for readout (6.25 Gbit/s)

# R&D strategy for the Dual-Readout Calorimeter

## From idea to prototype for IDEA

### Readout box and patch-panel for SiPMs for EM prototype (10 x 10 x 100 cm$^3$)



## Status of the EM-size DR prototype (10 x 10 x 100 $cm^3$)

- The absorber of all the modules has been assembled
- All fibers have been inserted
- PMT have been tested and verified
- Frontend boards testing is on going at Pavia
- FERS system are ongoing testing and verification
- System commissioning expected by the end of January 2021

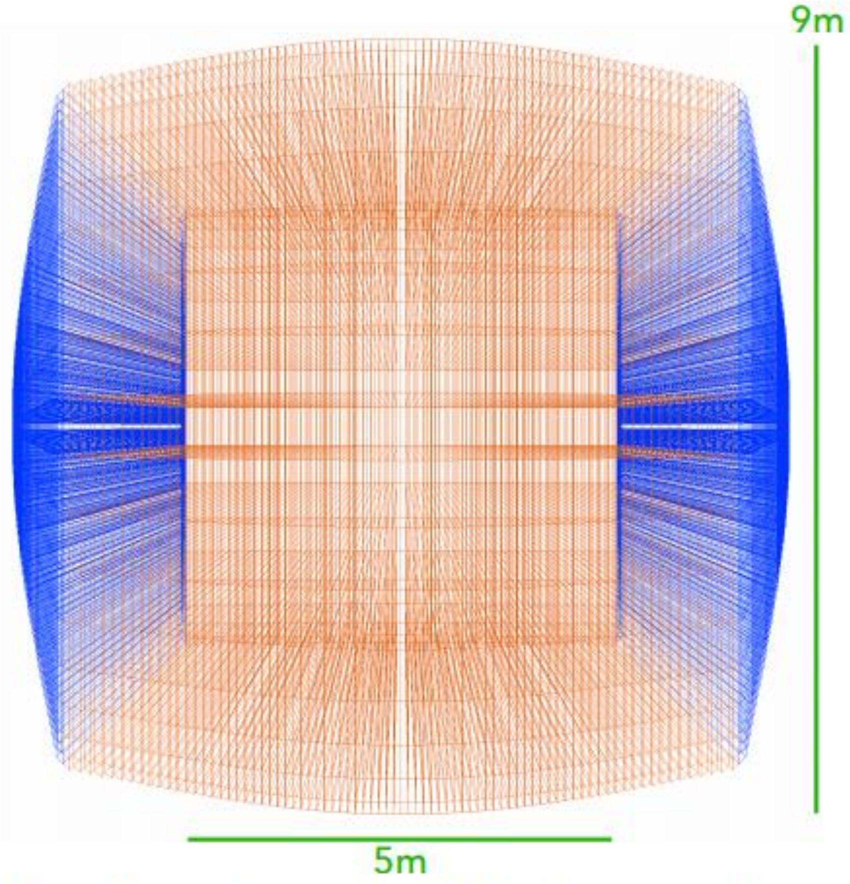
- Beam time at DESY is scheduled for the last two weeks of February 2021 – probably postponed until Summer due to travel restrictions

**Even if there are alternatives under study, the presented concept could be considered almost ready for large production**

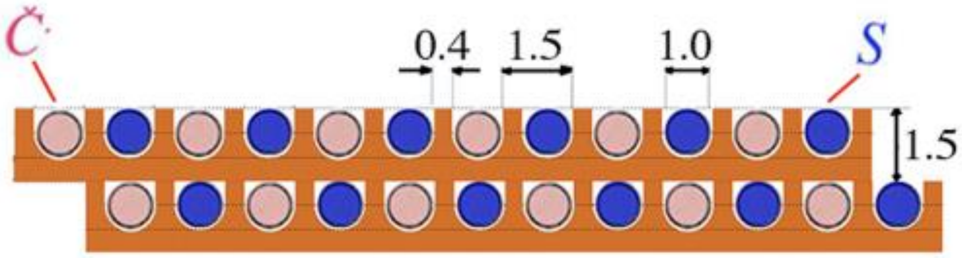
# Geant4 performance and analysis

## Design of the fully projective fiber calorimeter

Barrel: Inner length: 5m
Outer diameter: 9 m @ 90°
2 m long copper based towers
36 rotation around z axis




About $130 \times 10^6$ fibers considered.




Each fiber is coupled to a dedicated SiPM, to achieve:

- Excellent spatial resolution
- Excellent angular resolution
- Excellent shower shape sensitivity for PID.

If not stated otherwise, all results in the following are obtained with the Geant4 toolkit.

* Lorenzo Pezzotti talk at 4th FCC 2020
[GEANT4 performance and analysis]

# In a nutshell

**Features**

- Jet energy resolution of 3-4% for jets of 100 GeV, good particle ID capability ($\varepsilon(e) \sim 99\%$, ~0.2% $\pi^-$ mis-ID) and electromagnetic energy resolution of $\approx 11 - 13\% / \sqrt{E} \oplus 1\ \%$

… in a single calorimeter calibrated at the electromagnetic scale

- Excellent 2D spatial resolution by reading out each fiber with a dedicated SiPM.

**Concept:** Do not reach h/e=1 by construction, but measure the electromagnetic fraction in each event.

Cherenkov signal

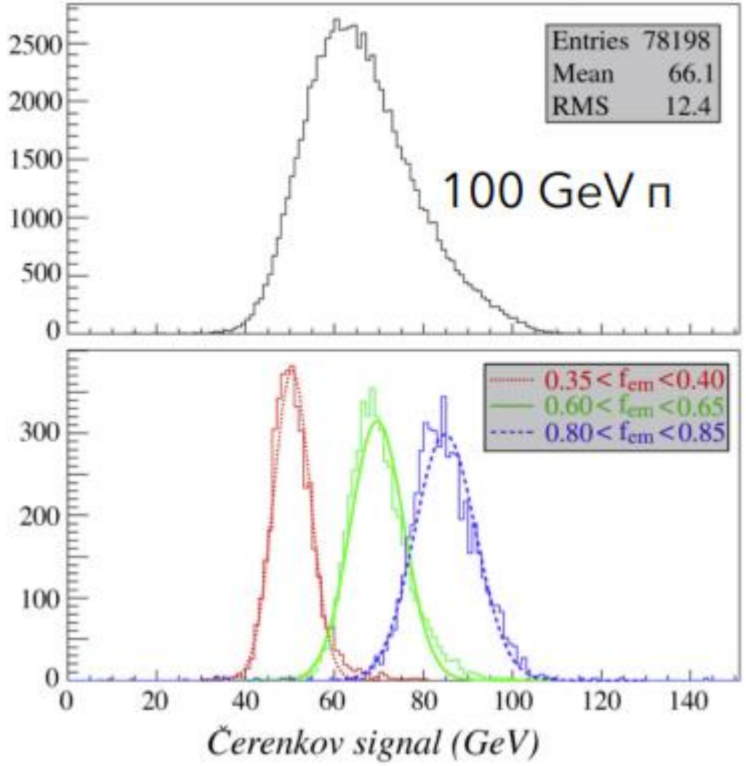
$$C = E\,[\,fem + \left(\frac{h}{e}\right)_c (1 - fem)\,]$$

Scintillation signal

$$S = E\,[\,fem + \left(\frac{h}{e}\right)_s (1 - fem)\,]$$

The best estimate of the energy lost is given by

$$E = \frac{S - \chi C}{1 - \chi} \qquad \chi = \frac{1 - (h/e)_s}{1 - (h/e)_c}$$




Data from RD52 Collaboration

* Lorenzo Pezzotti talk at 4th FCC 2020
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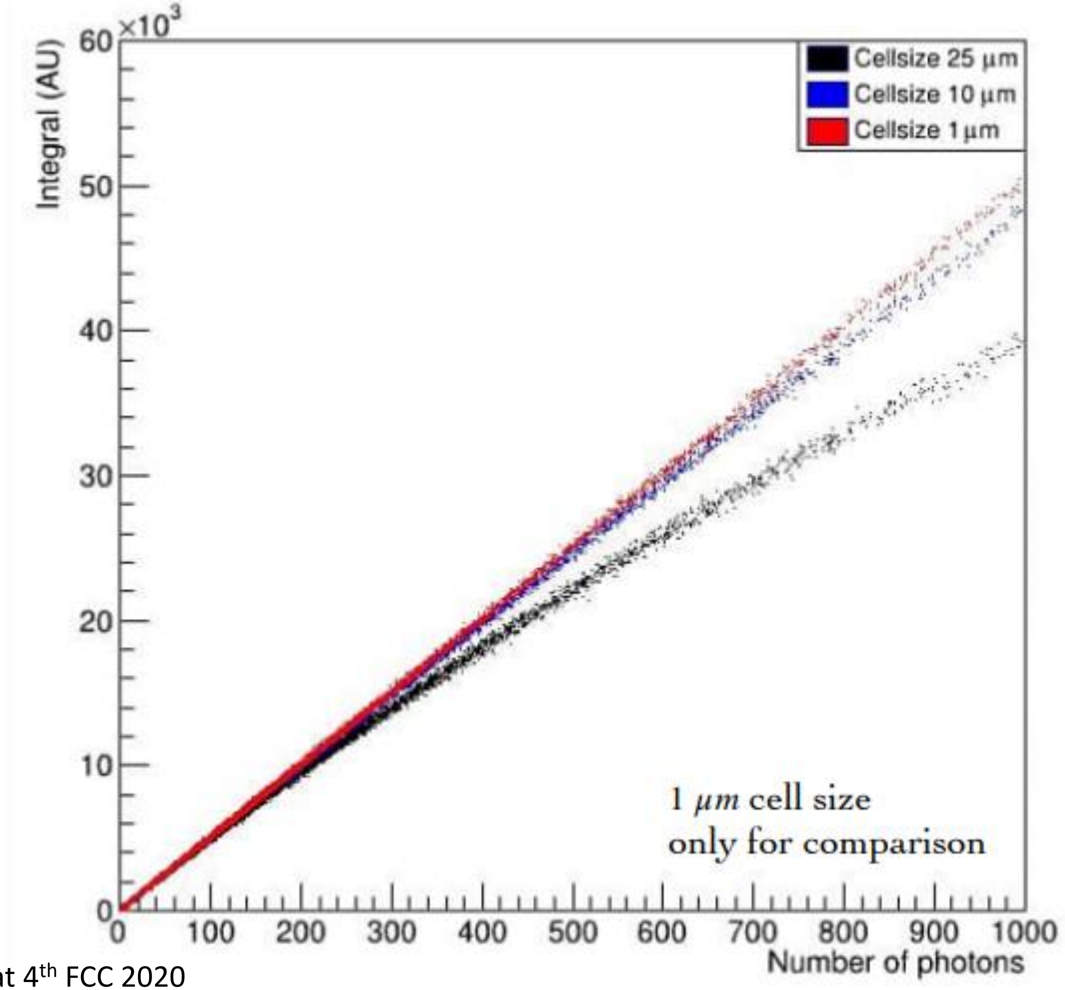
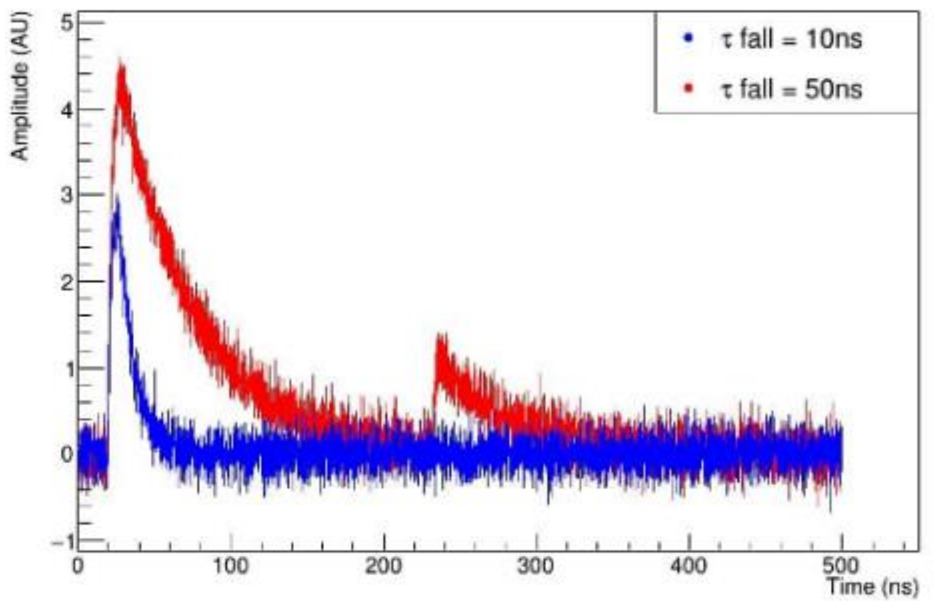
# SiPM sw digitization

A dedicated SiPM digitization code was developed. Optical photons are tracked with Geant4 till the light sensors. The digitization provides signal time of arrival, peaking time, time over threshold, charge integral, as well as the digitized waveform.




Negligible occupancy saturation effect is predicted for a cell size of 10 $\mu m$, considering $1 \times 1$ mm$^2$ SiPMs.

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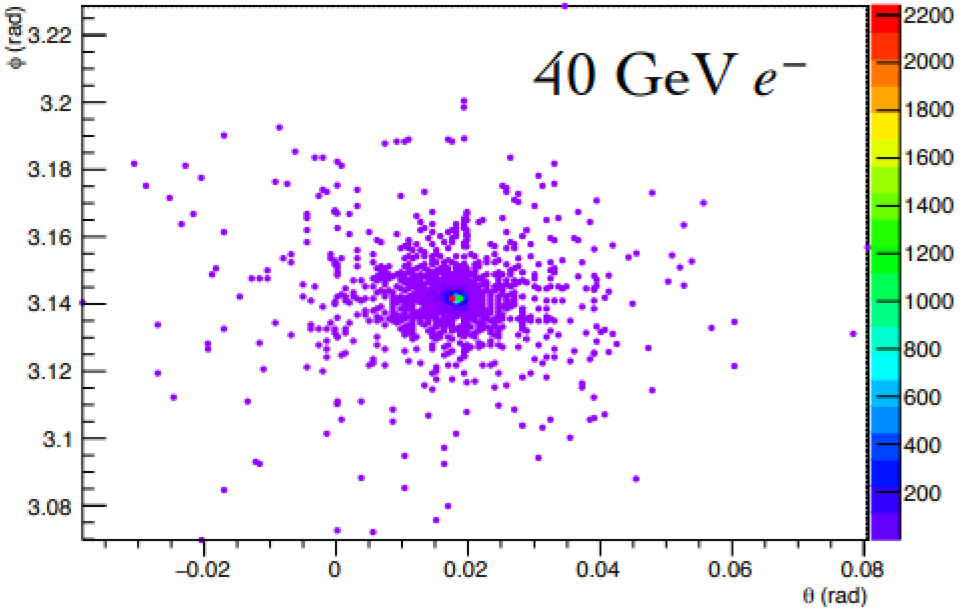
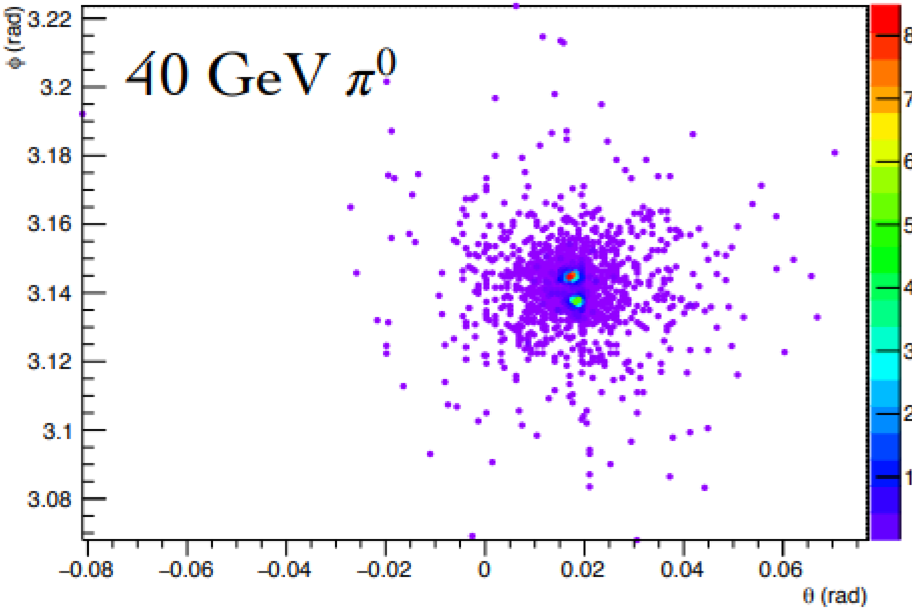
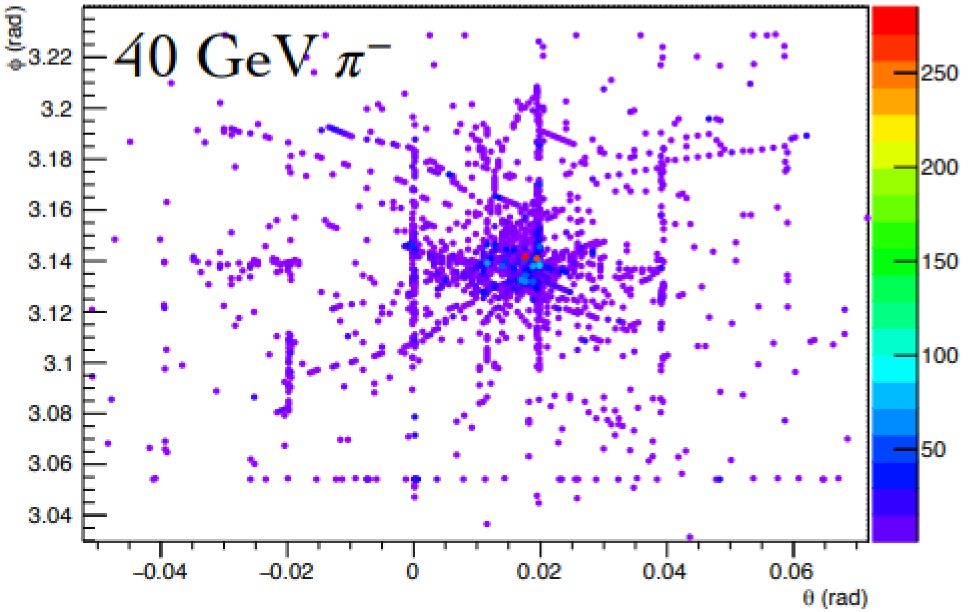
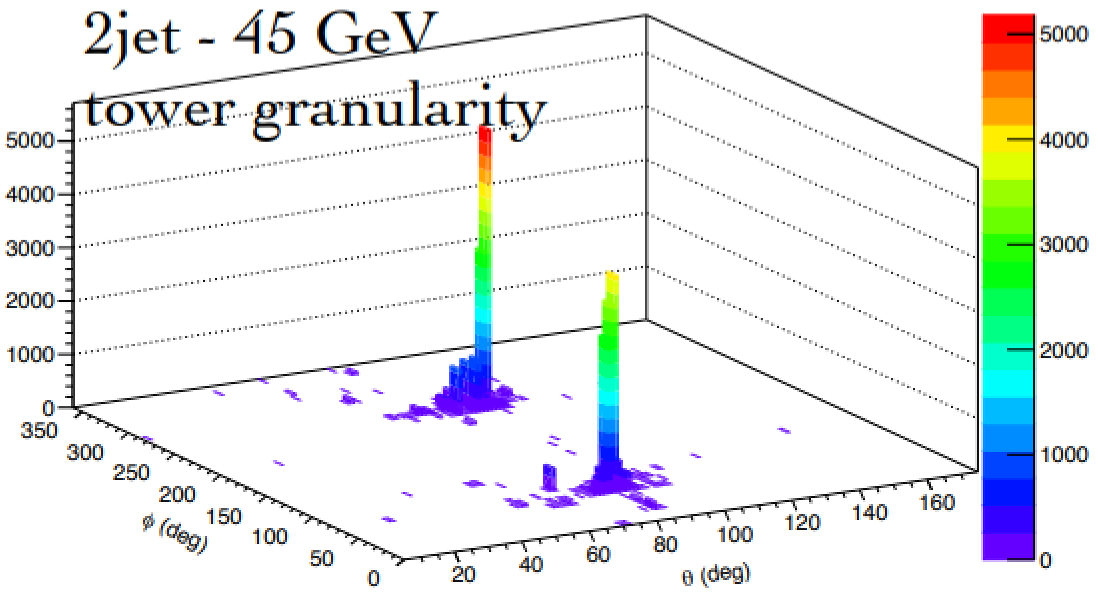
# Event displays (scintillating p.e.)

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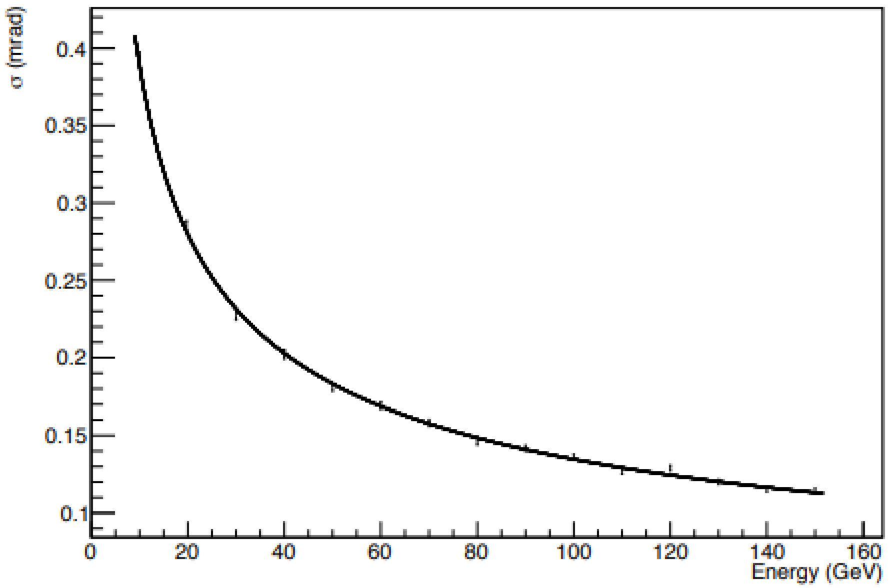
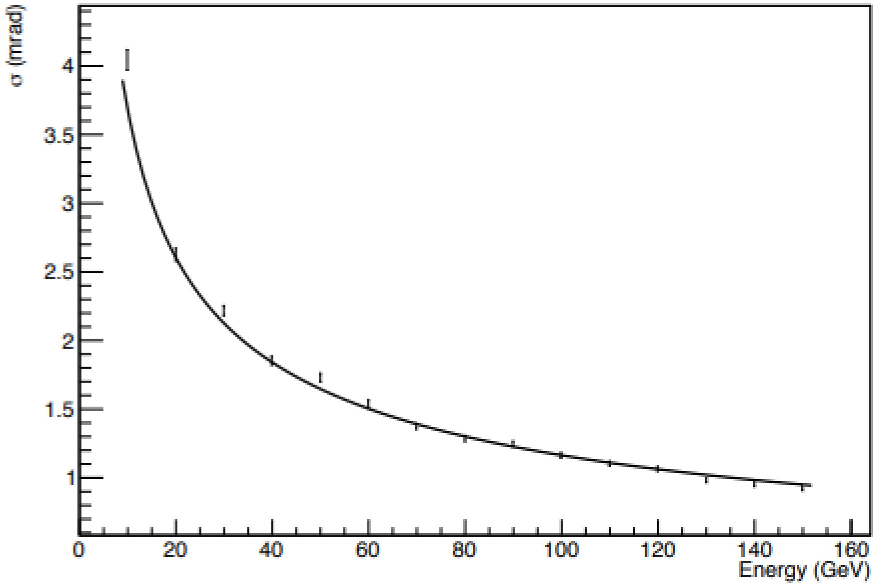
# Resolving angles

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.

* Lorenzo Pezzotti talk at 4th FCC 2020
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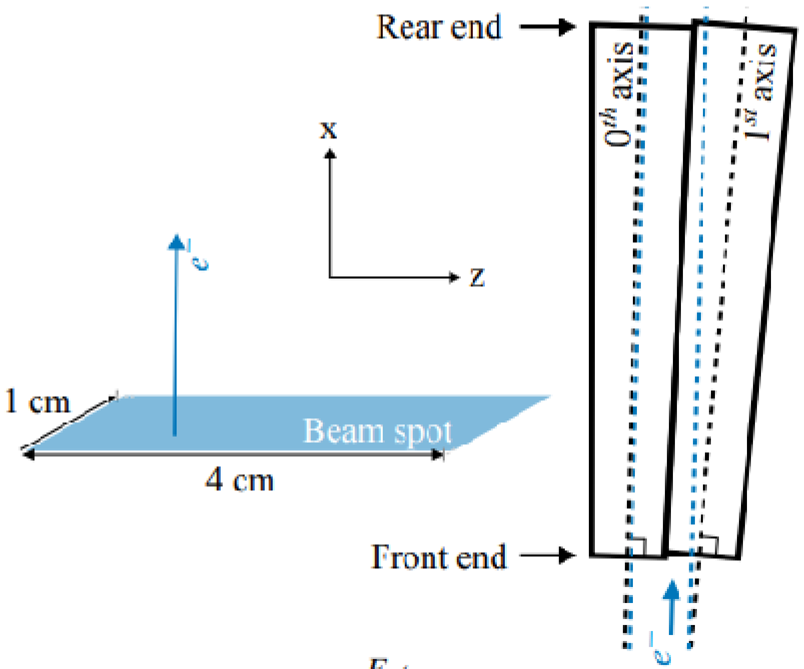
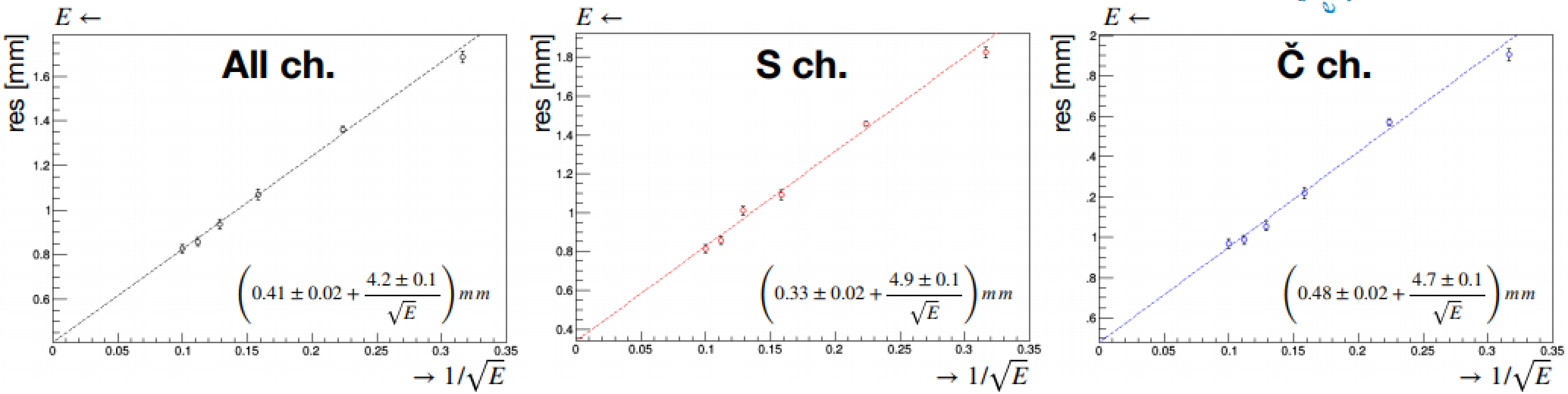
# Position resolution

- 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:
  - $4.2\ \text{mm}/\sqrt{E} + 0.4\ \text{mm}$




* Lorenzo Pezzotti talk at $4^{th}$ FCC 2020
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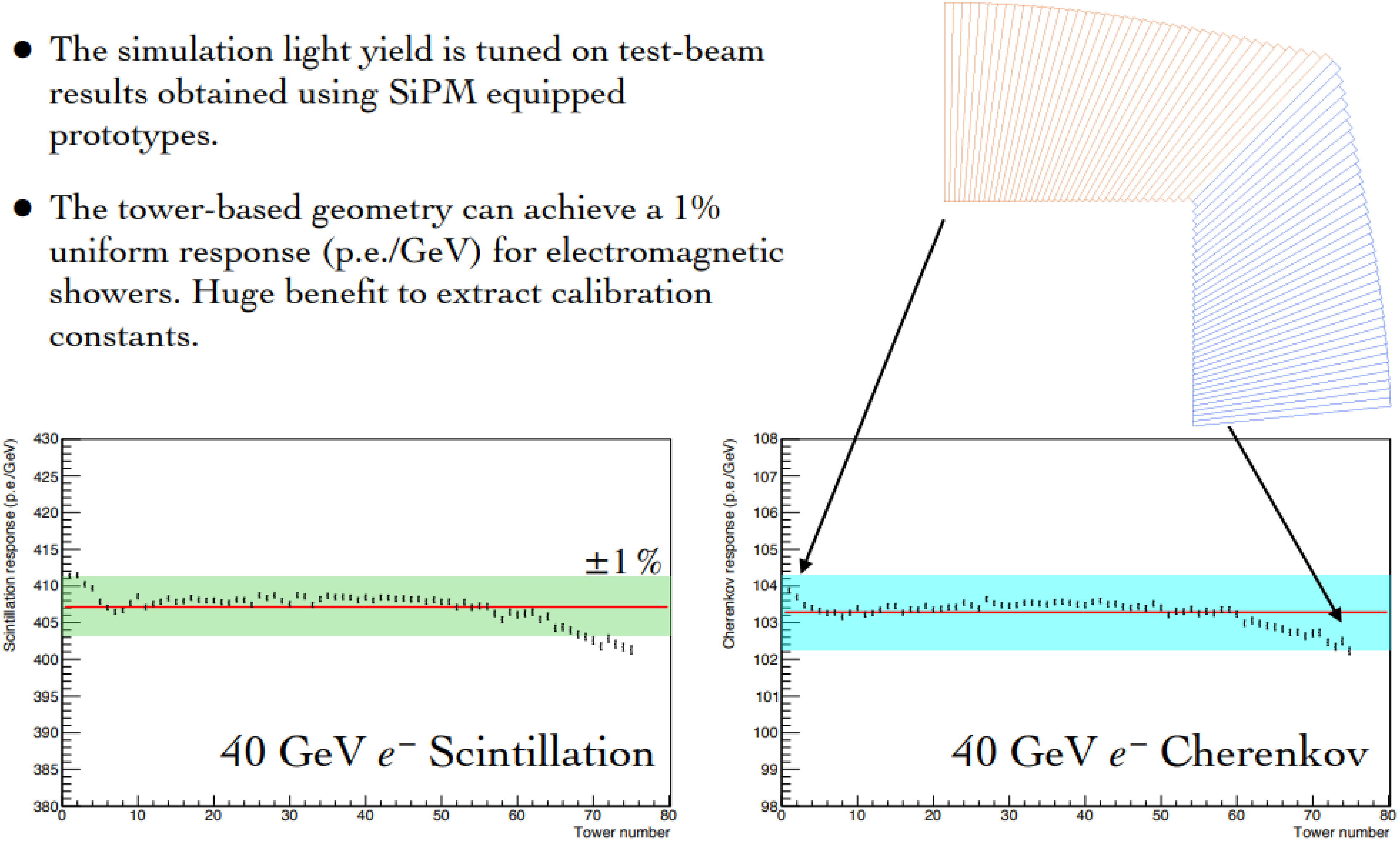
# Response uniformity

- 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.



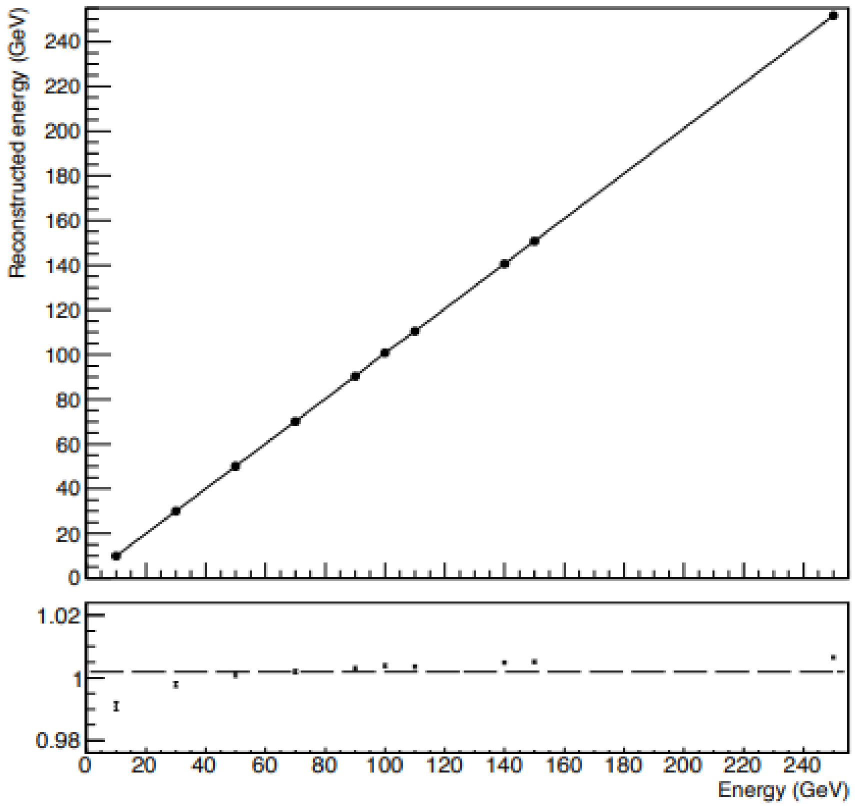


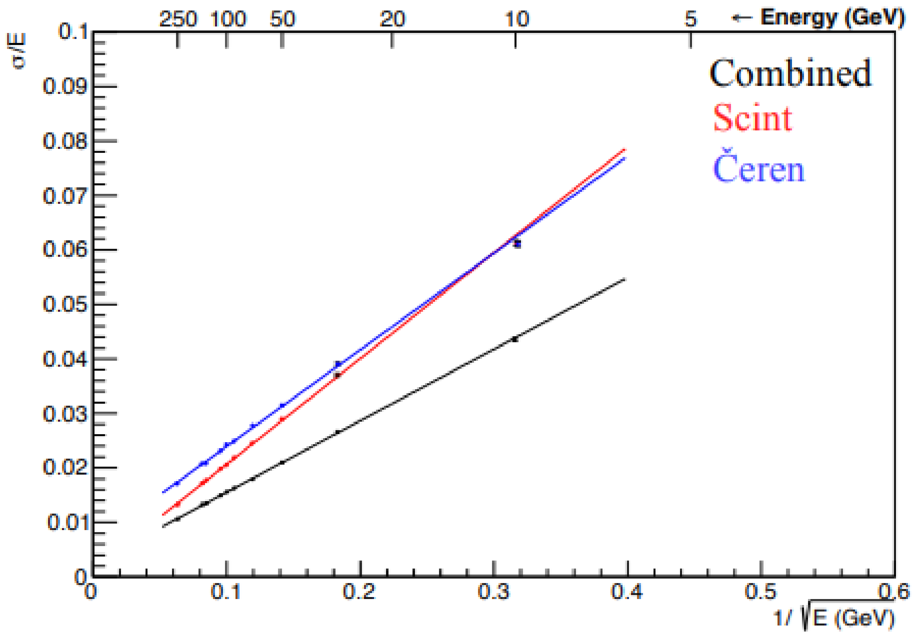

* Lorenzo Pezzotti talk at 4th FCC 2020 GEANT4 performance and analysis

# 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.

* Lorenzo Pezzotti talk at 4$^{th}$ FCC 2020
GEANT4 performance and analysis

# Electromagnetic performance

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

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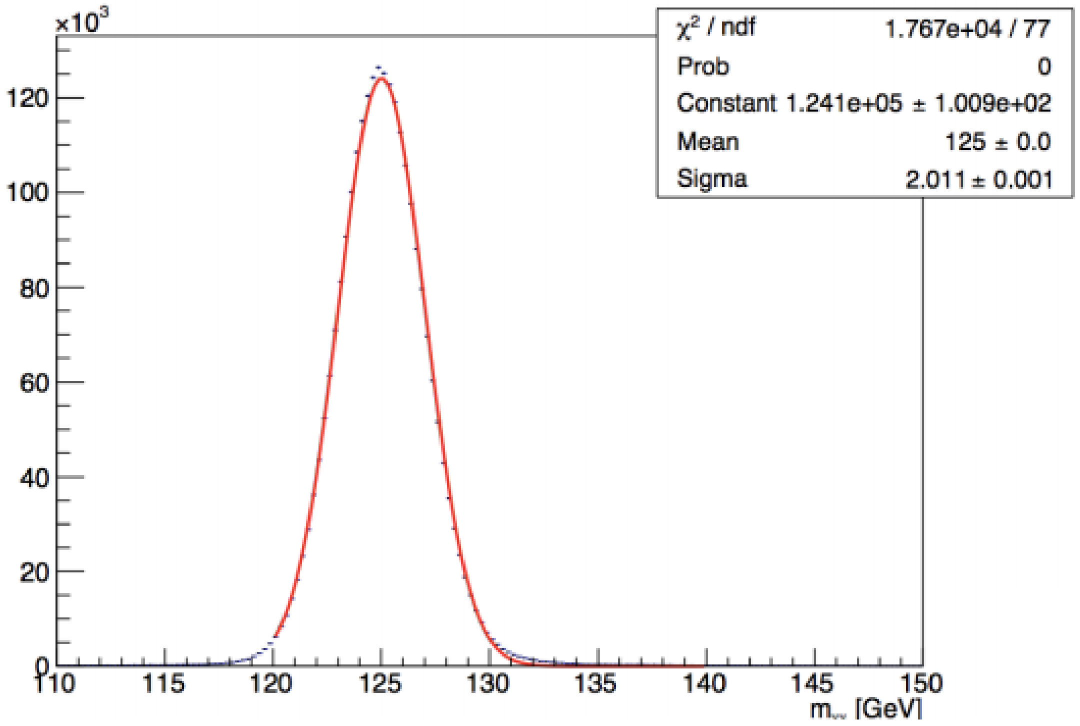
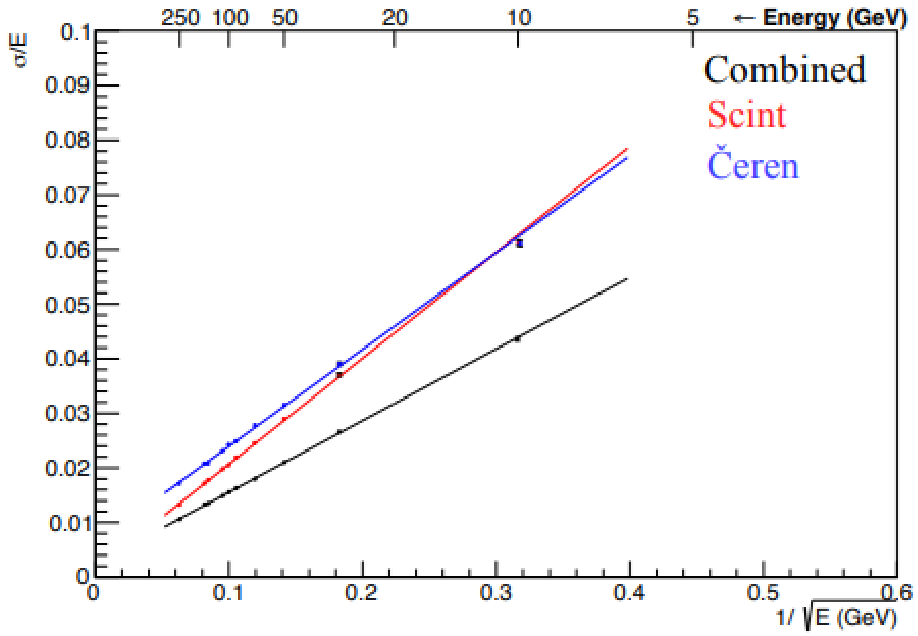
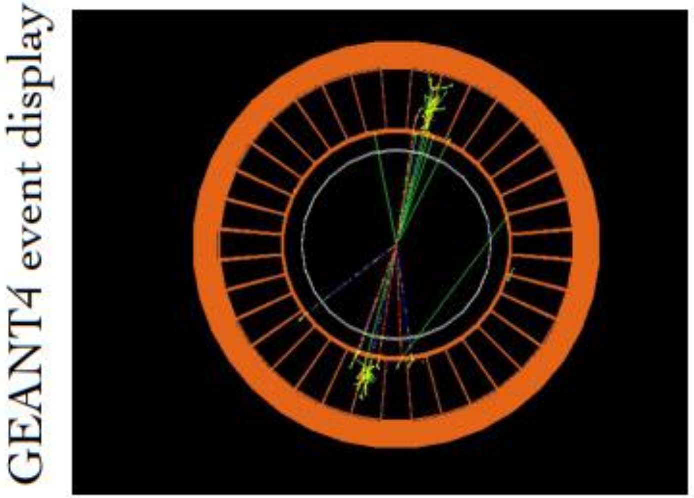


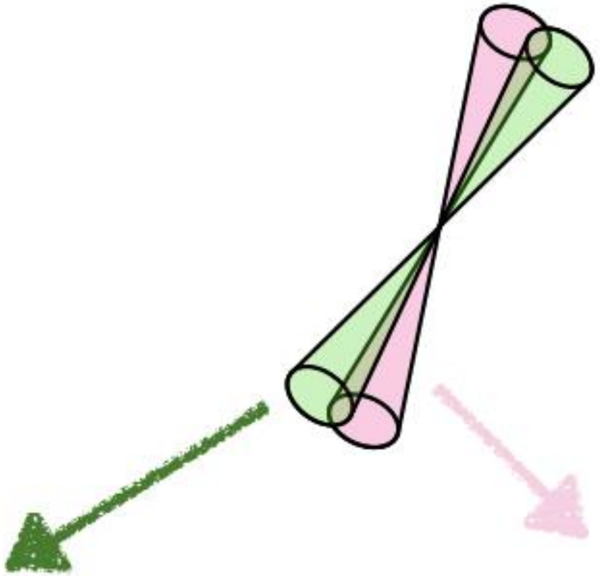




- $e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$:
  Higgs invariant mass reconstructed with a resolution of $\sigma = 2.011$ GeV out of the box.

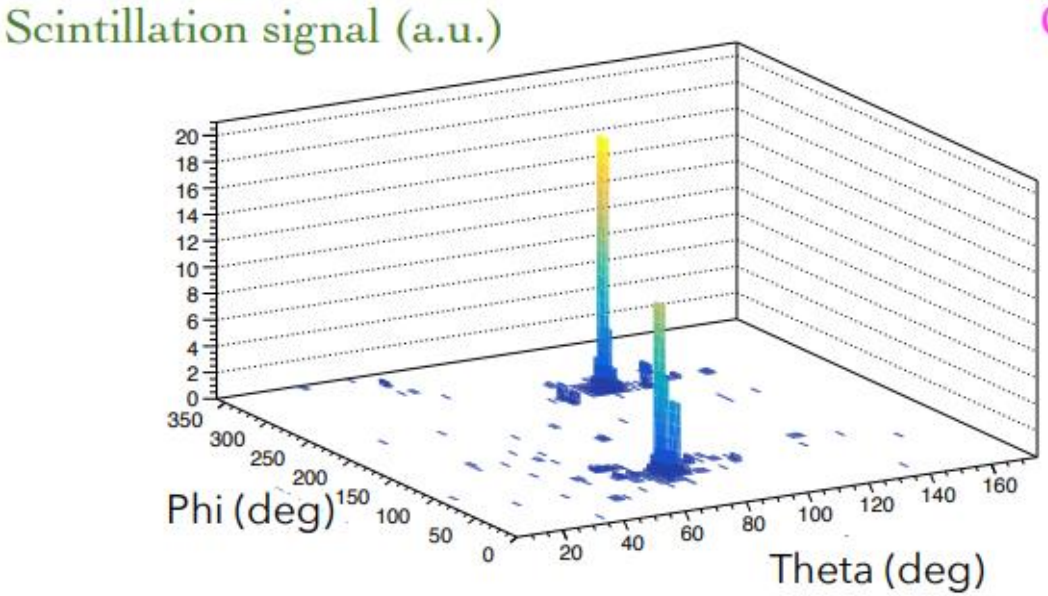
* Lorenzo Pezzotti talk at 4$^{th}$ FCC 2020 GEANT4 performance and analysis

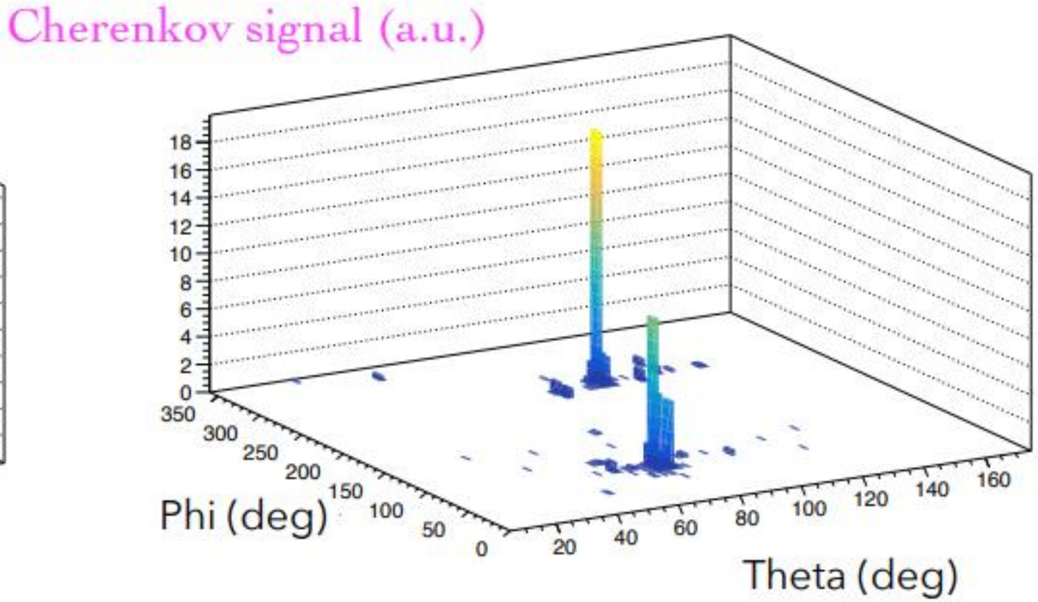
# $e^+e^- \rightarrow Z \rightarrow jj$ @90 GeV



We perform a clustering on the two signals simultaneously, using the (FASTJET) Durham kt algorithm. The scintillation and Cherenkov components of the two jets are later extracted.



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GEANT4 performance and analysis

# Two-jets performance

Two strategies are used to reconstruct jet energies out of the scintillation and Cherenkov components.

Calo only:

after the calibration at the em scale,

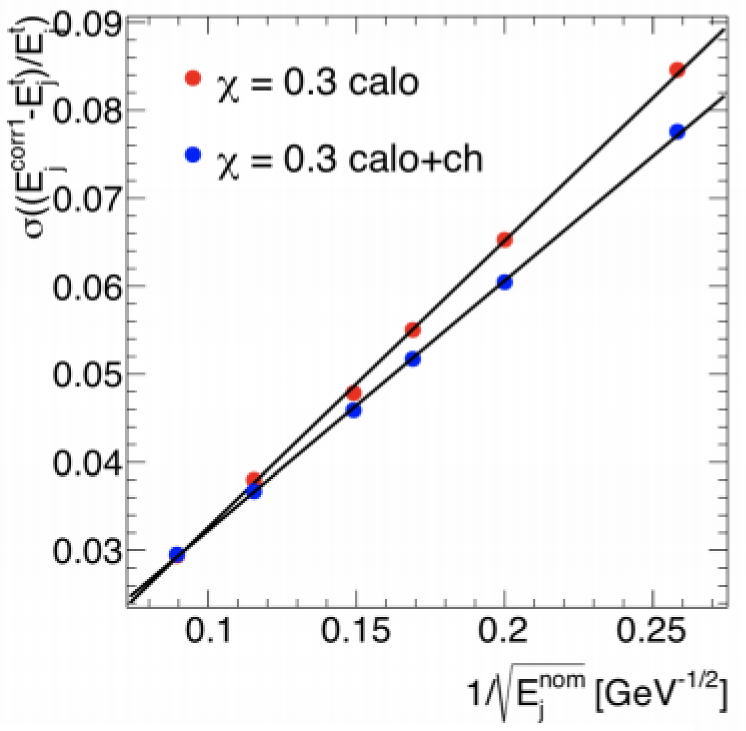
$$E_j^r = \frac{E_j^s - \chi E_j^C}{1-\chi}$$

Calo + charged:

after the calibration at the em scale,

$$E_j^{r*} = E_j^{ch} + E_j^s - \frac{E_j^s E_j^{ch}}{E_j^r},$$

i.e. sum the charged component and total energy and correct for double counting.




At present the best jet resolution found (for fully hadronic jets, i.e. no muons or neutrinos) is:

$$\frac{\sigma}{E} \simeq \frac{30\,\%}{\sqrt{E\ (\mathrm{GeV})}} + 0.5\,\%$$

* Lorenzo Pezzotti talk at 4th FCC 2020 GEANT4 performance and analysis

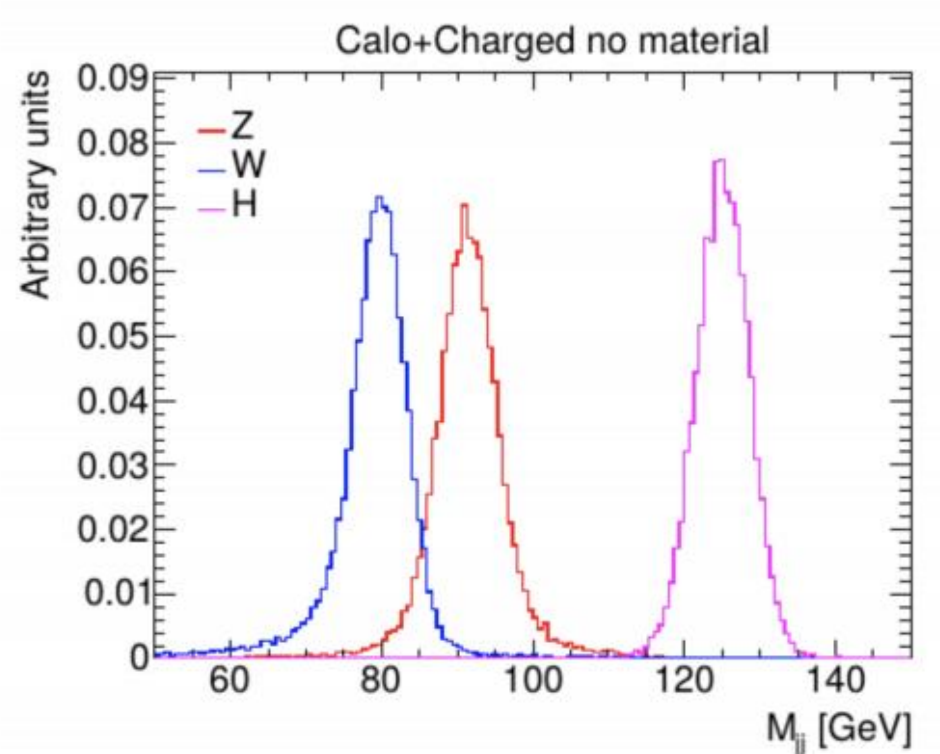
# Physics benchmarks - 2 jet final states

$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 jj$ → Decays to u,d,s,c, c semileptonic decays excluded

$e^+e^- \to WW \to \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal, c semileptonic decays excluded

$e^+e^- \to HZ \to bb\nu\nu$ → b semi-leptonic decays excluded

No budget material. →






* Lorenzo Pezzotti talk at 4th FCC 2020 GEANT4 performance and analysis

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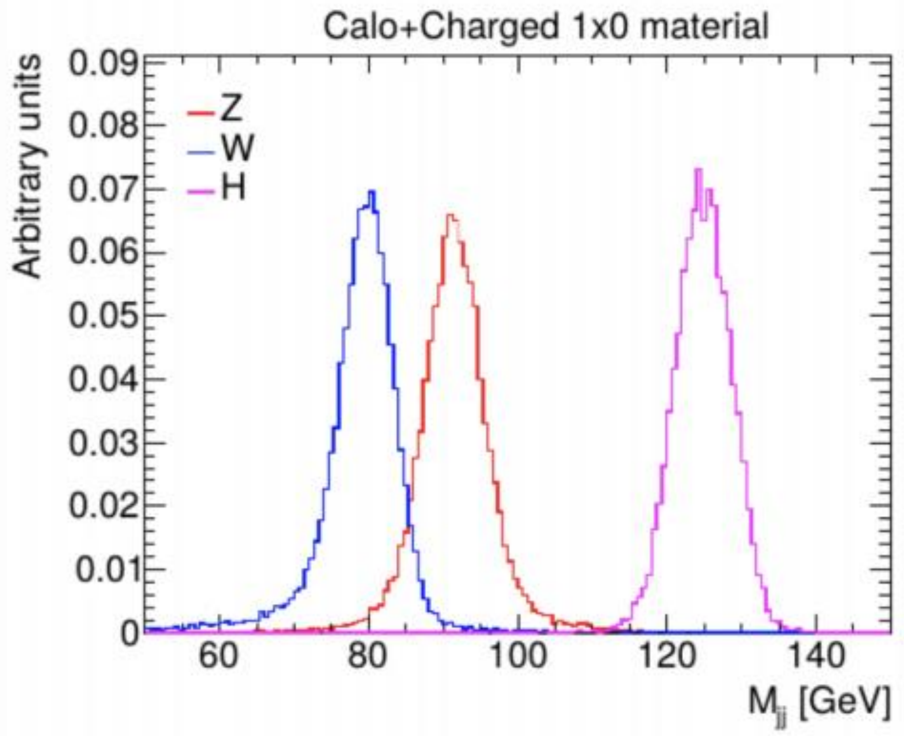
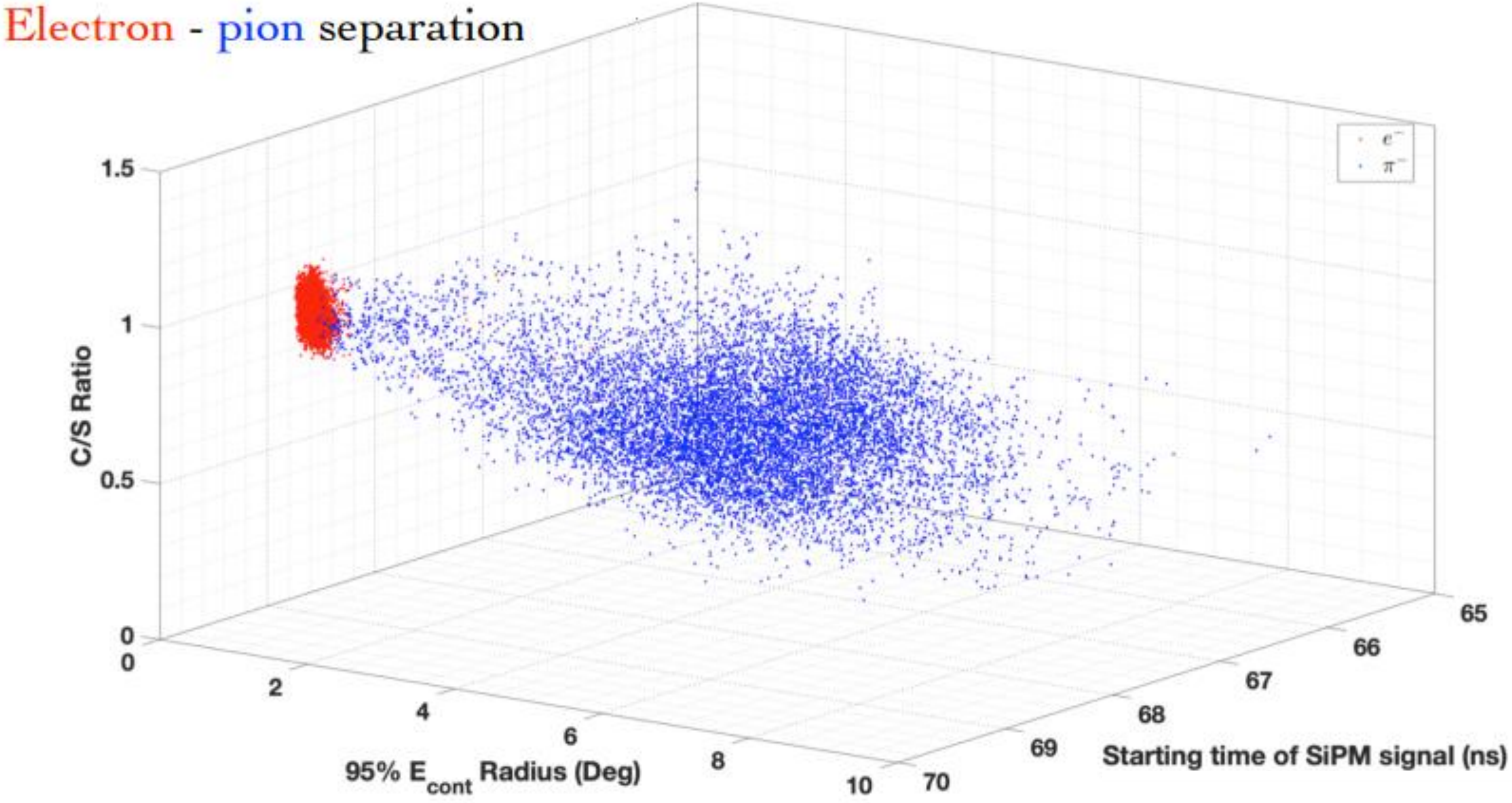
$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$ → b semi-leptonic decays excluded

1 $X_0$ budget material mimicking the solenoid upstream of the calorimeter. →




* Lorenzo Pezzotti talk at 4th FCC 2020 GEANT4 performance and analysis

# Particle identification




| | $e^-$ ID (%) | $\pi^-$ mis-ID (%) |
|---|---|---|
| IDEA (Pb) - 20 GeV: | 97.3 | 0.6 |
| IDEA (Cu) - 20 GeV: | 97.2 | 1.3 |
| IDEA (Pb) - 60 GeV: | 97.5 | 0.2 |
| IDEA (Cu) - 60 GeV: | 97.1 | 1.0 |

***** Lorenzo Pezzotti talk at 4th FCC 2020
GEANT4 performance and analysis

# Additional on going SW activities

## From idea to prototype for IDEA

- ML- based applications for Jet identification. See Tao Liu's talk at the 4th FCC - Learning physics at future $e^-e^+$ colliders with machine
- ML- based applications for Fastsim with GAN.
- Development of IDEA Delphes3 fast simulation. See Lorenzo Pezzotti's at the 4th FCC - GEANT4 performance and analysis
- From 2 jets to 4 jets event reconstruction.
- Development of a reliable digitization tool for the SiPM transfer function simulation (potentially useful for every FCC(ee or hh) detector).
- Development of deep learning algorithms for particle identification and tau-lepton identification. See Stefano Giagu's talk at the 4th FCC - Tau-identification in the Dual readout calorimeter
- Migration to new HEP-SW tools. See Sang Hyun Ko's talk at the 4th FCC - FCCSW integration

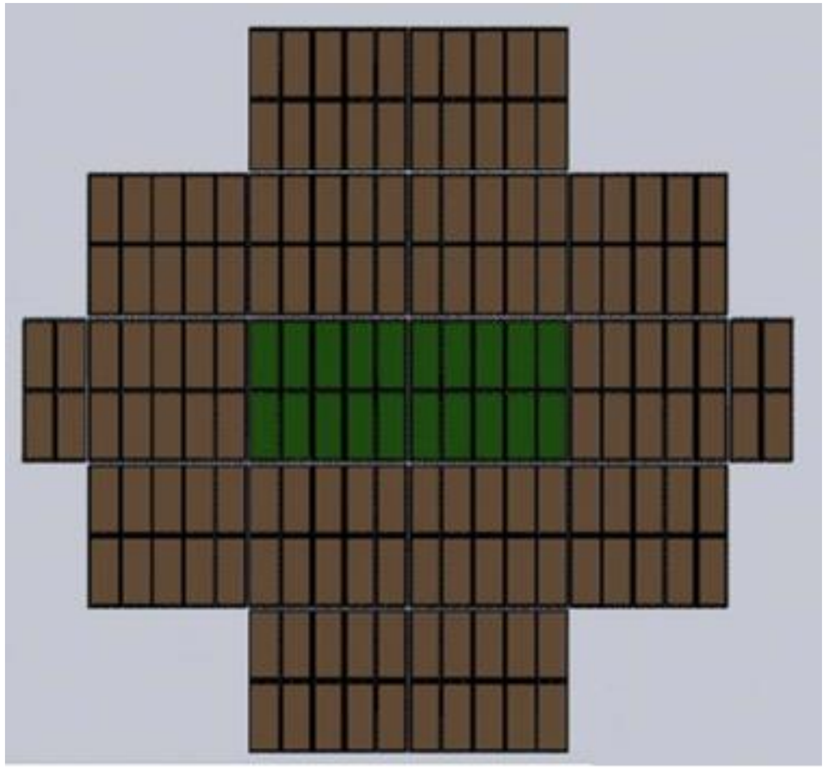
# What is ahead of us?

## From EM- to hadronic-size DR prototype

(10 x 10 x 100 $cm^3$) → (65 x 65 x 200 $cm^3$)

- ❑ New scalable design
- ❑ New readout scheme

- Alternative and scalable solution for the DR mechanical structure
- Alternative approach for the readout scheme
- Calibration of the DR calorimeter

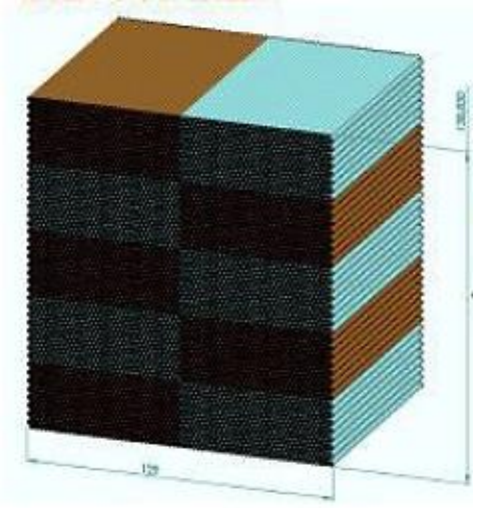


* One possible design

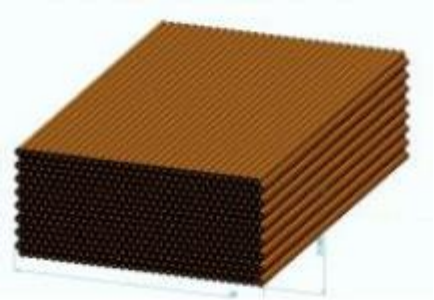
## Hadronic tower prototype (65 x 65 x 200 cm$^3$)

- 17 modules in total
- 2 central modules read out with SiPMs
- 15 modules read out with PMTs

Single module constructed from 10 mini-modules
~ 13 x 30 x 200 cm$^3$

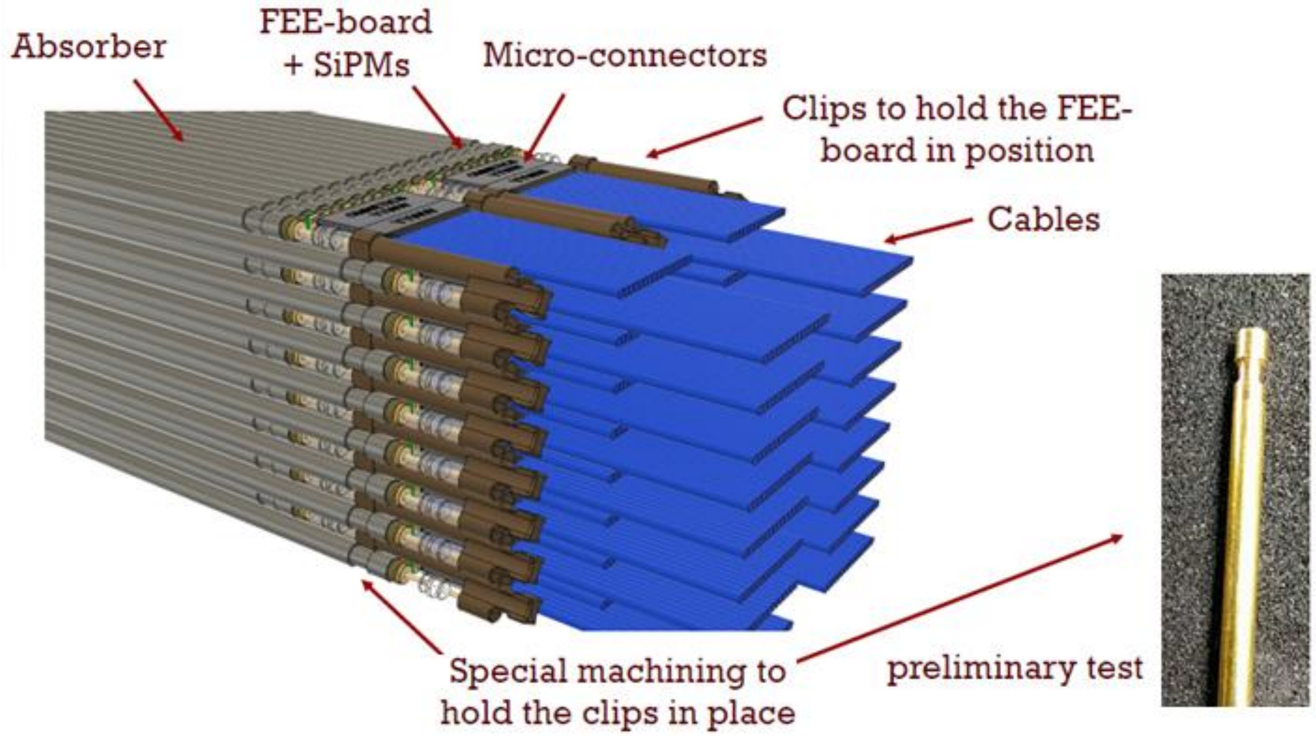


Mini-module constructed from
32 x 16 capillaries

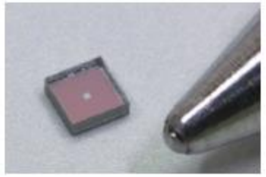


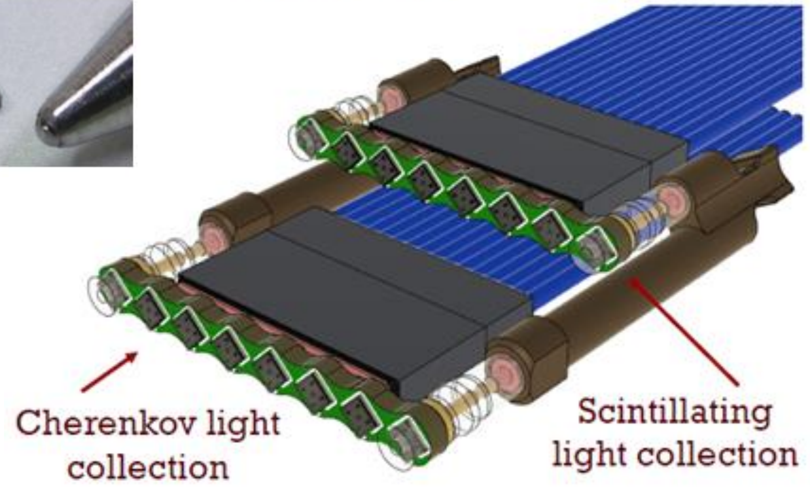
## Option based on capillaries

For the new design we are investigating scalable options which could allow to build large and projective modules.




Pair of FEE-boards joint togheter with the clips






The SiPMs will be directly connected to the fibers and fixed to the absorber. This option will allow to group signals from 8 SiPMs to reduce the number of channels to be read out.

# R&D Activities for Dual-Readout Calorimeter (2021-2025)

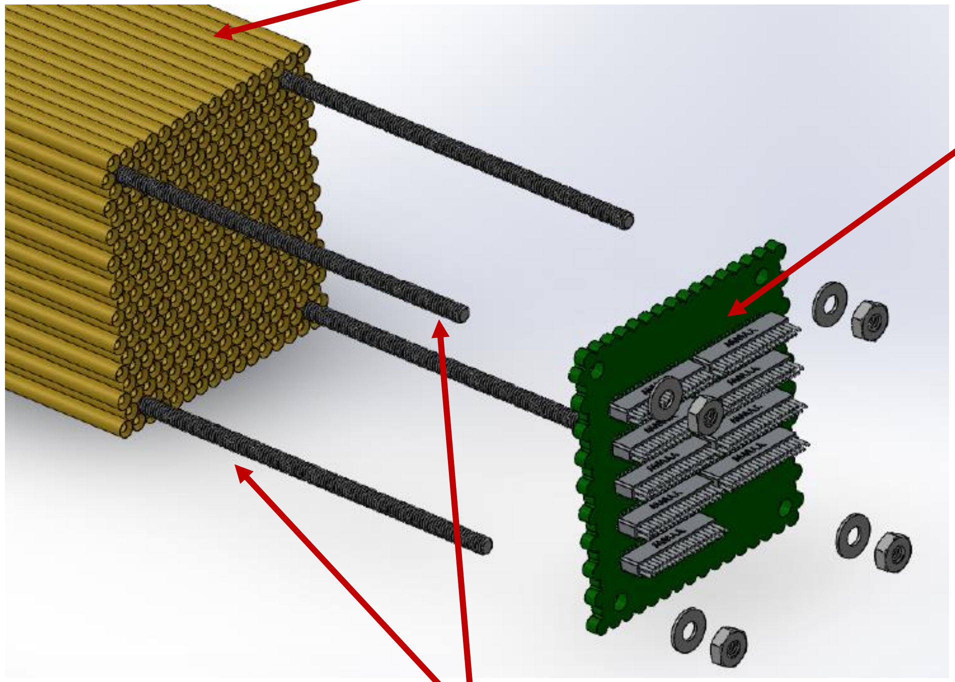

## Mockup with PCB and capillaries

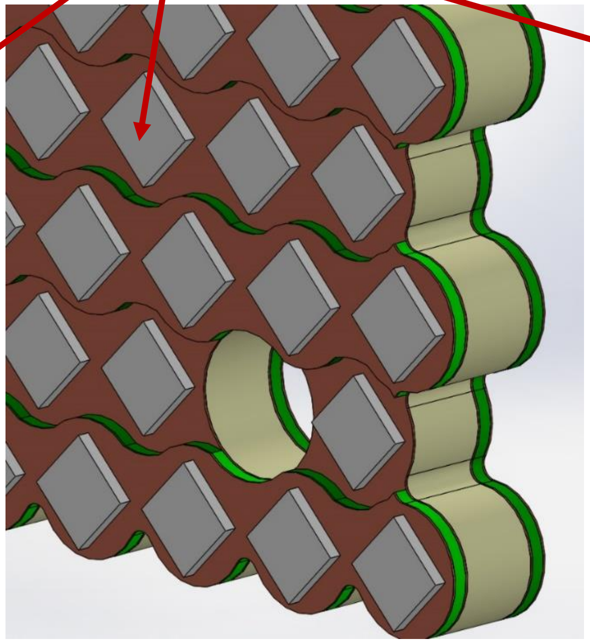
# R&D Activities for Dual-Readout Calorimeter (2021-2025)

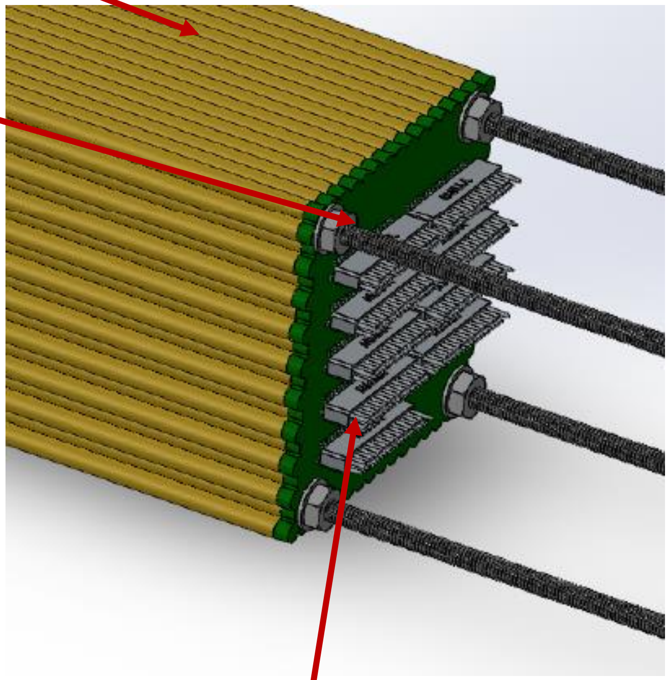
## One step further

Absorber

2 levels FEE board with SiPMs



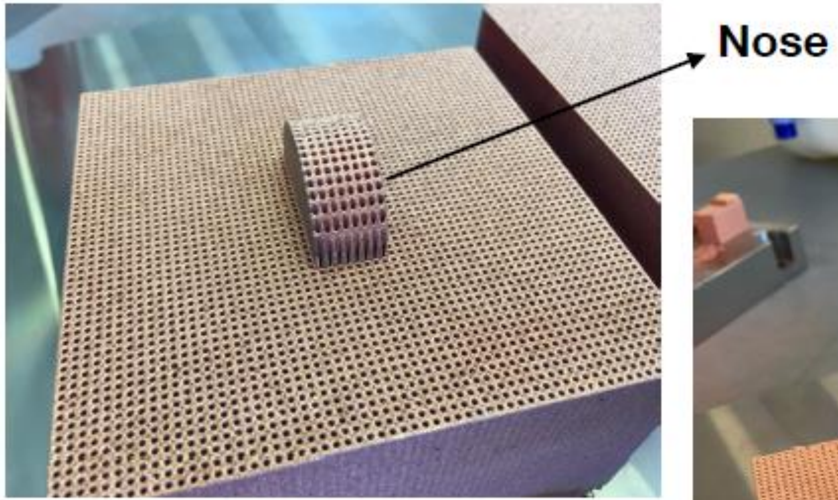


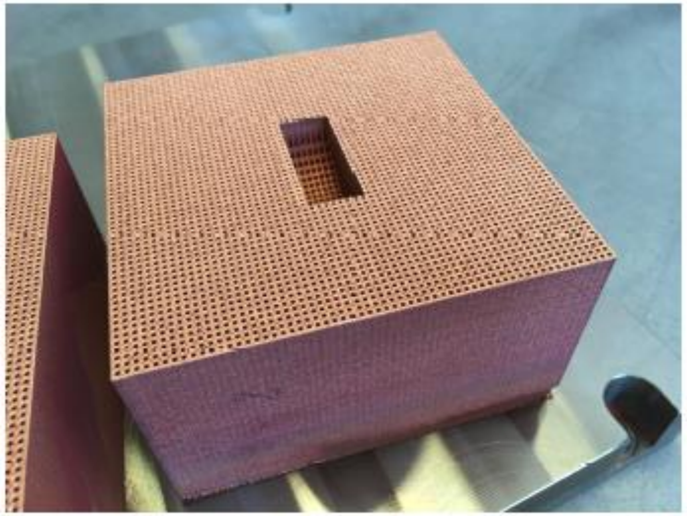


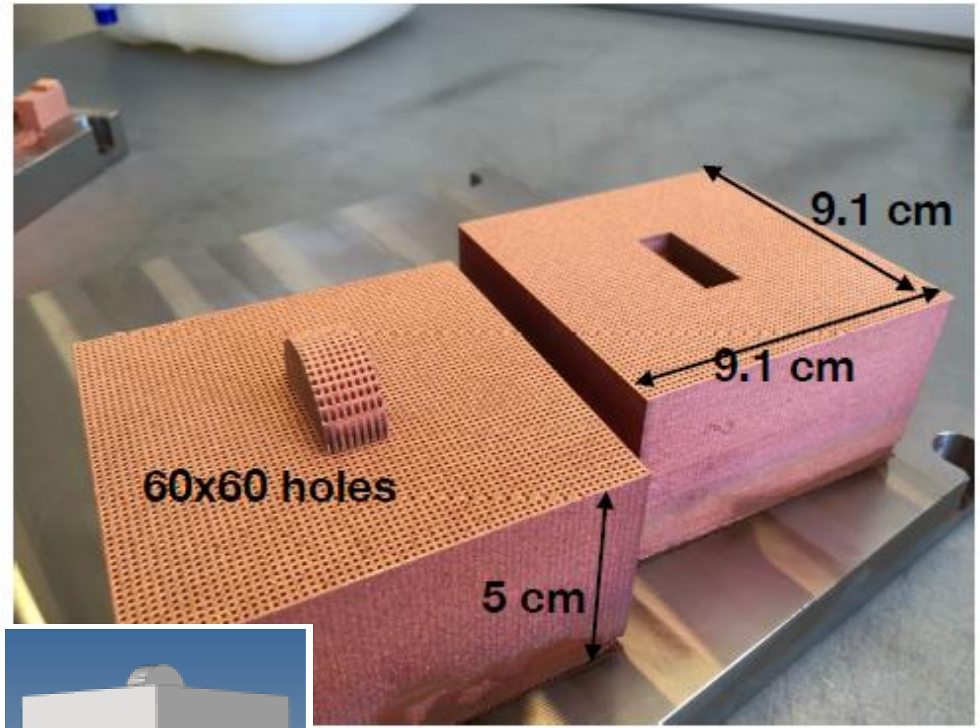
Rods for FEE board mounting and joining together adjacent towers

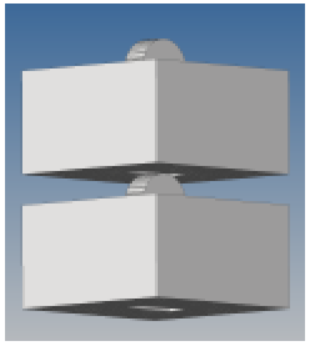
Micro-connectors

# Alternative solution for the DR mechanical structure



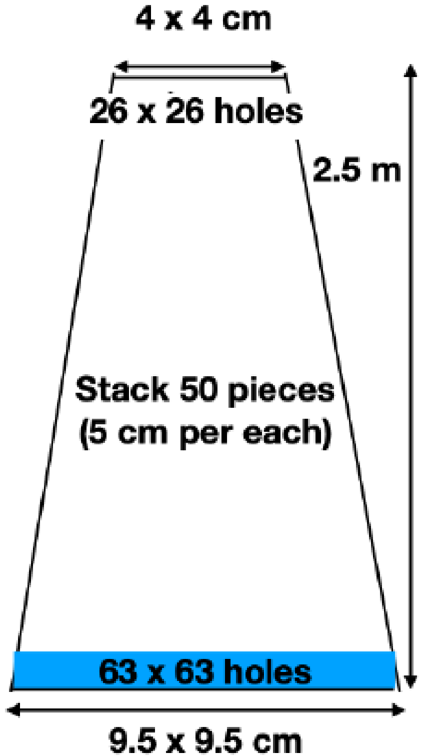





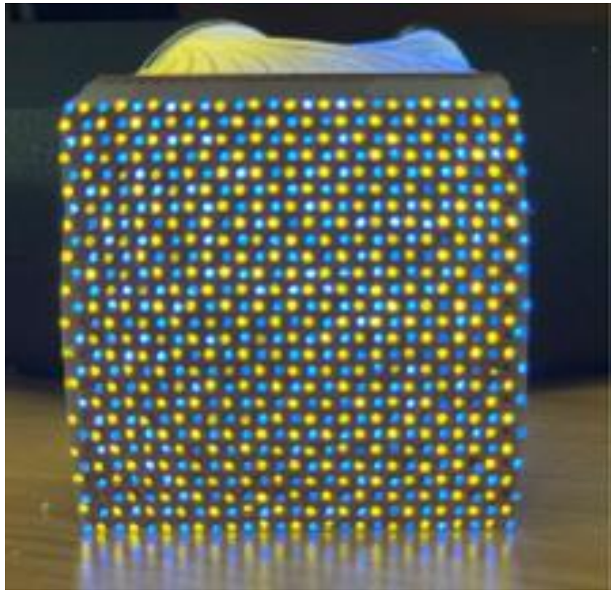
## 3D printing techniques are under study

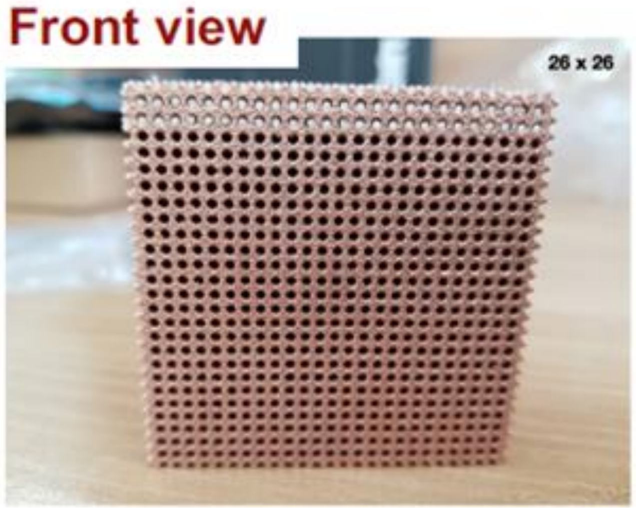
- Cu density: from 95 to 99.5%
- 1.3 mm diameter for a hole for fibers
- 0.7 mm pitch between two holes
- 60 x 60 holes with precise alignment in 9.2 x 9.2 cm (height 5 cm)

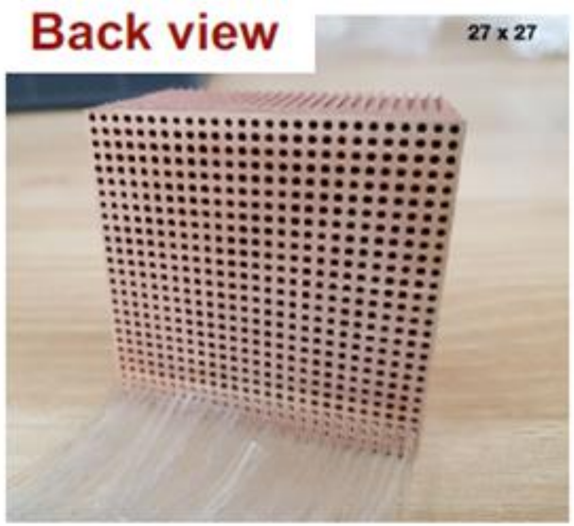


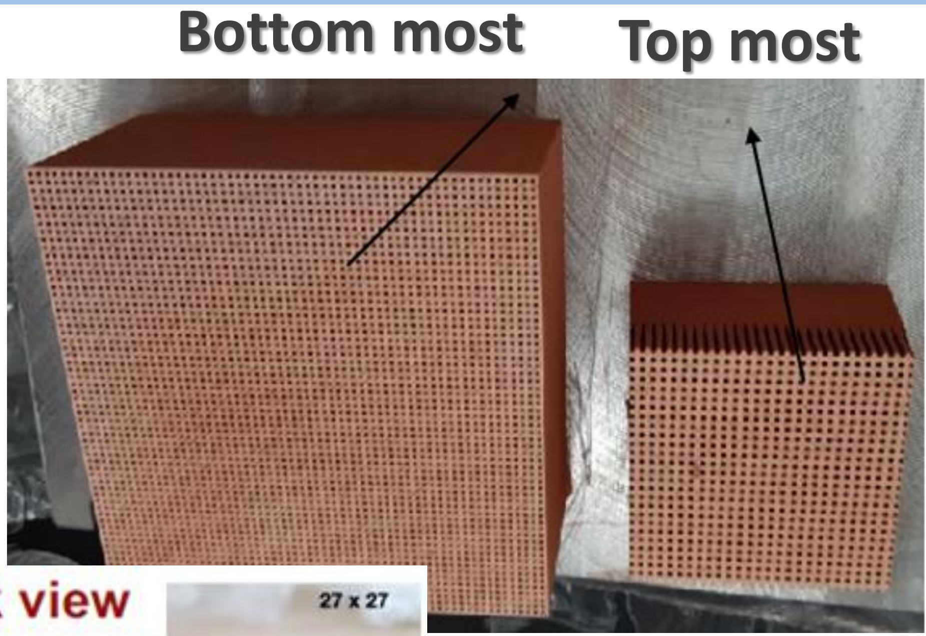
# Alternative solution for the DR mechanical structure

**Alternatives based on 3D printing techniques are under study**





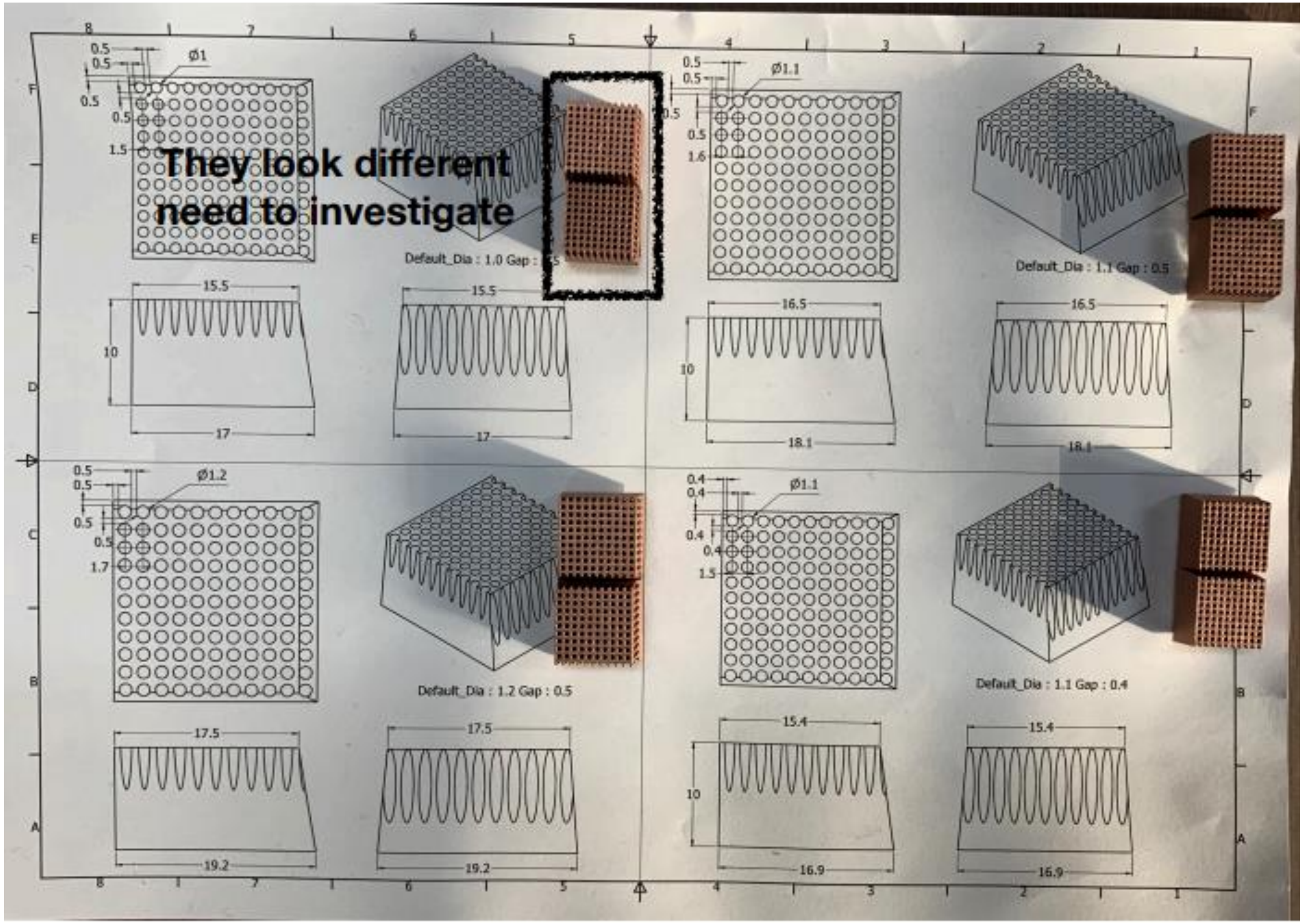
# Alternative solution for the DR mechanical structure

- 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 |

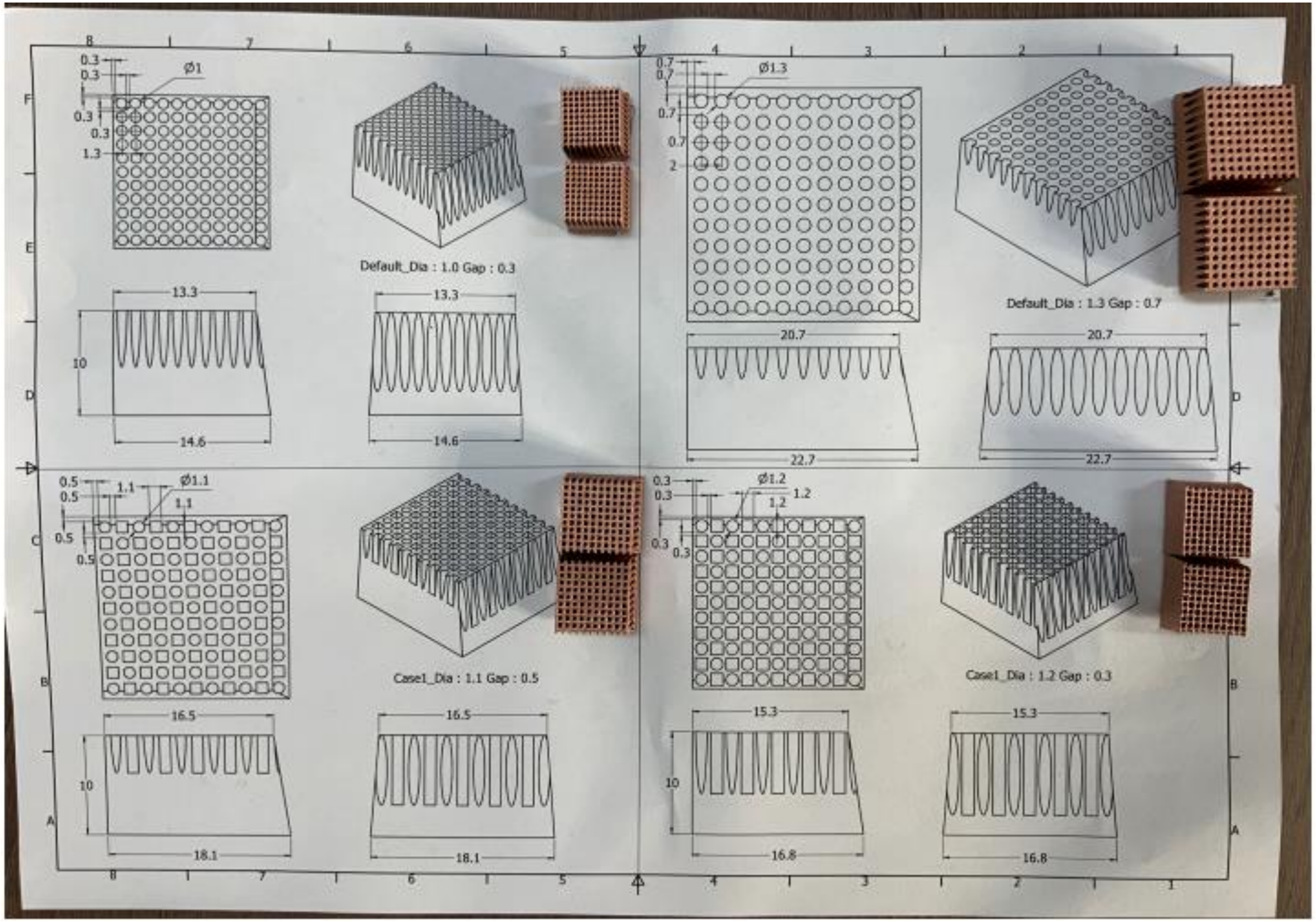
# Alternative solution for the DR mechanical structure

Sample 1 – 4



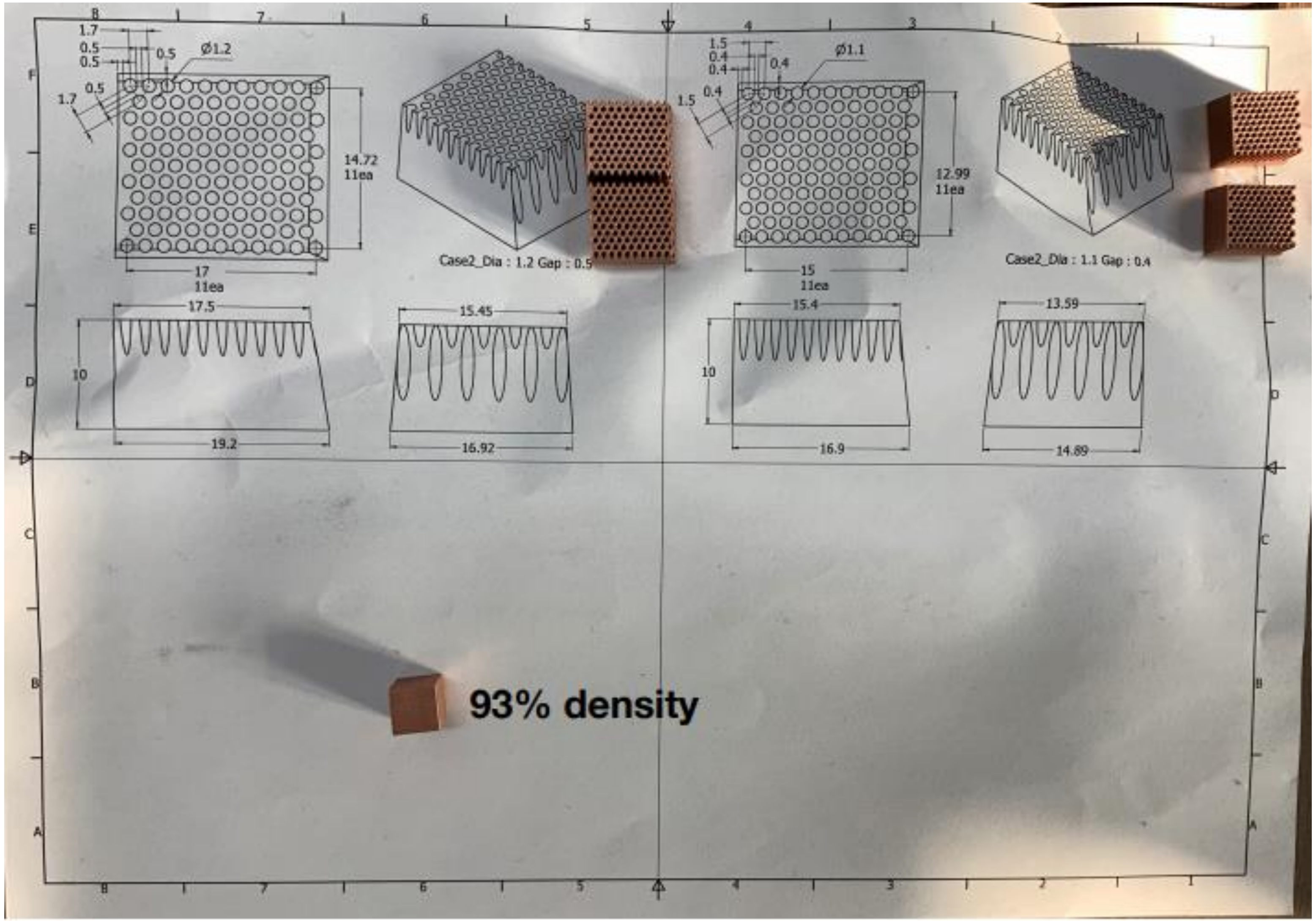
# Alternative solution for the DR mechanical structure

Sample 5 – 8



# Alternative solution for the DR mechanical structure

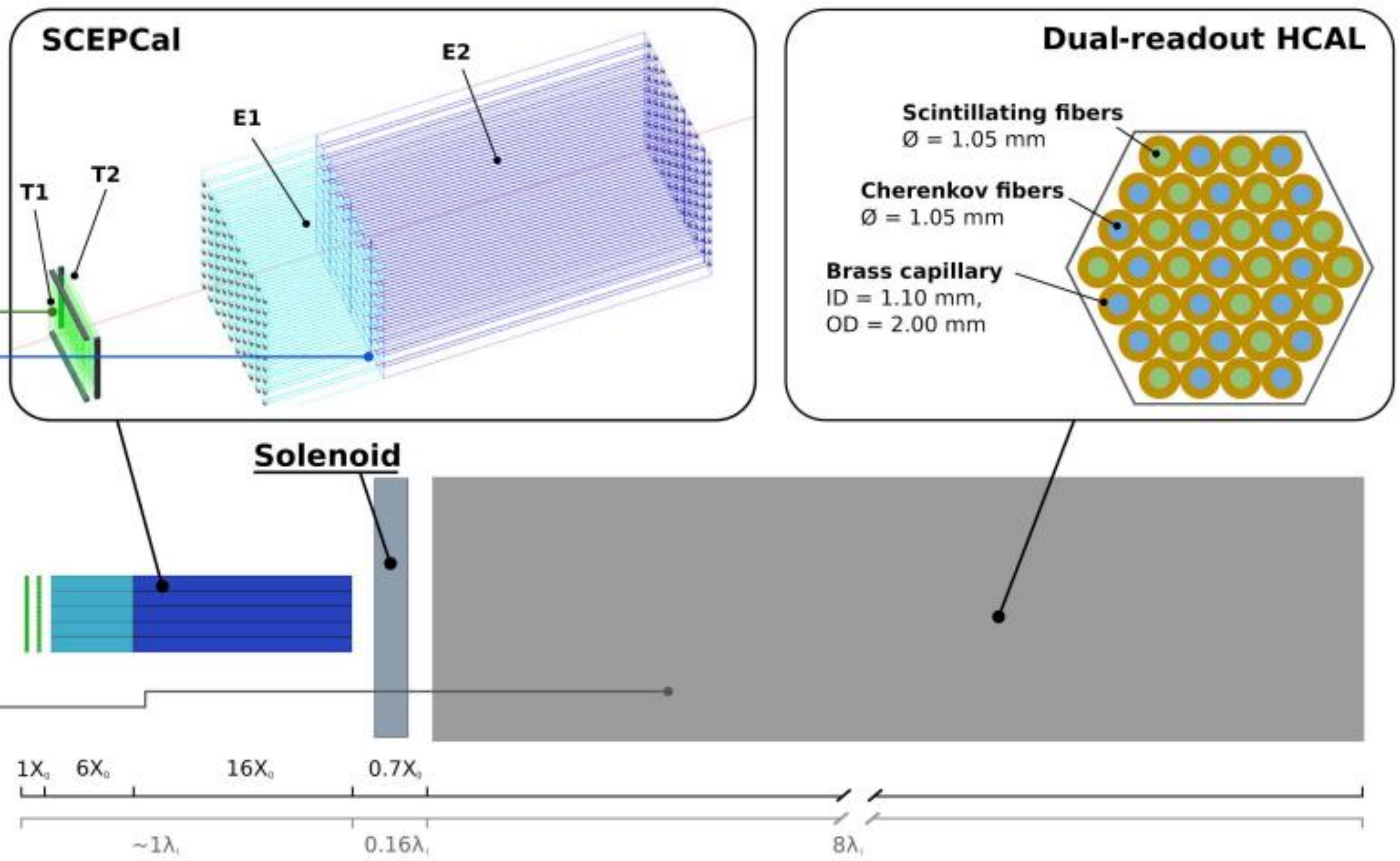
Sample 9 – 10



# Segmented Crystal EM option

- **SCEPCAL**: a **S**egmented **C**rystal **E**lectromagnetic **P**recision **Cal**orimeter
- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

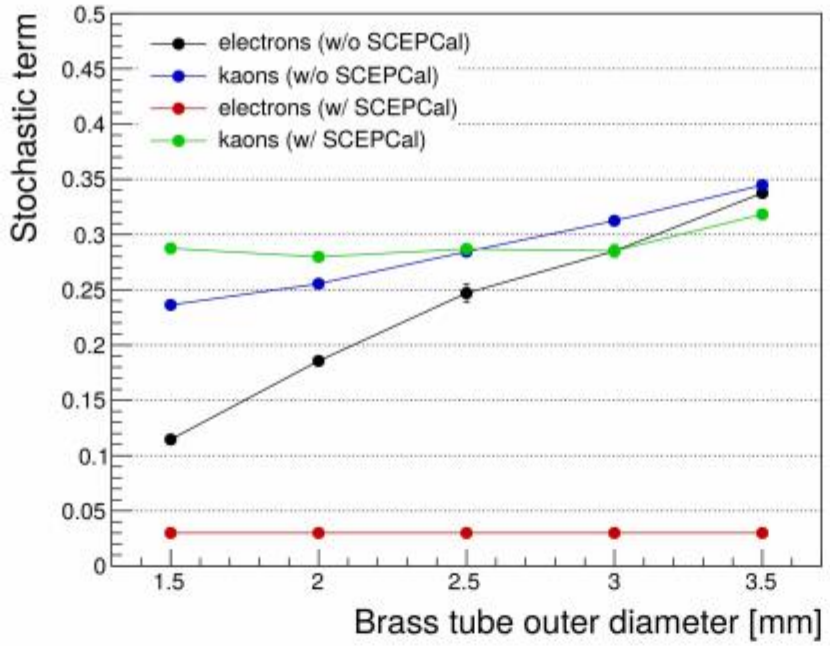
- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (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 A.Karadzhinova-Ferrer slides)

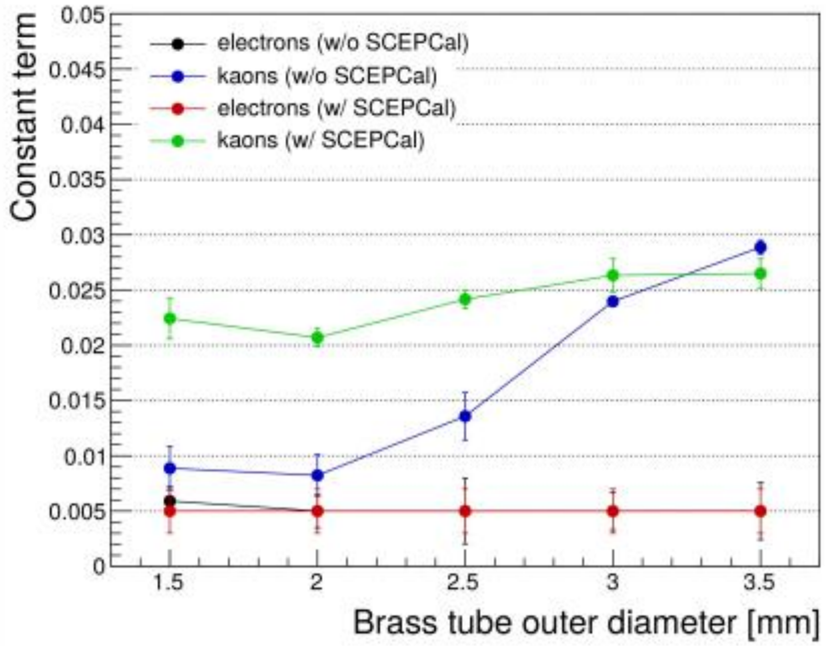



* Marco Toliman Lucchini talk at 4th FCC 2020
Dual-readout calorimetry with segmented crystals

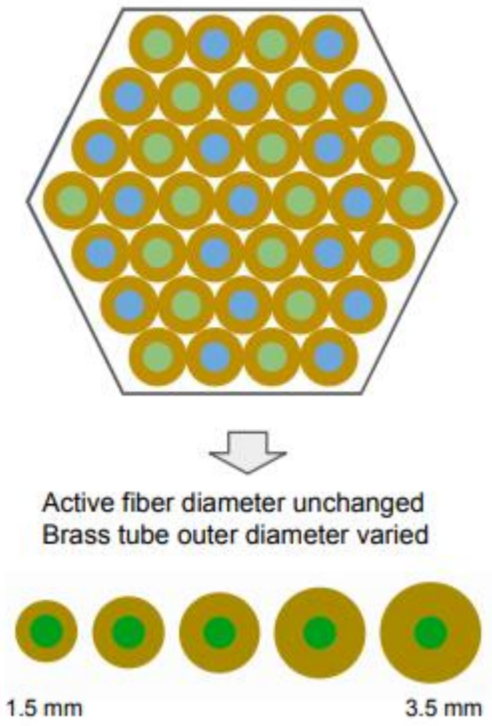
# Cost/performance optimization of HCAL segment

- Brass tube outer diameter (OD) can be increased to 3/3.5 mm with marginal impact on the hadron resolution
- Relative channel reduction and cost decrease approximately with ~1/OD$^2$




**Brass capillaries**
"Nominal" dimension
OD=2 mm, ID=1.1 mm




* Marco Toliman Lucchini talk at 4th FCC 2020
[Dual-readout calorimetry with segmented crystals]

# Summary

- The preparation of the proof of concept test beam at DESY in 2021
- The design of a scalable tower-like module is progressing well: different options have been identified and discussed
- The mid-term goal is to build a demonstrator with hadronic containment, partially equipped with SiPMs, to evaluate the hadronic performance
- Calibration of the DR calorimeter

We host a bi-weekly meeting on dual-readout calorimetry related topics, subscribe to the CERN e-group idea-dualreadout@cern.ch

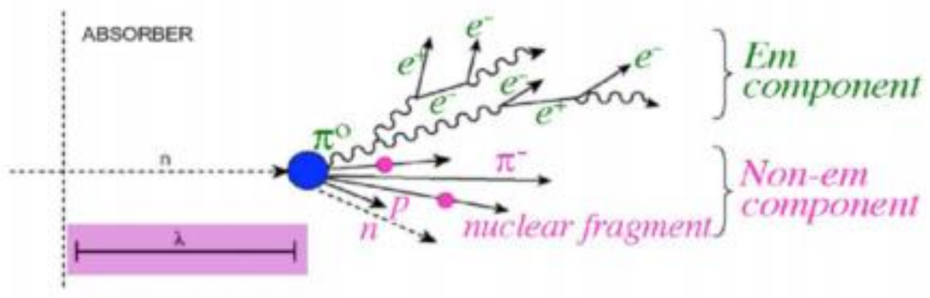
# Thank you for your attention!

# Backup slides

# Hadron showers development

**The hadronic showers are made of two components:**

- Electromagnetic component:
  from neutral meson (π0, η) decays
- Non electromagnetic component:
  charge hadrons π±, K± (20%)
  nuclear fragments, p (25%)
  n, soft γ's (15%)
  break-up of nuclei (invisible energy) (40%)




**The main fluctuations in the event-to-event calorimeter response are due to:**

- Large non-gaussian fluctuations in energy sharing em/non-em
- Large, non-gaussian fluctuations in "invisible" energy losses
- Increase of em component with energy

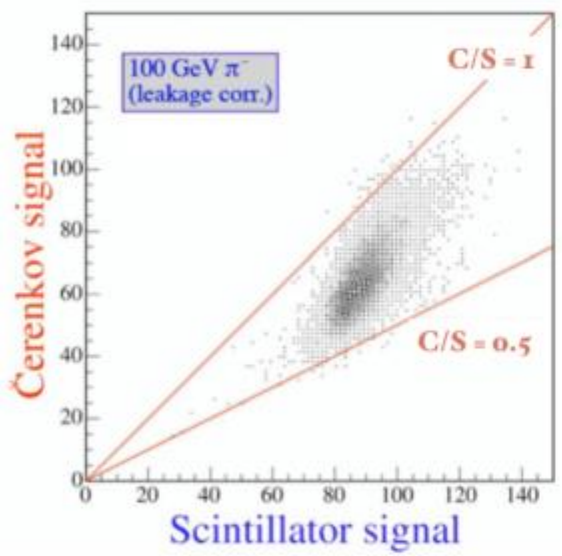
**The calorimetric performance at collider experiments has always been spoiled by the problem of non-compensation, arising from the dual nature of hadronic showers**

# Dual-Readout calorimetry

**The concept is to measure the $f_{em}$ component event by event. This eliminates the fem fluctuation effect on calorimeter performance**

**The measurement is performed using two different sampling processes:**

- Cherenkov light, produced by the relativistic particles, dominating in the e.m. shower component
- Scintillation light produced by the total deposited energy




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

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

e.g. if: (e/h) = 1.3(S) vs 4.7(C)

$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

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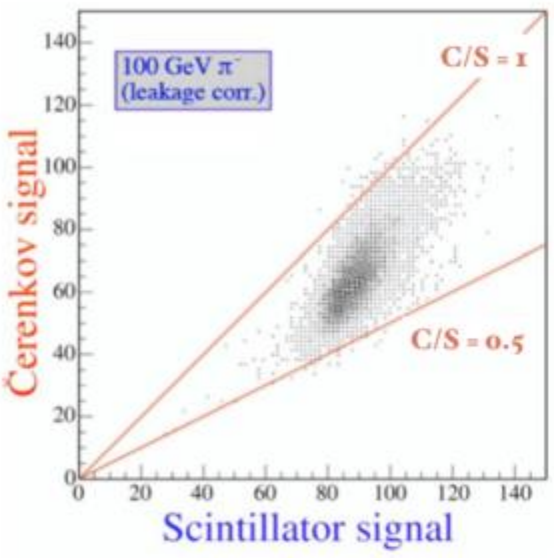



$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})\right]$$

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

e.g. if: (e/h) = 1.3(S) vs 4.7(C)

$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

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

**Universally valid!**

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

$\chi$ is independent of both:

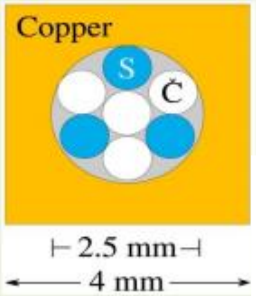
- Energy
- Type of hadron

# The history of Dual-Readout Fiber Calorimeter

## Nearly 20 years of R&D qualified the dual-readout calorimetric technique

**2003 DREAM**

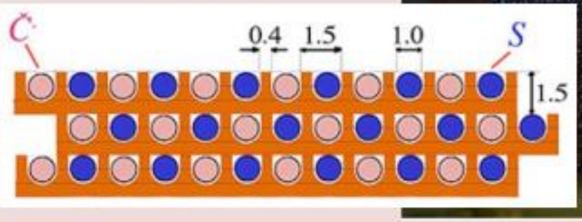
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%





**2012 RD52**

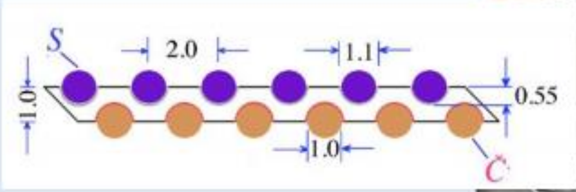
Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250$ cm$^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 $\lambda_{int}$





**2012 RD52**

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





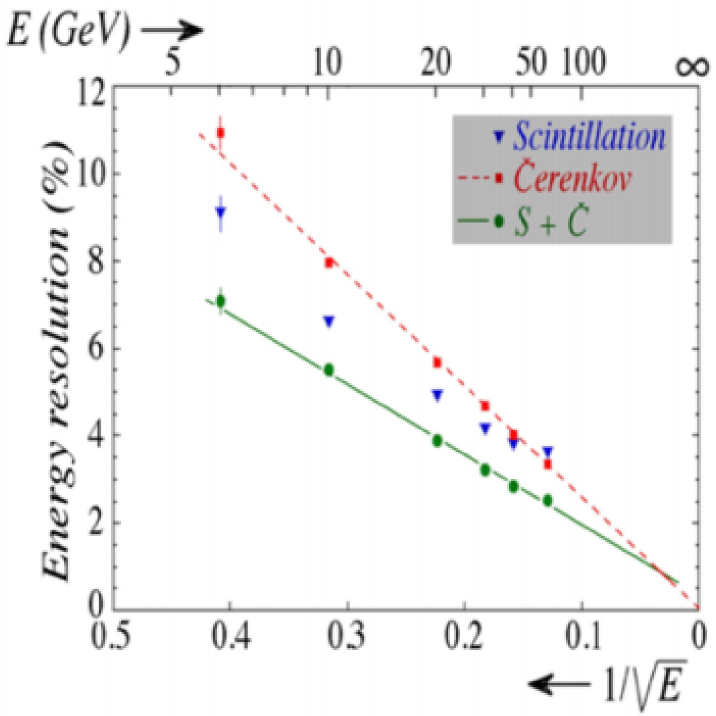
* Dual-Readout Calorimetry
DOI: 10.1103/RevModPhys.90.025002

# Energy resolution

- **Electromagnetic resolution:**

$$\frac{\sigma_{EM}}{E} = \frac{11\%}{\sqrt{E}} \oplus 1\%$$

**Copper module**
NIM A735, 130-144 (2014)

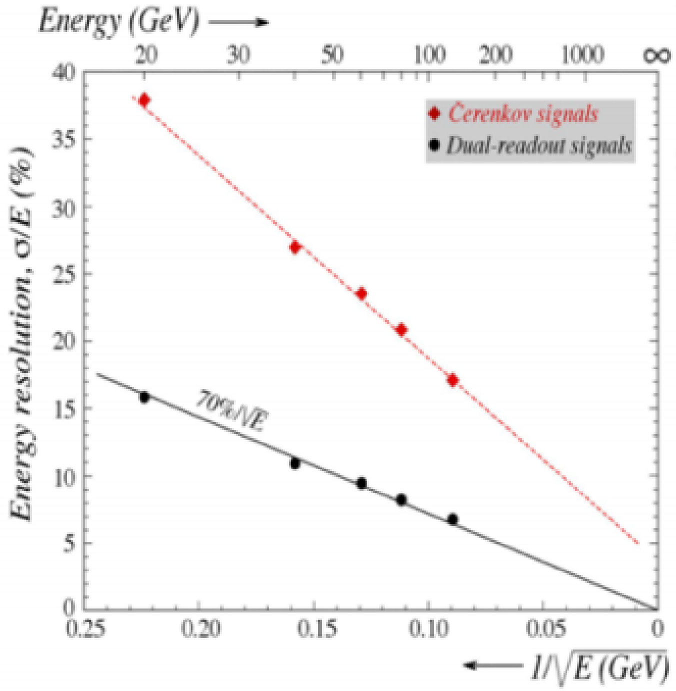



- **Hadronic resolution:**

$$\frac{\sigma_{HAD}}{E} = \frac{70\%}{\sqrt{E}}$$

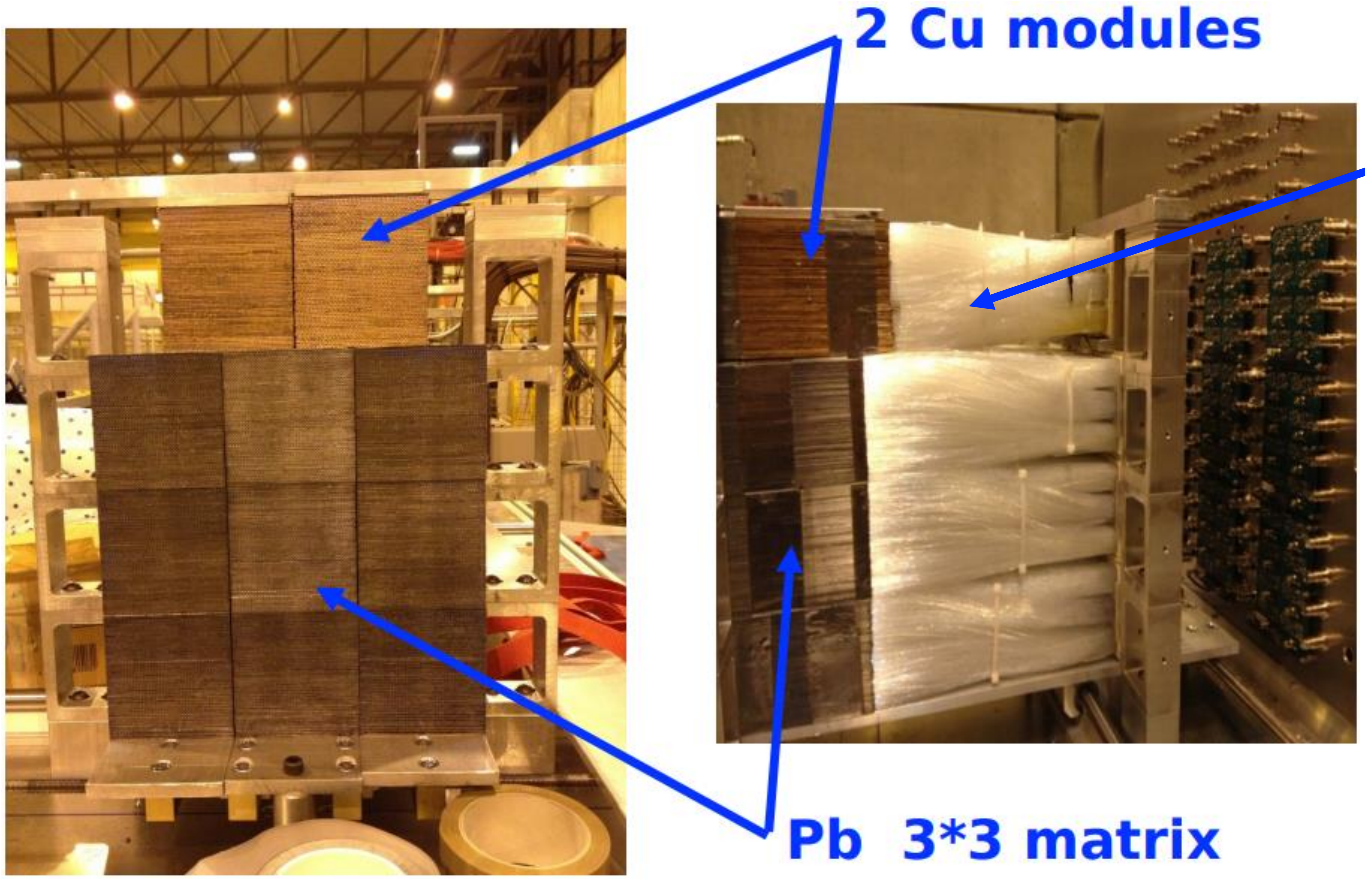
**Lateral Leakage**

**Lead module**
NIM A537, 537-561 (2014)



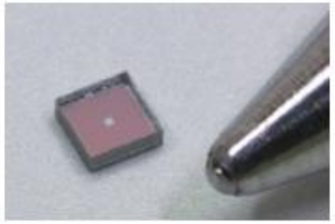
# The history of Dual-Readout Fiber Calorimeter

The generic R&D phase has demonstrated that the dual-readout technique fulfil the requirements for future high energy lepton colliders (i.e. CEPC, FCC-ee, ILC) where resolutions of the order of $\frac{16\%}{\sqrt{E}}$ (EM) and $\frac{50\%}{\sqrt{E}}$ (Had) are required




Bundle of fibers (≈ 30 cm long) to bring the light towards the PMT

What about Single-fibre readout with SiPM?

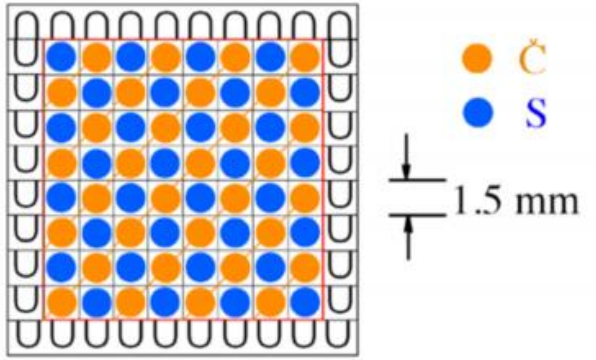


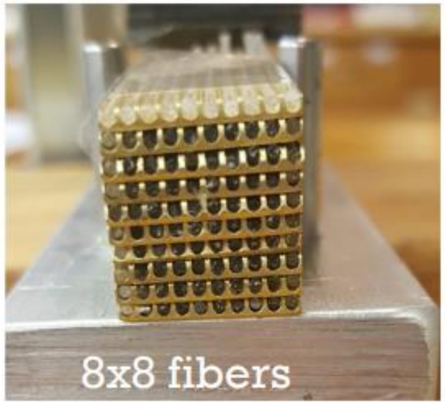
# PMT vs SiPM

SiPM Pros : - compact readout (no fibres sticking out)
- longitudinal segmentation possible
- operation in magnetic field
- larger light yield (main limitation to Čerenkov signal)
- high readout granularity → particle flow "friendly"
- photon counting (calibration)

SiPM Cons : - signal saturation (digital light detector)
- cross talk between Čerenkov and scintillation signals
- dynamic range
- instrumental effects (temperature gain variation, dark count rate, etc.)

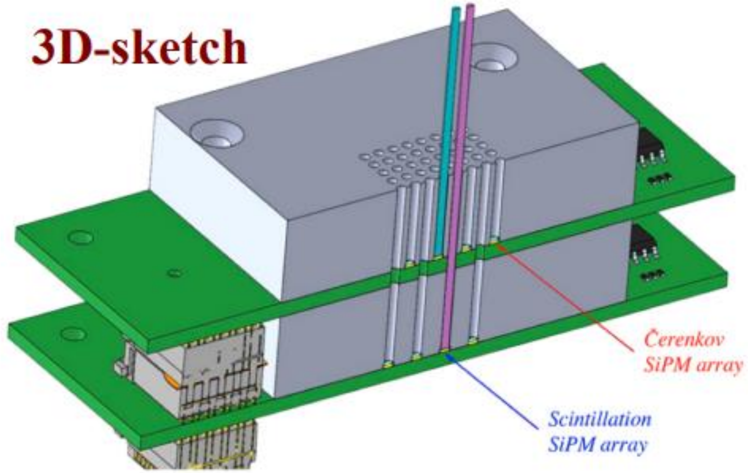
# 2018 - RD52 SiPM module



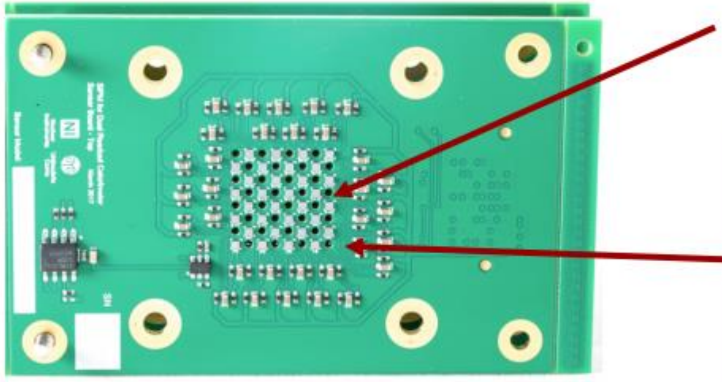



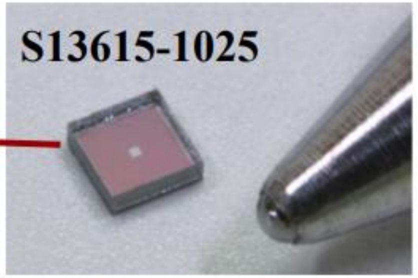

The module (112 cm long, X0 = 29 mm) is built from stacked brass layers, housing 1mm diameter clear & scintillating fibres with a pitch of 1.5 mm (RM = 31 mm)

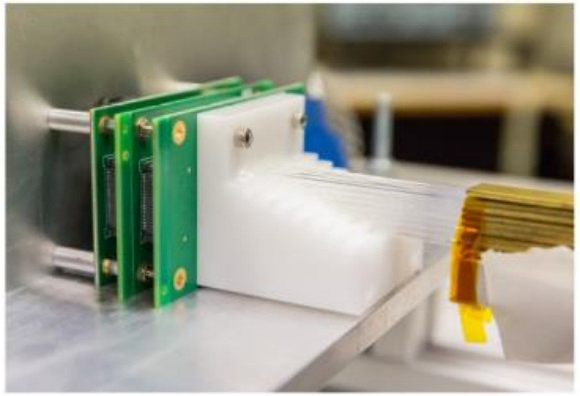
•DOI: 10.1016/j.nima.2018.10.169




Top layer (Front view)



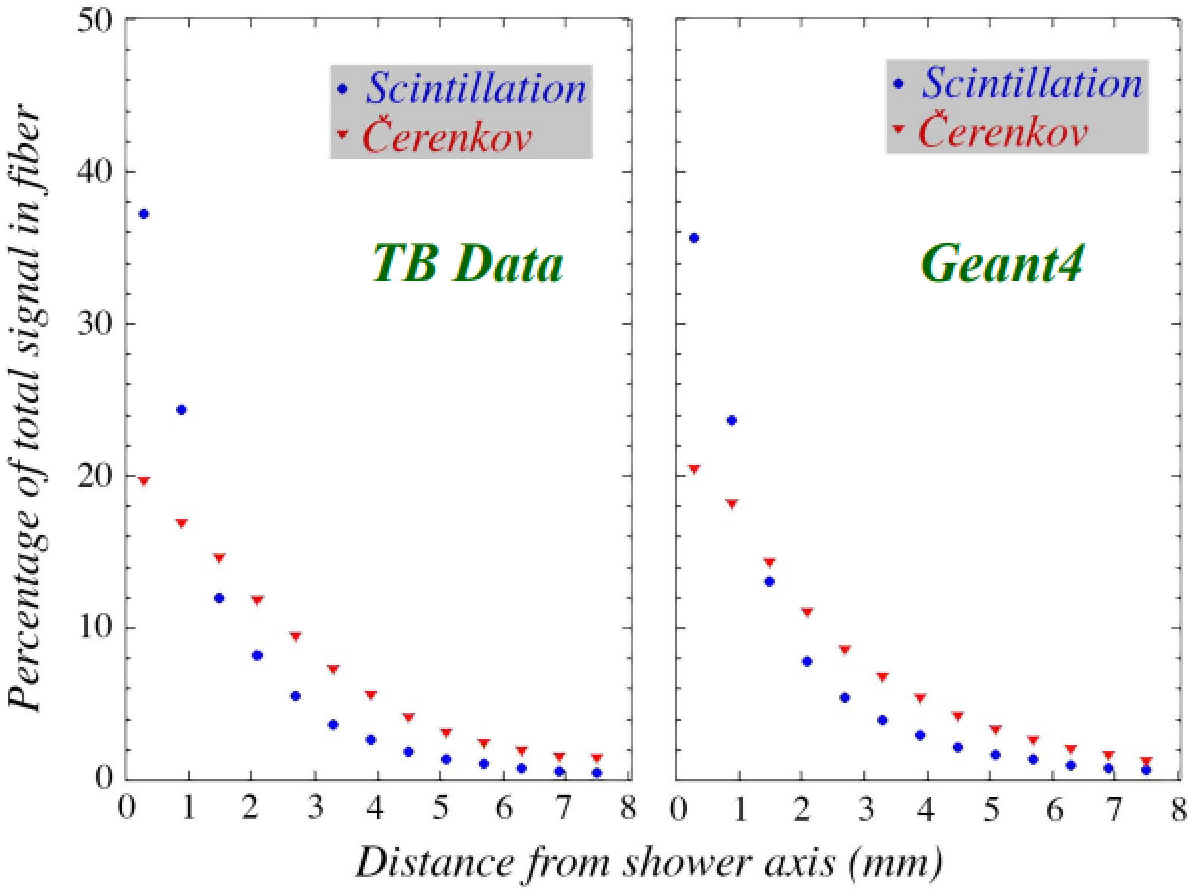
The light propagated in each fiber is sensed by individual SiPMs

The SiPMs collecting Cerenkov / Scintillating light are placed on separate boards to avoid that Cherenkov light is contaminated by scintillating light. The latter is expected to be ≈ 50 time more intense

# Lateral shower profile with SiPM

10 / 40 GeV $e^-$

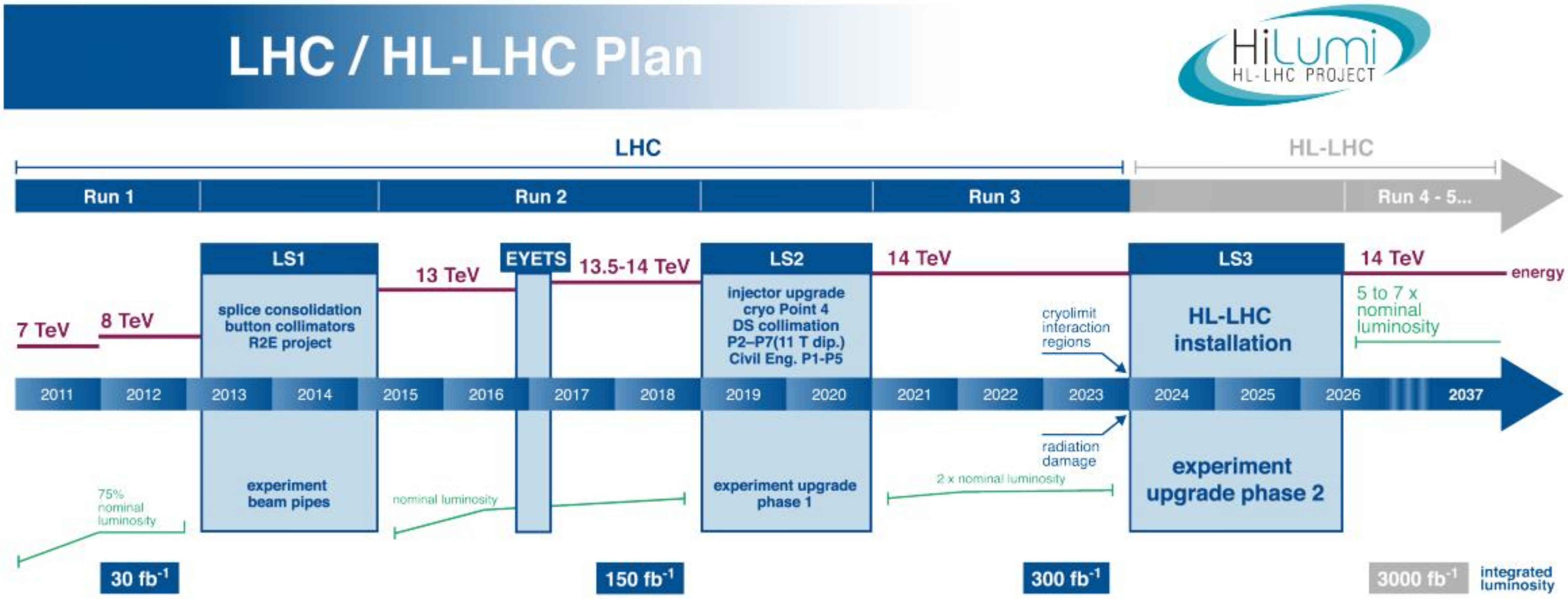
$\theta, \Phi = 0°$




**em shower are very narrow:** ~10% (~50%) within ~1 (~10) mm from shower axis

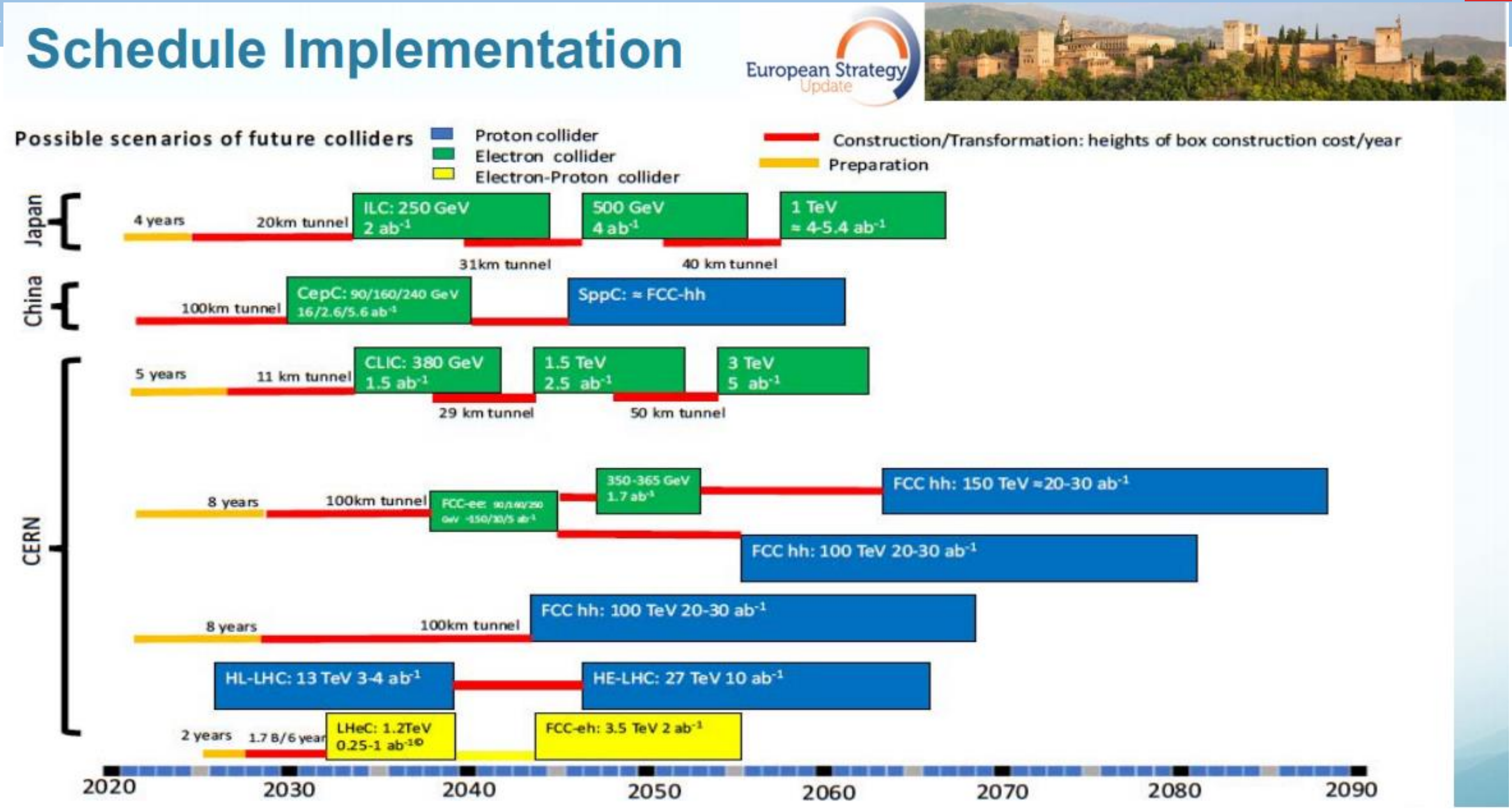
→ fibre readout can easily provide (powerful) input to PFA

# Future colliders: Where, How, Why?




* The High-Luminosity LHC (HL-LHC) Project

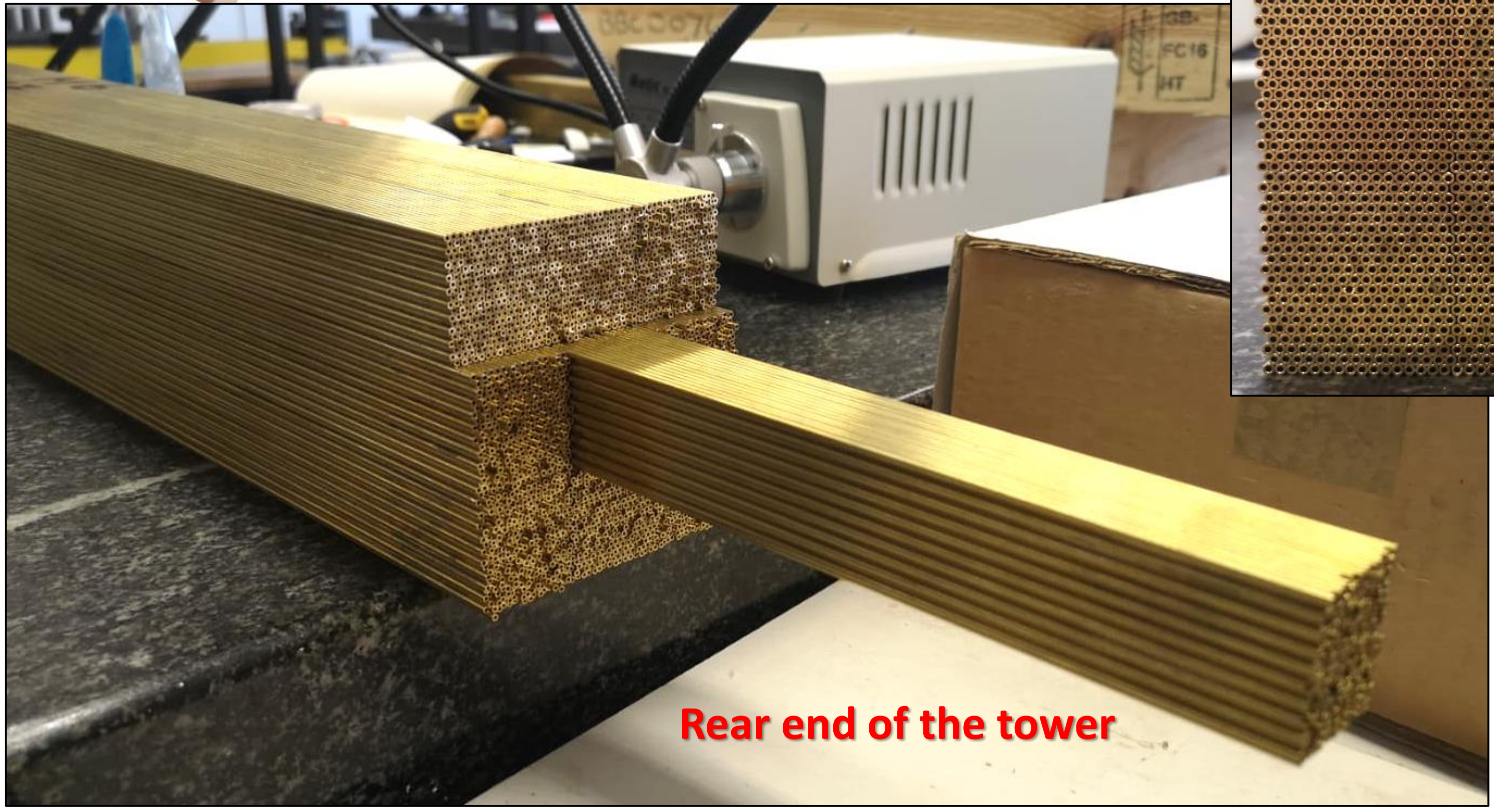
# Future colliders: Where, How, Why?

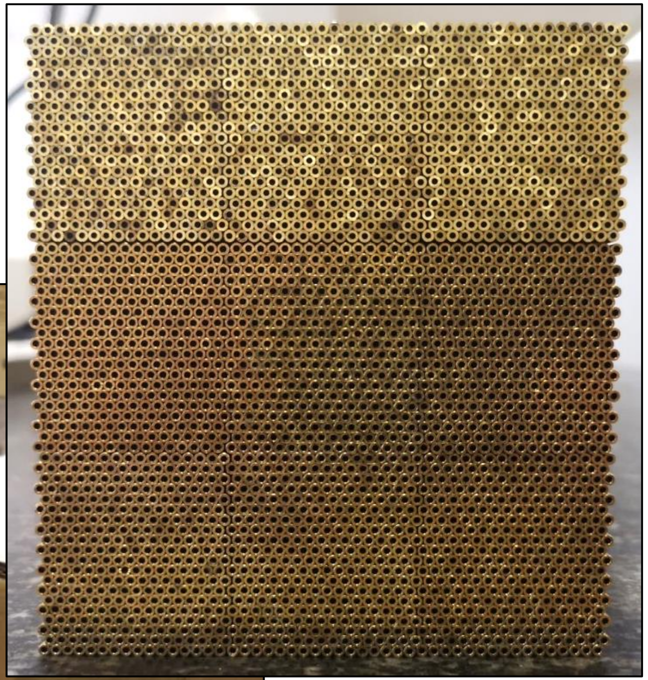





* [Highlights and perspectives of future accelerators – CECP Oct 2020]

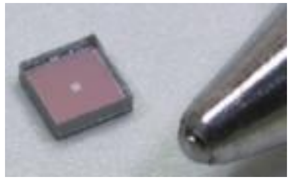
# The Bucatini Calorimeter: EM-size prototype

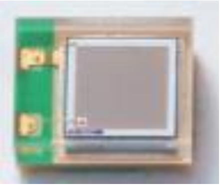



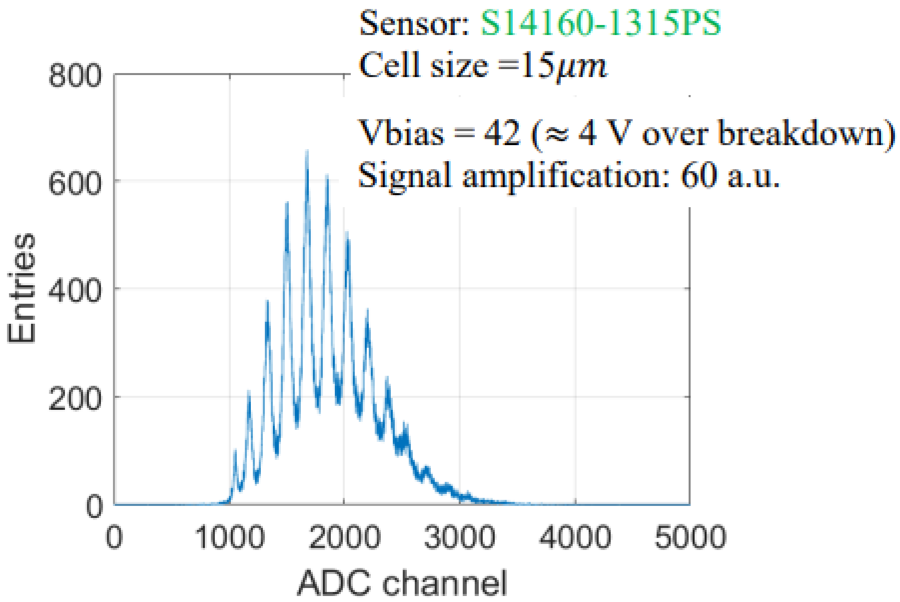
Face of the tower

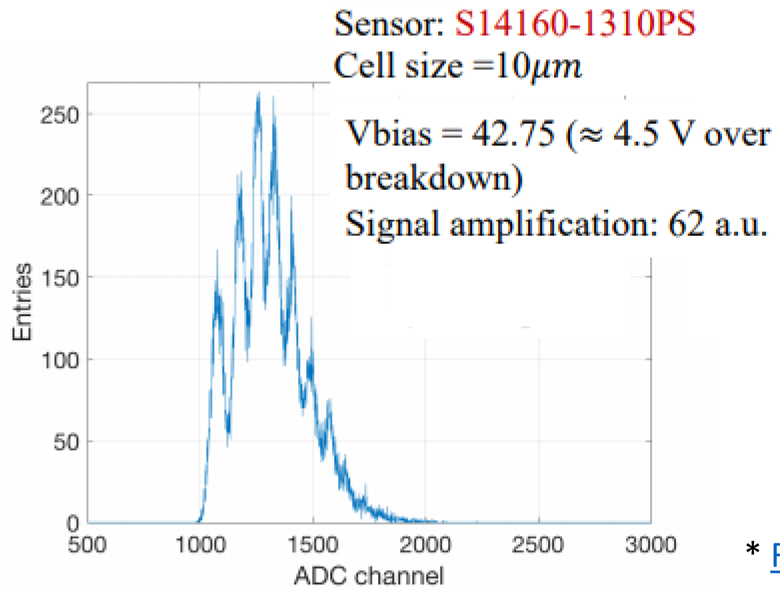
# SiPMs considered for the prototypes





| SiPM | Pixel pitch ($\mu$m) | Sensitive area (mm²) | Dyn-range | Package (mm²) | Eff (%) | DCR (kHz) | Cross talk (%) | After pulse (%) |
|---|---|---|---|---|---|---|---|---|
| S13615-1025 | 25 | 1x1 | ≈1600 | 1,13x1,13 | 25 | 50 | 1-3 | ≈1 |
| S14160-1315PS | 15 | 1.3x1.3 | ≈7300 | 2.6x1.3 | 32 | 120 - 360 | ≈1 | ≈1 |
| S14160-1310PS | 10 | 1.3x1.3 | ≈16700 | 2.6x1.3 | 18 | 120 - 360 | ≈1 | ≈1 |

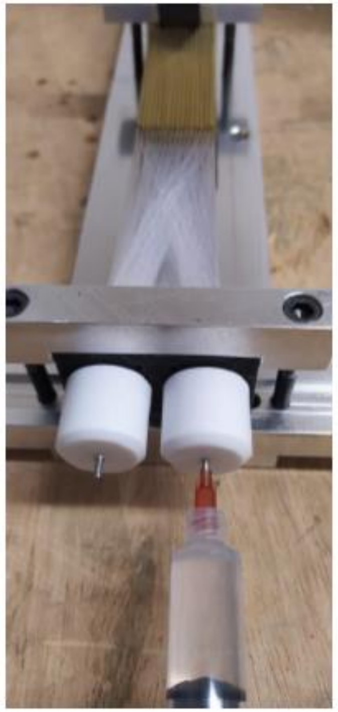



The quality of the multi-photon, obtained with the same ASIC (Citiroc1A) that will be use at the Feb 2021 test beam.

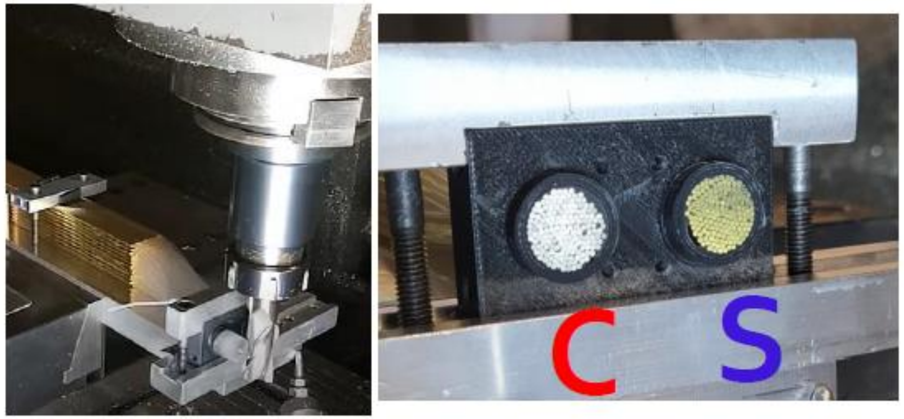
* R. Santoro talk at CECP Oct 26-28, 2020

# Machining the glued fibers



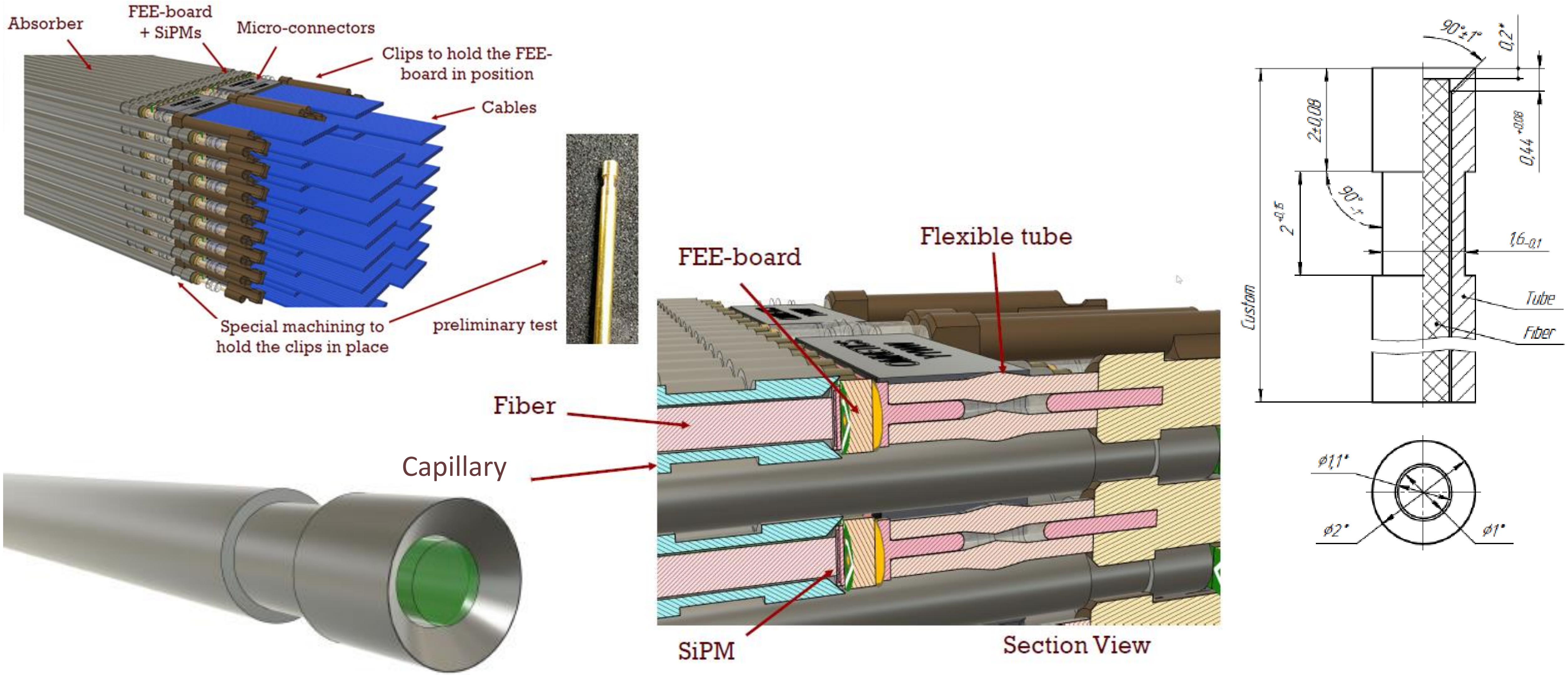
Syringe removed

Teflon containers removed

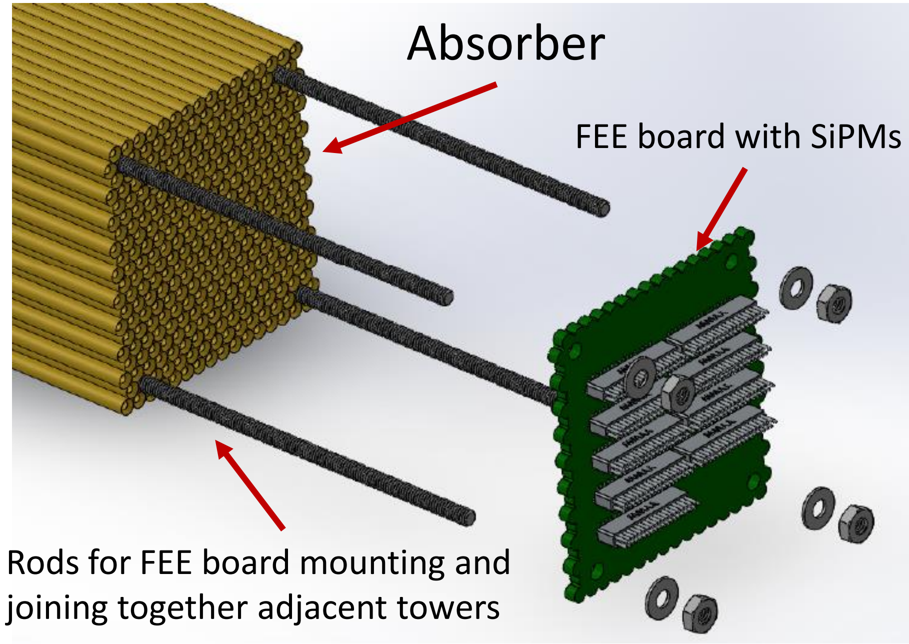


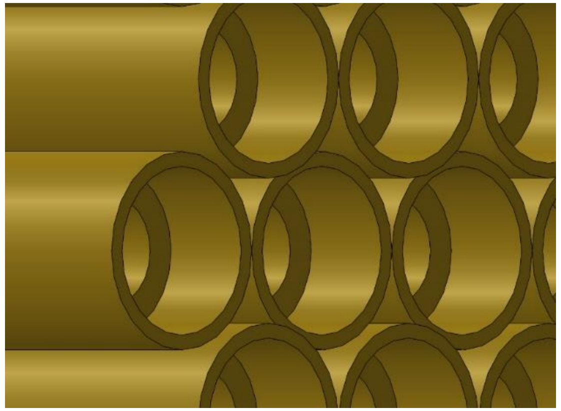

Grouped glued fibers outside 3d printed holder are cut off by milling machine

# Idea of readout scheme 2.0 (hadronic-size prototype)

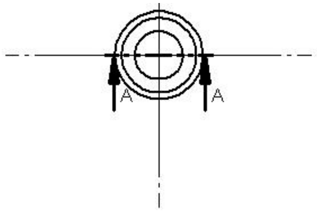


# Idea of readout scheme 2.1 (hadronic-size prototype)



Another consideration regarding the inner profile of the capillaries




2 levels FEE board with SiPMs