FUTURE CIRCULAR COLLIDER

UNIVERSITÀ DI PAVIA

INFN

Status of Dual-Readout calorimetry for future HEP experiments

Andrea Pareti - INFN and Università di Pavia

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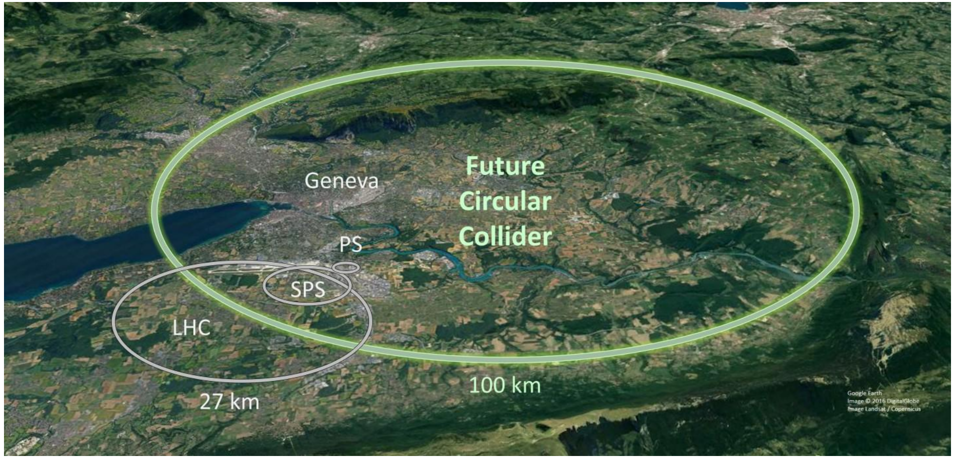
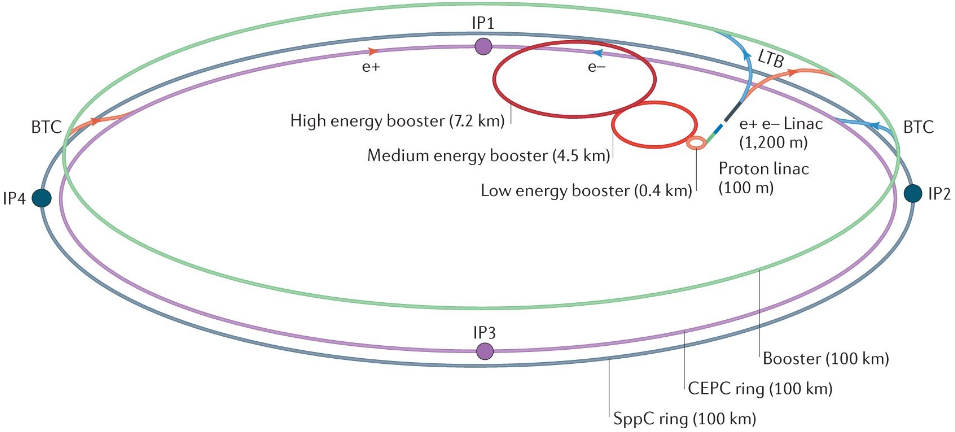
Searches at e^+e^- colliders

Two main projects for future e^+e^- colliders
FCC at CERN, CepC (China)

Energies in the center-of-mass frame:
[90, 160, 240, 365] GeV
Up to 100 TeV in hadron-hadron phase





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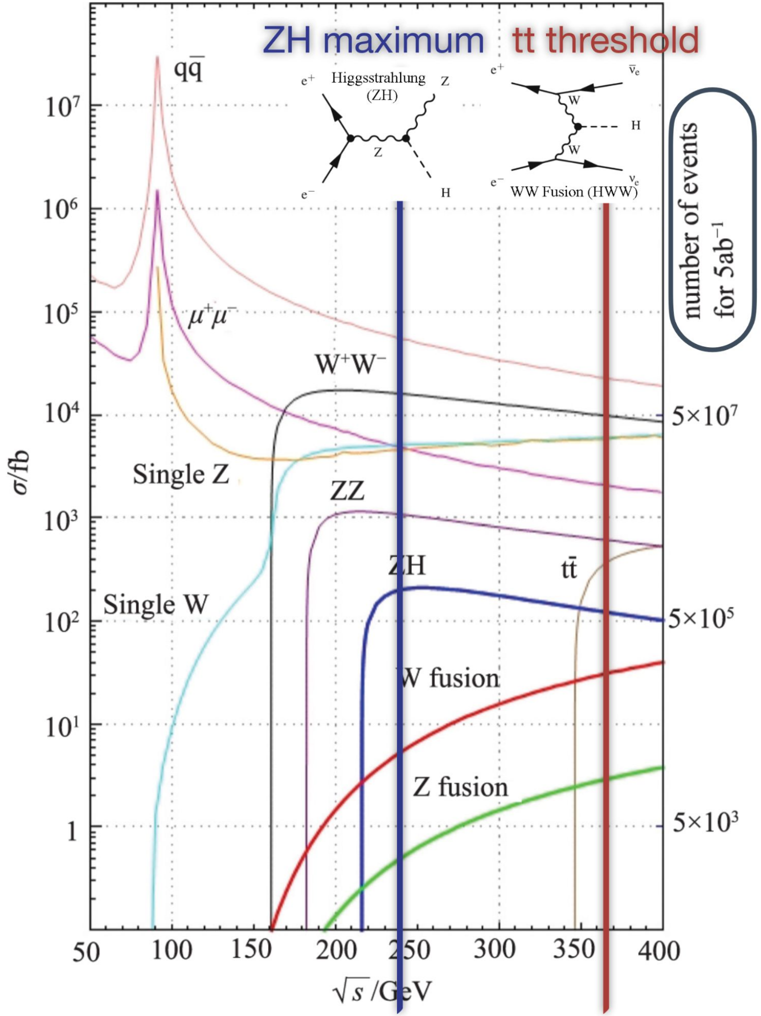
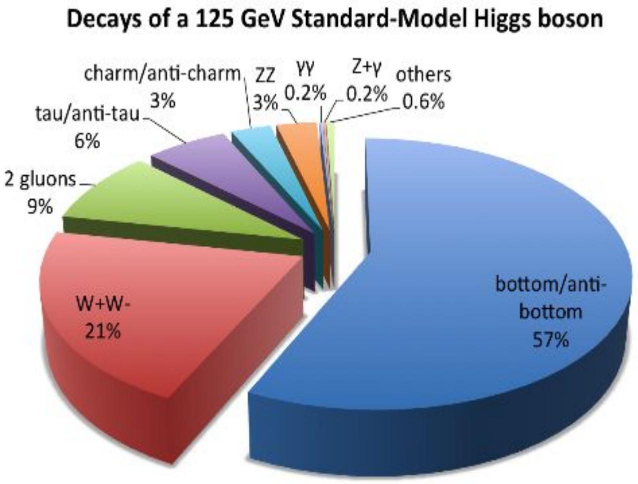
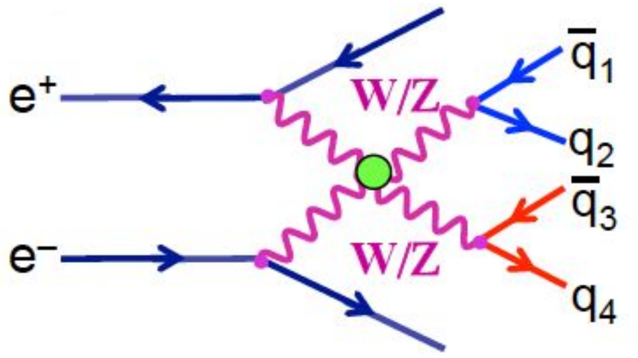
[90, 160, 240, 365] GeV
Up to 100 TeV in hadron-hadron phase

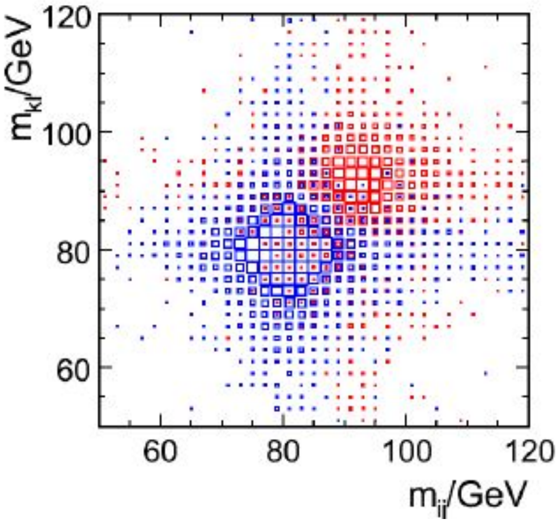
Broad physics potential:

- ElectroWeak physics at Z pole and W^+W^- threshold
- Higgs precision measurements
- Direct searches for new physics
- Heavy Flavour Physics









Jet measurement benchmarks

Large W/Z/H hadronic branching ratio: 90% of events will contain at least one hadronic jet

Main benchmark:
distinguish W and Z boson hadronic decay through jet invariant mass

Target resolution: $\frac{\sigma}{E} = \frac{30\%}{\sqrt{E}}$

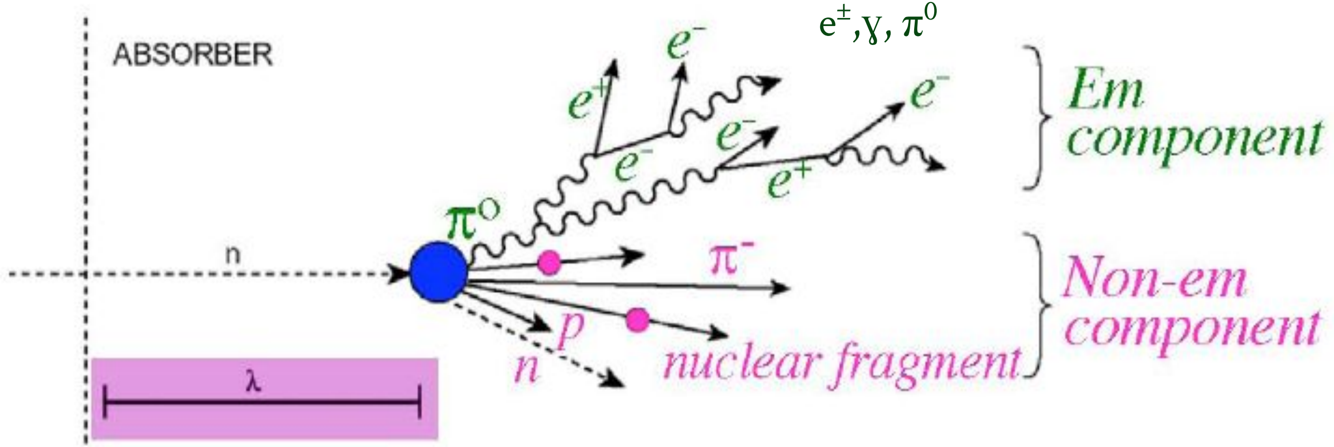
IDEA detector @ FCC/CepC:
Reach target resolution through a Dual-Readout, highly granular, fibre-based calorimeter

Dual-Readout Calorimetry

Different response of calorimeters to *em* and *non-em* components: $\frac{e}{h} \neq 1$

Electromagnetic fraction f_{em}: fraction of the primary jet energy carried by the em component particles

$e^{\pm}, \gamma, \pi^0$



Charged hadrons ($\pi^{\pm}$,K…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Hadronic jet reconstruction problems:

1. Event-based fluctuations in the f_{em}
2. f_{em} increases with energy (non-linearity)
3. Event-based fluctuations in the invisible energy

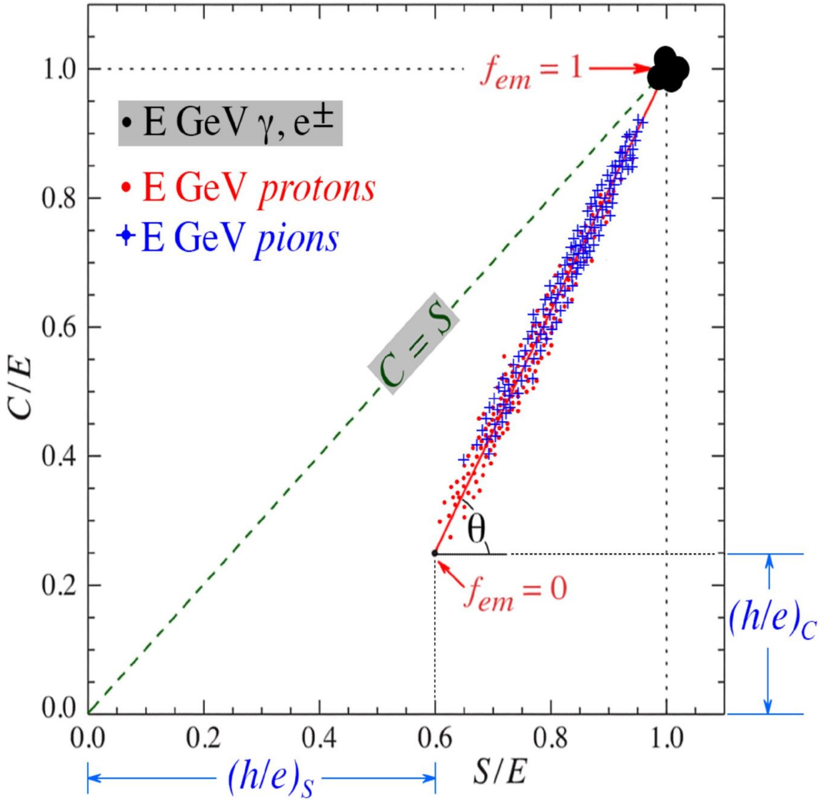
Dual-Readout Calorimetry

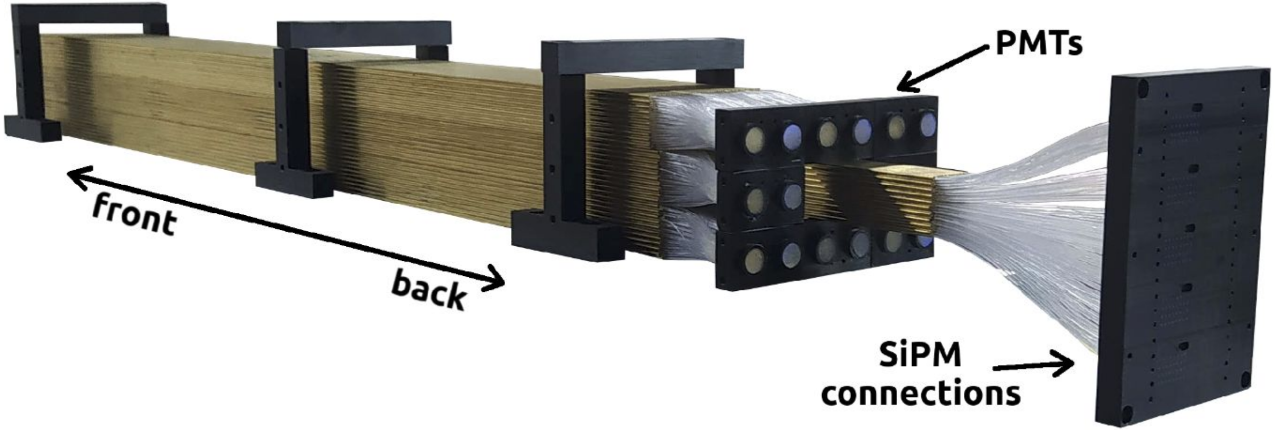
Idea: use two different physical processes to measure shower f_{em}

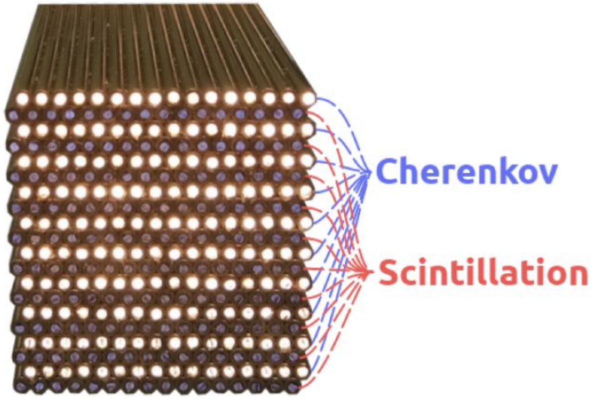
- Scintillation light:
  - ➢ measure total energy deposition
- Cherenkov light:
  - ➢ mostly emitted by $e^{\pm}$ (*em* component)

Use f_{em} to correct the reconstructed energy:

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







Dual-Readout fibre calorimeter

Fibre Calorimeter:
Longitudinally unsegmented fiber calorimeter
Modular design with alternating rows of Scintillating or Cherenkov fibers

One calorimeter for both electromagnetic and hadronic showers
- ➢ Only one calibration with electron is required
- ➢ Excellent spatial and angular resolution

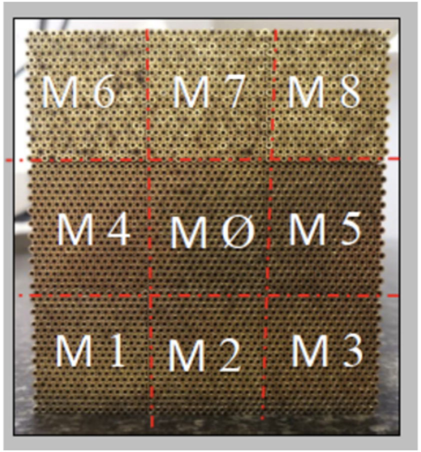
Drive towards highly-granular design:
- ➢ Particle Flow-friendly
- ➢ Particle Identification
- ➢ Heavy-Flavour jet tagging

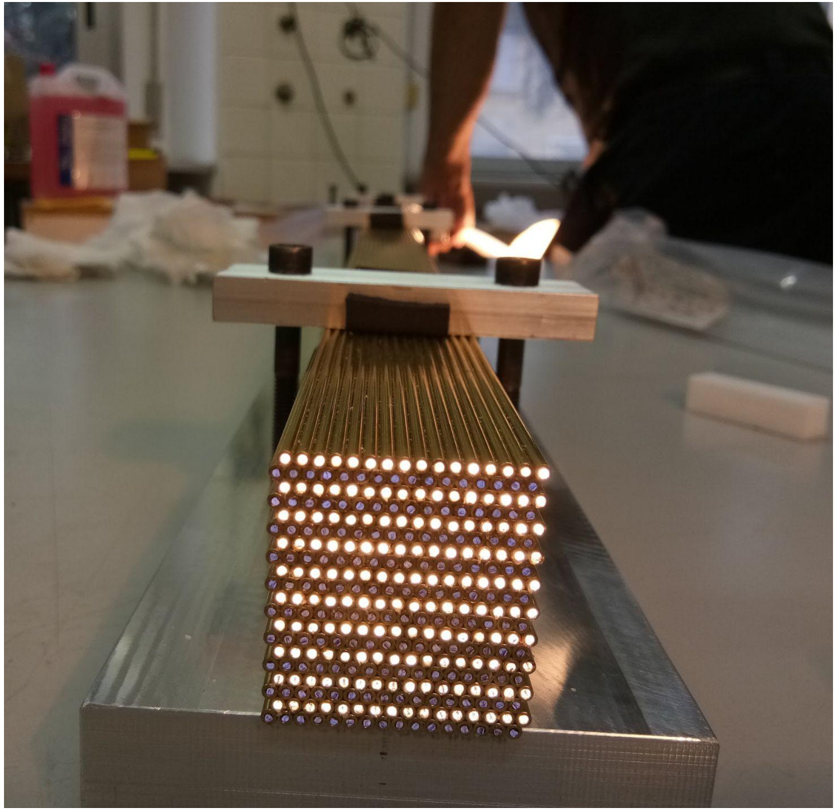
EM shower-sized prototype

First prototype built in 2021 and tested at DESY and CERN's SPS

9 modules made of 16x20 capillaries
M0 readout with SiPMs, M1-M8 with PMTs
→ 320 SiPMs

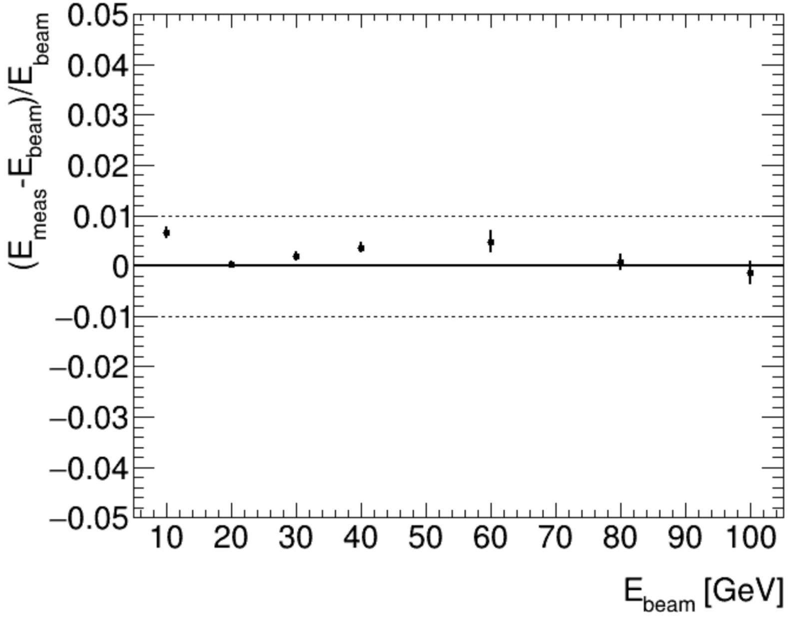
SiPMs with packages small enough were not ready at the time of production, fibers in M0 leaking out from the back of the calorimeter



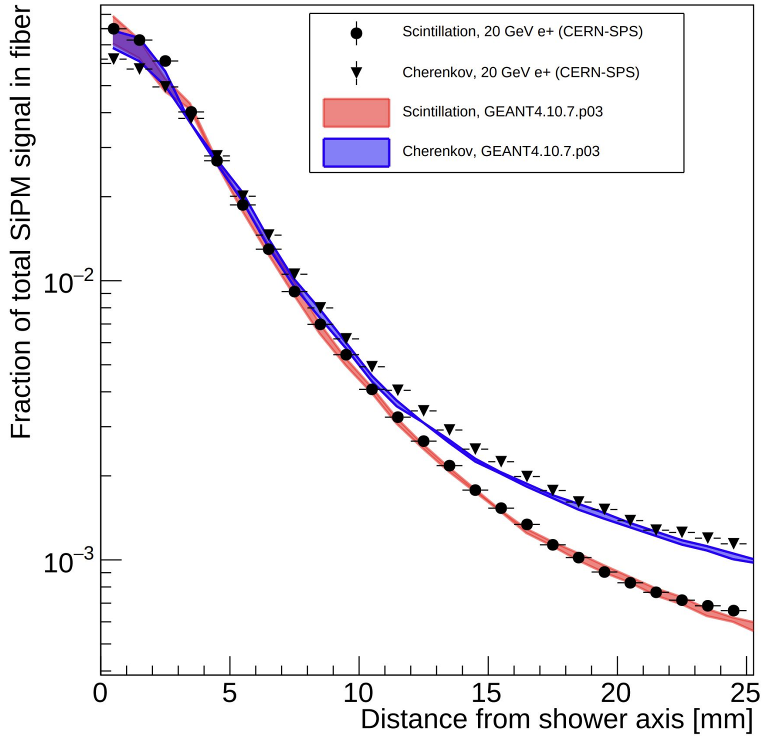


EM shower-sized prototype

Energy well reconstructed within 1% range



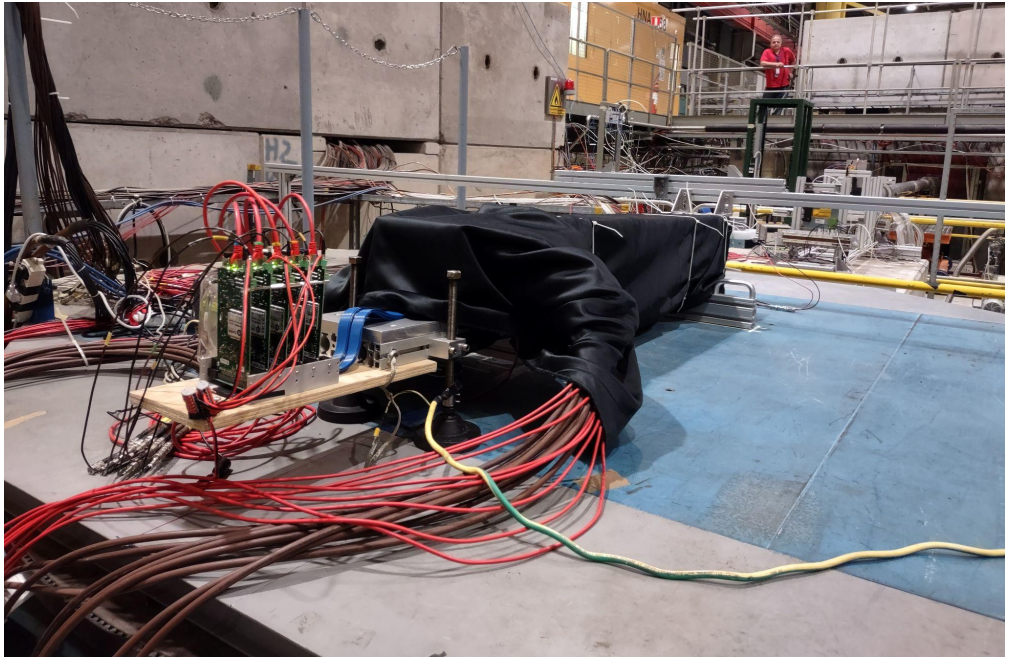
Lateral shower profile measured through independent SiPM information

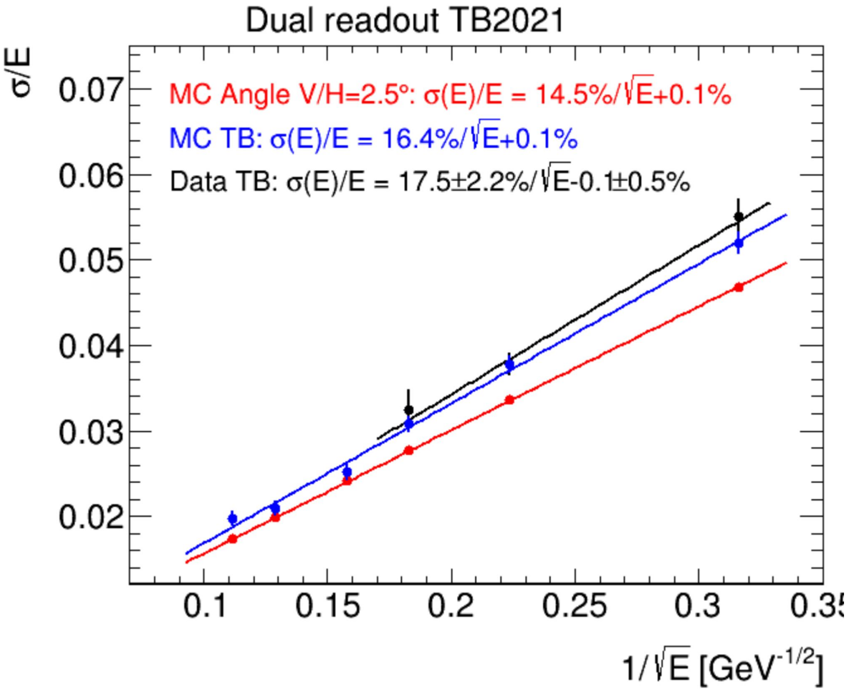


EM shower-sized prototype

Agreement between measured and simulated energy resolution

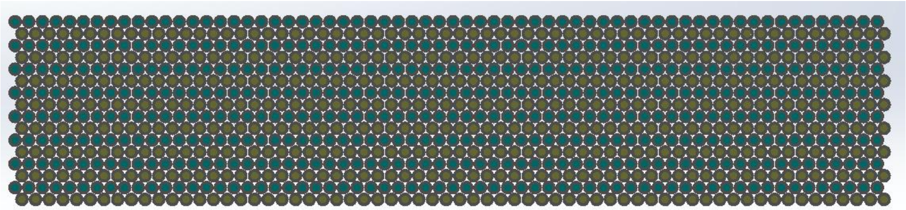
Second round in July 2023 for further characterization
→ Data analysis ongoing





More information on test beam here

HiDRa Prototype

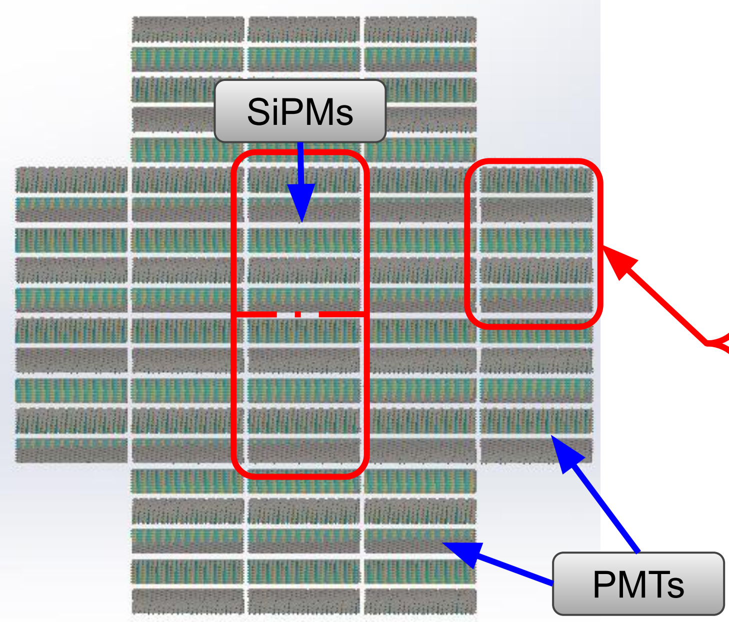


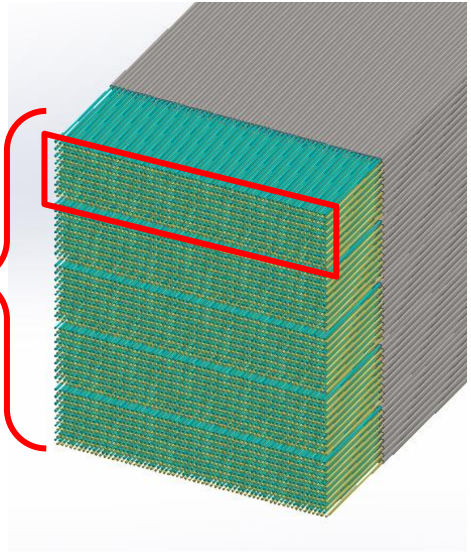
Demonstrate the feasibility of the Dual Readout technique in association with SiPM readout, with high-energy test beams

Each module is readout by two photodetectors, one for S fibers and the other for C fibers

Build an almost fully-containing hadron shower calorimeter:
80 mini-modules, each one made of 16×64 capillaries

10 mini-modules readout with SiPMs, all others with PMTs
→ Cost/Performance optimization
→ Gradual increase in DAQ complexity (10240 SiPMs)



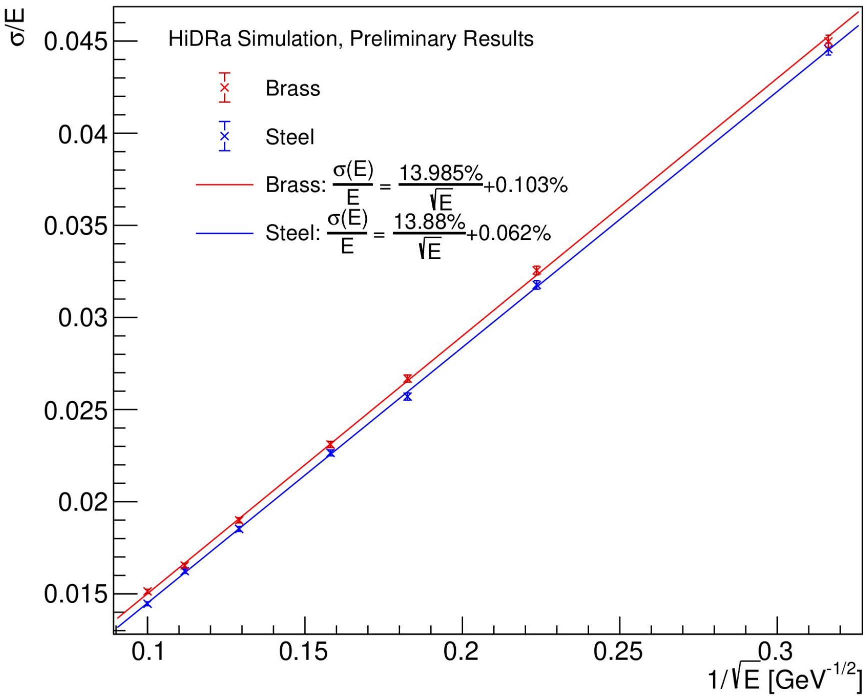


HiDRa energy resolution

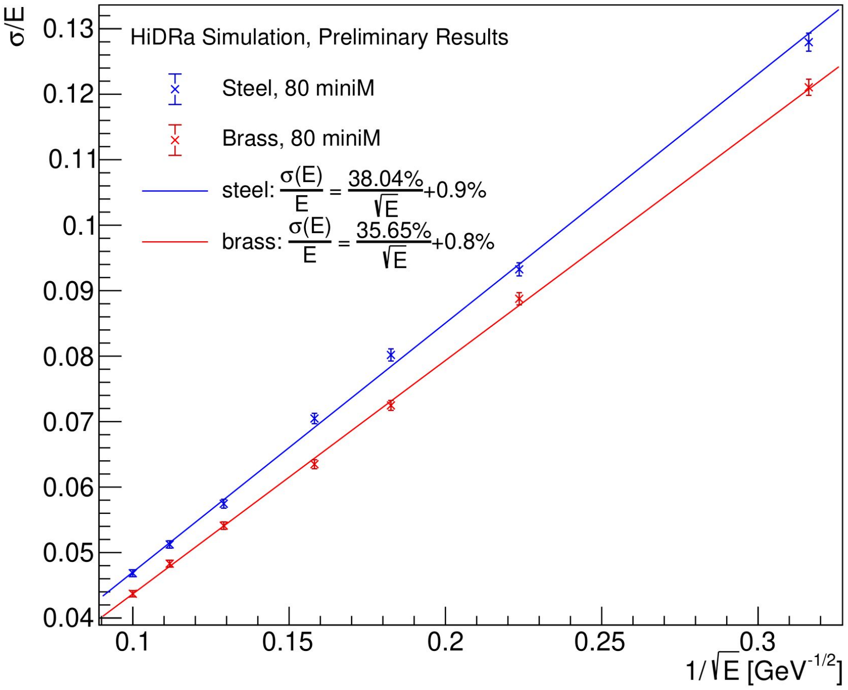
Brass absorber seems to slightly improve resolution, but more expensive to produce and use for a smaller-scale prototype

Geant4 simulation-based resolution, for electrons and pions

Electron resolution in [10, 100] GeV Range



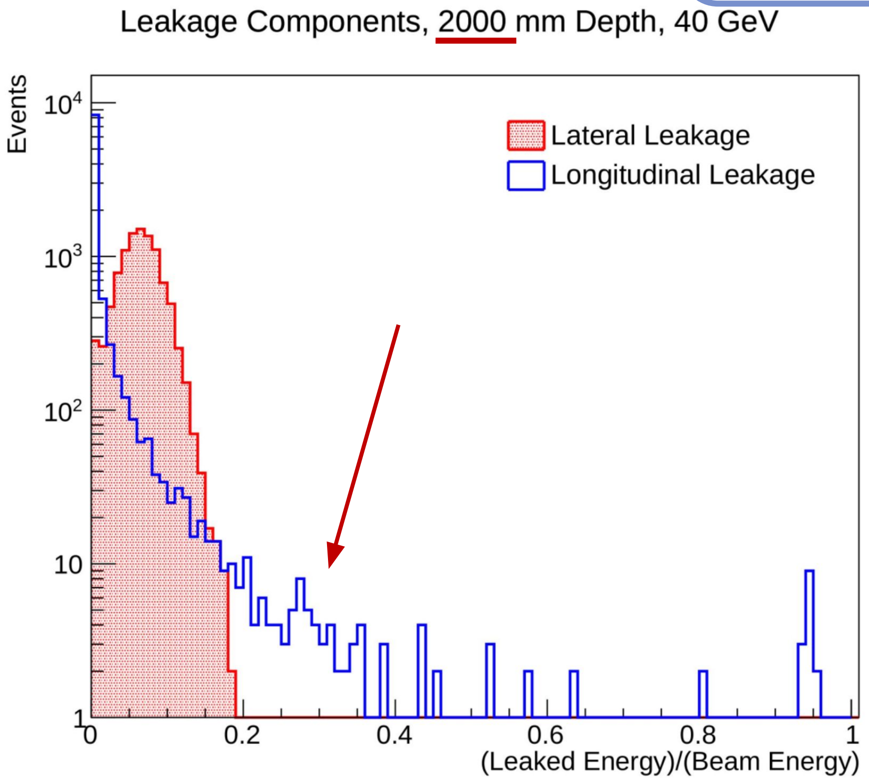
Pion resolution in [10, 100] GeV Range

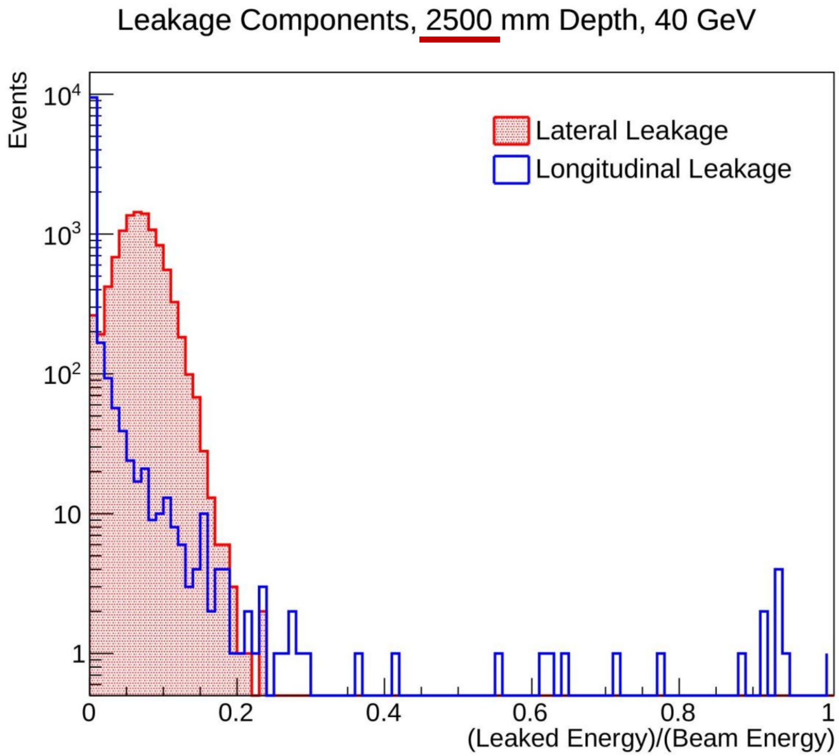


Leakage studies

Distribution of leaked energy outside calorimeter in lateral and longitudinal directions (hadron beam)

- ➢ Lateral leakage has major impact on energy resolution
- ➢ Longitudinal leakage leads to low-reconstructed energy events





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Distribution of leaked energy outside calorimeter in lateral and longitudinal directions (hadron beam)

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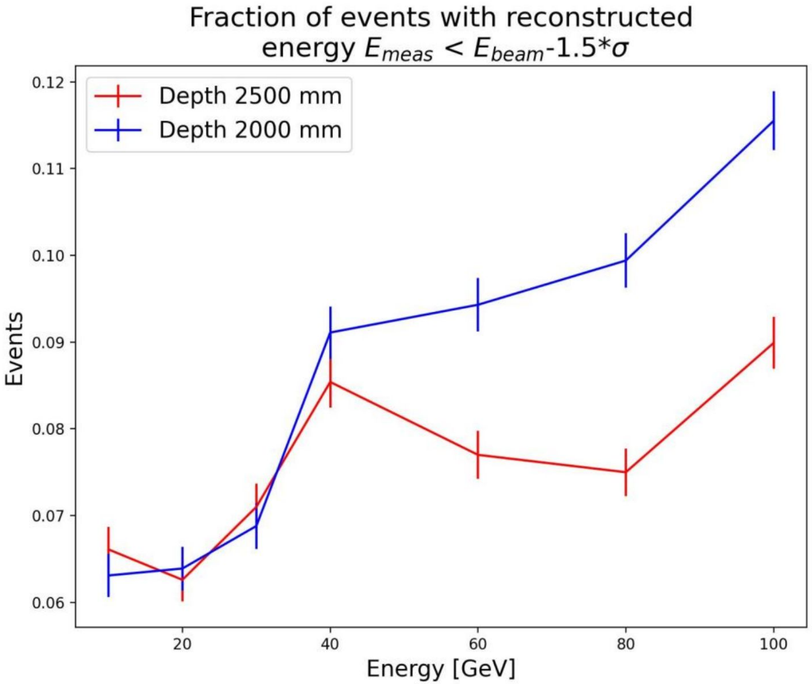
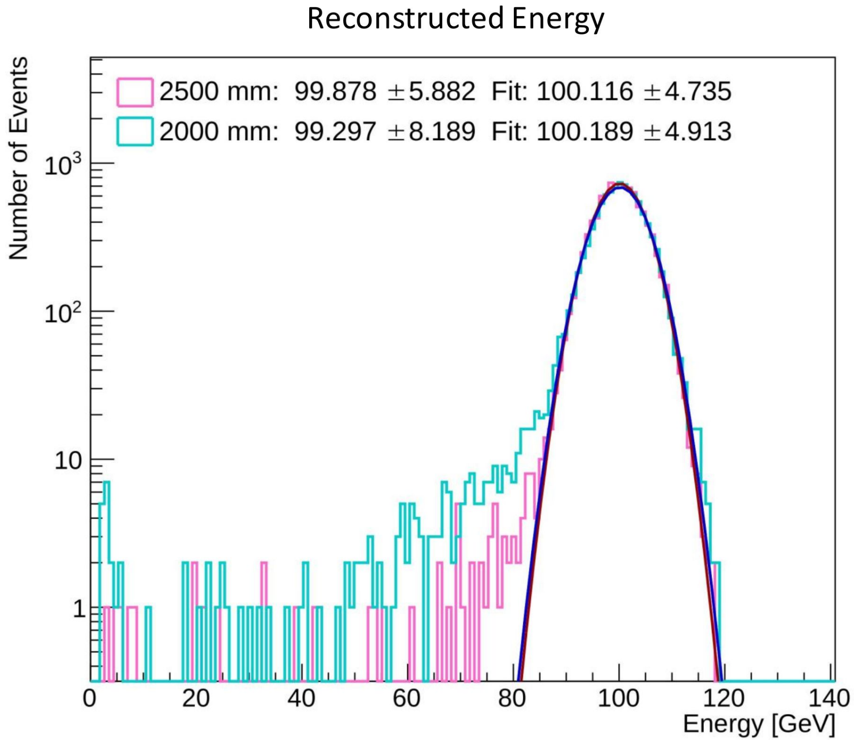
- ➢ Longitudinal leakage leads to low-reconstructed energy events

Smaller effect of longitudinal leakage on energy resolution (estimated using a gaussian fit)

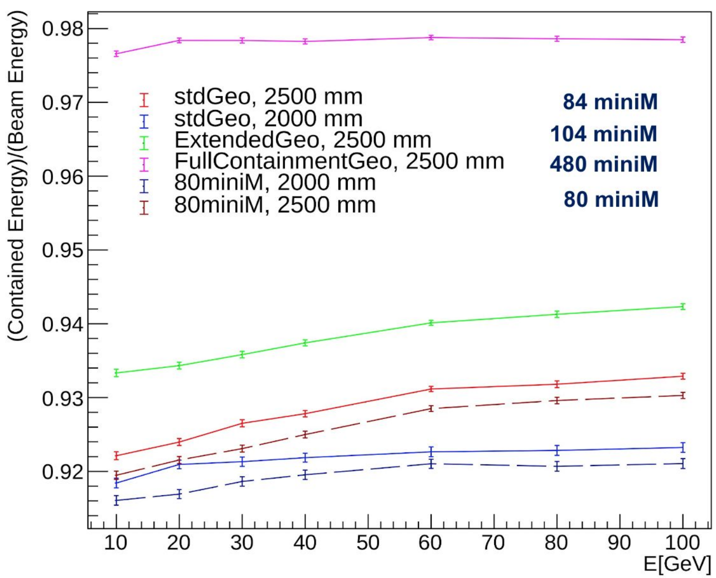




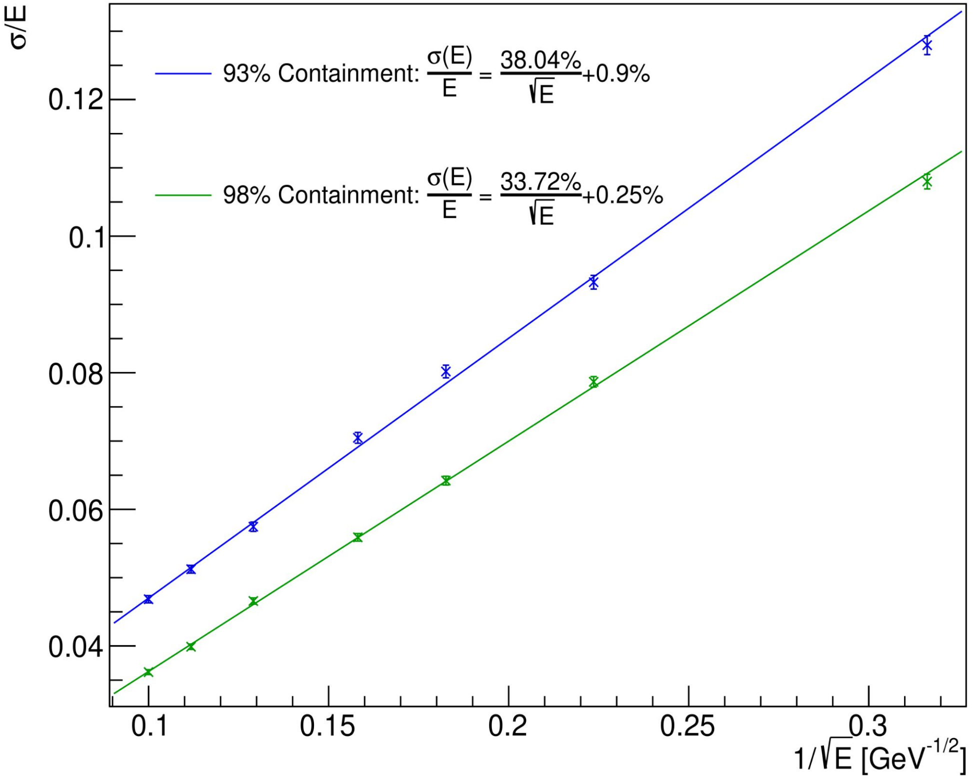
HiDRa energy resolution

Improvement in resolution by increasing the calorimeter lateral dimension
(add more modules in simulation)

Pion Containment in [10, 100] GeV Range



Pion resolution in [10, 100] GeV Range

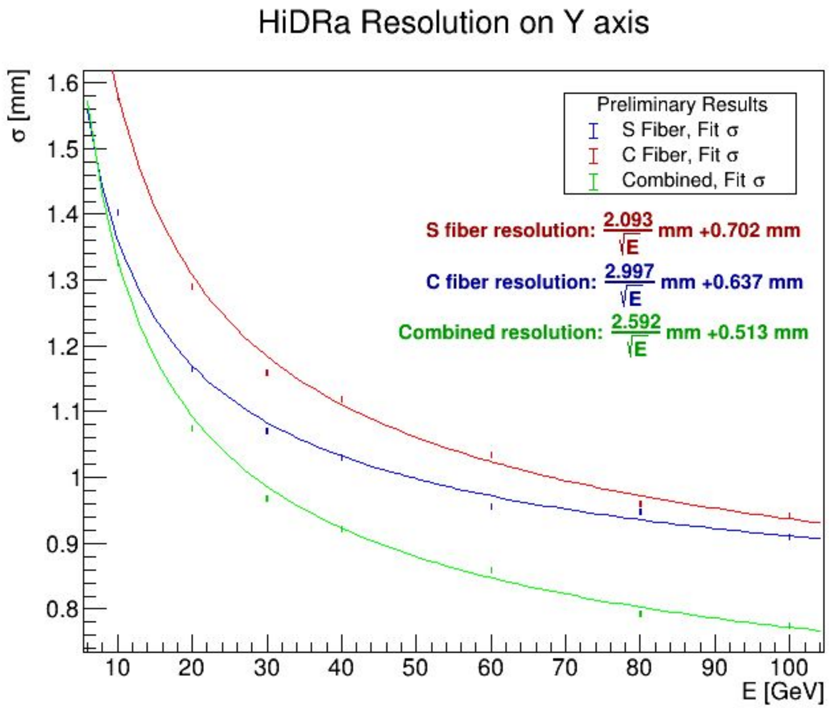


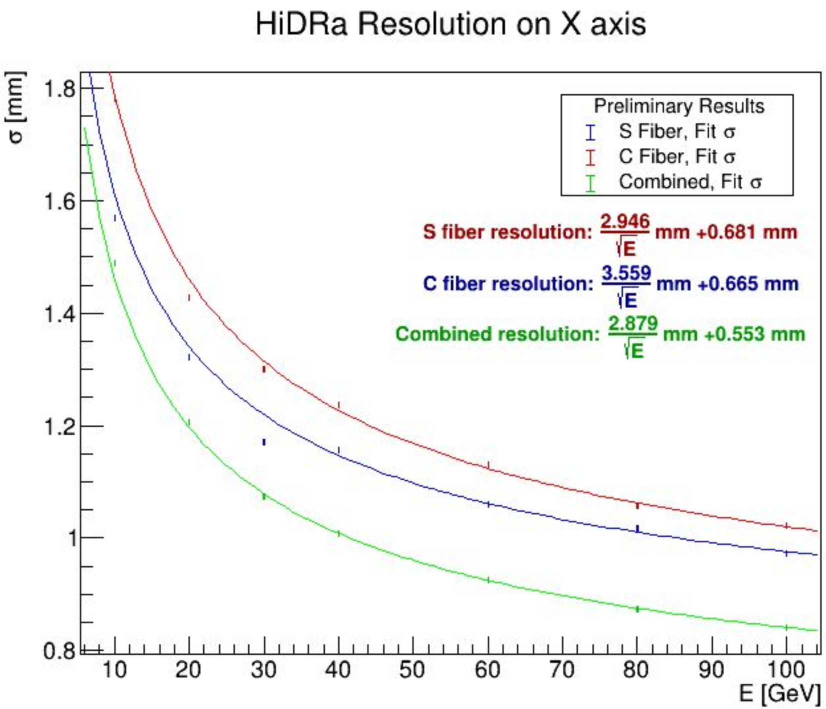
HiDRa space resolution

PRELIMINARY

Spatial resolution dependence on energy for electron beams, in the range [10, 100] GeV estimated through center of gravity of shower correlated with beam coordinates

Plots obtained with independent SiPM information, study with 8-fiber grouping ongoing





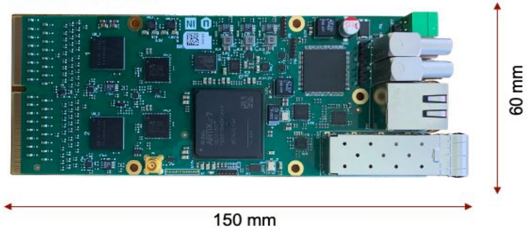
HiDRa SiPM integration & Readout

Custom designed module with 8 Hamamatsu SiPMs (1x1 mm^2)
Two options: 10 and 15 μm pitch (optimize dynamic range/photon detection efficiency for S/C fibers)

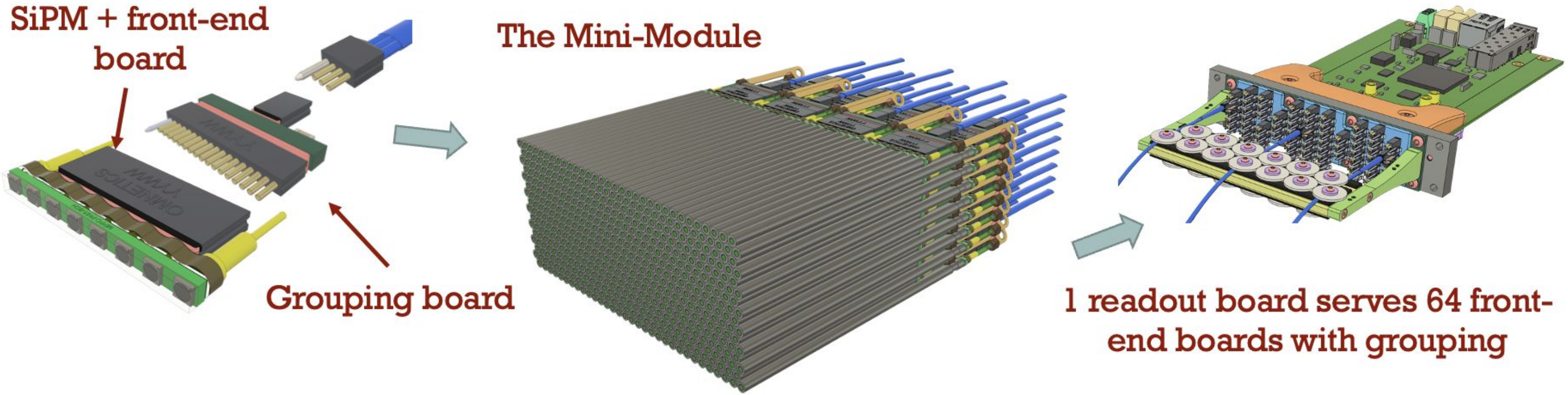
Baseline solution:

- ➢ Signals from 8 SiPMs summed up on grouping board
- ➢ 2 FERS operate 1 full minimodule
- ➢ 20 FERS operate high-granularity core of HiDRa prototype

FERS: A5202



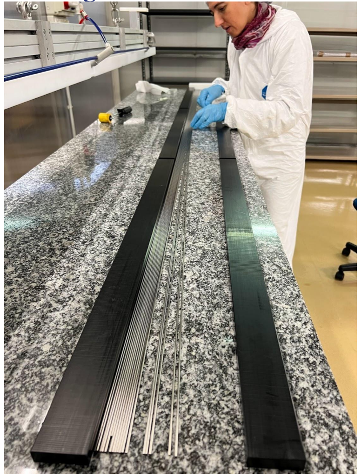
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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



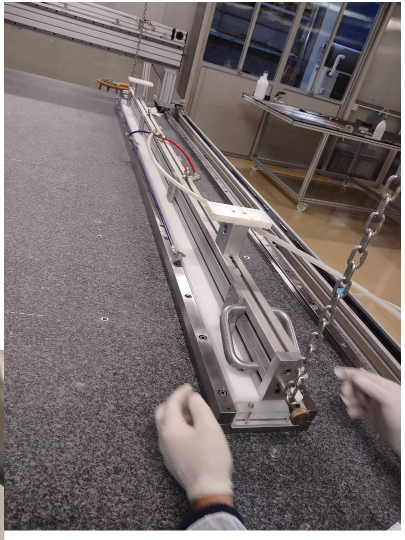
HiDRa first module construction

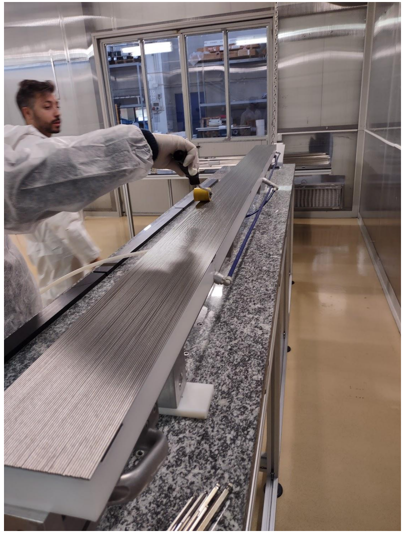
Definition of constructing technique and quality assessment on the modules geometry

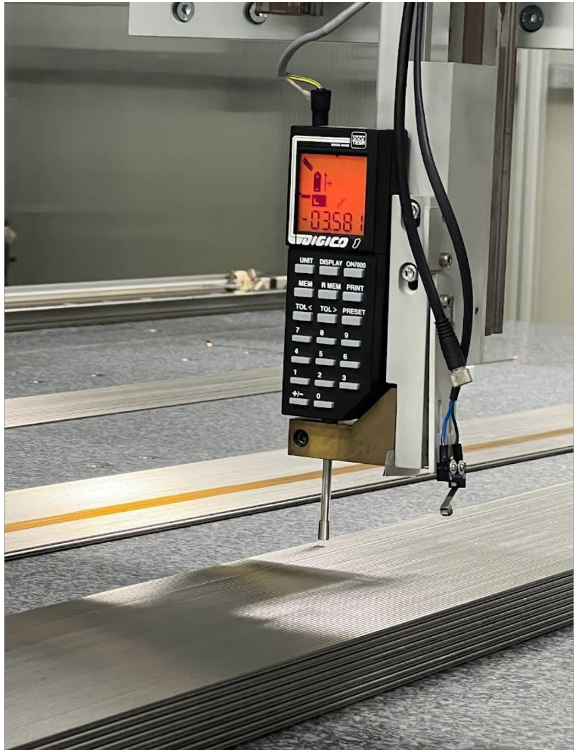
Tube aligned in a reference tool



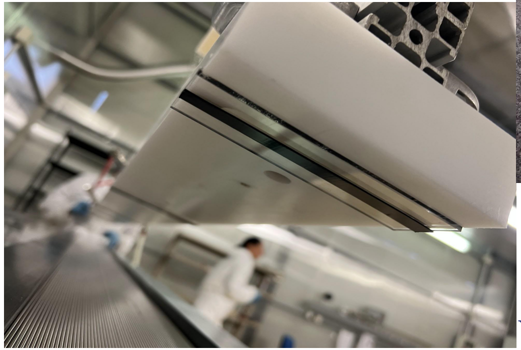
Stiffback-like technique for tube handling, glueing and positioning in the assembly tool







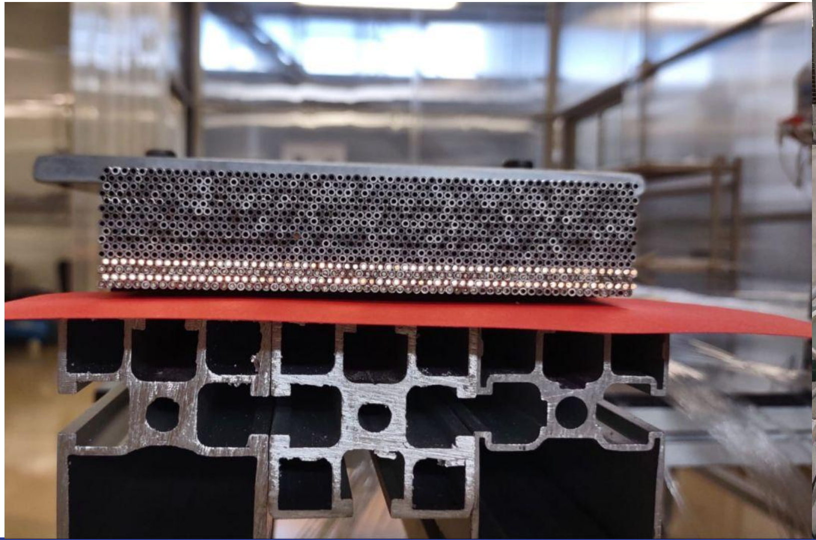
Semi-automatic system for planarity QAQC



Vacuum + double-sided tape for tube handling

Conclusions:

- Dual-Readout is a promising technique for precision studies at future colliders
- Proof of principle demonstrated in 20 years of R&D
- Highly granular prototypes construction and characterization ongoing
- Target: have a fully-understood calorimeter for the IDEA detector at FCC/CepC



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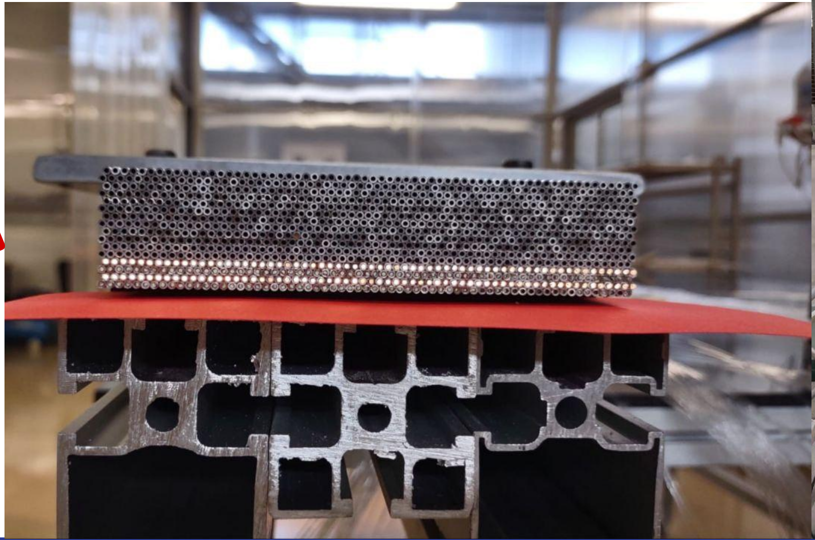
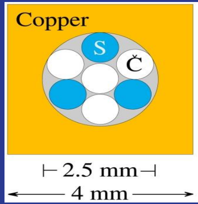


BACKUP

Long story short

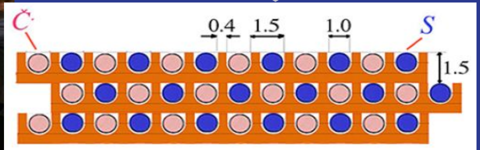
DREAM (2003),
Texas Tech Uni

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



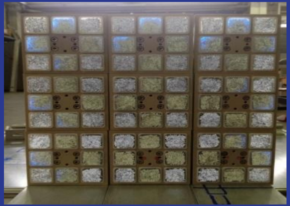
RD52 (2012),
INFN Pisa

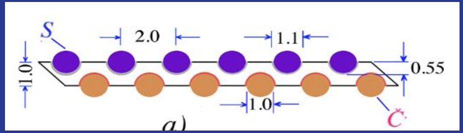
Copper, 2 modules,
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT.
Sampling fraction: 4.5%, 10 λ_{int}



RD52 (2012)
INFN Pavia

Lead, 9 modules,
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}



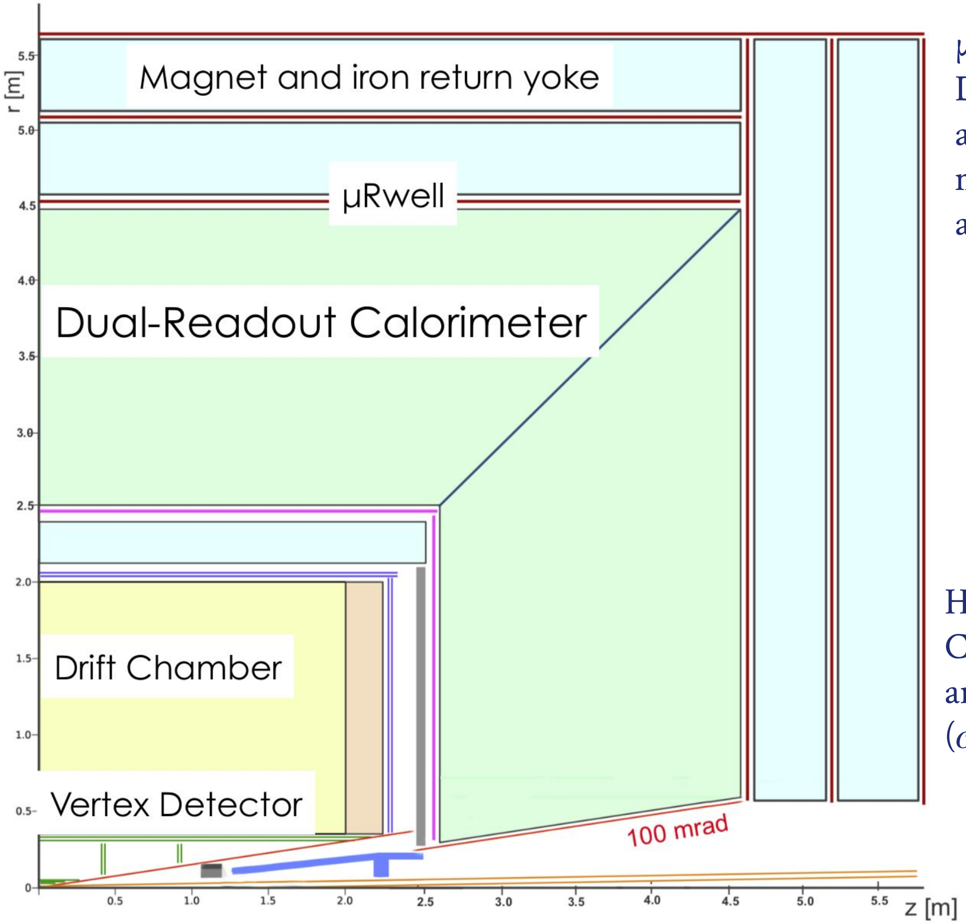


IDEA Detector

2T magnetic field solenoid located between tracking and calorimeter volumes

Dual-Readout Calorimeter for both EM and hadronic showers
Also crystal based DR ECAL taken into consideration

Vertex detector based on pixel sensors, targeting few micron resolution



μ-RWELL MicroPattern Gas Detector stages for muon ID and momentum measurement located before and after the calorimeter

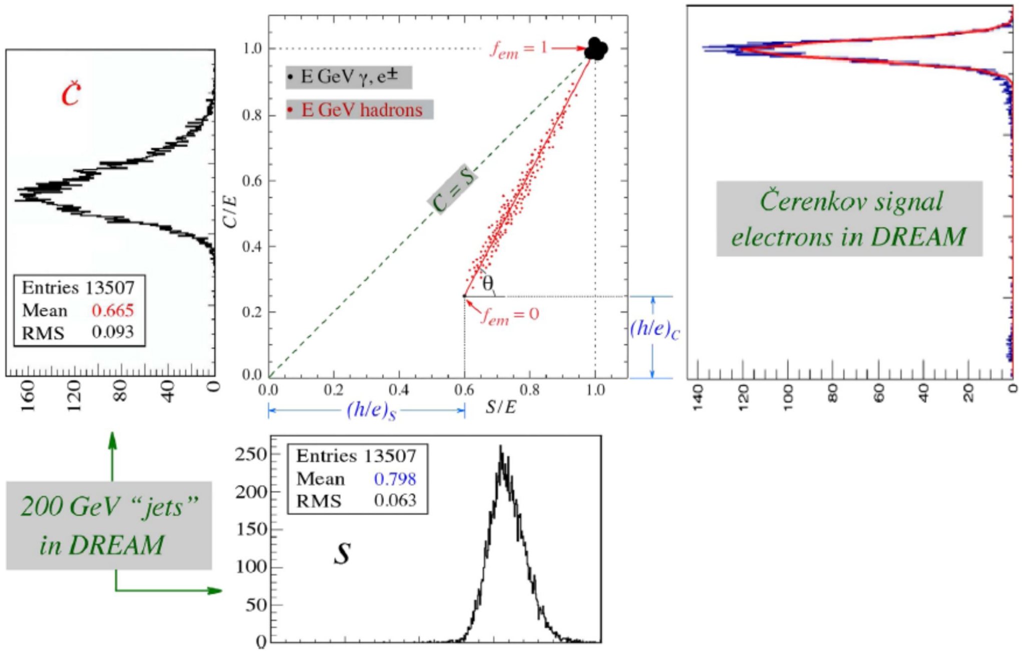
High-transparency Drift Chamber for excellent PId and spatial resolution (σ<100μm)

Dual-Readout Calorimetry

Before Dual-Readout correction:
Scintillating and Cerenkov signals do not match the correct energy for hadron showers

$$\frac{S}{E} \neq 1, \; \frac{C}{E} \neq 1$$

Non-linearity of the reconstructed energy due to the dependence of the electromagnetic fraction f_{em} on energy E



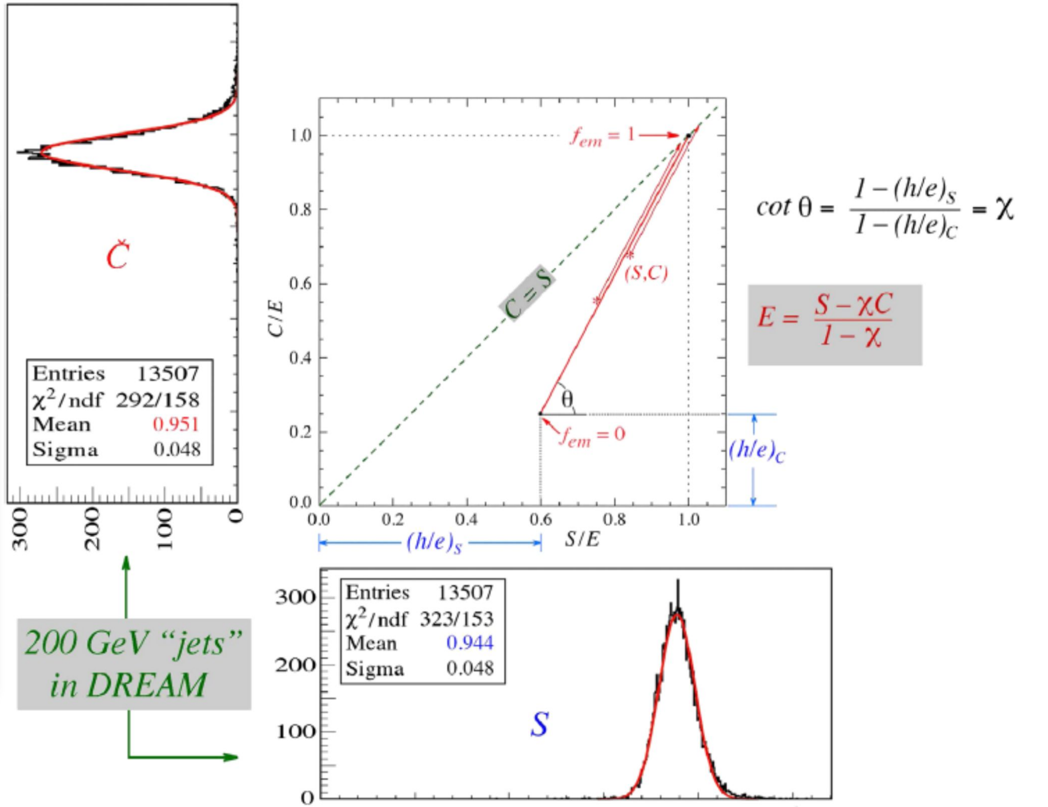
Dual-Readout Calorimetry

After Dual-Readout correction:
Estimating the f_{em} on event basis we can restore the linearity of the calorimeter response

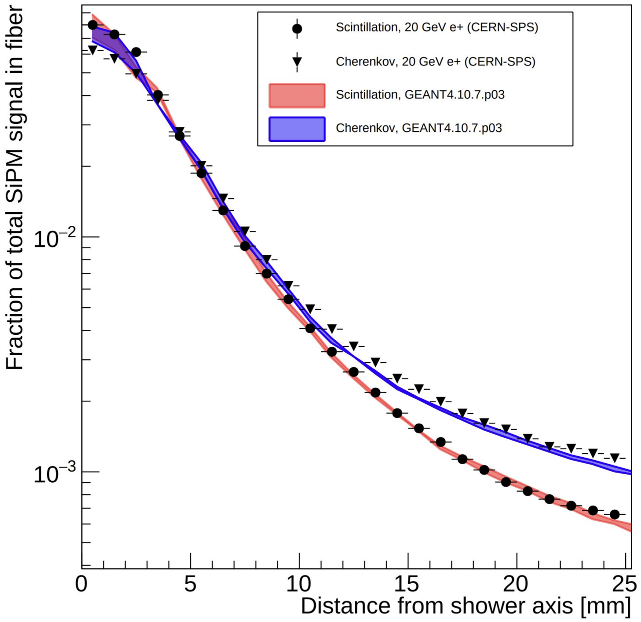
$$\frac{S}{E} \simeq 1, \; \frac{C}{E} \simeq 1$$

Reconstructed energy closer to the correct one

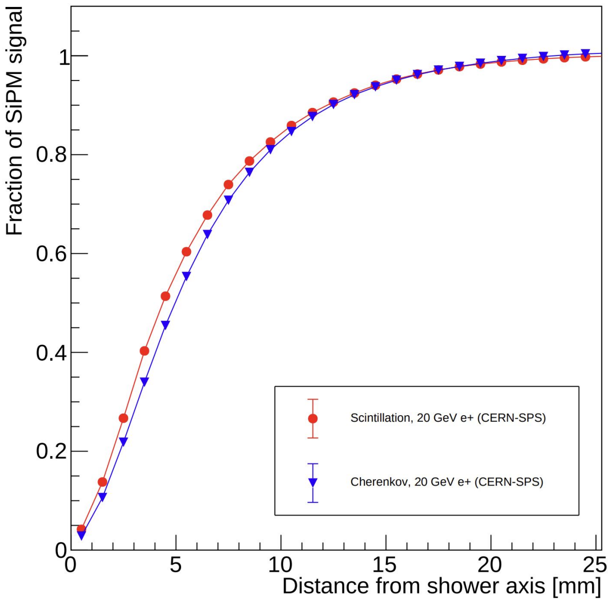
Proof of principle prototypes built and tested within the DREAM/RD52 collaboration



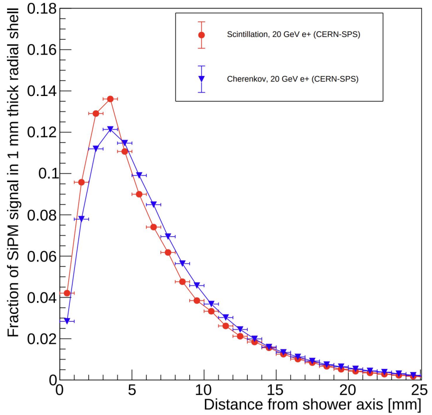
TB2021



Fraction of total SiPM signal in fiber
10^{-2}
10^{-3}
0
5
10
15
20
25
Distance from shower axis [mm]
Scintillation, 20 GeV e+ (CERN-SPS)
Cherenkov, 20 GeV e+ (CERN-SPS)
Scintillation, GEANT4.10.7.p03
Cherenkov, GEANT4.10.7.p03

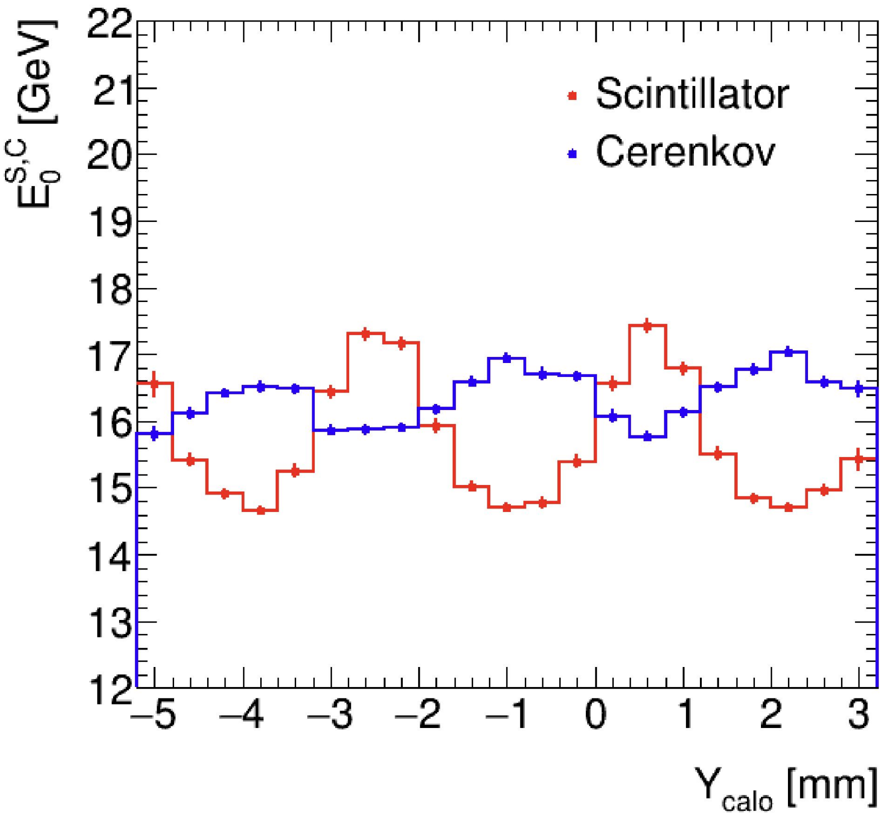


Fraction of SiPM signal
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
Distance from shower axis [mm]
Scintillation, 20 GeV e+ (CERN-SPS)
Cherenkov, 20 GeV e+ (CERN-SPS)

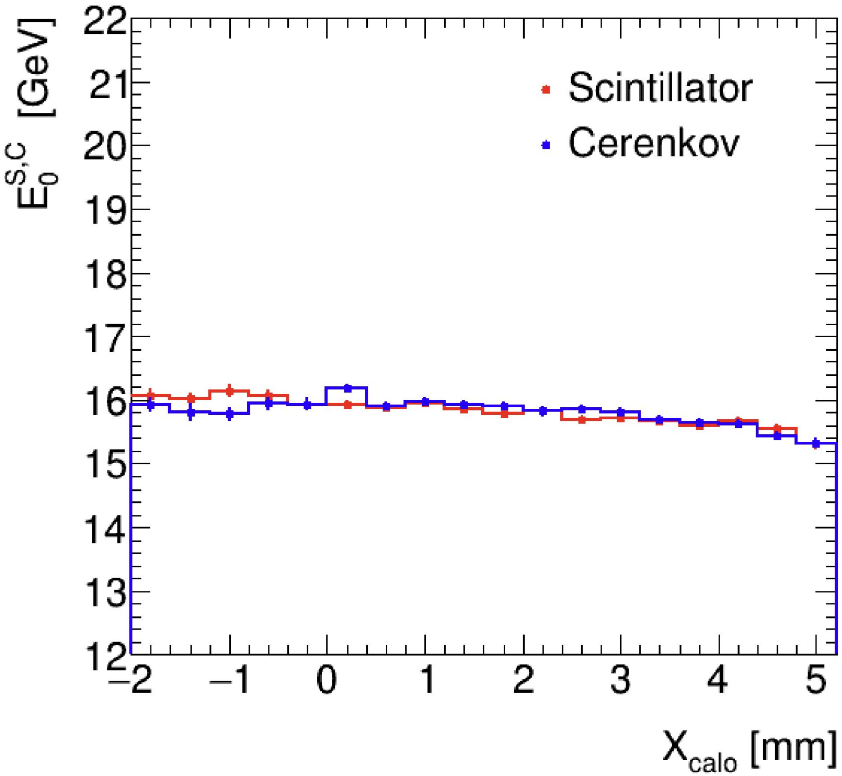


Fraction of SiPM signal in 1 mm thick radial shell
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0
5
10
15
20
25
Distance from shower axis [mm]
Scintillation, 20 GeV e+ (CERN-SPS)
Cherenkov, 20 GeV e+ (CERN-SPS)

TB2021

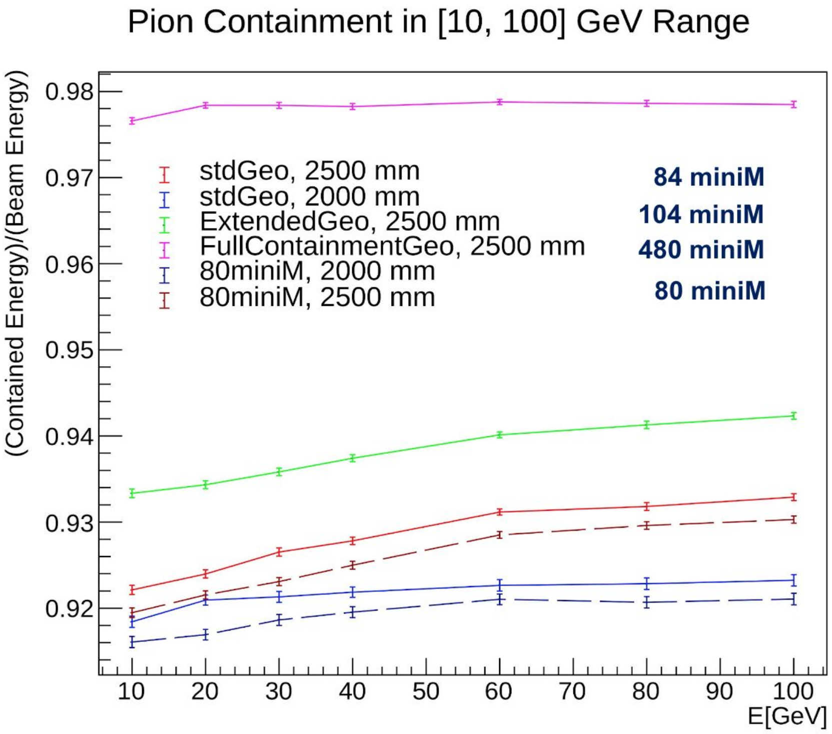


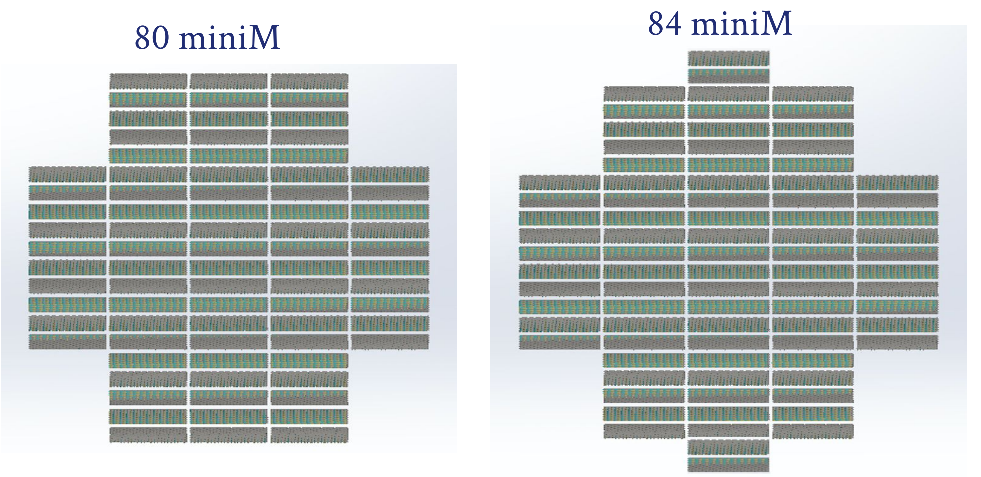
$E_0^{S,C}$ [GeV]
Scintillator
Cerenkov
Y_{calo} [mm]

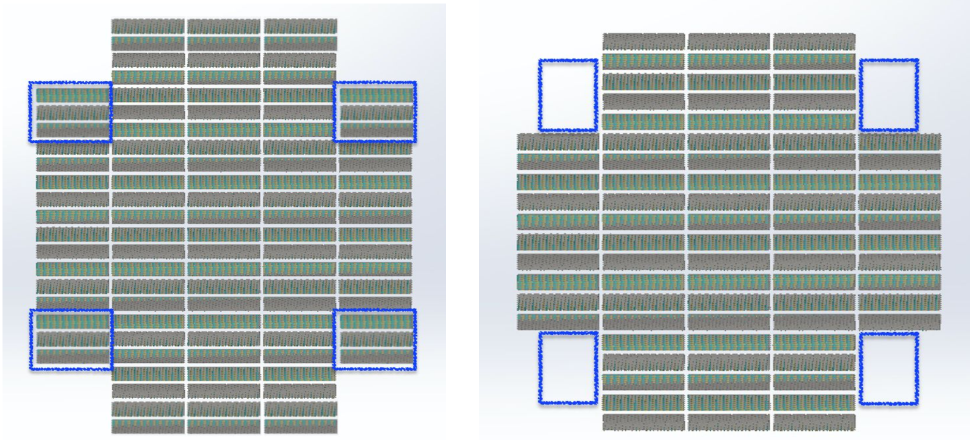


$E_0^{S,C}$ [GeV]
Scintillator
Cerenkov
X_{calo} [mm]

Containment studies

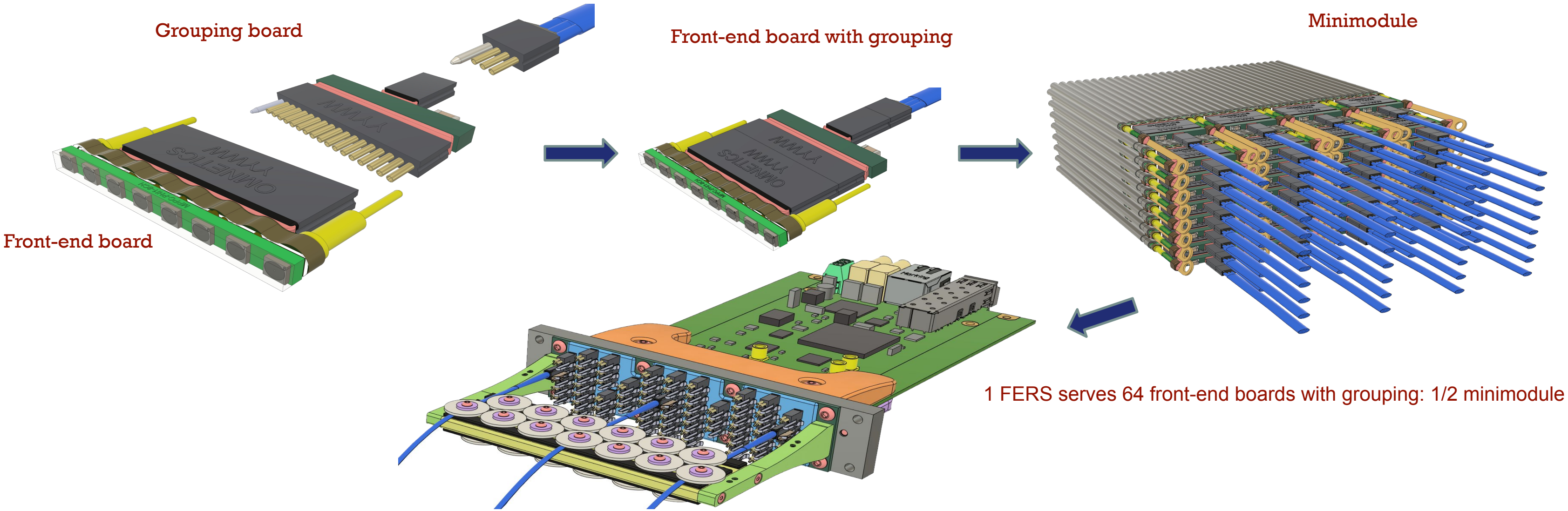






"Extended Geo": 104 miniM

FEE-boards and cabling



Baseline solution

- Each bar of SiPMs operated at same voltage
- Signals from 8 SiPMs summed up grouping board
- 2 FERS operate 1 full minimodule
- 20 FERS operate high-granularity core of HiDRa prototype

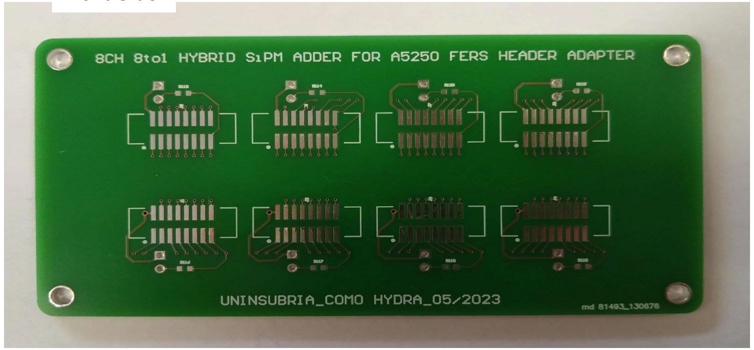
SiPMs for DR prototypes

Table 1. Main figure of the SiPM used for the em-size prototype compared with the SiPMs considered for the had-size prototype. The numbers are extracted from the vendor's specifications and are referred to an operating temperature T = 25 °C.

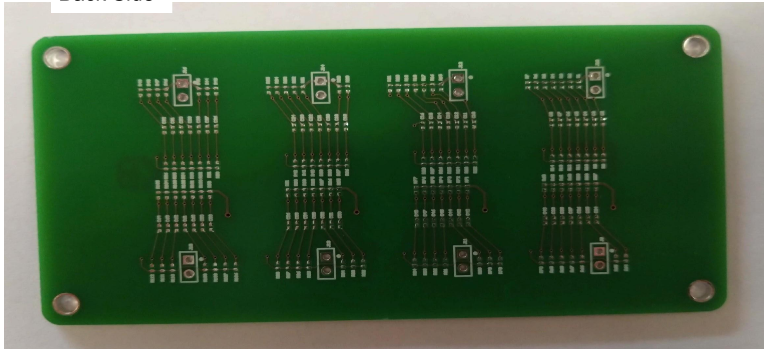
	TB2021	HiDRa, Cerenkov	HiDRa, Scintillator
Parameter	S14160-1315PS	S16676-15(ES1)	S16676-10(ES1)
Effective photosensitive area (mm^2)	1.3×1.3	1×1	1×1
Pixel pitch (μm)	15	15	10
Number of pixels	7284	3443	7772
Recommended operating voltage (Vop)	+4 V	+4 V	+5 V
PDE at the Vop (%)	32	32	18
Direct cross talk at the Vop (%)	< 1	< 1	< 1
Dark count rate (kHz)	120 (360 max)	60 (200 max)	60 (200 max)
Gain (10^5)	3.6	3.6	1.8

Grouping board

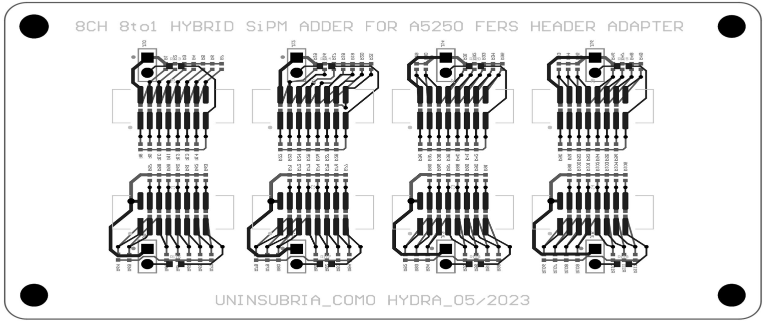
Front Side



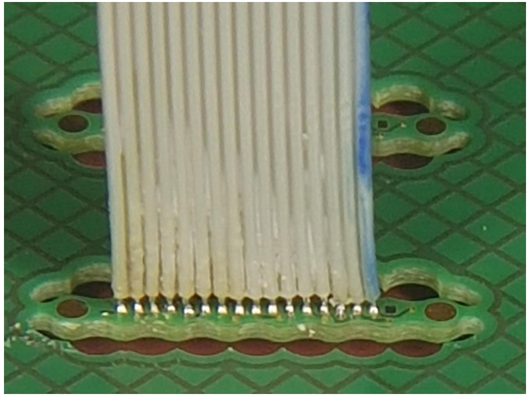
Back Side

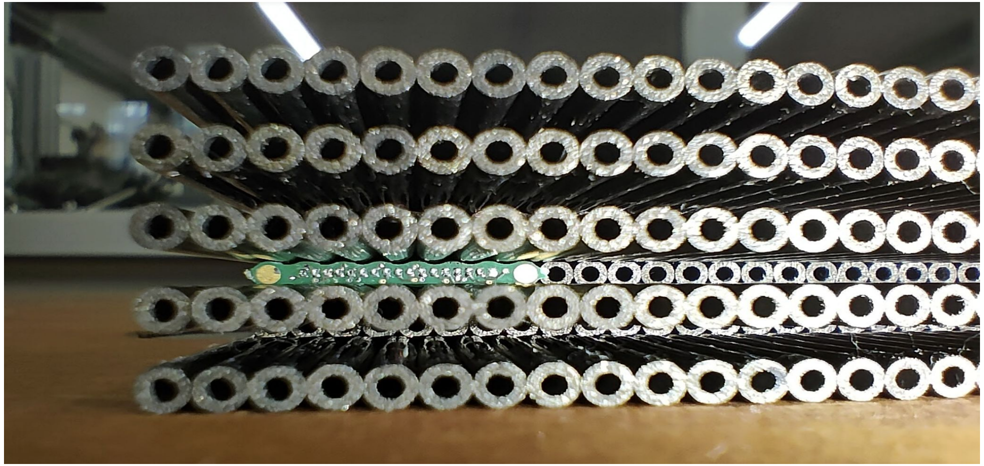


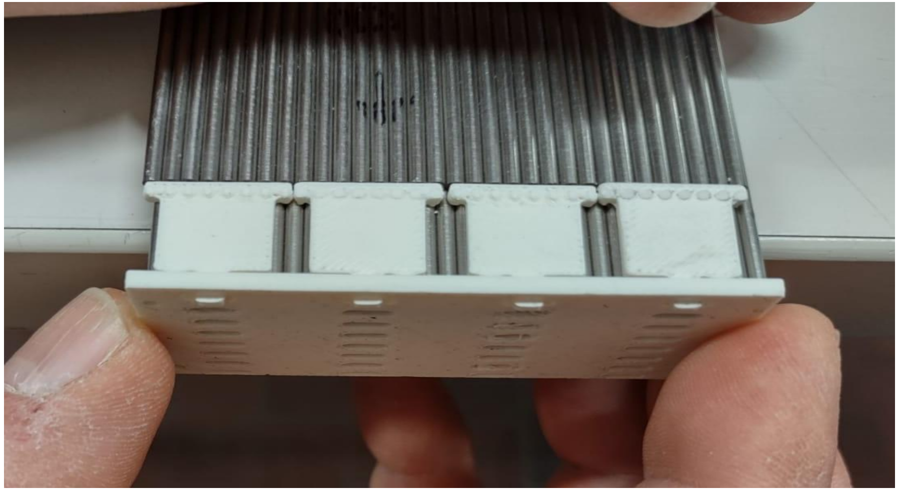
- Grouping board only for test purposes. Once design frozen, it will be fully integrated
- Supports up to 8 front-end boards and is connected to FERS A5202 with patch-panel A5250
- Two grouping schema will be tested and compared
- Passive components will be mounted in lab to have maximum flexibility



Frontend Board

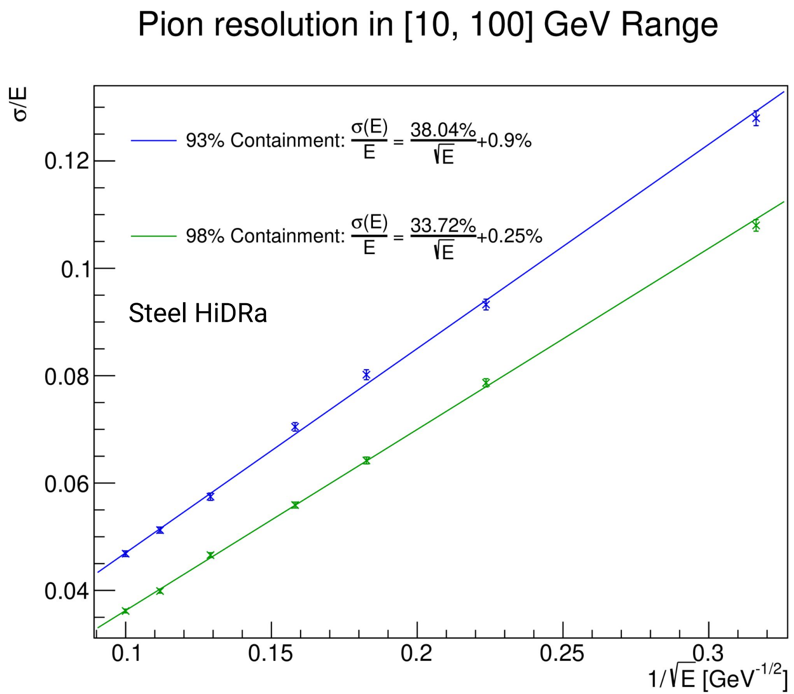


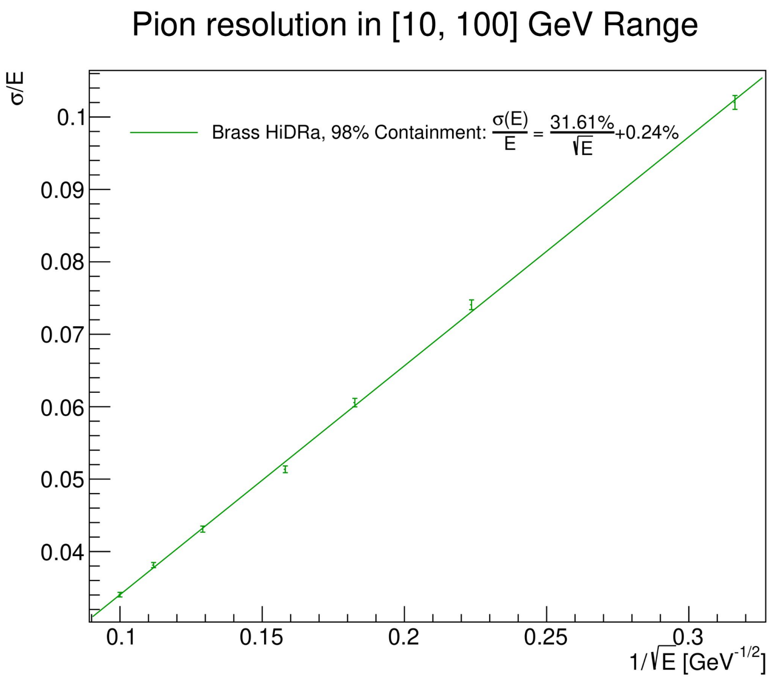




HiDRa energy resolution

Dependence of the energy resolution for hadrons on the overall containment
Add mini-modules in the simulation to estimate resolution for larger calorimeters

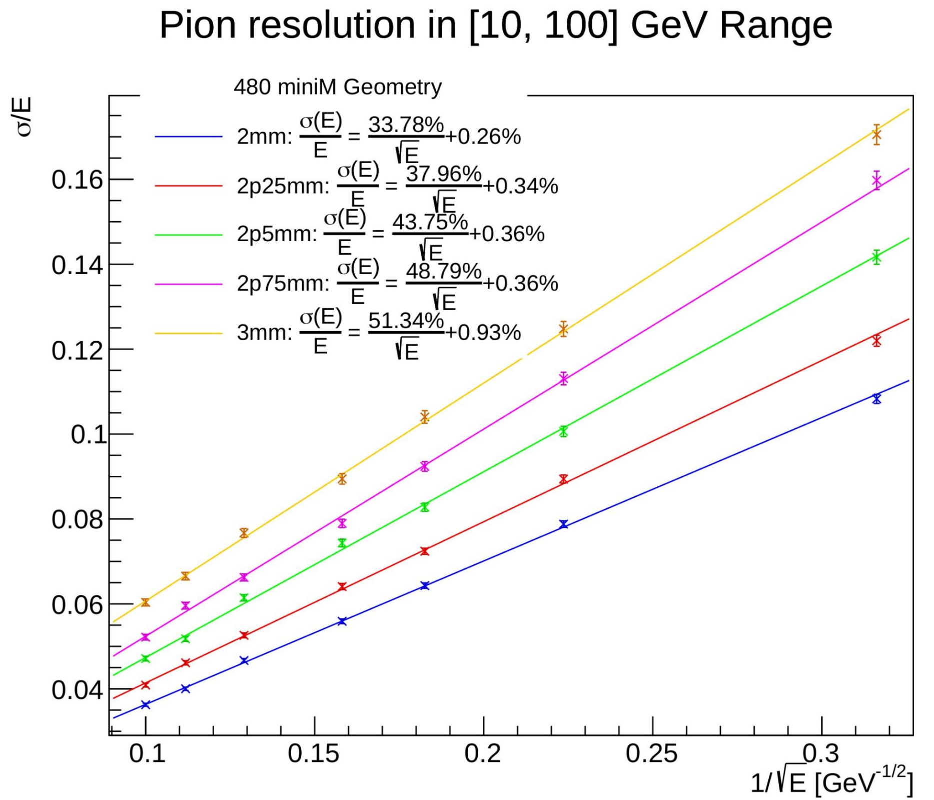




Resolution Vs Sampling Fraction

See the effect of increasing the capillary absorber outer diameter in the G4 simulation

Using the same geometry (480 mini-modules here) if one increases the outer diameter also the whole prototype containment increases



High-Granularity

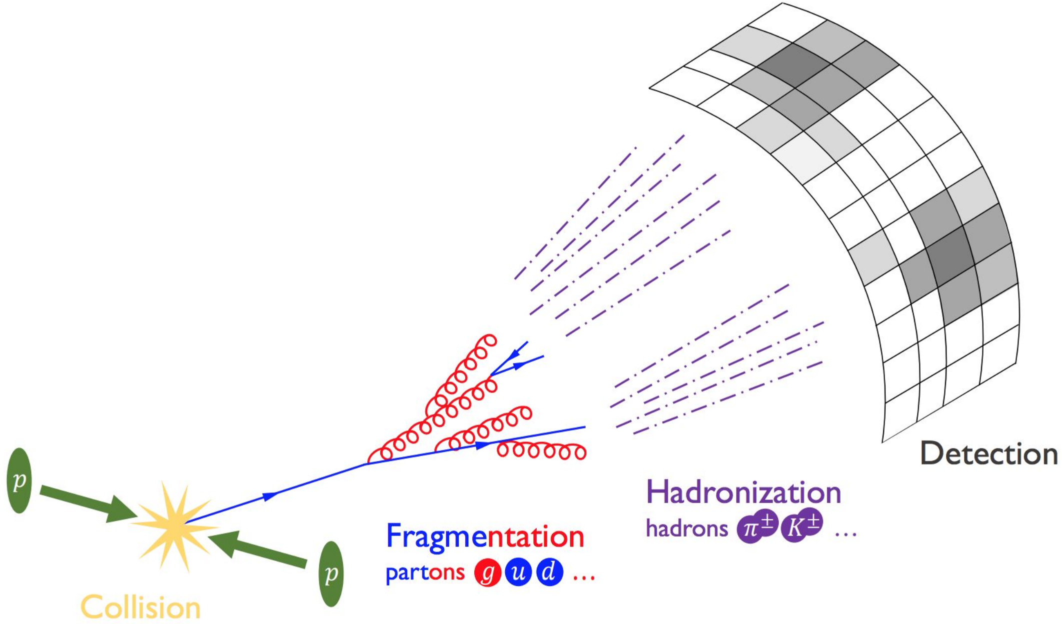
1mm fiber diameter with independent SiPM readout

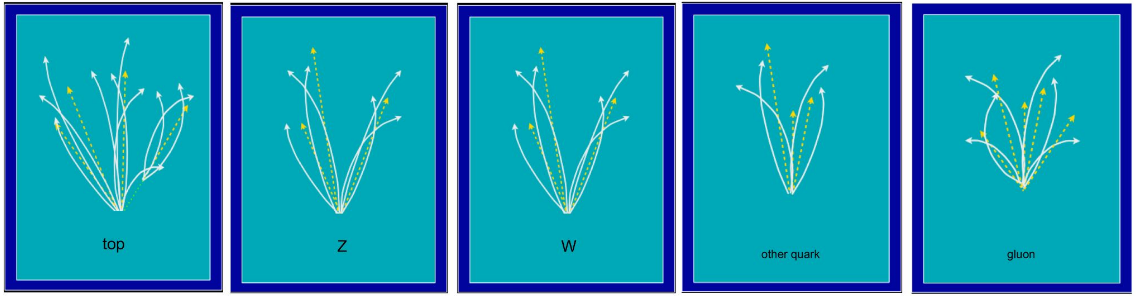
Exploit ~$O(10)$ picosecond SiPM timing information to recover longitudinal segmentation
→ **Particle Flow-friendly calorimeter**

Allows 3D event reconstruction and unveiling shower sub-structures

Large amount of data to deal with
~74M channels for IDEA calorimeter

Extensive Deep Learning applications to take advantage of both DR + high granularity





t→bW→bqq **Z→qq** **W→qq** **q/g background**

Future developments on DR

Combined effect of Dual Readout and Particle Flow, taken from https://arxiv.org/pdf/2202.01474.pdf

Crystal-based, Dual-Readout ECAL was used here to obtain the plots with Particle Flow