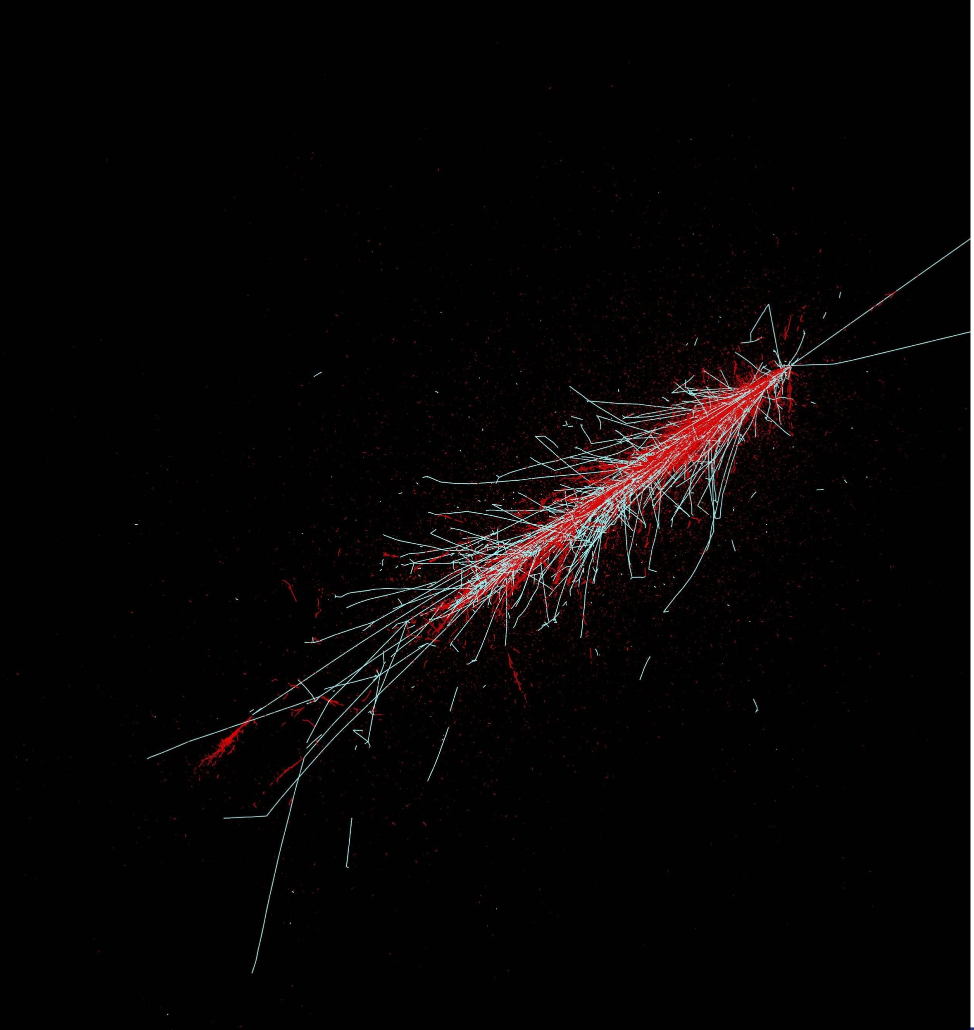
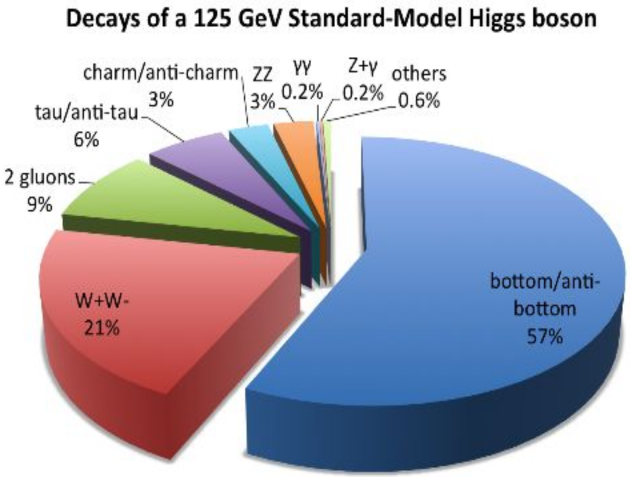
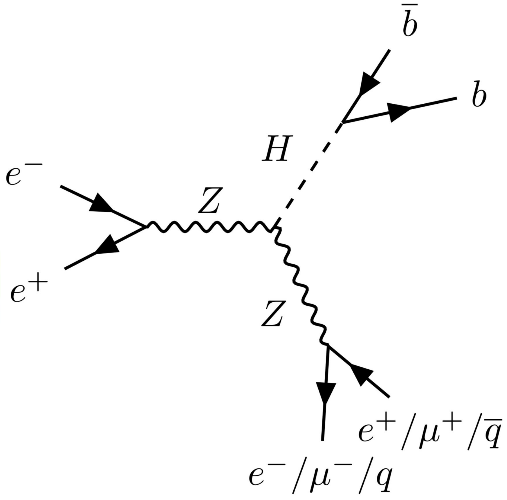
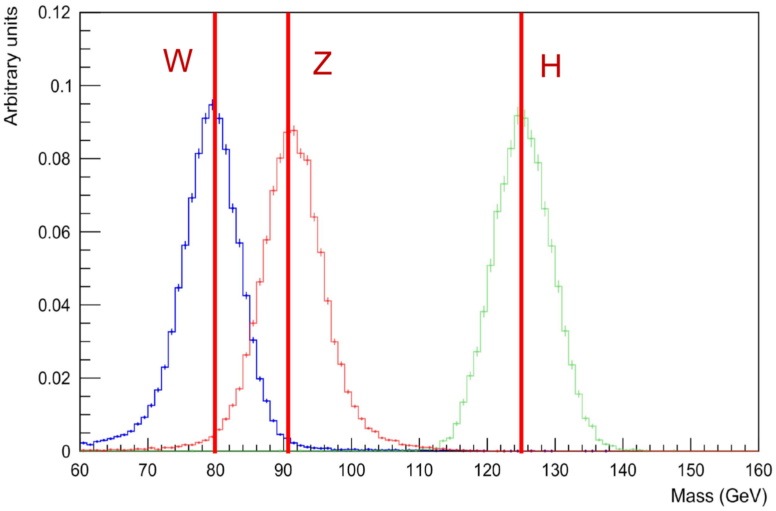


Updates on Dual-Readout fiber calorimeters

Andrea Pareti - INFN and Università di Pavia
2023 International Workshop on Circular Electron Positron Collider - 04/07/2023







Jet measurement benchmarks

Large W/Z/H hadronic branching ratio:
Good jet energy resolution is fundamental for future collider measurements

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

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

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

Experimental Challenges

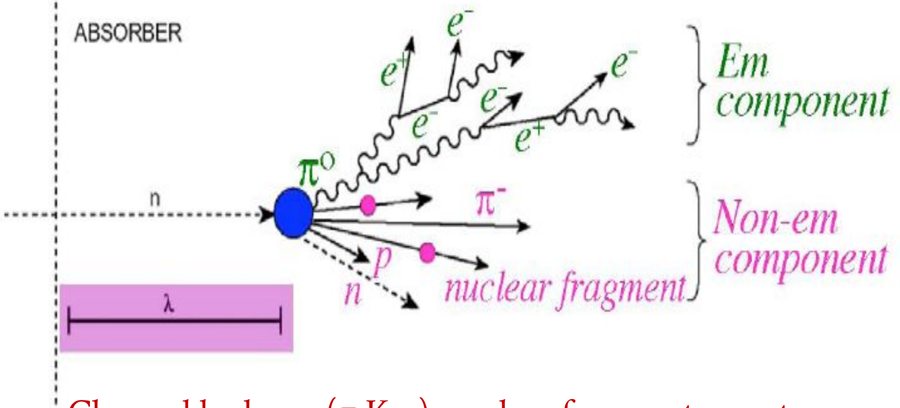
Any hadronic shower has two components, *em* and *non-em*, to which the calorimeter response is different: $\frac{e}{h} \neq 1$

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

Hadronic jet reconstruction problems:

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

electrons, positrons, photons, π^0



Charged hadrons (π,K…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Dual-Readout Calorimetry

Idea: use two different physical processes to better sample each incoming object → evaluate shower f_{em}

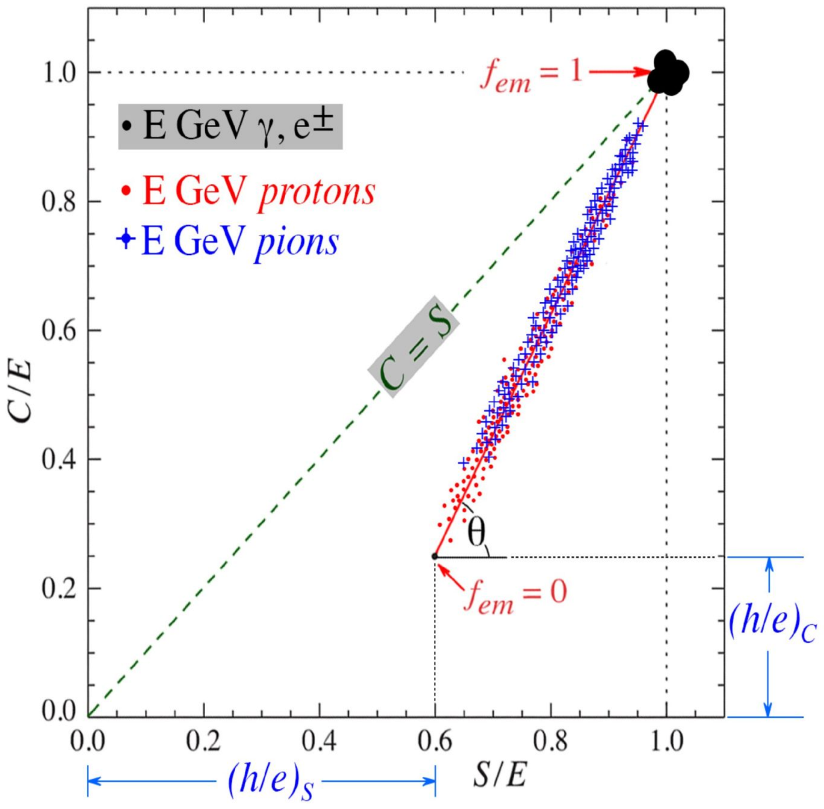
- Scintillation light:
  - ➢ measure total energy deposition
- Cerenkov light:
  - ➢ sensitive to relativistic particles, mostly due to the *em* component of the shower

The responses to hadronic and electromagnetic showers $\left(\frac{h}{e}\right)_S, \left(\frac{h}{e}\right)_C$ are detector-dependent parameters to be measured

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

Given the particle energy estimated by scintillation (S) and Cerenkov (C) signals, one can correct the reconstructed energy

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

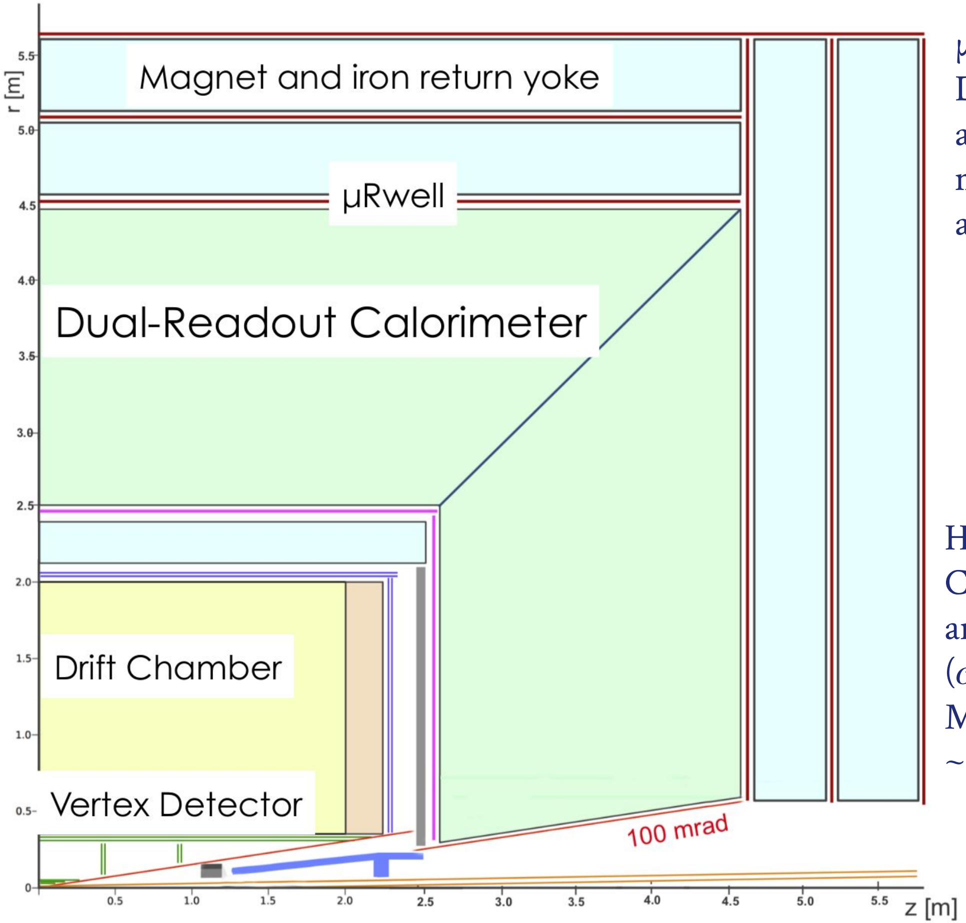


IDEA Detector

2T magnetic field solenoid located between tracking and calorimeter volumes

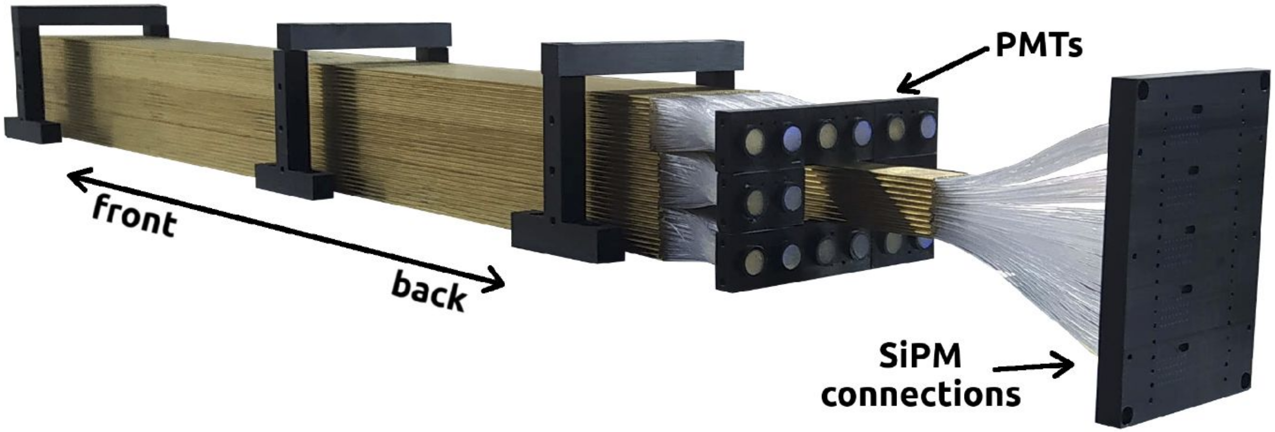
Dual-Readout Calorimeter for both EM and hadronic showers
Also crystal based DR ECAL taken into consideration

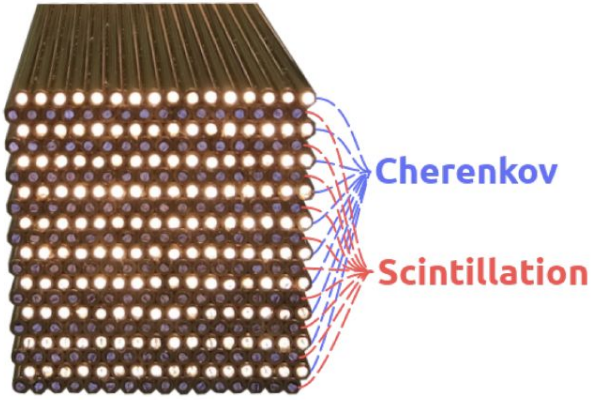
Vertex detector based on pixel sensors, targeting few micron resolution



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)
Momentum resolution: ~28% for 100 GeV tracks





Dual-Readout fiber calorimeter

Drive towards highly-granular design:

- ➢ Particle Identification
- ➢ Heavy-Flavour jet tagging

Fiber Calorimeter:
Longitudinally unsegmented fiber calorimeter
Modular design with alternating rows of Scintillating or Cerenkov fibers

One calorimeter for both electromagnetic and hadronic showers

- ➢ Only one calibration with electron is required
- ➢ Excellent spatial and angular resolution

SiPM Readout

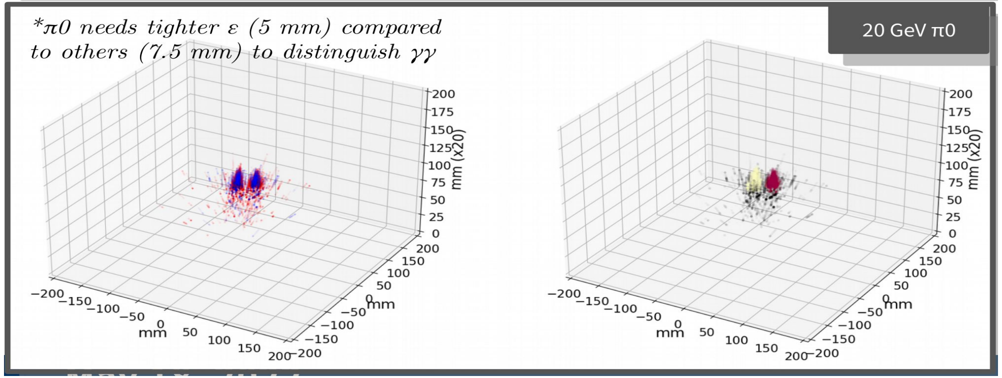
1mm fiber diameter with independent SiPM readout

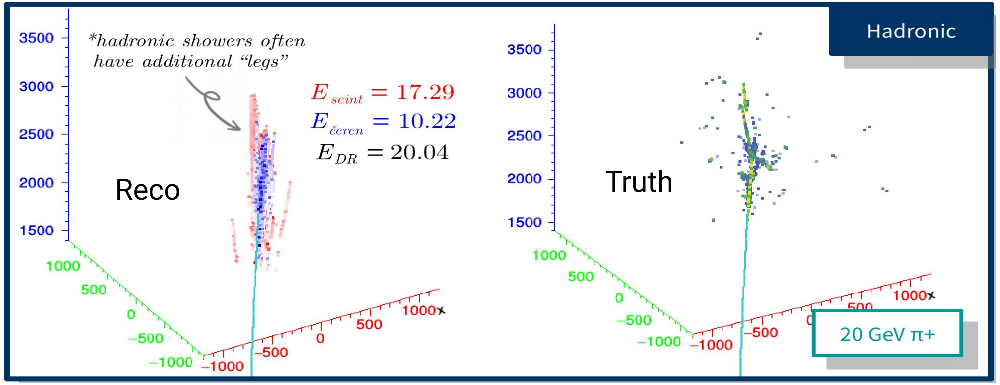
Exploit ~$O(10)$ picosecond SiPM timing information to recover longitudinal segmentation
→ **Particle Flow-friendly calorimeter**

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



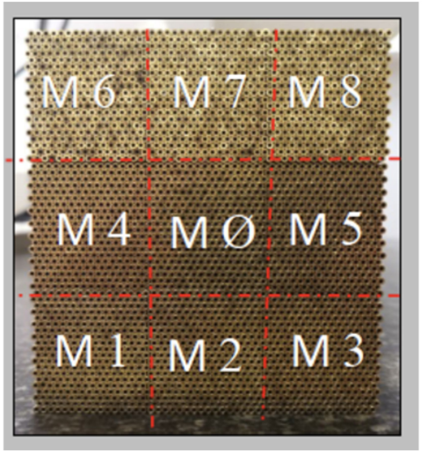


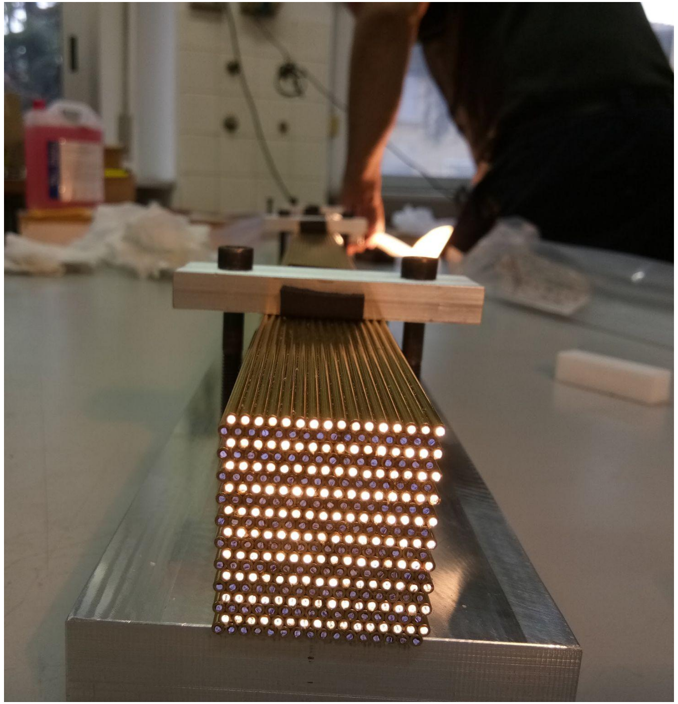
See Ko's talk:

EM shower-sized prototype

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

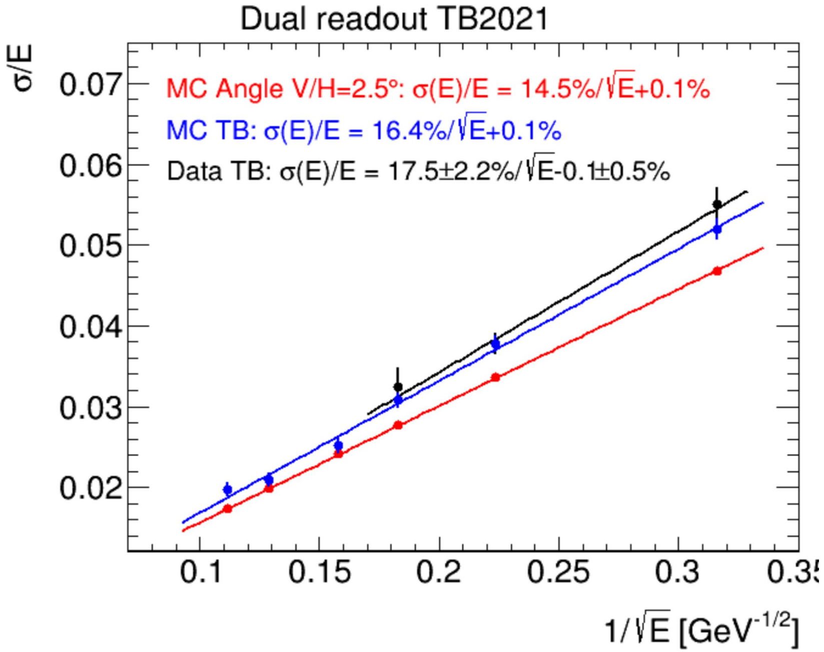
9 modules made of 16x20 capillaries
M0 readout with SiPMs, M1-M8 with PMTs
→ 320 SiPMs
SiPMs with packages small enough were not ready at the time,
fibers in M0 leaking out from the back of the calorimeter

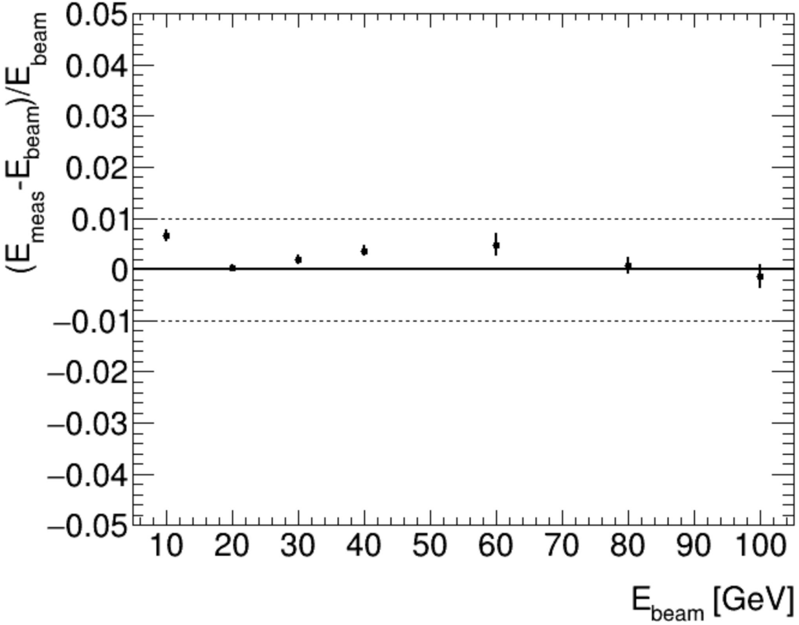




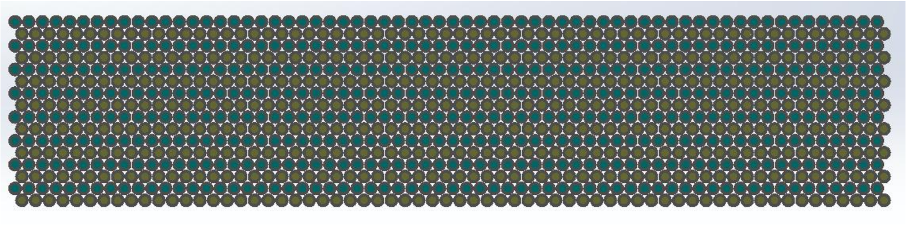
EM shower-sized prototype

Energy Resolution found to be dependent on fiber orientation with respect to beam axis
Simulation seems to be in good agreement with test beam conditions
Under beam test this week for further characterization





HiDRa Prototype

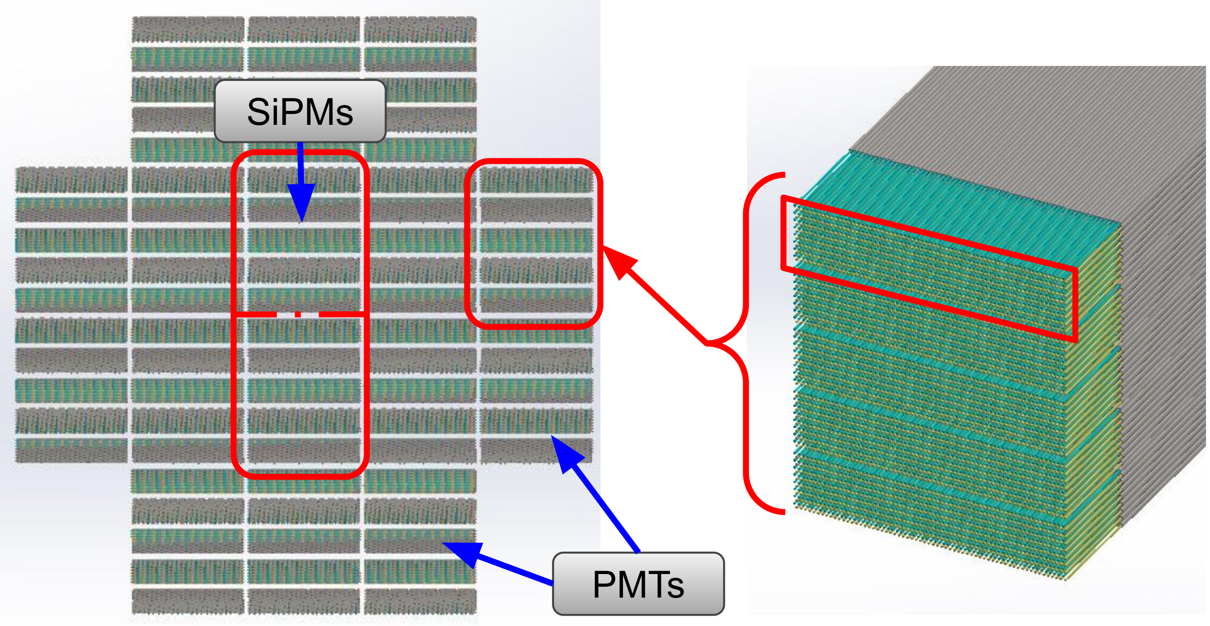


Demonstrate the feasibility of the Dual Readout technique in association with SiPM readout, with high-energy test beams

Each mini-module is readout by two PMTs, one for S fibers and the other for C fibers

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

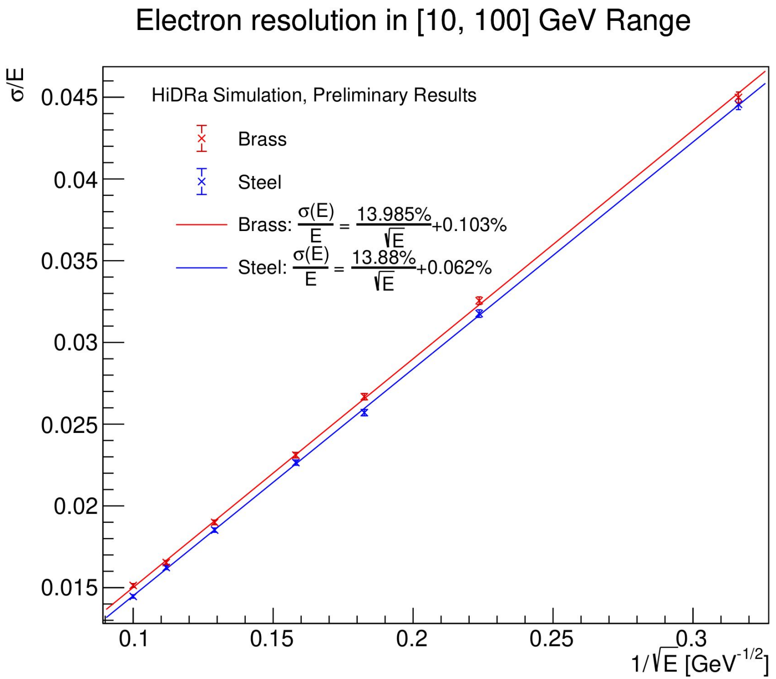
10 mini-modules readout with SiPMs, all others with PMTs
→ Cost/Performance optimization
→ Gradual increase in DAQ complexity (10240 SiPMs)

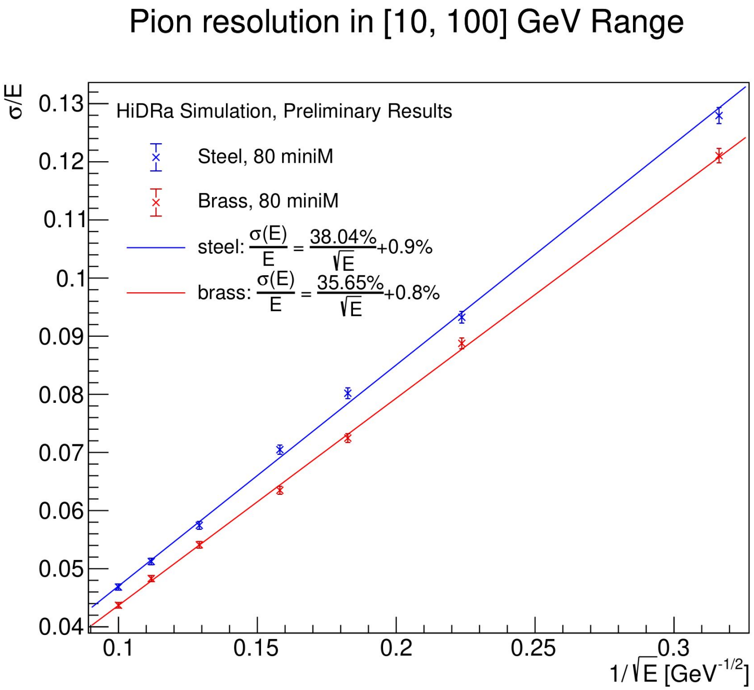


HiDRa Performance

Geant4 Simulation-based expected resolution for the HiDRa prototype, for electrons and pions respectively

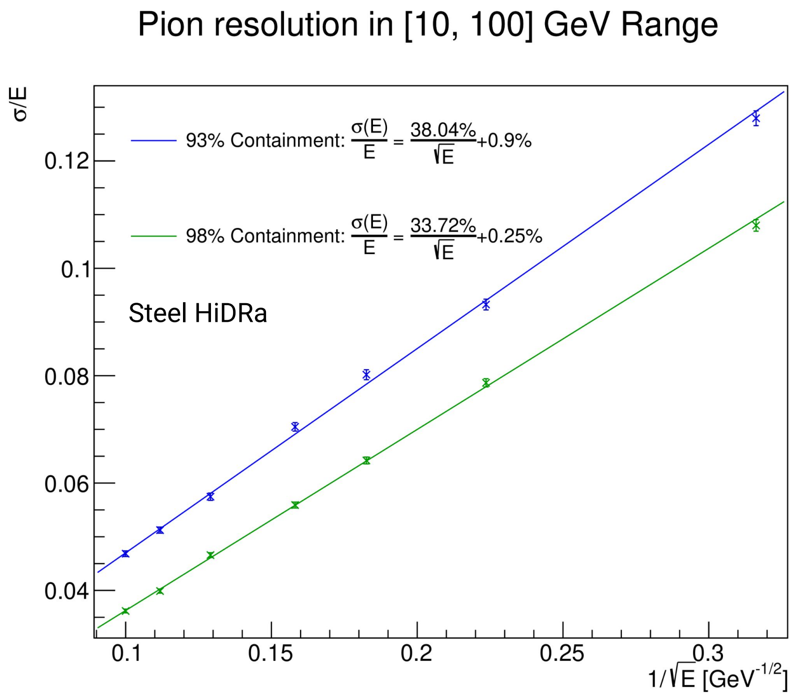
Brass absorber material seems to guarantee better results, but more expensive to produce and use for a smaller-scale prototype

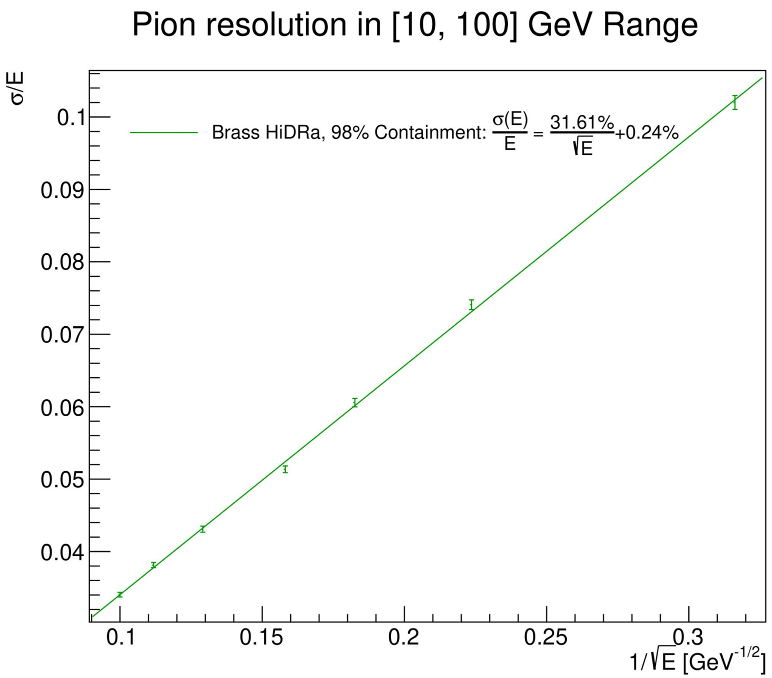




HiDRa Performance

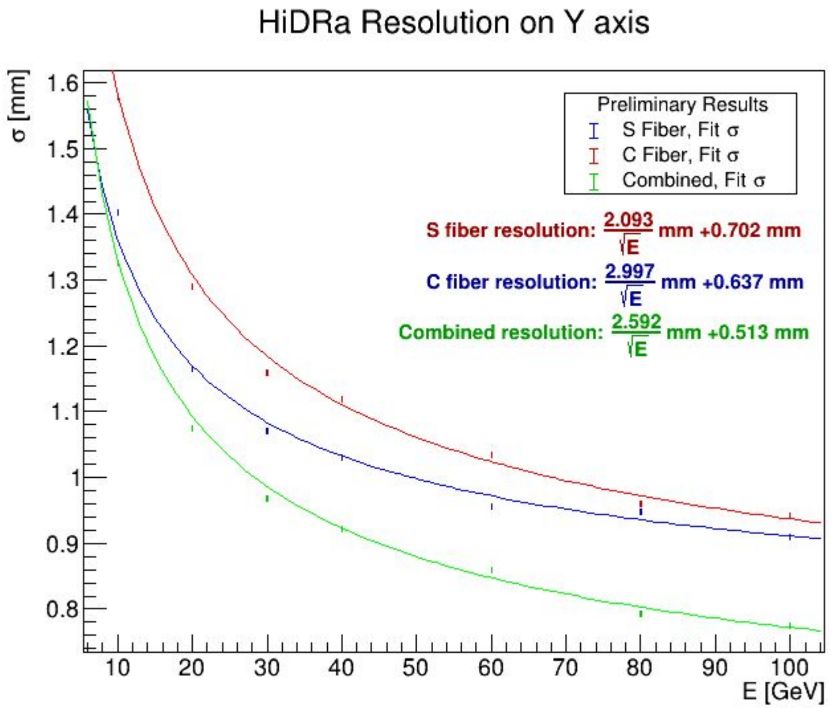
Dependence of the energy resolution for hadrons on the overall containment
Add mini-modules in the simulation to estimate resolution for larger calorimeters

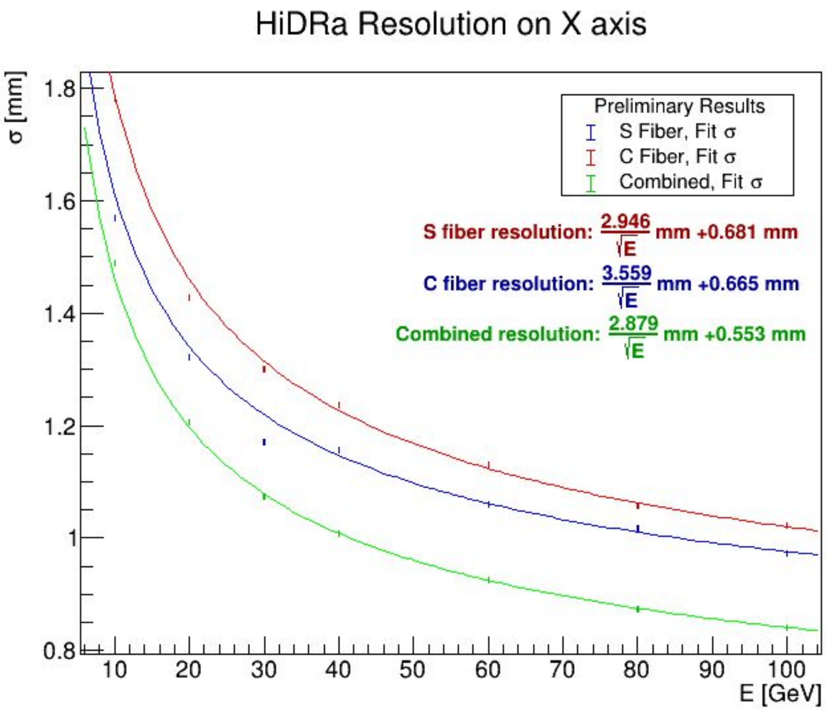




HiDRa Performance

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



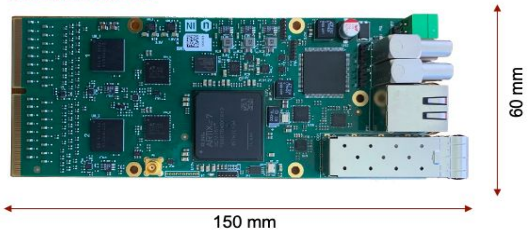


HiDRa SiPM integration & Readout

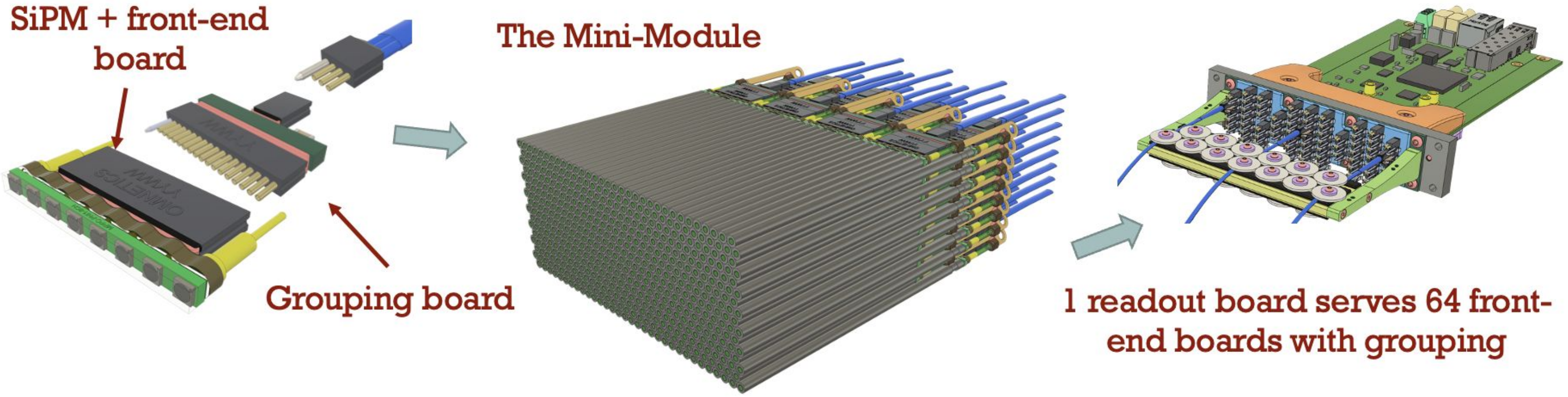
Custom designed module with 8 Hamamatsu SiPMs (1x1 mm^2)
2mm interspace between adjacent SiPMs
Two options under study: 10 and 15 μm pitch

First SiPM batch delivered (20 modules)
Frontend board in production
FERS patch panel design finalized & ready for production

FERS: A5202



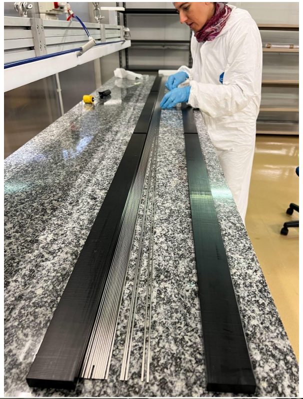
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

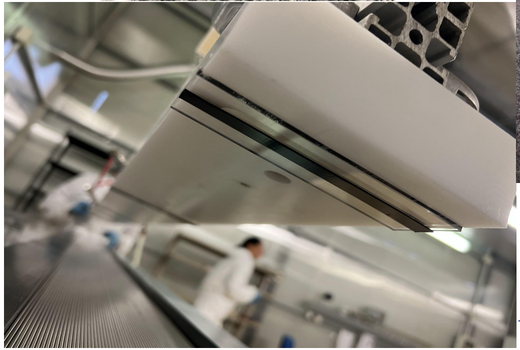


HiDRa first module construction

Definition of constructing technique and quality assessment on the modules geometry

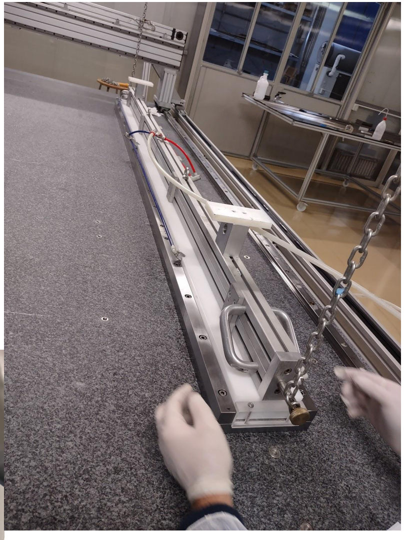
tube aligned in a reference tool

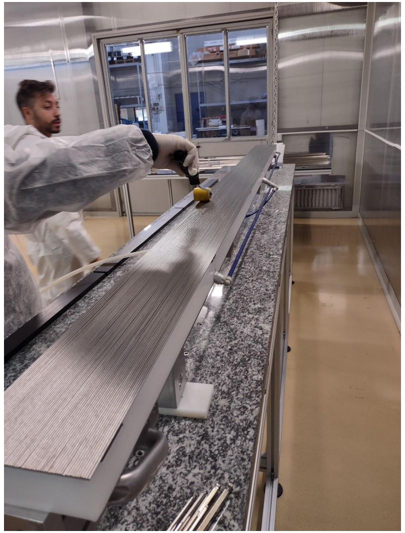


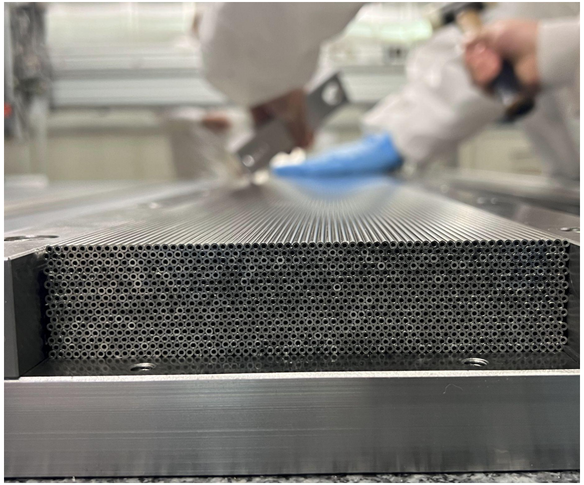


Vacuum + double-sided tape for tube handling

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



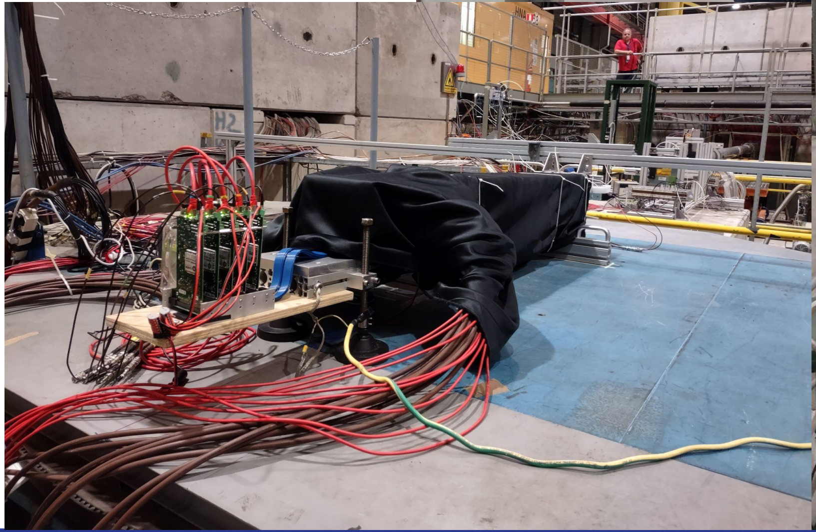




First mini-module constructed

…Let's get back to work

And Thank You!

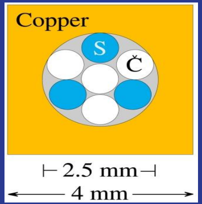


BACKUP

Long story short

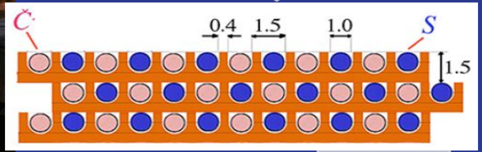
DREAM (2003),
Texas Tech Uni

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



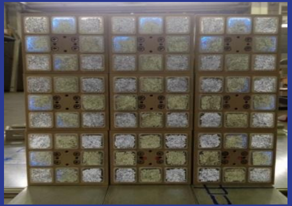
RD52 (2012),
INFN Pisa

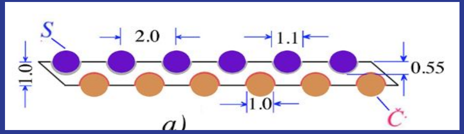
Copper, 2 modules,
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT.
Sampling fraction: 4.5%, 10 λ_{int}



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}



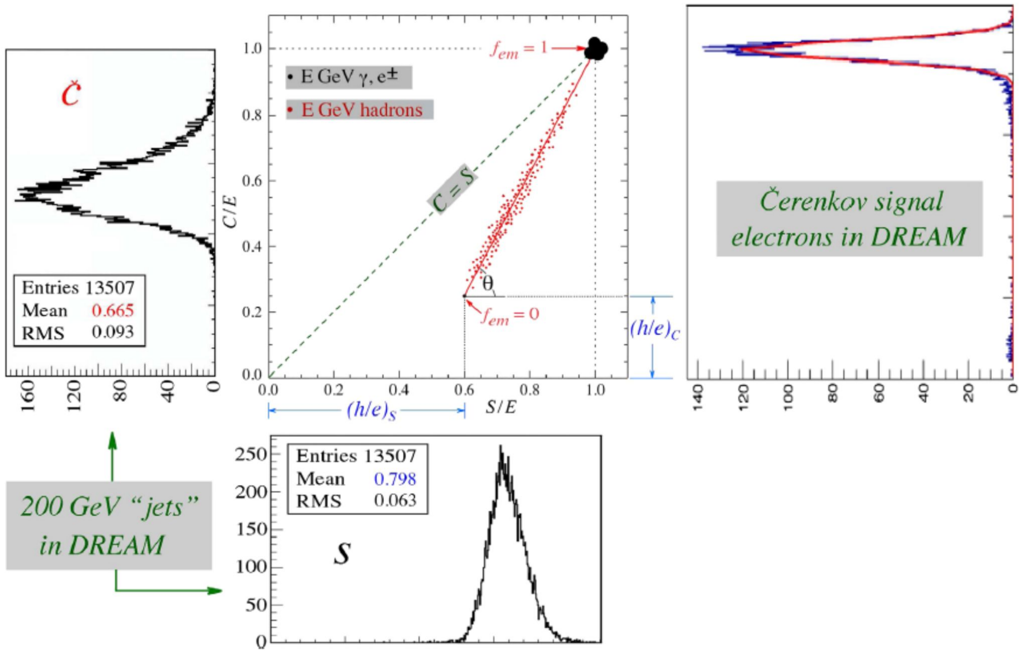


Dual-Readout Calorimetry

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



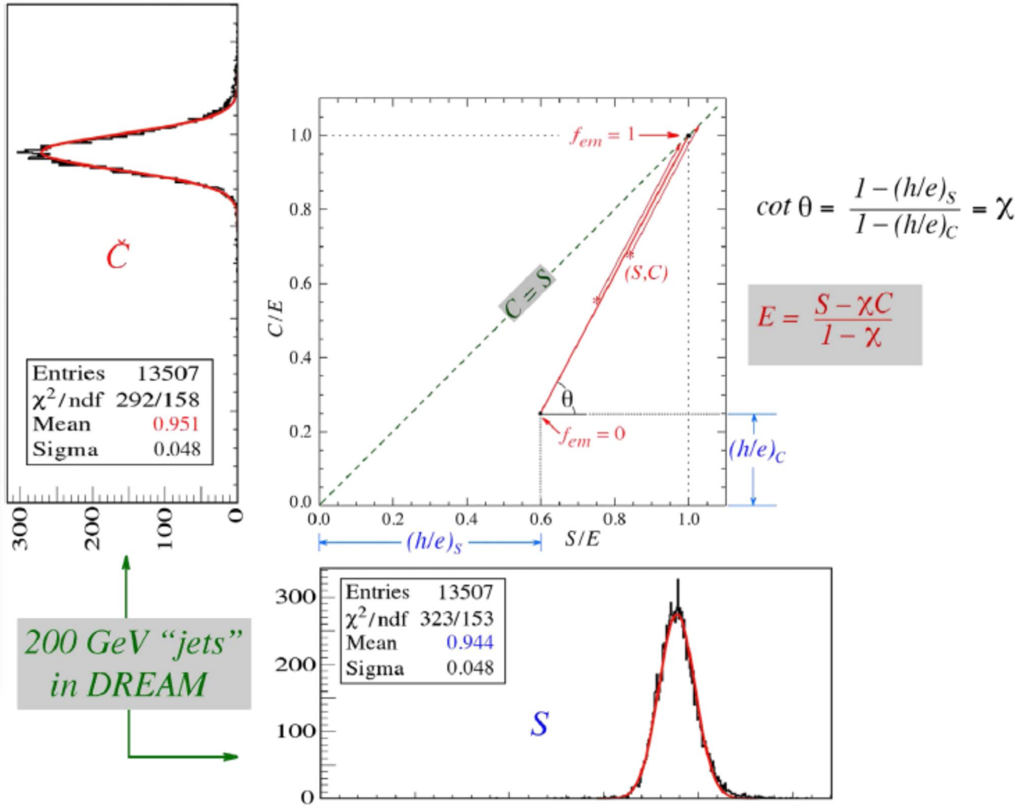
Dual-Readout Calorimetry

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

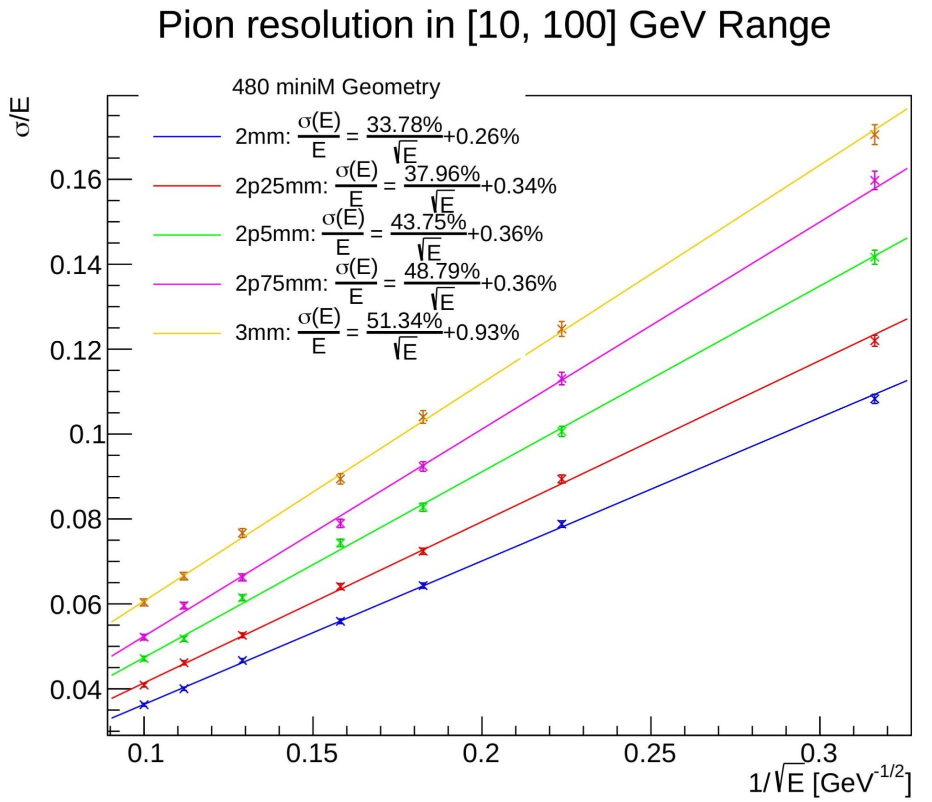
Proof of principle prototypes built and tested within the DREAM/RD52 collaboration



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



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