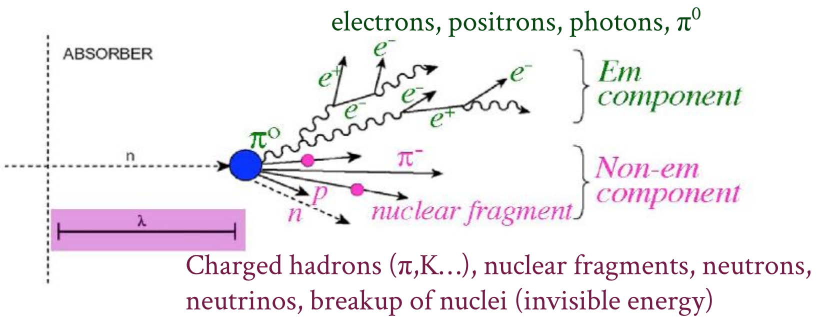
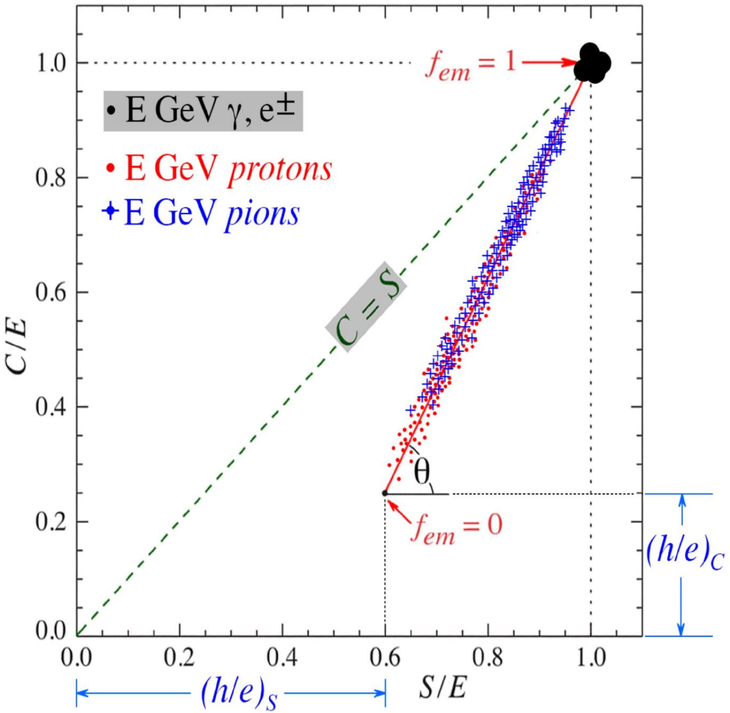
Updates on dual-readout fibre calorimeter development

Andrea Pareti - INFN and Università di Pavia

7th FCC Physics Workshop - Annecy, 30/01/2024

Dual-Readout in a nutshell





Non-linear response to hadron showers and fluctuations in f_{em} and invisible energy heavily affect calorimeters energy resolution

Dual-Readout: measure signals produced by two different physical processes to evaluate shower f_{em}

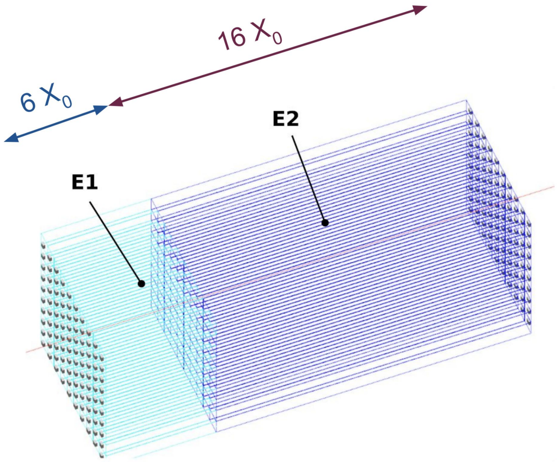
Given the particle energy estimated by scintillation (E_S) and Cerenkov (E_C) signals, one can correct the reconstructed energy

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

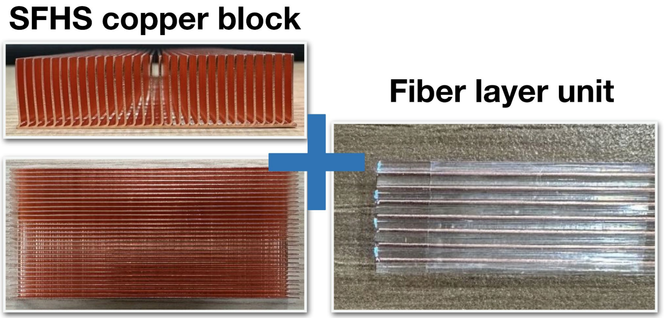
Overview on dual-readout calorimetry

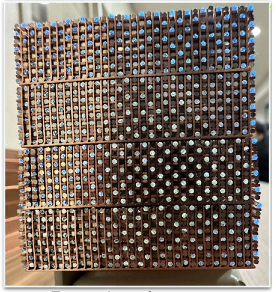
DR calo projects currently under development

Crystal-based, dual-readout ECAL in front of the hadronic one
See Sarah's talk



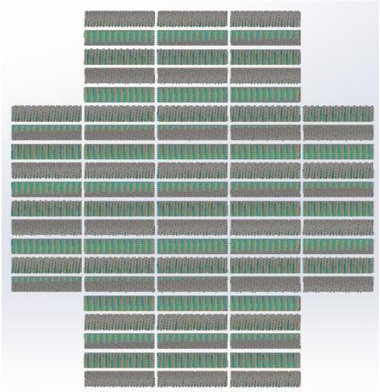
Skiving Fin Heat Sink technique from Korean team colleagues
Cho's presentation on prototype assembly

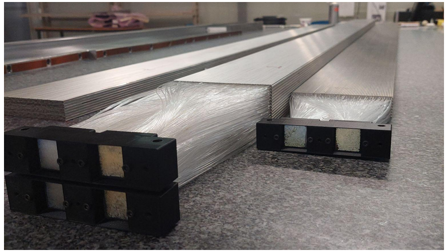




Front size of a tower

Capillary tubes calorimeter from "Europe" team (INFN, Sussex, CERN)
Here we'll focus on this project



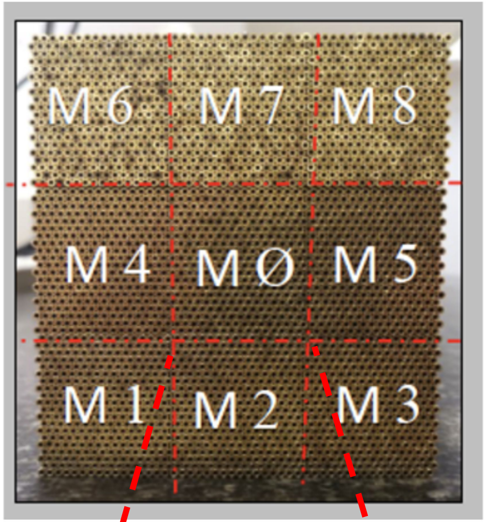


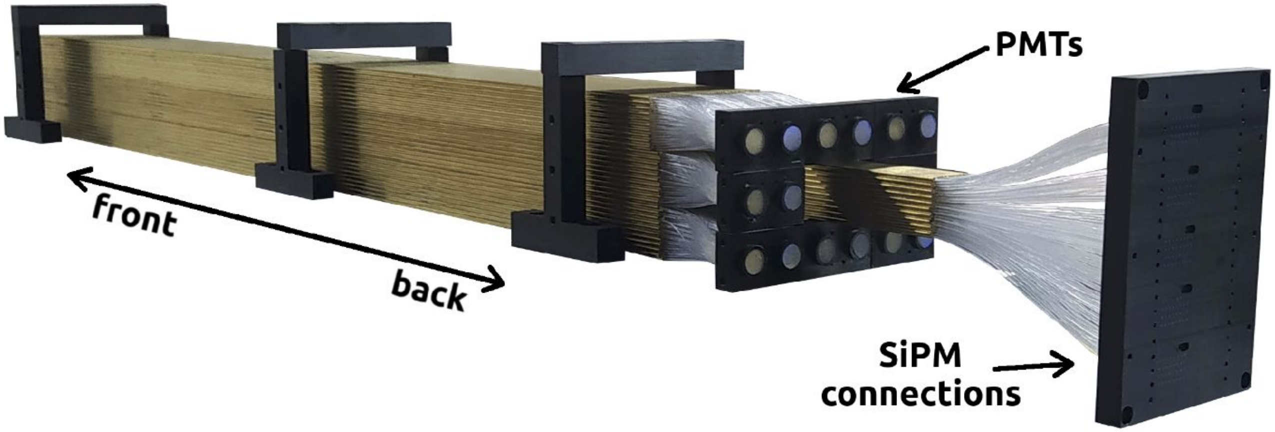
EM shower-size prototype

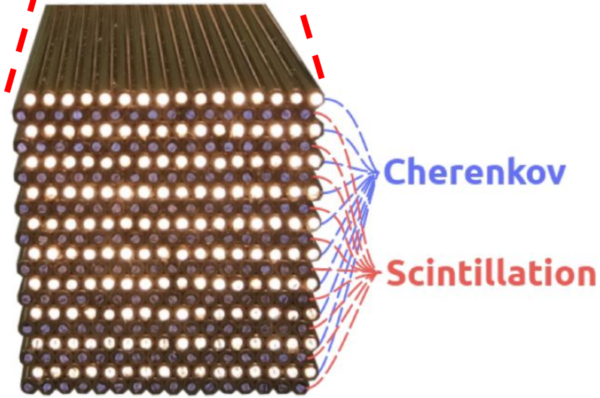
First high-granularity DR prototype built in 2021 and tested at DESY and CERN SPS
→ SPS results reported in detail here

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

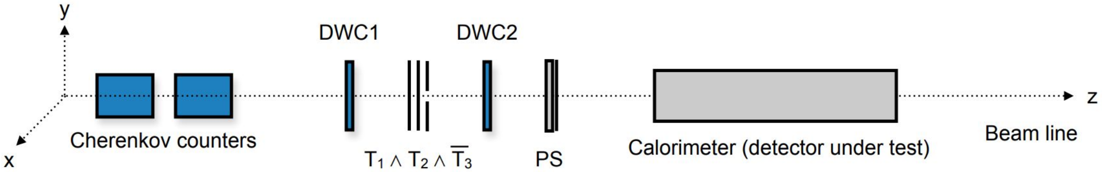
SiPMs with packages small enough were not ready at the time of production, fibres in M0 leaking out from the back of the calorimeter







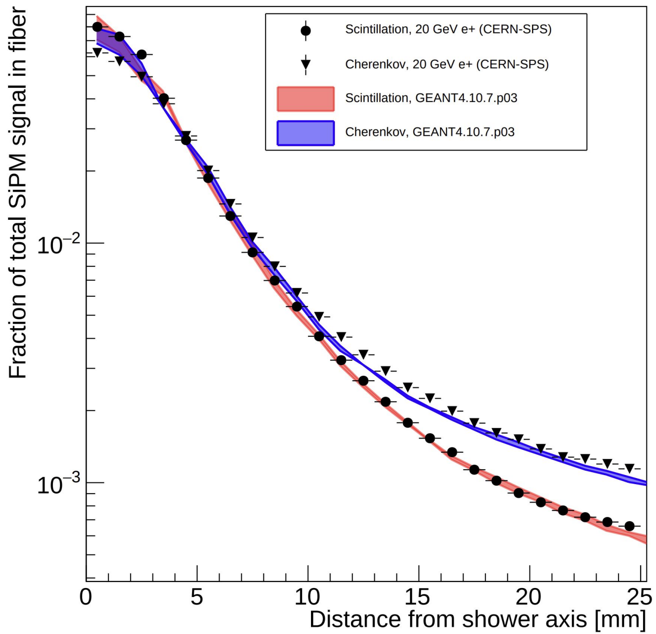
SPS 2021 Test Beam



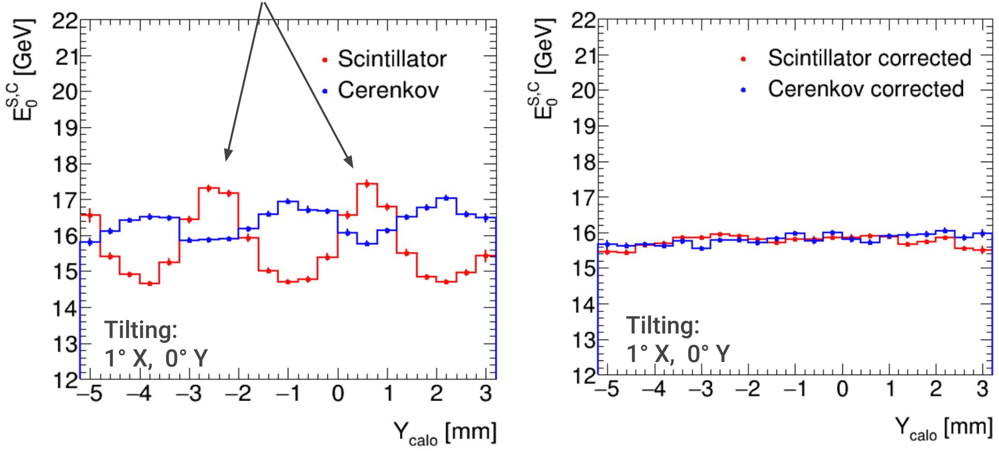
A few problems experienced during data taking:

- ➢ Bad beam purity
- ➢ Preshower far from the detector for access issues
  → em showers not well contained
- ➢ Small calorimeter rotation angle
  1° on X direction, 0° on Y direction
  → signal highly dependent on impact point

Lateral electromagnetic shower profile measurement in agreement with Geant4 simulation



Distance between two rows of same-type fibres (TB 2021 data)

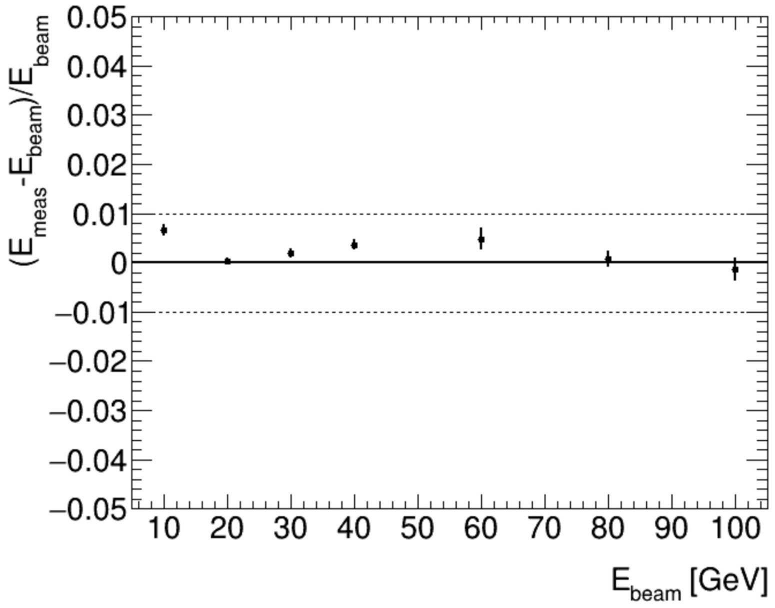


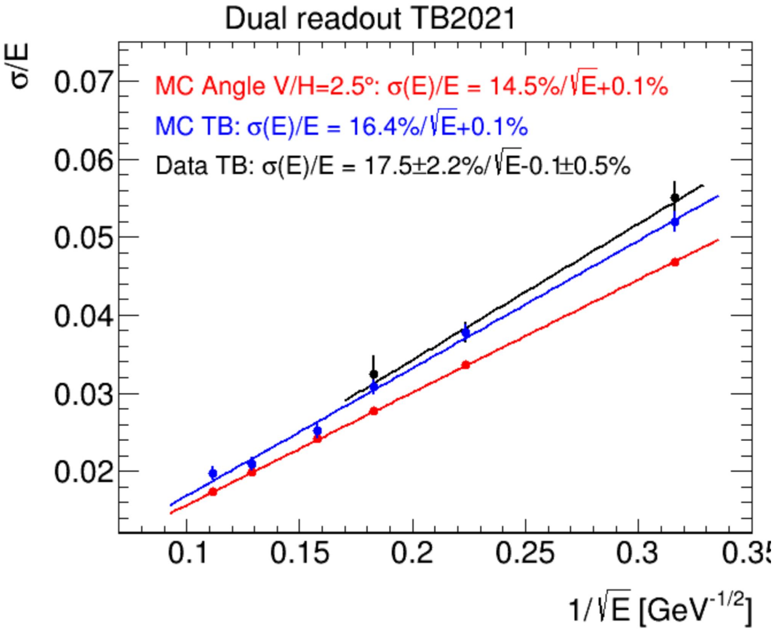
SPS 2021 Test Beam

Energy resolution estimated only for [10-30] GeV range, where positron selection could be done with upstream Cerenkov counters (w/o preshower)

Energy well reconstructed within 1% range

Simulation with beam test setup correctly reproducing energy resolution

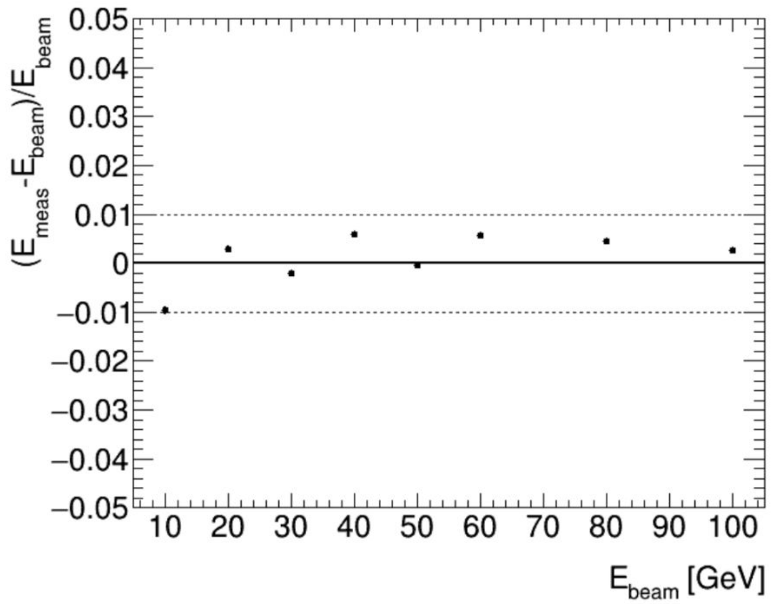


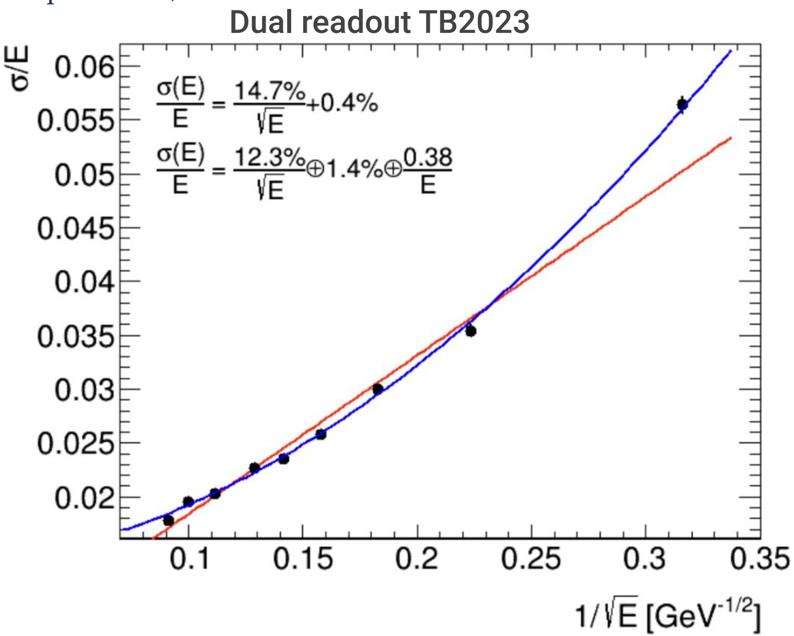


SPS 2023 Test Beam

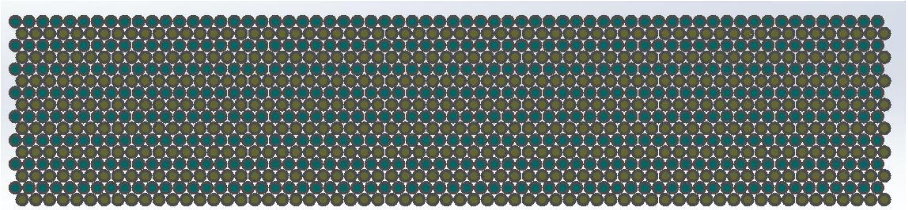
Most of the issues from previous test beam have been addressed, early studies look promising
Still large electronic noise contribution, but better overall resolution and nominal beam energy reconstruction
Beam energy uncertainty ~1-2% → compatible with constant term

Data with pion and muon beams have also been taken for further studies
(Geant4 hadron model validation, fibres attenuation length measurement, muon response etc.)





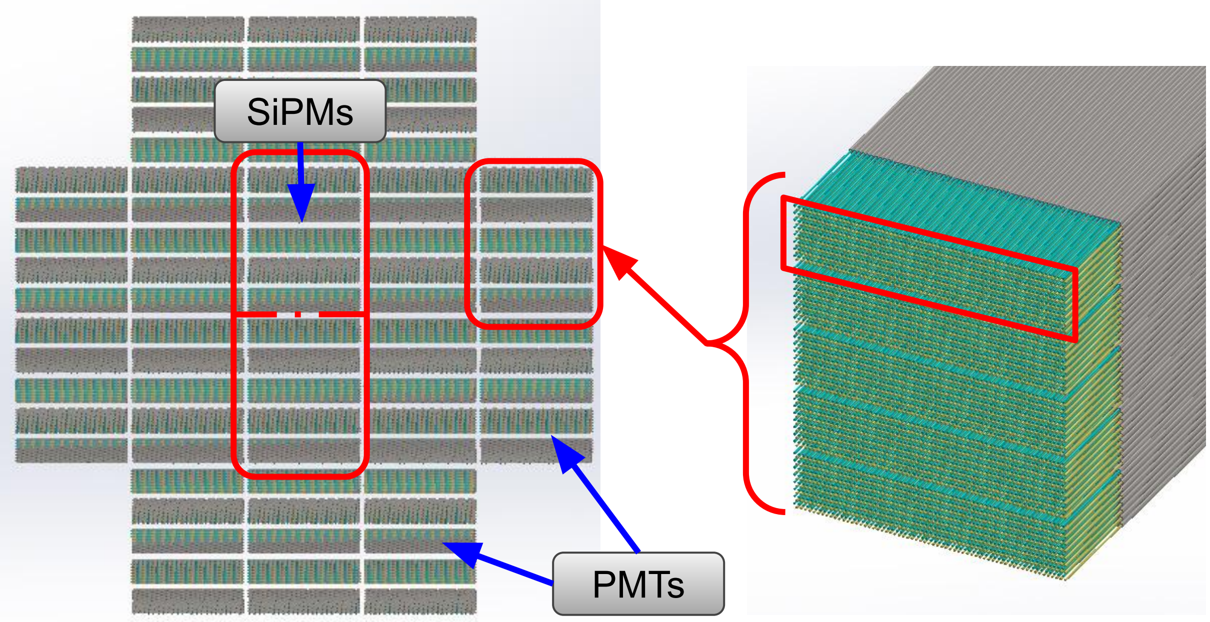
HiDRa prototype



Each external minimodule read out by two PMTs, one for S fibres and the other for C fibres (512 fibres each)

Prototype large enough to (almost) fully contain hadron showers, ~ 65 × 65 × 250 cm^3:
80 minimodules, each one made of 16✕64 capillaries

Mixed SiPM and PMT readout
→ Cost/Performance optimization
→ Significant increase in DAQ complexity (10240 SiPMs)

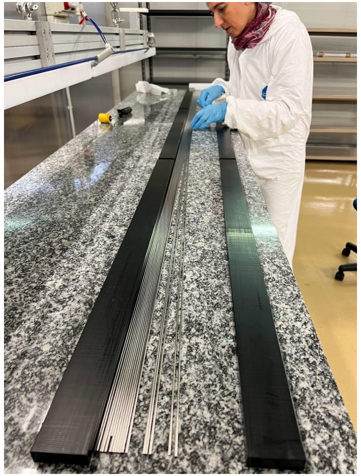


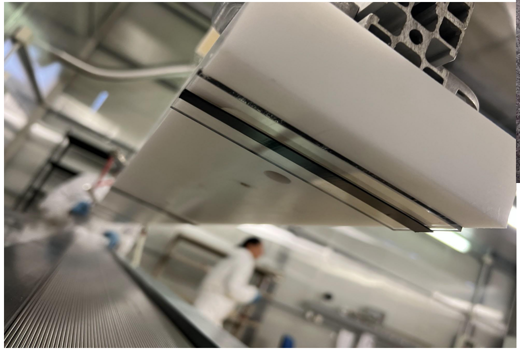
Design and a few results briefly described here

Module construction

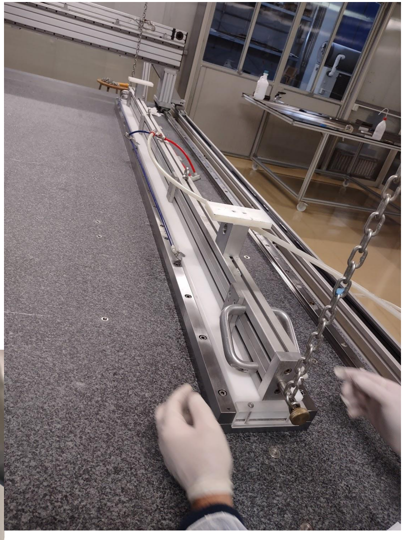
Definition of constructing technique and quality assessment on the modules geometry

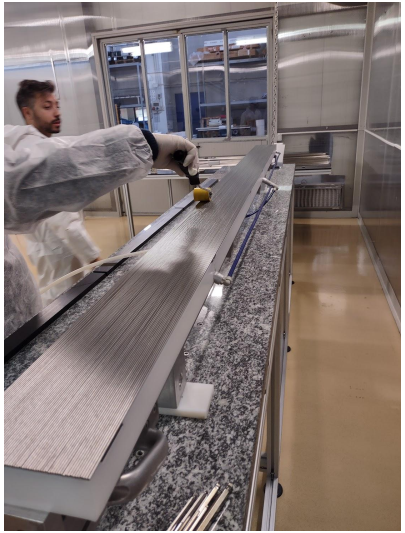
Tube aligned in a reference tool

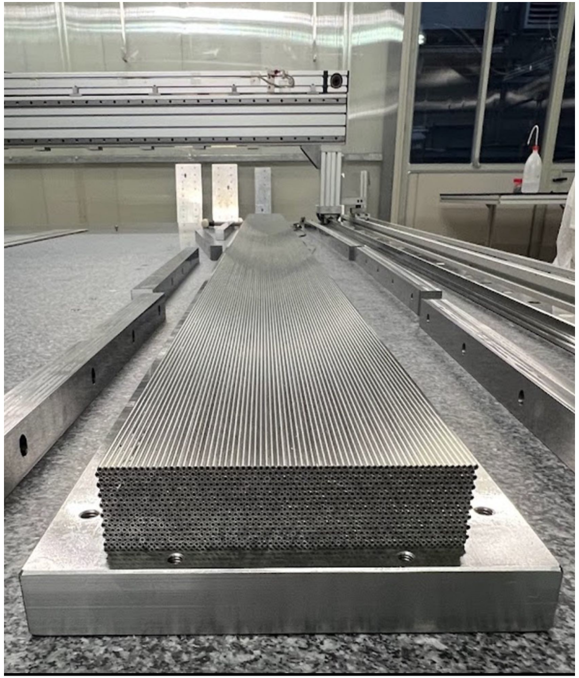




Stiffback-like technique for tube handling, gluing and positioning in the assembly tool



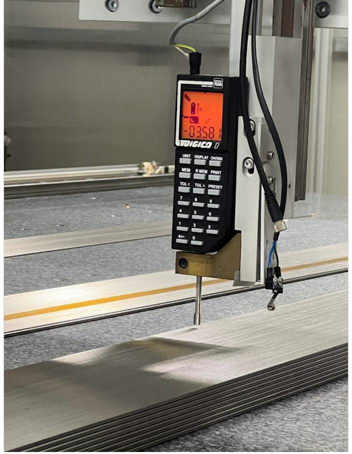


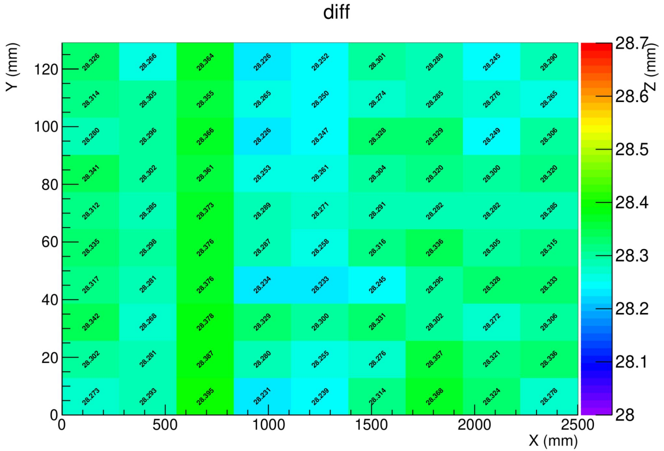


Vacuum + double-sided tape for tube handling

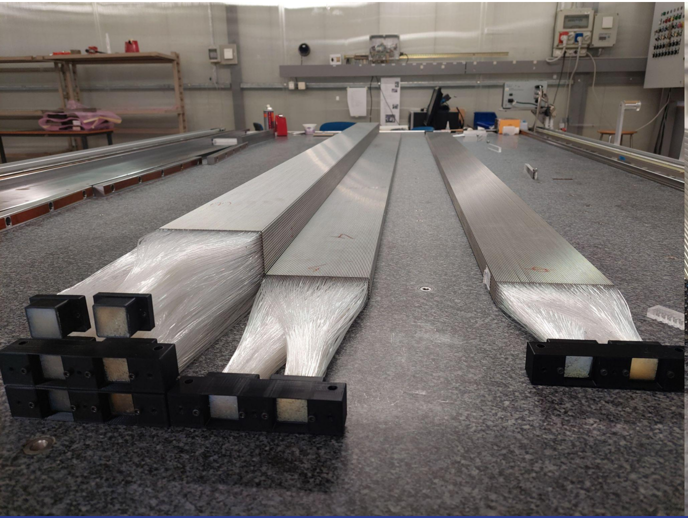
Module construction

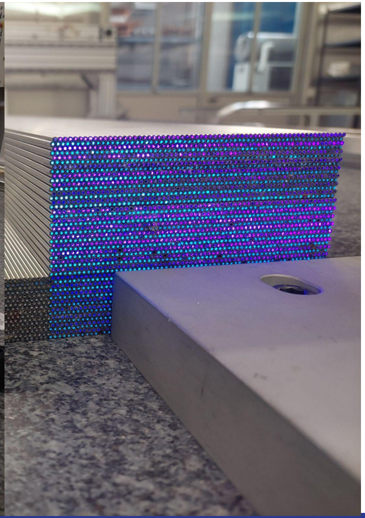
- ➢ Capillary tubes: ✅
- ➢ Cerenkov fibres: ✅
- ➢ Scintillating fibres: 5 batches arrived, then 1 batch/month
- ➢ PMTs: 100/140 available, others to be ordered in 2024
- ➢ SiPMs: to be ordered (May/June 2024)
- ➢ Readout boards: 10/20 available, others to be ordered in 2024





Semi-automatic system for planarity QAQC

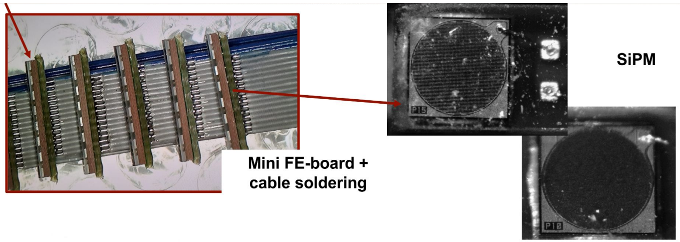




First 5 mini-modules construction completed before Christmas
Mini-modules #9 and #10 to be glued this week

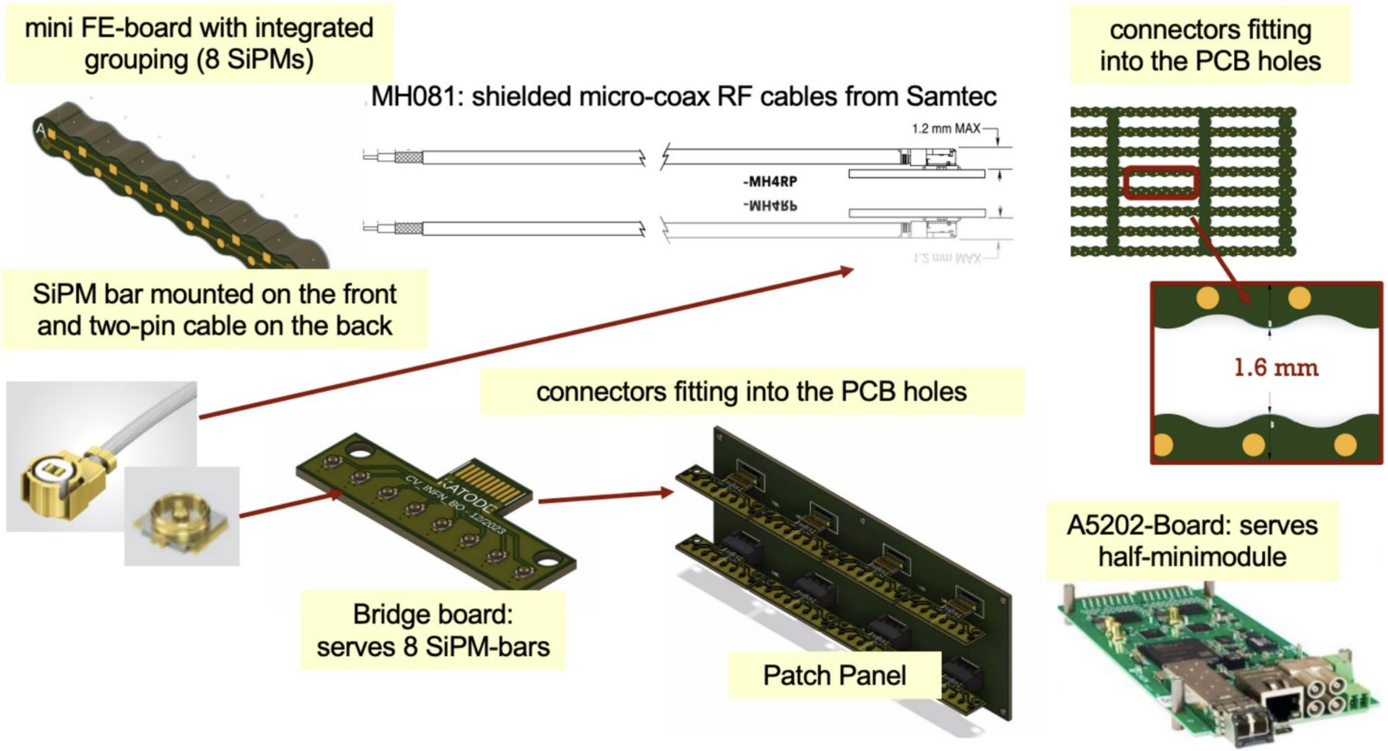
Construction can be partially done in parallel
→ (ideally) two modules/week

HiDRa SiPM integration & readout



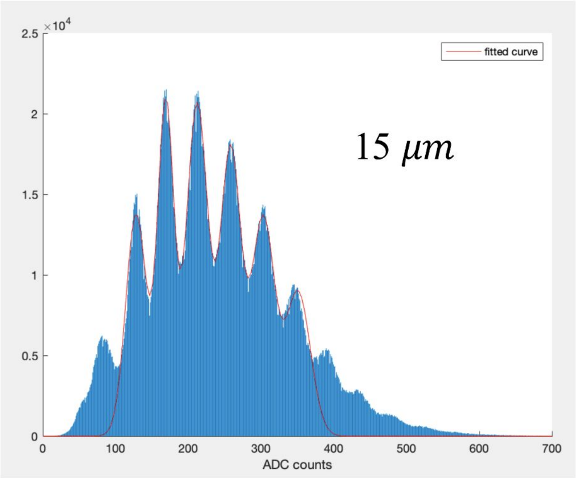
Hamamatsu SiPMs with 10 and 15 μm pitch
(optimise dynamic range/photon detection efficiency for S/C fibres)

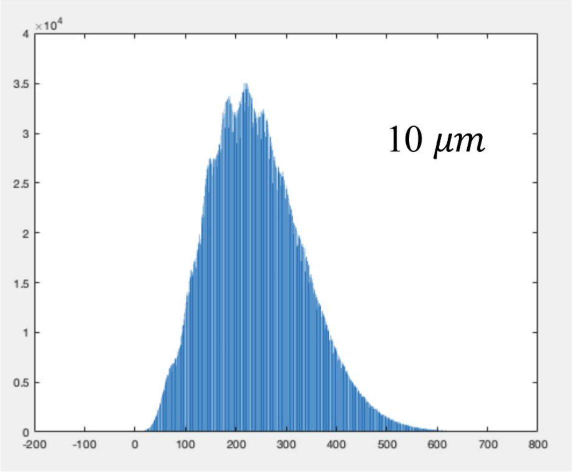
- 8 SiPMs grouping directly on frontend board
- 2 FERS operate 1 full minimodule
- 20 FERS operate high-granularity core of HiDRa prototype

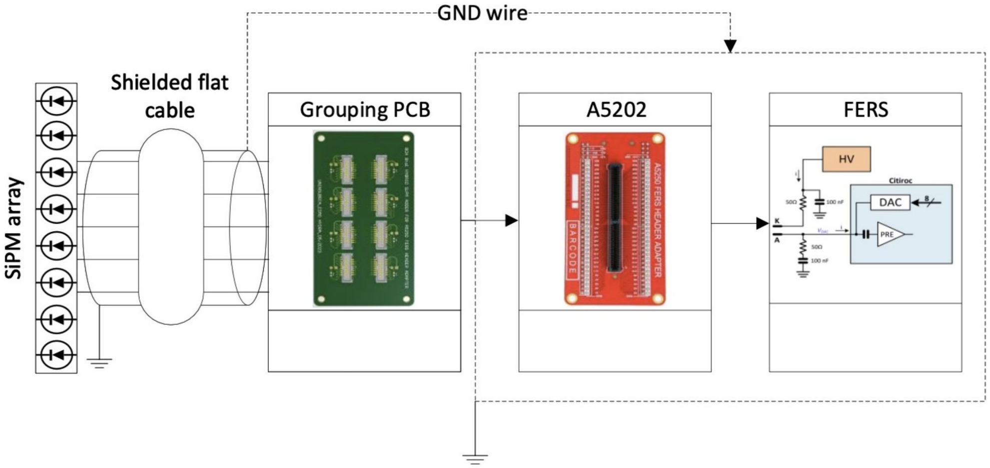


HiDRa SiPM integration & readout

Multiple grouping scheme connections were tested to find the most compact and performing solution
Multiphoton spectra has been used in previous test beams for channel equalisation
→ OK for 15 μm pitch SiPMs, not obvious can be observed for 10 μm ones



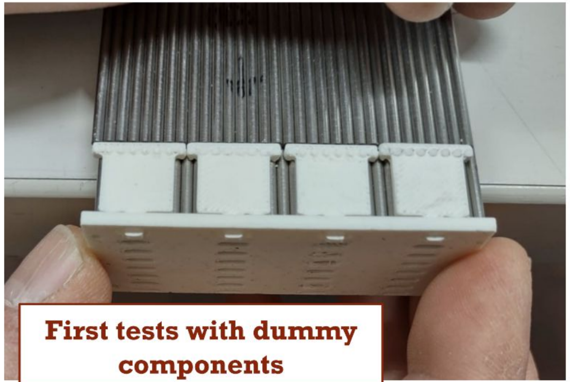




More information in R. Santoro's presentation

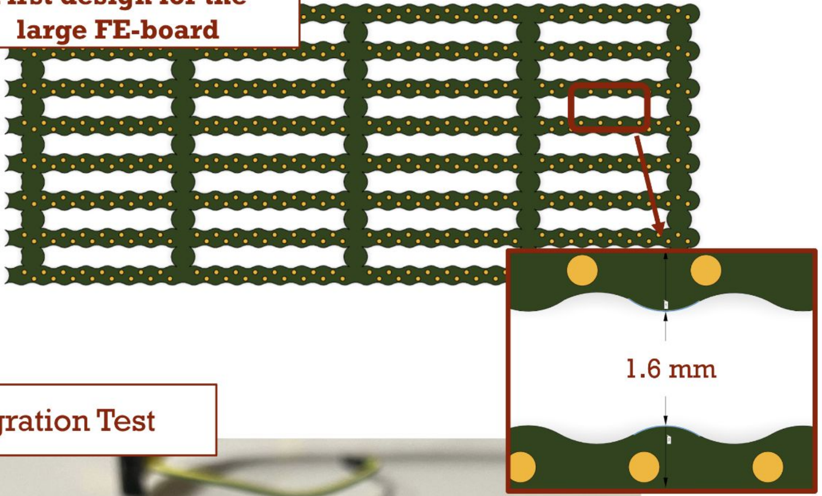
SiPM Mechanical integration

- Design ready for mini-frontend and bridge boards, and patch panel almost ready as well
- Large frontend board (32 SiPM bars) under study
- SiPM integration to be demonstrated soon with both dummies and, when available, real components

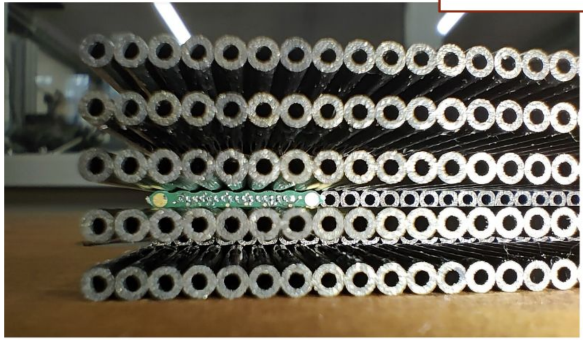


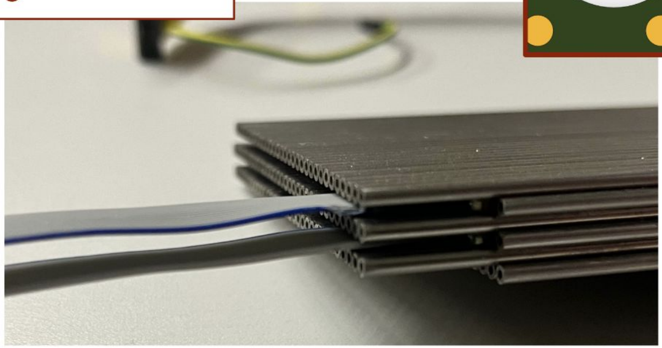
First tests with dummy components

First design for the large FE-board



Board Integration Test



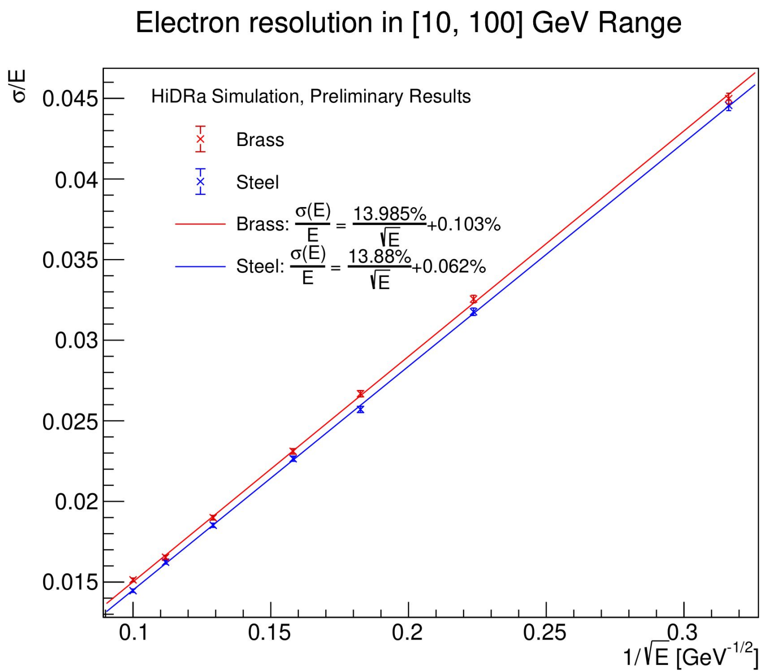


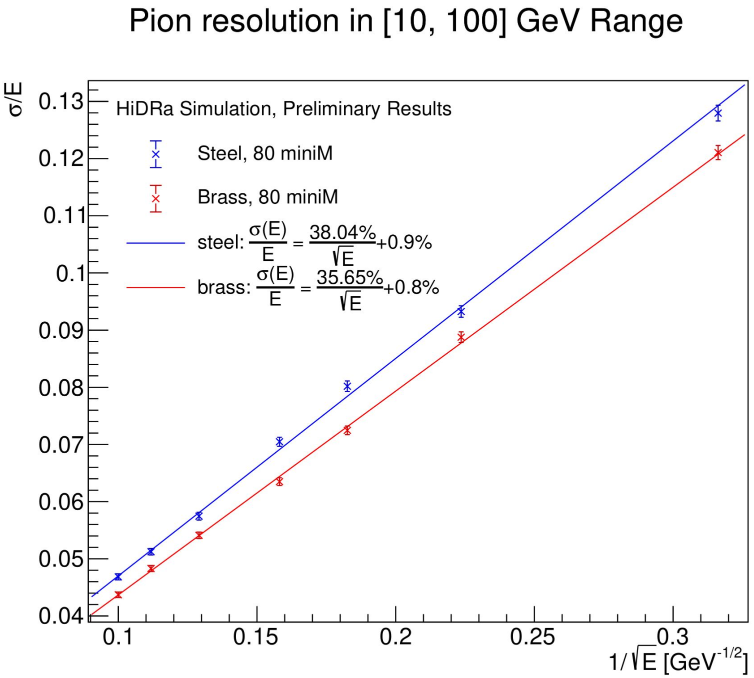
Test Beam already in 2024 with ~50/60% of HiDRa modules under discussion
(TB time shared with other DR calo teams)

HiDRa energy resolution

Geant4 simulation-based energy resolution, for electrons and pions

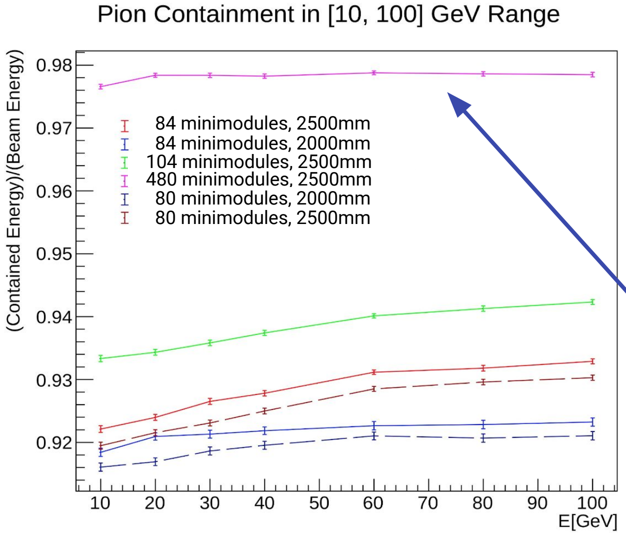
Brass absorber seems to slightly improve resolution for single hadrons, but more expensive to produce and use for a smaller-scale prototype



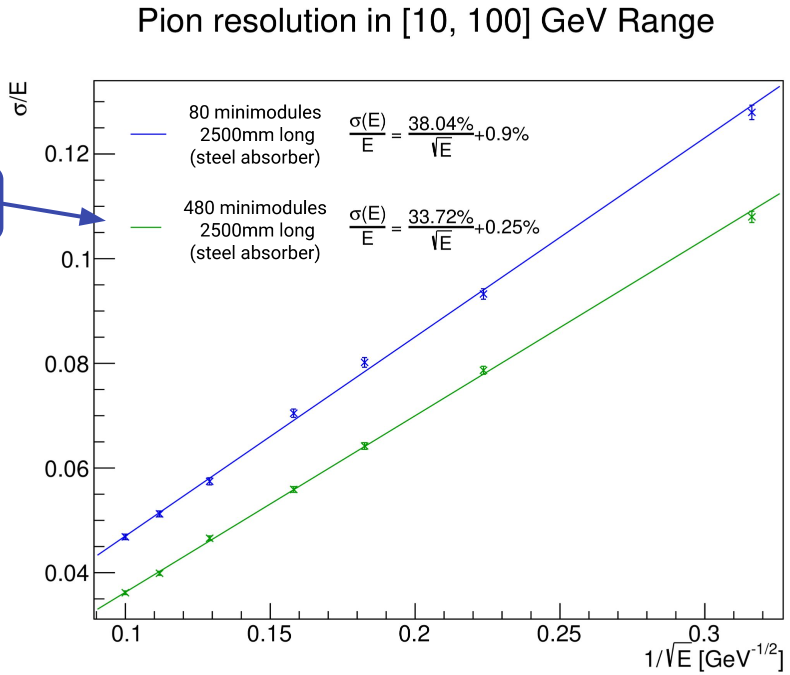


HiDRa energy resolution

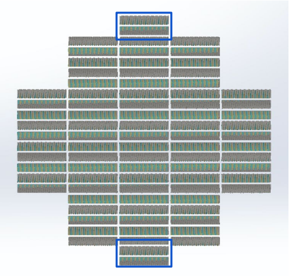
Improvement in resolution by increasing the calorimeter lateral dimension
(add more modules in simulation)



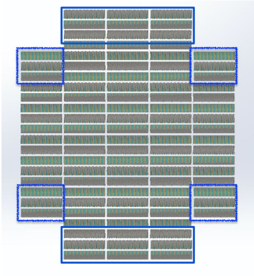
~ IDEA



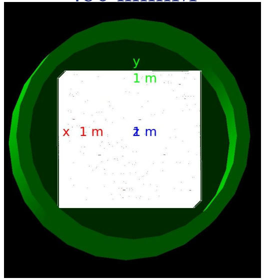
84 miniM



104 miniM



480 miniM



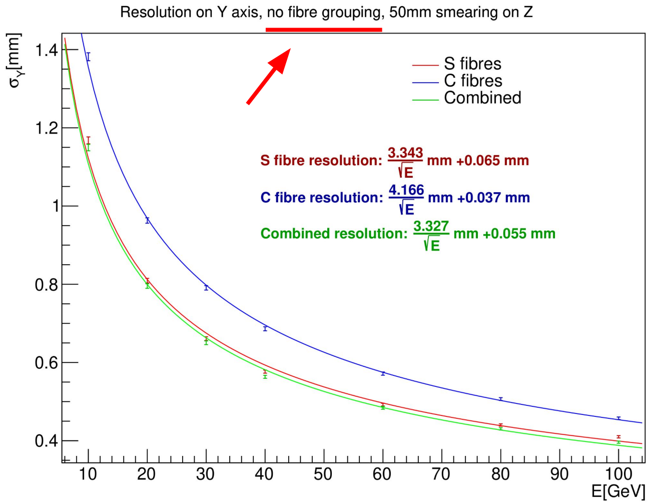
HiDRa space resolution (e^+)

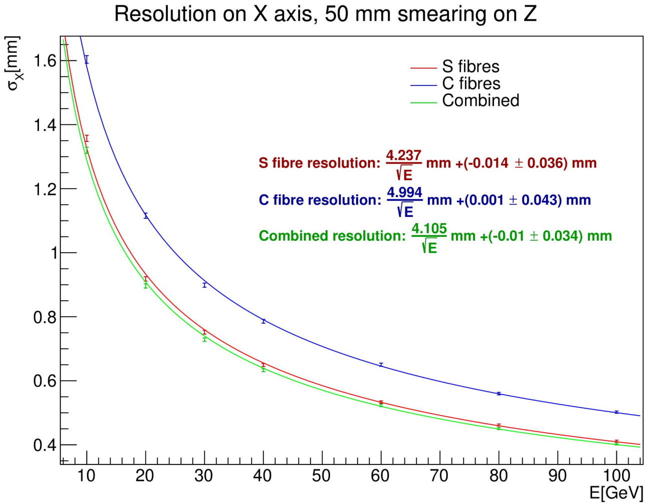
Reconstruct coordinates through centre-of-gravity method

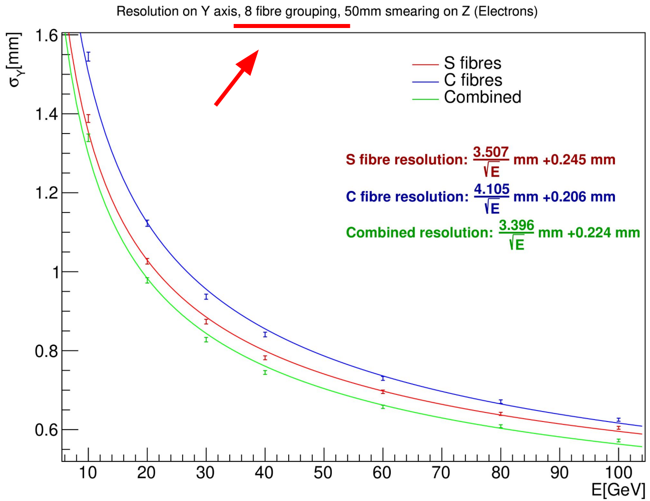
$$x_{\text{Bar}} = \frac{\sum_i E_i x_i}{\sum_i E_i} \qquad y_{\text{Bar}} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

Calorimeter tilting effect (2.5° in both X and Y directions) corrected assuming MC truth knowledge of shower barycenter along Z axis with 5 cm gaussian smearing

Molière radius in HiDRa: ~24.7 mm → marginal impact of 8 channel grouping (16 mm)







Conclusions

- ➢ Fervent activity in dual-readout, fibre-based calorimeter for IDEA detector
- ➢ Construction is ongoing and electronics is reaching its final design
- ➢ Full prototype is expected to be ready by the end of the year, and already partially characterized with test-beam campaign
- ➢ Geant4 simulation has been validated with em shower-scale prototype, and results seem promising
- ➢ Full Sim of IDEA calorimeter will have to be updated with HiDRa design

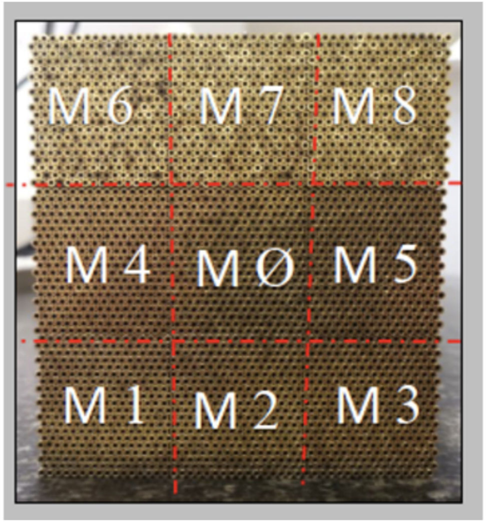
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA n° 101004761"

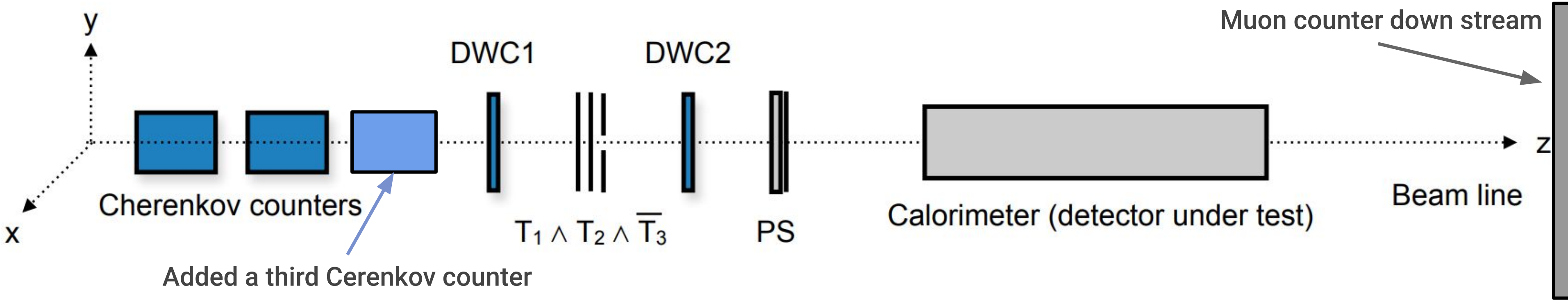
BACKUP

SPS 2023 Test Beam

SPS - H8 beamline:

- ➢ Beam purity definitely improved
- ➢ Distance from preshower to calorimeter: 155 mm
- ➢ Calorimeter rotation:
  - ○ Vertical angle: 0°, 2.5°
  - ○ Horizontal angle scan
  - ○ A small horizontal angle offset may have been introduced
- ➢ Positron ([10-120] GeV), muon (160 GeV) and pion ([20-180] GeV) beams



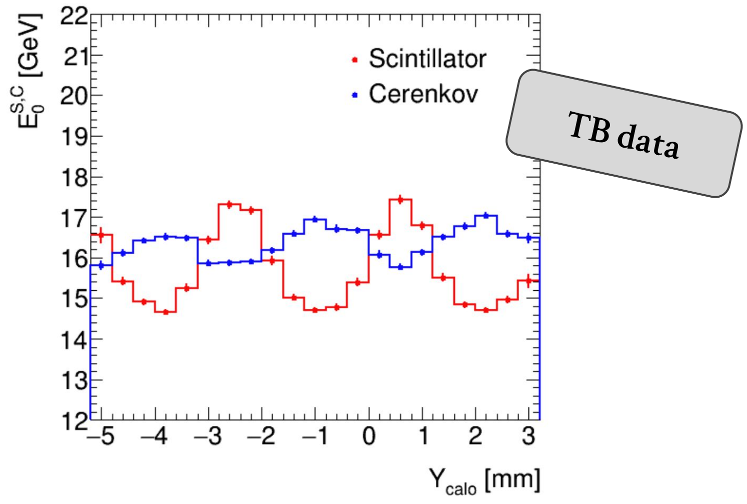


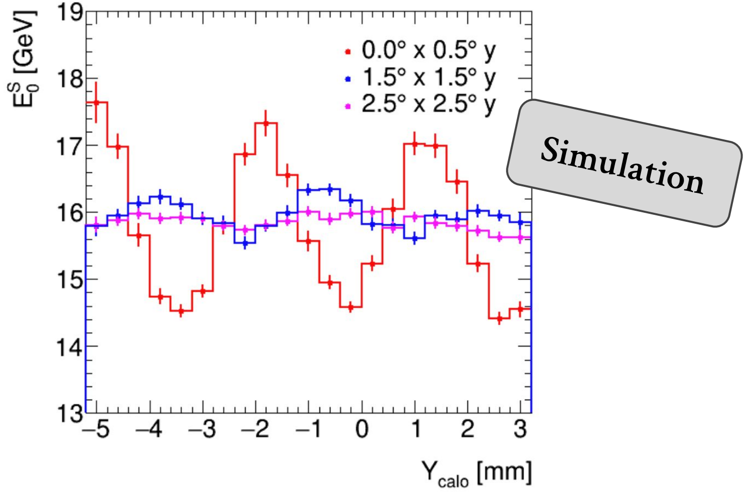
SPS 2021 Test Beam

SPS - H8 beamline (2021 test beam)
Positrons could nonetheless be selected with sufficient efficiency below 40 GeV, using upstream Cerenkov counters

Dependence of both S and C signal on impact point position, estimated through shower barycenter, with periodical modulation equal to same-type fibres distance

Behaviour well described in the G4 simulation, increase angle up to 2.5 degrees to remove this effect

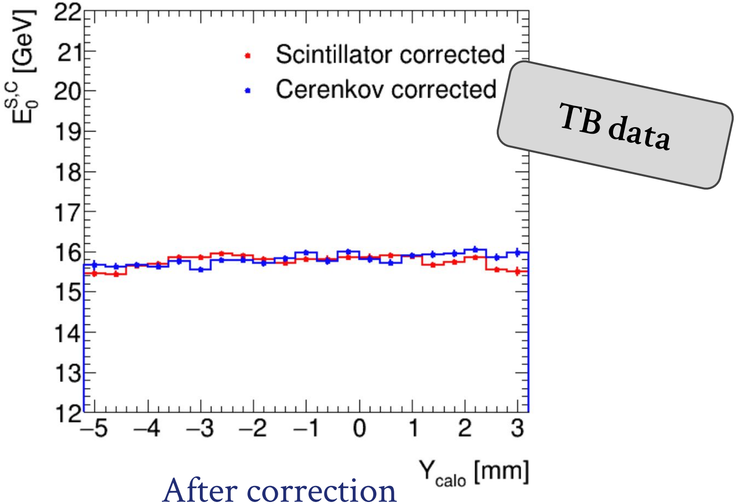




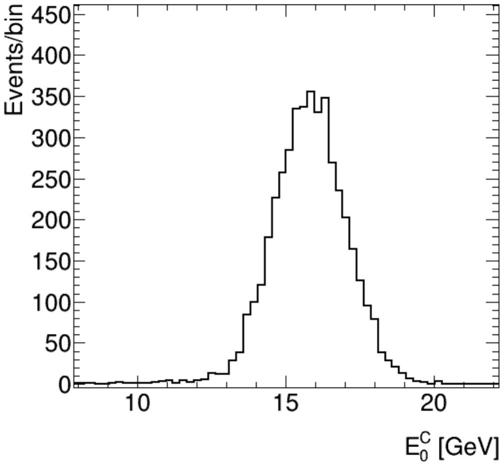
SPS 2021 Test Beam

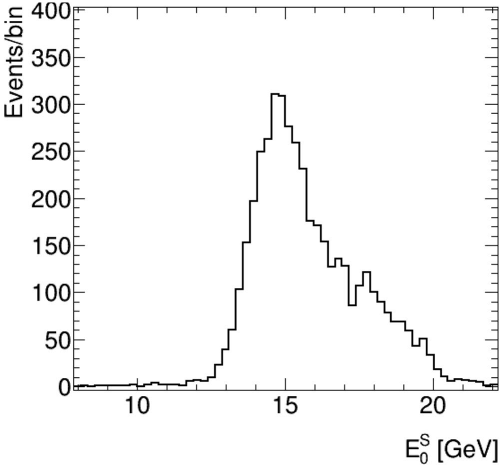
Benefit of the high-granularity feature:
Define an accessory variable to correct the impact point position issue, here the fraction of energy in the row with maximum signal with respect to energy in all scintillating fibres

$$R_{\max} = \frac{\sum_{\text{Row with highest signal}} E_S}{\sum_{\text{All Rows}} E_S}$$

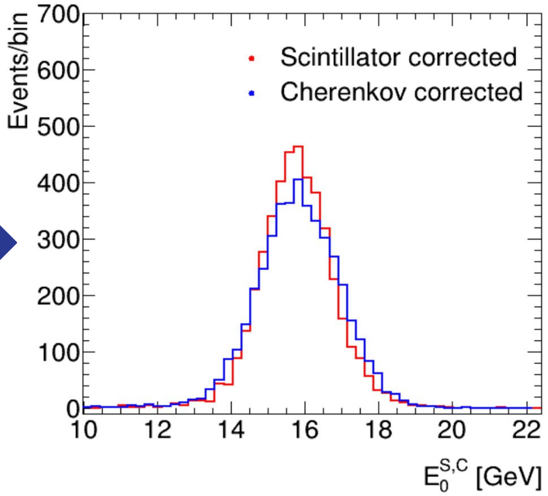


C (S) calibrated signal before correction





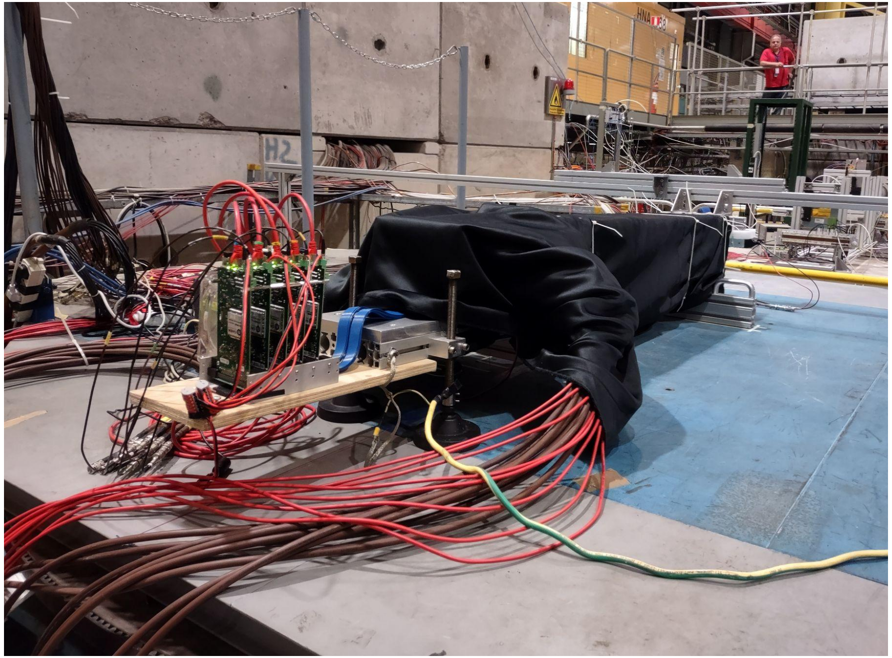
After correction



SPS 2023 Test Beam

Main objectives

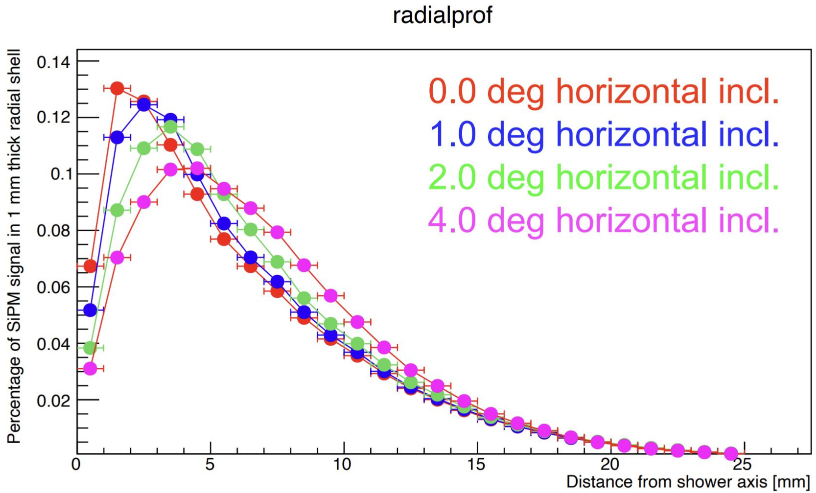
- Electrons:
  - response linearity with energy
  - energy resolution
  - response modulation over impact point
  - performance dependence over impact angle
  - position resolution
  - shower shape
  - M0 tower uniformity
- Muons:
  - response dependence over impact angle and position
  - (try) γ-radiation measurement
  - (try) lepto-nuclear process probability
- Pions:
  - response to shower core
  - Geant4 hadronic models validation

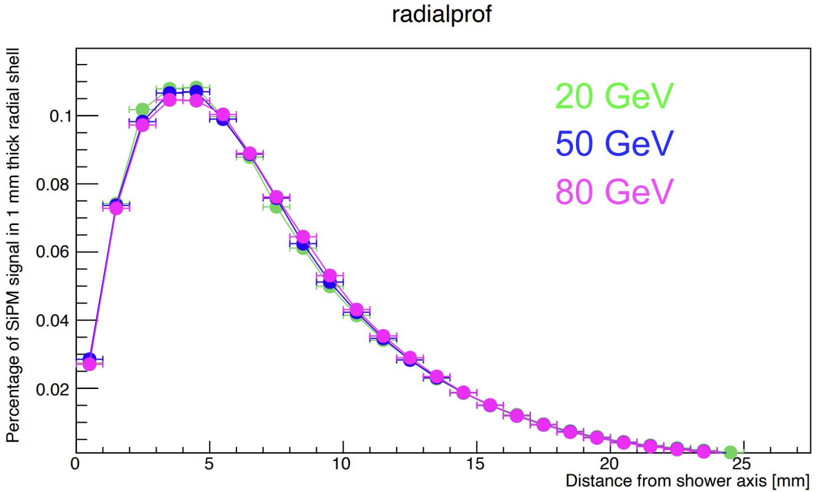


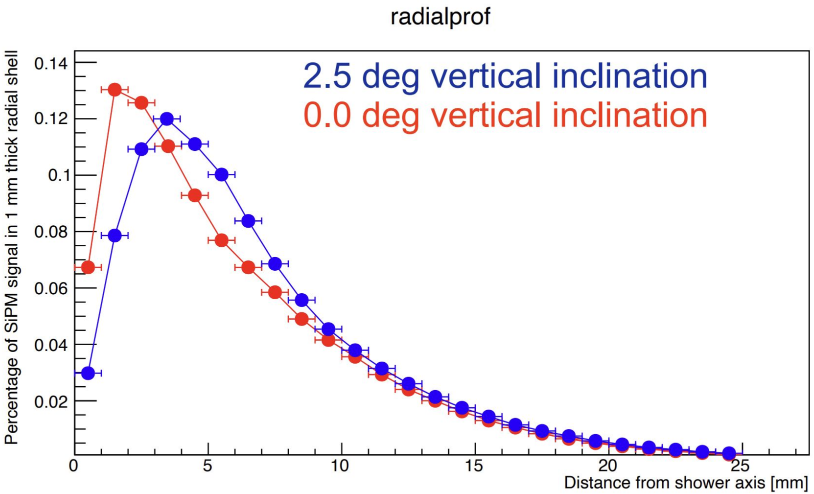
SPS 2023 Test Beam (electrons)

<u>Measurements of lateral shower profile</u>

- ➢ independent of beam energy, as expected
- ➢ dependent on horizontal and vertical rotations







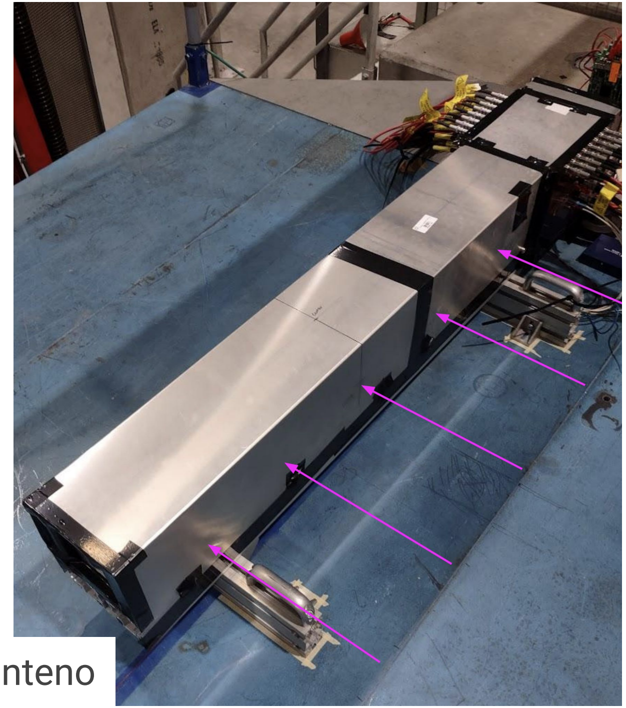
L. Pezzotti

SPS 2023 Test Beam

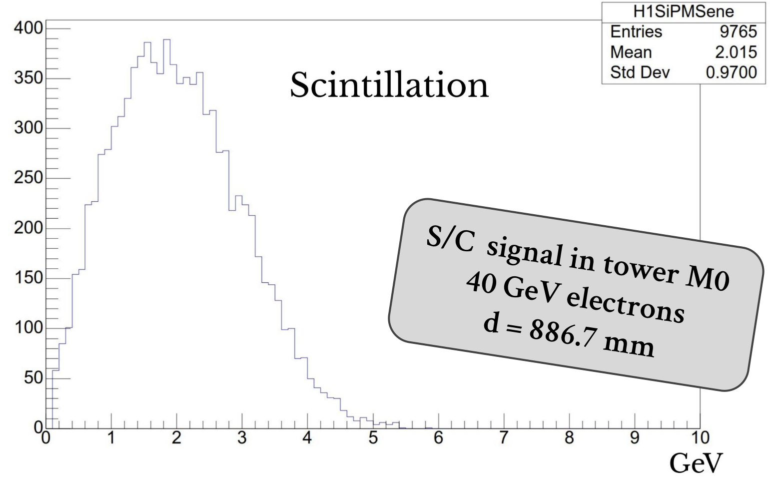
PRELIMINARY

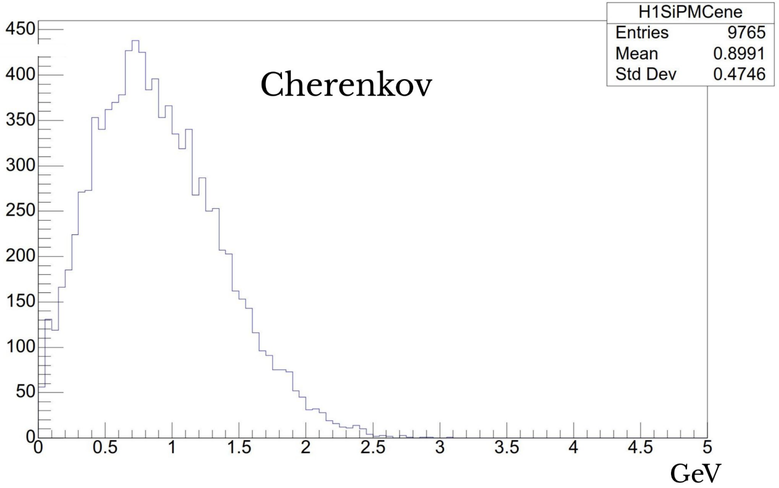
Attenuation length measurement

Calorimeter rotated by 90° in horizontal direction at the end of test beam (40 GeV e^+ and 160 GeV μ^+). Only SiPM information is being used



A. Loeschcke-Centeno





SPS 2023 Test Beam

Attenuation length measurement

Effect introduced in simulation and well-reproduced

To be used in further studies also in HiDRa simulation

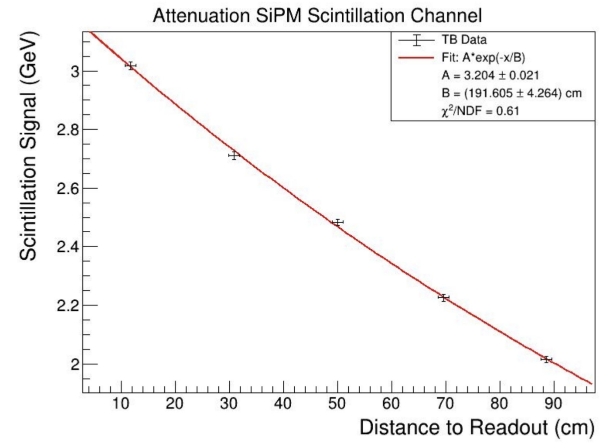
S fibres attenuation length:
191.6 cm

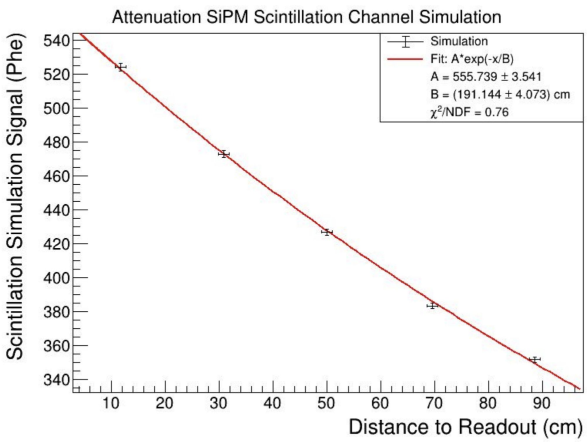
C fibres attenuation length:
388.9 cm

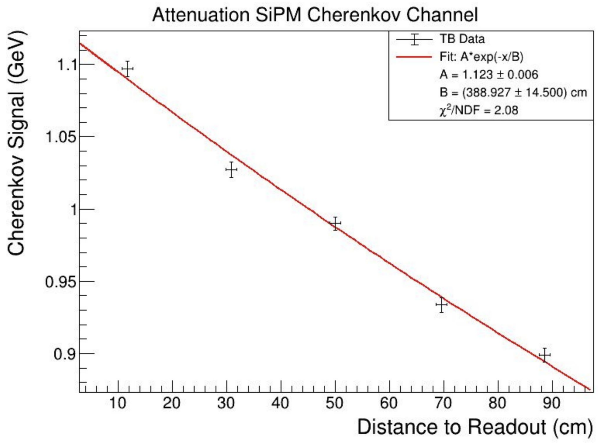
A. Loeschcke-Centeno

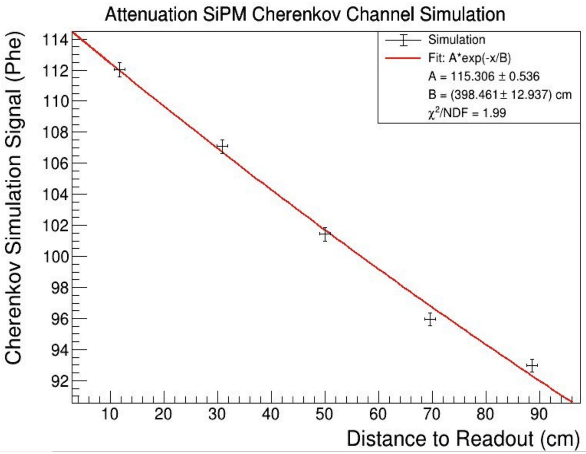
TB data

Simulation







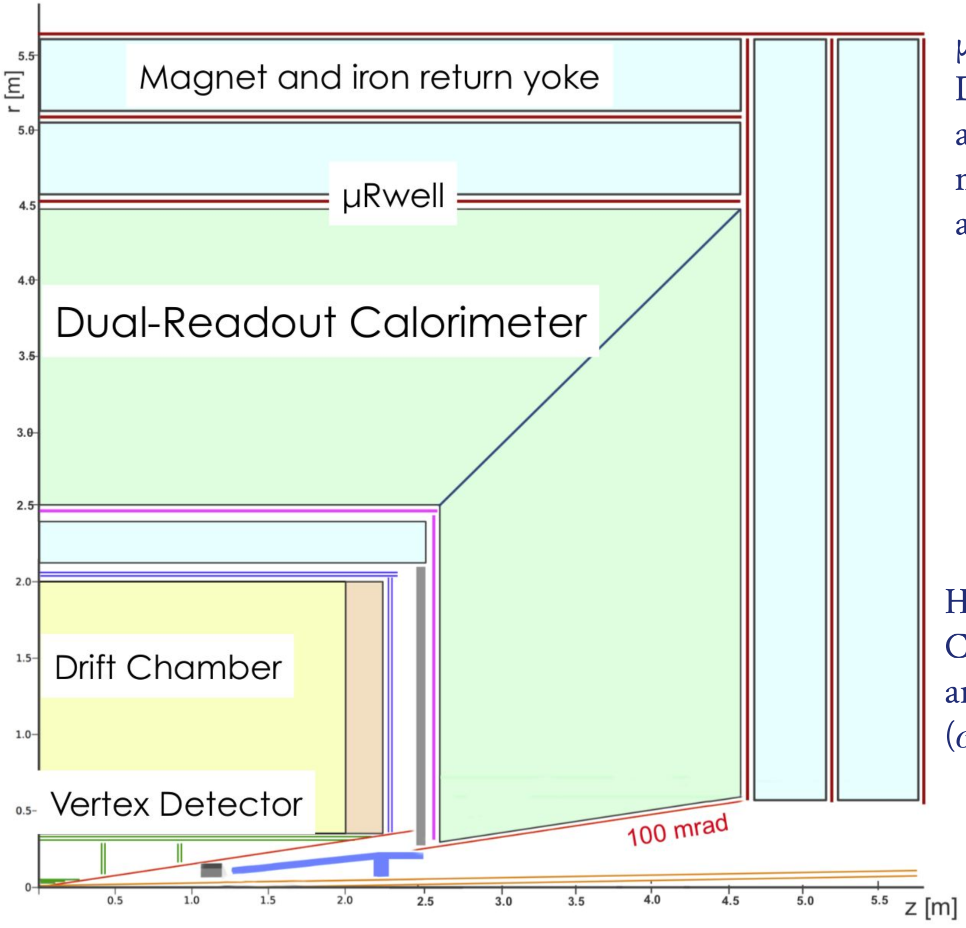


IDEA Detector

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

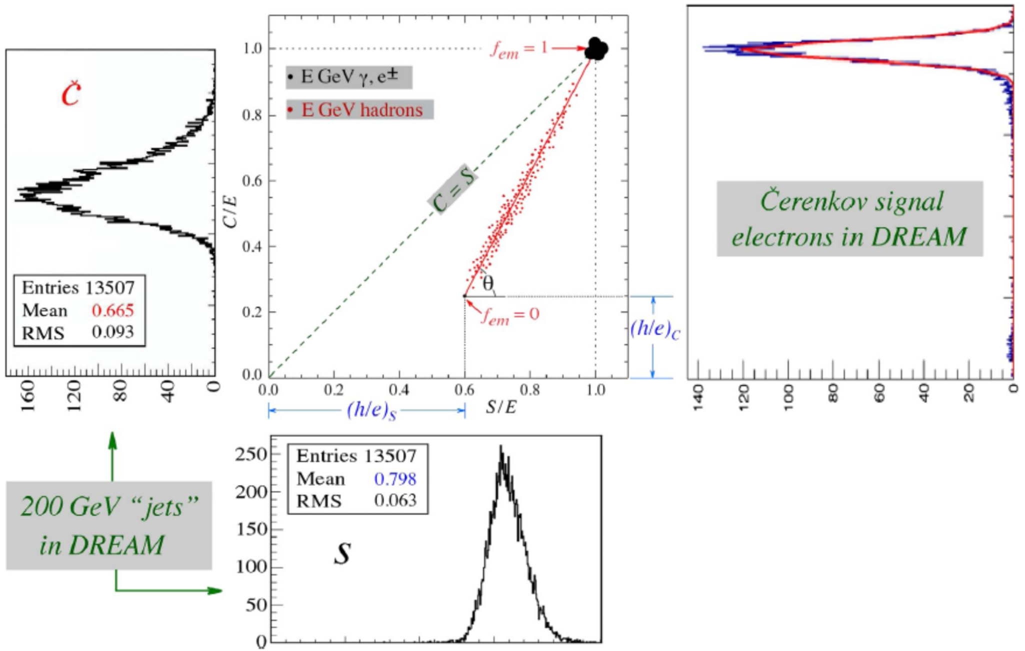
High-transparency Drift Chamber for excellent PId and spatial resolution (σ<100μm)

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



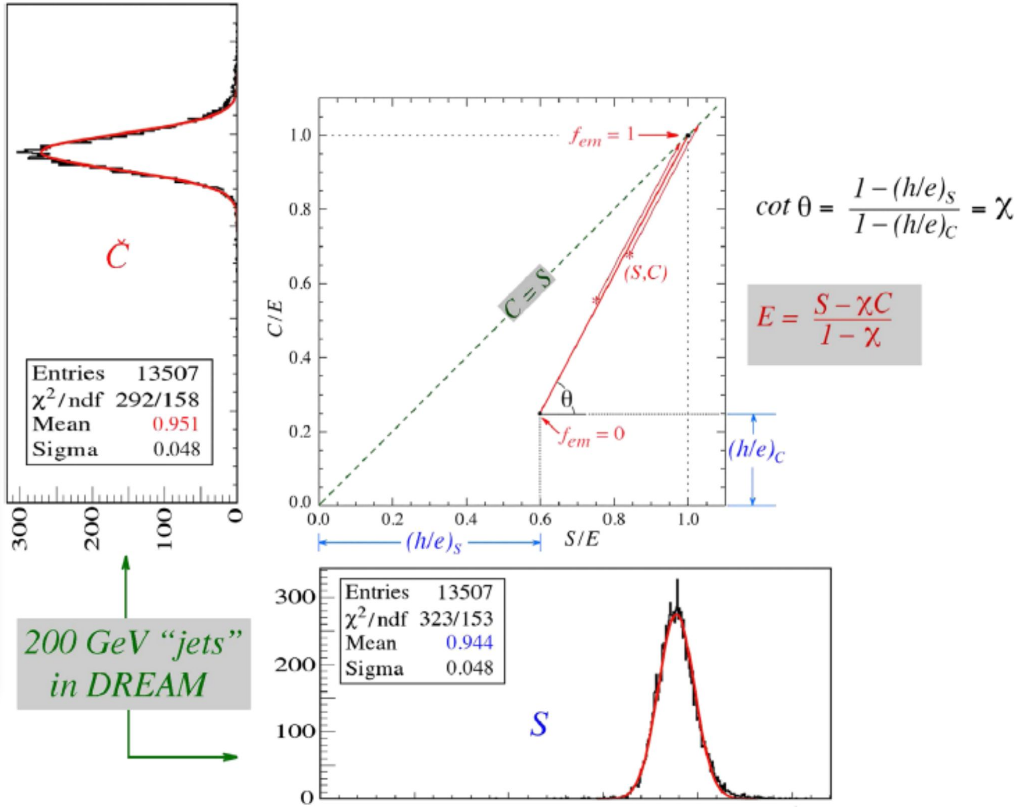
Dual-Readout Calorimetry

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

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

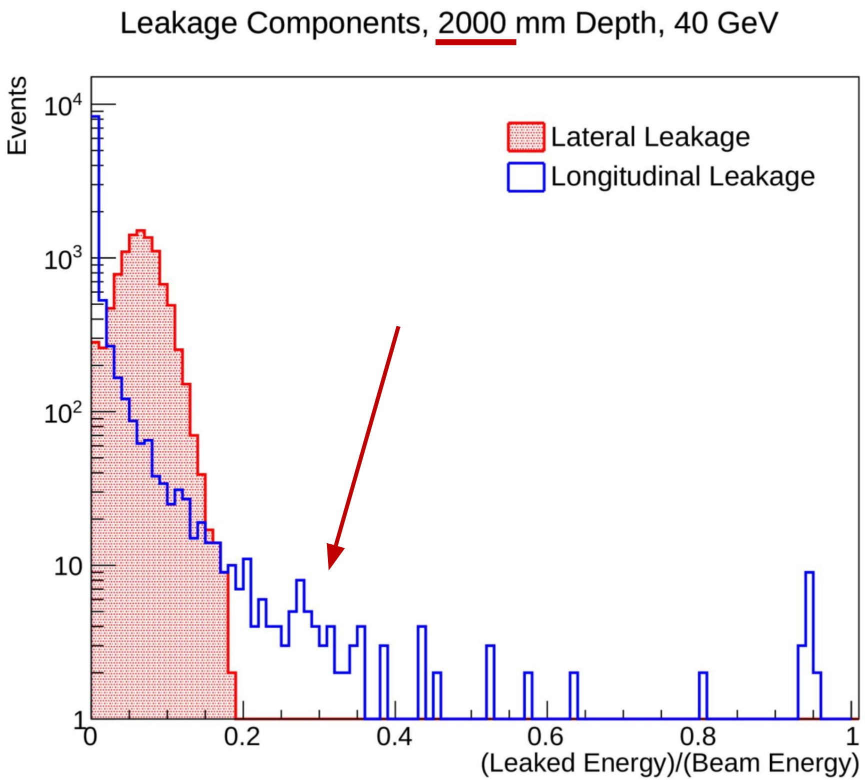
Reconstructed energy closer to the correct one

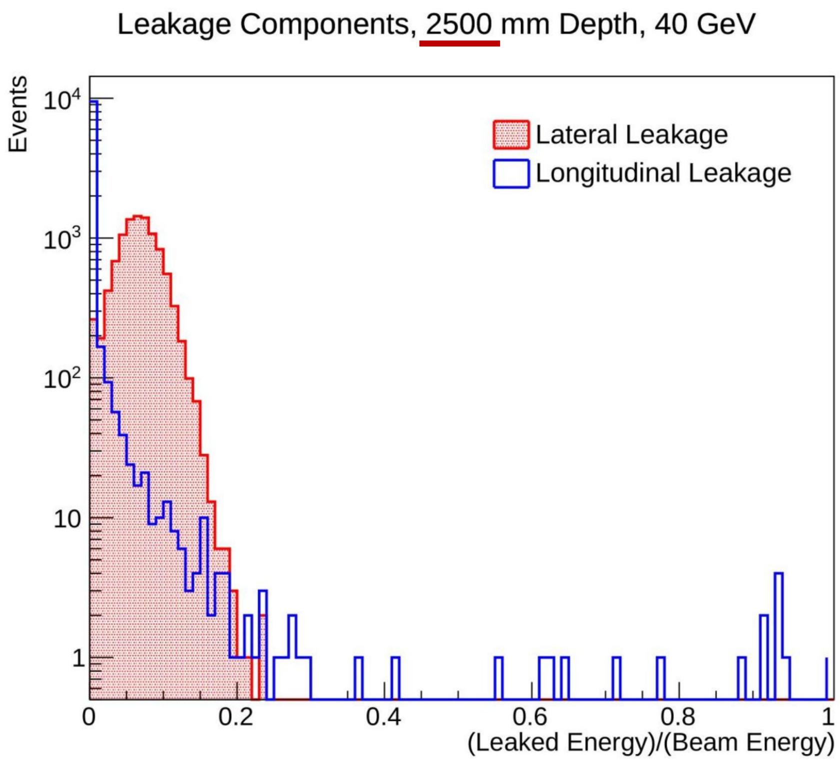
Proof of principle prototypes built and tested within the DREAM/RD52 collaboration



HiDRa Leakage studies

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

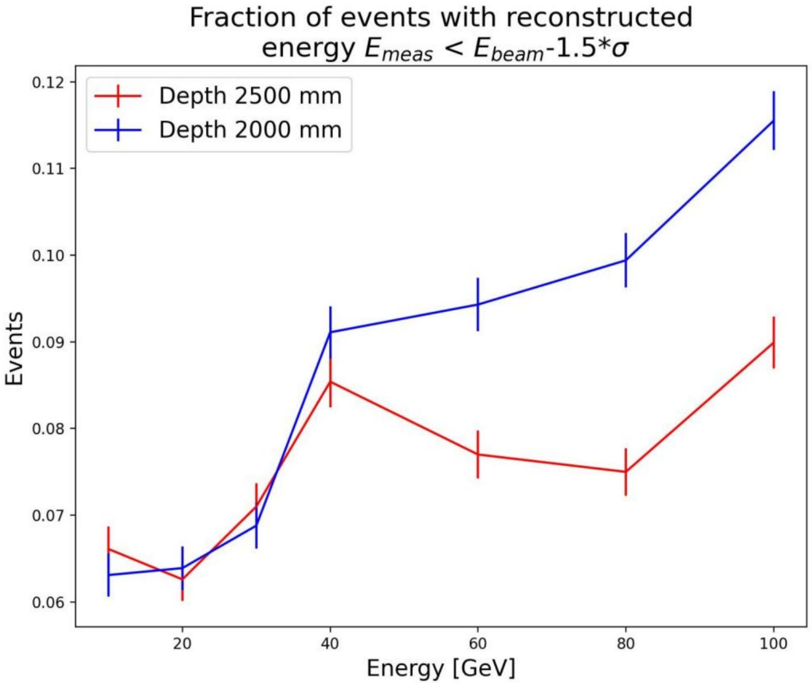


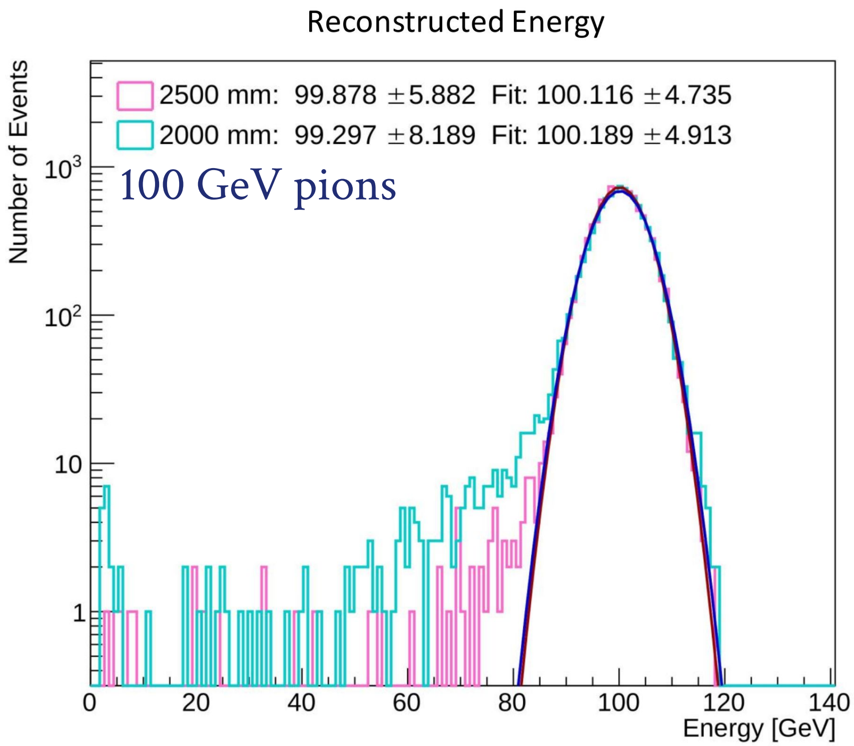


HiDRa Leakage studies

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

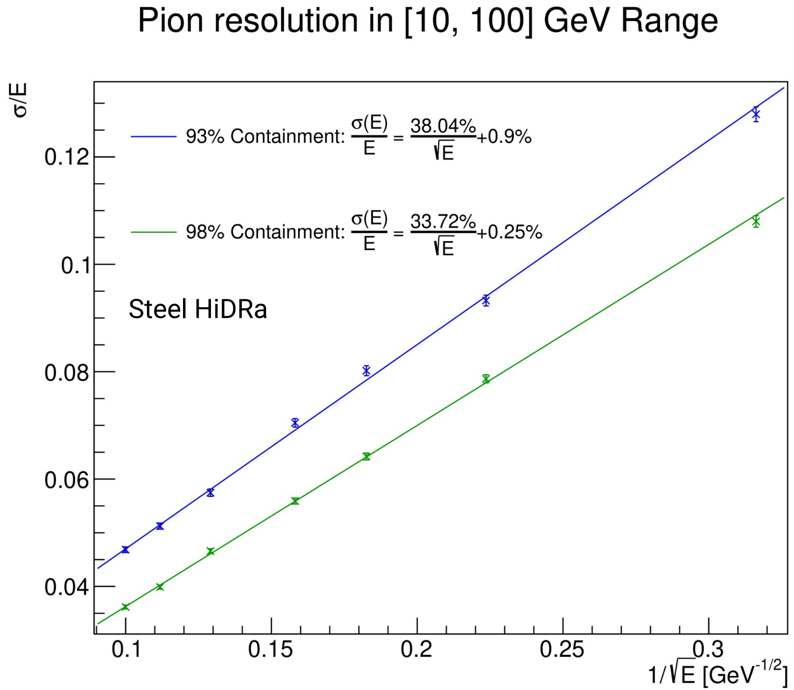
Smaller effect of longitudinal leakage on energy resolution (estimated using a gaussian fit)

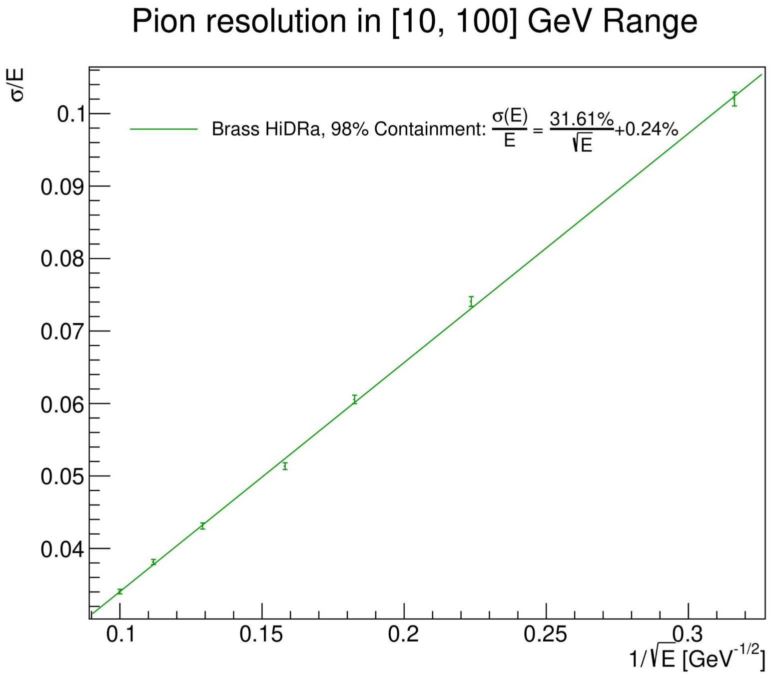




HiDRa energy resolution

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

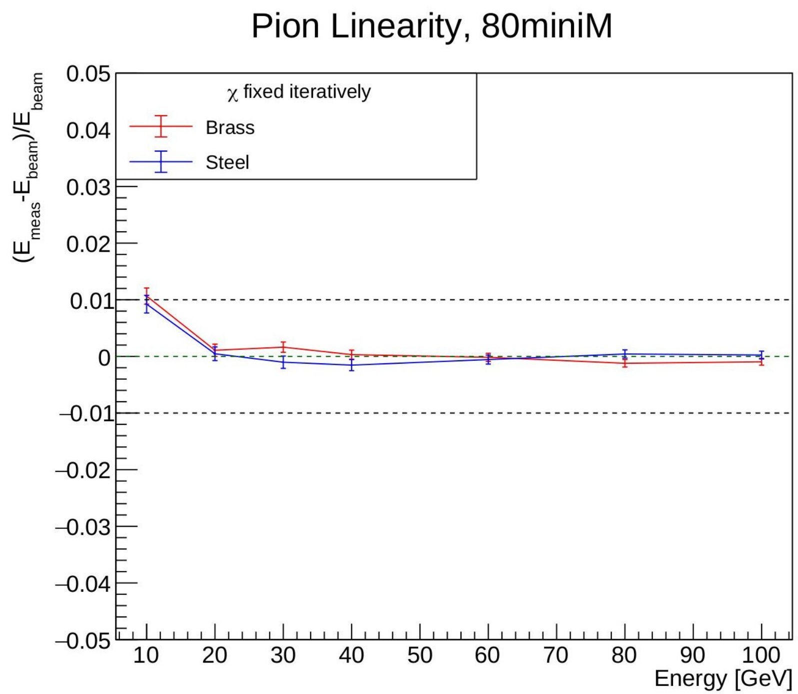




HiDRa energy resolution

For each tested geometry, absorber material etc., select the value of χ which improves the most the linear response of the calorimeter to different hadron energies

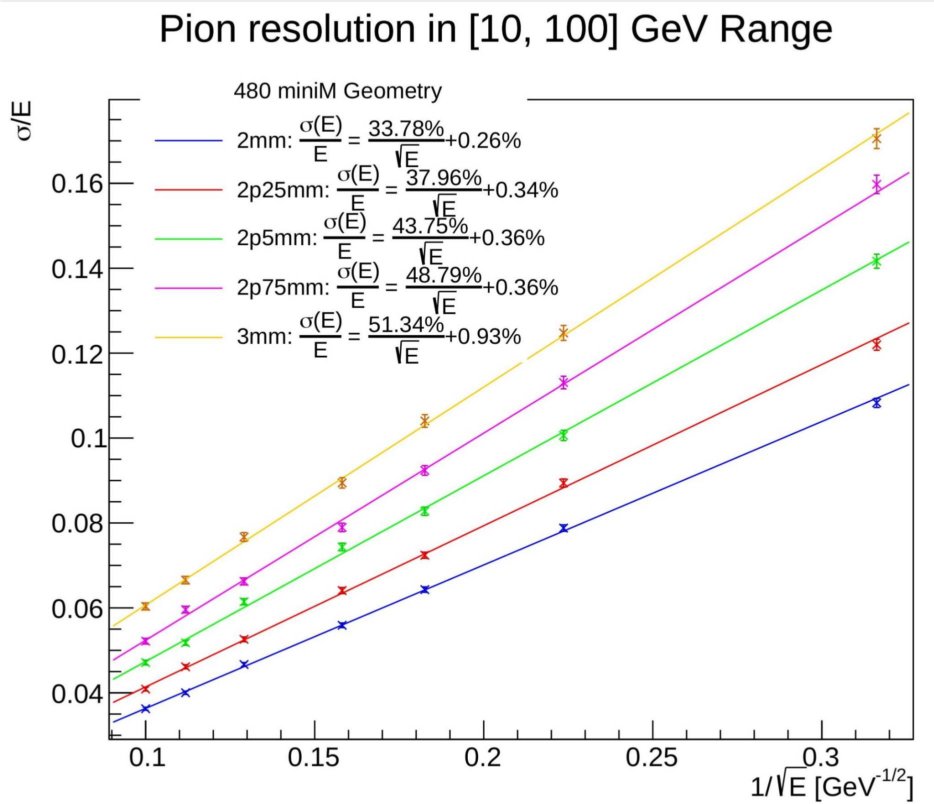
$$E = \frac{E_S - \chi E_C}{1 - \chi}$$



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

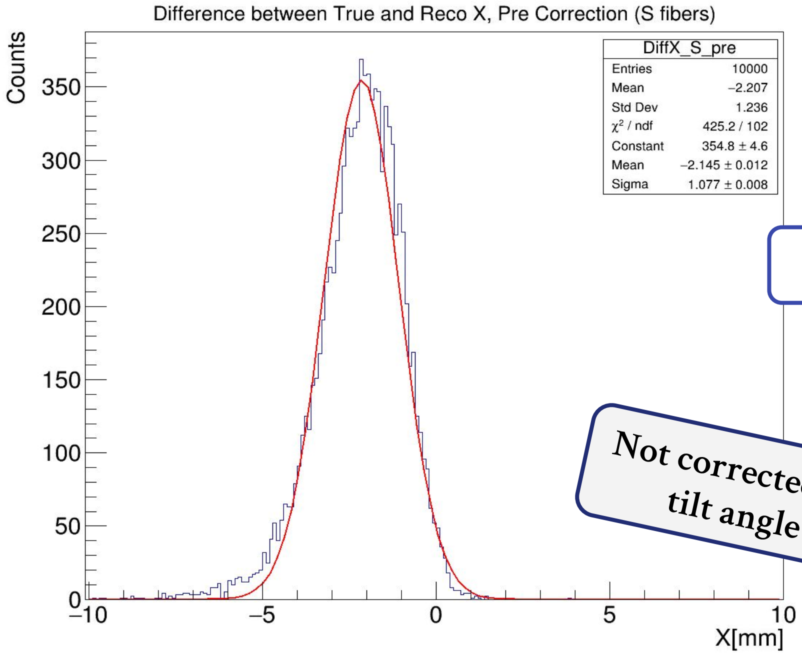


HiDRa Space Resolution

Reconstruct coordinates through centre-of-gravity method
Plots obtained with independent SiPM information

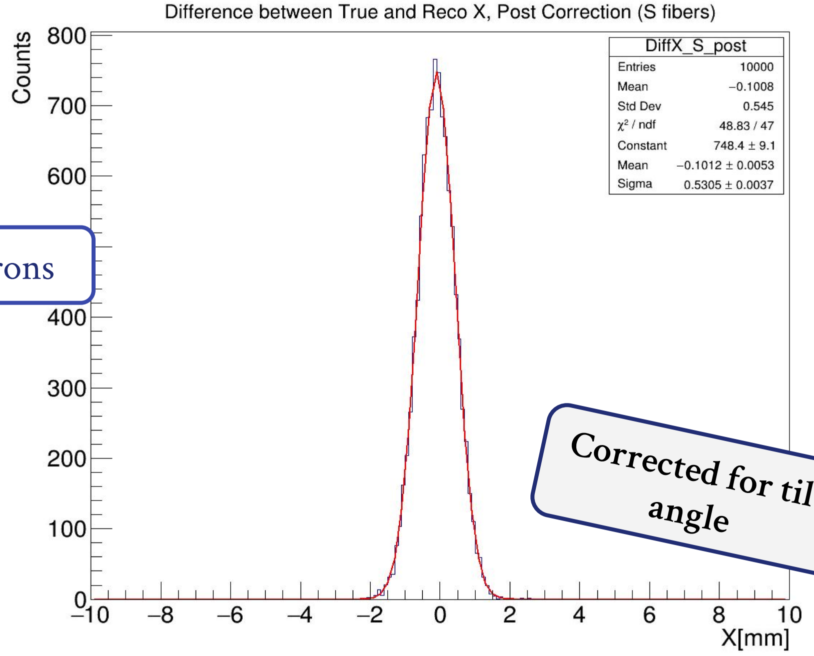
$$x_{\mathrm{Bar}} = \frac{\sum_i E_i x_i}{\sum_i E_i} \qquad y_{\mathrm{Bar}} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

Correct calorimeter tilting effect (2.5° in both X and Y directions) **assuming MC truth knowledge of shower barycenter along Z axis**



Not corrected for tilt angle

60 GeV electrons



Corrected for tilt angle

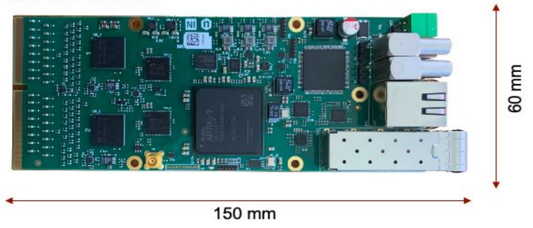
HiDRa SiPM integration & readout

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 fibres)

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)