FUTURE CIRCULAR COLLIDER

UNIVERSITÀ DI PAVIA

INFN Istituto Nazionale di Fisica Nucleare

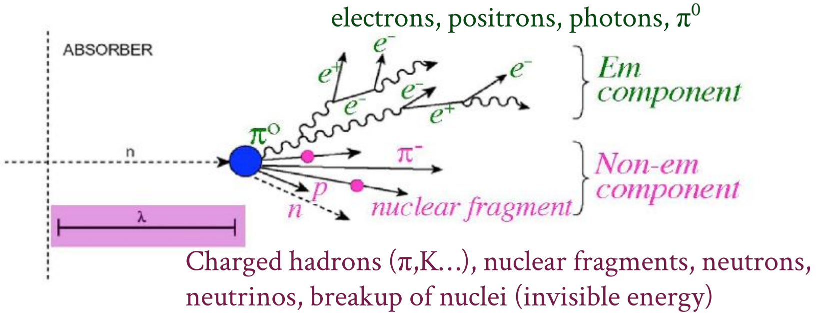
Capillary-based dual-readout calorimeter prototypes: results and prospects

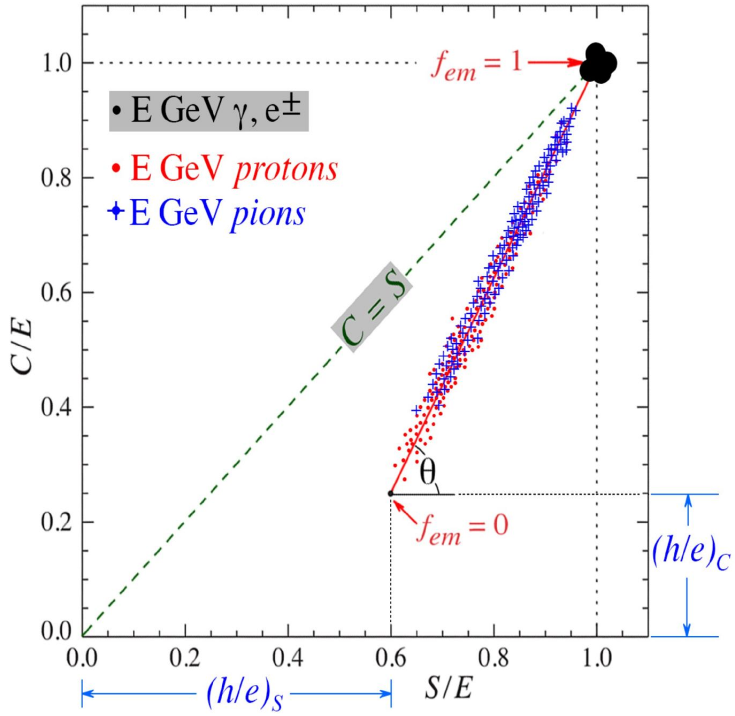
"Exposing a dual-readout fibre calorimeter to beams of electrons" +
"HiDRa: high-resolution calorimeter for e^+e^- colliders"

Andrea Pareti - INFN and Università di Pavia
on behalf of the Dual-Readout group - ECFA DRD 6 Collaboration
29/05/2024

AIDA innova

Dual-Readout calorimetry





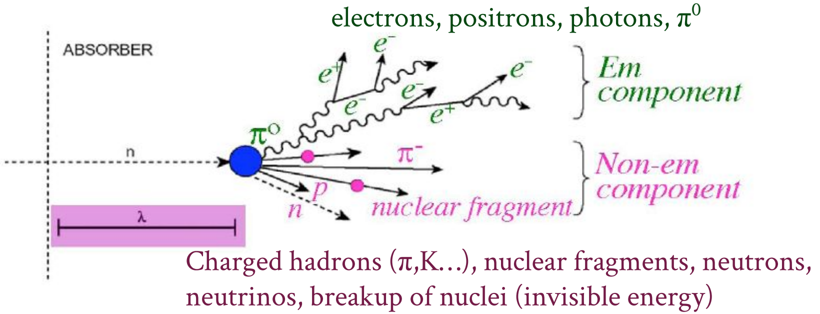
Non-linear response to hadron showers due to fluctuations in f_{em} and invisible energy heavily affects calorimeters energy resolution

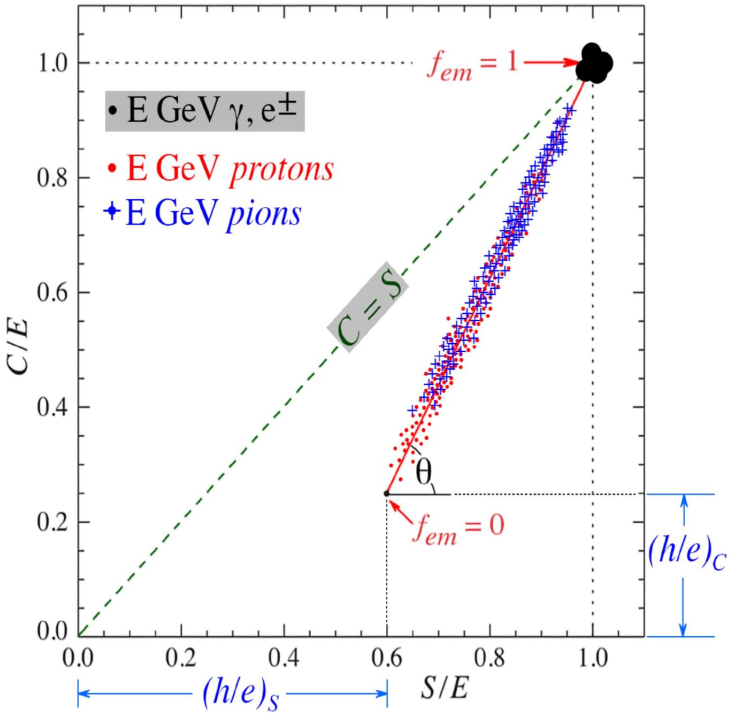
Dual-Readout: measure signals produced by two different physical processes to evaluate shower f_{em}

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

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

Dual-Readout calorimetry





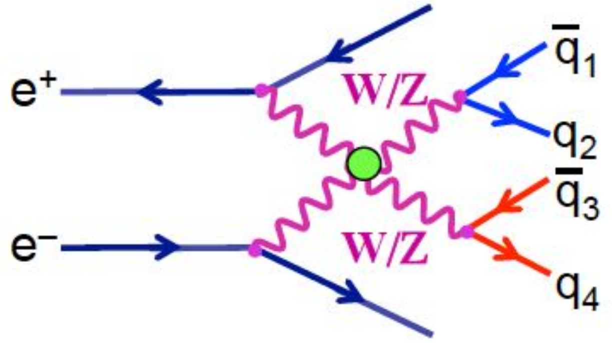
Advantages:

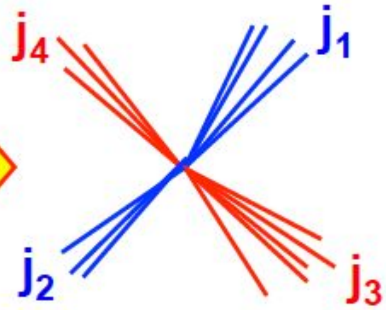
Calibration with $e^{\pm}$ beam

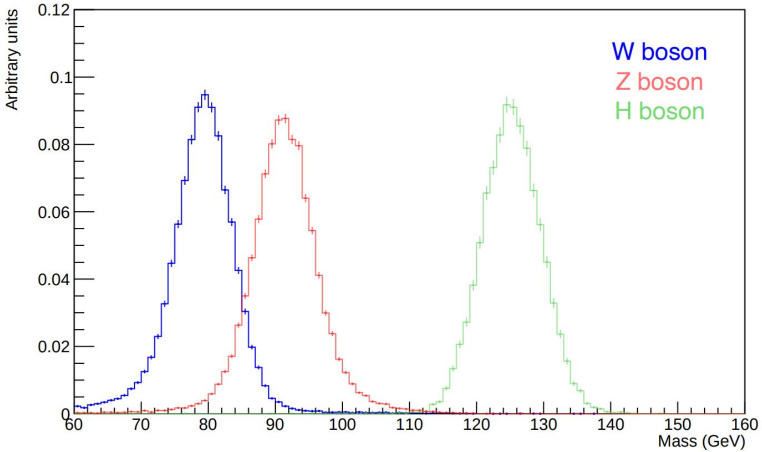
Same (electromagnetic) energy scale for both electromagnetic and hadronic shower measurements

Gaussian-shaped and linear response (e.g. correction for invisible energy)

Overview on dual-readout calorimetry







Jet measurement benchmarks at the FCC-ee

Higgs and electro-weak physics precision measurements programme
Large W/Z/H hadronic branching ratio:
90% of events will contain at least one hadronic jet

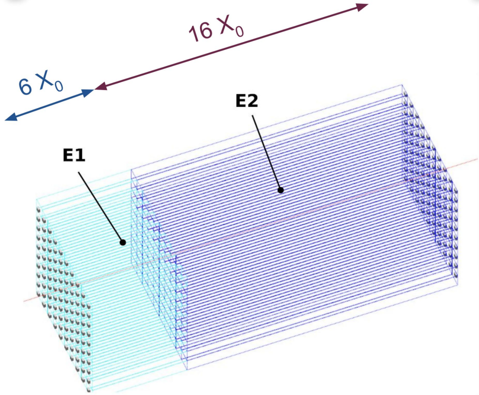
Main benchmark:
distinguish W and Z boson hadronic decay through jet invariant mass

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

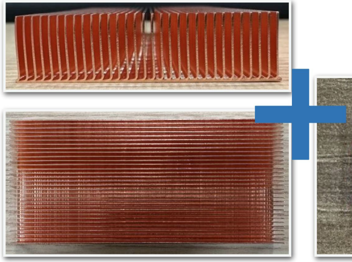
DR calo projects currently under development

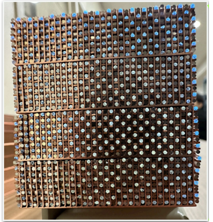
Crystal-based, dual-readout ECAL in front of the hadronic one
→ See Giulia's poster on MAXICC project



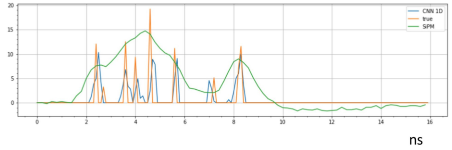
Skiving Fin Heat Sink technique from Korean team colleagues

SFHS copper block

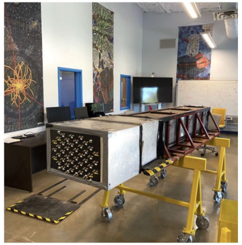


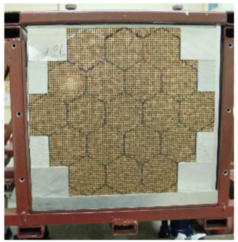

Front size of a tower

Fiber layer unit

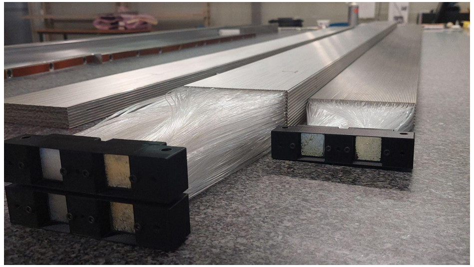


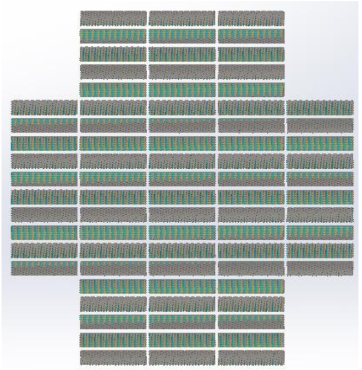
Study of timing information





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





Dual-Readout prototypes

2021

2023

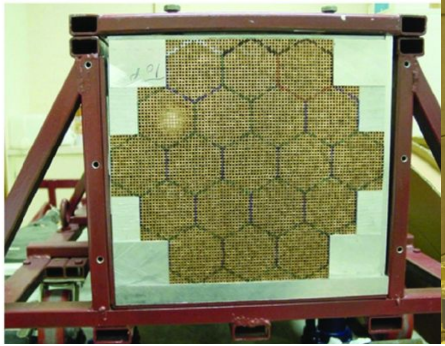
2024

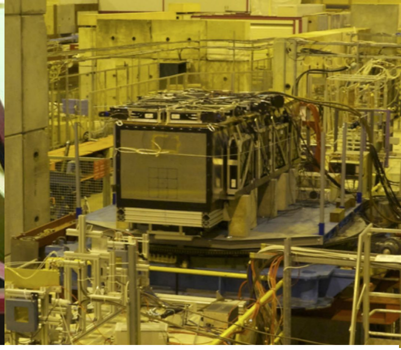
DREAM/RD52 collaboration
Proof of concept for the DR technique

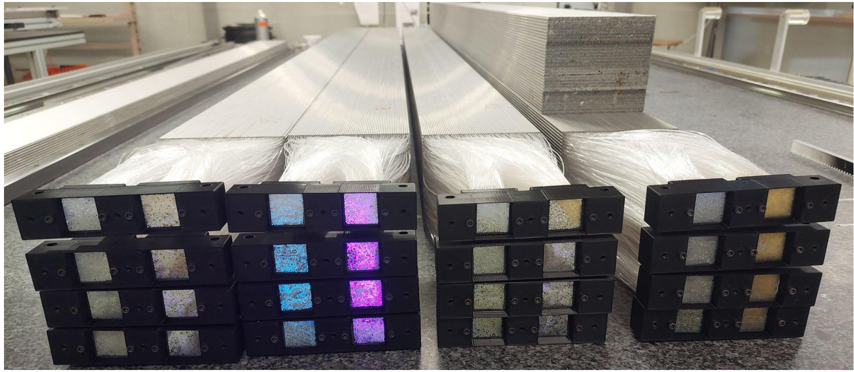
First prototype with high-granularity core
First beam tests at CERN SPS and DESY (Germany)

Start of hadronic prototype construction
And second beam test

Test beam with partially completed hadronic prototype
And hadronic prototype completion







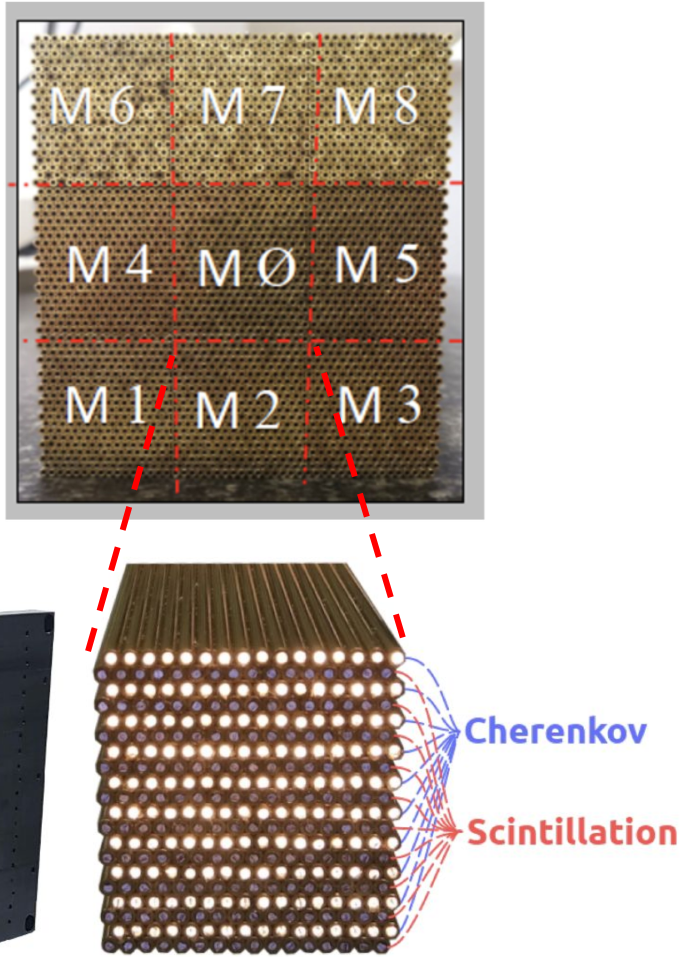
EM-shower-size prototype

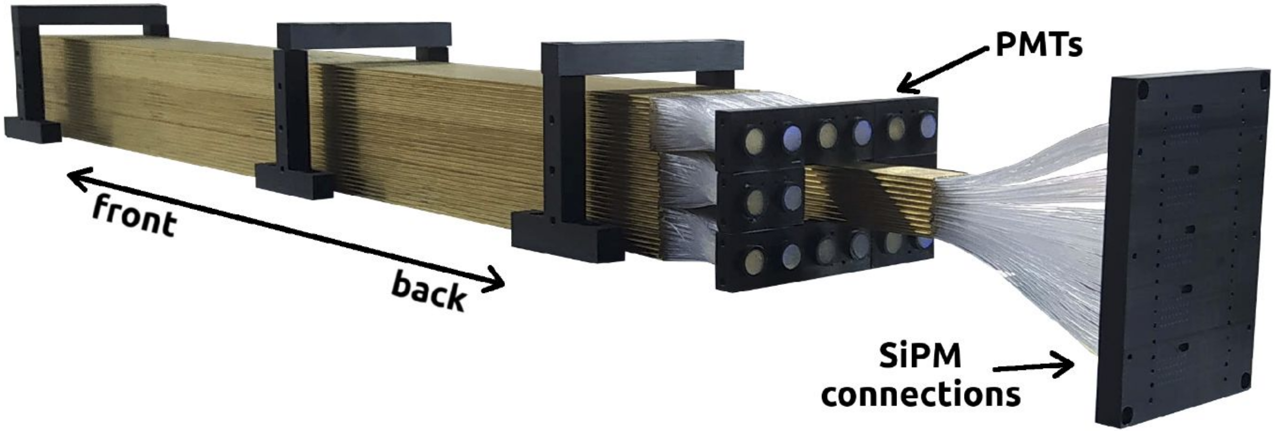
First high-granularity DR prototype built in 2021 and tested at CERN SPS
→ DOI 10.1088/1748-0221/18/09/P09021

9 modules made of 16x20 brass capillaries → 10x10x100 cm^3 volume

Tube inner diameter: 1.1 mm, outer diameter: 2 mm

Alternating rows of scintillating and clear (→ Cherenkov) optical fibres



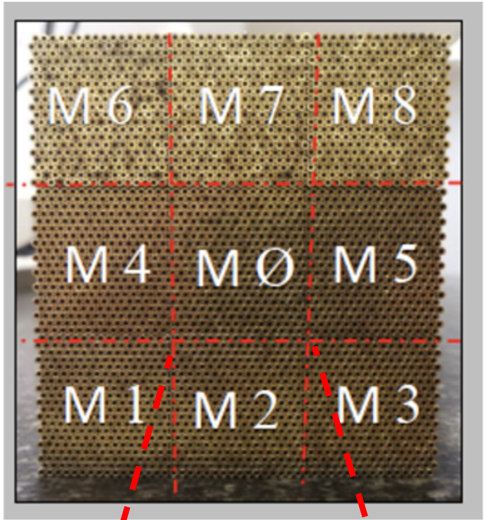


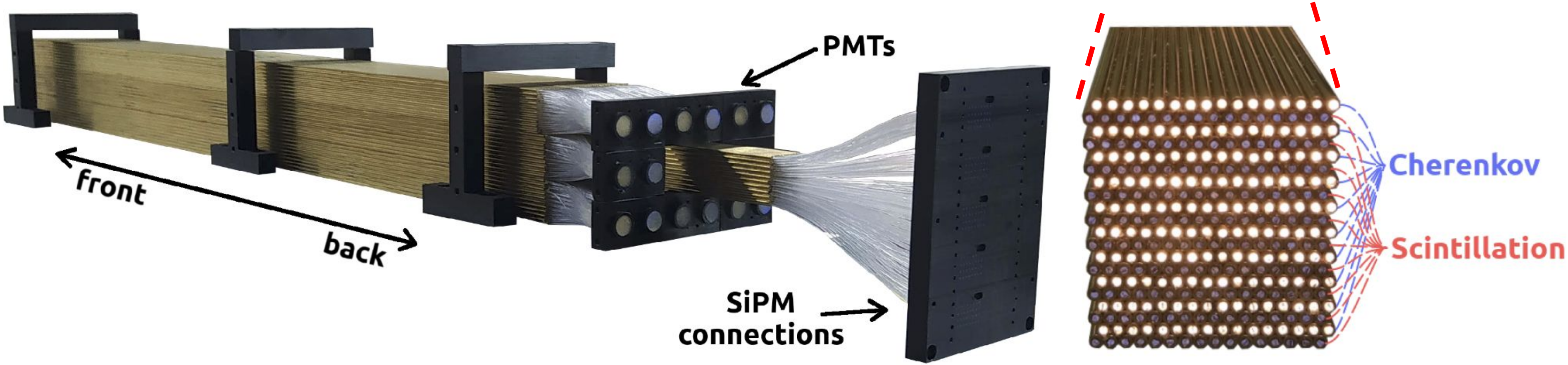
EM-shower-size prototype

Mixed SiPM/PMT readout solution:
Central module (M0) read out with SiPMs, M1-M8 with PMTs → 320 SiPMs
Hamamatsu S14160-1315 PS SiPMs and R8900 PMTs

15 µm pitch SiPMs with 1.3 x 1.3 mm^2 sensitive area for wide dynamic range

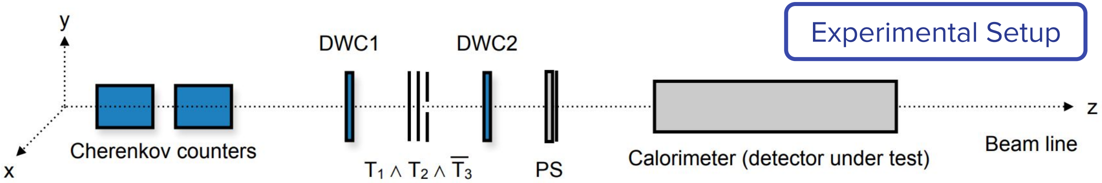
Kodak Wratten 3 yellow optical filters to cut short wavelengths from scintillation





SPS 2021 Test Beam

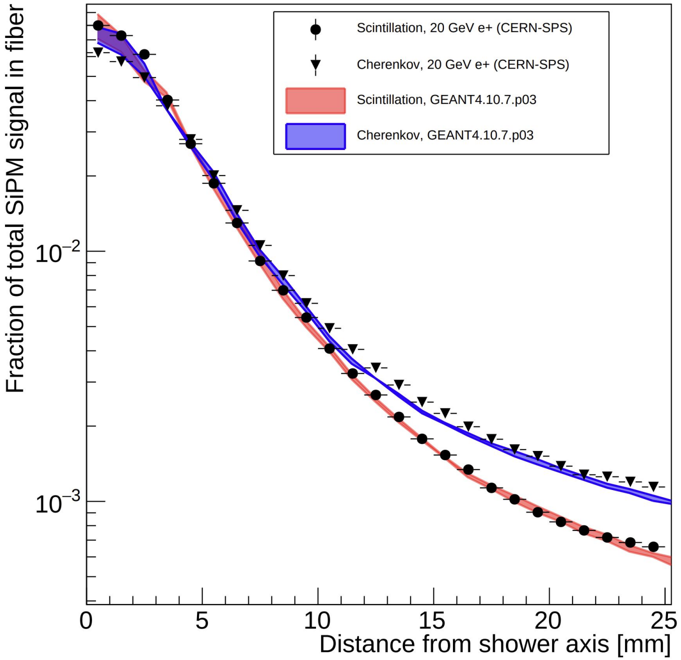
Experimental Setup



A few issues arose 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

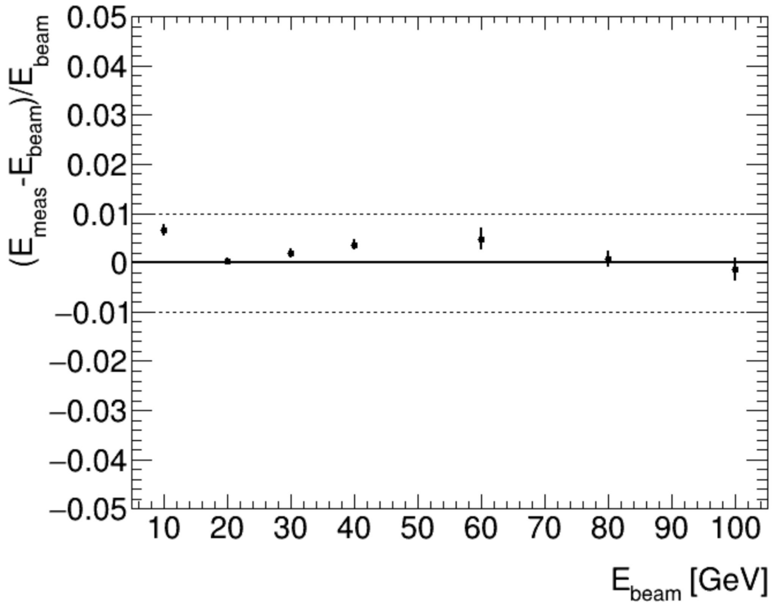


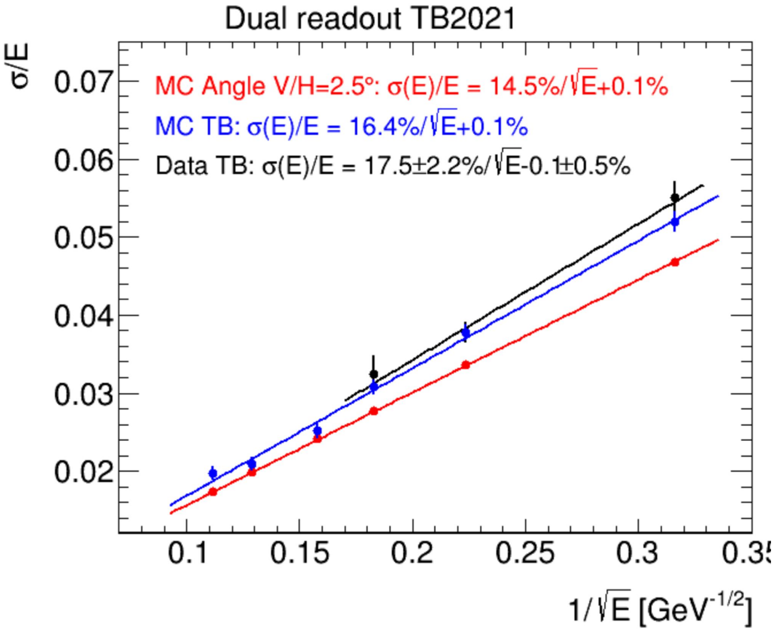
SPS 2021 Test Beam

Energy resolution measured 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



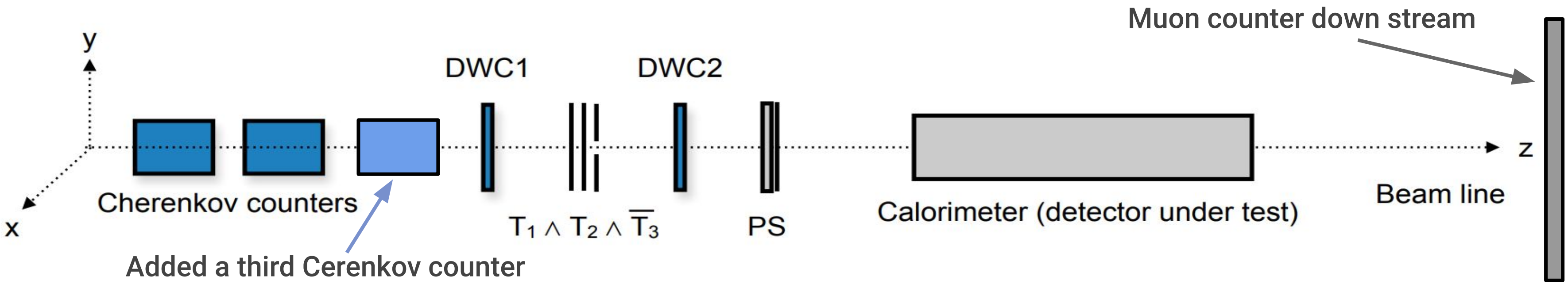


SPS 2023 Test Beam

Lots of data to be analysed, only very preliminary results will be shown in the next slides

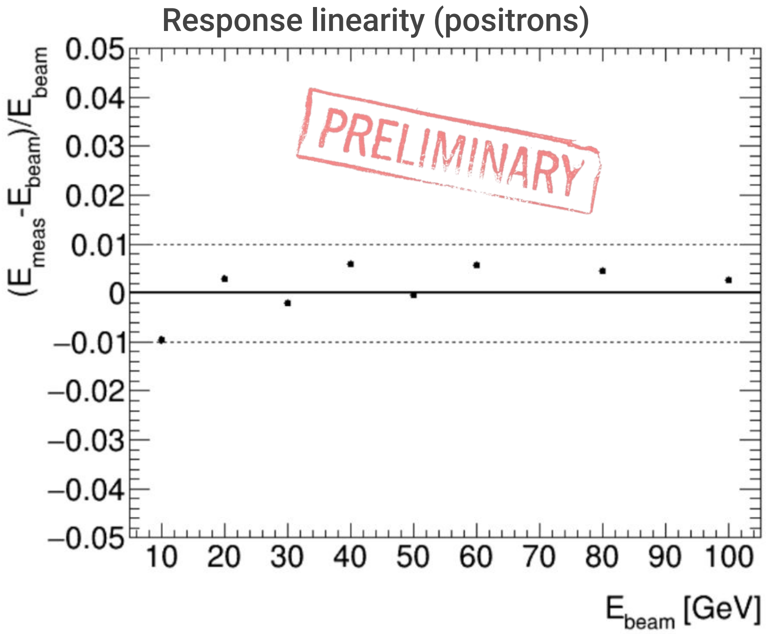
SPS - H8 beamline:

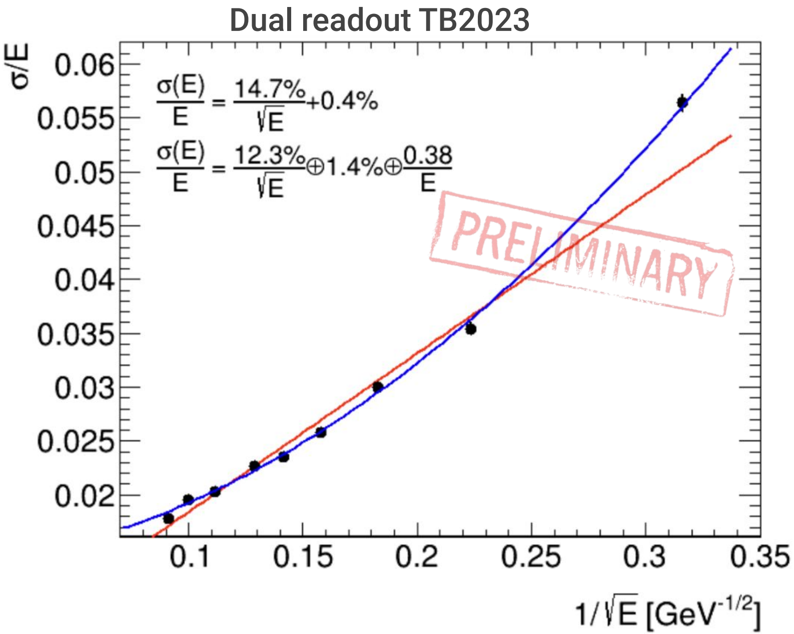
- **Beam purity definitely improved**
- Distance from preshower to calorimeter: 155 mm
- Calorimeter rotation:
  - Vertical angle: 0°, 2.5°
  - Horizontal angle scan: [-2.5°, ..., +4°] + run at 90^0 for light attenuation measurement
- **Positron ([10-120] GeV), muon (160 GeV) and pion ([20-180] GeV) beams**



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

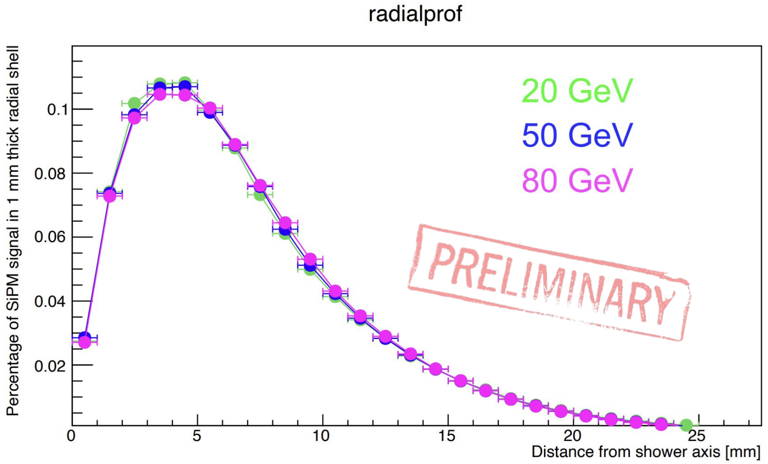


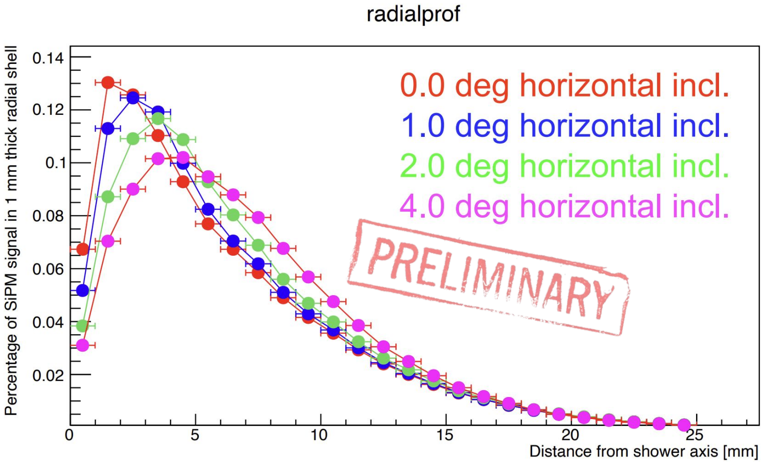


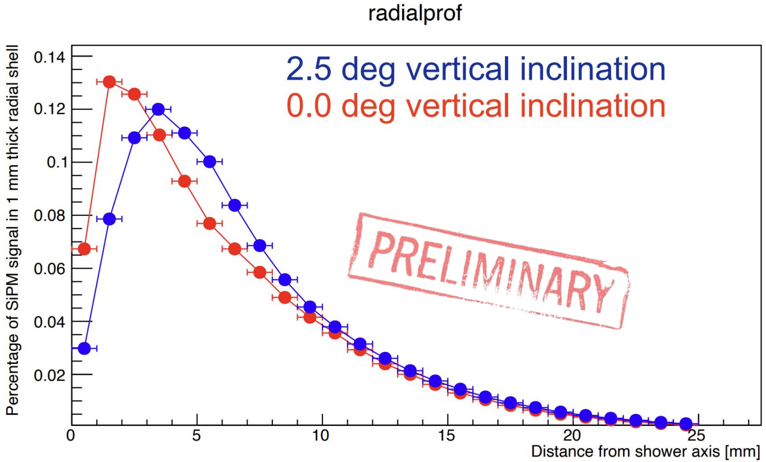
SPS 2023 Test Beam

Measurements of lateral electromagnetic shower profile

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

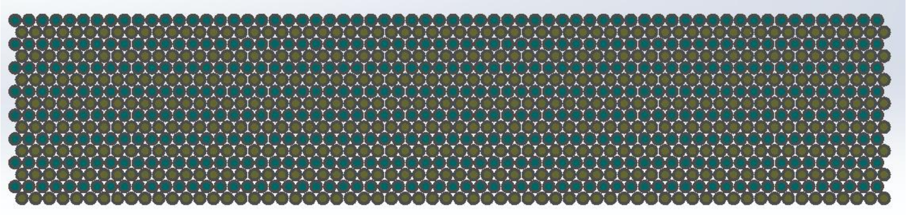






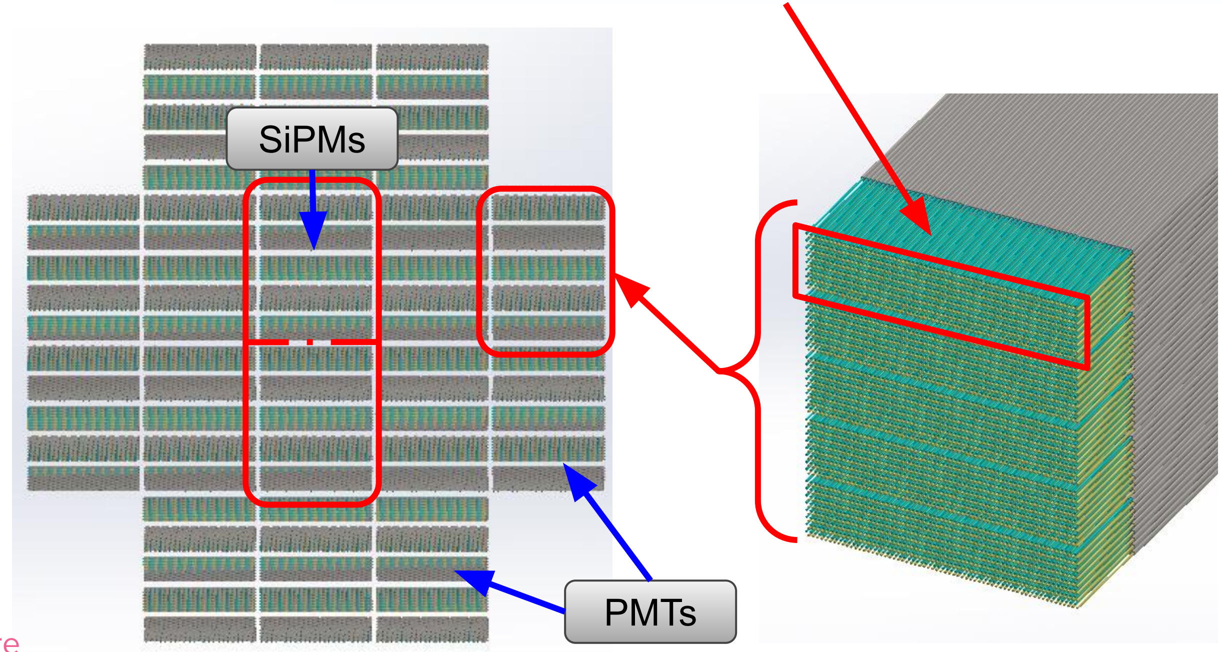
HiDRa prototype

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



High Resolution, highly granular Dual-Readout demonstrator
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)

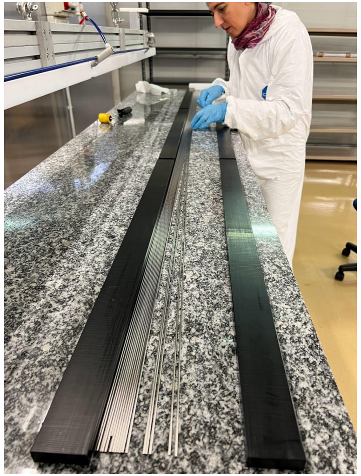


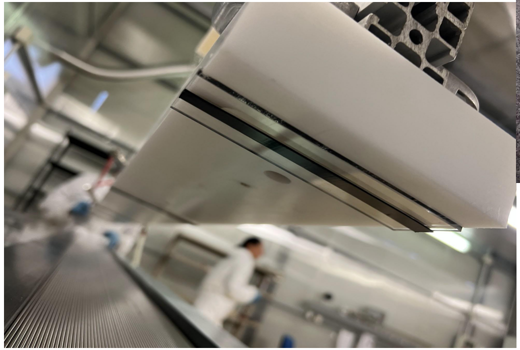
Design and a few results briefly described here

Module construction

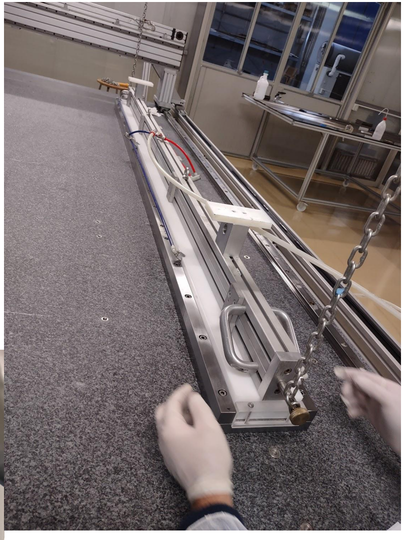
Definition of constructing technique and quality assessment on the modules geometry

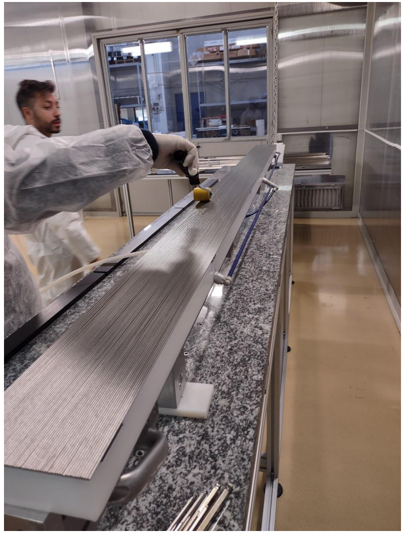
Tube aligned in a reference tool

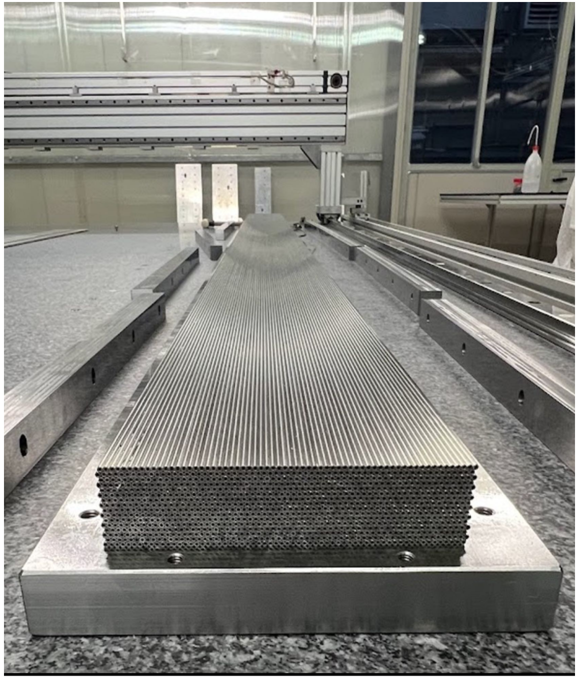




Stiffback-like technique for tube handling, gluing and positioning in the assembly tool



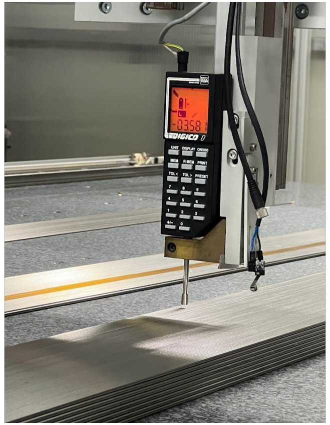
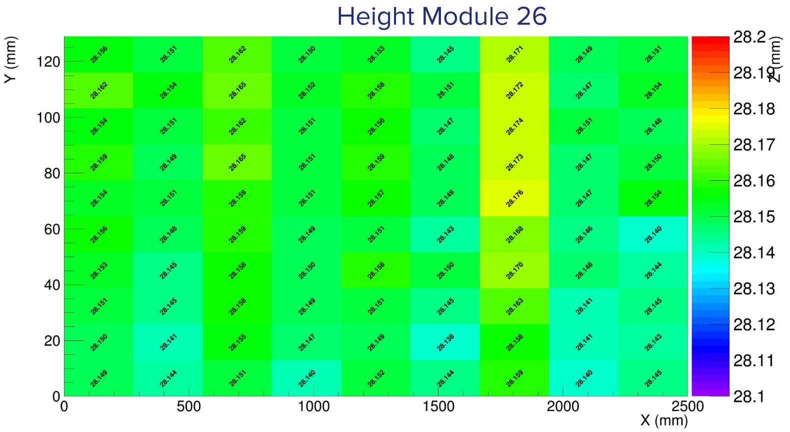




Vacuum + double-sided tape for tube handling

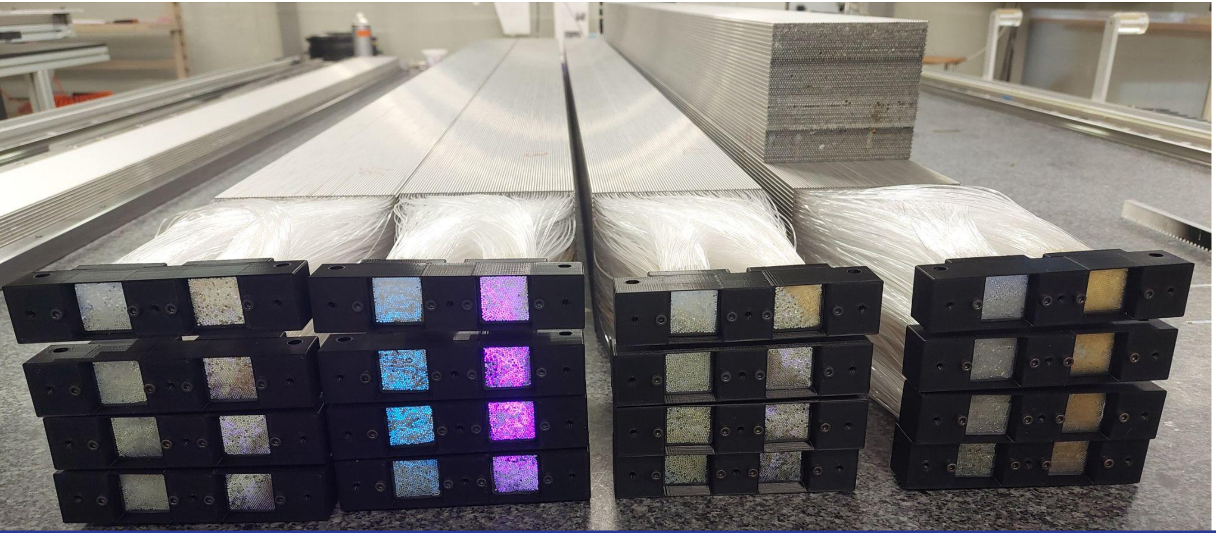
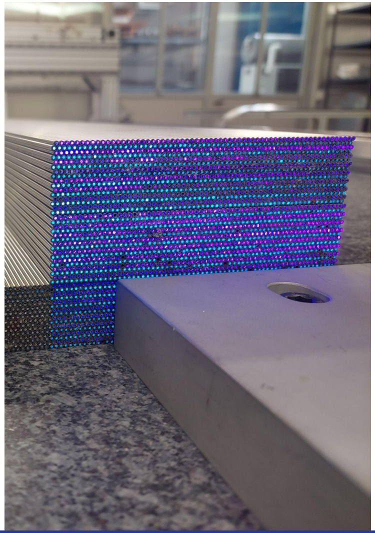
Module construction

Production started in November 2023
Currently 30/80 mini-modules have been assembled
First test beam with 36 mini-modules planned in August 2024 (PMT readout only)
SiPMs ordered, to be delivered later this year

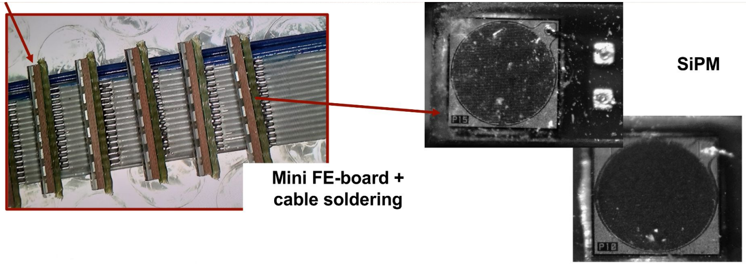



Semi-automatic system for planarity QAQC

Reached O(10μm) precision in mini-module height

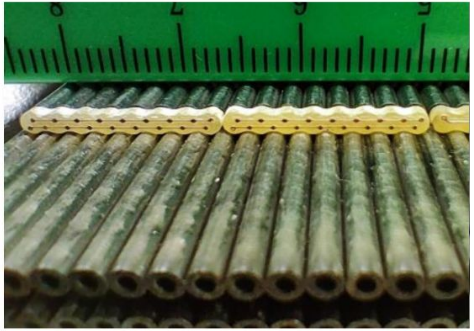



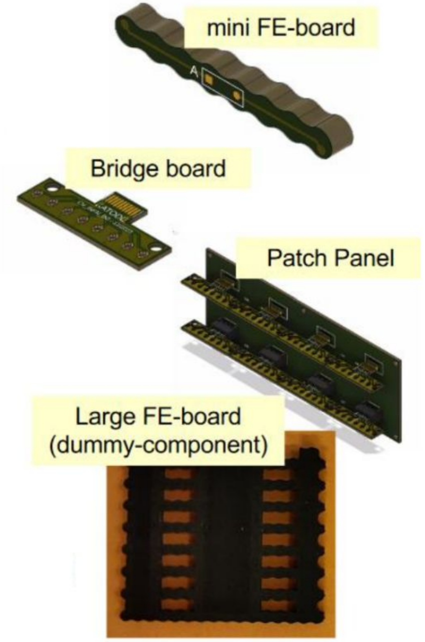
SiPM integration & readout



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





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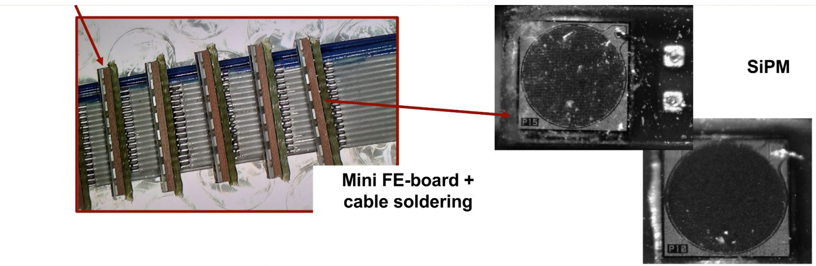

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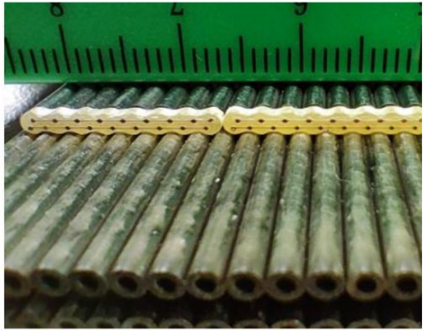
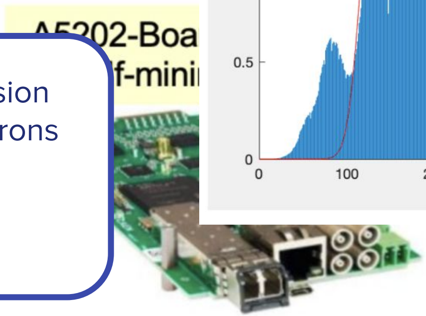
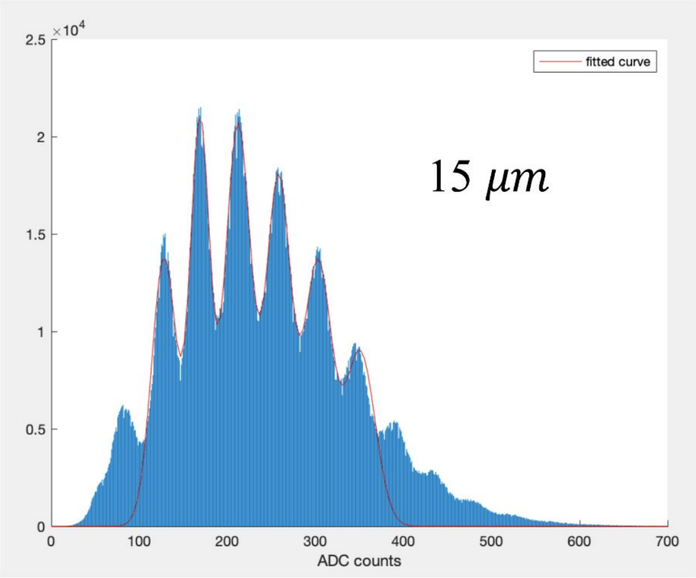






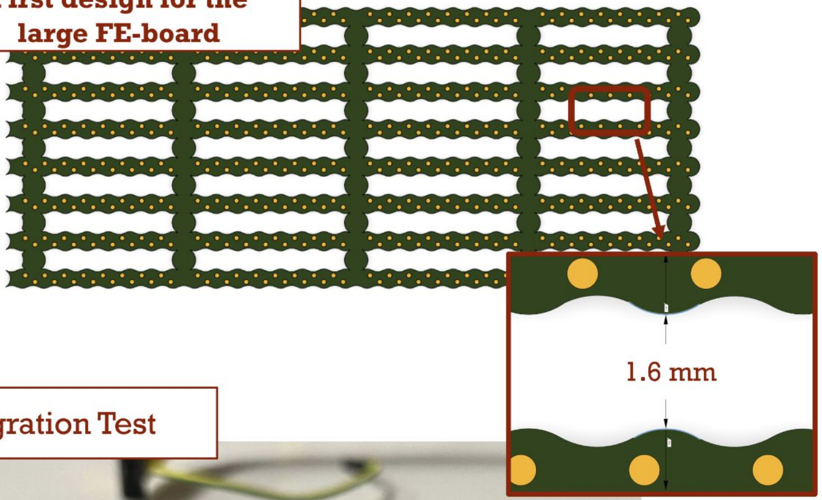
- ➢ Multi-photon spectra was used for conversion from ADC counts to number of photoelectrons during first test beam
- ➢ Procedure for 10 µm pitch SiPMs is under discussion

SiPM Mechanical integration

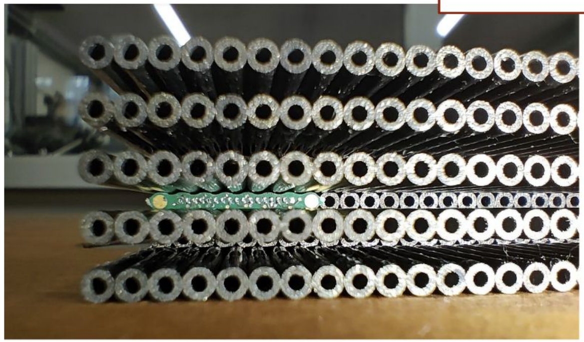
- Design ready for mini-frontend and bridge boards, and patch panel almost ready as well
- Large frontend board (32 SiPM bars) under study
- SiPM integration to be demonstrated soon with both dummies and, when available, real components

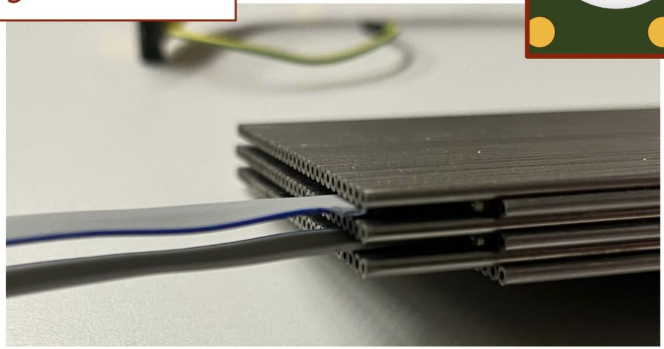
First tests with dummy components

First design for the large FE-board



Board Integration Test

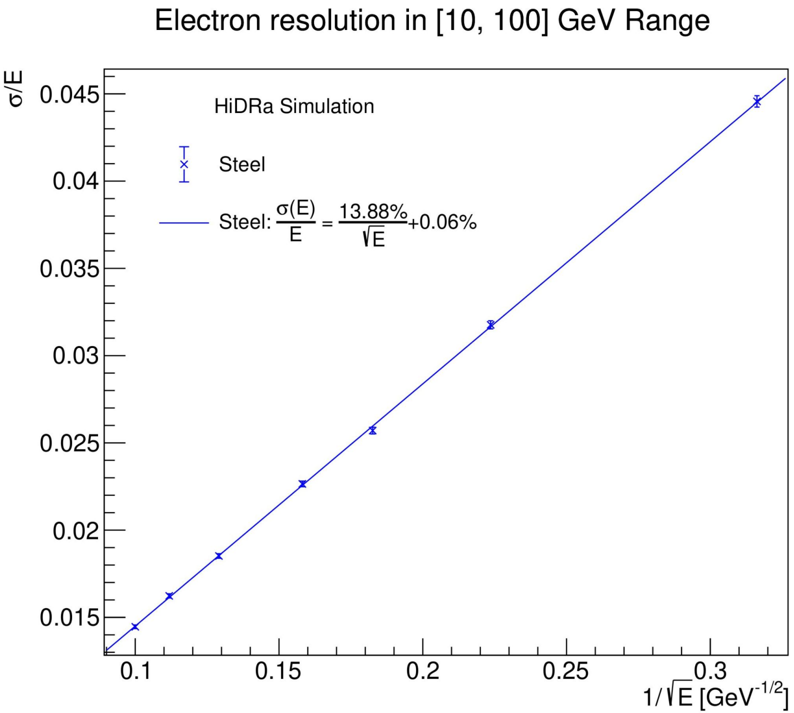


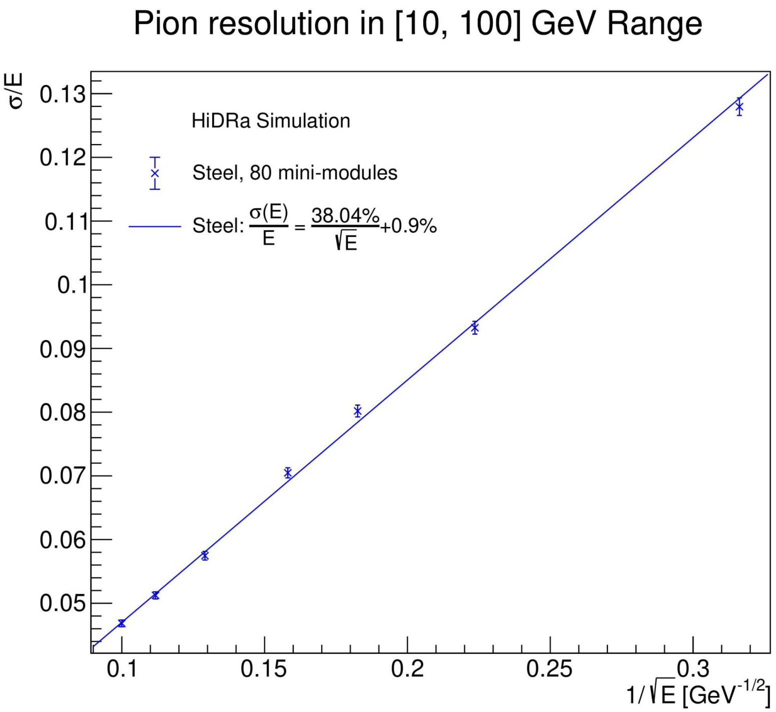


HiDRa performance studies

→ See more results on Geant4-based simulations for both HiDRa prototype and the IDEA dual-readout calorimeter in Andreas' poster

Geant4 simulation-based energy resolution, for electrons and pions





HiDRa performance studies

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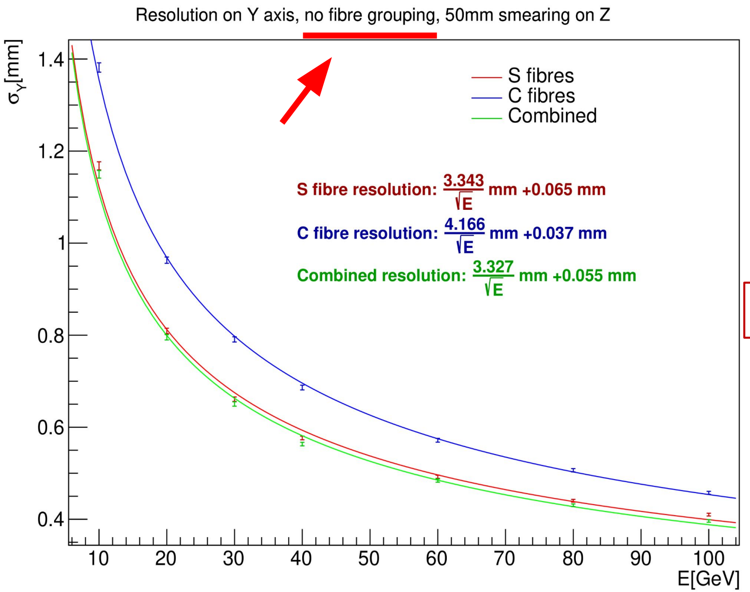
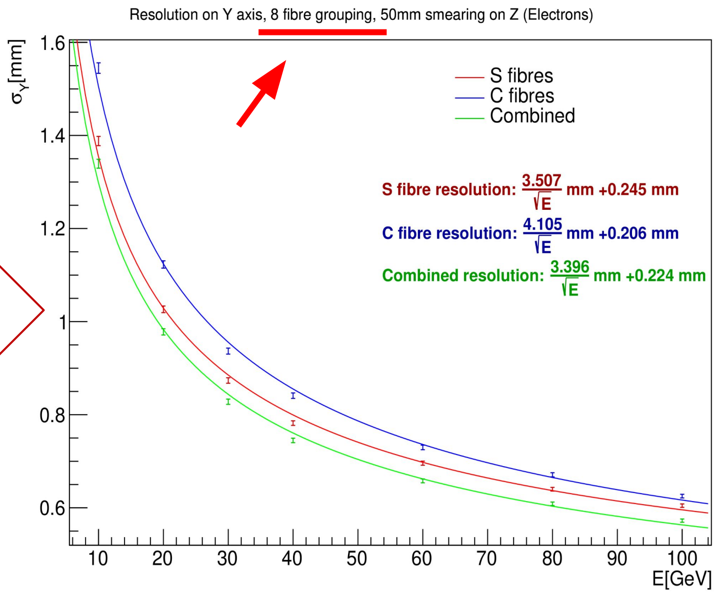
Geant4 simulation-based spatial resolution (e^+ beam)

Grouping does not significantly affect spatial resolution
Molière radius in HiDRa: *O*(25) 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 characterised with test-beam campaign
- ➢ Geant4 simulation has been validated with em shower-scale prototype, and results seem promising
- ➢ Full Simulation of IDEA calorimeter with capillary tubes geometry under development
- ➢ Dual-readout crystal calorimeter option under study. Preliminary results show it can boost performance in several measurements (e.g. flavour physics)

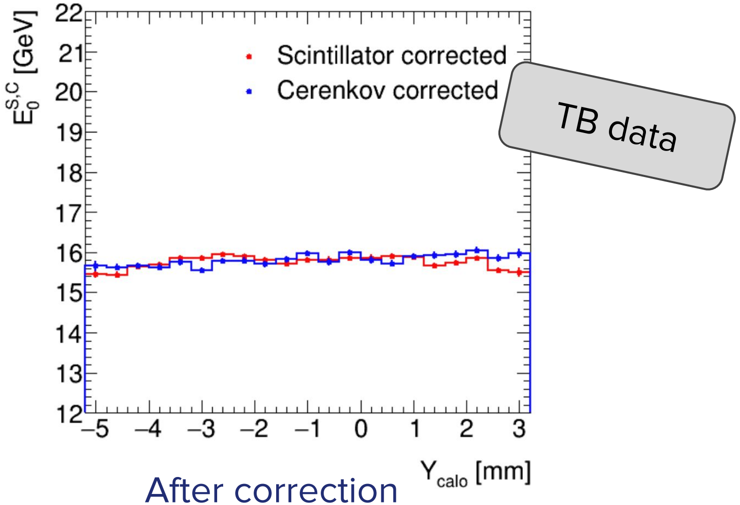
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA nº 101004761"

BACKUP

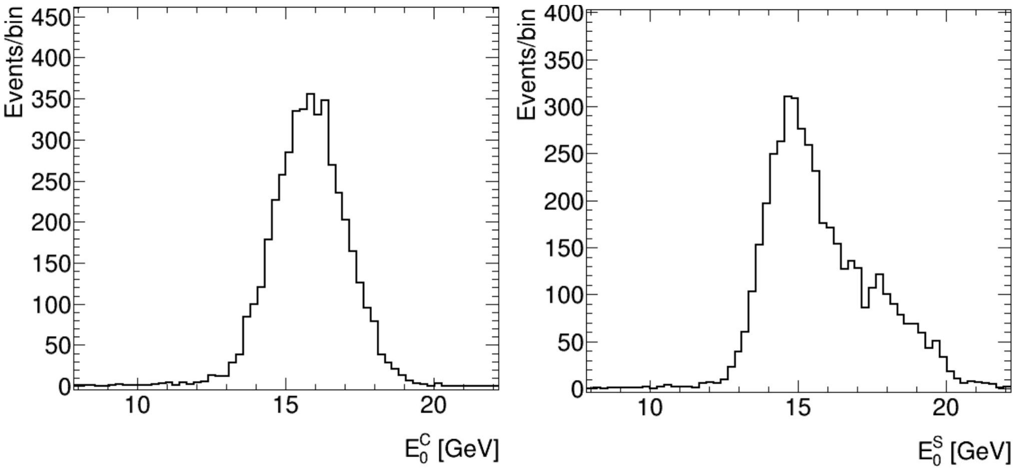
SPS 2021 Test Beam

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

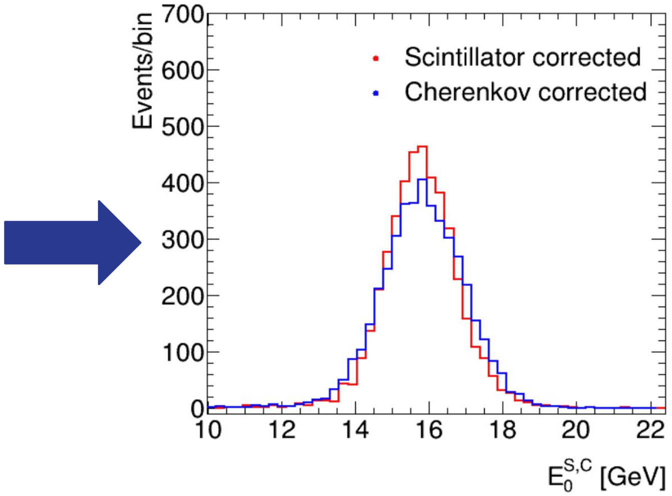
$$R_{\max} = \frac{\sum_{\text{Row with highest signal}} E_S}{\sum_{\text{All Rows}} E_S}$$



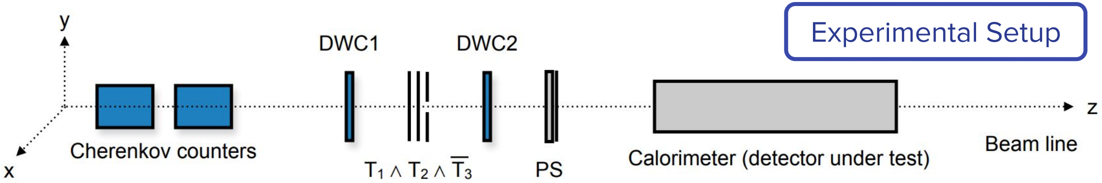
C (S) calibrated signal before correction



After correction



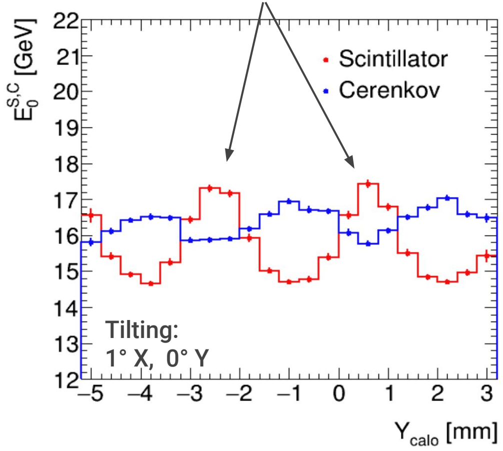
SPS 2021 Test Beam



A few issues arose during data taking:

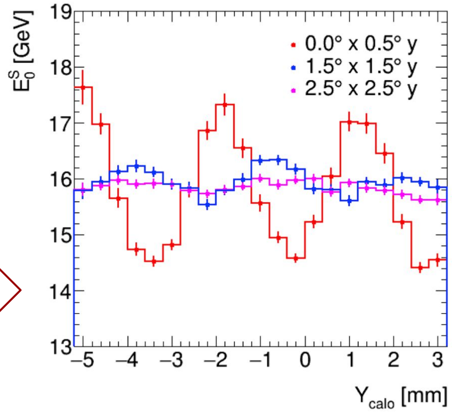
- ➢ Bad beam purity
- ➢ Preshower far from the detector for access issues
  ➜ em showers not well contained
- ➢ Small calorimeter rotation angle
  1° on X direction, 0° on Y direction
  ➜ signal highly dependent on impact point

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

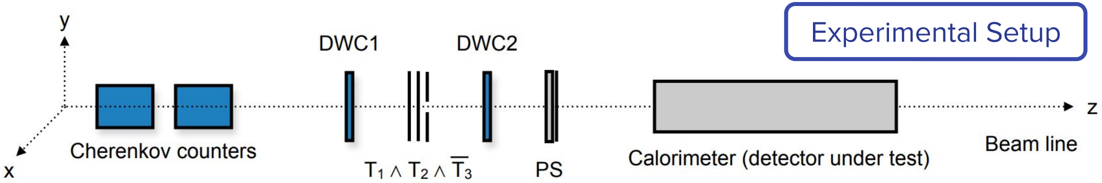


DATA

SIMULATION



SPS 2021 Test Beam

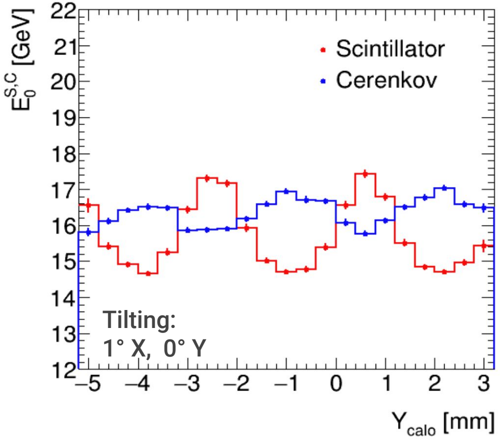


Experimental Setup

A few issues arose during data taking:

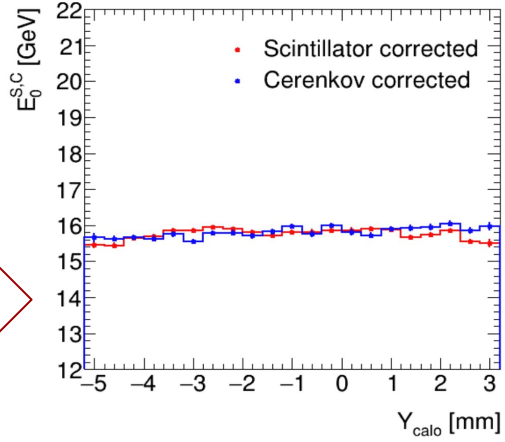
- ➢ Bad beam purity
- ➢ Preshower far from the detector for access issues
  - ➔ em showers not well contained
- ➢ Small calorimeter rotation angle
  1° on X direction, 0° on Y direction
  - ➔ signal highly dependent on impact point

Correction for impact point position dependence by exploiting finely segmented information provided by SiPMs



DATA

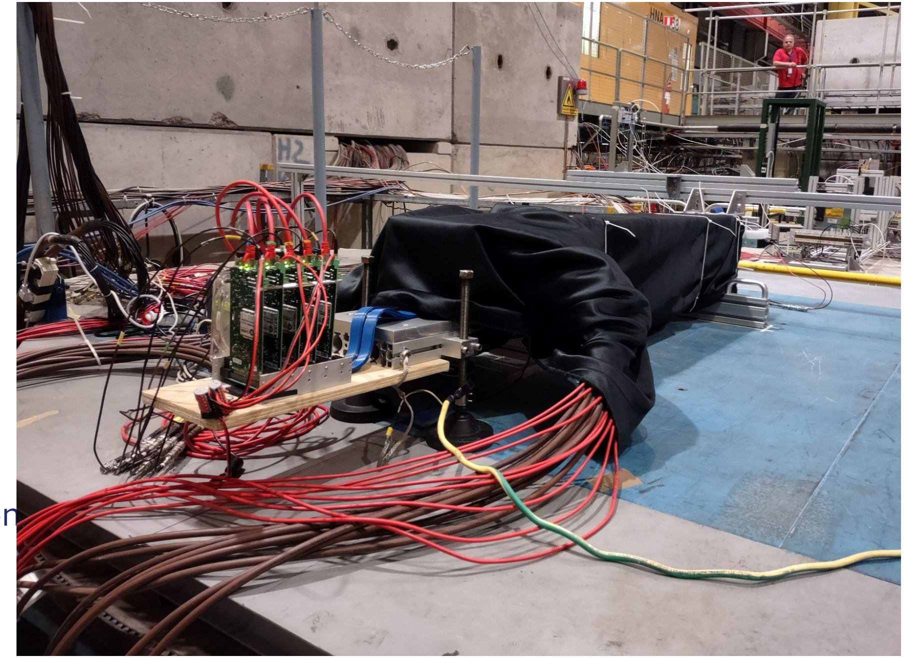
DATA



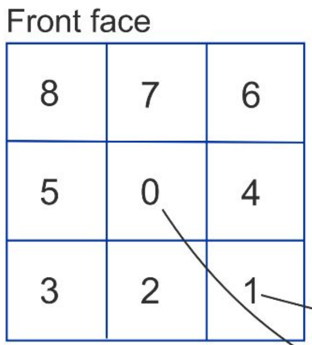
SPS 2023 Test Beam

<u>Main objectives</u>

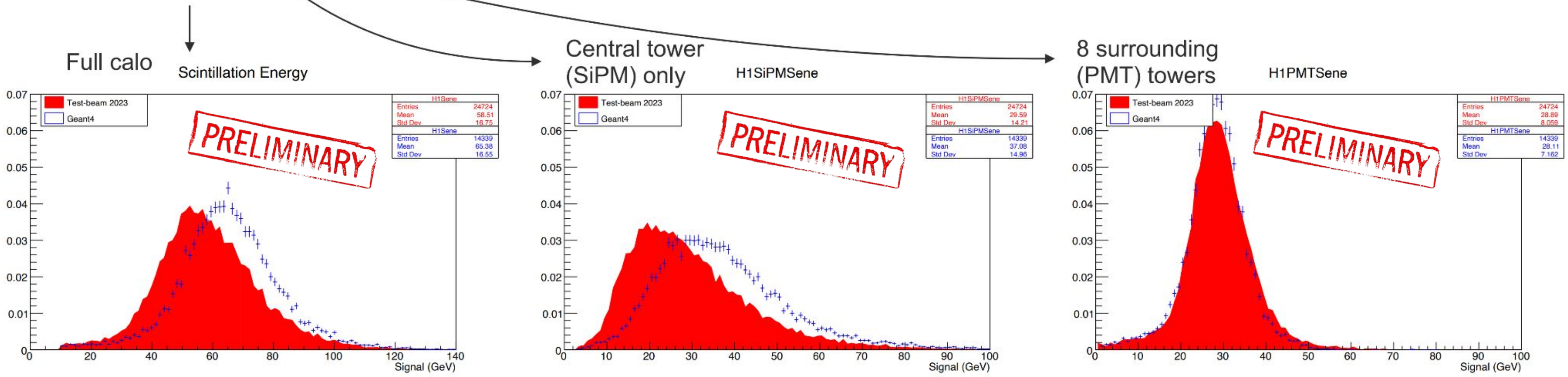
- Electrons:
  - response linearity with energy
  - energy resolution
  - response modulation over impact point
  - performance dependence over impact angle
  - position resolution
  - shower shape
  - M0 tower uniformity
- Muons:
  - response dependence over impact angle and position
  - (try) γ-radiation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



SPS 2023 Test Beam (pions, scintillation channel)

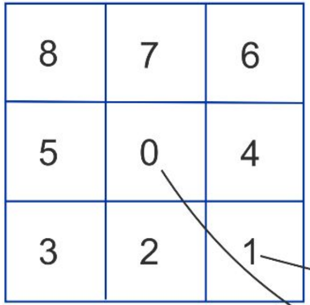


- The scintillation response predicted by Geant4 is higher than the data
  - This discrepancy almost entirely arises from the narrow core of the shower → too much ionizing signal in the hadronic shower core
- The S signals fluctuations are (only!) 1.2% smaller than the data for the full calo case



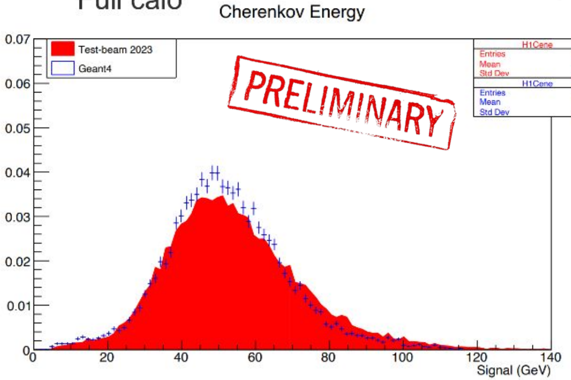
SPS 2023 Test Beam (pions, Cerenkov channel)

Front face

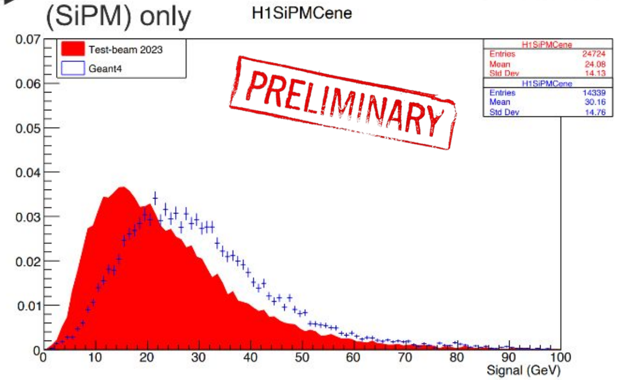


- The Cherenkov response is on average well reproduced by Geant4 for the full calo case
  - However there is too much signal in the core and too little signal in the surrounding tower
- The C signal fluctuations agree within 10% for the full calo case

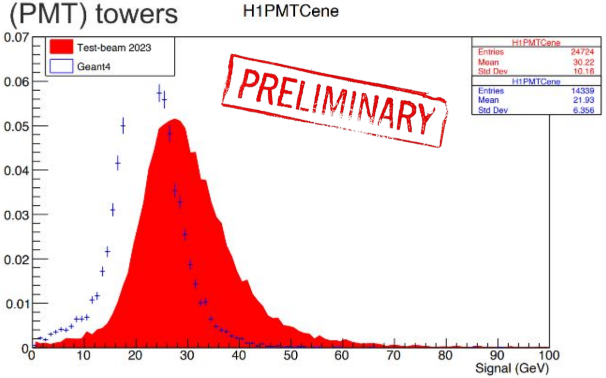
Full calo



Central tower (SiPM) only



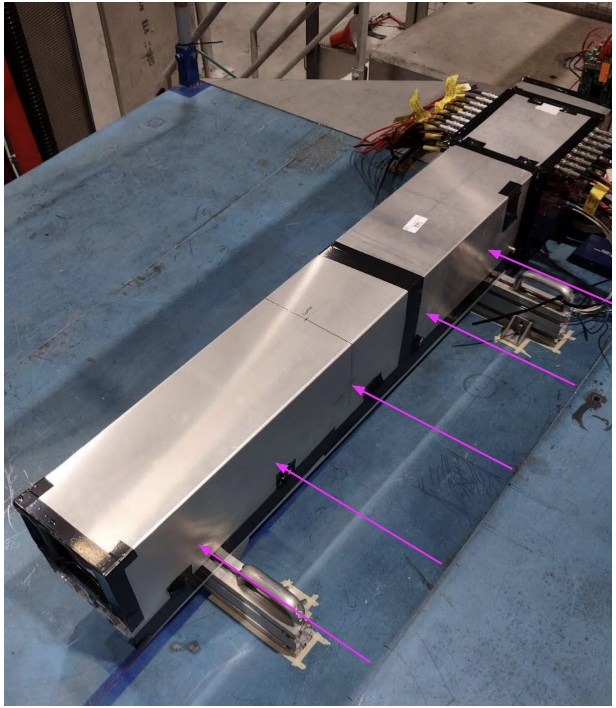
8 surrounding (PMT) towers

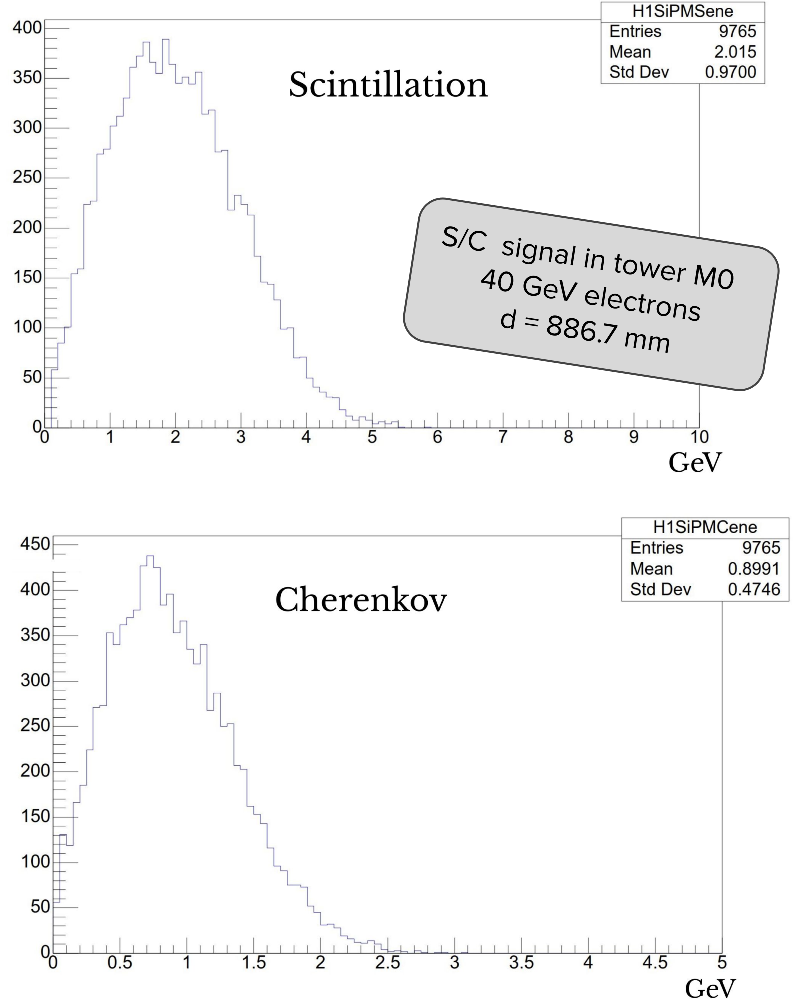


SPS 2023 Test Beam

Attenuation length measurement

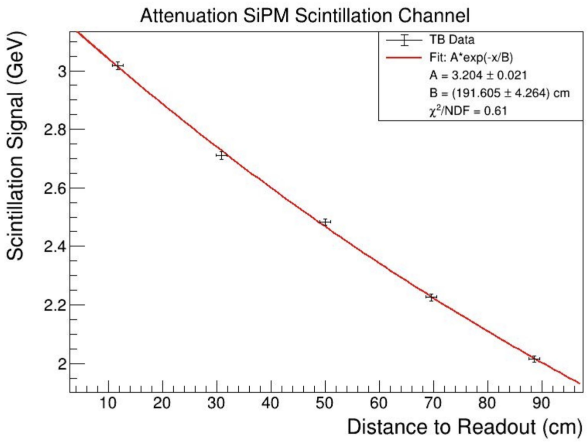
Calorimeter rotated by 90° in horizontal direction at the end of test beam (40 GeV e^{+} and 160 GeV μ^{+}). Only SiPM information is being used

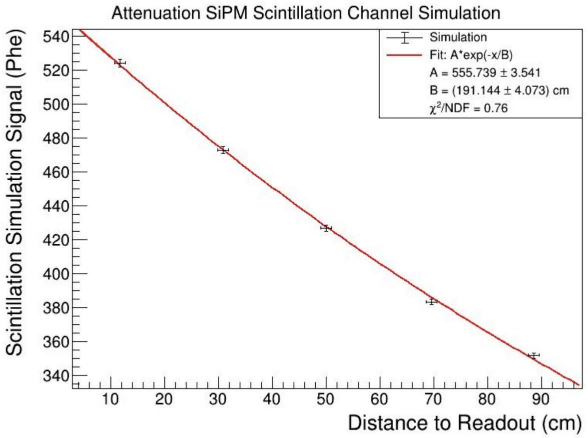




SPS 2023 Test Bear

TB data | **Simulation**



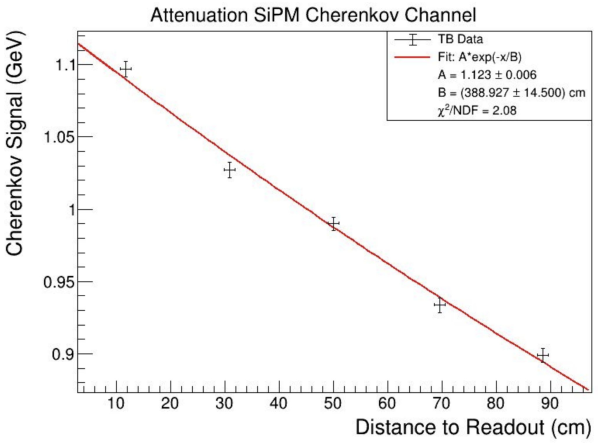


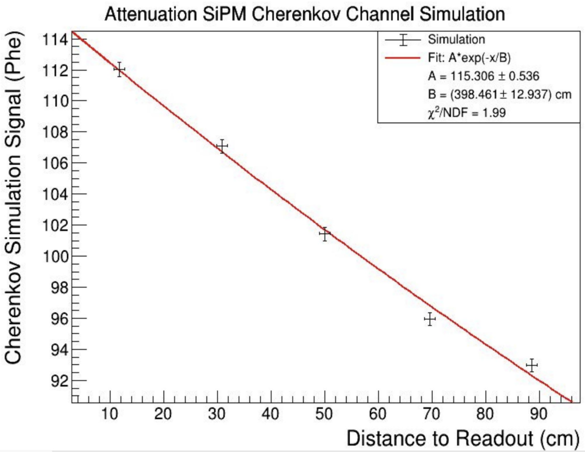
<u>**Attenuation length measurement**</u>

Effect introduced in simulation and well-reproduced

To be used in further studies also in HiDRa simulation

S fibres attenuation length:
191.6 cm





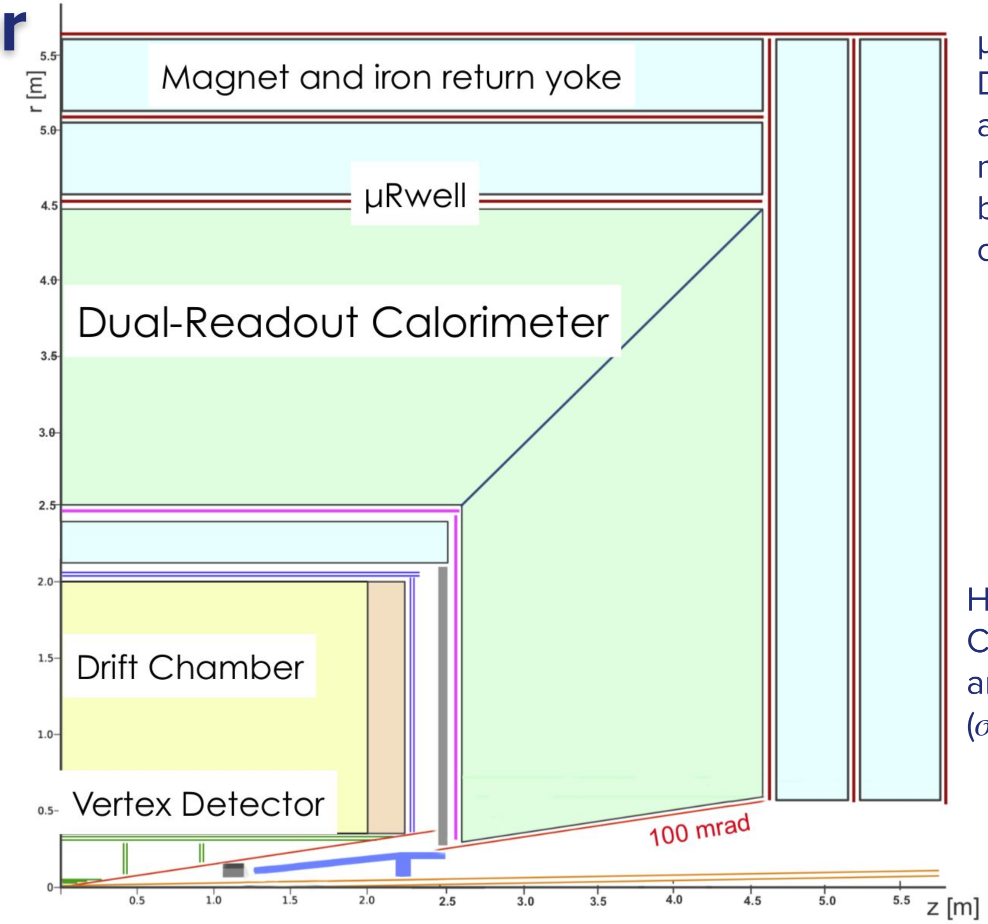
C fibres attenuation length:
388.9 cm

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

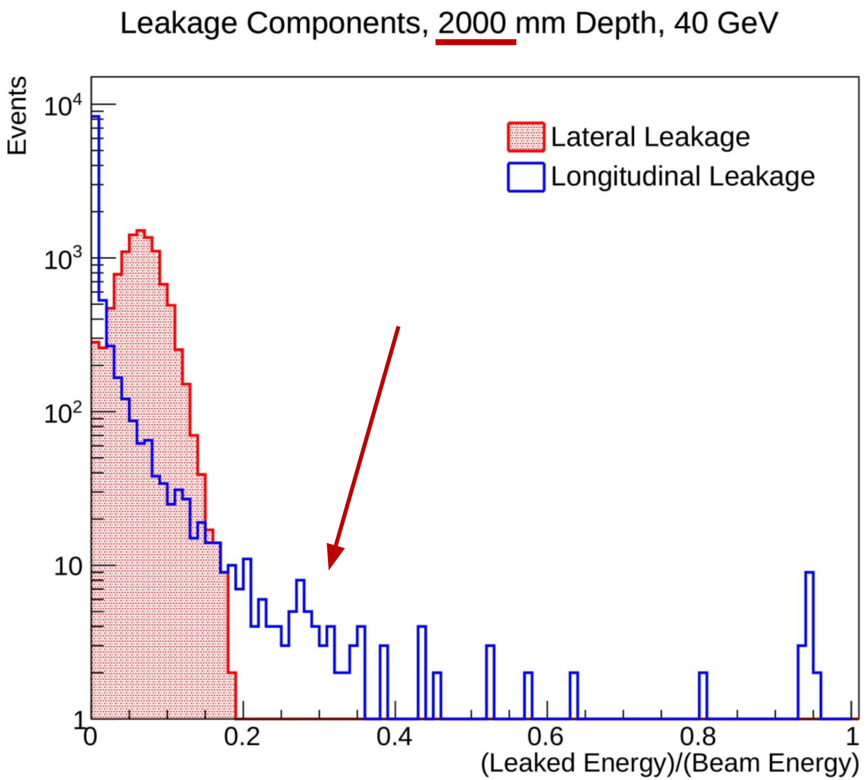


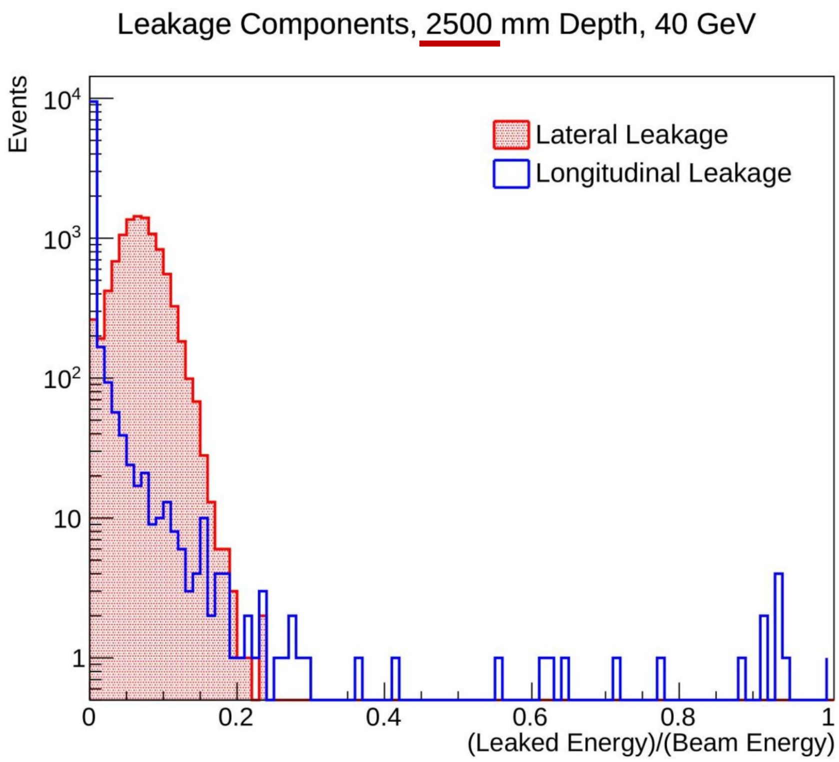
µ-RWELL MicroPattern Gas Detector stages for muon ID and momentum measurement located before and after the calorimeter

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

HiDRa Leakage studies

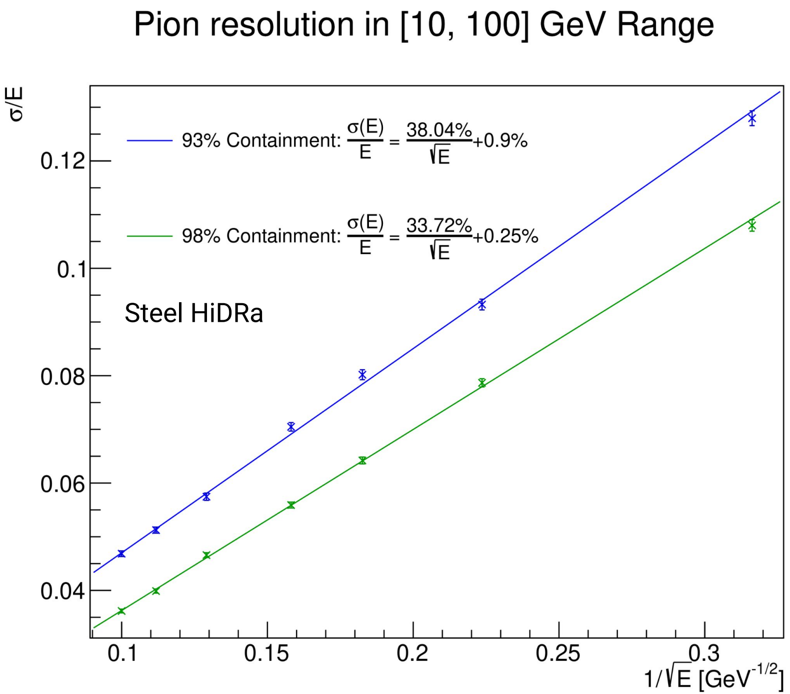
- ➢ Lateral leakage has major impact on energy resolution
- ➢ Longitudinal leakage leads to low-reconstructed-energy events

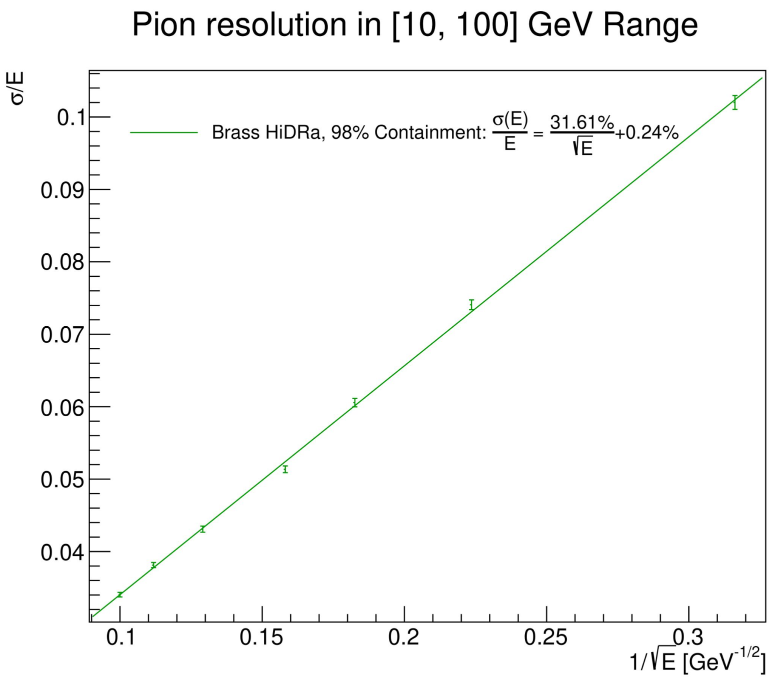




HiDRa energy resolution

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

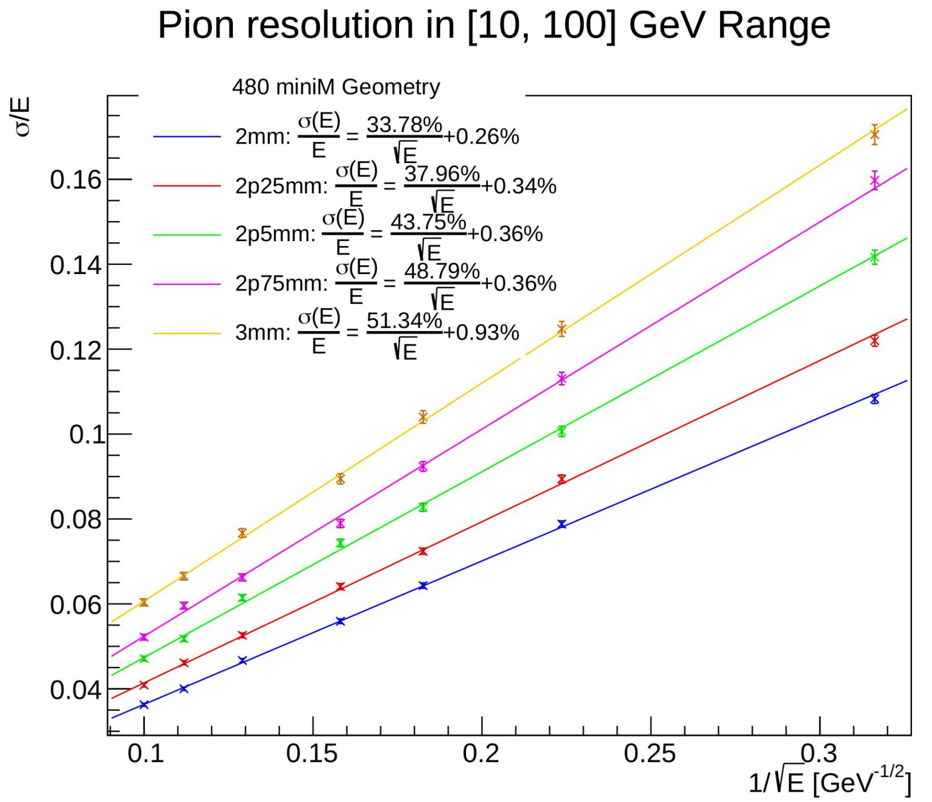




Resolution Vs Sampling Fraction

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

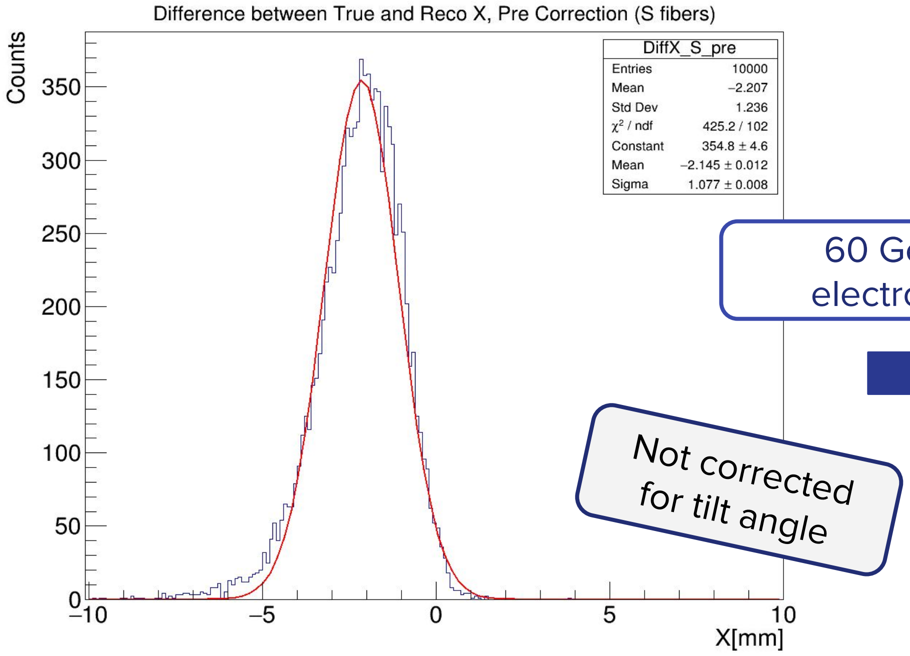


HiDRa space resolution

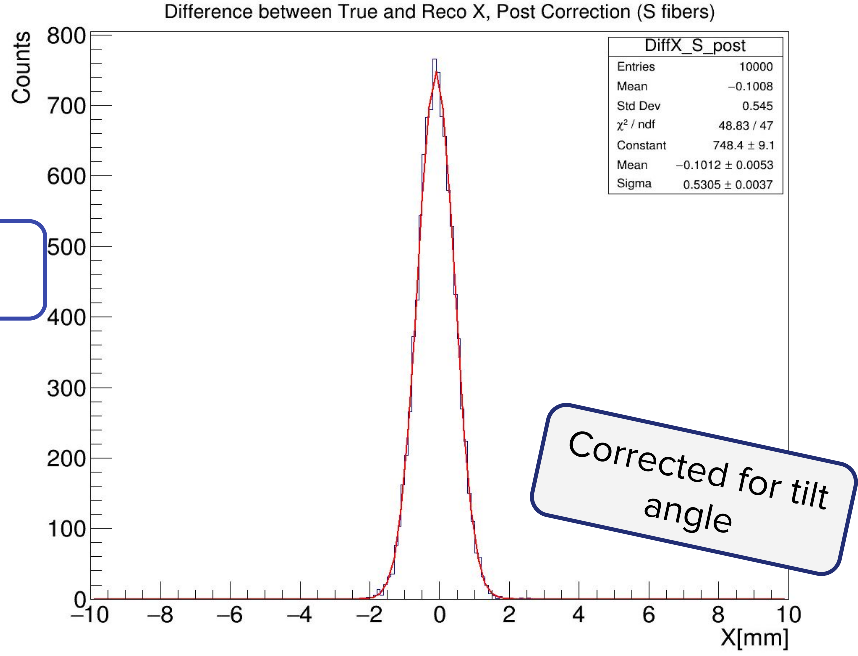
Reconstruct coordinates through centre-of-gravity method
Plots obtained with independent SiPM information

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

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



60 GeV electrons



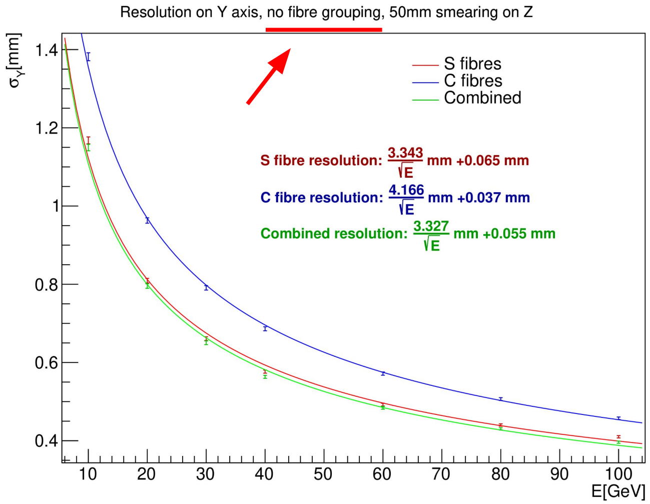
HiDRa space resolution (e^+)

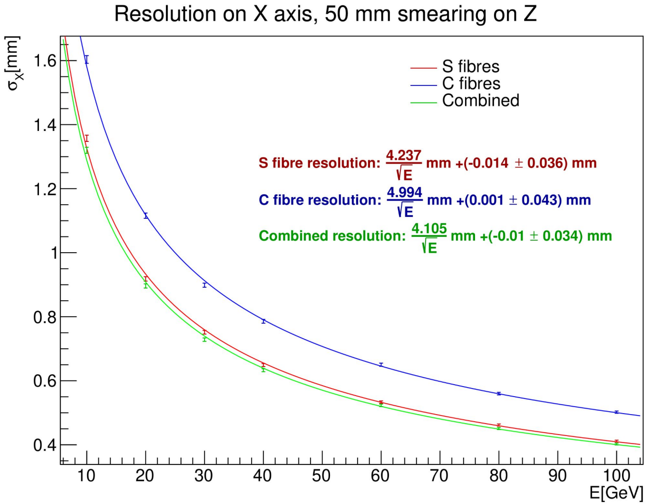
Reconstruct coordinates through centre-of-gravity method

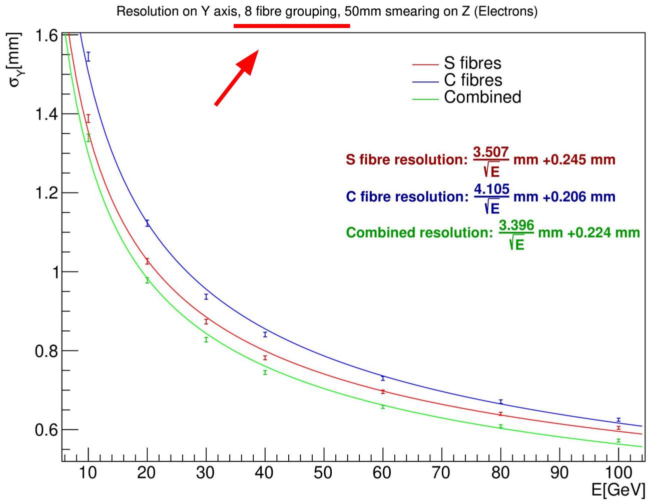
$$x_{\text{Bar}} = \frac{\sum_i E_i x_i}{\sum_i E_i} \qquad y_{\text{Bar}} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

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)







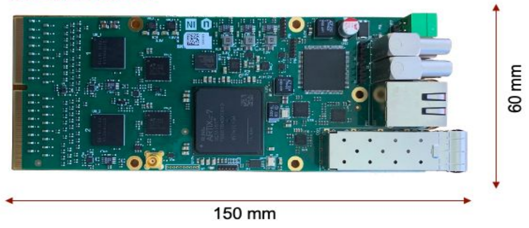
HiDRa SiPM integration & readout

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)

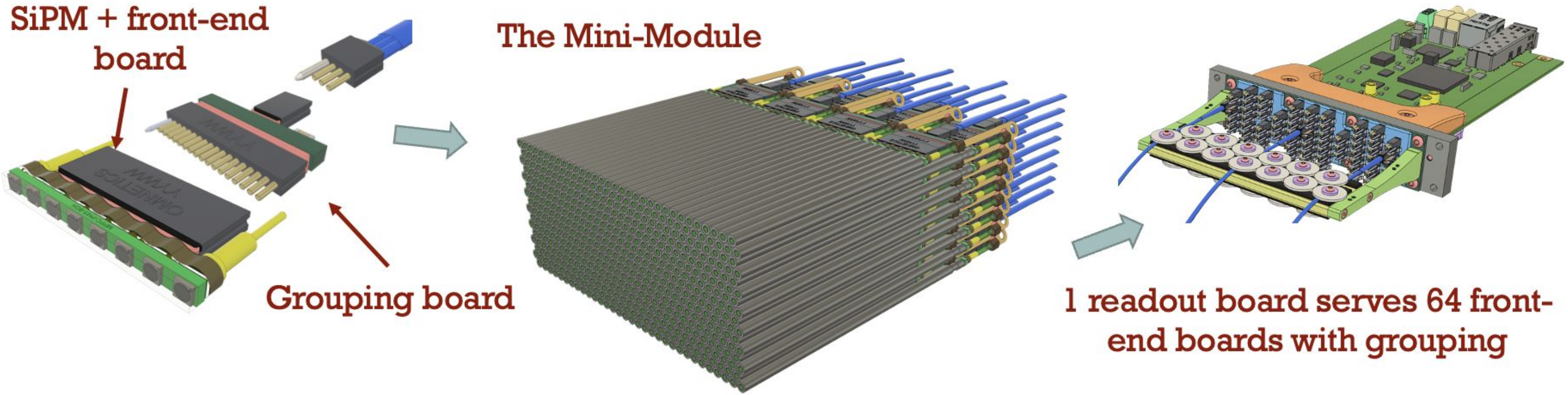
Baseline solution:

- ➢ 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

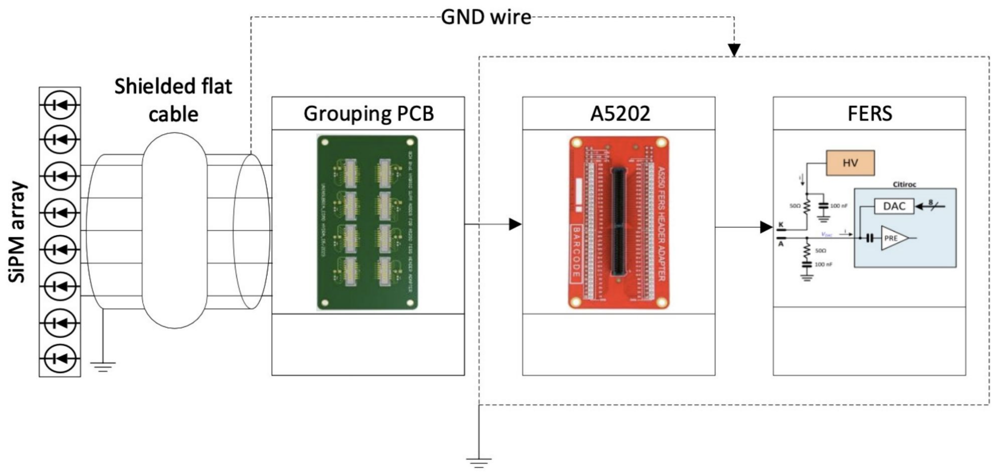


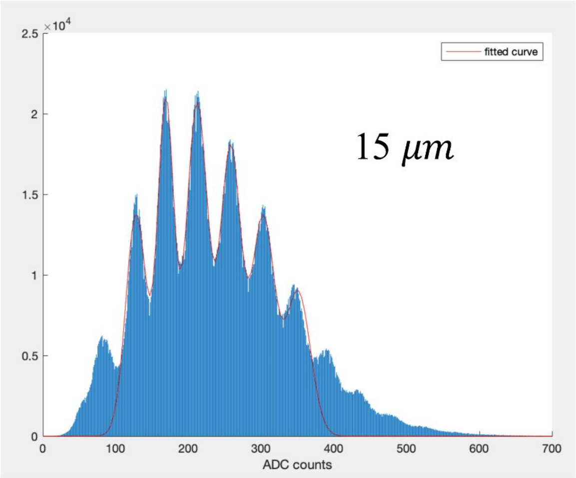
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

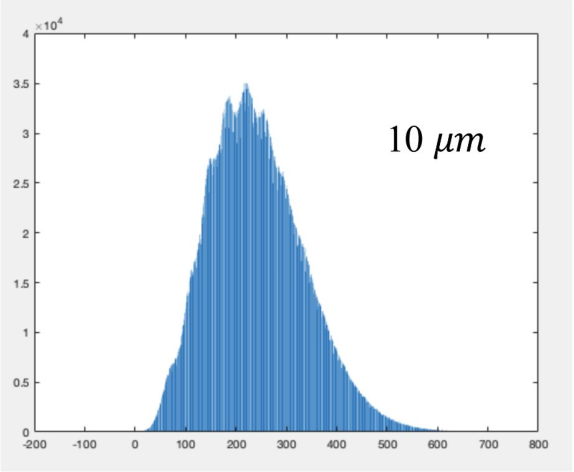


HiDRa SiPM integration & readout

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]