Exposing a fibre-based dual-readout calorimeter prototype to beams of electrons

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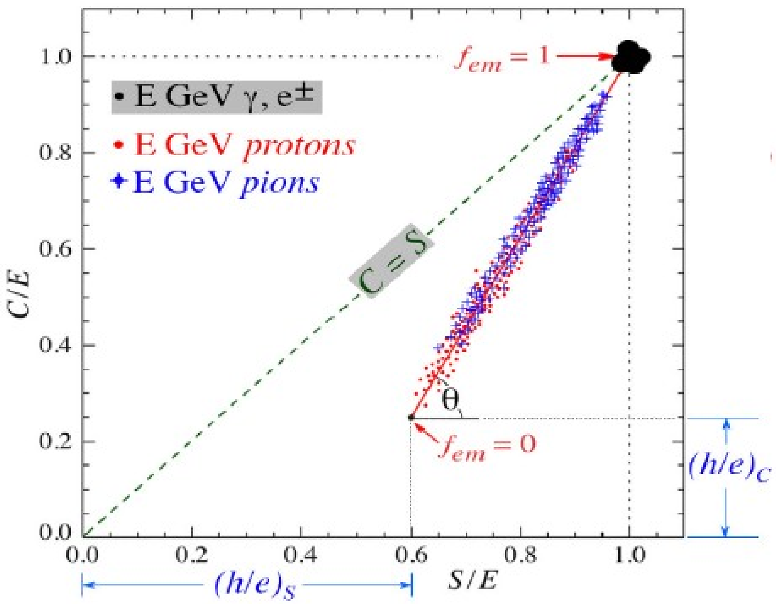
On behalf of the

IDEA Dual-Readout Calorimeter Collaboration

Dual readout calorimetry

Fluctuations in energy measurement of hadronic showers: correct event-by-event through measurement of EM fraction of shower using simultaneously two sampling processes

- Cherenkov light (mainly EM shower component)
- Scintillation light (total deposited energy)



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

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

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

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

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

Universally valid!

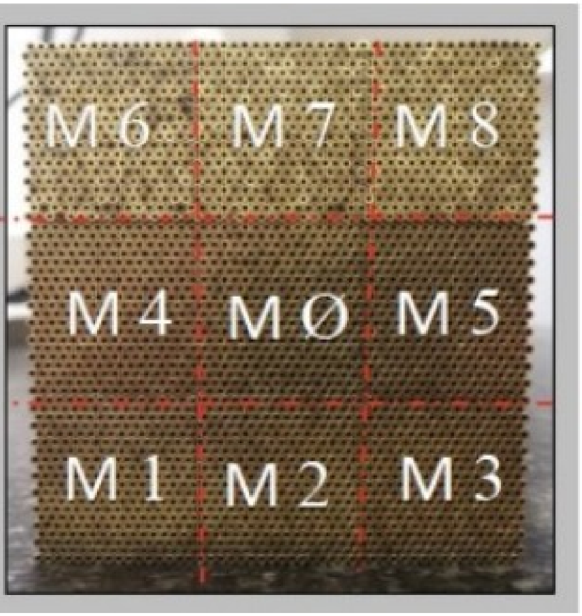
with: $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_C}$

Independent of energy and particle type

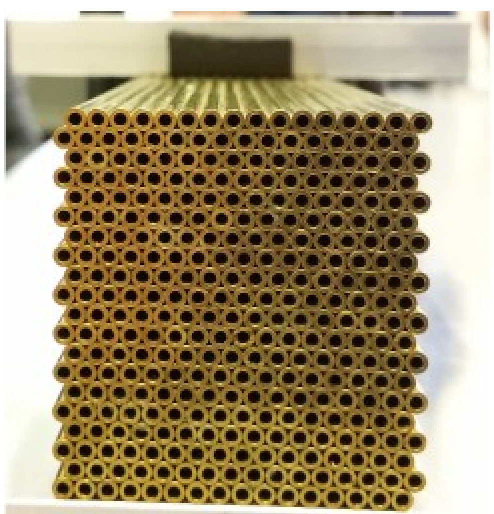
Aims of the test beam

- Long term R&D project aiming by 2025 to test full hadronic containment prototype with partial SiPM readout (HiDRa INFN CSN5 project)
- 2020/21: Build and test an em containment ($10 \times 10\,cm^2 \times 1\,m$) DR fibre prototype partially equipped with SiPMs. Aims:
  - Start handling a scalable readout for SiPMs
  - Consolidate EM performance
  - Exploit mm-level space resolution for particle id and shower shape studies
  - Tune detailed simulation
- Two beam periods
  - DESY (June) e^- beam 1-6 GeV
  - CERN (August) e^+ beam 6-100 GeV

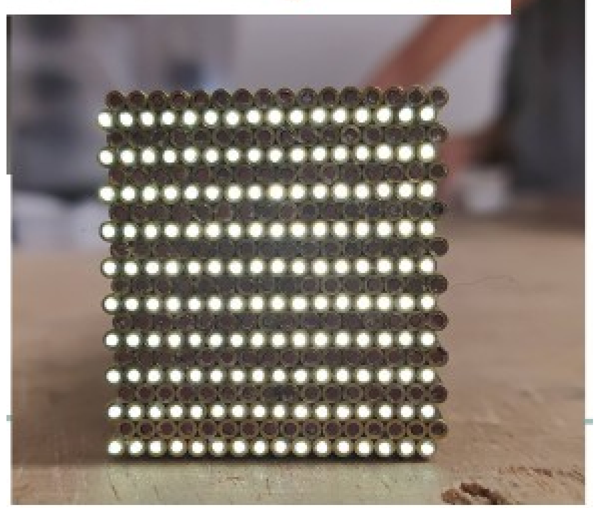
Prototype design



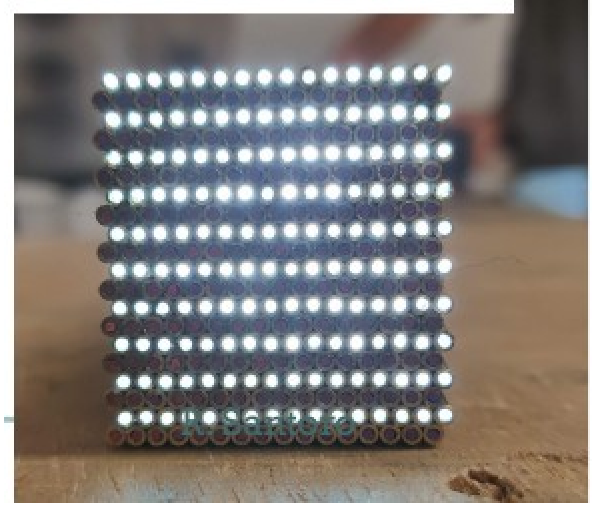
- EM-prototype ($10x10x100\ cm^3$)
  - 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
  - Capillaries (brass): 2 mm outer diameter and 1.1 mm inner diameter
- EM-prototype readout
  - Each capillary of the central module is equipped with its own SiPM: highly granular readout
  - 8 surrounding modules equipped with PMTs (each module will use 1 PMT for C and 1 PMT for Sc fibres)



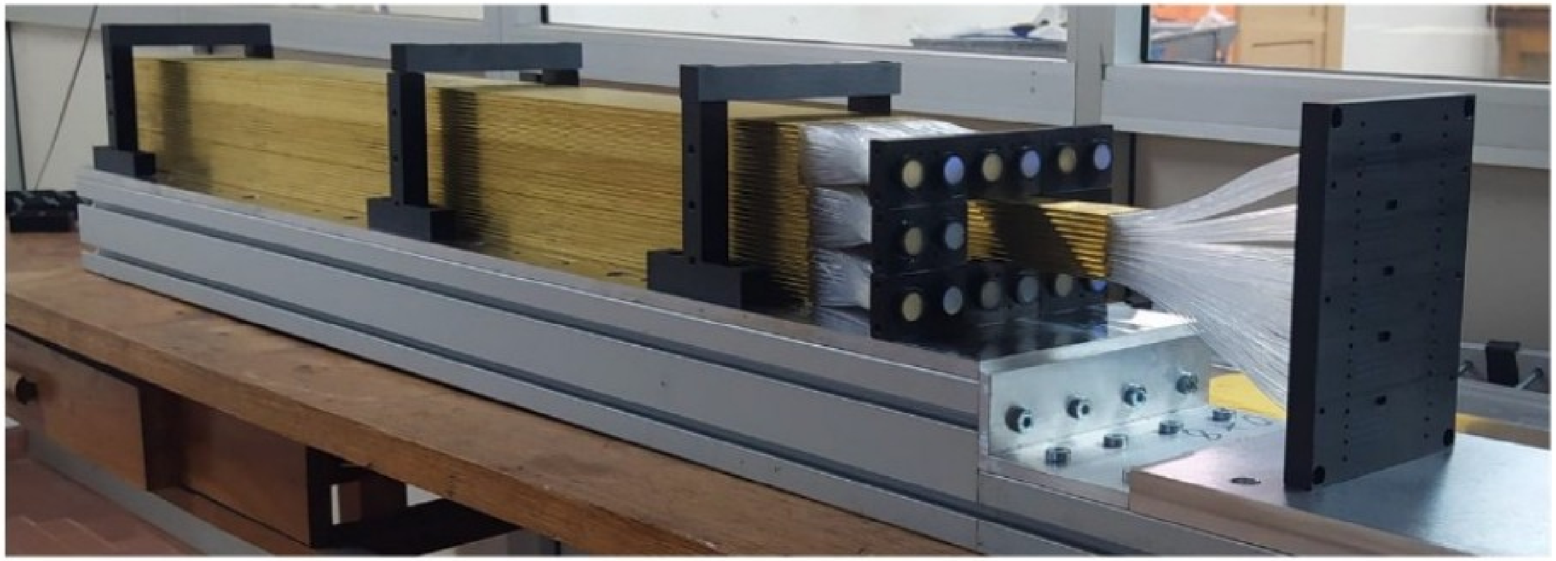
Scintillating fibres

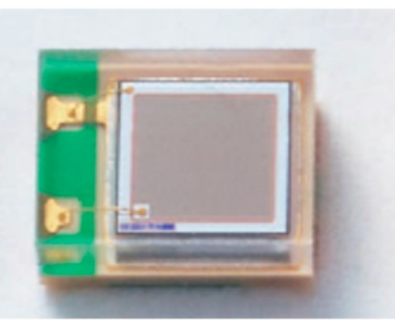


Cherenkov fibres



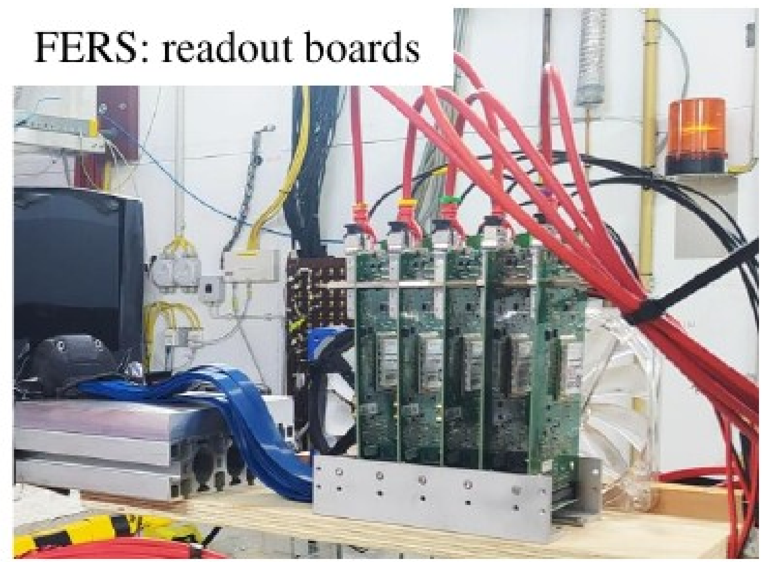
Assembled prototype and readout



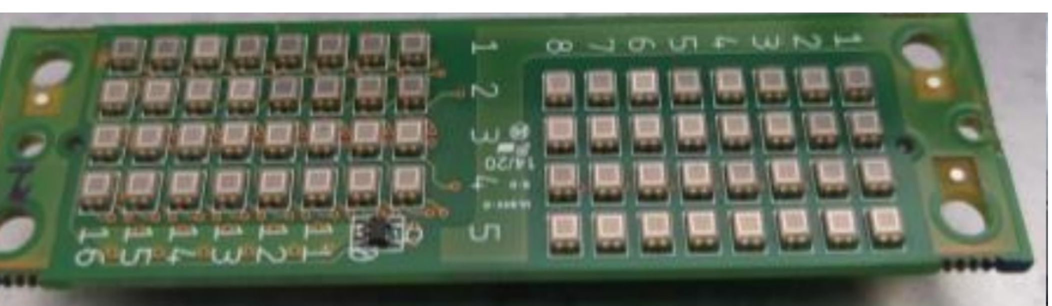


Hamamatsu SiPM
S14160-1315 PS
Cell size: 15 μm

FERS: readout boards



Front-End board



DESY Test Beam

DESY (June 2021)

e^- beam in the energy range of 1-6 GeV

Good opportunity to qualify the SiPM readout

Large statistics and high purity beam to study the impact point dependence and the shower shape (useful to tune the simulation)

CERN test beam

CERN-SPS H8 beam line (August 2021)

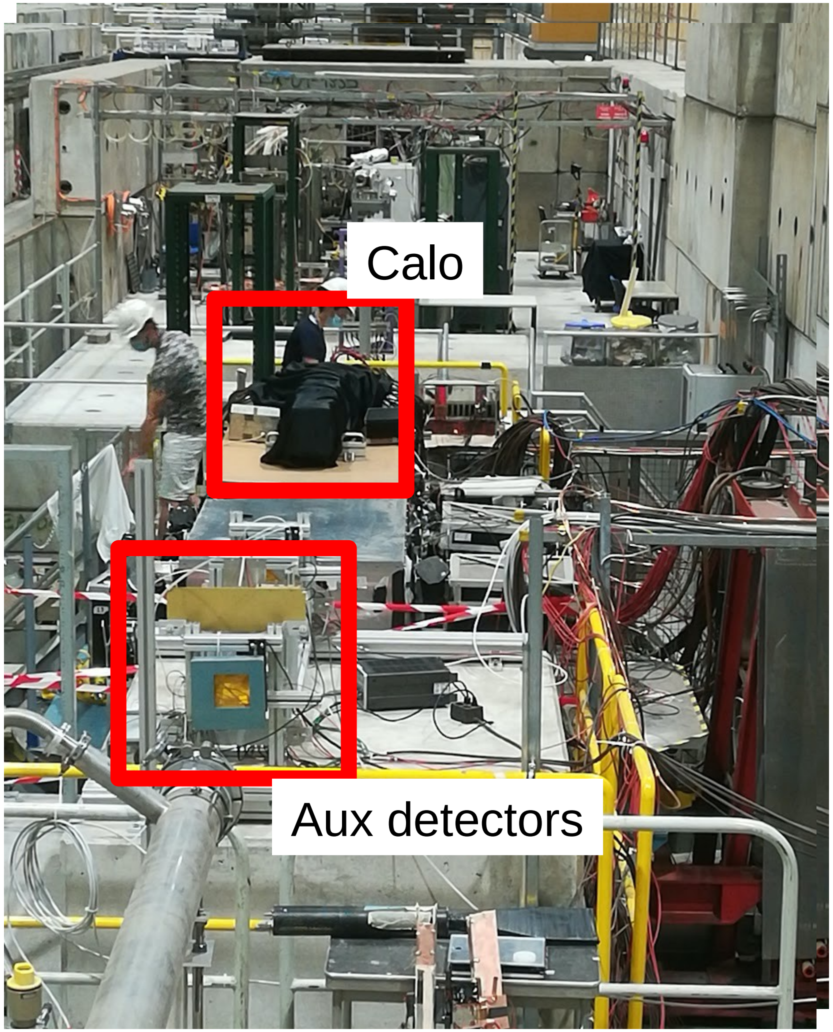
e^+ beam in the energy range of 10-125 GeV

Energy and position scan

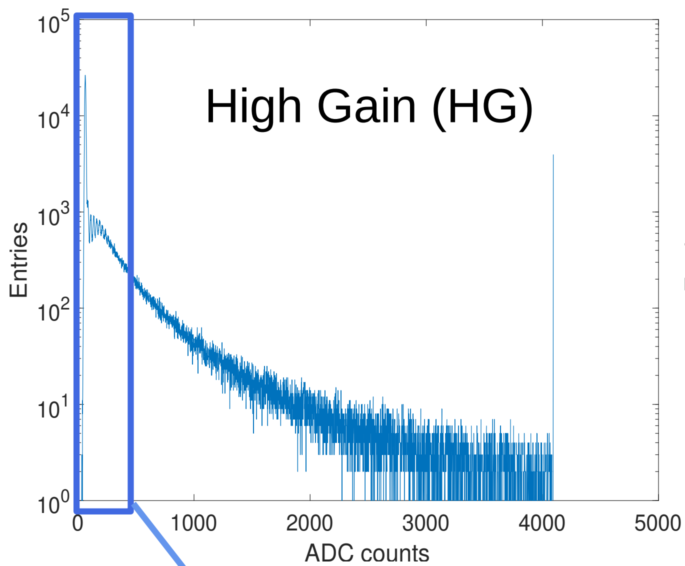
e^+ beam highly contaminated by π^+ in non-monochromatic beams

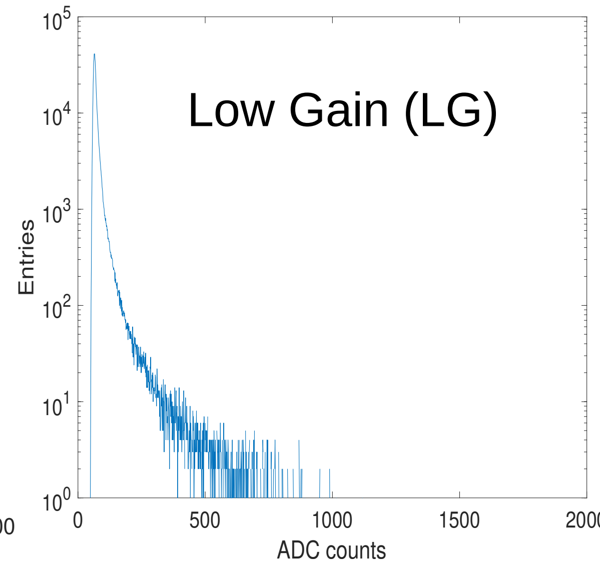
Use preshower and Cherenkov detectors to identify positrons.

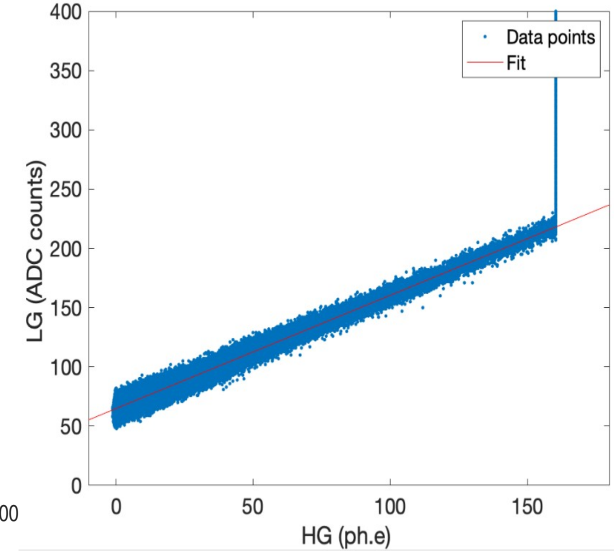
Very low e^+ statistics above 40 GeV

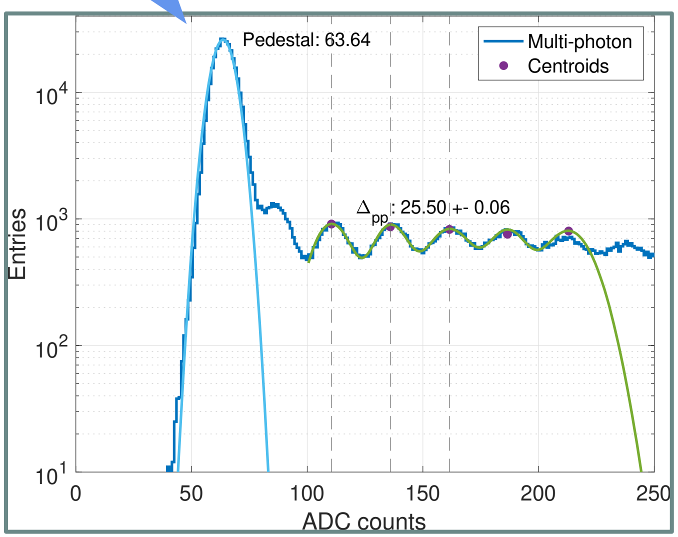


SiPM calibration: ADC/Ph-e









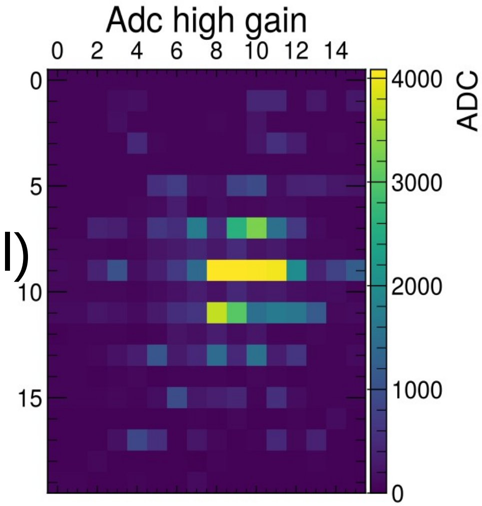
HG calibration (ADC/Ph-e)

The pedestal and distance peak to peak were measured in each run and per each SiPM

LG calibration (ADC/Ph-e)

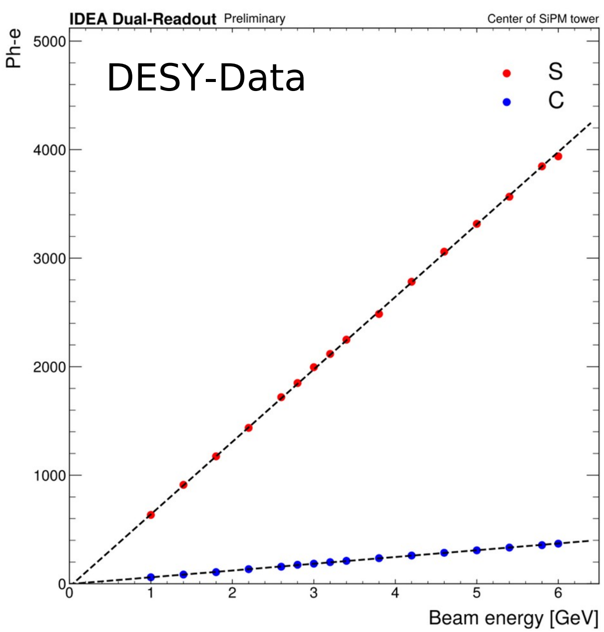
Low gain calibration based on low-gain/high-gain correlation plots after high-gain calibration

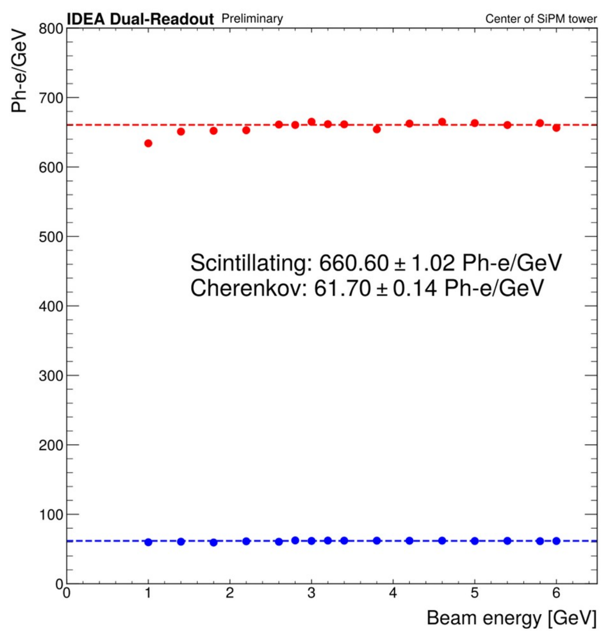
SiPM Calibration: Ph-e to GeV

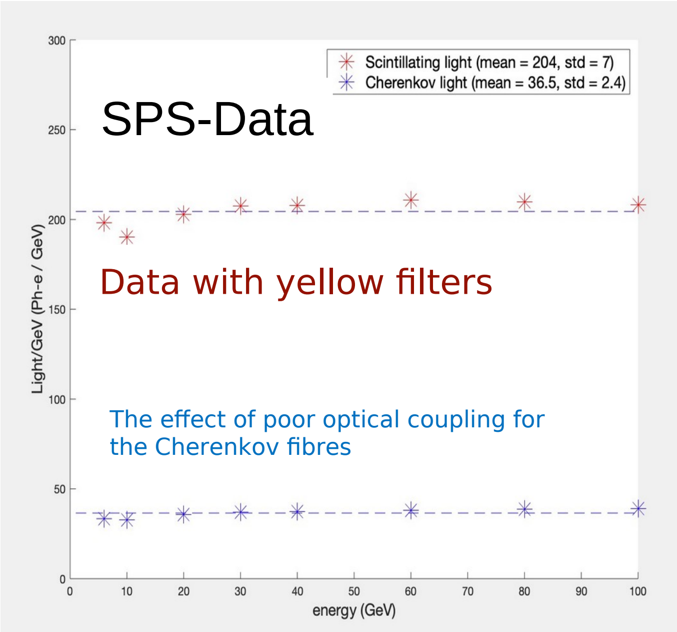


Sum the light detected by all SiPMs event-by-event

- Require leading fiber placed in centre of tower (4x4 cell)
- Take MPV of distribution for each energy for linearity
- Ph-e/GeV calculated assuming 70% containment in cell 0 (from simulation)







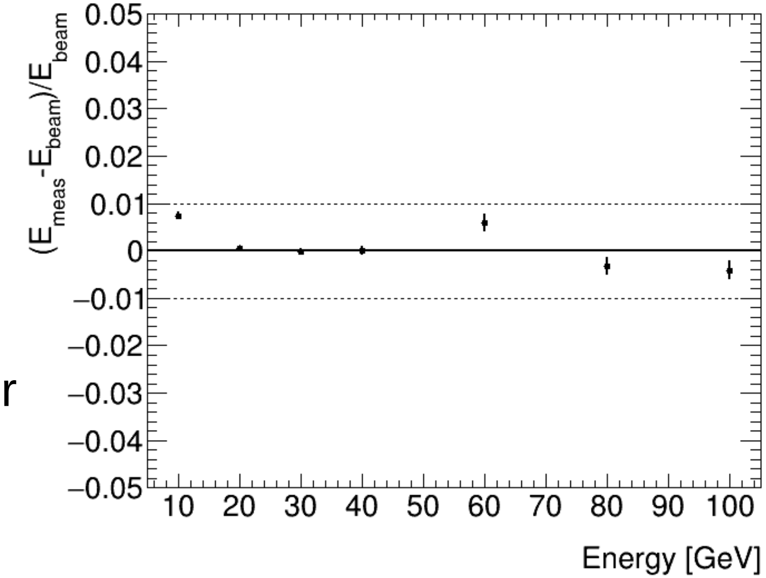
Light collection measured without optical filters

SPS data analysis

Circular beam spot 1 cm radius in calo centre
Nominal beam angles:

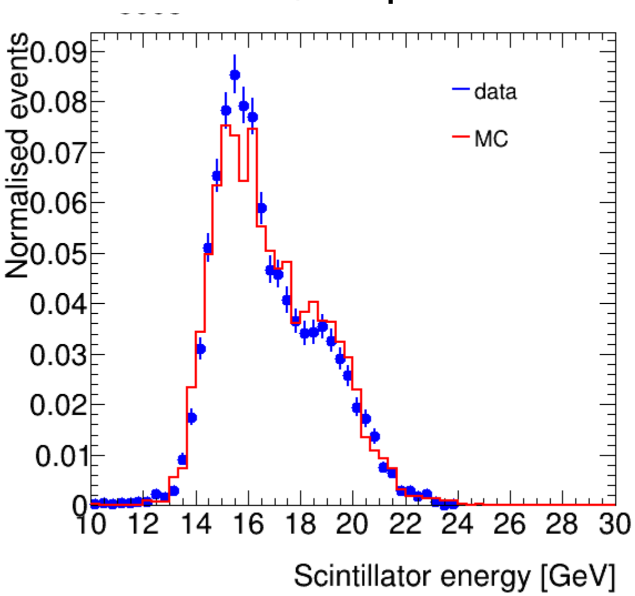
- $+1^{o}$ horizontal
- 0^{o} vertical

Linearity in 10-100 GeV range



Select events with >3 mips in preshower.
Energy: sum of all Sci and Cherenkov SiPM and PMT channels, with a correction factor proportional to signal in preshower

20 GeV e+, no preshower

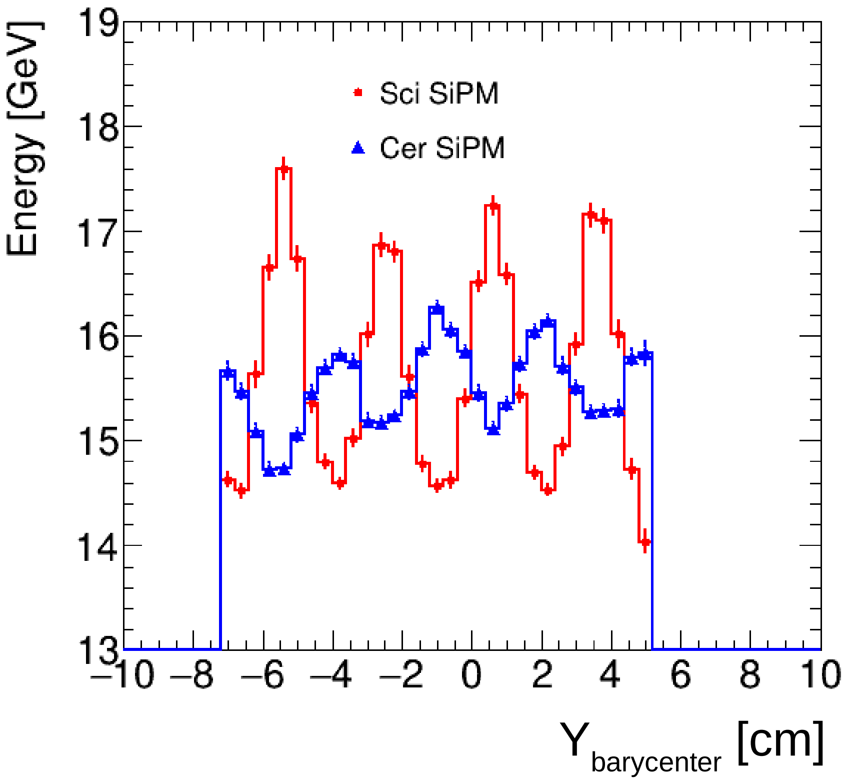


Distribution of scintillator signal not Gaussian
Angle/impact point in MC tuned to reproduce distribution.
Good agreement for angle:

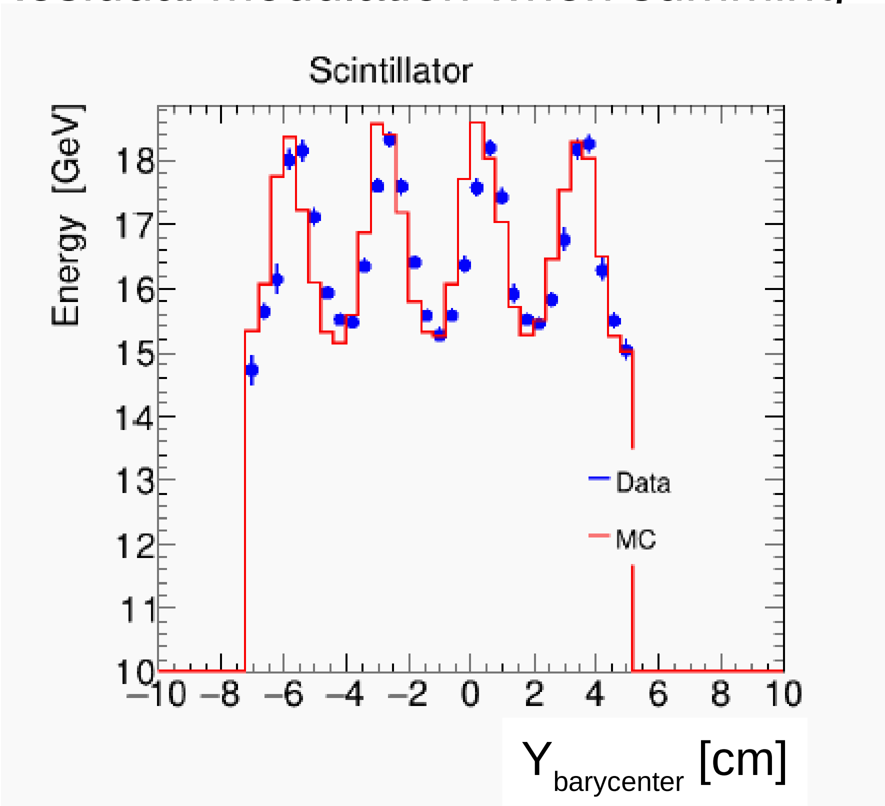
- 1.5^{o} horizontal
- -0.4^{o} vertical

Try to understand reason for non-Gaussian shape

Position dependence of response

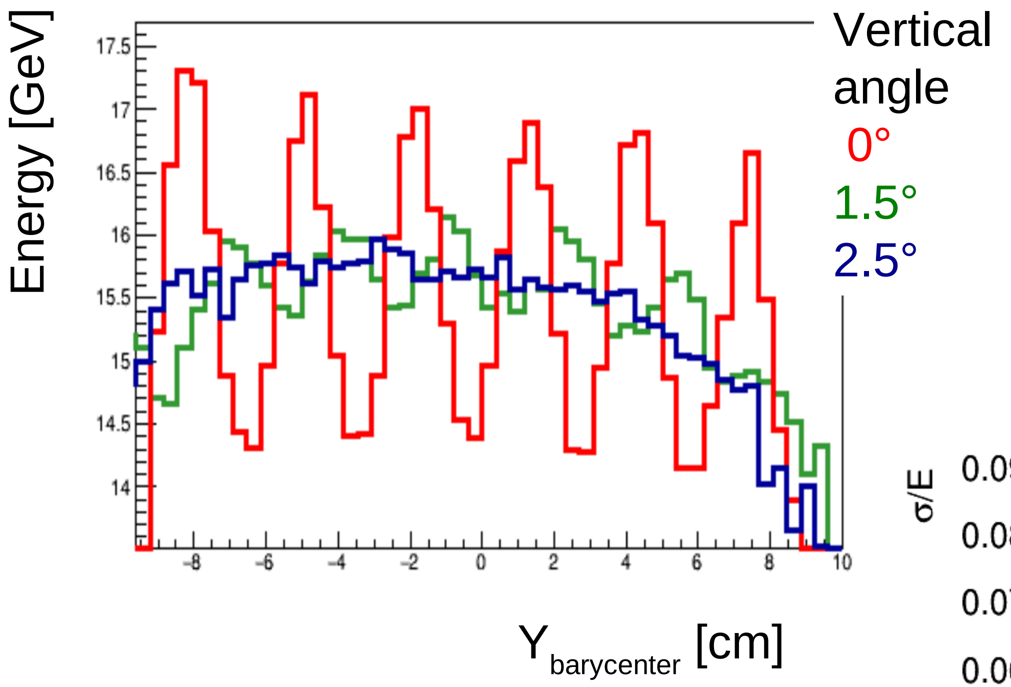


Periodic modulation of SiPM response as function of beam barycentre in y for both Scintillator and Cherenkov with opposite phase
Smaller amplitude for Cherenkov → Residual modulation when summing

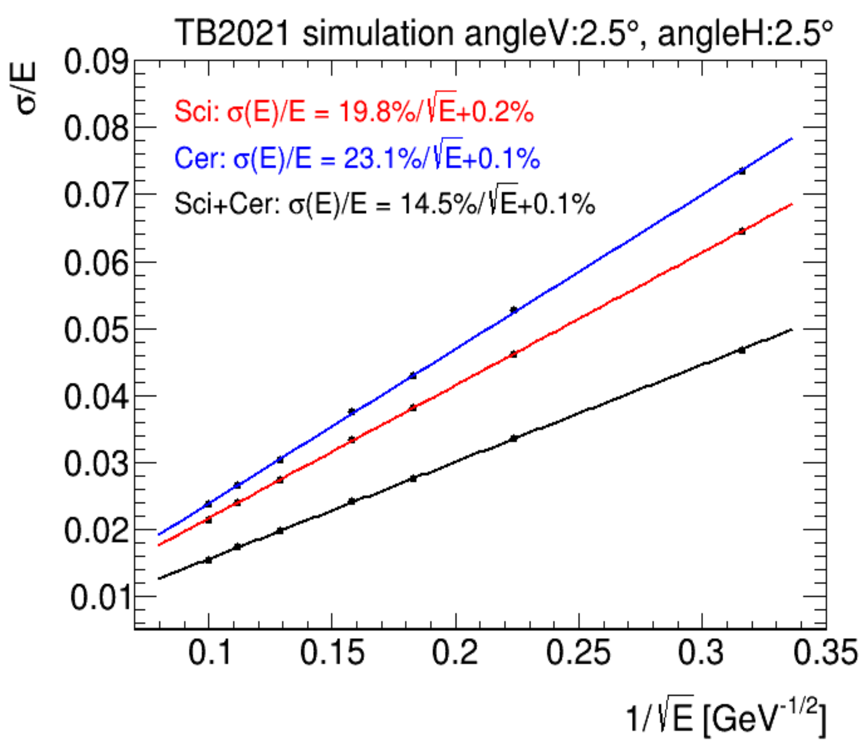


Modulation in scintillator response reproduced by simulation

Response modulation versus beam angle (MC)



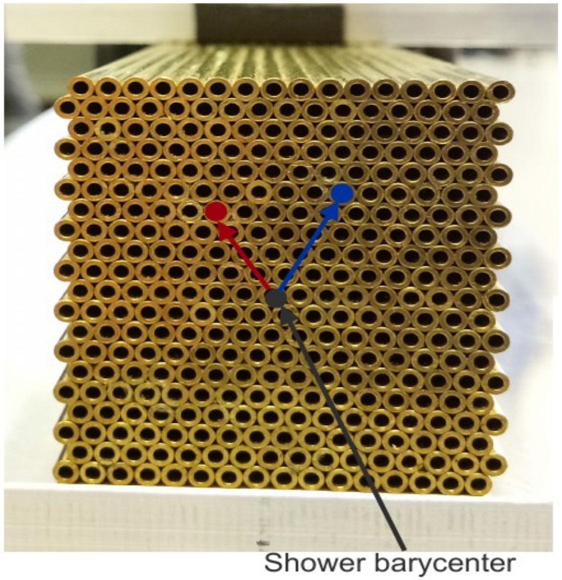
Amplitude of energy modulation depends on impact angle.
For an impact angle of 2.5° modulation disappears



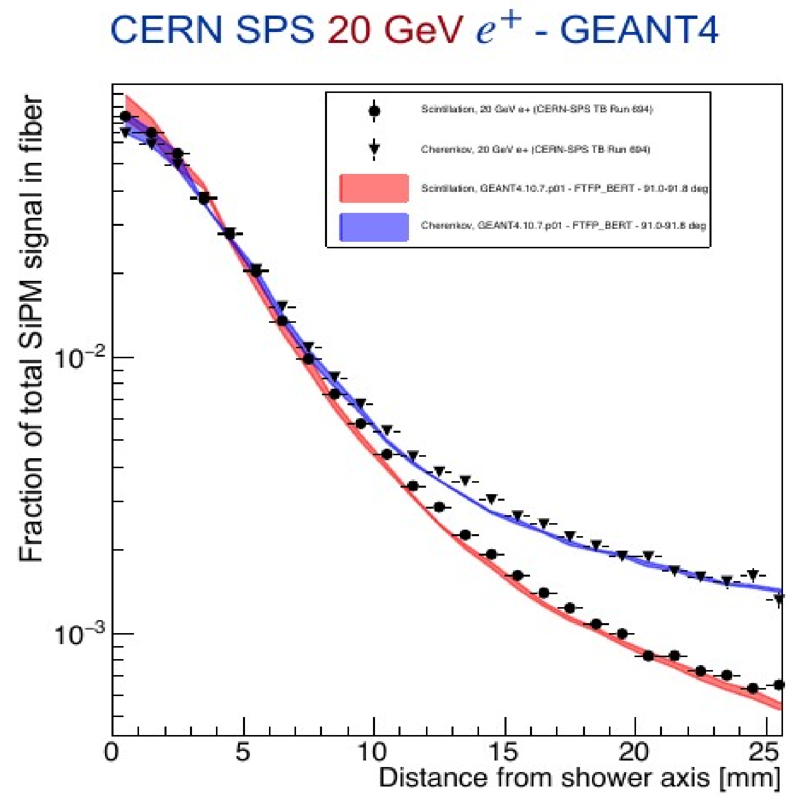
When sending an electron beam in the centre of calorimeter with a 2.5° angle in both X and Y, expect a resolution of 14.5%/√E

Measurement of shower shape

Study by G4 Collaboration on our unpublished data, see talk by L. Pezzotti at CALOR2022



Lateral profile: average signal in a fibre located at a distance r from shower barycentre



Measurement:

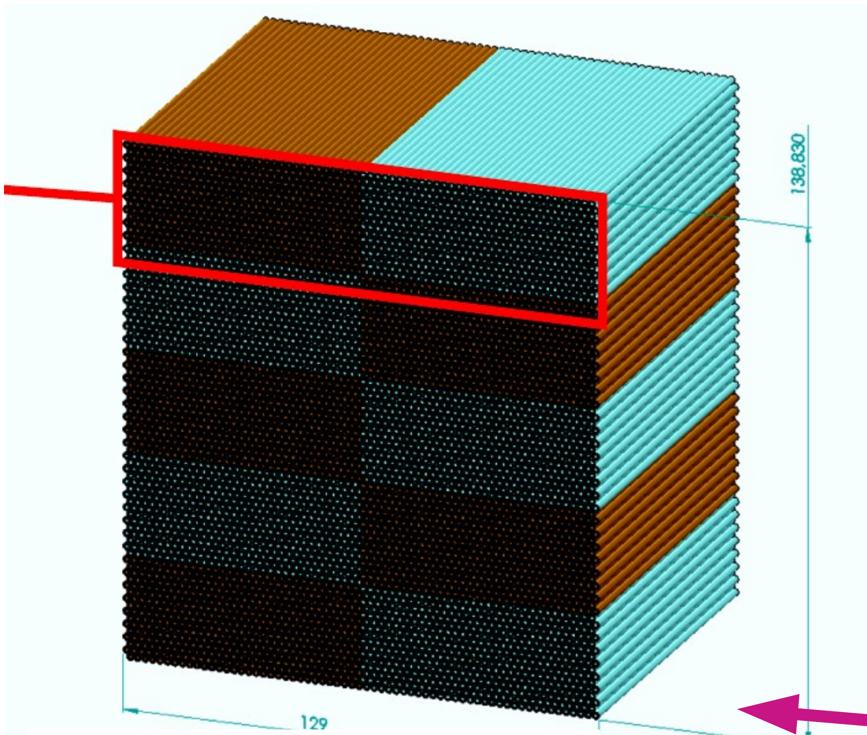
For every event and every fibre populate a scatter plot (signal vs. distance)

Lateral profiles are extracted as average value for every x-bin

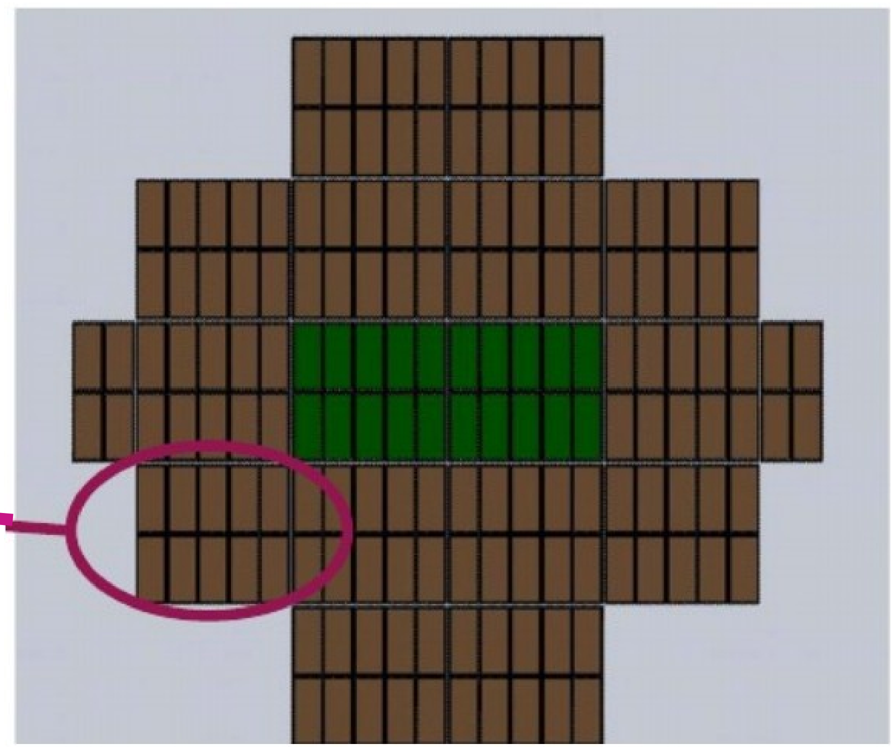
The near future

Double Mini-Module (MM):
64× 16 channels (1024 ch)
→ 512 S + 512 Č fibres

Build a prototype with full hadronic containment (HiDRa project funded by INFN)



16 modules
2 modules read with SiPM (~10k SiPMs)
Rest with PMTs (~150 PMTs)



1 Module:
2 × 5 MMs = 5x1 double MM
→ 10 FEE boards
(8-channel grouping)
~ 13 × 13 × 250 cm^3

Conclusions

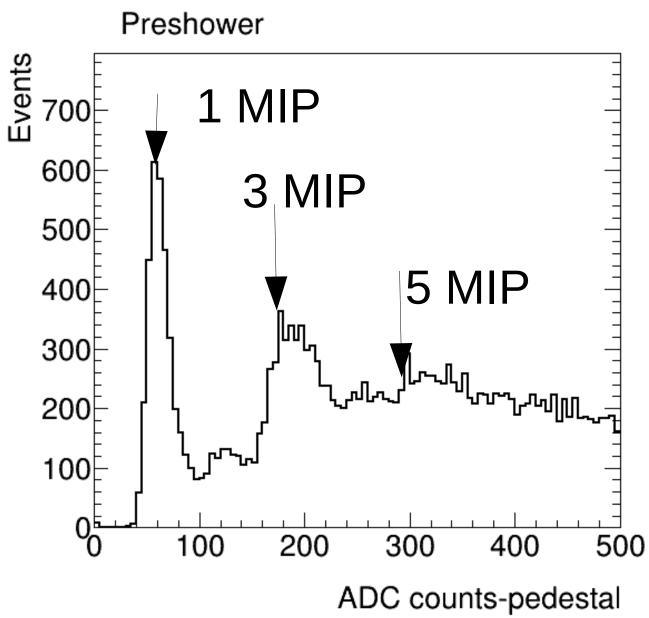
- EM containment DR module built and tested in beam in 2021
- Data collected in two beam periods at DESY and CERN SPS
  - Rich and clean set of data up to 6 GeV from DESY
  - Full energy scan available up to 100 GeV from CERN, but low statistics at high energy because of beam purity issues
- Work ongoing to exploit these data, high granularity of the SiPM readout allows detailed comparison with simulation

  Significant insight on angle/position dependence of response achieved, which will be used in next testbeam rounds.
- Still quite some work to master the complexity of the data and extract final performance figures
- Simulation tuned to TB2021 helping the design of full hadronic containment HiDRa prototype

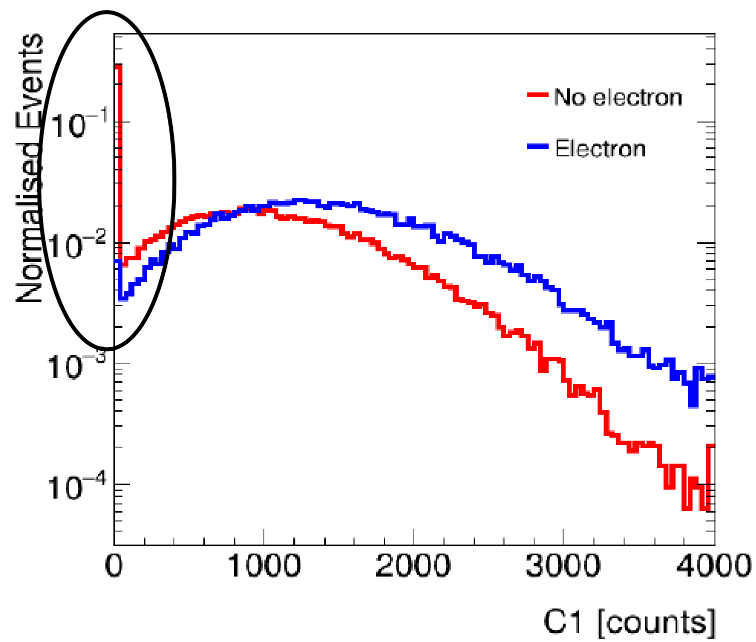
Backup

Electron ID

Preshower detector and two SPS Cerenkov detectors



Distribution of counts in preshower
For events with firing Cerenkov detectors
And energy in calo compatible with beam energy



Distribution of counts in Cerenkov Detector.

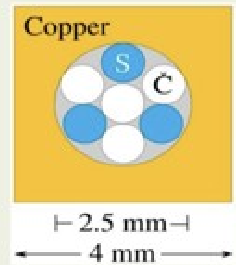
Electron: >3 mip in PS, energy in calo compatible with beam

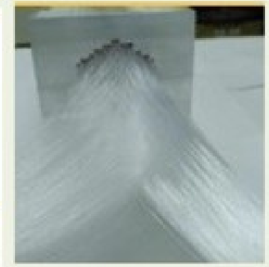
No electron <3 mip in PS, energy in calo much smaller than beam energy

Dual readout R&D

2003
DREAM

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

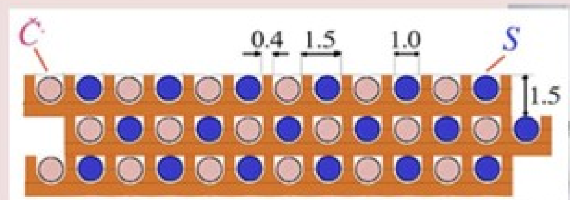




2012
RD52

Copper, 2 modules

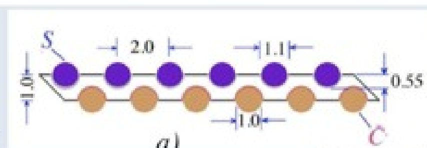
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

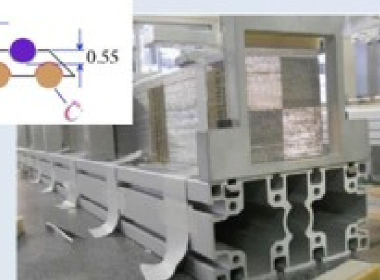


2012
RD52

Lead, 9 modules

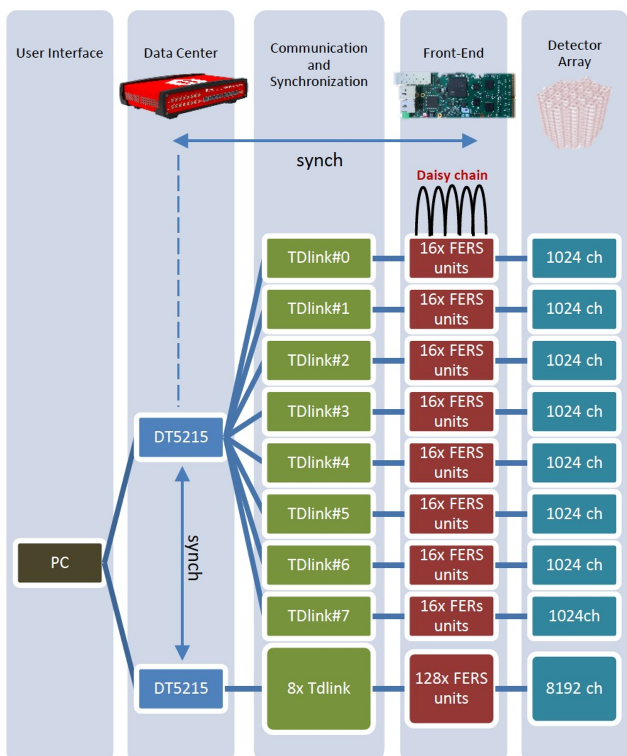
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}



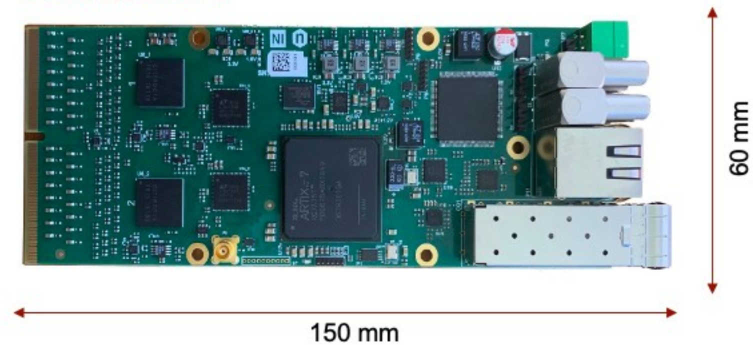


EM-size prototype readout

- PMTs read out with QDC (V792AC) and TDC (V775N) modules from Caen
- The highly granular module (320 SiPMs) read out with the Caen FERS system (5200) using 5 readout boards (A5202)

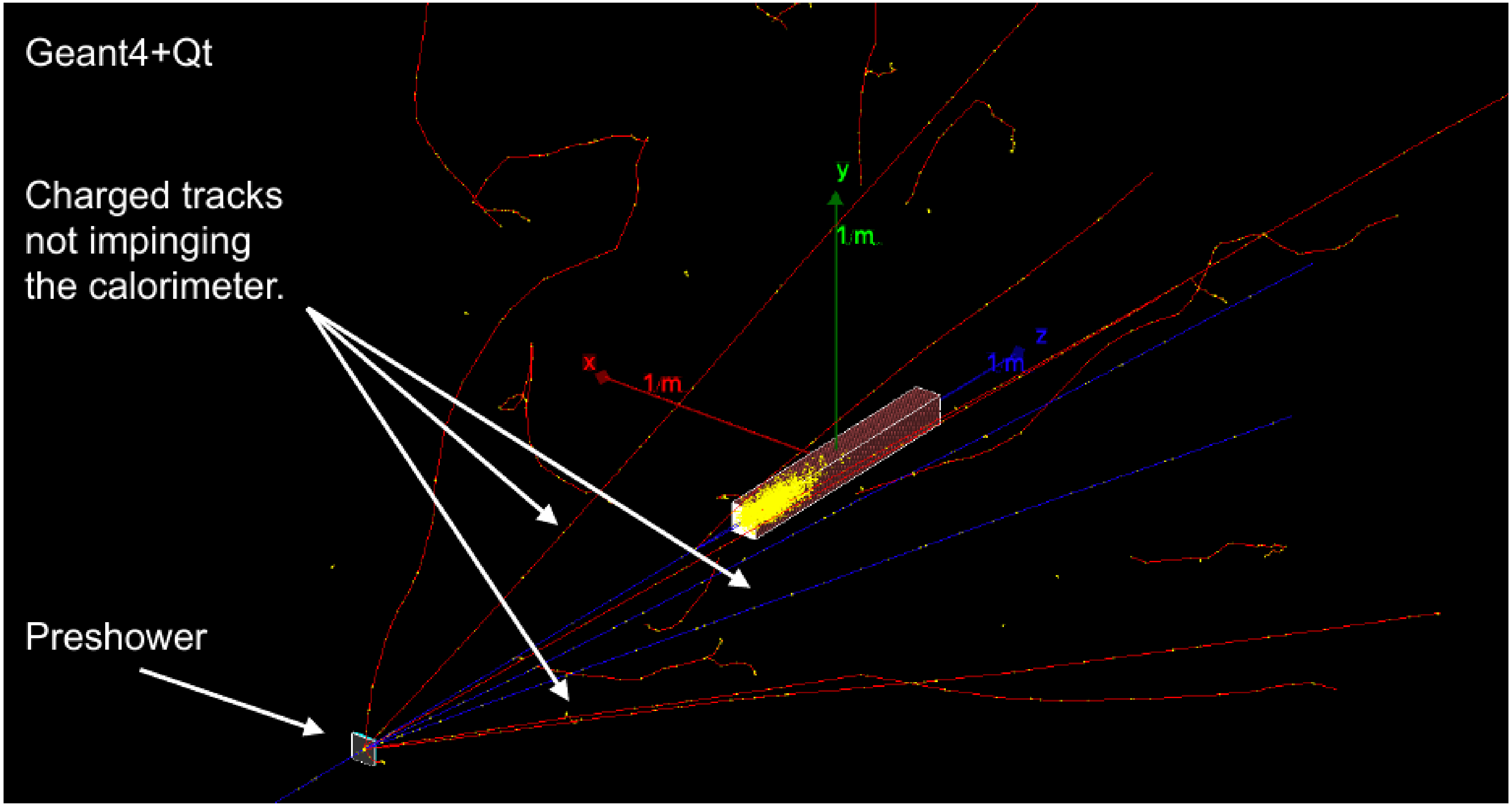


FERS: A5202



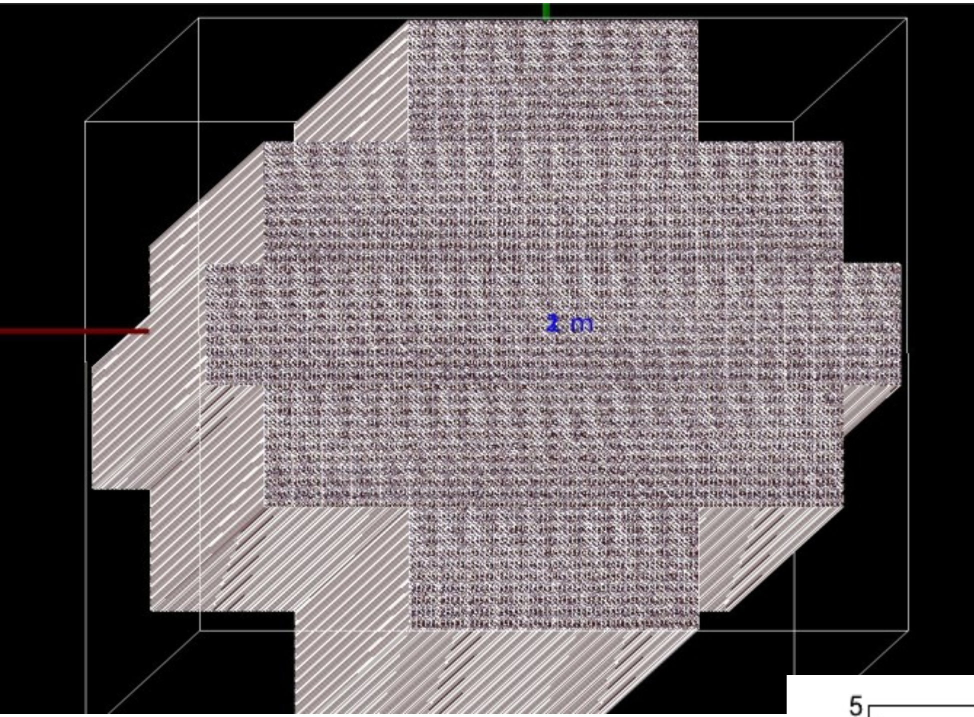
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

Simulation of full TB setup



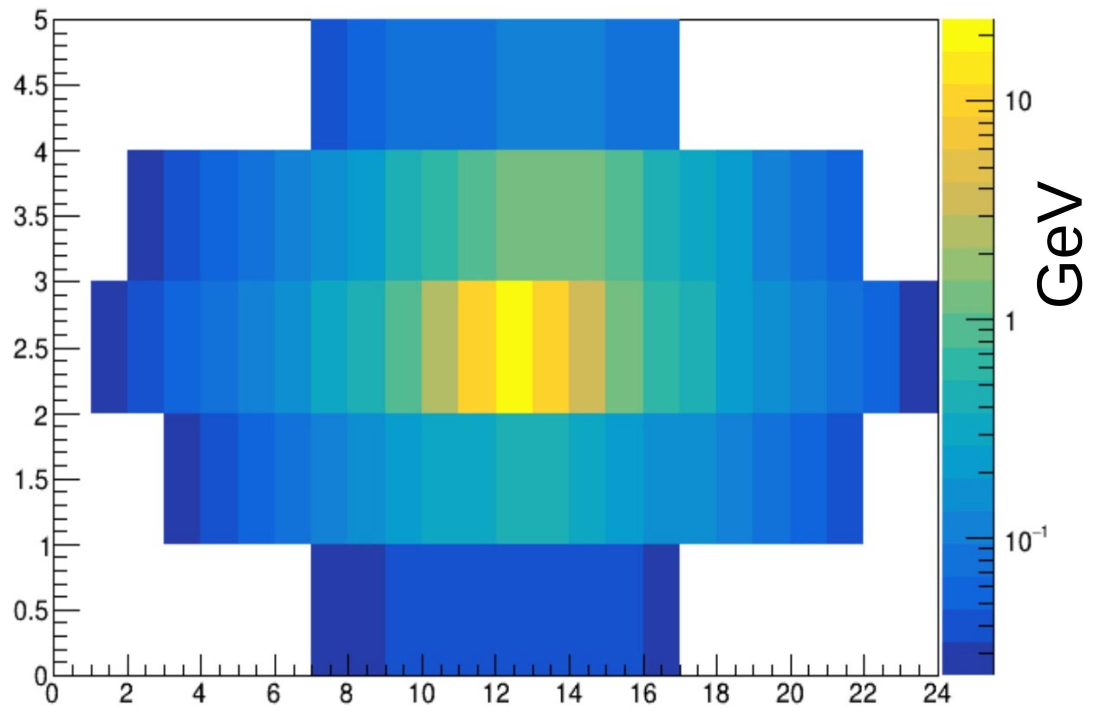
Dependence of energy containment on preshower signal ascribed to Broadening of early starting shower in preshower detector, verify with full simulation of full testbeam setup

Hidra simulation



Based on simulation validated on TB2021 result implement HiDRa geometry

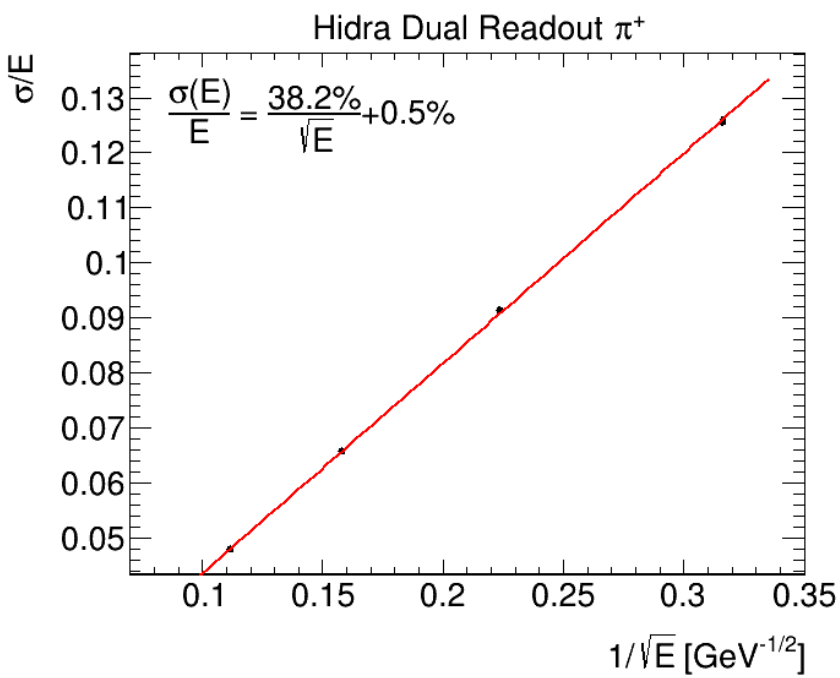
80 GeV π^+ impact angles 2.5 deg, 2.5 deg: calo map
Brass absorber

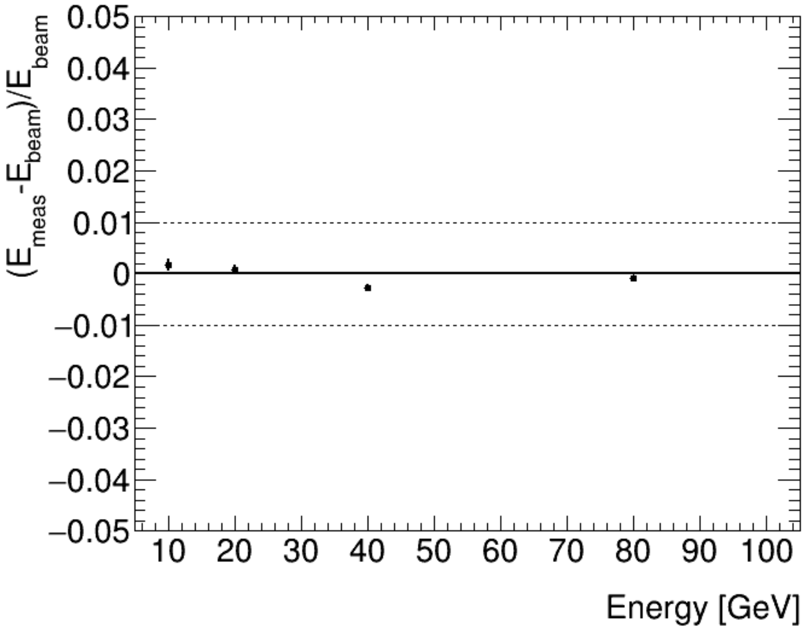


~97% containment

HiDRa expected performance

Use simulation validated with 2021 testbeam to evaluate expected performance of prototype and guide the finalisation of design

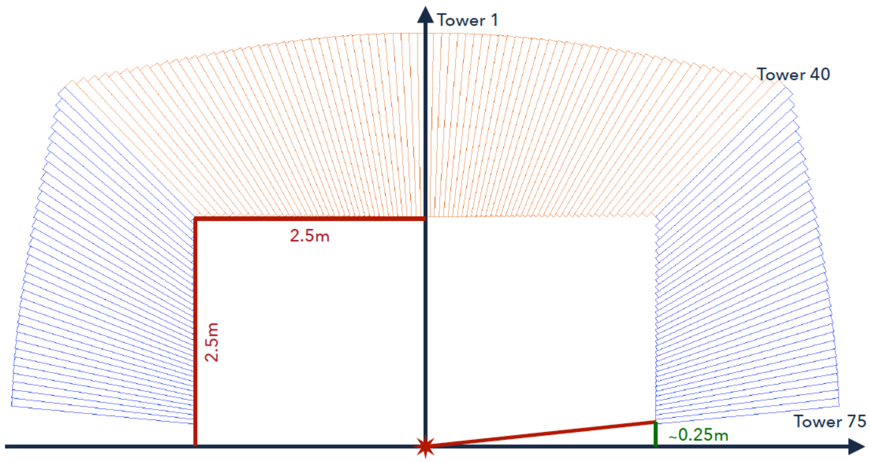


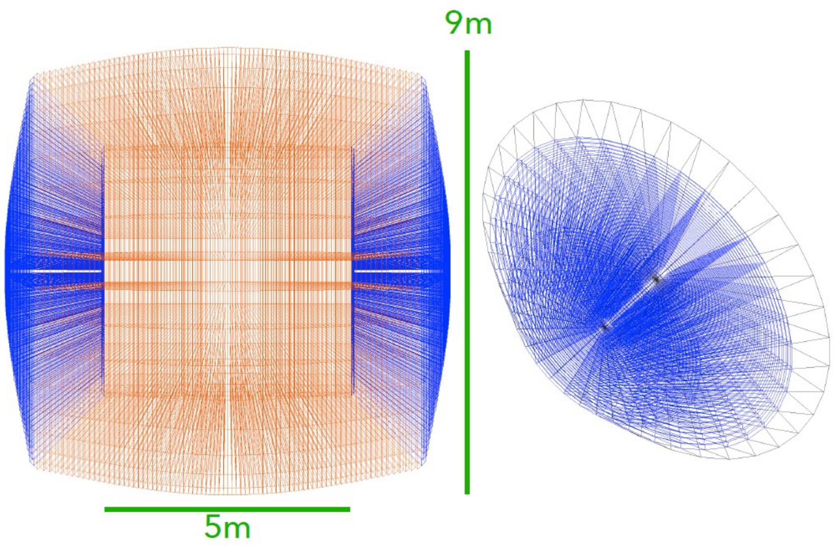


Preliminary resolution and linearity for the HIDRA prototype with brass absorber

Baseline geometry IDEA

- 2m long copper based towers
- 36 towers around the beam axis
- Inner diameter: 5 m
- Outer diameter: 9m @ 90°





Expected performances

- 10% - 15% / EM energy resolution
- 25% - 30% / Energy resolution for single hadron
- 5% energy resolution for jets @ 50 GeV
- Less than the percent linearity in the FCC-ee energy ranges for e-/, hadrons and jets