SiPMs for dual-readout calorimetry

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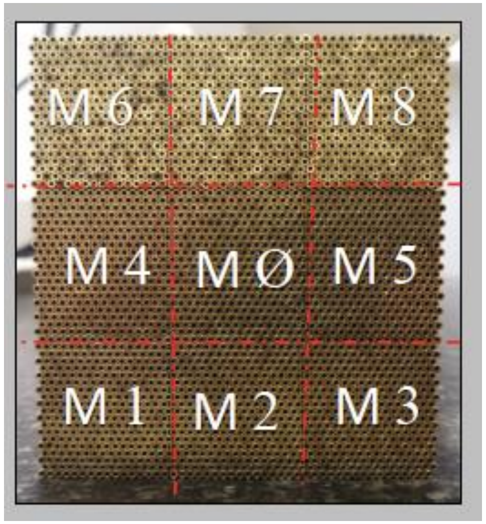
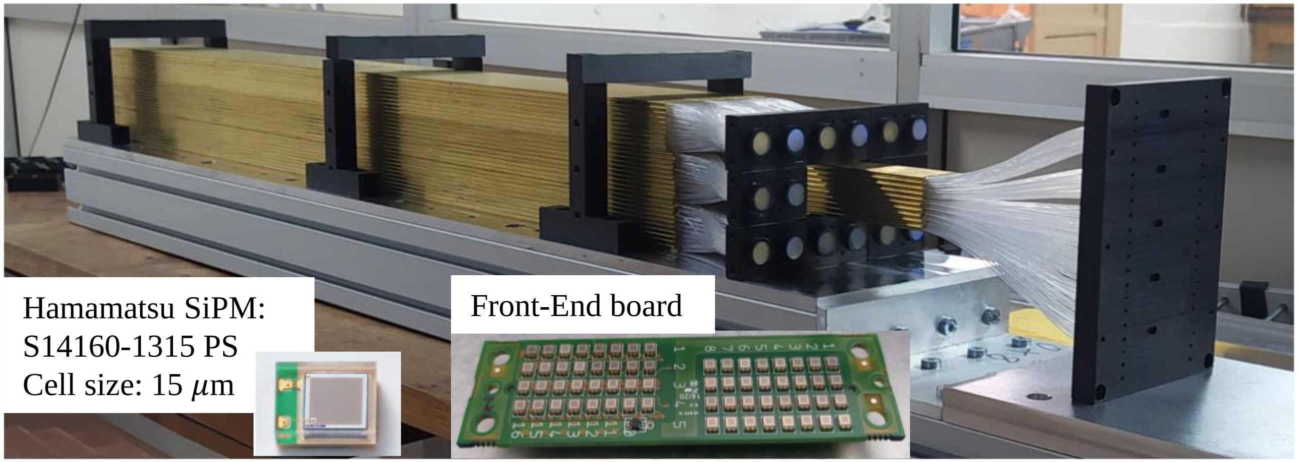
Before starting

- To save time, there will be no introduction on the dual readout method in this talk
  - Refer to the R. Wigmans talk for a comprehensive overview
- I'll focus on the test beam results we had last year (DESY and CERN) using an e-m size prototype with a highly granular core
- Few final numbers will be extrapolated using a detailed Monte Carlo simulation tuned on data
  - Refer to the L. Pezzotti talk for details and curiosities concerning the simulation
  - Refer to the A. Loeschcke Centeno poster for the resolution studies with the simulation
- Finally I'll comment on the on-going R&D which will allow us to build & qualify on beam a scalable prototype with hadronic containment

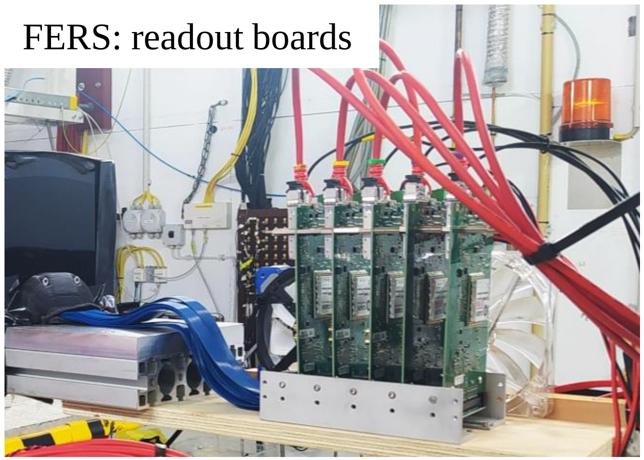
The EM-size prototype



- EM-size 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-size 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)

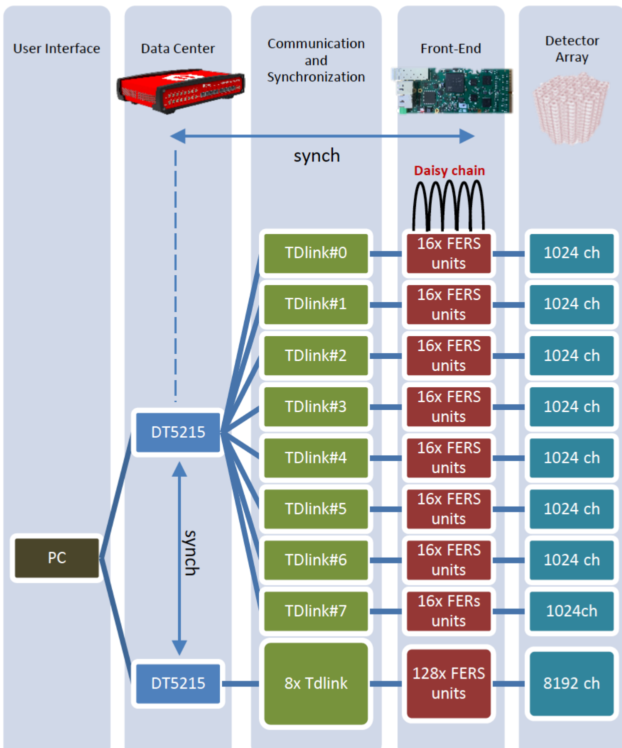


FERS: readout boards

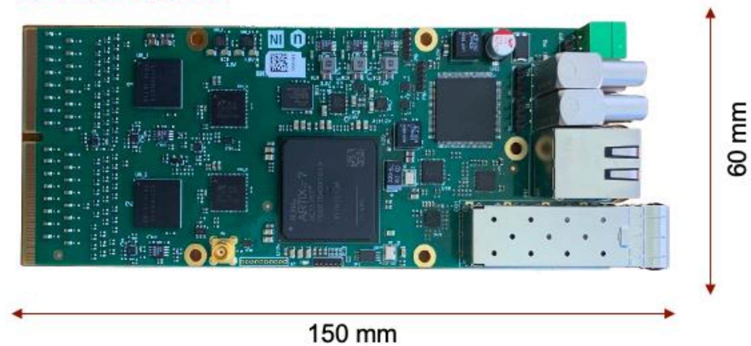


The EM-size prototype: readout

- 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

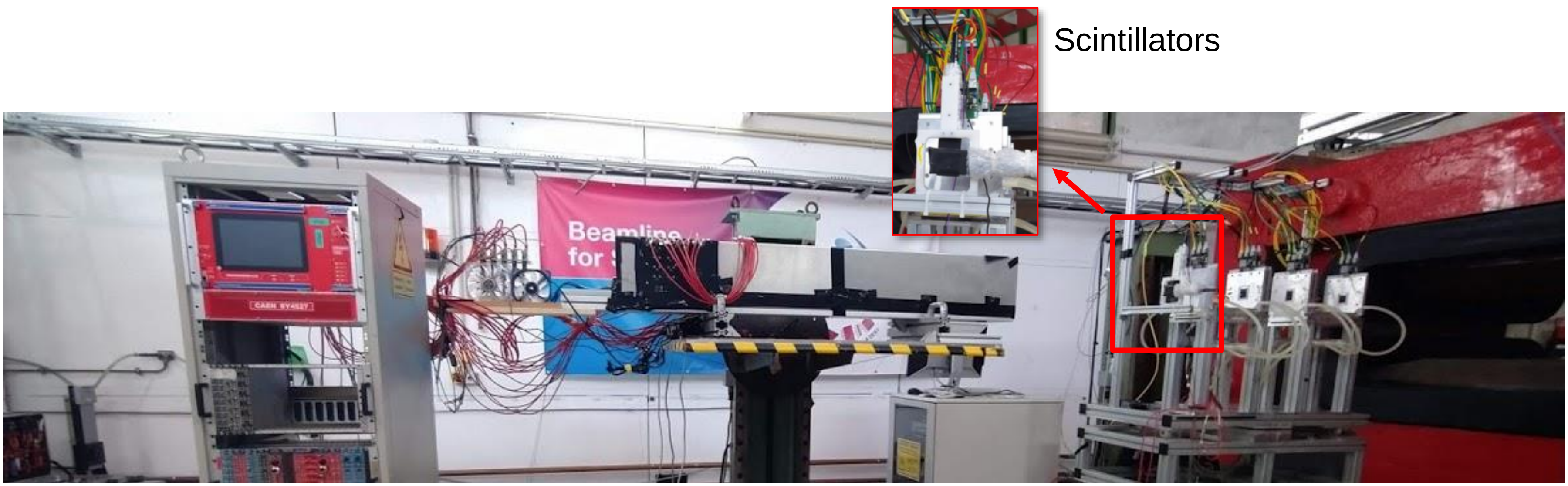


- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

Two beam tests in 2021

DESY (June 2021)

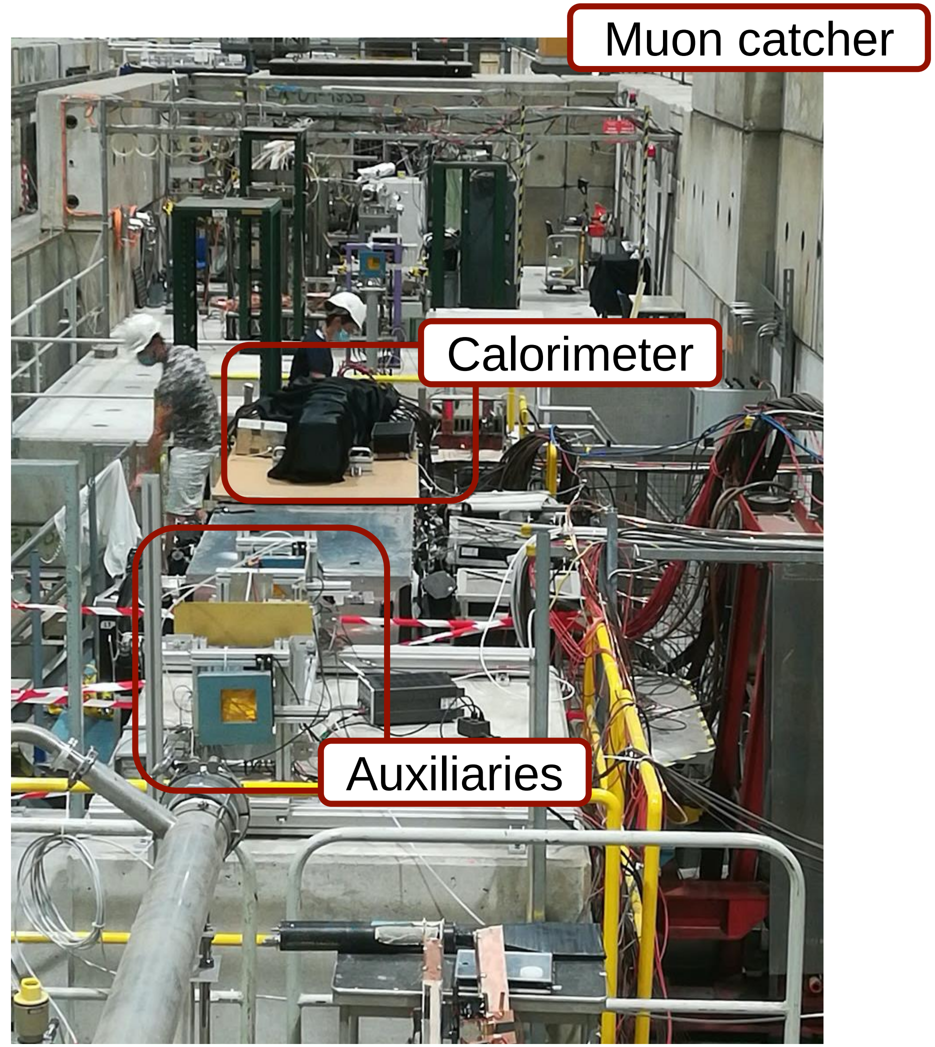
- e^- beam in the energy range of 1-6 GeV
- Good opportunity to qualify the SiPM readout
- Large statistics and high purity beam to study the impact point dependence and the shower shape (useful to tune the simulation)



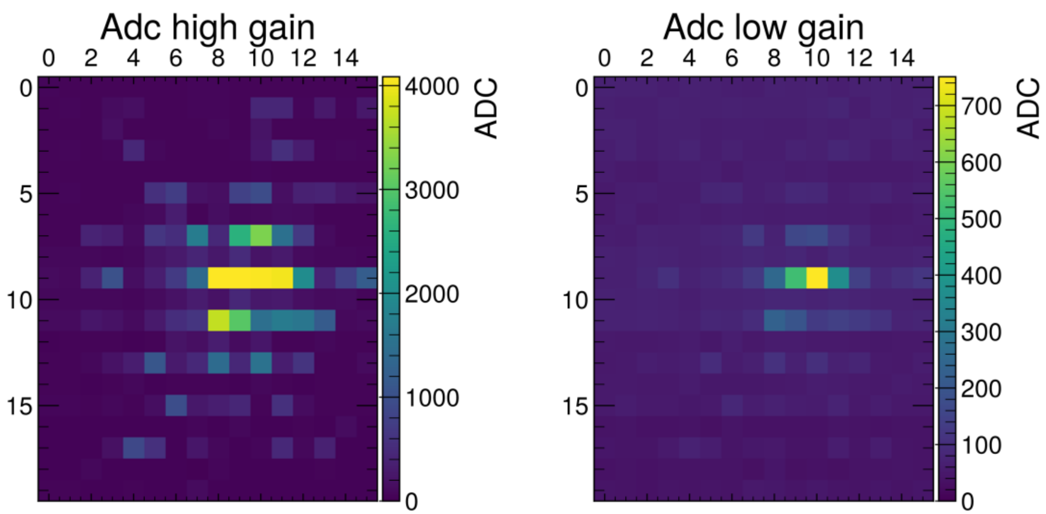
Two test beam in 2021

CERN-SPS H8 beam line (August 2021)

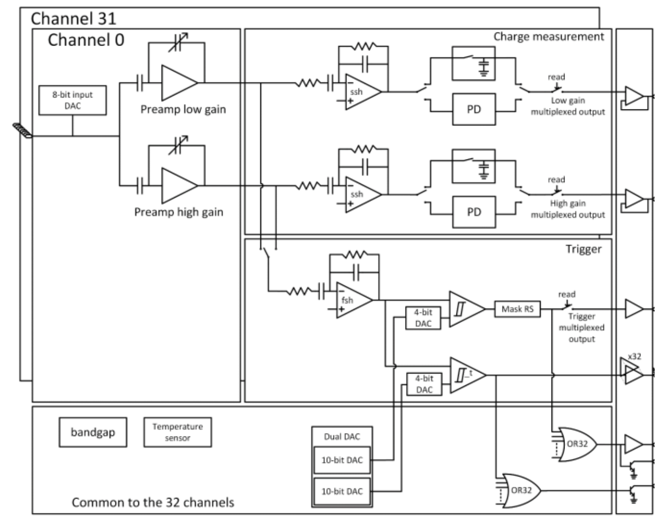
- e^+ beam in the energy range of 10-125 GeV
- Energy and position scan
- e^+ beam highly contaminated by π^+
- μ in non-monochromatic beams



- 6 GeV event centred on the SiPM tower (Raw data)



CITIROC 1A: block diagram



The impact of high granularity (@ DESY)

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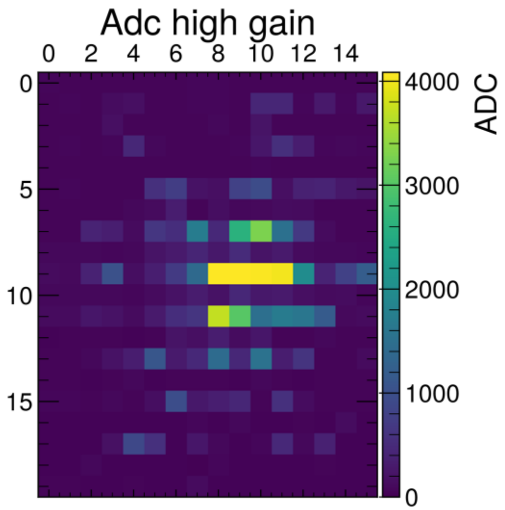

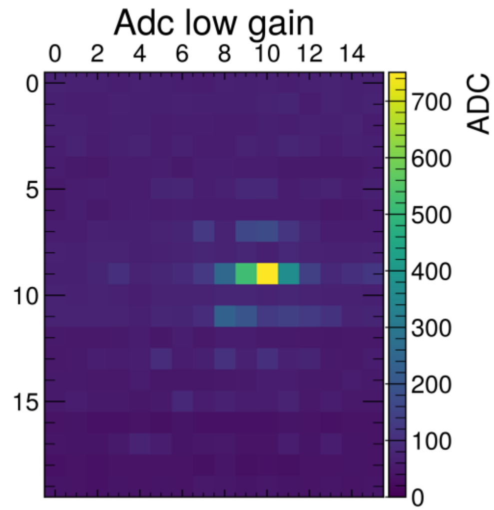

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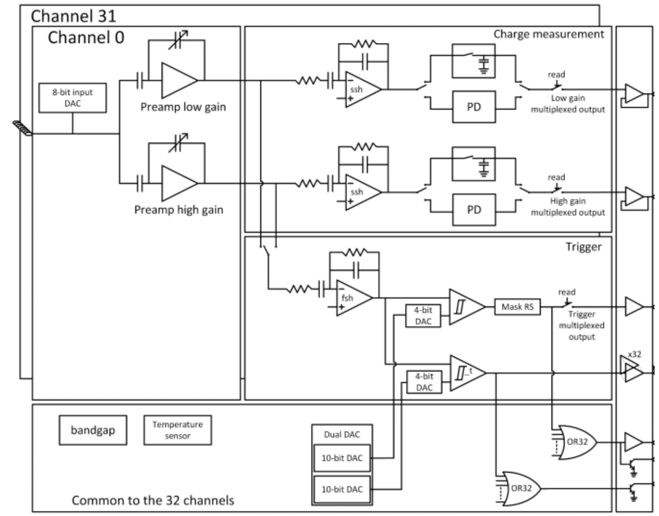
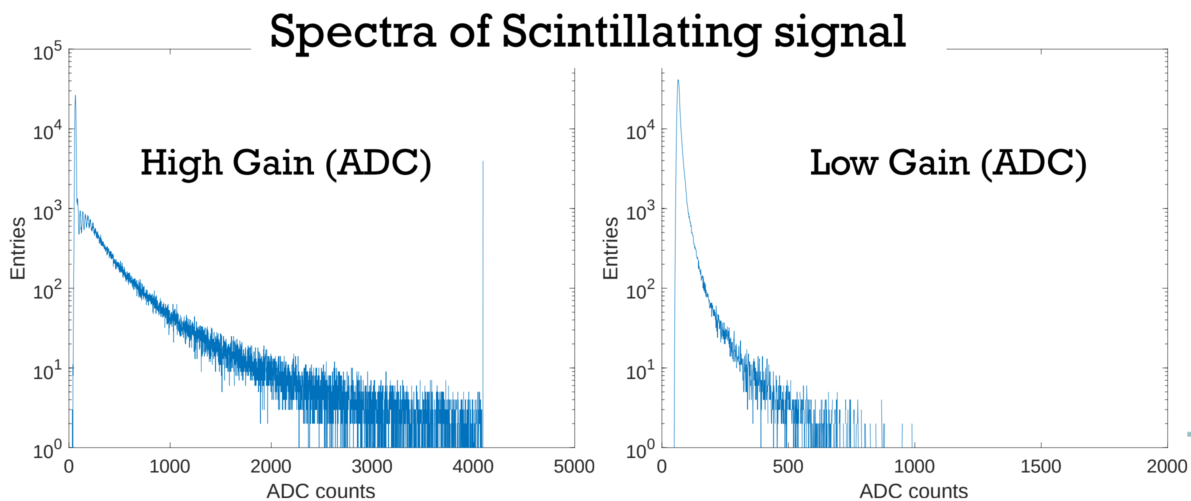
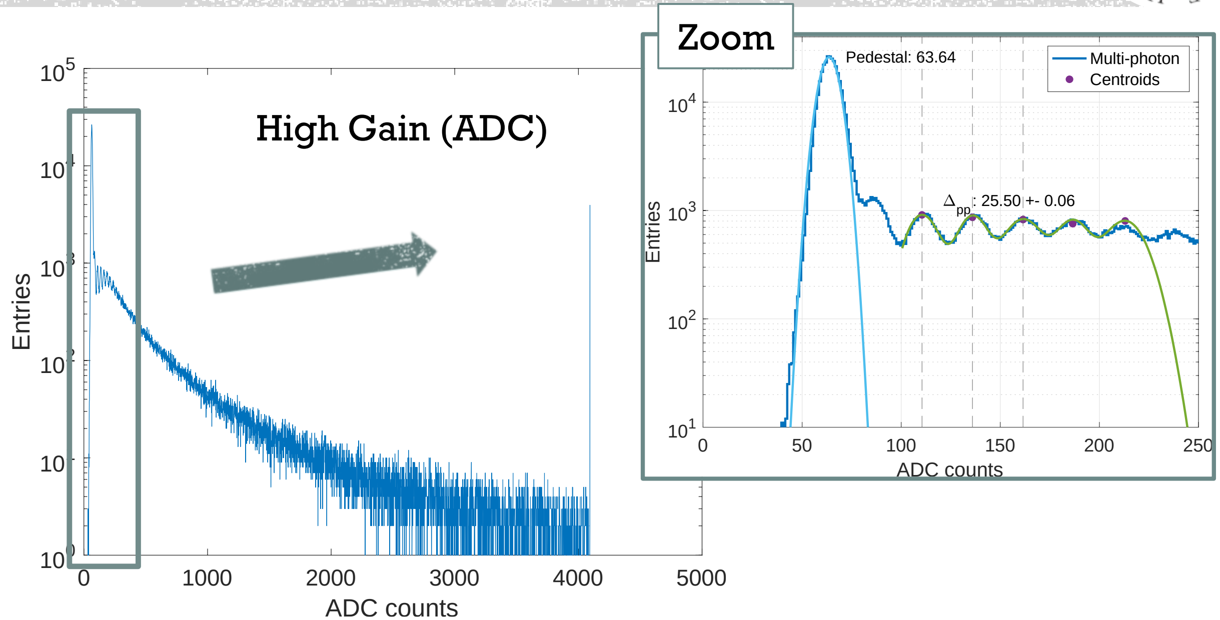




SiPM calibration (High Gain)

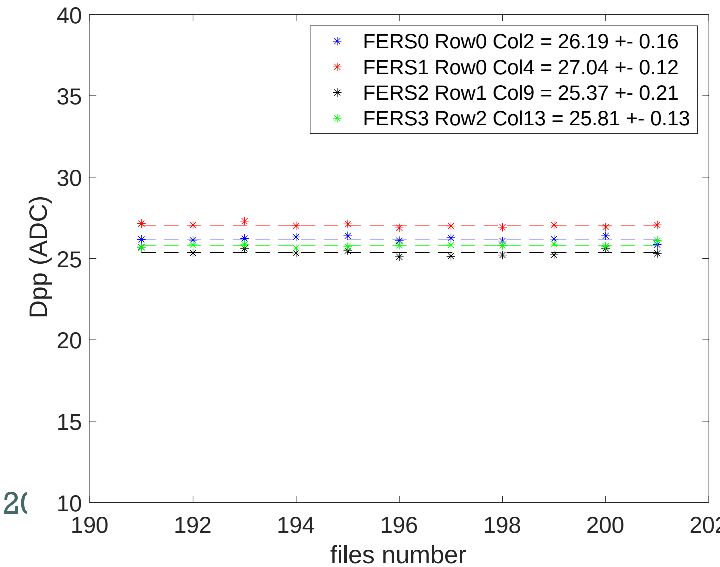
HG calibration (ADC/Ph-e)

The pedestal and dpp were measured in each run and per each SiPM



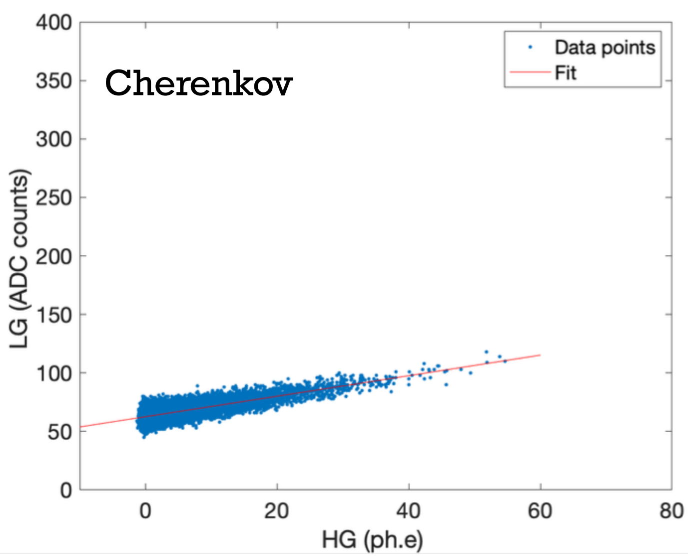
Stability:

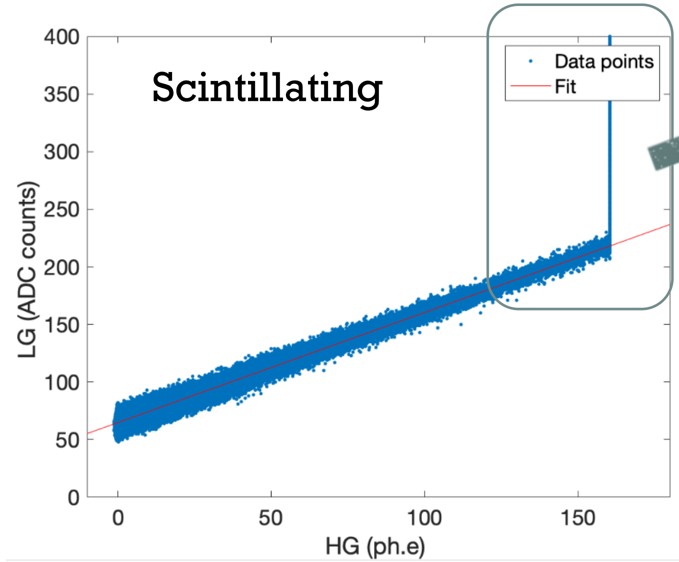
a small dpp fluctuation (<1%) was measured for a subset of runs and for all SiPMs



SiPM calibration (Low Gain)

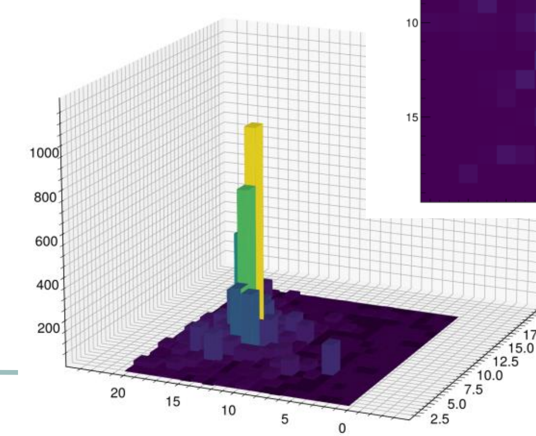
- Low gain calibration (ADC/Ph-e) is based on HG - LG correlation plots

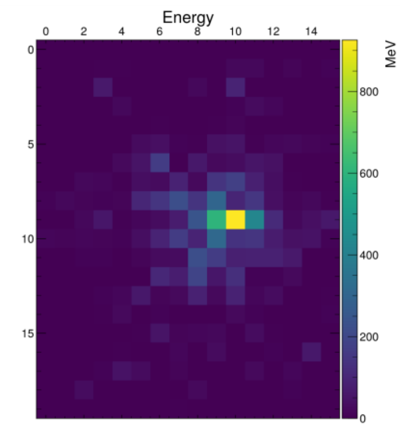




This line shows where the HG saturates and it demonstrates the possibility of using the LG

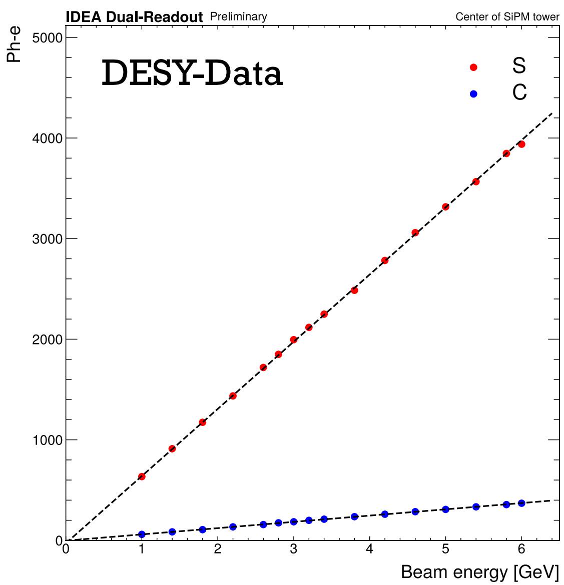
- After the calibration we can see the deposited energy in each fiber

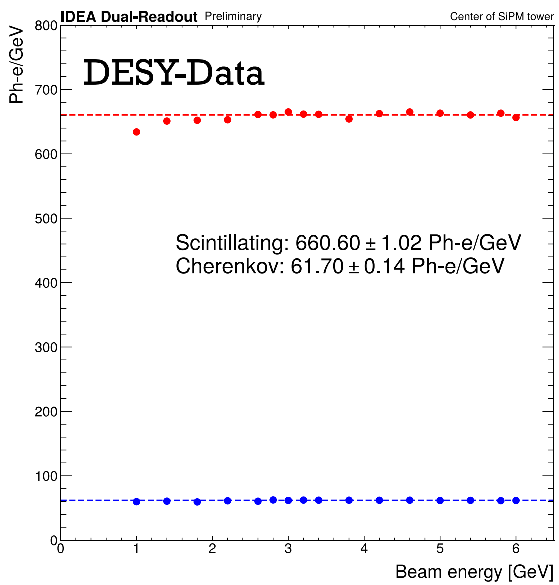


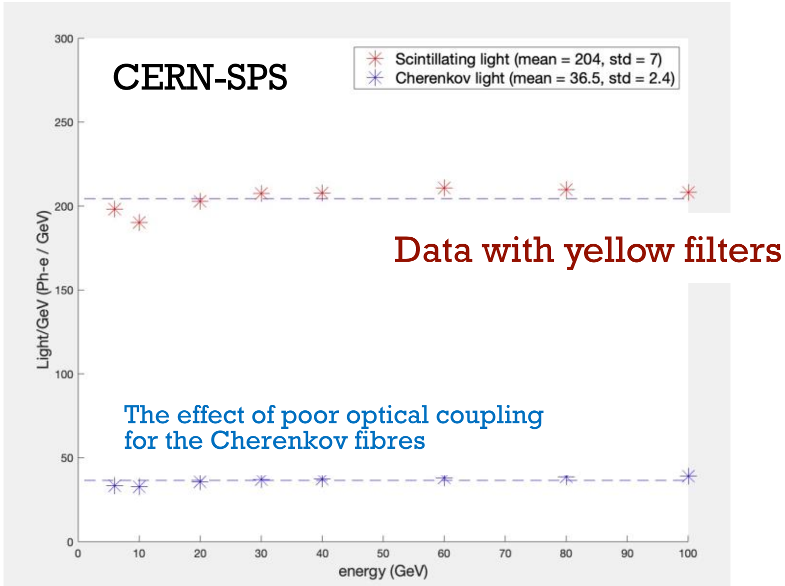


SiPM: final results

- The signals, calibrated in Ph-e, are summed on a event-by-event basis
- The MPV in the distributions are used to verify the linearity
  - Event selection based on the leading fibre fired in the centre of the module (4x4 cells)
- Ph-e/GeV has been estimated assuming the 70% containment in the module (from simulation)



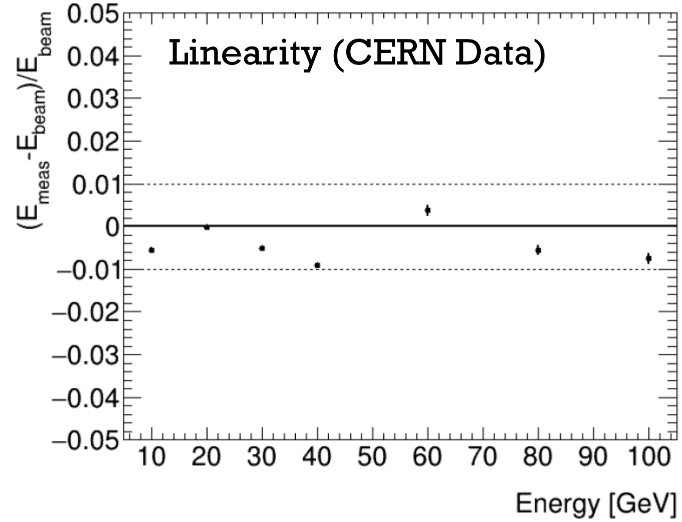




Light collection measured without optical filters

Final results and Monte Carlo comparison

- The TB data analysis is still ongoing
  - We measured a good linearity with e^+ over the full energy range
  - We are still investigating the impact of instrumental effects on the detector performance



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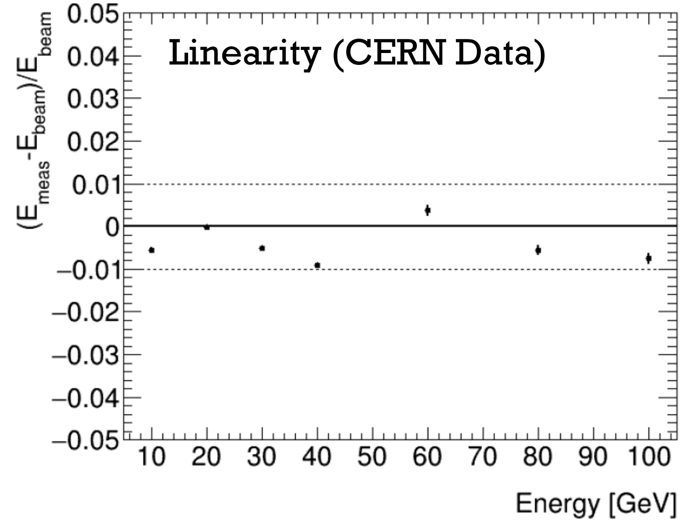
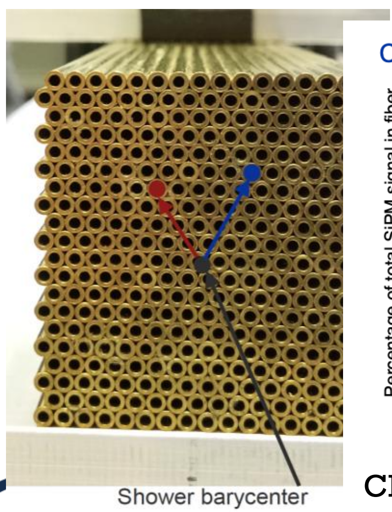
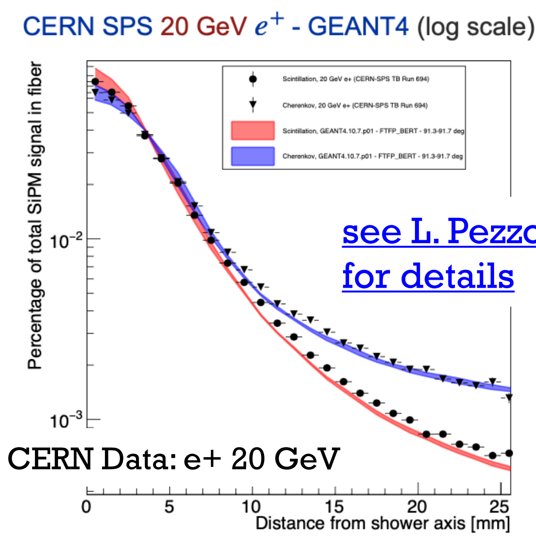
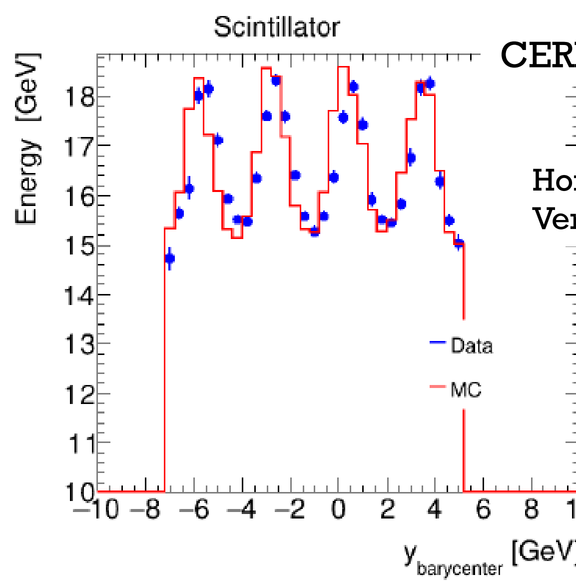






see L. Pezzotti talk for details

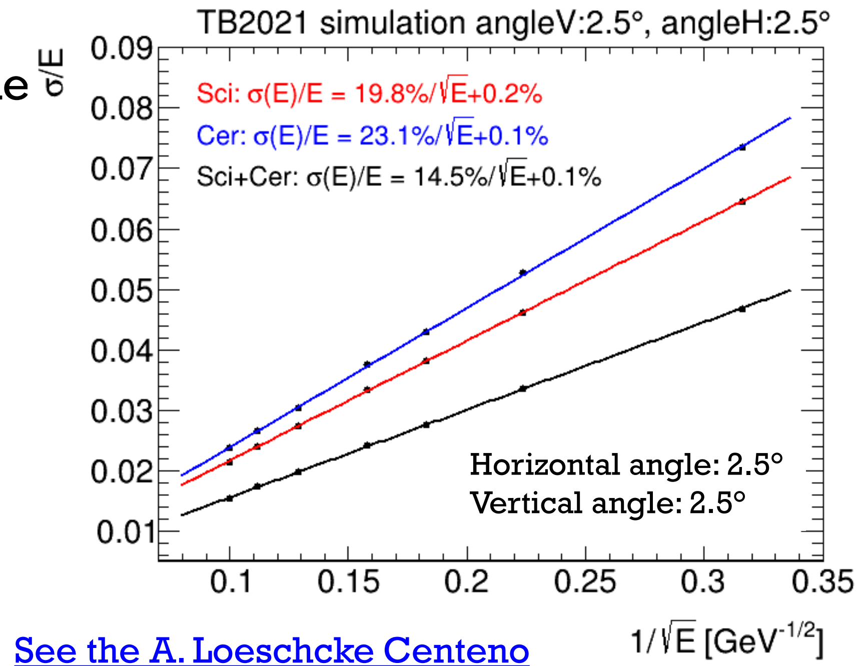


CERN Data: 20 GeV e^+

Horizontal angle: 1.5°
Vertical angle: -0.4°

Final results and Monte Carlo comparison

- The TB data analysis is still ongoing
  - We measured a good linearity with e^+ over the full energy range
  - We are still investigating the impact of instrumental effects on the detector performance
- In this respect a simulation tuned with test beam data is beneficial
- This the expected energy resolution for this prototype

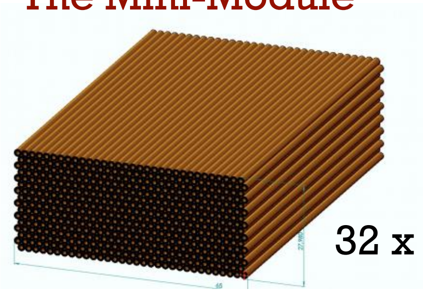


[See the A. Loeschcke Centeno poster for details]

Next step is to scale up towards a hadronic size prototype

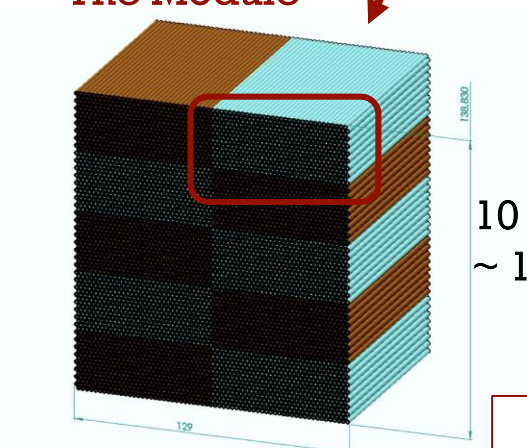
Prototype with hadronic containment: HiDRa

The Mini-Module



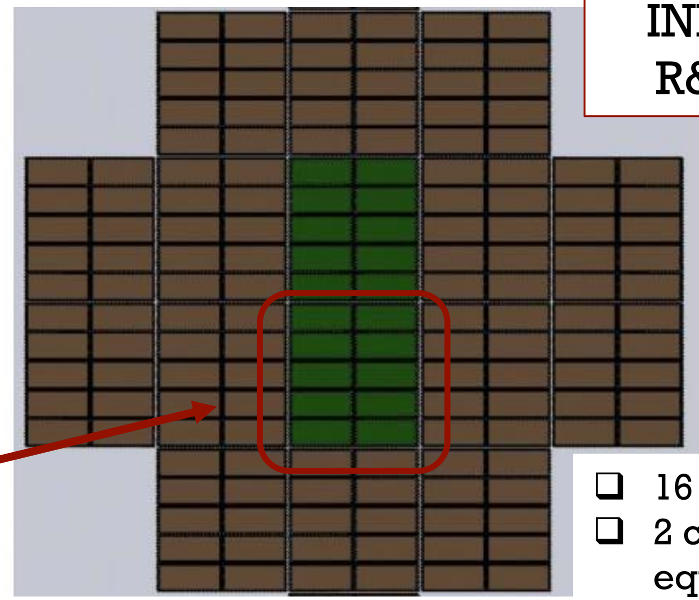
32 x 16 capillaries

The Module



10 Mini-modules
~ 13 x 13 x 250 cm^3

The hadronic prototype



INFN-funded
R&D project

- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm^3

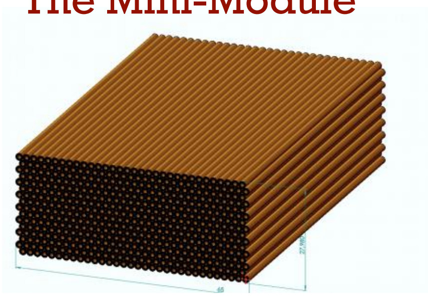
The challenge:

We have10240 SiPMs, fitting the back side of the detector

The design of a scalable solution

Additional requirements

The Mini-Module

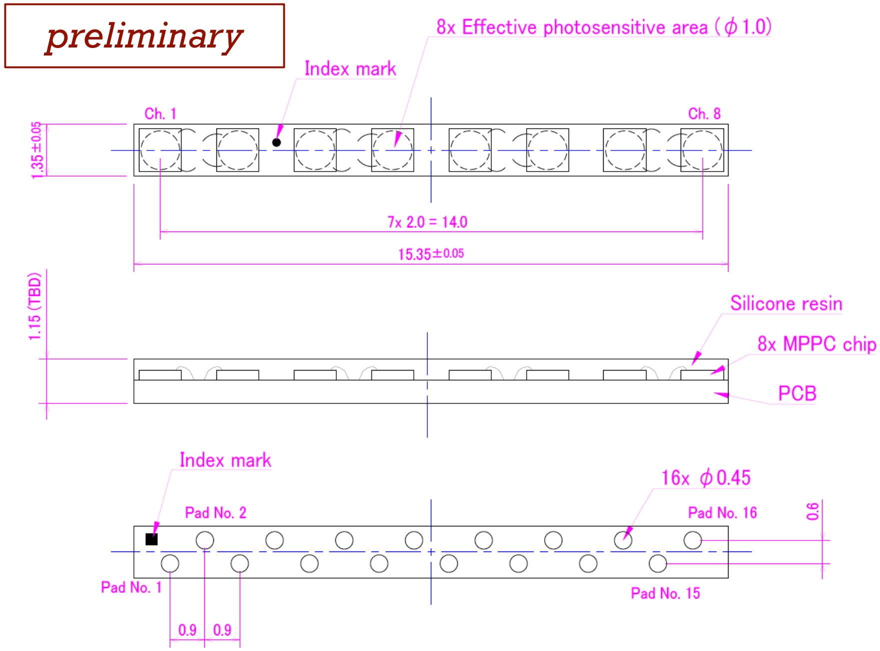


32 x 16 capillaries
1 capillary: (2 mm OD and 1.1 mm ID)

- 1 SiPM per fibre: compact package
- SiPM with wide Dyn-Range: 10 μm pitch
- No contamination between Cherenkov and scintillating light
- Affordable costs for a large production

SiPM module from Hamamatsu

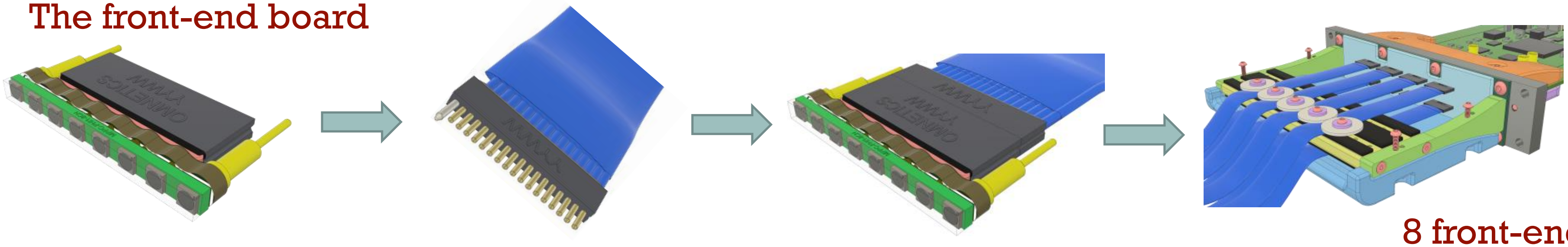
preliminary



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

The design of a scalable solution

The front-end board

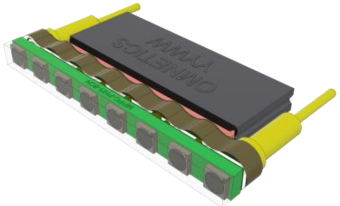


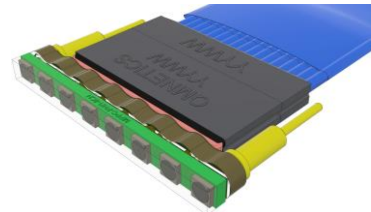
8 front-end boards connected to 1 FERS

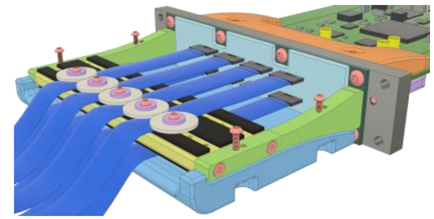
- Each SiPM is individually qualified: crucial for the system commissioning

The design of a scalable solution

The front-end board







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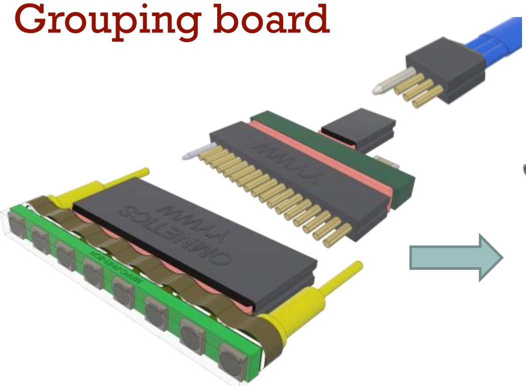
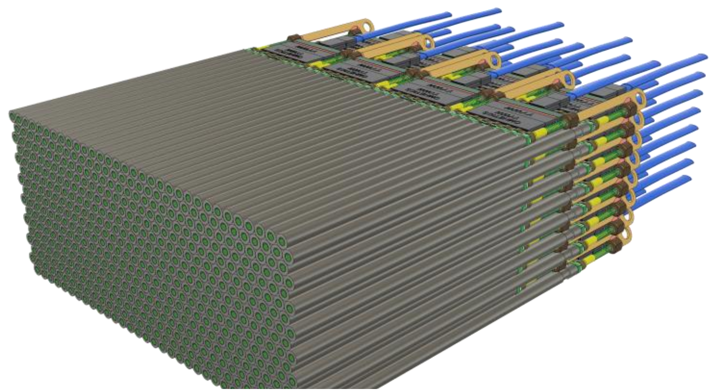
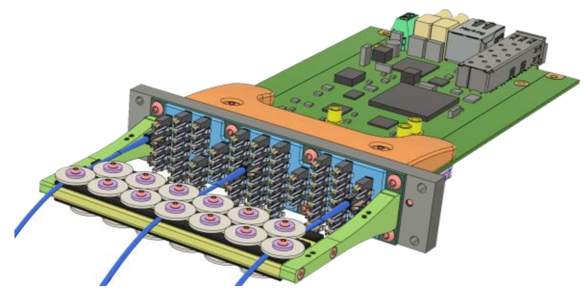
Grouping board



The Mini-Module



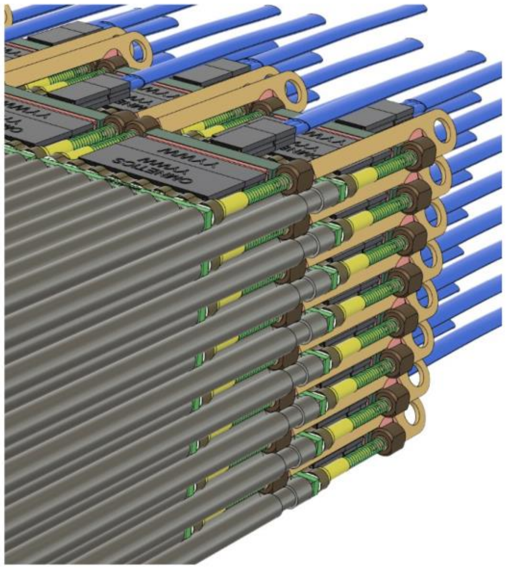


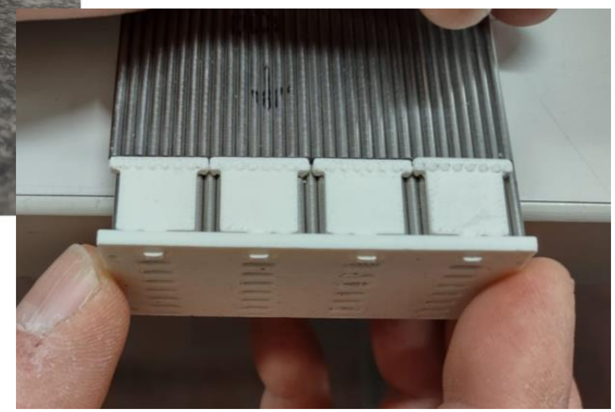
1 FERS serves 64 front-end boards with grouping

- Each bar of SiPMs will be operated at the same voltage (ΔV_{bd}<0.15V)
- The signals from 8 SiPMs are summed up in the grouping board

Hidra R&D: mechanical integration

Very preliminary!

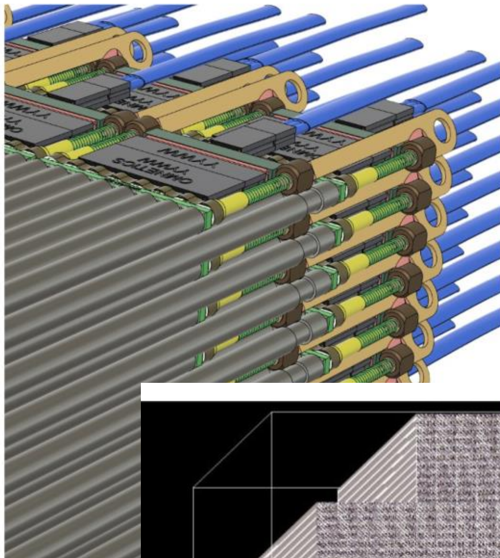


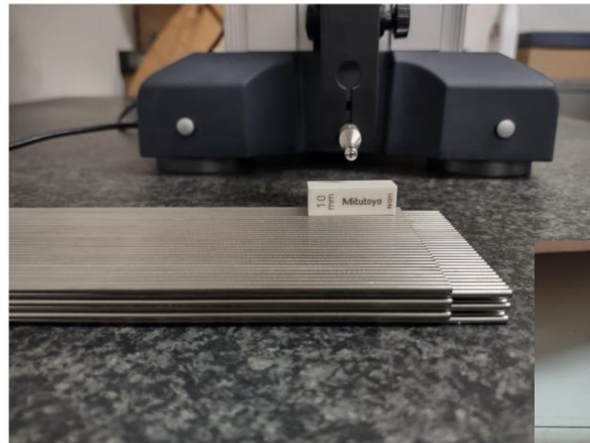


First tests with dummy components

Hidra R&D: mechanical integration + simulation

Very preliminary!





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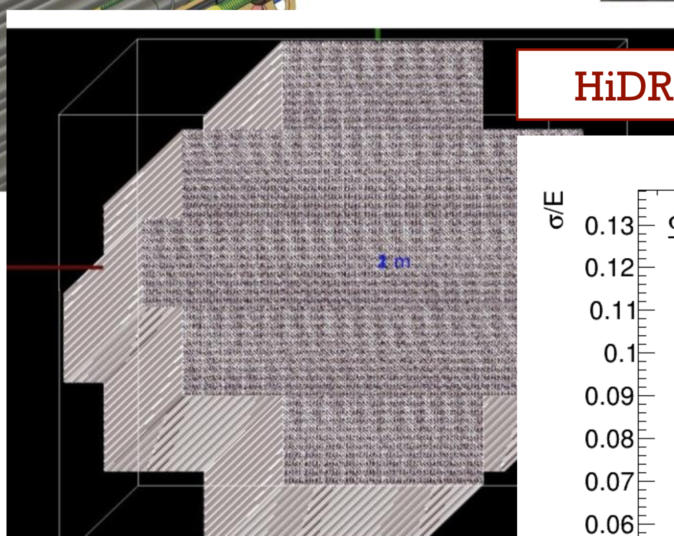
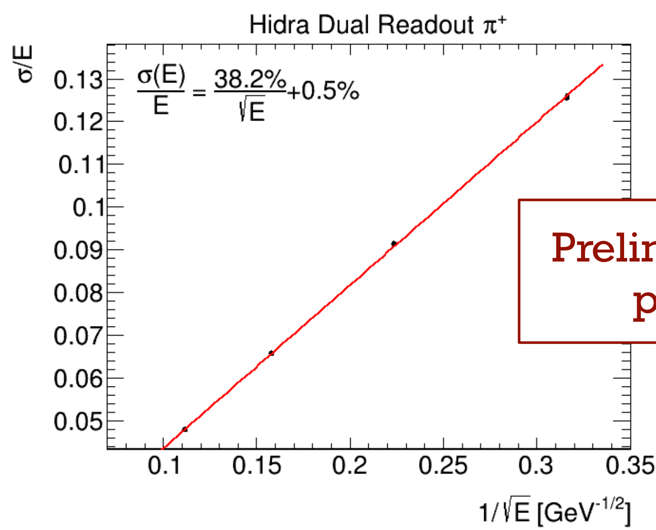


HiDRa geometry



Preliminary Hadronic performance

Summary

- The first e-m size prototype with a highly granular core equipped with SiPMs has been qualified on beam
  - Good understanding of the SiPM calibration strategy
  - Useful data to tune and validate the GEANT4 simulation
  - Analysis still ongoing, but the the agreement with simulation is excellent
- Next goal: design, build and qualify on beam a scalable prototype with hadronic containment
  - To investigate an assembly procedure that could fit the 4π geometry requirements
  - To handle a large number of SiPMs (10k sensors)
  - To assess the hadronic performance
- Two projects have been funded by national agencies (INFN-Italy and Korea) for this achievement
  - We are exploiting different solutions, sharing expertise and the simulation framework

Backup

Dual Readout in a nutshell

Simultaneous measurement on event-by-event basis of em fraction of hadron showers

$$S = [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ] \times E$$
$$C = [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ] \times E$$

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

e/h ratios (c = $(h/e)_c$ and s = $(h/e)_s$ for either Cherenkov or scintillation structure) can be measured

Θ and χ are independent of both energy and particle type

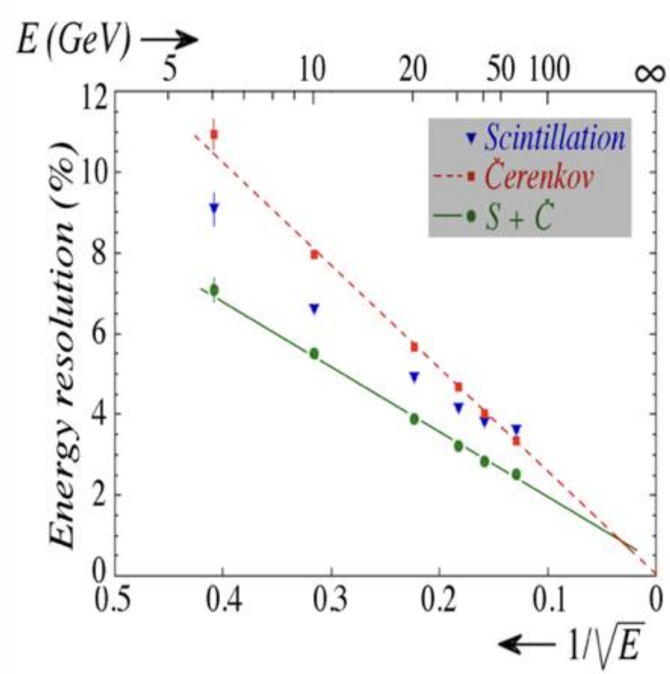
It is possible to evaluate $f = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$ and $E = \dfrac{S - \chi C}{1 - \chi}$

Energy resolution

- Electromagnetic resolution:

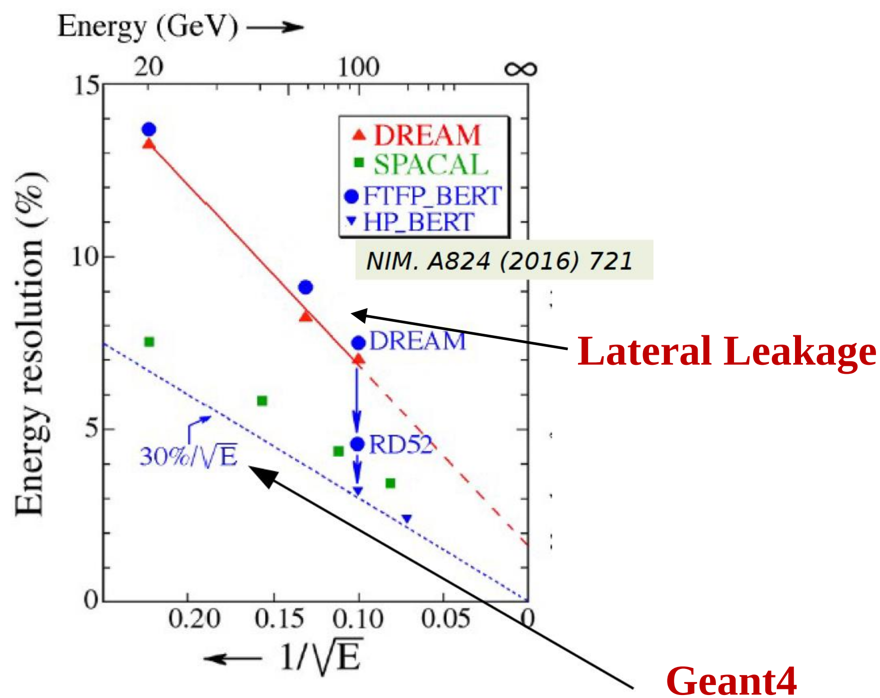
$$\frac{\sigma_{EM}}{E} = \frac{11\%}{\sqrt{E}} \oplus 1\%$$

Copper module
NIM A735, 130-144 (2014)

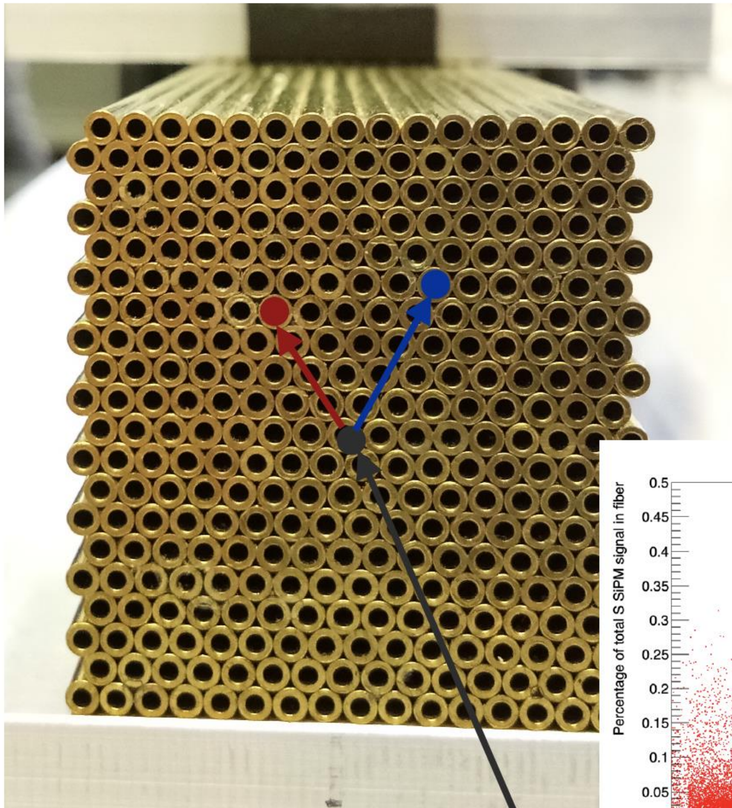


- Hadronic resolution:

$$\frac{\sigma_{HAD}}{E} = \frac{30\%}{\sqrt{E}}$$



How to measure e^+ shower shape



- Lateral profile, *i.e.* the average signal carried by a fiber located at a distance r from the shower barycenter.
- Measurement:
  - For every event, and for every fiber we populate a scatter plot (signal *vs.* distance).
  - Lateral profiles are extracted as average values for every x-bin (ROOT::TProfile).