R&D on DR fibre sampling calorimeters

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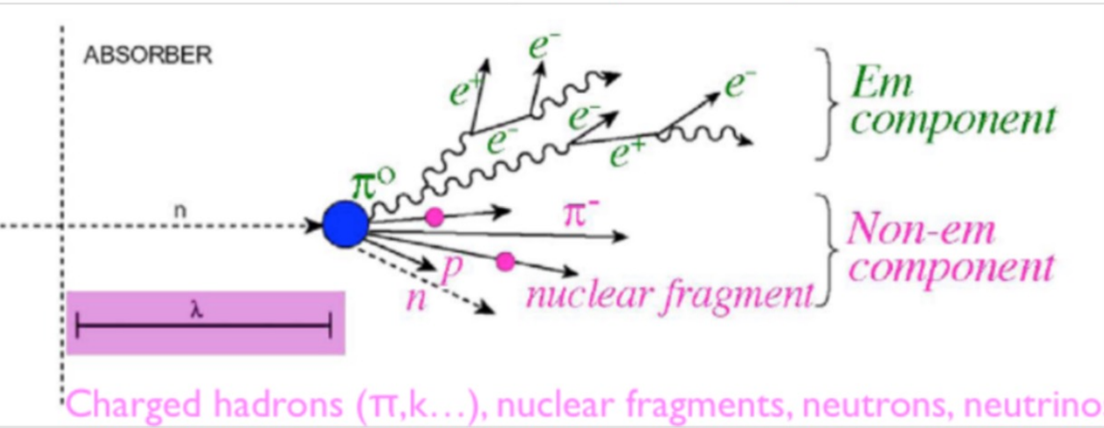
Dual Readout in a nutshell

electrons positrons, photons, π^0



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

Cherenkov light (C)	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light (S)	measure dE/dx

Measure the electromagnetic fraction event by event to equalize the response off-line

- **Compensation** achieved without construction constraints
- **Calibration** of a hadron calorimeter just with electrons
- **High resolution** EM and HAD calorimetry

The R&D strategy

- Ongoing R&D (2020 – 2021): build and qualify on beam a module with EM shower containment (10x10x100 cm^3) partially equipped with SiPMs:
  - To start handling a scalable readout system for SiPMs (Citiroc1A / FERS)
  - To consolidate the EM performances and to exploit new techniques for particle ID
- R&D plan (2022-2025): design, build & qualify on beam a scalable solution with hadronic containment
  - To study an assembly procedure that could fit the 4π geometry requirements
  - To handle a large number of SiPMs
  - To assess the hadronic performance
- Simulation: detailed studies to support the detector design optimisation and to validate and tune the GEANT4 showering models.

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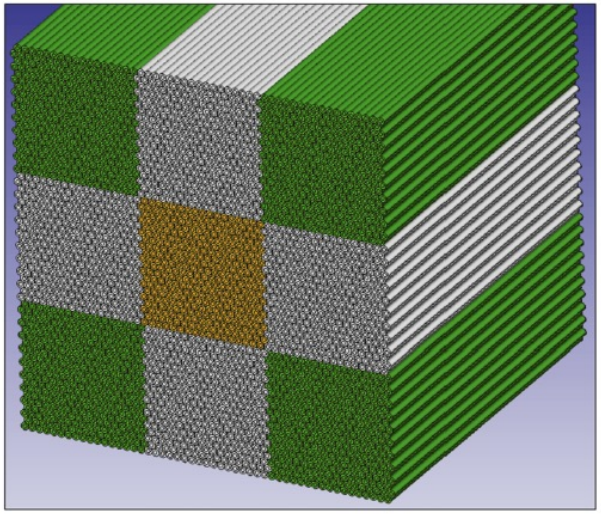
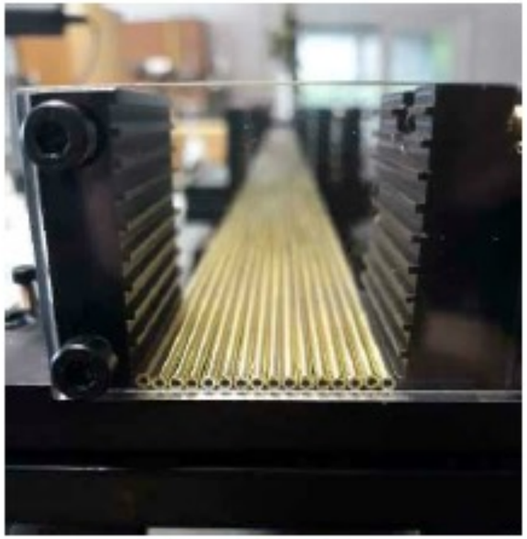
Test beam: mechanics and assembly

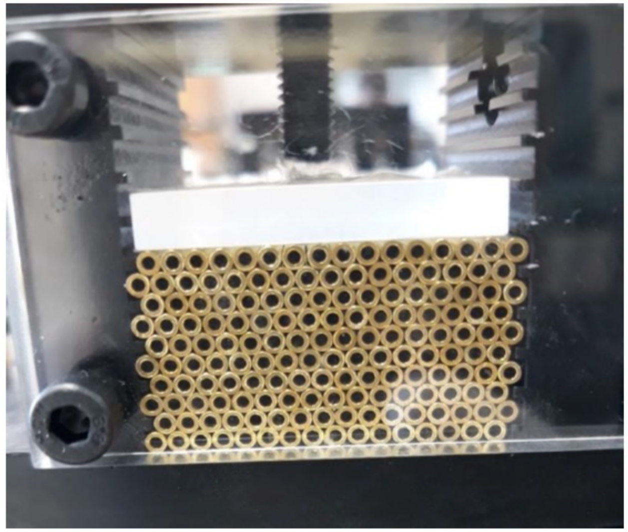


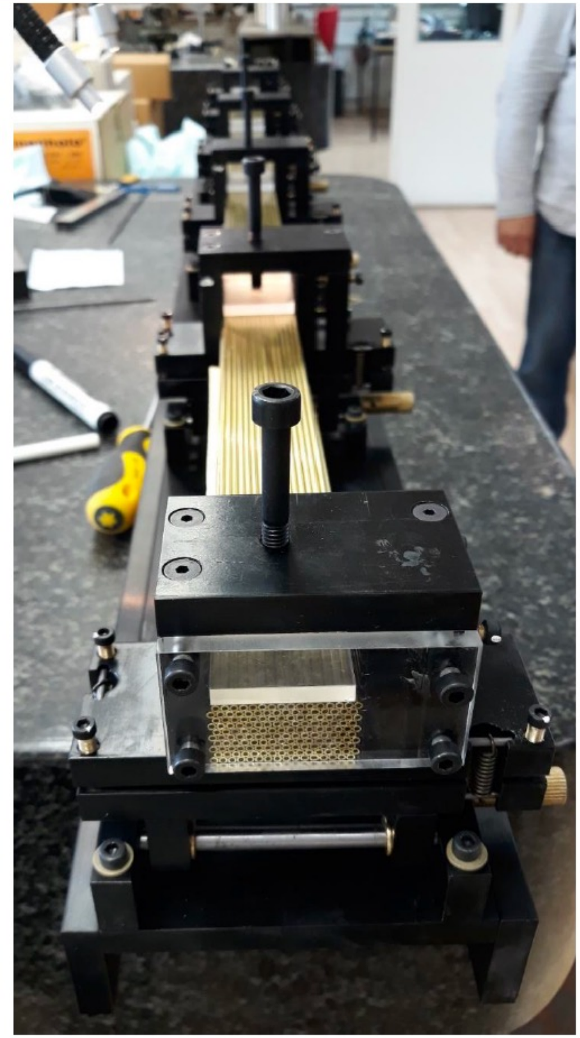
- EM-prototype (10x10x100 cm^3)
  - 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
  - Capillaries (brass): 2 mm outer diameter and 1.1 mm inner diameter
- EM-prototype readout
  - Each capillary of the central module is equipped with its own SiPM: highly granular readout
  - 8 surrounding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

Assembly procedure (RBI)

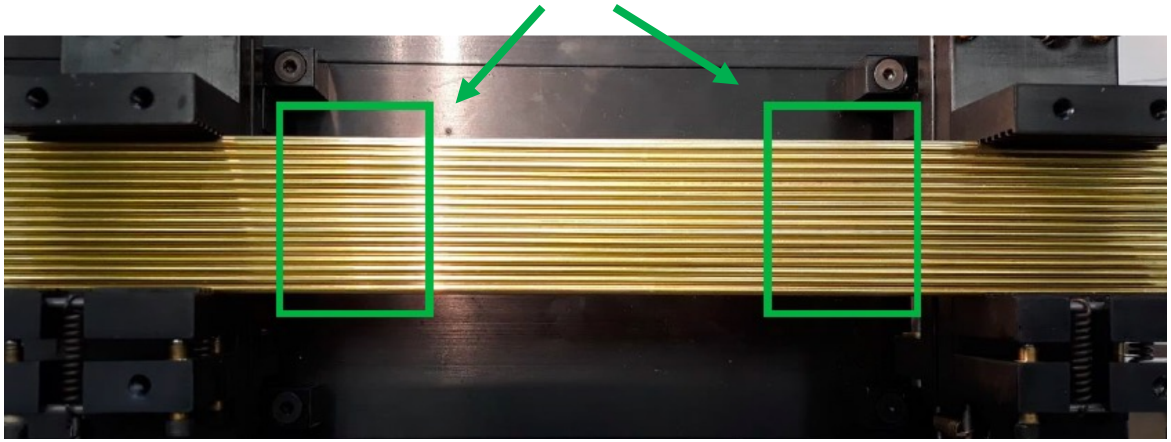
Horizon 2020
European Union Funding
for Research & Innovation
Grant Agreement No 669014







Glue



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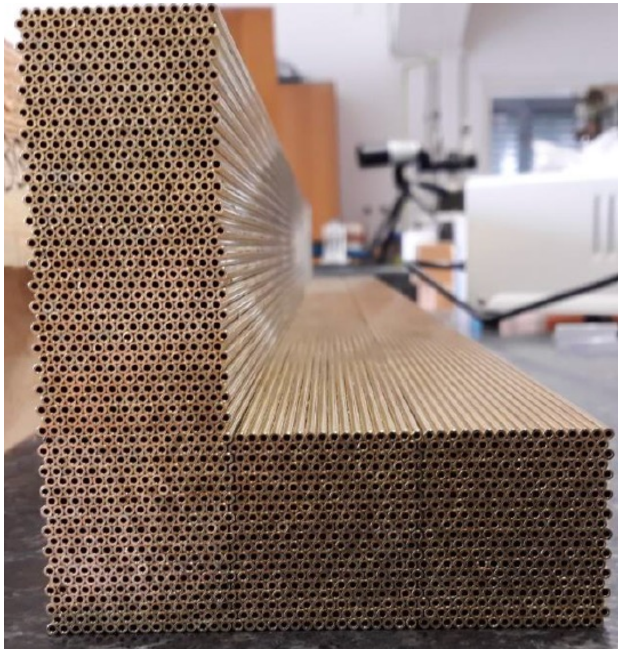
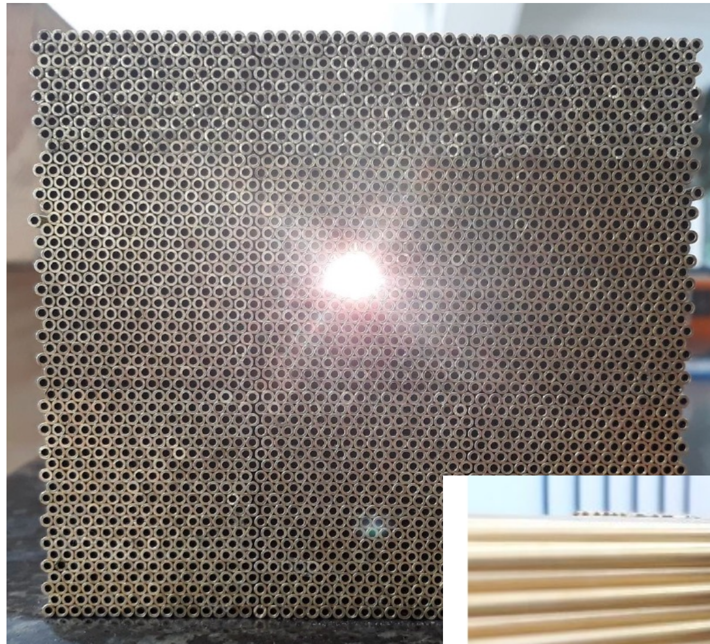
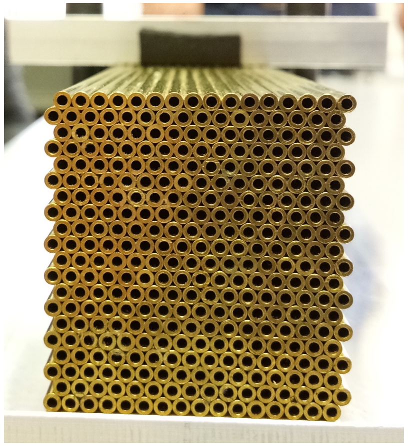
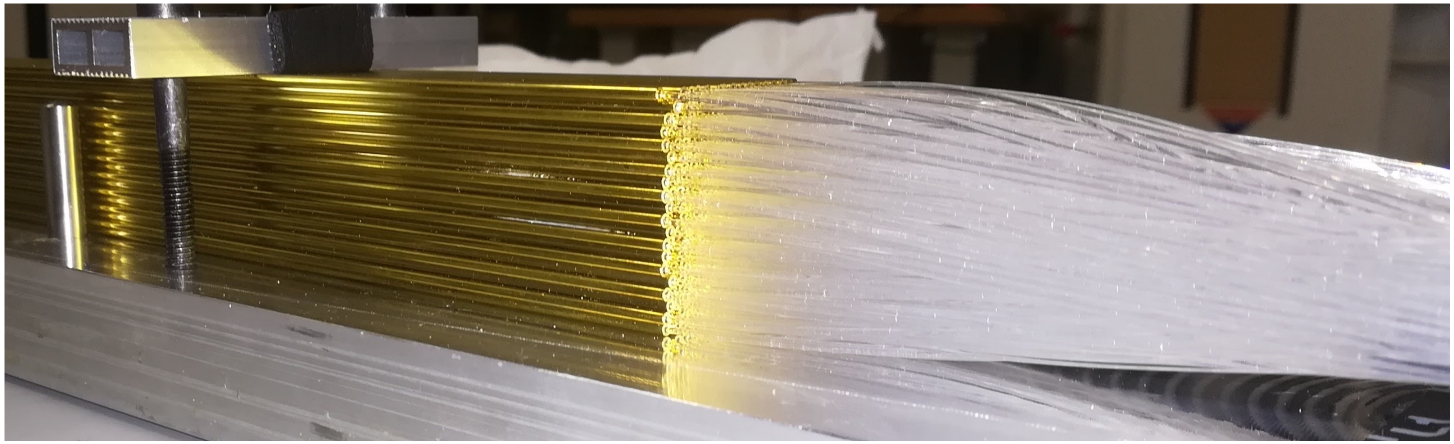




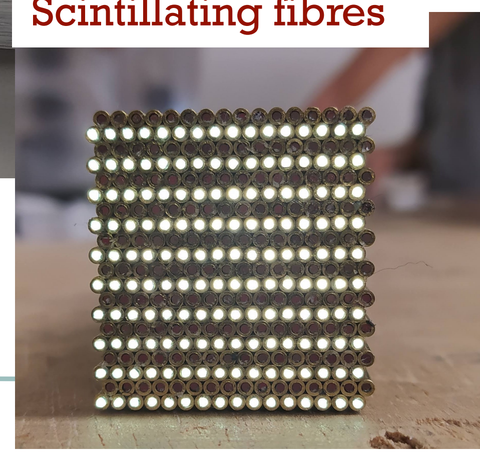
The assembly procedure is quite simple and allows to achieve the expected precision

Modules equipped with PMTs



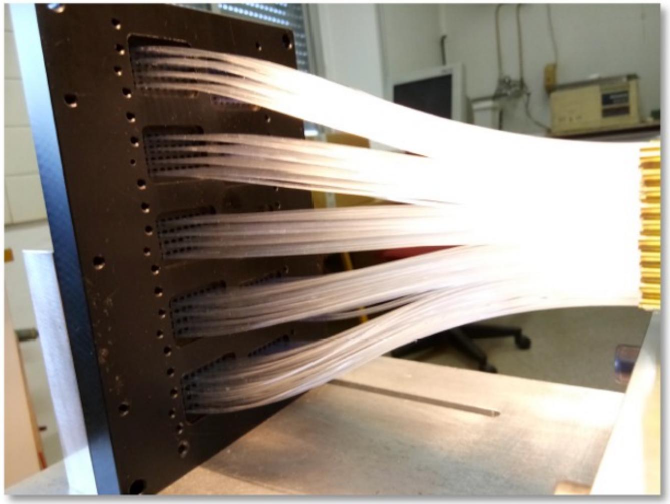


Scintillating fibres

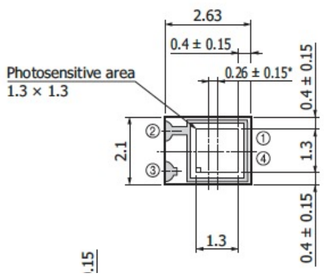


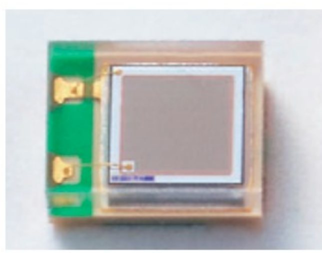
Cherenkov fibres

Module equipped with SiPMs

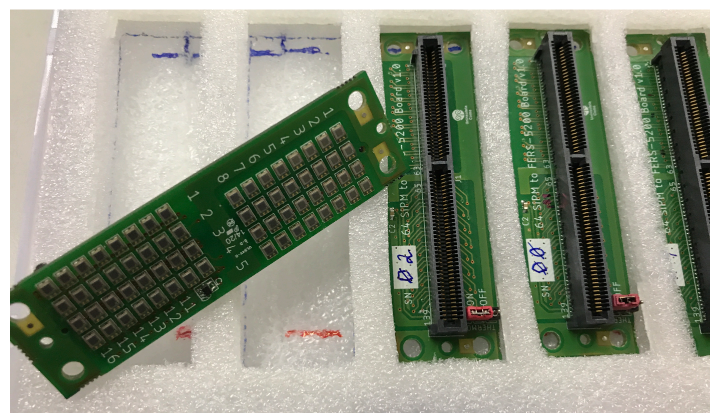


Dummy SiPM FEE board



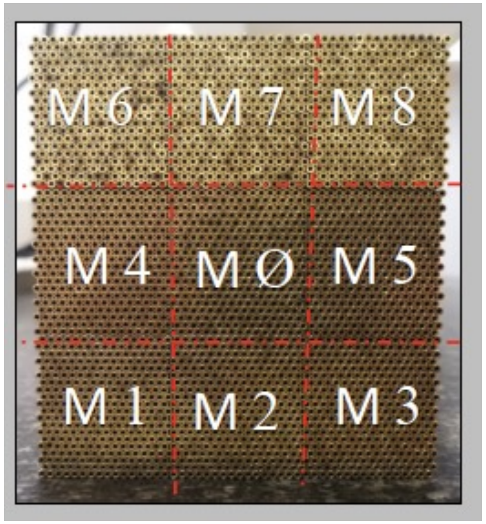


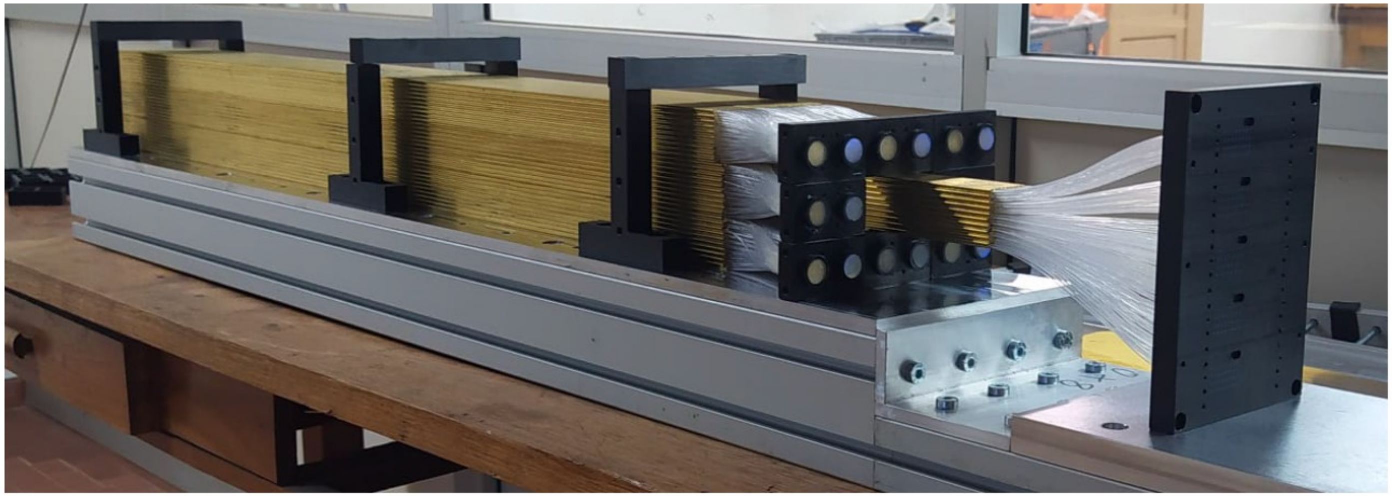
5 FEE Boards (320 SiPMs)

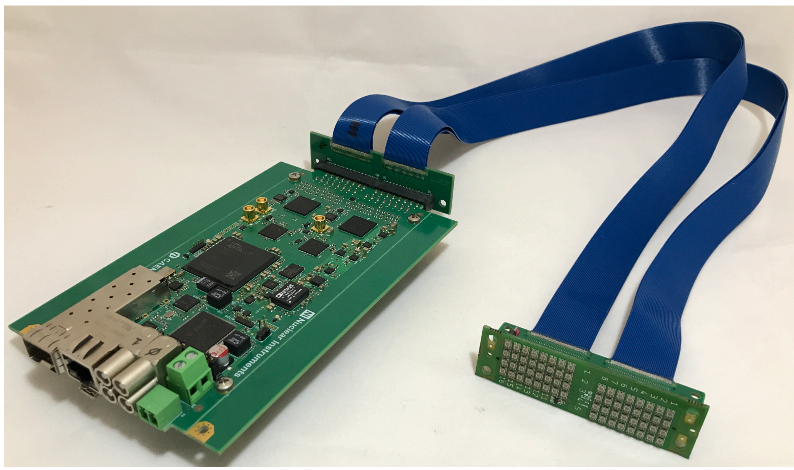


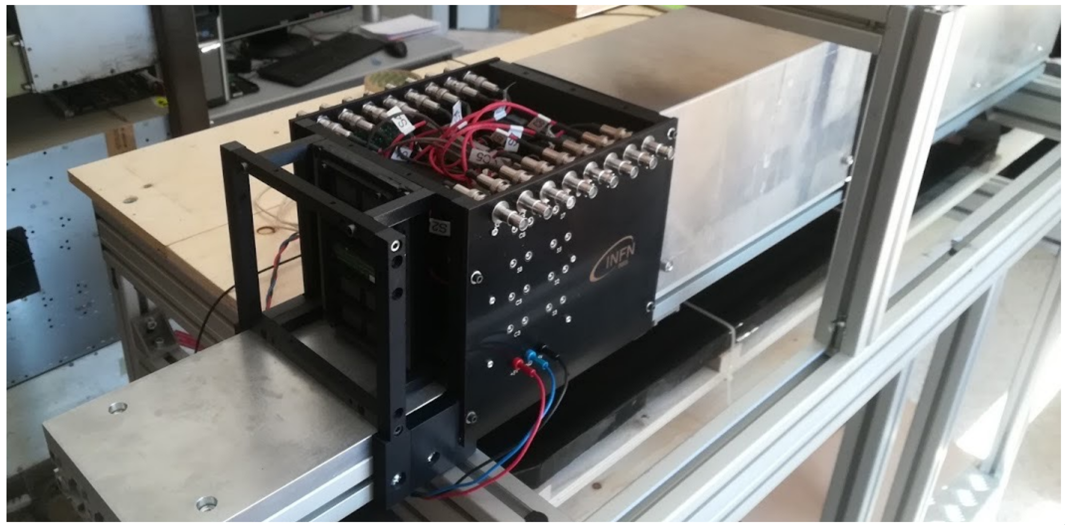
Hamamatsu SiPM: S14160-1315 PS
Cell size: 15 μm

The test beam prototype



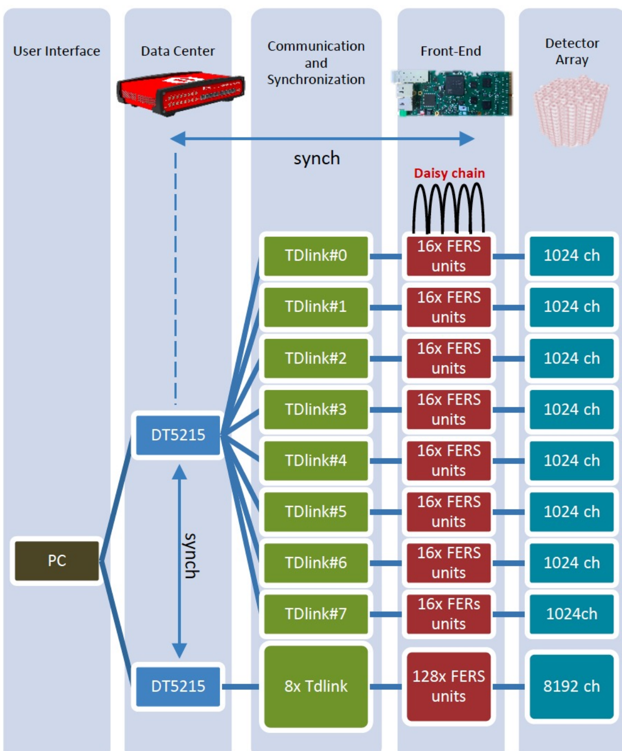




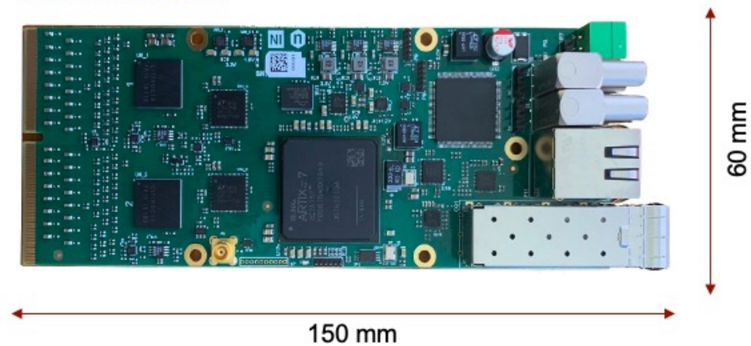


Test beam: readout scheme

- 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)



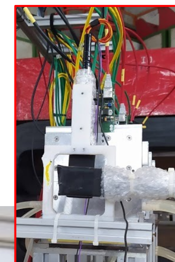
FERS: A5202



- 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)

Trigger and readout schema

- The coincidence between two scintillators has been used to trigger both the PMTs and the tracker
- The SiPM readout (FERS) was running in self-trigger with a majority algorithm. The trigger from the scintillators has been used to flag and store the data on disk (event accept)



Scintillators

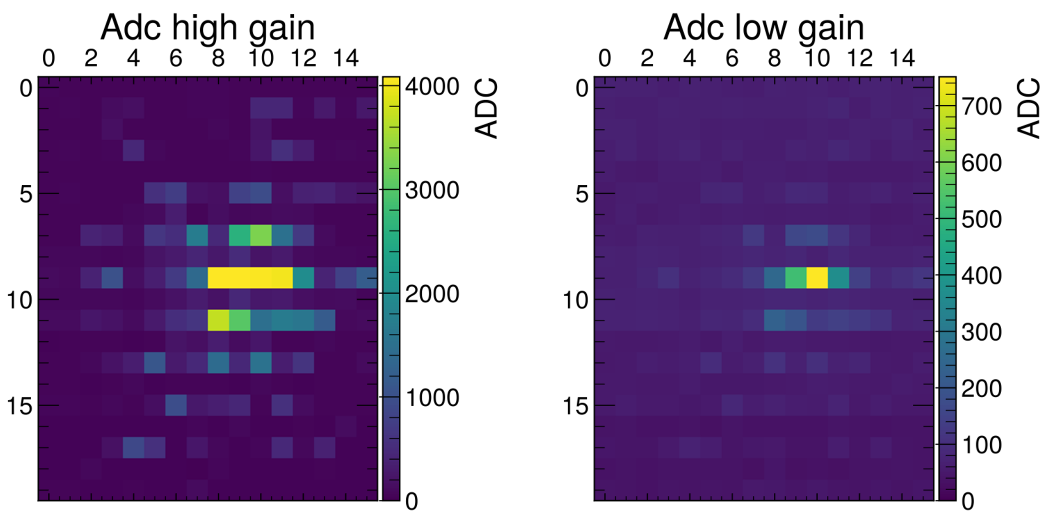
Measurements

New readout system commissioned and several good data collected:

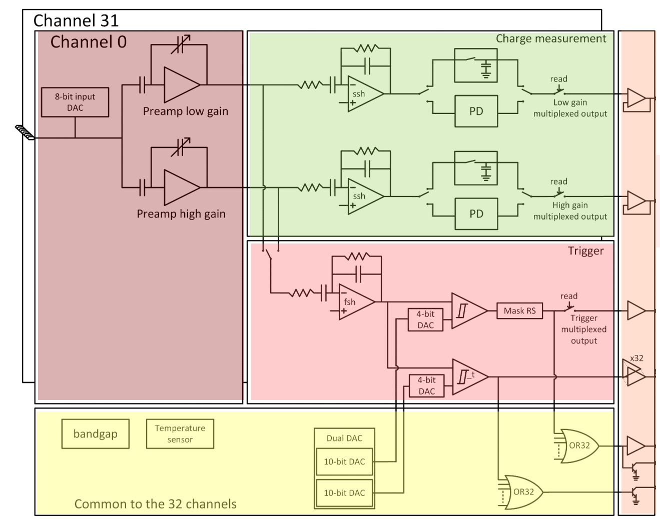
- PMT towers calibration with the beam steered in the centre of each tower
- Energy scan from 1 to 6 GeV with the beam steered in the centre of the prototype
- Long runs with a narrow beam steered in the centre of the prototype @ 3 GeV for Monte Carlo studies
- Series of runs to measure the shower tail with the SiPM tower for Monte Carlo studies
- Series of runs with the beam steered between towers to investigate any possible performance degradation

SiPM calibration

- Beam @ 6GeV centred on the SiPM tower



CITIROC 1A: block diagram



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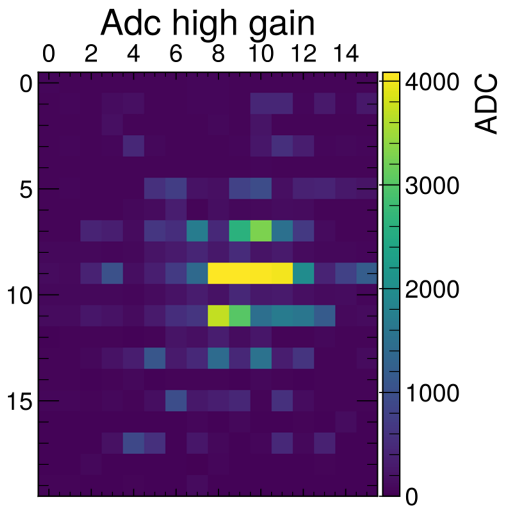

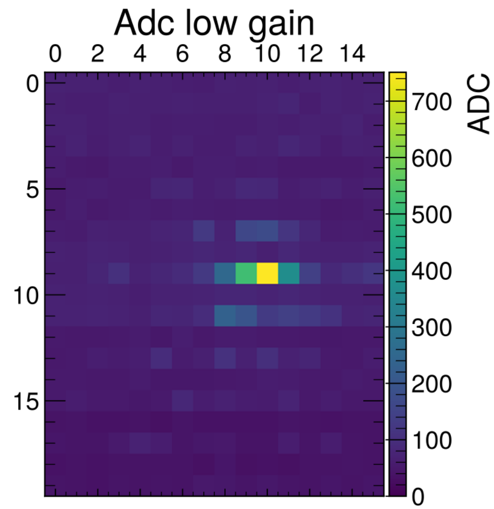

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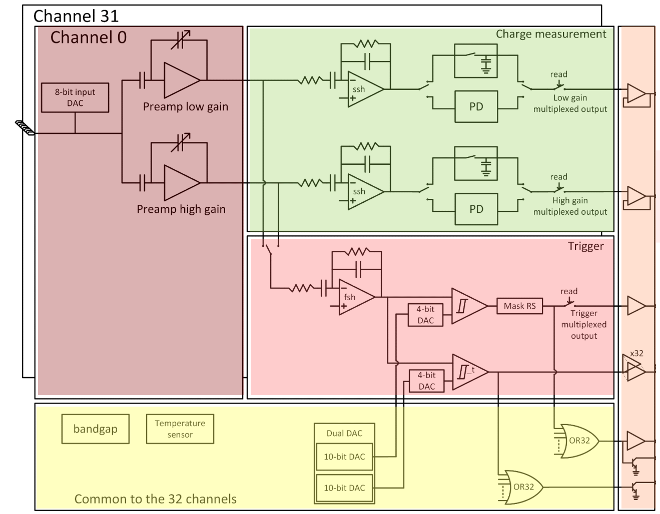
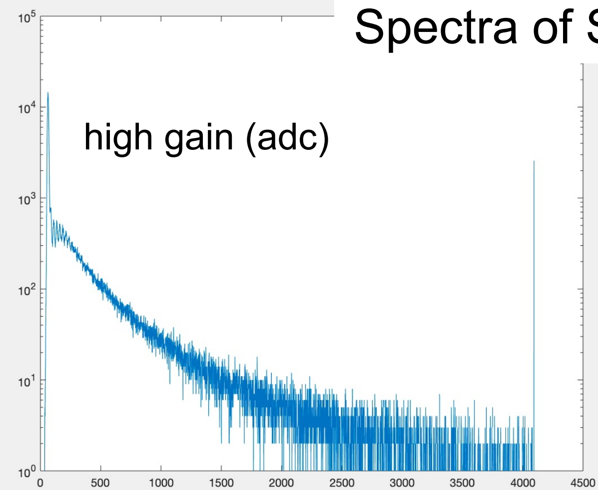
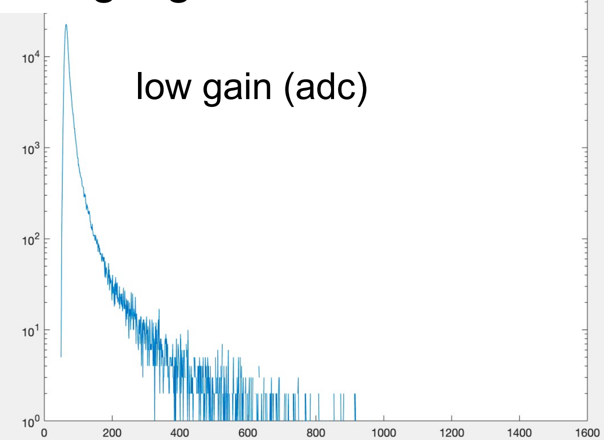


Spectra of Scintillating signal

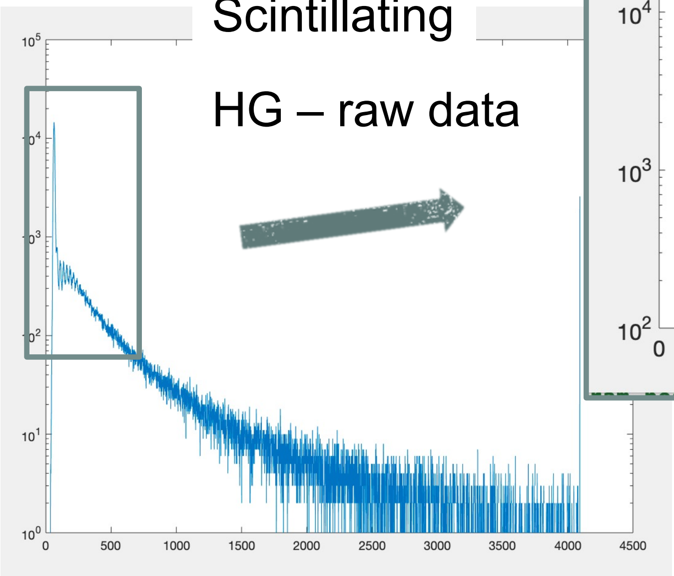


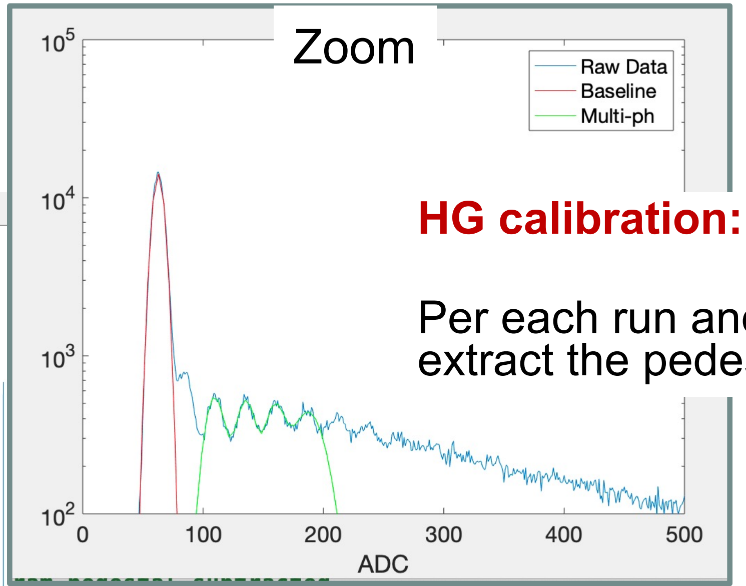


SiPM calibration (High Gain)

Scintillating

HG – raw data





HG calibration: from adc to Ph-e

Per each run and per each SiPM we extract the pedestal and dpp

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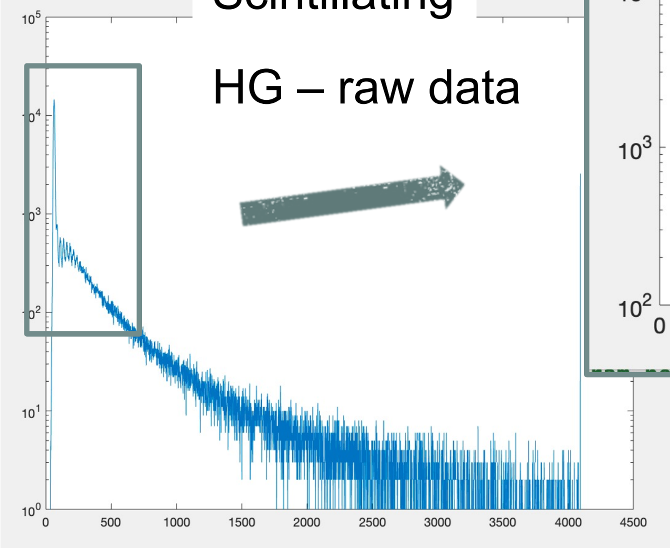
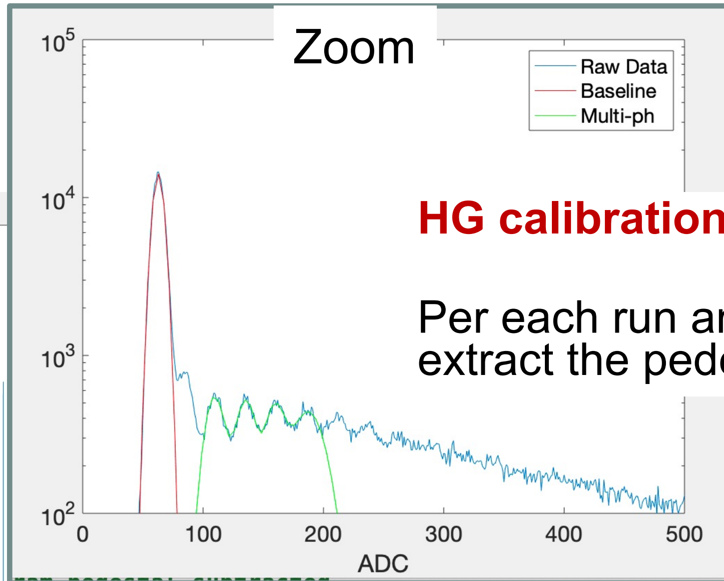


Zoom



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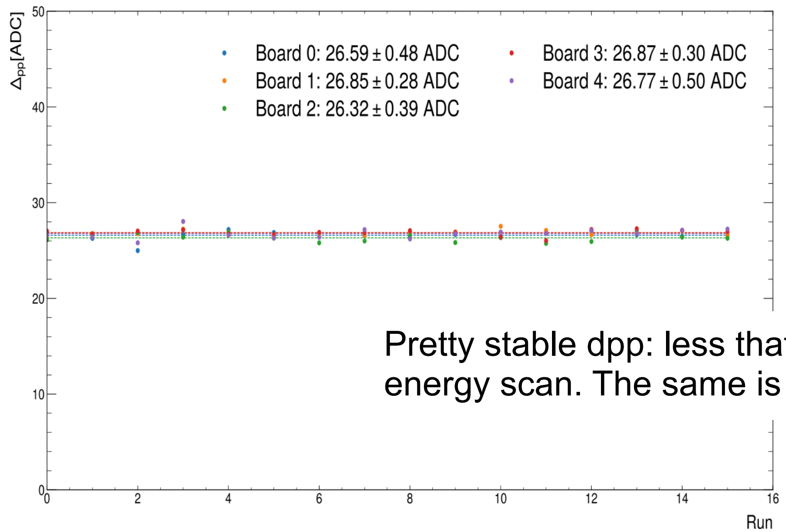
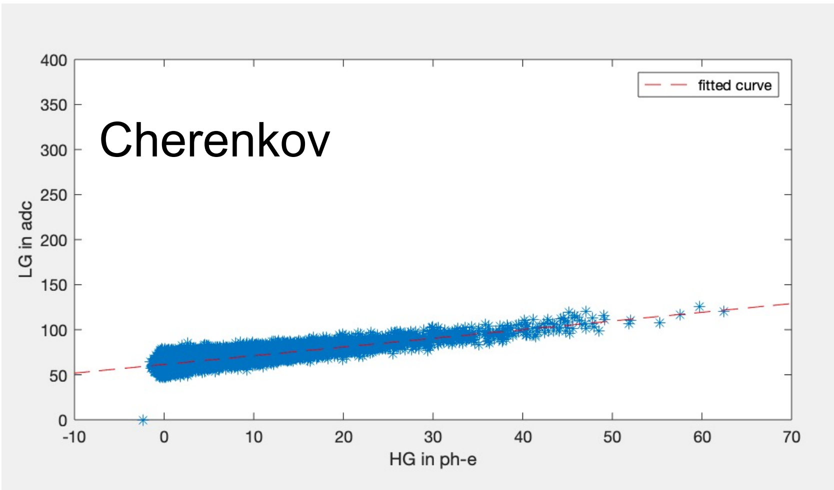
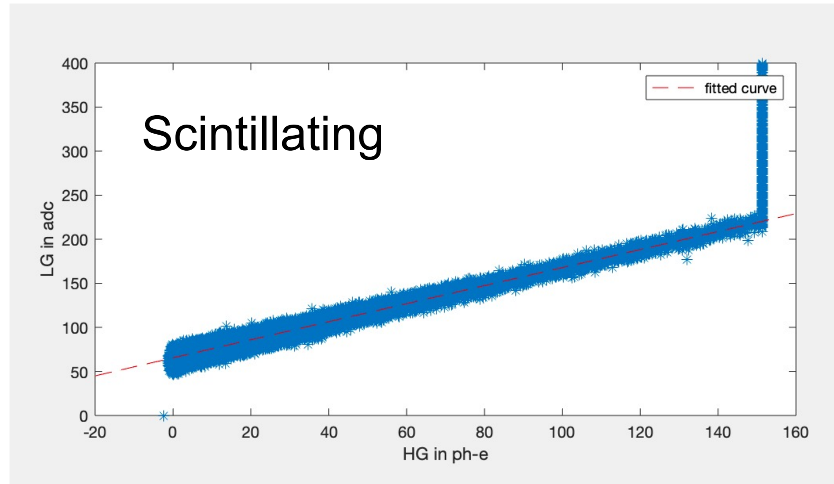


Pretty stable dpp: less that 1 adc during the full energy scan. The same is true for the pedestal

SiPM calibration (Low Gain)

- Low gain calibration using the HG - LG correlation plots

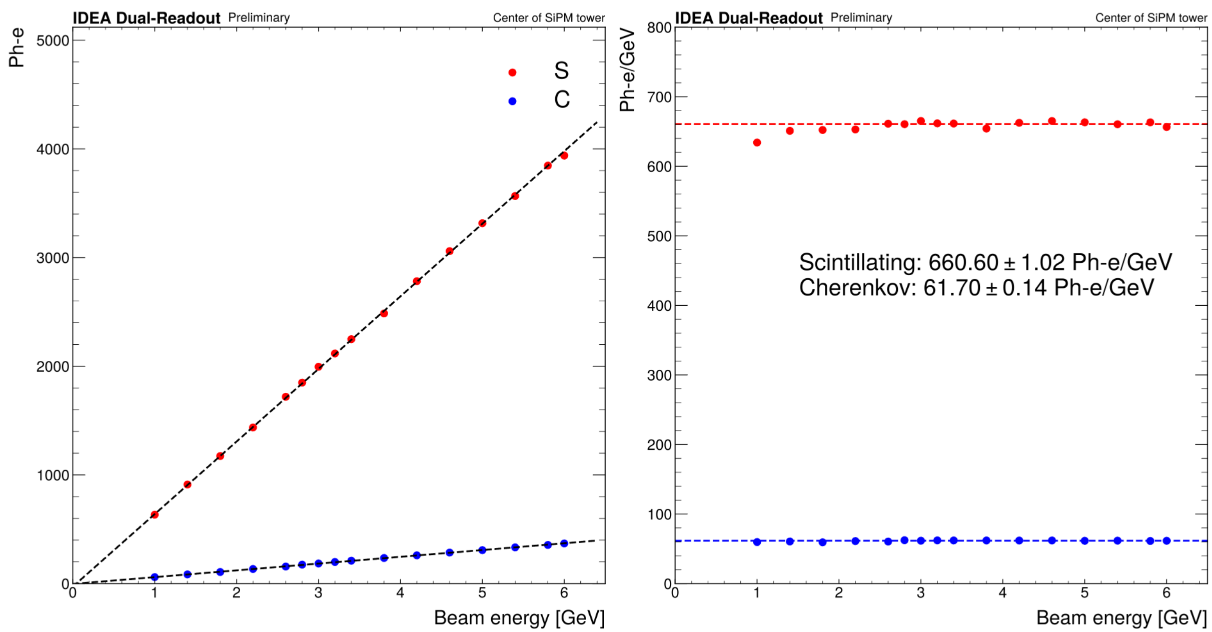




From this plots we get the calibration for the low gain (ADC - phe) for each run and each SiPM

Calibrated plots

- Once the signals are calibrated we sum the light detected by all the SiPMs event by event
- From the distribution we get the energy calibration and the linearity
  - Event selection is based on the leading fibre placed in the centre of the tower (4x4 cell)
  - The assumed containment is 70% (to be verified with simulations)



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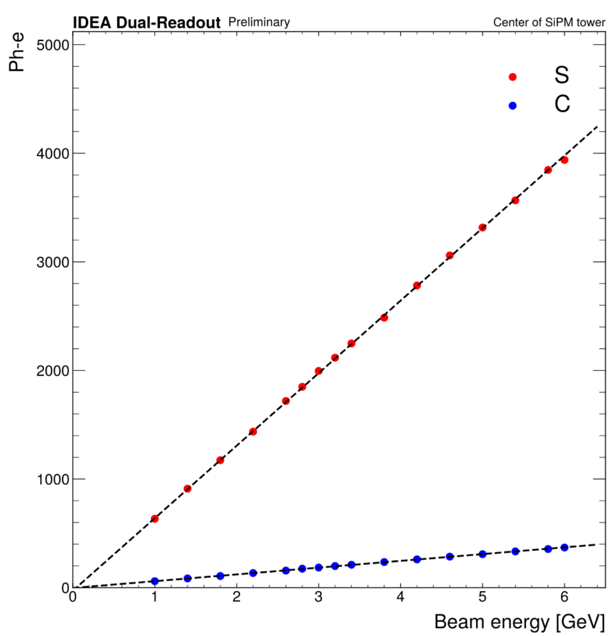
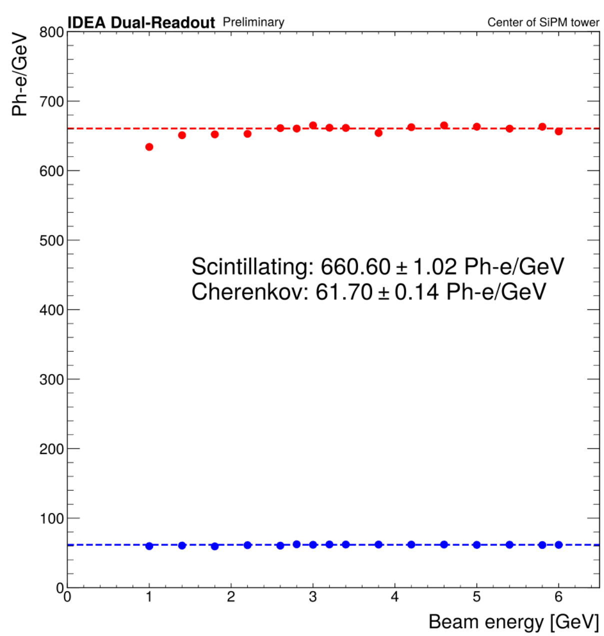
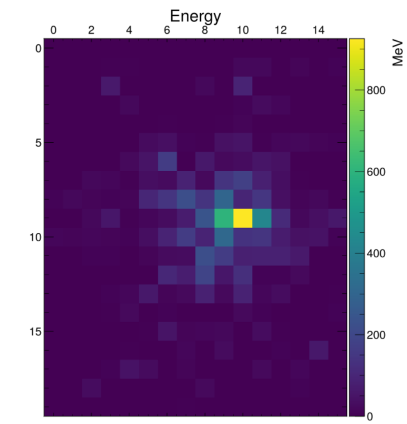
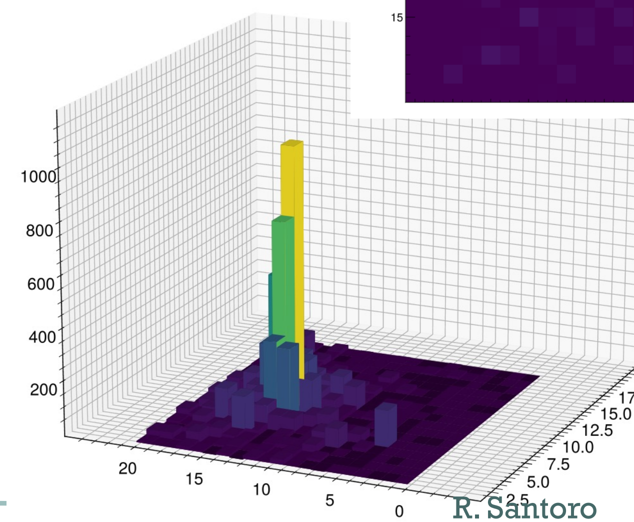


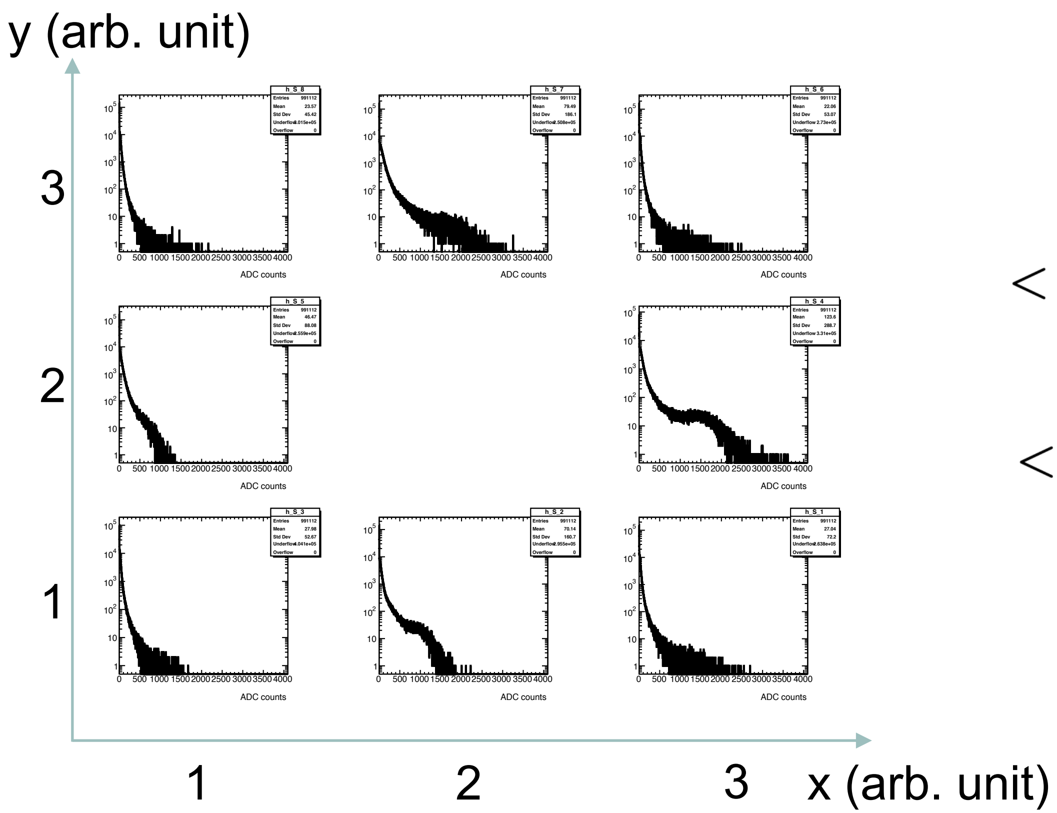






PMT and SiPM: events synchronization

- The light measured in the towers with the PMTs is used to estimate the impact point of the electrons (event by event)

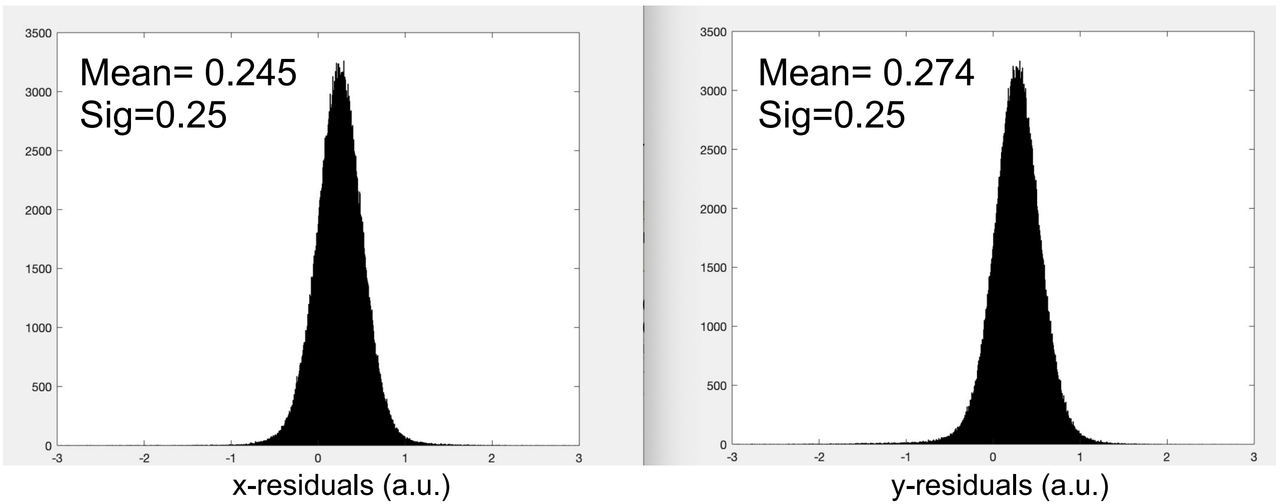


$$< x >= \frac{\sum E_j x_j}{\sum E_j}$$

$$< y >= \frac{\sum E_j y_j}{\sum E_j}$$

PMT and SiPM: events synchronization

- The light measured in the towers with the PMTs is used to estimate the impact point of the electrons (event by event)
- The same is done with the central tower using the signals from the SiPMs to check the events synchronization



- This plot shows we can marge the data from the SiPMs and the PMTs to estimate the energy resolution (will come soon)

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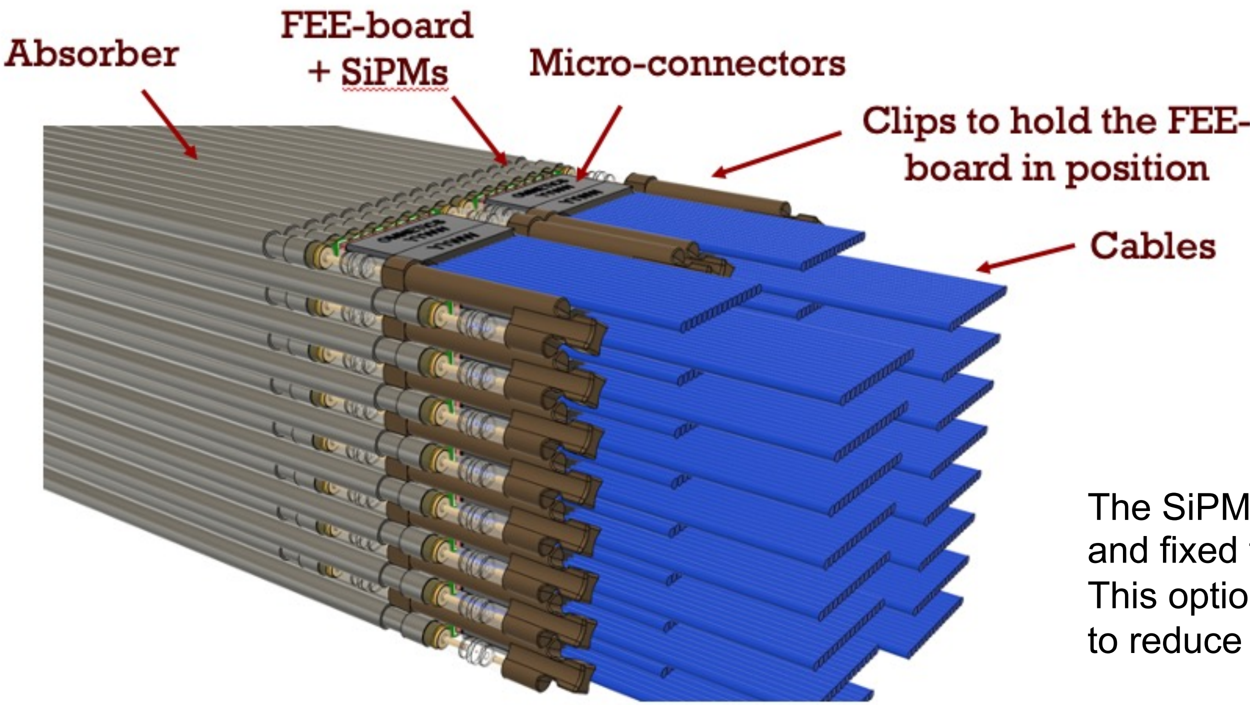
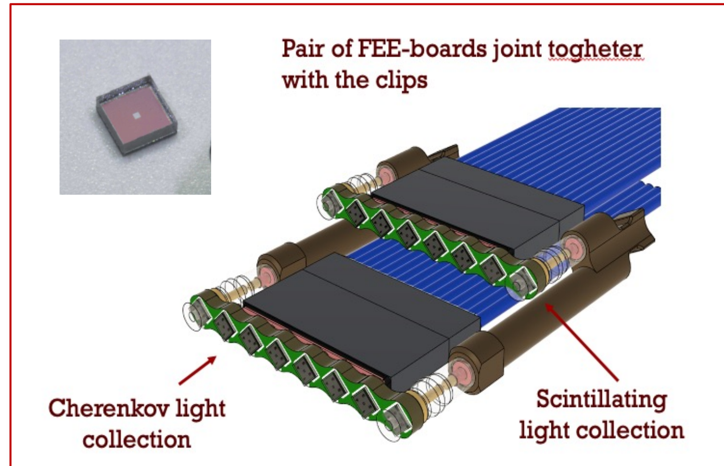
New module design

For the new design we are investigating a scalable option which would guarantee the possibility to build large and projective modules.

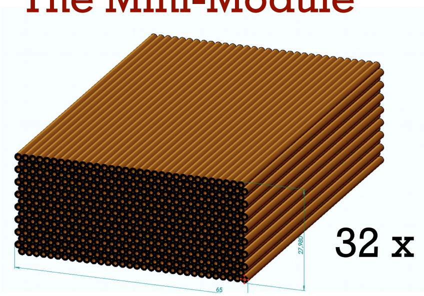




The SiPMs will be directly connected to the fibres and fixed to the absorber
This option will allow to group signals from 8 SiPMs to reduce the number of channels to be read out

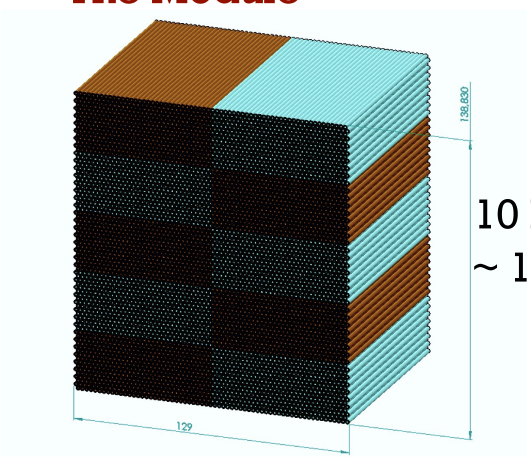
Prototype with hadronic containment

The Mini-Module



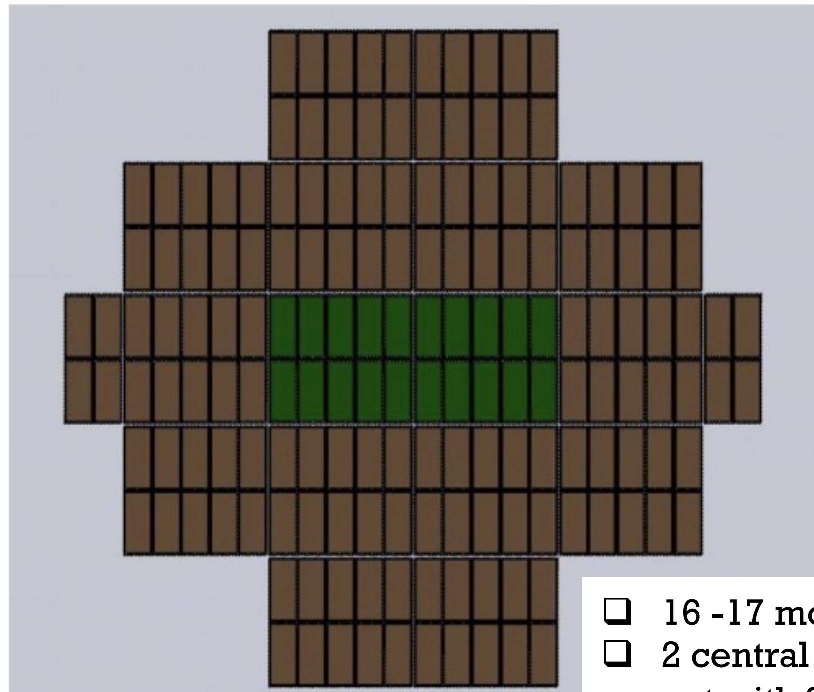
32 x 16 capillaries

The Module



10 Mini-modules
~ 13 x 13 x 200 cm^3

The hadronic prototype



- ❑ 16 -17 modules in total
- ❑ 2 central modules read out with SiPMs
- ❑ 14 -15 modules read out with PMTs
- ❑ ~ 65 x 65 x 200 cm^3

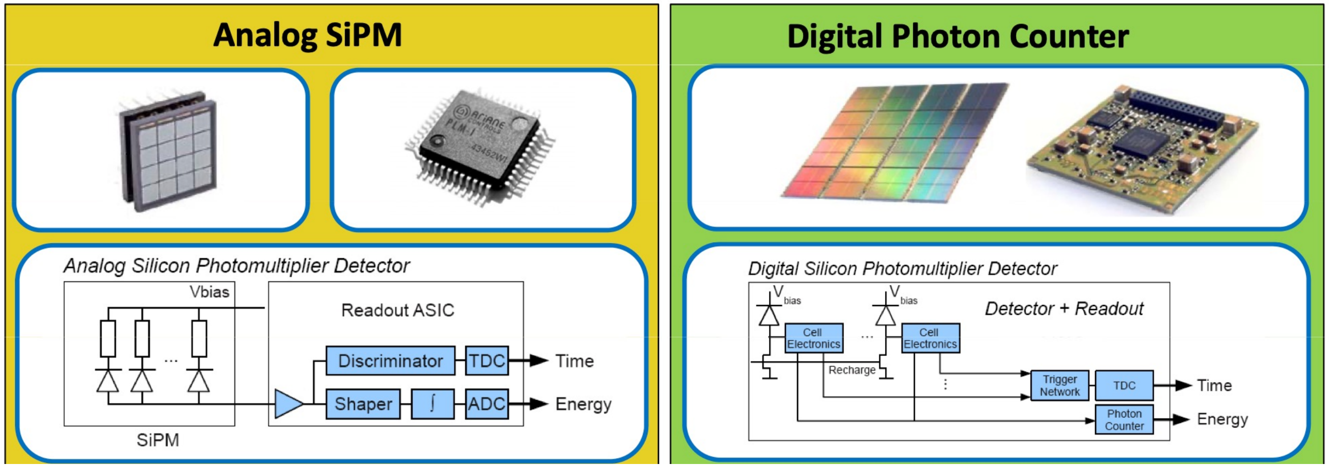
Readout scheme: an alternative approach

We are also considering to use a waveform sampler with feature extraction (i.e. the HDSoC designed by Nalu Scientific)

Parameter	Spec
Sampling Rate	1-2 GSa/s
ABW	> 600MHz
Depth	2k Sa
Trigger Buffer	~3 us*
Deadtime	0**
Channels	64
Supply/Range	2.5
ADC bits	12
Timing accuracy	80-120ps
Technology	250 nm CMOS
Power	TBD

- Ready to test any available demo board for preliminary tests and qualification

Do we really want to be analogue?



https://indico.cern.ch/event/192695/contributions/353376/attachments/277251/387863/TIPP2014_Amsterdam_lecture_Philips_Haemisch_pub.pdf

- The technology is not yet consolidated and the performance is not yet at the level of the SiPMs. Nevertheless they are rapidly improving
- This R&D could bring to a series of advantages:
  - Custom sensor design with reduced cost for mass production
  - Simplified readout system
  - Improved timing performance
  - The non-linearity could be corrected before merging the information from different sensors

Interesting review: NIM-A, 809 (2016), 31-52

Summary

- In the last two years we built the EM prototype exploiting an assembling solution that could be considered for mass production
- We are ready to assess the EM performance
  - The DESY test beam allowed to qualify the new readout system and to collect good data for specific Monte Carlo studies
  - The CERN test beam will allow us to qualify the prototype at higher energies (mid-august)
- The hadronic prototype is calling for new challenges (i.e. readout, integration …)
- The simulation is running in parallel to all these activities
  - It is tuned with the test beam results
  - A 4π geometry is also implemented
  - First tests using ML and Particle Flow algorithms are on-going

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

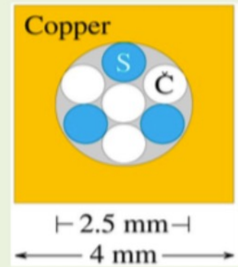
Θ and χ are independent of both energy and particle type

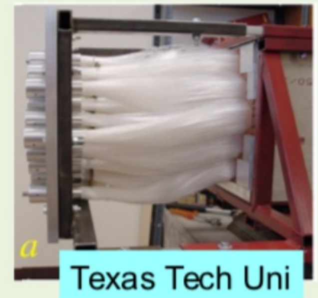
It is possible to evaluate $$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$ and $$E = \frac{S - \chi C}{1 - \chi}$$

Dual Readout calorimeters (PMT readout)

2003
DREAM

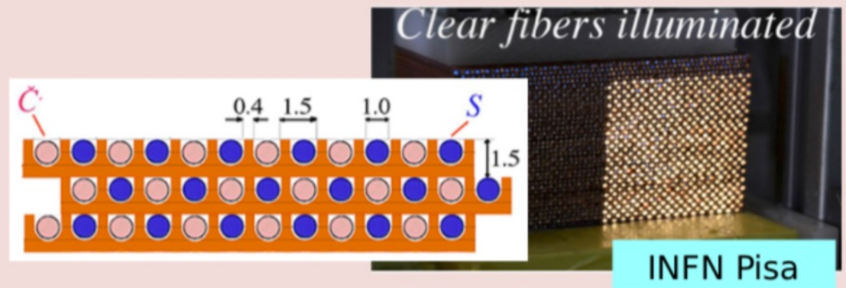
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%





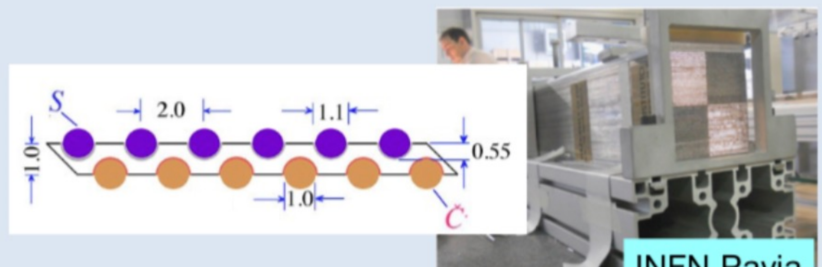
2012
RD52

Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}

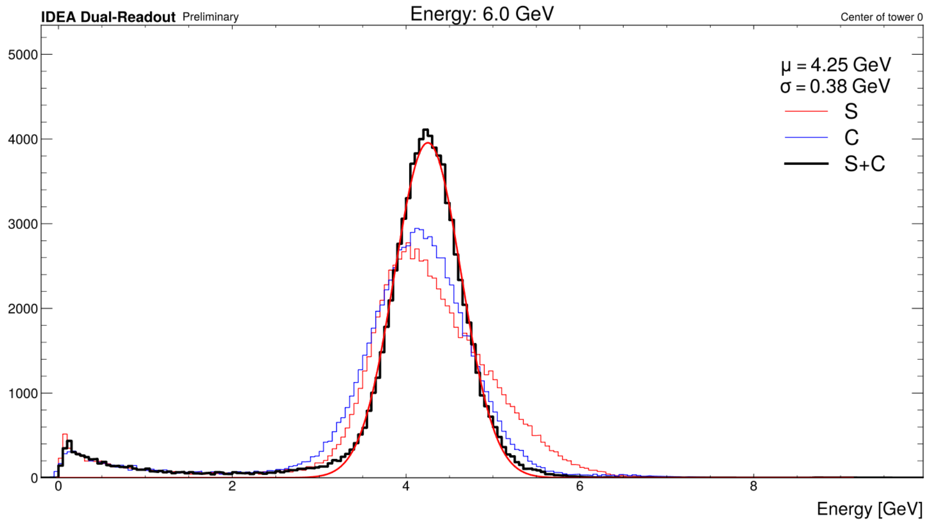


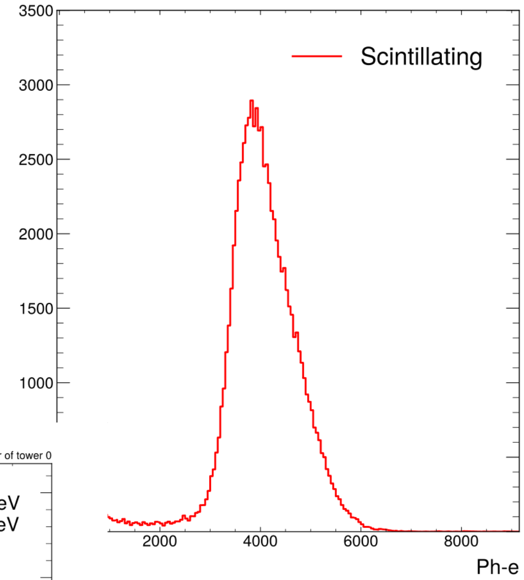
2012
RD52

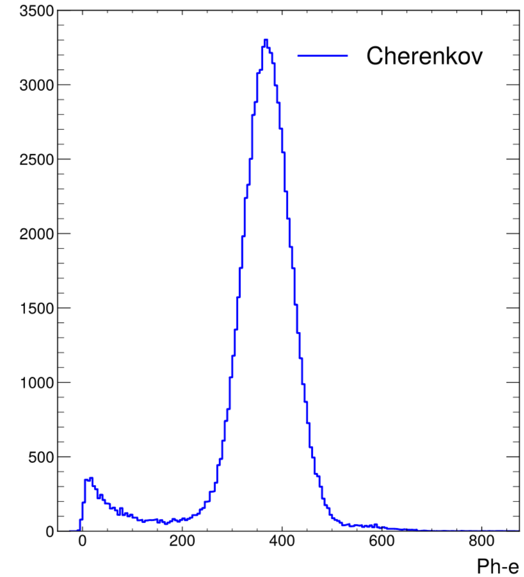
Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



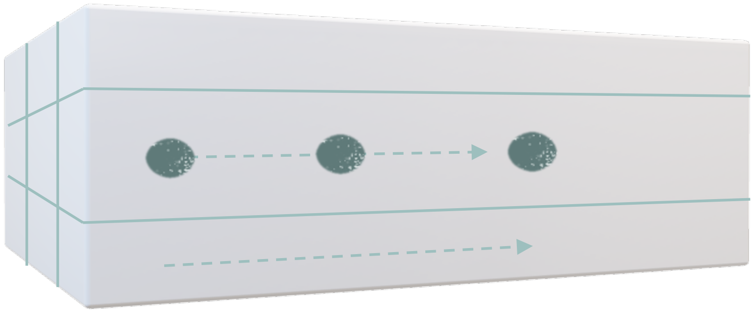
Spectra at 6 GeV





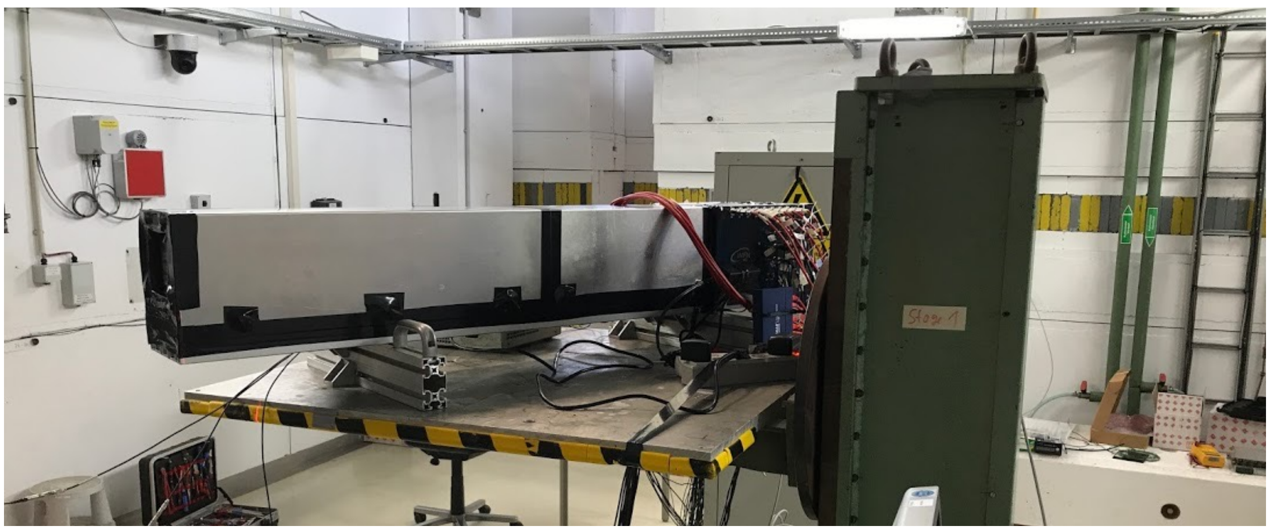


Measurements: longitudinal scan



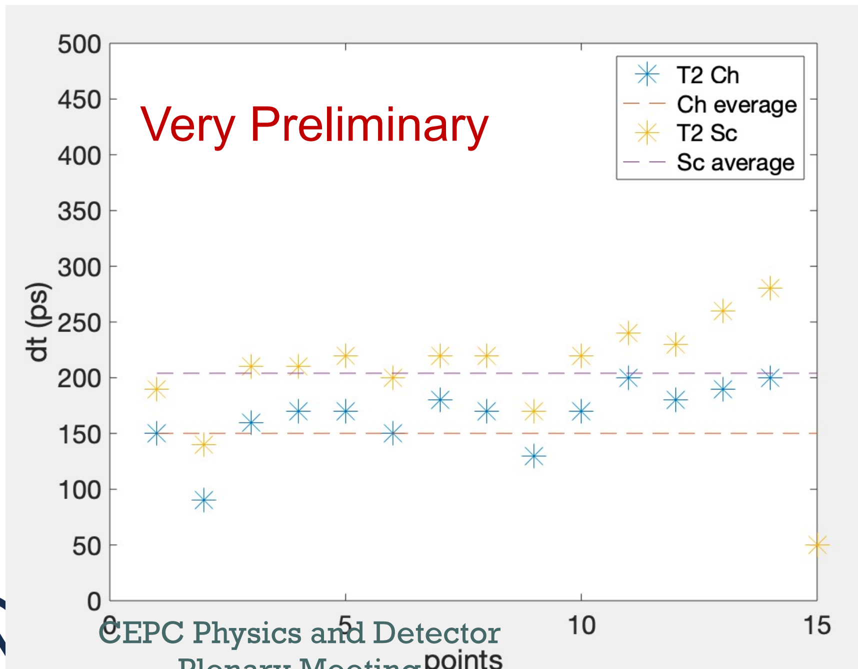
Scan of interest to exploit the timing information

Prototype tilted by 26°

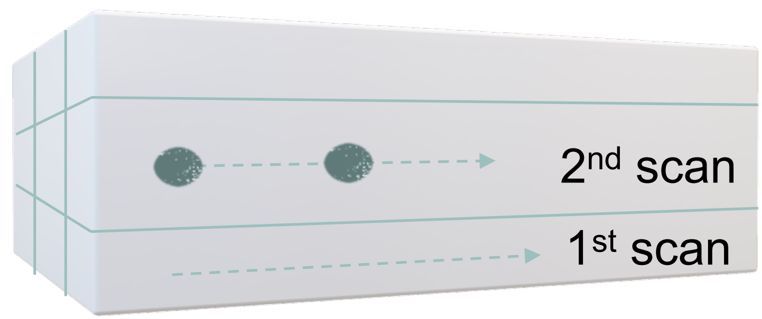


Timing studies

- Calorimeter tilted by 26°
- Longitudinal scan from 0 to 100 cm (6.8 cm step) with a 3 GeV beam
- 1st scan:
  - T = Trigger – PMT signal
  - dt = $T_i - T_{i+1}$ = PMT signal (i) - PMT signal (i+1)



Longitudinal scan



Average Sc = 204 ps
Average Ch = 150 ps