HiDRa – High resolution calorimeter for e^+e^-

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on behalf of the HiDRa collaboration

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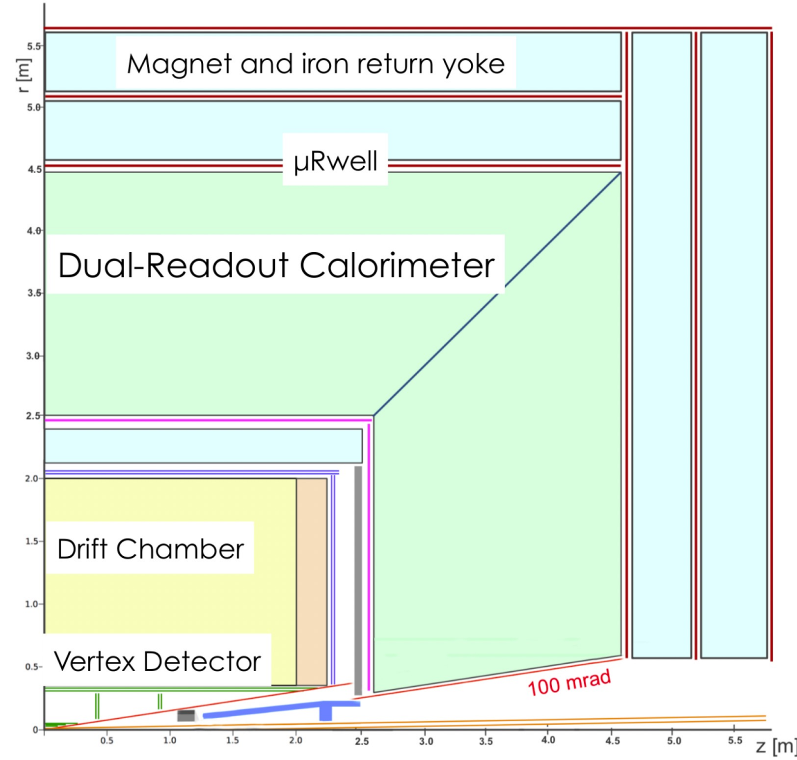
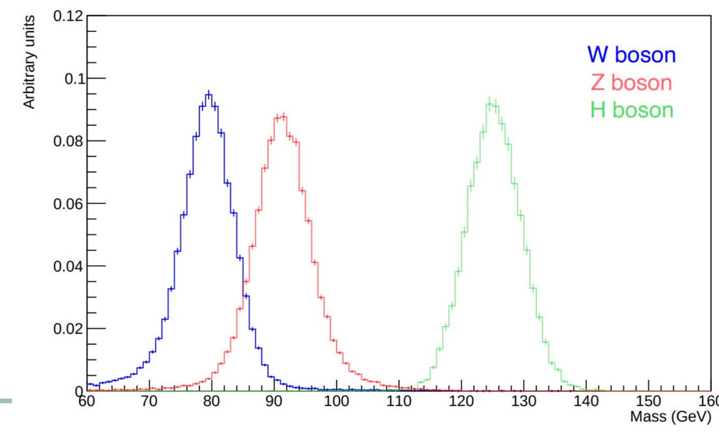
IDEA: baseline concept

- Beam pipe: 1.5 cm
- Highly transparent tracking
  - Si pixel vertex detector (monolithic technology)
  - Drift Chamber
  - Si wrappers (strips)
- Thin superconducting solenoid
  - 2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - µ-RWELL preshower
- Muon chambers
  - µ-RWELL in return yoke

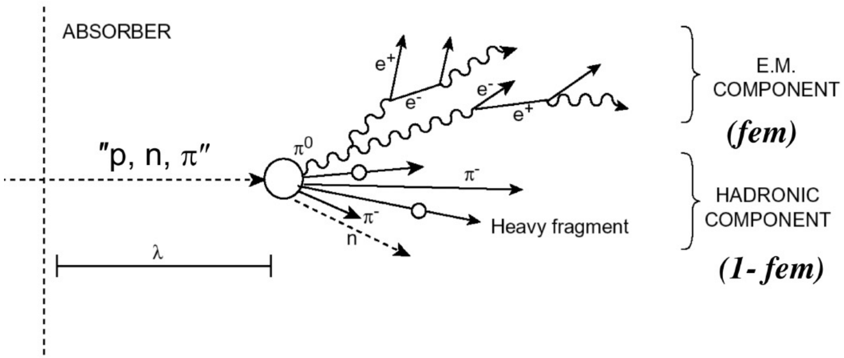


Target jet-jet mass resolution $\frac{\sigma}{E} = \frac{30\ \%}{\sqrt{E}}$



Eur. Phys. J. Special Topics 228, 261–623 (2019)
DOI: 10.1140/epjst/e2019-900045-4

Dual-Readout: the principle



- Non compensating calorimeter (h/e<1): has a different response to electromagnetic (fem) and hadronic component (1-fem)
- The fem is energy dependent: it induces a non-linear calorimetric response to hadrons and large fluctuations

- By reading two calorimetric signals (S and C) with different h/e, the fem can be measured event by event and the compensation can be achieved off-line

$$E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right)$$

$$E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right)$$

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

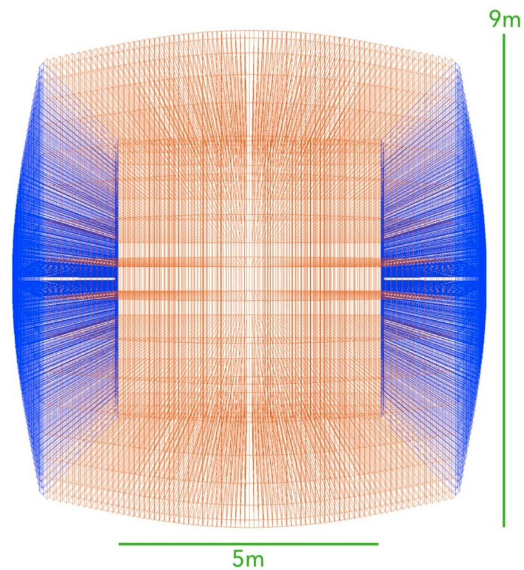
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

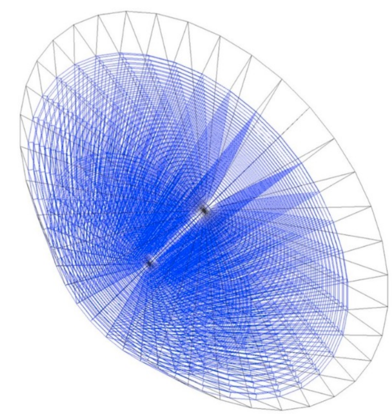
χ does not depend from energy and particle type. It is detector dependent: it can be measured on beam tests

S. Lee et al, RevModPhys, 90, 025002 (2018)
DOI: 10.1103/RevModPhys.90.025002

Dual-Readout in IDEA

- Almost 75 millions of 2 mm outer diameter stainless steel tubes
- In each tube there is a 1 mm diameter fibre connected to a SiPM
- Signals from 8-SiPMs grouped to reduce the number of channels to be read out
- Some TBs performed at CERN to:
  - define equalisation strategy
  - fine-tune the G4 simulation
  - assess detector performance
  - better constrain hardware specifications



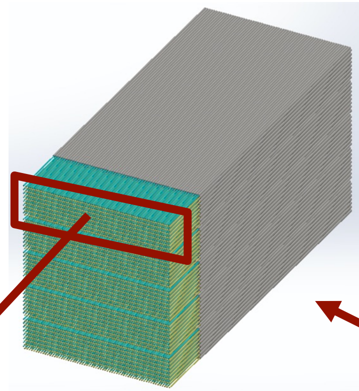


HiDRa aims to identify a scalable and cost-effective solution to build a dual-readout calorimeter for IDEA.

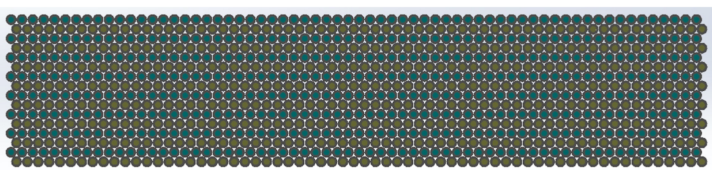
HiDRa: High-Resolution Highly Granular Dual-Readout Demonstrator

The Module

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



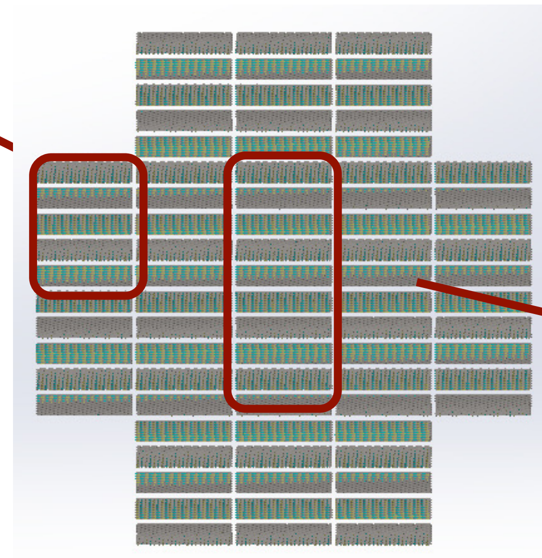
The Mini-Module



64 x 16 stainless steel capillaries, 2 mm outer diameter, equipped with scintillating and clear fibres (alternated in rows) to apply the dual-readout method

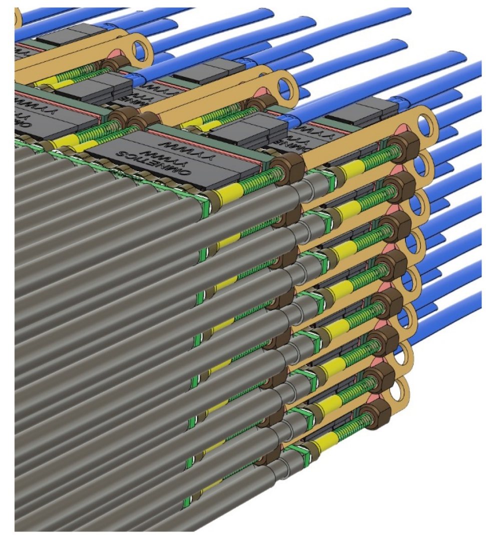
The HiDRa prototype

Designed to be scalable and large enough to measure the hadronic performances



The highly granular modules

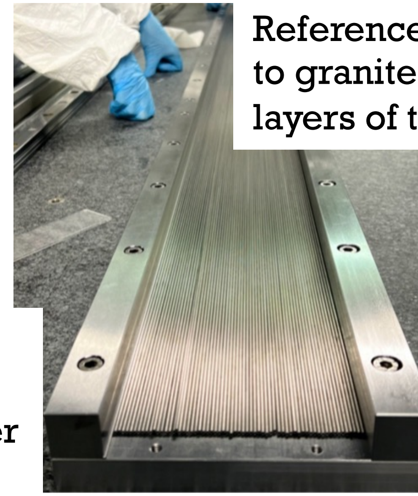
Two central modules read out with 10k SiPMs (one per fibre)



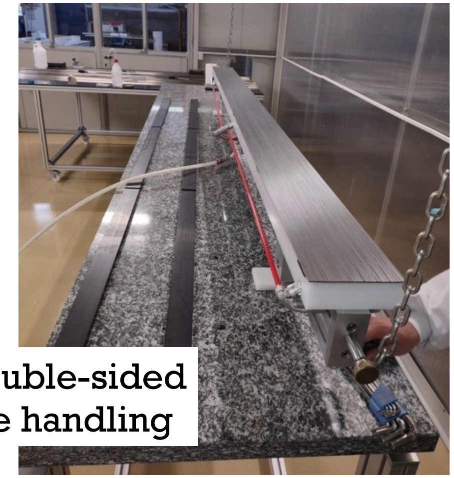
Challenging integration requiring a precise assembly procedure and the use of compact components (i.e. SiPMs, services and mechanical) to fit in the back of the calorimeter

Construction technique

High quality tube selection:
Accurate measurement of thickness, straightness, length, and internal diameter (pass/fail test with fibre insertion)

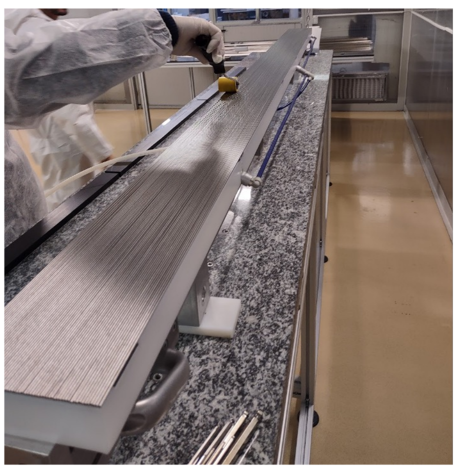


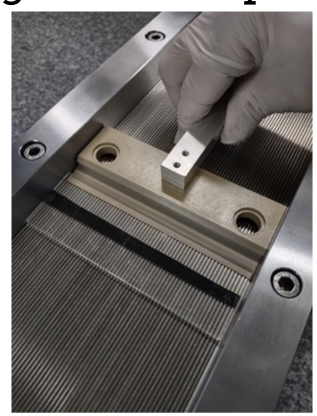
Reference structure anchored to granite table for stacking layers of tubes



Vacuum + double-sided tape for tube handling

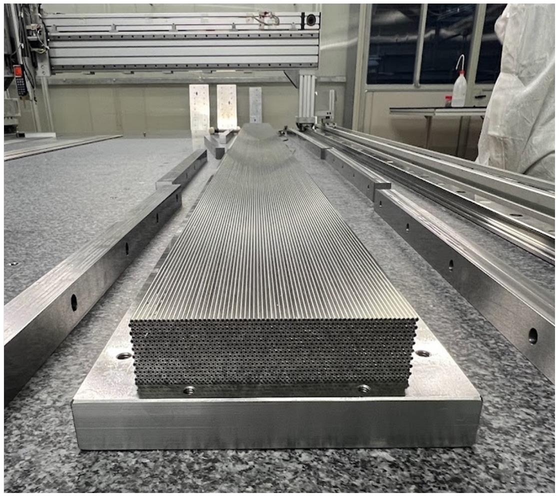
Glue dispensing and tube alignment and positioning

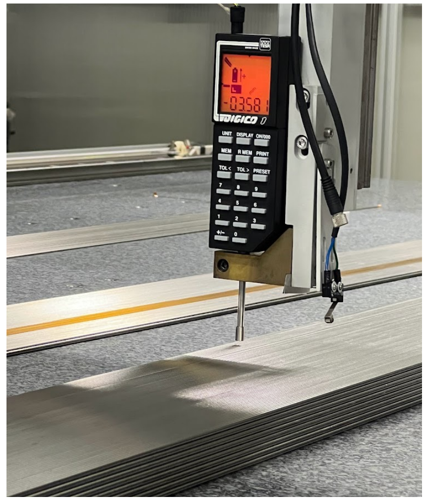




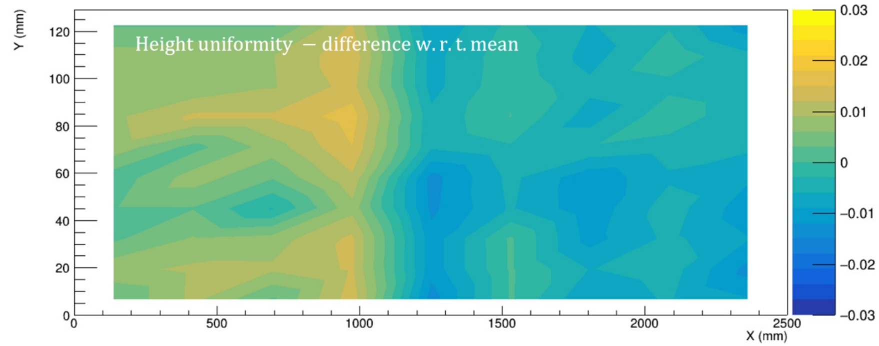
Construction technique and mechanical precision

Semi-automatic system for planarity measurement: 90 measurements per mini-module

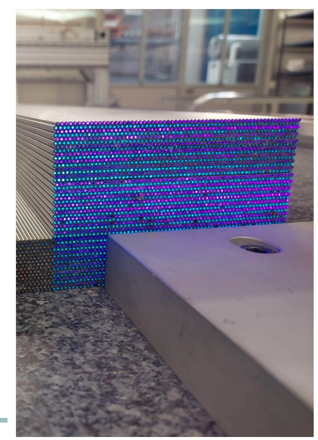




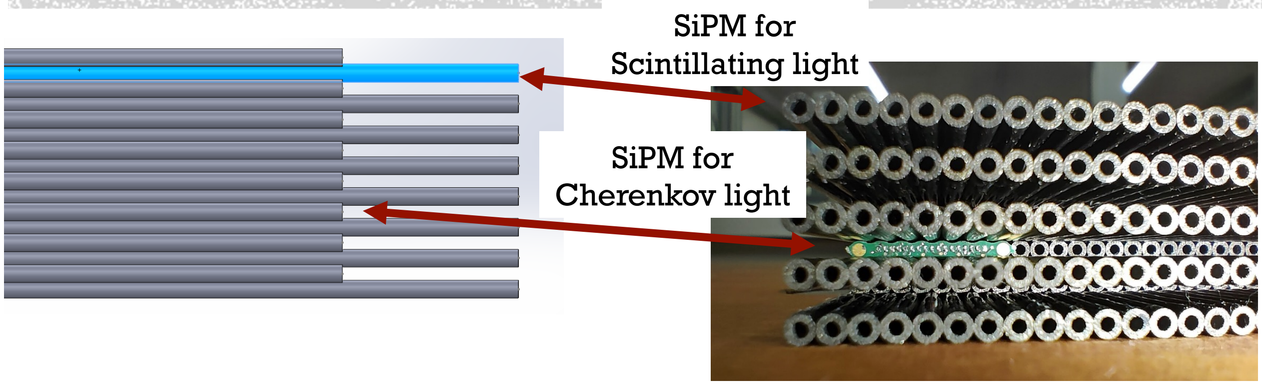
O (10 μm) precision on the mini-module height (calor2024)



Production started in November 2023: 36/80 mini-modules have been assembled
First test beam with the available modules planned in August 2024 (PMT readout only)

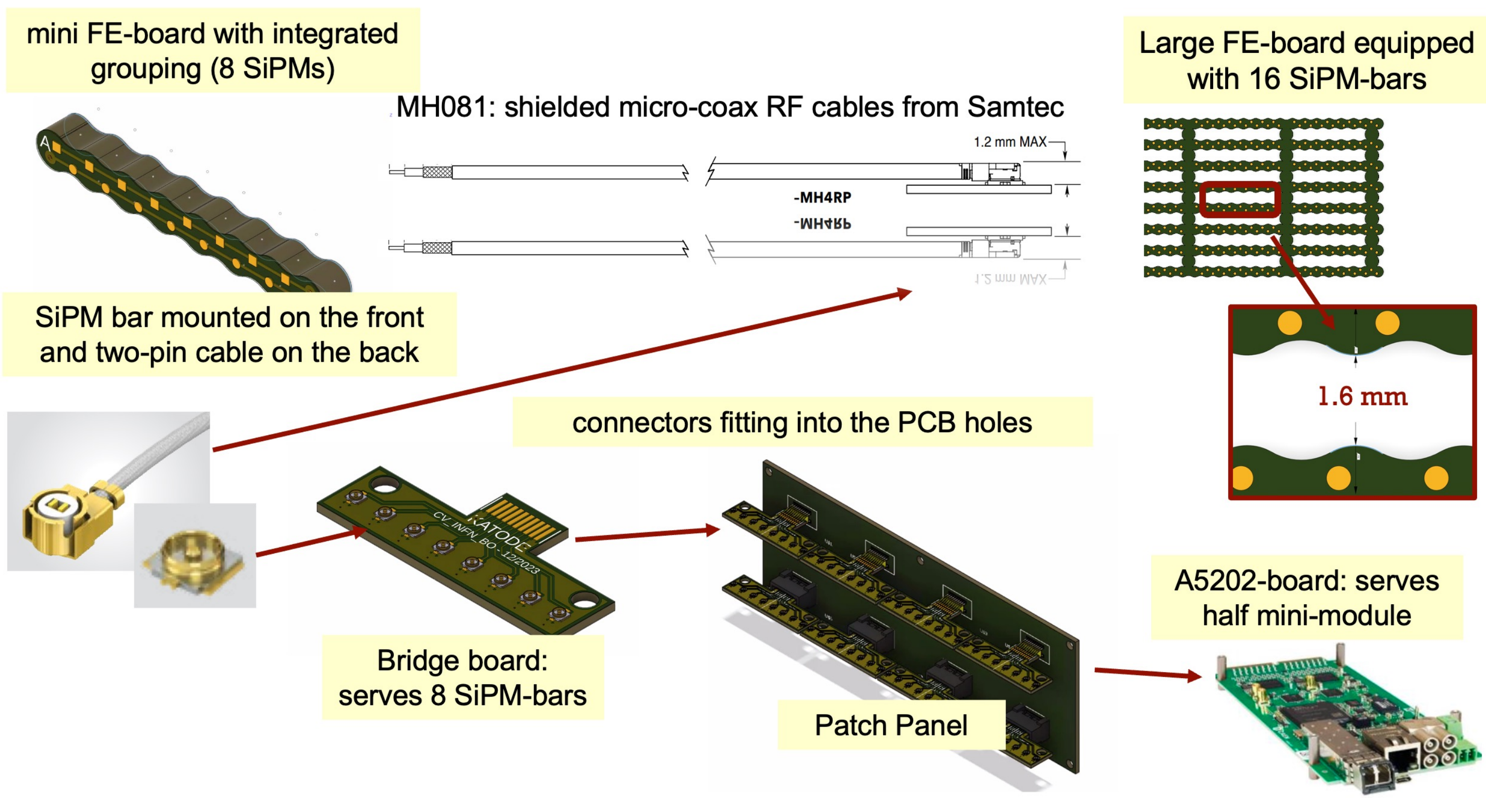


Integration of highly granular modules



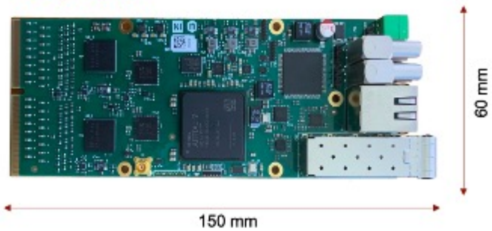
High-precision mechanical assembly is required to align each SiPM to the fibres inserted in the tubes

Pcb designed to follow the shape of the tubes and self-align the SiPMs to the fibres



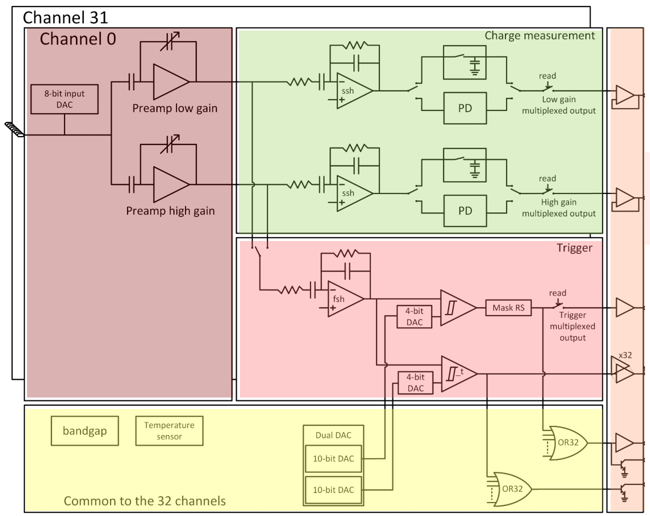
Integration and signal integrity

FERS: A5202

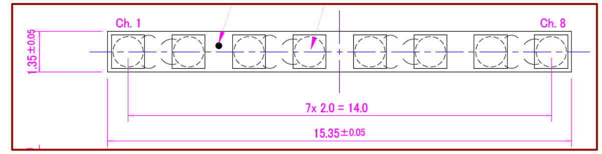


- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

Citiroc1A – block-schema

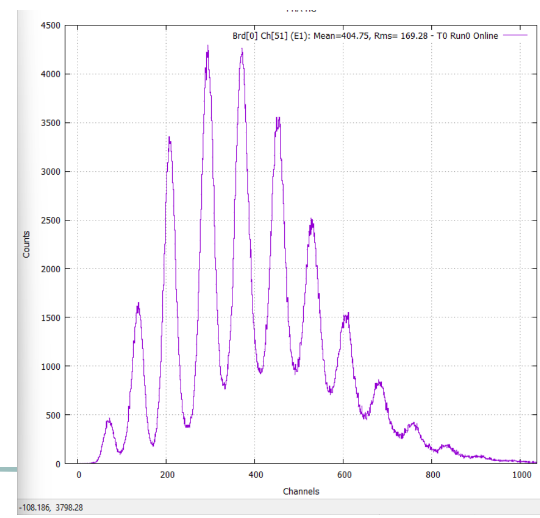


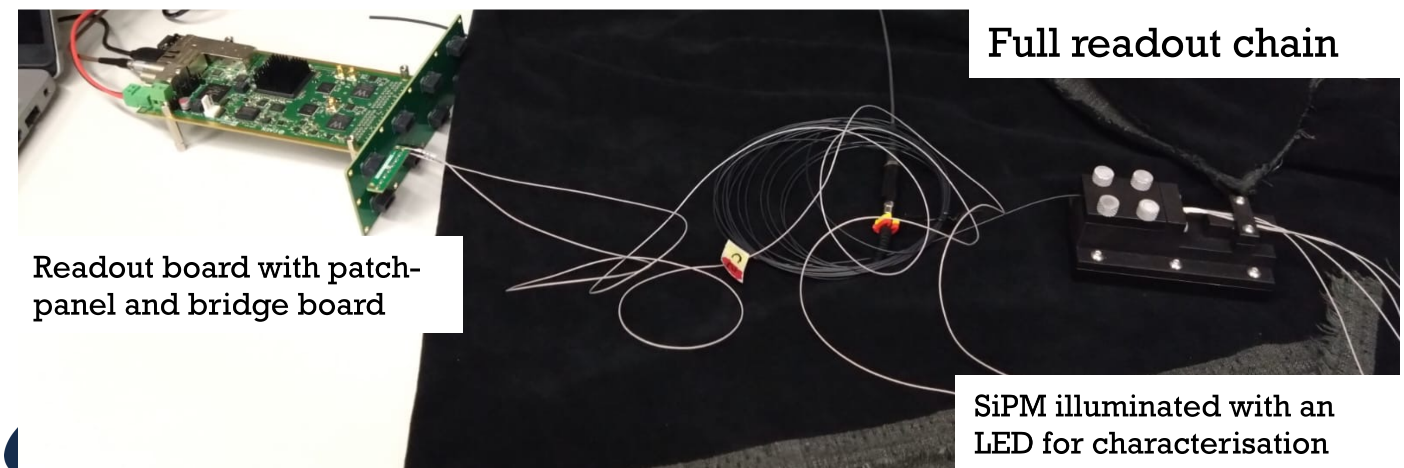
Customised package with 8 SiPMs, 2 mm spaced (S16676-15 / S16676-10)



SiPM with 10 μm pitch for scintillating and 15 μm putch for Cherenkov light (better PDE)

15 μm pitch SiPM operated at $\approx$ + 6 V Over-Voltage



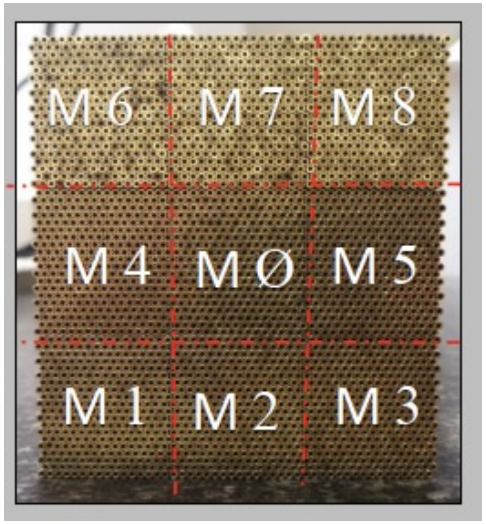


Full readout chain

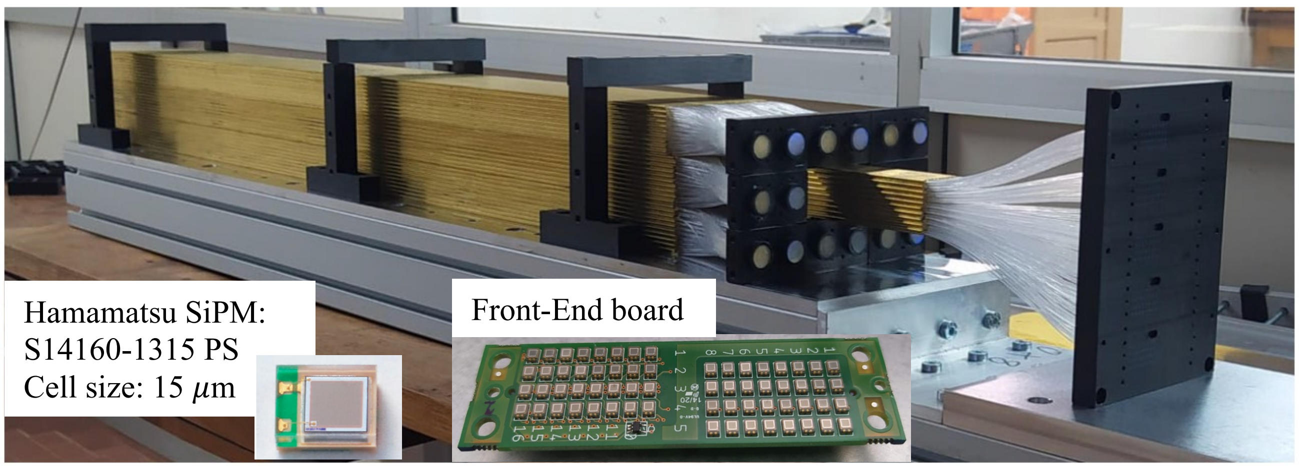
Readout board with patch-panel and bridge board

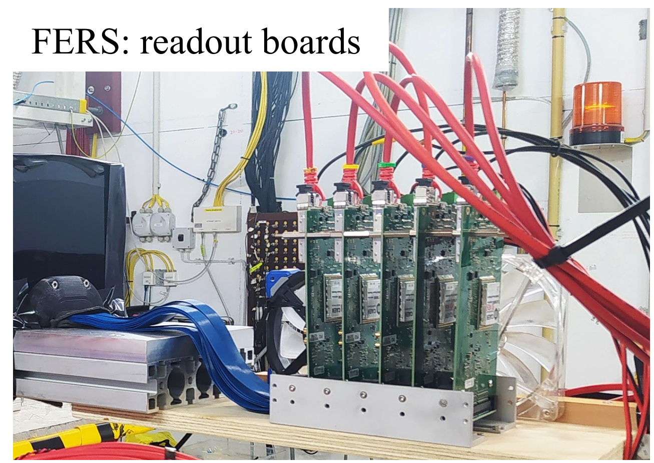
SiPM illuminated with an LED for characterisation

The EM-size prototype tested on beam



- EM-size prototype (10x10x100 cm^3)
  - 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
  - Brass capillaries: 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)

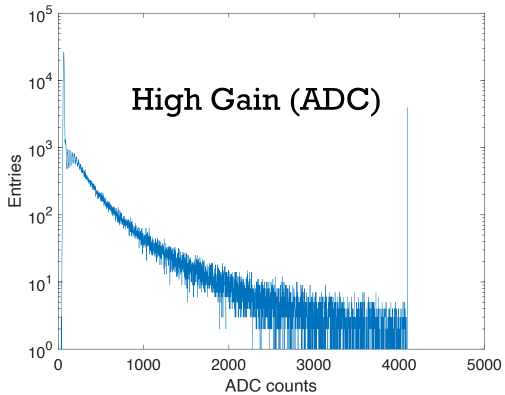


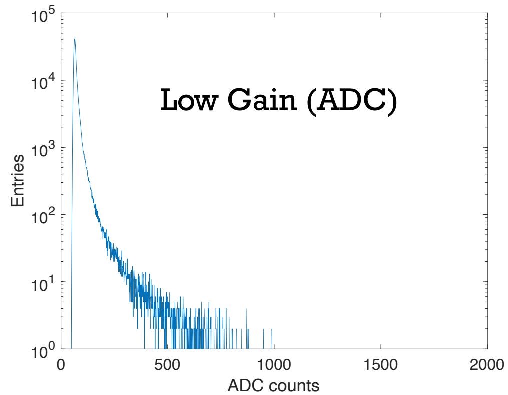


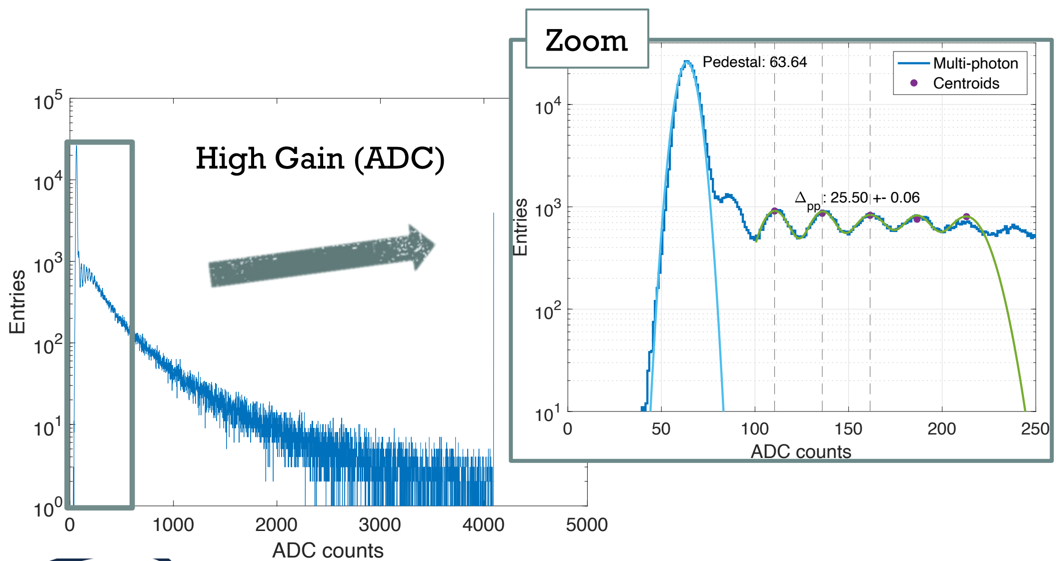
[Details on TB results and simulation in Andreas' talk]

The importance of SiPM equalisation

We need single photons resolution and large dynamic range







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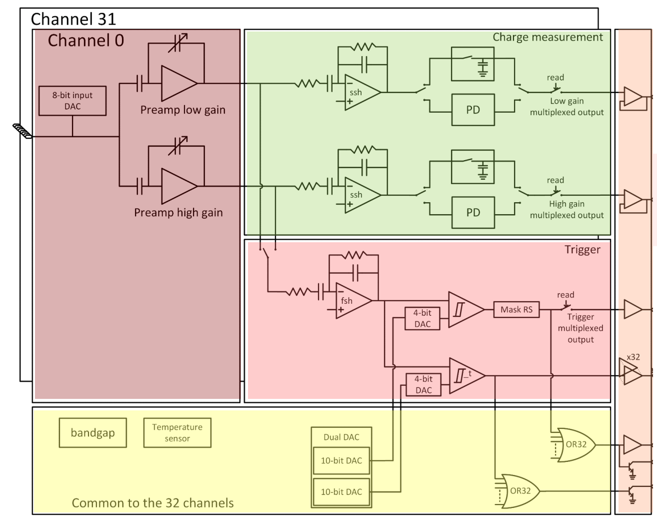

HG equalisation

Dpp: used to convert ADC in Ph-e (monitored in all runs and for all SiPMs)

Pedestal width: used to measure the noise contribution to the energy resolution

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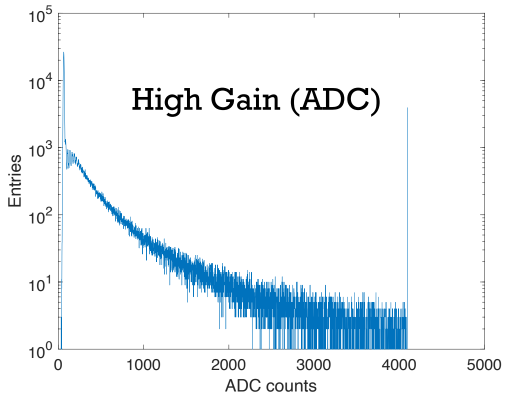

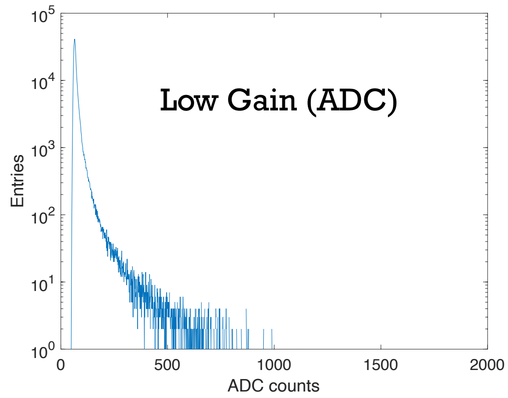

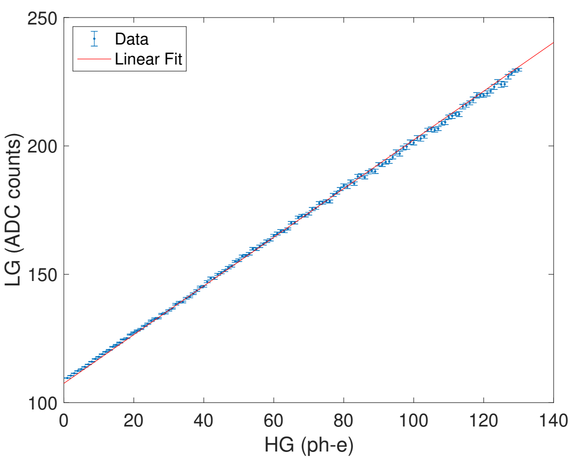

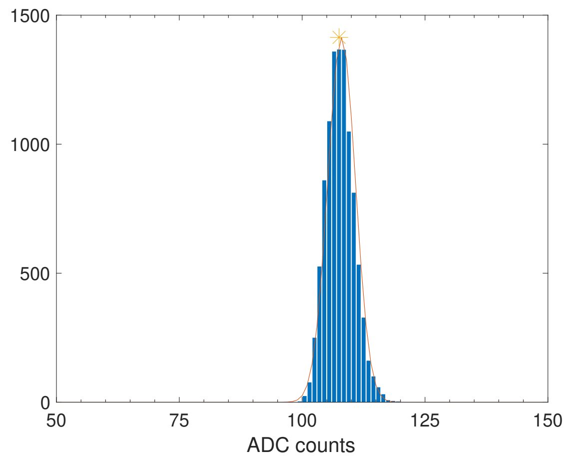

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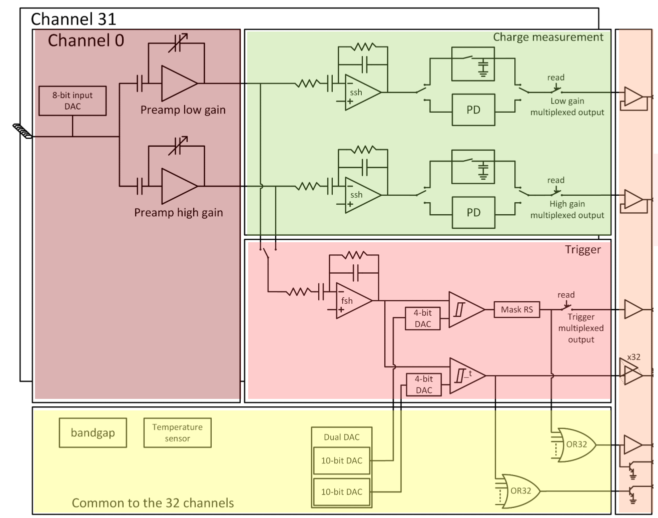
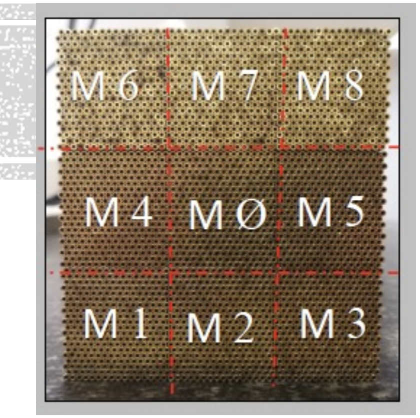


LG equalisation

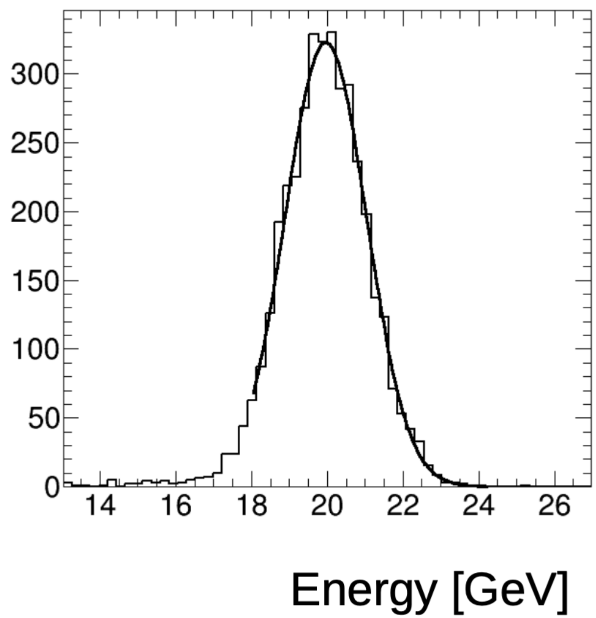
Slope of the correlation plot provides the ADC to Ph-e conversion factor

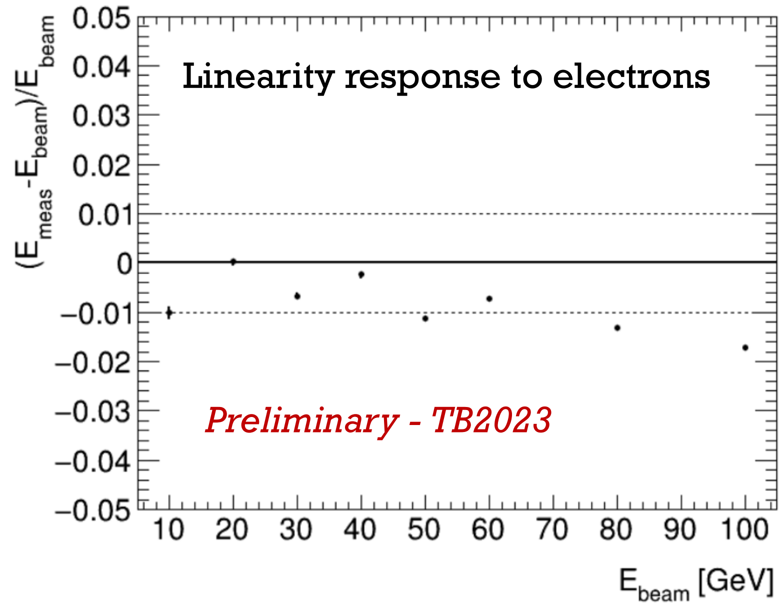
Pedestal width measured selecting noise events in the HG

Energy calibration and linearity



- The SiPM signals are summed after ph-e equalisation
- The 20 GeV beam is steered at the centre of M0 (read out with SiPM) to calibrate in energy
- The same is done for the other modules read out with PMTs





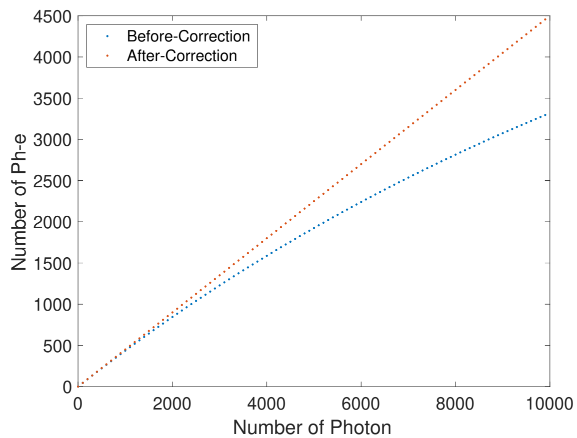
Pretty good linearity but never forget that SiPMs are digital sensors: the same cell cannot be fired twice

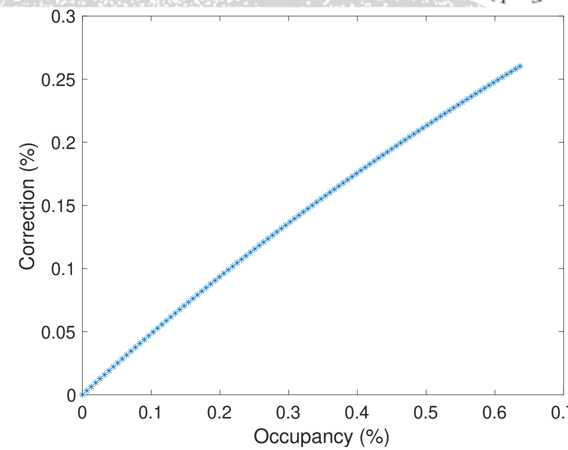
More on SiPM linearity

Parameter	S14160-1315PS
Effective photosensitive area (mm2)	1.3 x 1.3
Pixel pitch (mu)	15
Number of pixels	7284

$$N_{\text{fired}} = N_{\text{cells}} \times \left[1 - \exp\left[-\frac{N_{\text{photons}} \times \text{PDE}}{N_{\text{cells}}}\right]\right]$$

With 700 Ph-e (10% occupancy) in a single fibre -> 5% correction to the signal





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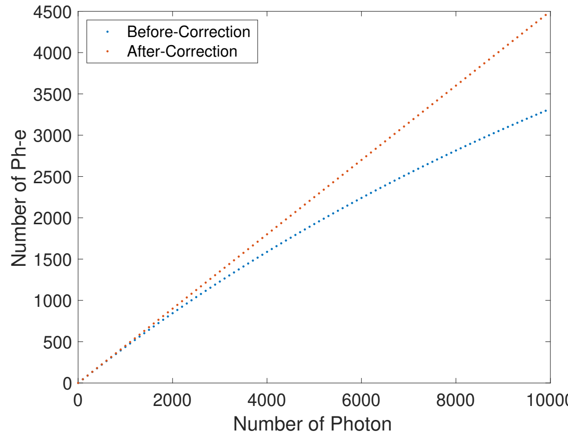
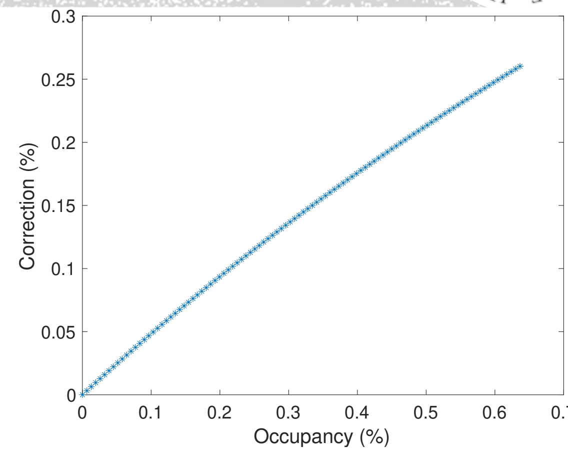
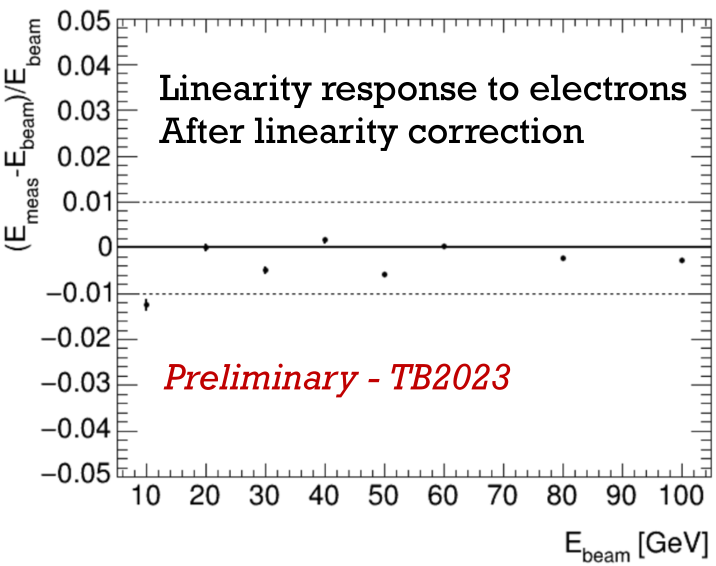


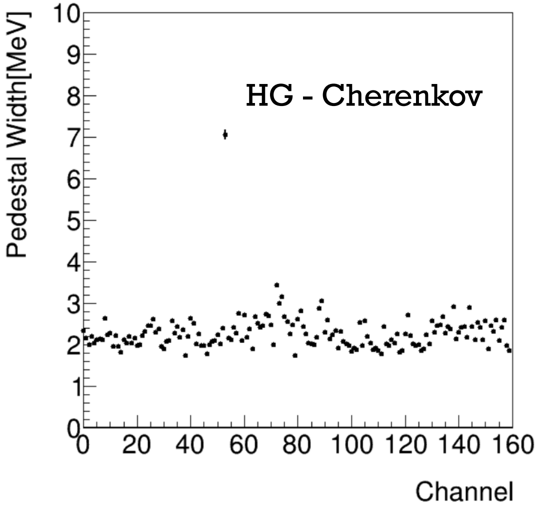


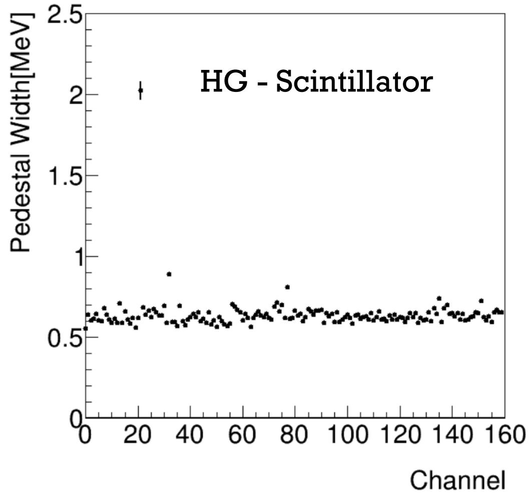


High granularity readout in DR needs competing requirements:

- Large micro-cells
  - Higher efficiency
  - Better ph-e resolution
- Small micro-cells
  - Larger dynamic-range and better linearity
- A readout system fulfilling the wide dynamics of the sensor with a good multiphoton spectrum

SiPM noise contribution to energy resolution (HG)





Expected noise for Cherenkov signals:
$2\sqrt{160} \approx 25\ MeV$
(assuming uncorrelated noise)

Expected noise for Scintillating signals:
$0.6\sqrt{160} \approx 8\ MeV$
(assuming uncorrelated noise)

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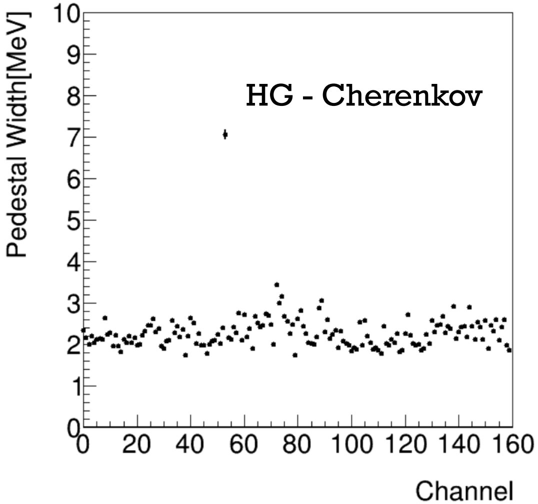

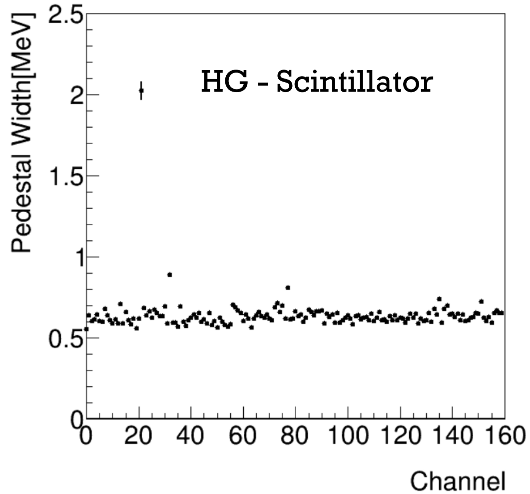

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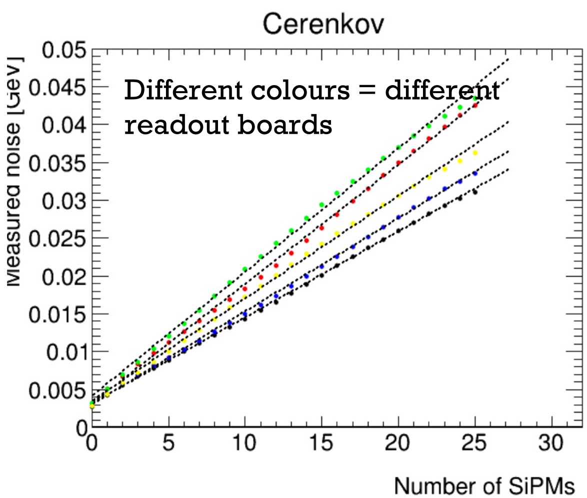
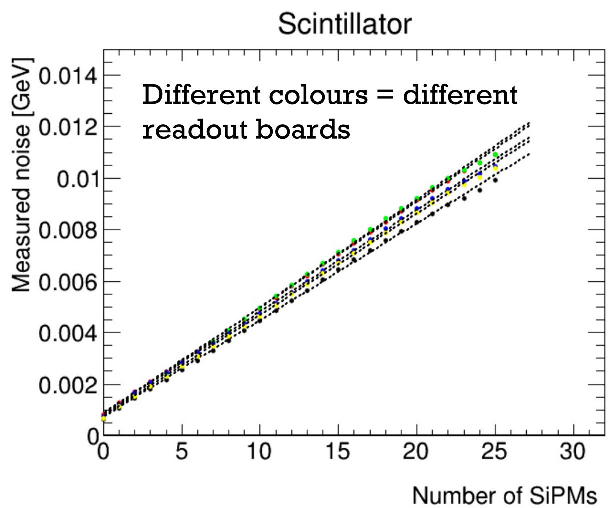


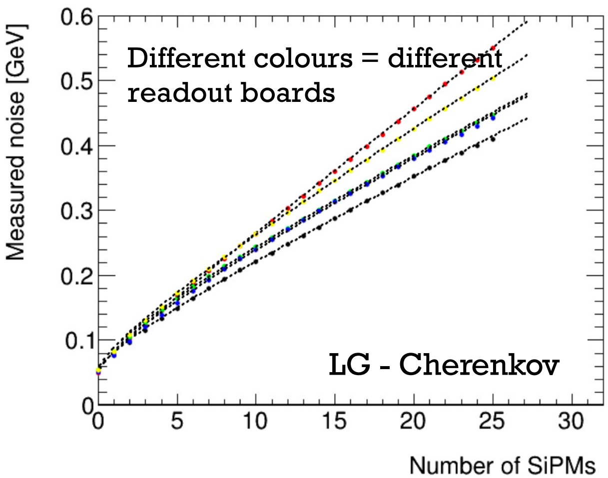


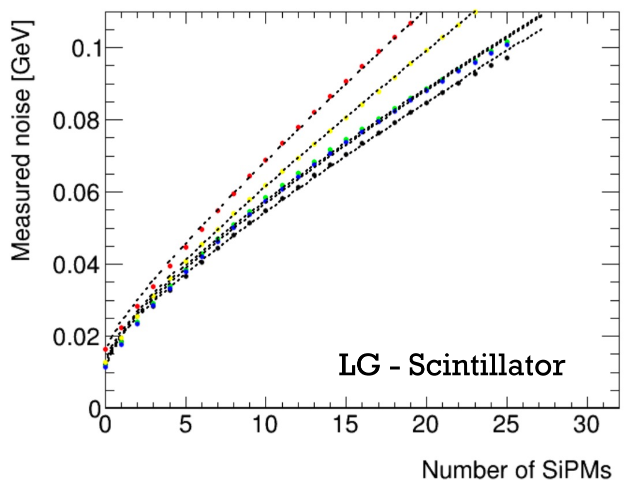
Measured noise

Approximately linear dependence inside each board. Summing in quadrature contribution from different boards we get:

Results for 160 channels:
Cer~90 MeV, Sci~30 MeV

SiPM noise contribution to energy resolution (LG)





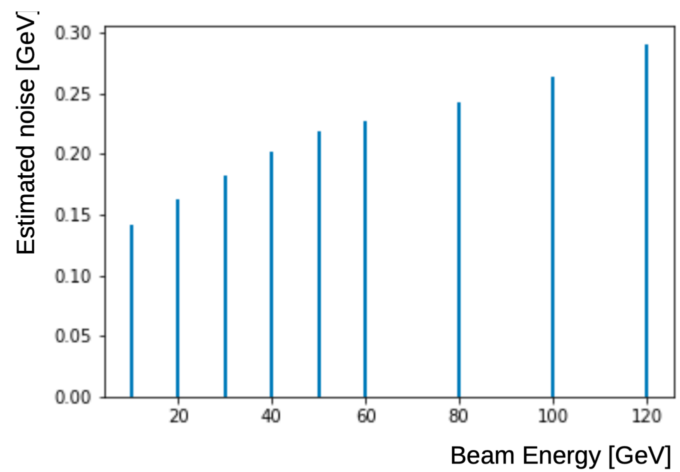
LG noise parametrisation:

$$a + b * \sqrt{N_{SiPM}} + c * N_{SiPM}$$

The final SiPM noise contribution is estimated by considering the average number of sensors operating in the HG and LG regime

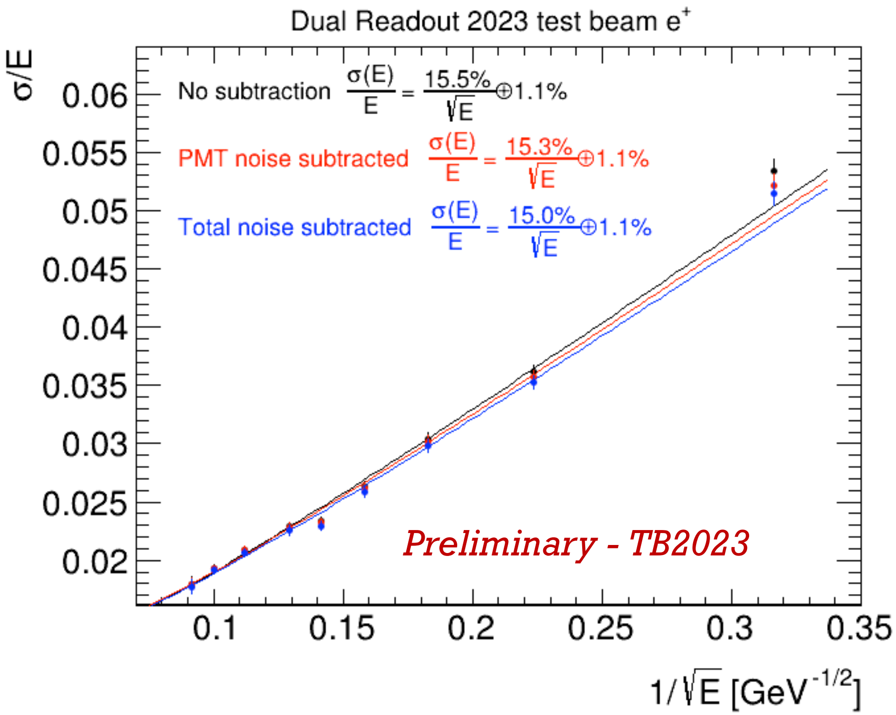
Noise increases with energy because the ratio of SiPMs in the LG regime changes with the beam energy

Total noise considering the contribution from PMTs (≈ 120 MeV) and SiPMs



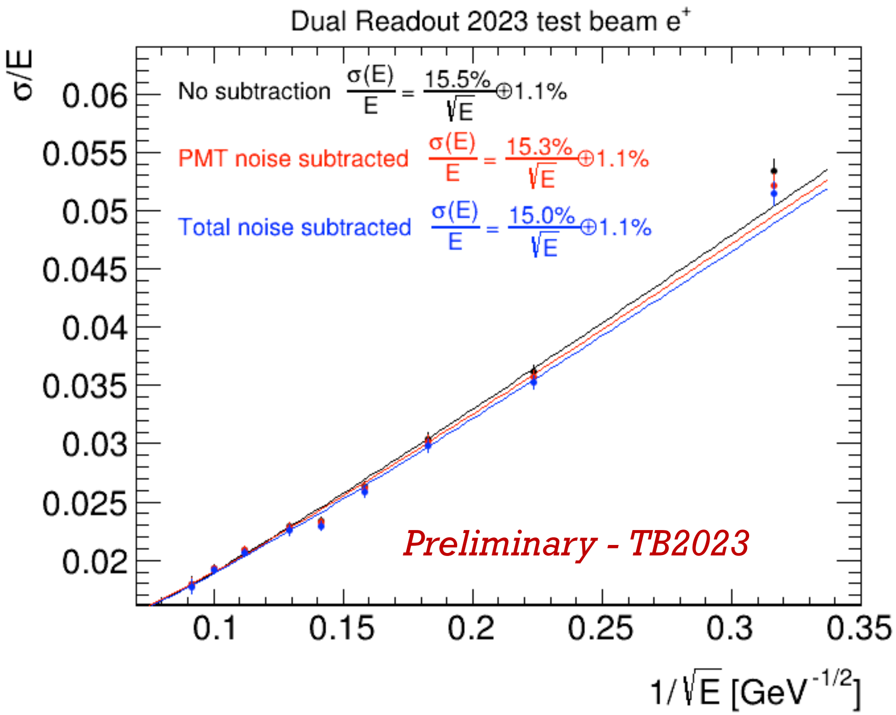
Final results

Noise contribution to the energy resolution

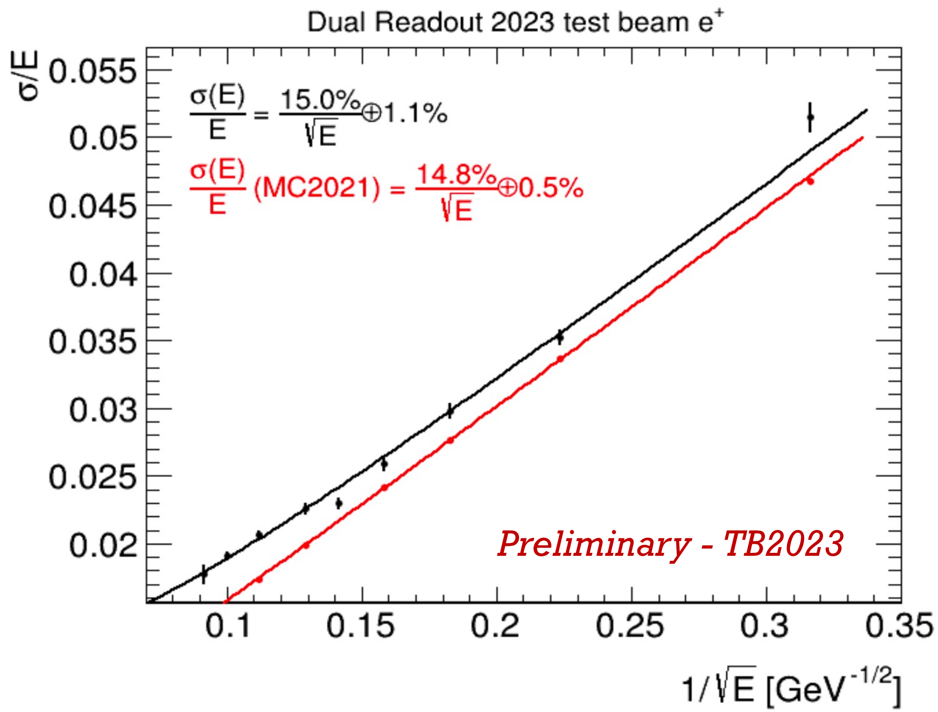


Final results

Noise contribution to the energy resolution



Results well in agreement with G4 simulation

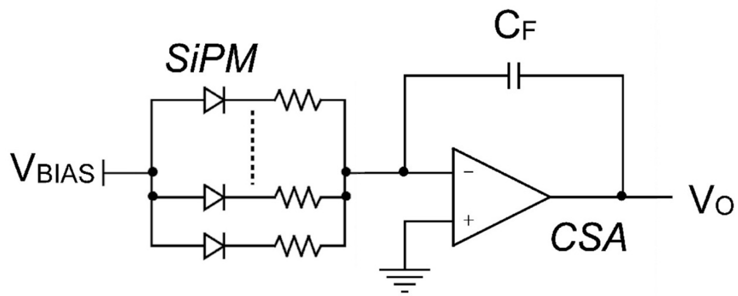


The ≈ 1% difference in quadrature wrt G4 is consistent with the beam energy spread

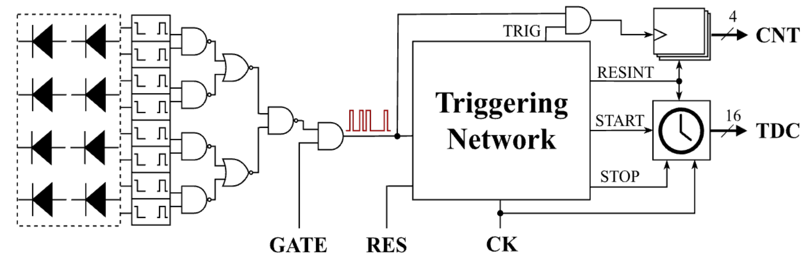
[Additional results on TB and simulation in Andreas' talk]

Are dSiPMs a valid option to be considered?

SiPMs: analogue signal proportional to number of fired cells, readout performed externally



Digital (CMOS) SiPMs: readout functionalities implemented in the sensor substrate (e.g. binary counters, SPAD masking, TDCs …)



M. Perenzoni et al. 2017 – IEEE JSSC

- SPAD array in CMOS technologies may offer the following benefits:
  - front-end can be optimised to preserve signal integrity (especially useful for timing)
  - Easier linearisation and calibration – direct digital output vs digital/analog (including noise + non uniformity)/digital conversion
  - the monolithic structure simplifies the assembly for large area detectors
  - Costs can be kept relatively low if the design is based on standard process

Summary

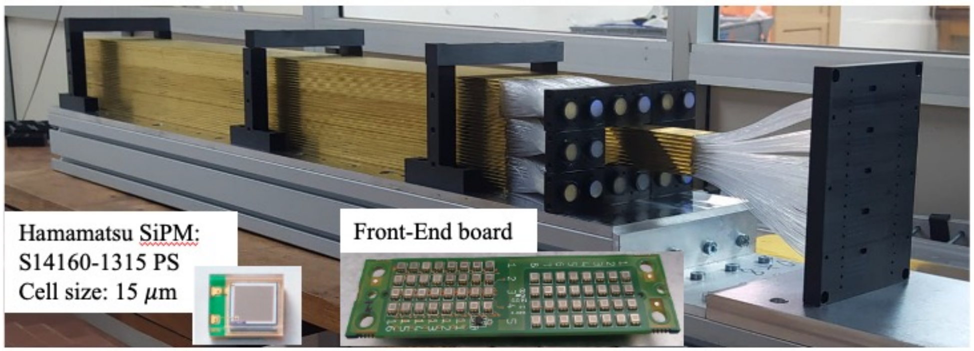
- We are building a scalable prototype with hadronic containment
  - To investigate an assembly procedure that could fit the 4π geometry requirements
  - To handle a large number of SiPMs (10k sensors)
  - To assess the hadronic performance
- The e-m size prototype with a highly granular core equipped with SiPMs has been qualified on beam
  - Good understanding of the SiPM calibration strategy
  - Useful data to fine-tune and validate the GEANT4 simulation
- Not covered in the talk but something we are looking for are d-SiPMs
  - Cost-effective solution once developed (CMOS technology)
  - Equalisation not-needed and straightforward occupancy correction
  - Prone to good time tagging

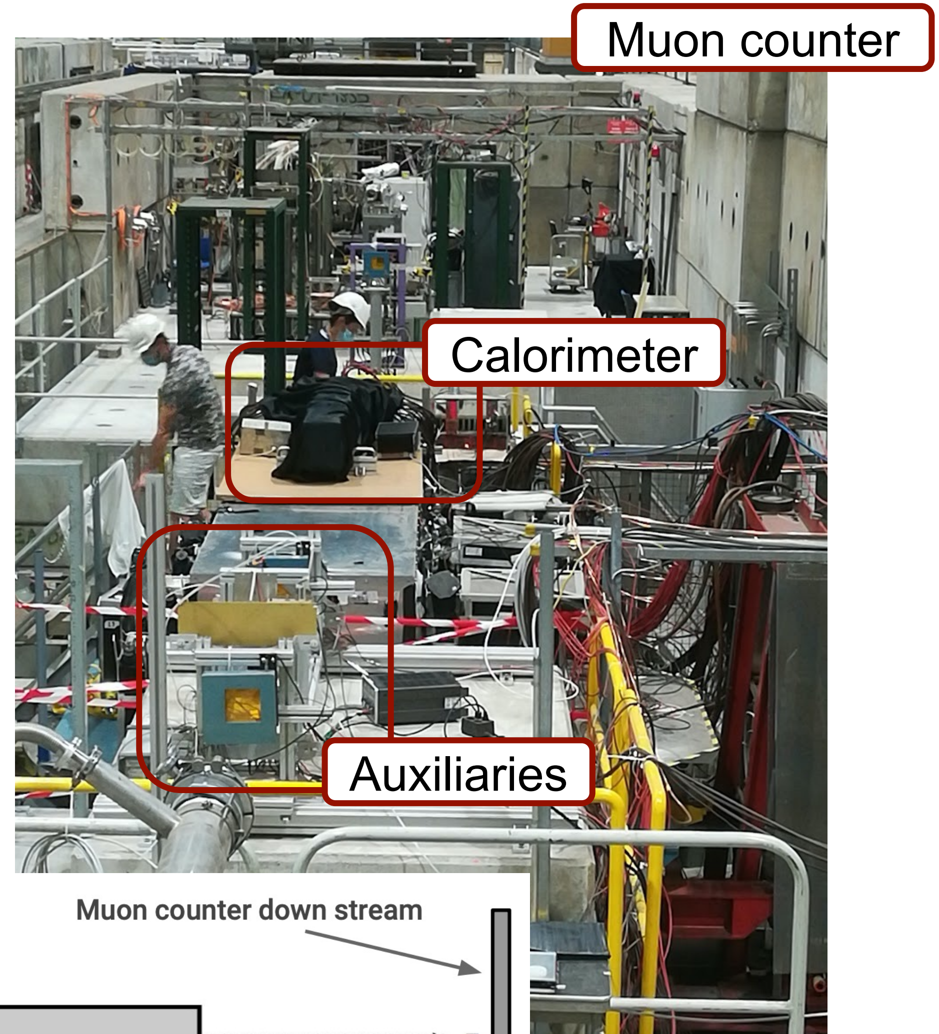
Backup

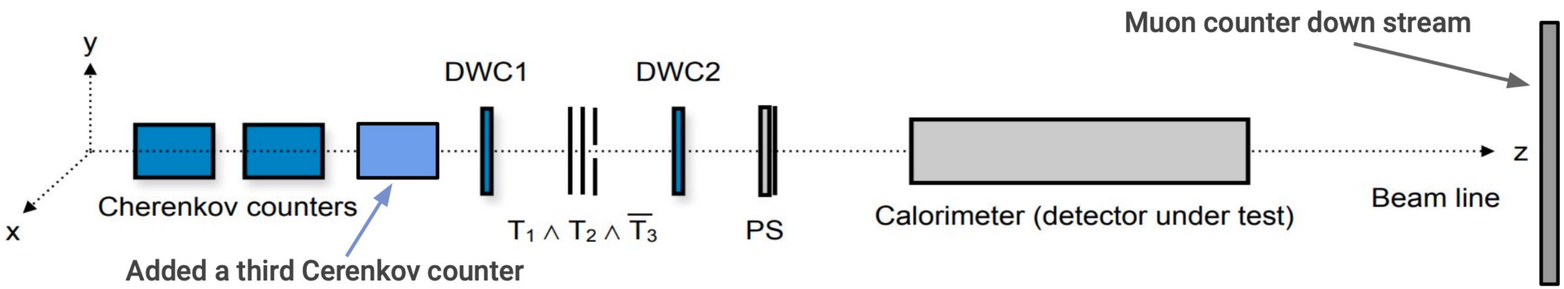
Test beam performed in 2021 and 2023

CERN-SPS H8 beam line

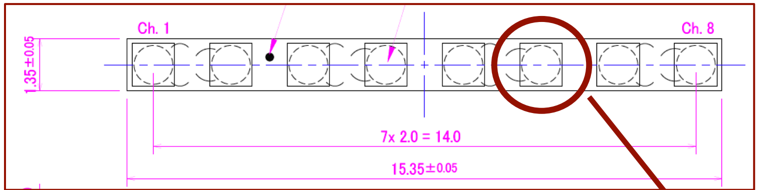
- e^+ beam in the energy range of 10-100 GeV
- Energy and position scan
- μ in non-monochromatic beams

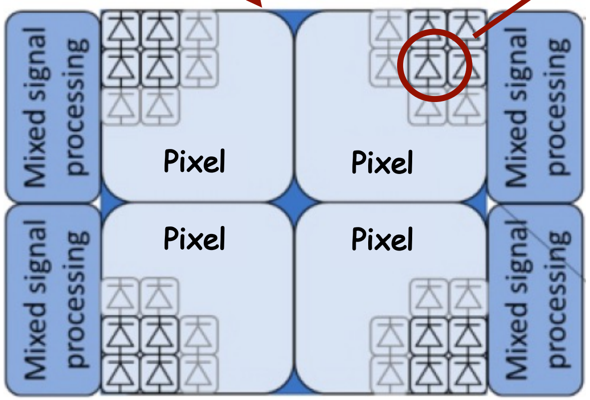




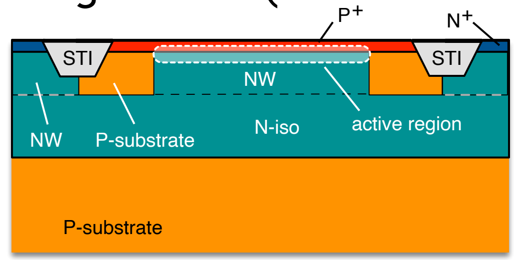


A possible floorplan and readout architecture





Single SPAD (110 nm CMOS technology)



- p+/n-well junction, isolated from substrate by deep n-well
- Readout electronics integrated in a monolithic structure with the sensor

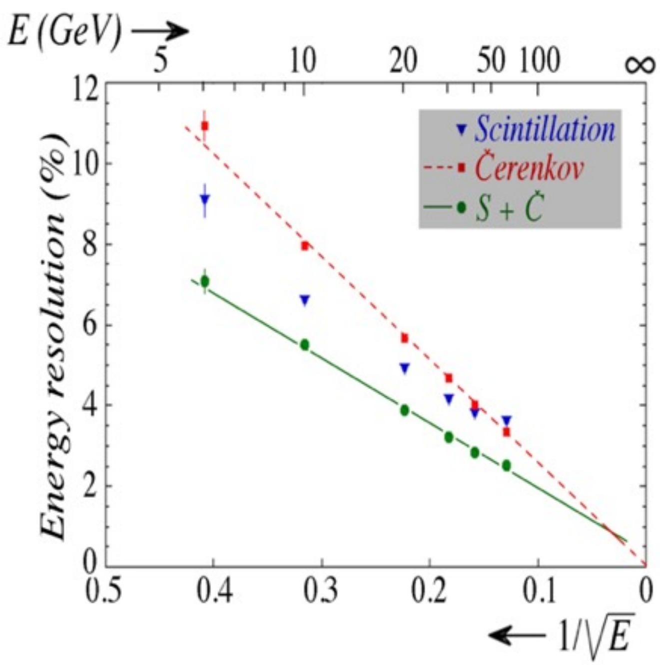
- The building block consists of 8, 1x1 mm^2, dSiPM based on SPAD arrays with 15 μm pitch or less
- The local electronic circuits will be kept to a minimum to guarantee high fill-factor
- The inter-dSiPM spacing is used to accommodate the processing electronics
- The 1 mm^2 dSiPM will be subdivided in quadrants (Pixels), each served by dedicated, mixed analogue and digital electronics

Energy resolution

- Electromagnetic resolution:

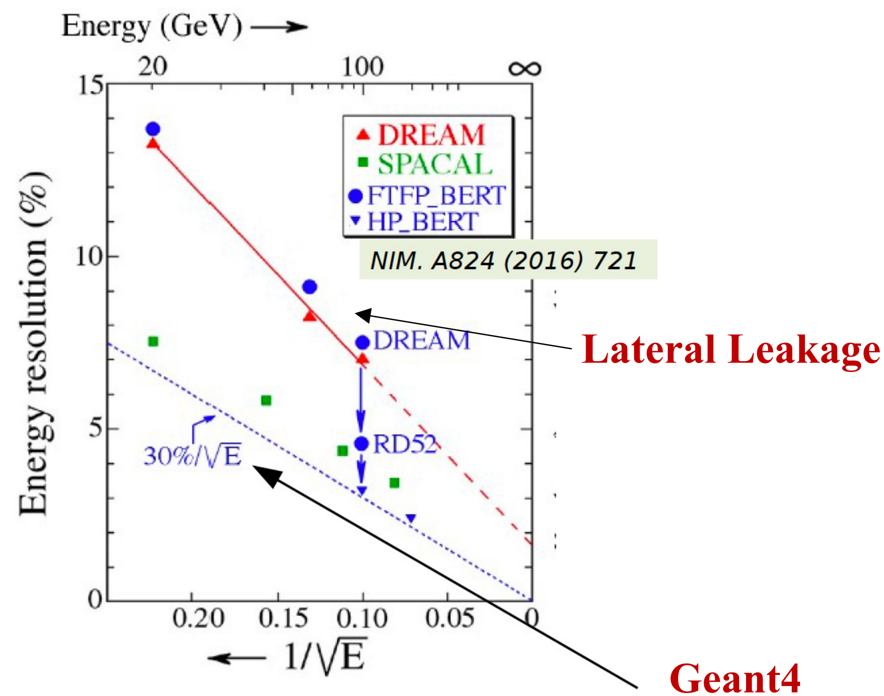
$$\frac{\sigma_{EM}}{E} = \frac{11\%}{\sqrt{E}} \oplus 1\%$$

Copper module
NIM A735, 130-144 (2014)



- Hadronic resolution:

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



SiPM main parameters

Used for the 2021 and 2023 prototype

Options considered for the hadronic-size prototype

Parameter	S14160-1315PS	S16676-15(ES1)	S16676-10(ES1)
Effective photosensitive area (mm2)	1.3 x 1.3	1 x 1	1 x 1
Pixel pitch (mu)	15	15	10
Number of pixels	7284	3443	7772
Recommended operating voltage (Vop)	+4 V	+4 V	+5 V
PDE at the Vop (%)	32	32	18
Direct cross talk at the Vop (%)	<1	<1	<1
Dark count rate (kHz)	120 (360 max)	60 (200 max)	60 (200 max)
Gain (10^5)	3.6	3.6	1.8