Digital SiPM for Dual-readout calorimetry

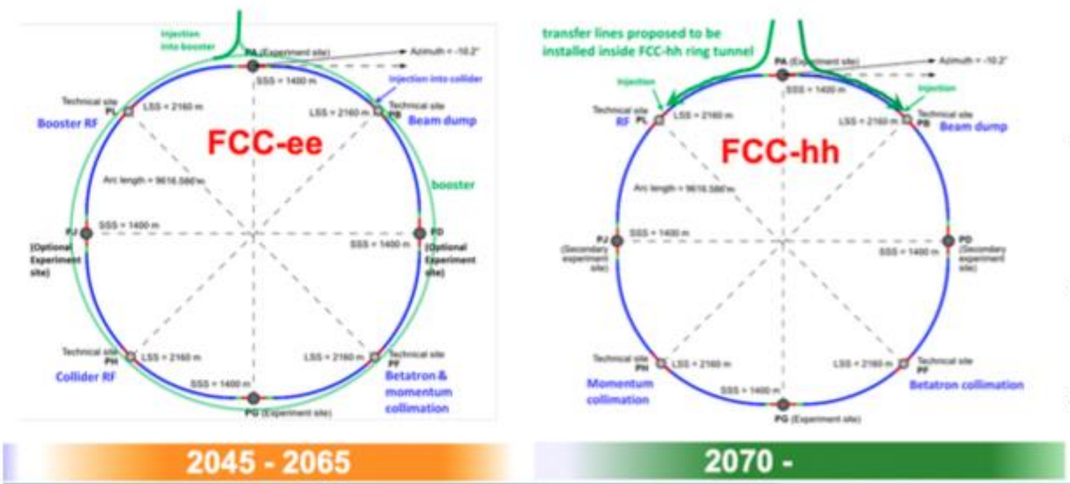
R. Santoro
on behalf of the HiDRa collaboration

Università dell'Insubria and INFN – Milano

European Strategy for Particle Physics Update (2026)

A comprehensive discussion in recent workshop at cern:
[The 8th FCC Physics workshop]

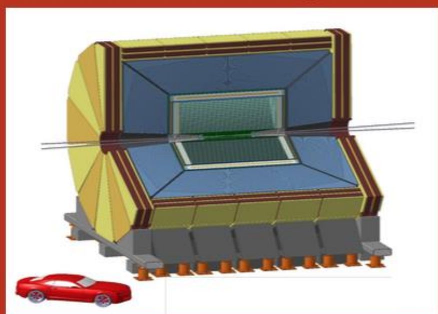
- The **new update of the ESPPU** is on us.
- **National processes** already in full swing. ECFA has published guidelines to provide national input.
  - … and let me remind you of the INFN workshop at Bicocca.
- The **integrated FCC programme** is the **baseline** option.



- **Stage 1:** FCC-ee (Z, H, WW, $t\bar{t}$) - high-precision exploration of the EW sector of the Standard Model, flavour physics, feebly coupled BSM physics.
- **Stage 2:** FCC-hh (pp @ 100 TeV) - exploration of the energy frontier.
- **Synergic programme** starting **a few years** after the completion of the **high-priority HL-LHC physics.**

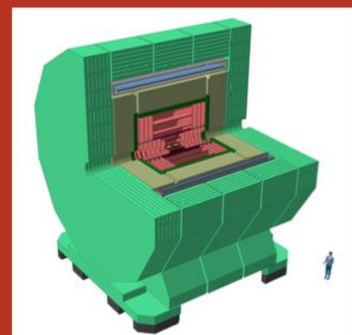
FCC detectors

IDEA (Innovative Detector for e^+e^- Accelerators)



2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual Readout Calorimeter + pre-shower
MPGD (µRwell) based Muon detector

CLD (CLIC-like Detector)



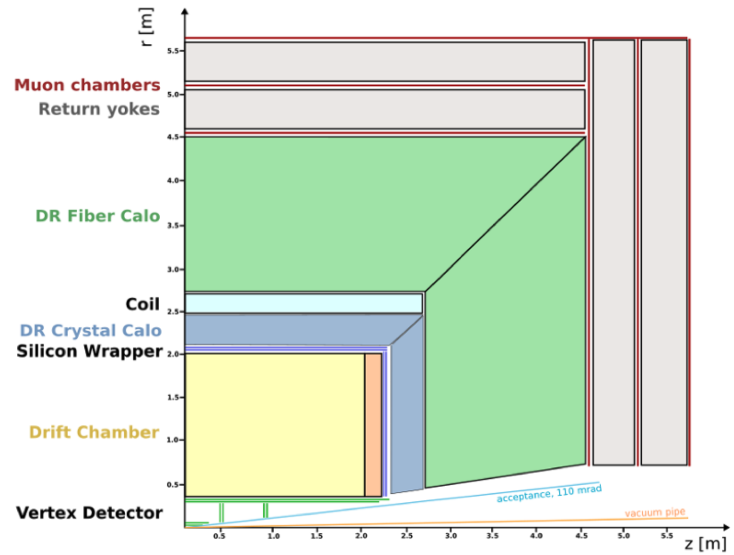
2 T solenoid **outside calo**
Full silicon tracker
SiW high-granularity EM Calo
Sci-steel high-granularity HAD Calo
RPC-based Muon detector

ALLEGRO - A Noble-Liquid Ecal based

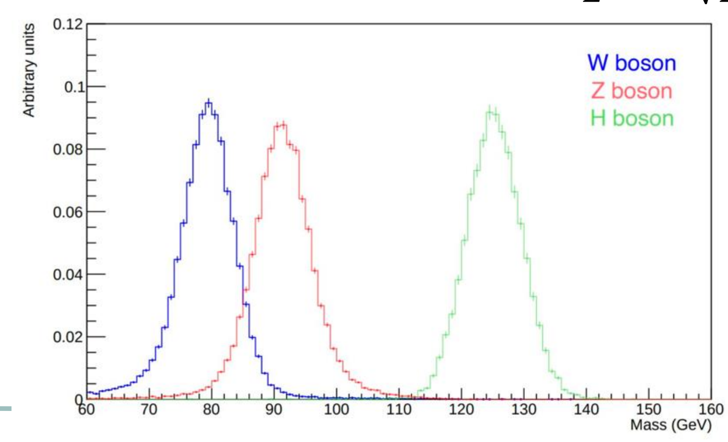
2 T solenoid **outside calo**
Tracking with ultra light drift chamber +
Si Wrapper (improved tracking + timing)
LAr EM Calo + Sci-steel HAD Calo

IDEA: detector concept for FCC-ee

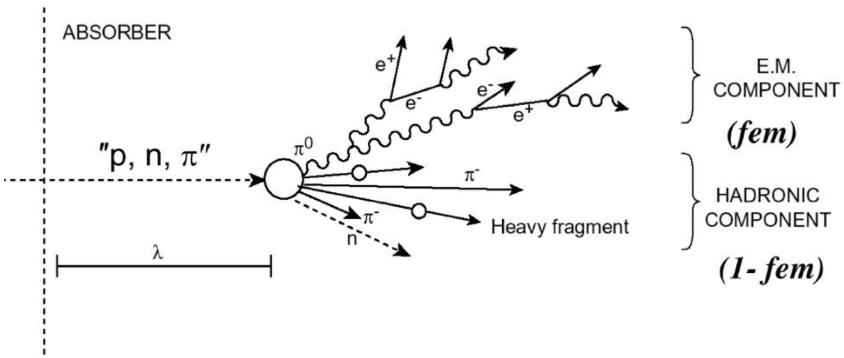
- Beam pipe: R ≈1.0 cm
- Highly transparent tracking
  - Si pixel vertex detector (monolithic technology)
  - Drift Chamber
  - Si wrappers (strips)
- Dual-readout crystal ecal: ≈ 22 X_0
- Thin superconducting solenoid: 3 T
- Dual-readout calorimetry 2 m / 7 λ_{int}
- Muon chambers
  - µ-RWELL in return yoke



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



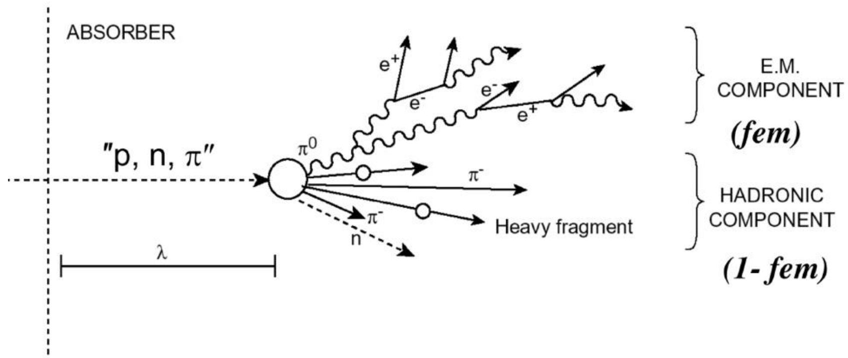
Dual-Readout: the principle



- 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

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

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

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

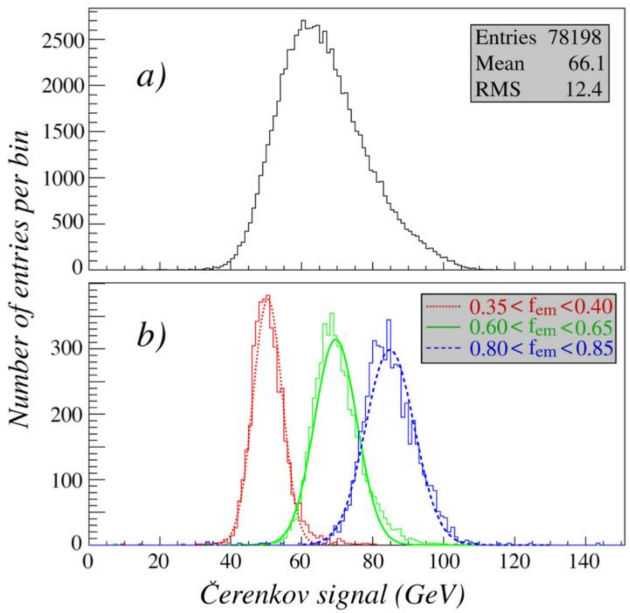
$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

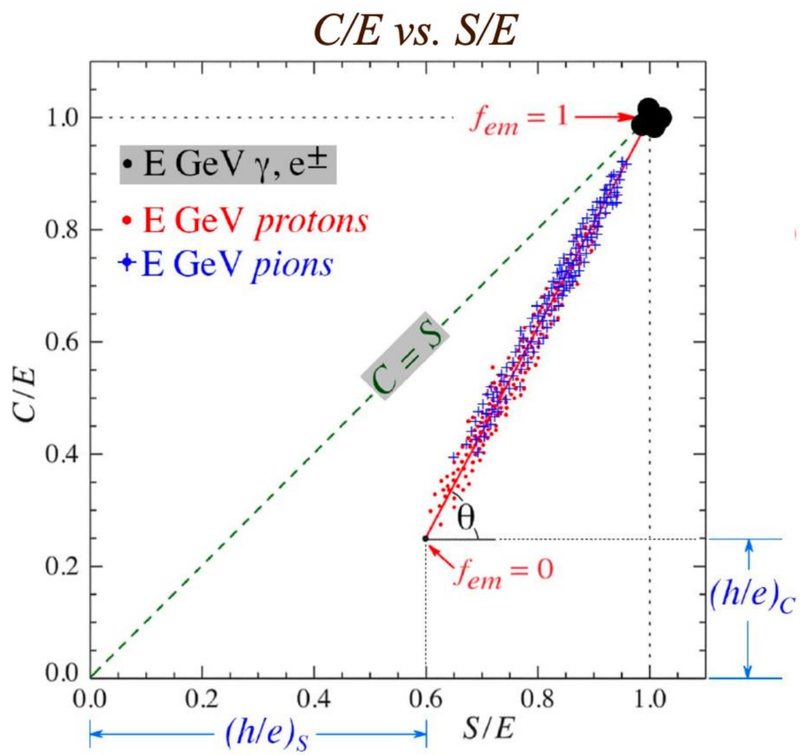
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

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: the principle





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

θ, χ independent of both:

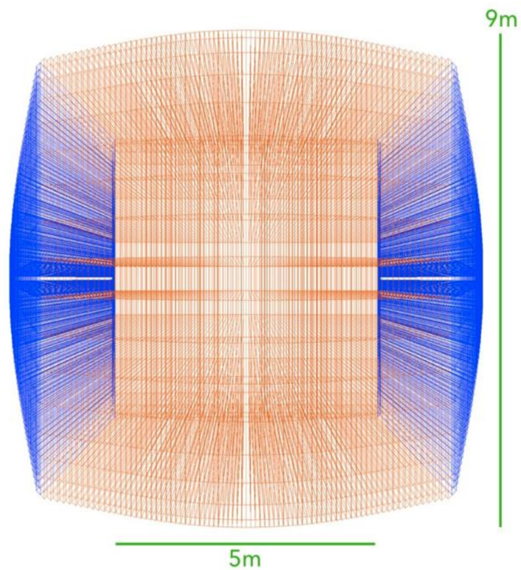
i) energy (!)

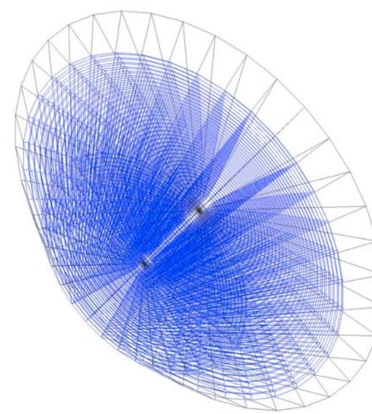
ii) type of hadron (!!)

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



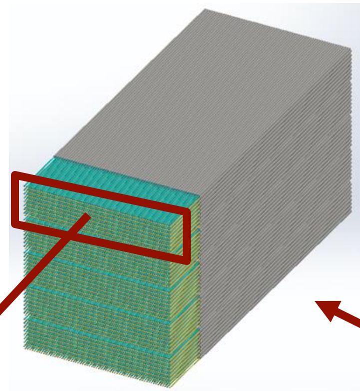


HiDRa project (supported by INFN) aims to identify a scalable and cost-effective solution to build a dual-readout calorimeter for IDEA.

HiDRa: High-Resolution Highly Granular Dual-Readout Demonstrator

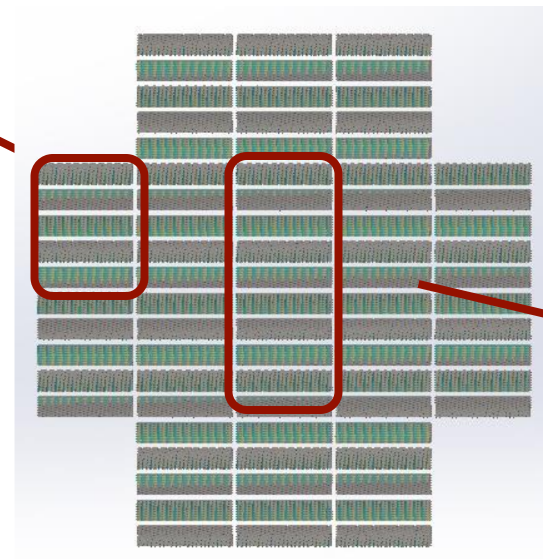
The Module

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

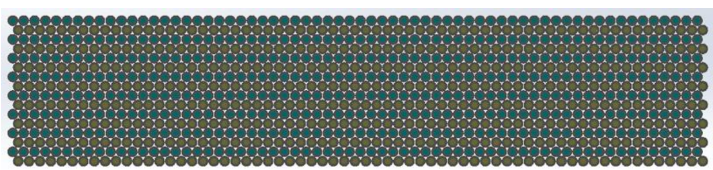


The HiDRa prototype

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



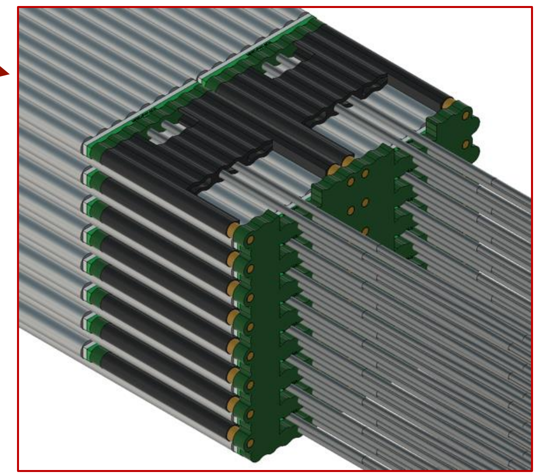
The Mini-Module



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

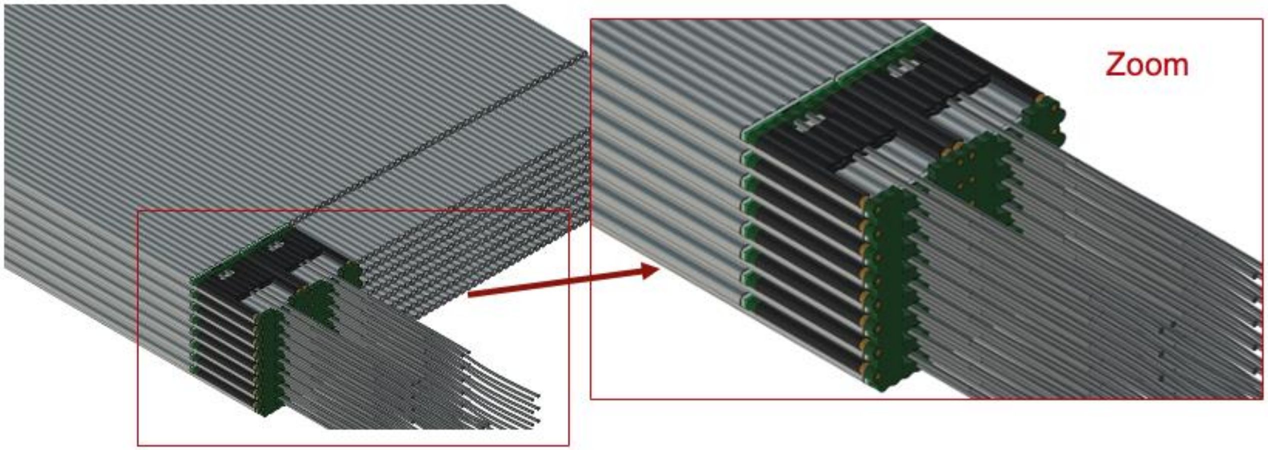
The highly granular modules

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

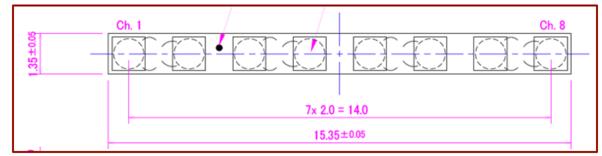


Challenging integration requiring a precise assembly procedure and the use of compact components (i.e. SiPMs, services and mechanical) to fit in the back of the calorimeter

Integration of highly granular modules



SiPM with 10 μm pitch for scintillating and 15 μm pitch for Cherenkov light



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

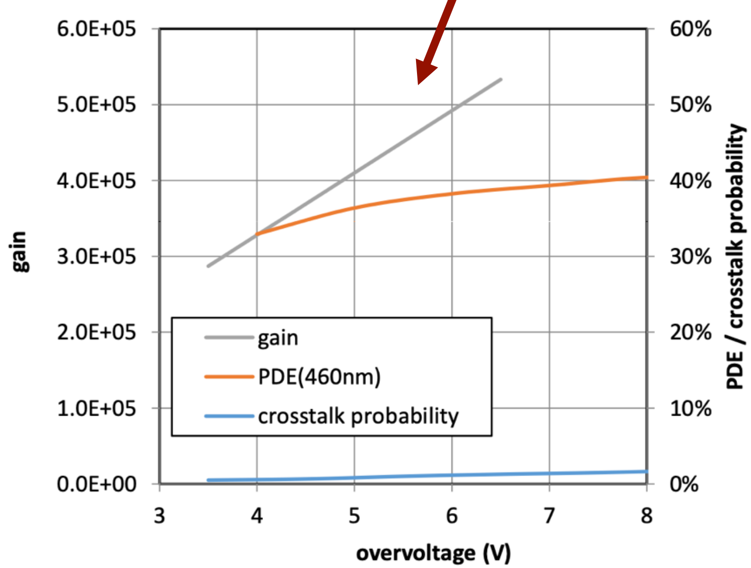
Analogue signals from 8 SiPMs connected in parallel

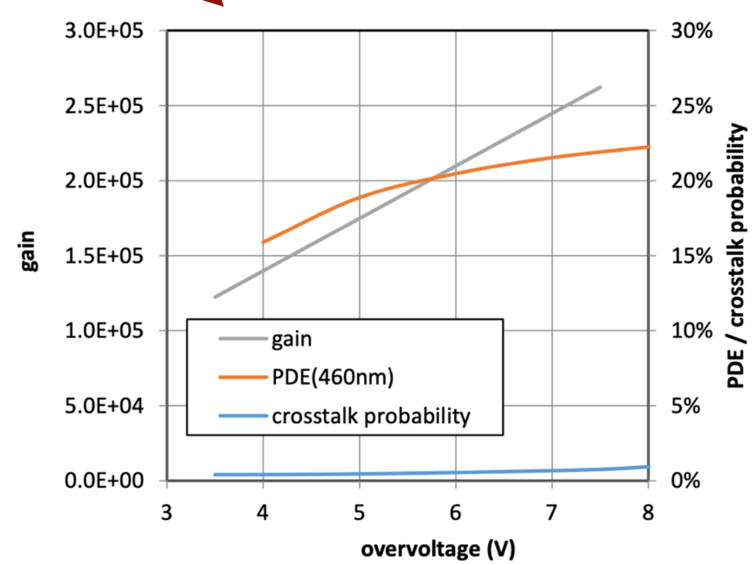
SiPM parameters (Hamamatsu datasheet)

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

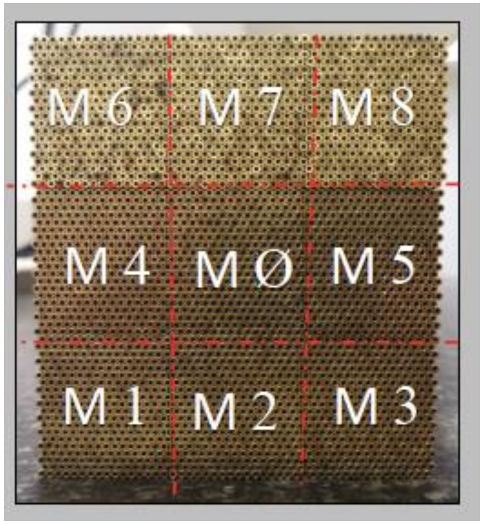
SiPM main parameters

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

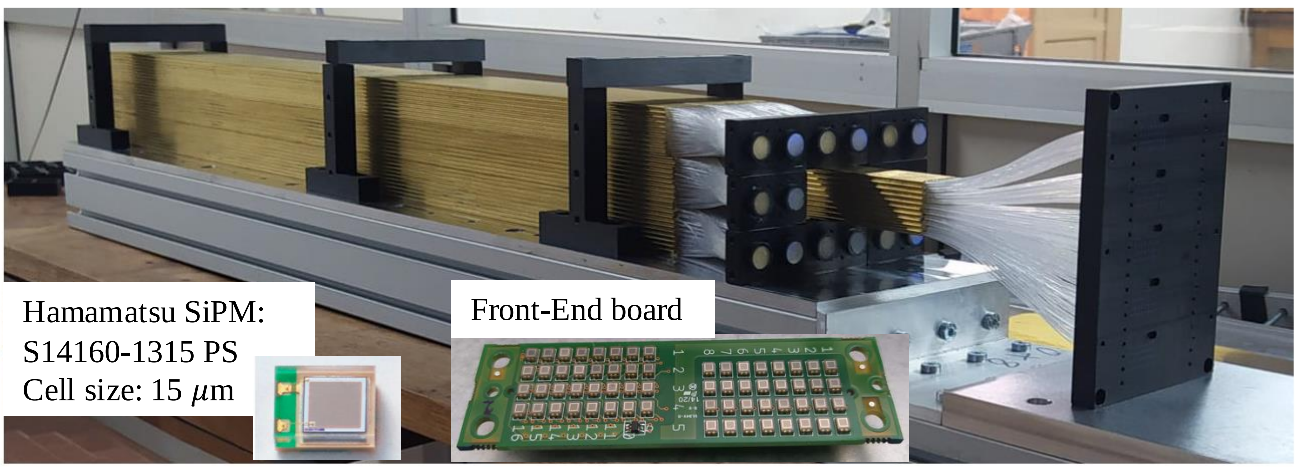


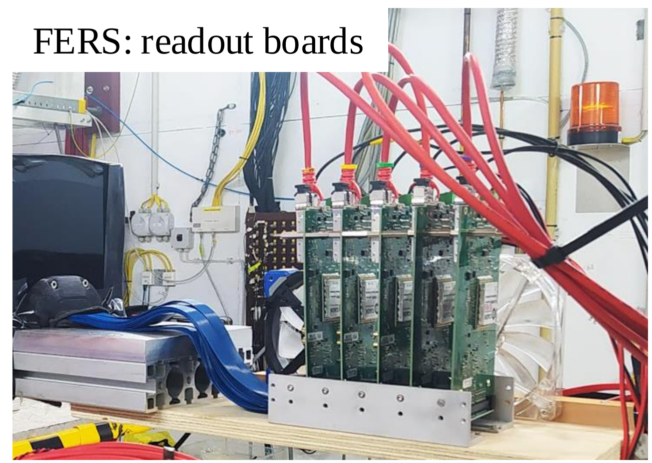


The EM-size prototype tested on beam (2021 and 2023)

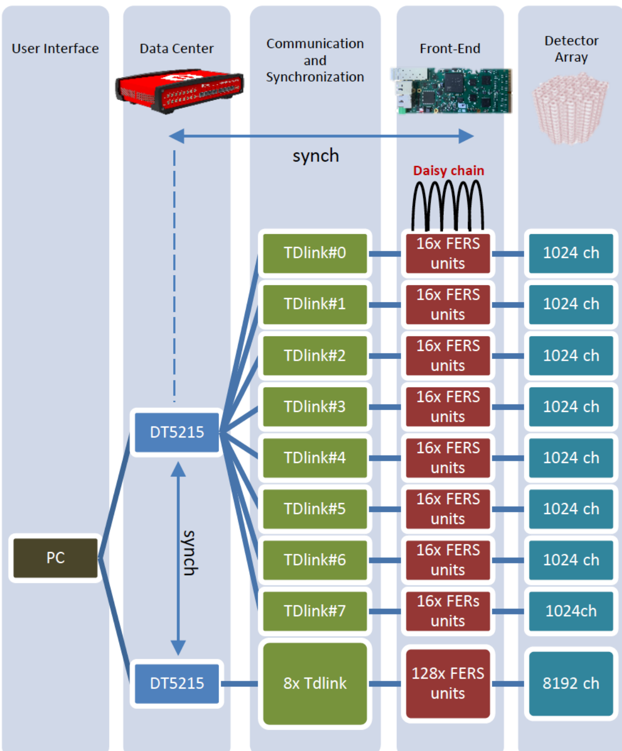


- EM-size prototype (10x10x100 cm^3)
  - 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
  - Brass capillaries: 2 mm outer diameter and 1.1 mm inner diameter
- EM-size prototype readout
  - Each capillary of the central module is equipped with its own SiPM: highly granular readout
  - 8 surrounding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





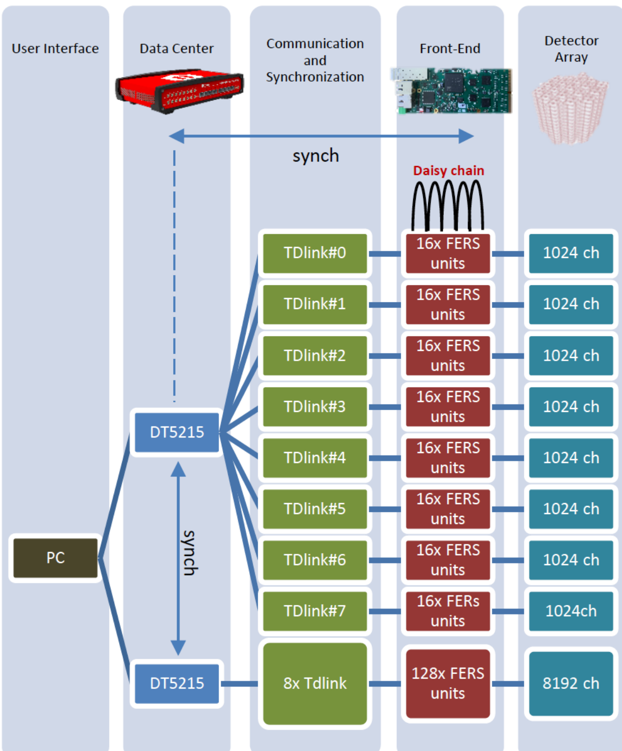
Readout: baseline solution



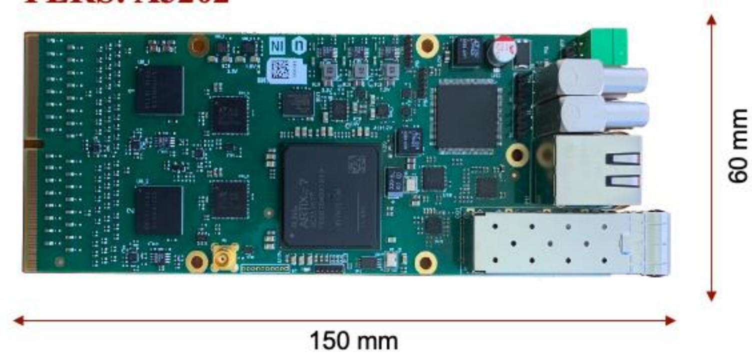
FERS-system

- FERS unit can be used in standalone or connected to the system
- Up to 16 FERS units can be connected in daisy chain (FERSnet)
- The FERSnet communicates to the concentrator board DT5215 via TDlink (6.25 Gbit/s) optical link
- A DT5215 houses 8 high-speed optical links (TDLink) to read out up to 8192 channels (SiPMs)
- The DT5215 has an embedded ARM processor (Quad Core) running Linux for data processing / data compression
- The connection to the host PC is performed over a 10 Gbit ethernet
- Further scalability can be reached synchronizing more concentrator boards

Readout: baseline solution



FERS: A5202

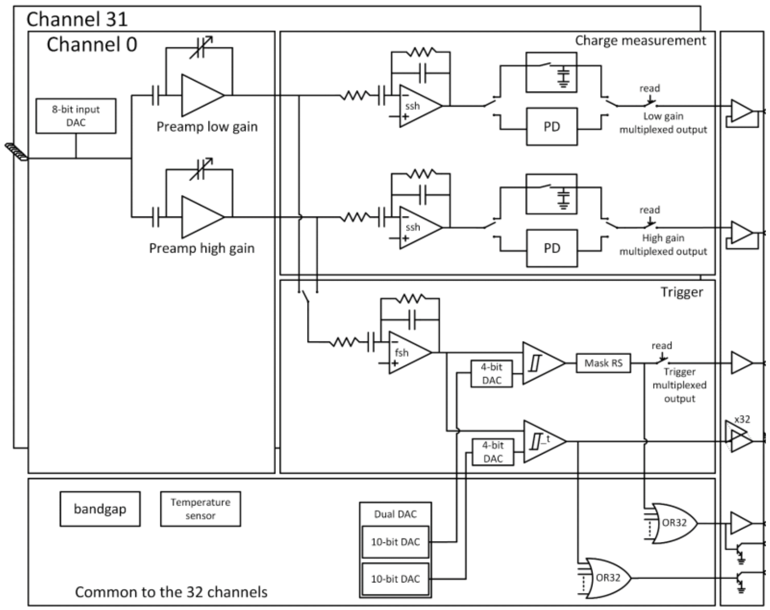


- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

CITIROC 1A

Block diagram

IN from SiPM

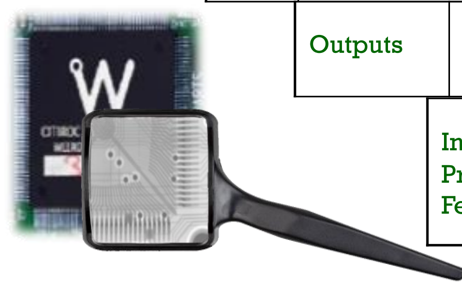


OUT to DAQ

https://www.weeroc.com/my-weeroc/download-center/citiroc-1a/16-citiroc1a-datasheet-v2-5/file

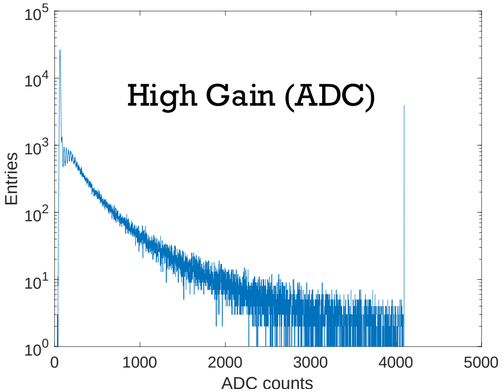
Specification

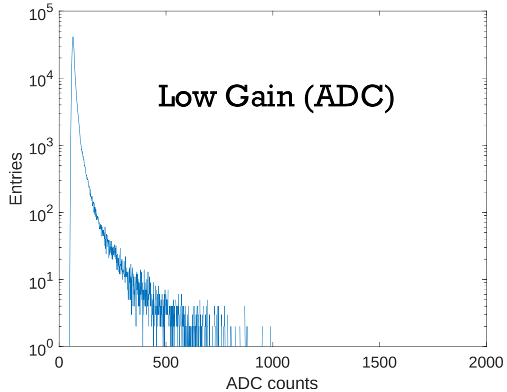
Detector Read-Out	SiPM, SiPM array
Number of Channels	**32**
Signal Polarity	Positive
Sensitivity	Trigger on **1/3 of photo-electron**
Timing Resolution	Better than **100 ps RMS** on single photo-electron
Dynamic Range	0-400 pC i.e. 2500 photo-electrons @ 10^6 SIPM gain
Packaging & Dimension	TQFP160-TFBGA353
Power Consumption	225mW - Supply voltage: 3.3V
Inputs	32 voltage **inputs with independent SiPM HV adjustments**
Outputs	**32 digital outputs (for timing)** **2** multiplexed **charge output, 1** multiplexed **hit register and 2 trigger outputs**
Internal Program. Features	32 HV adjustment for SiPM (32x8bits), Trigger Threshold Adjustment, channel by channel gain tuning, 32 Trigger Masks, Trigger Latch, internal temperature sensor



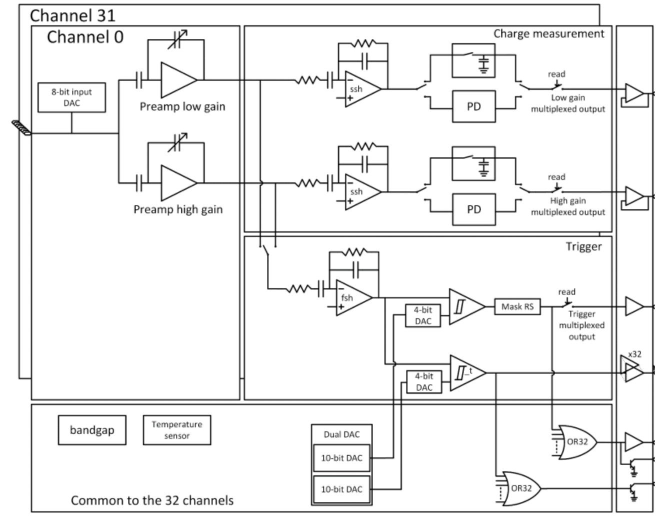
The importance of SiPM equalisation

We need single photons resolution and large dynamic range



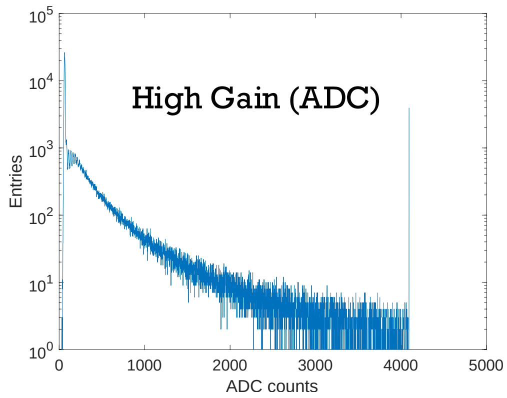


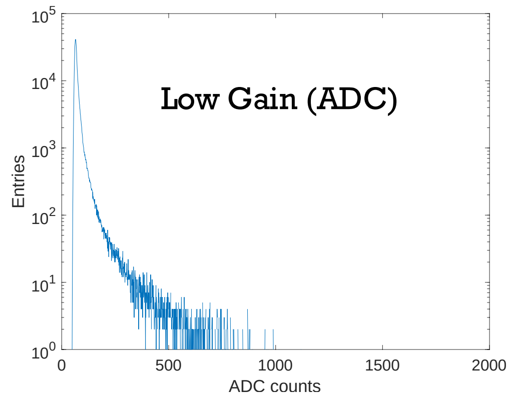
Citiroc1A – block-schema

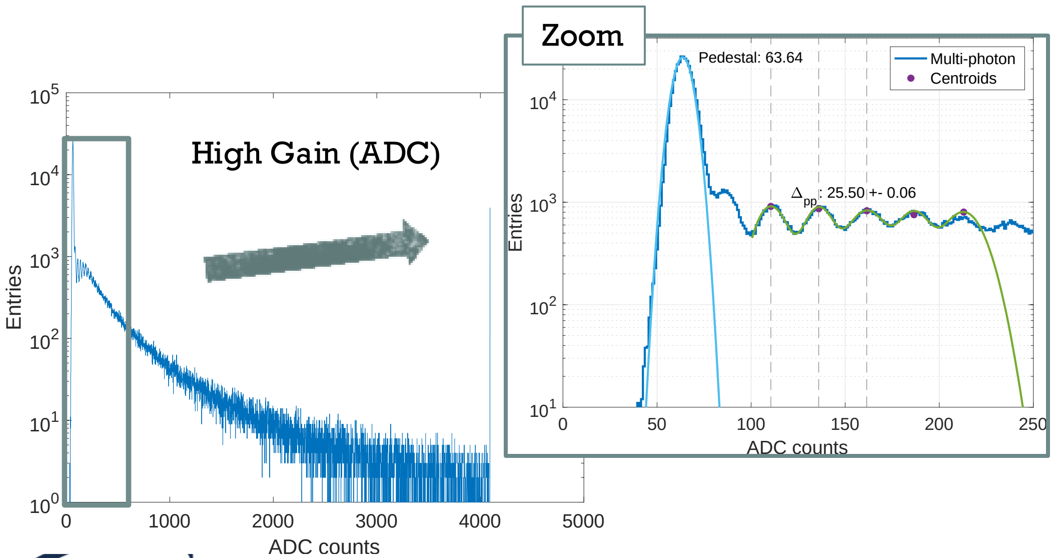


The importance of SiPM equalisation

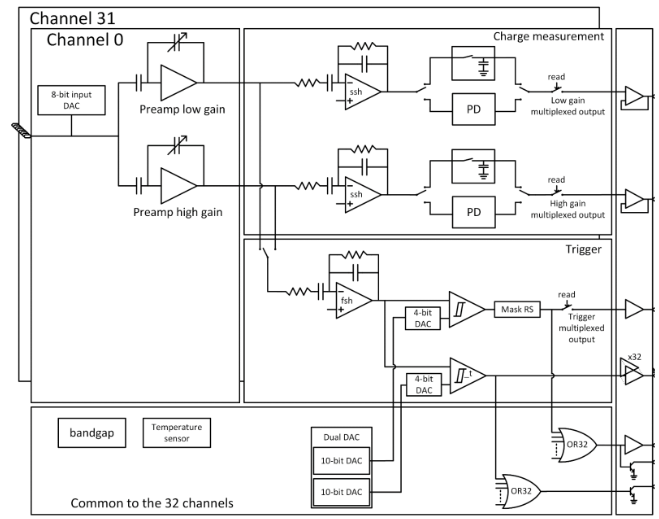
We need single photons resolution and large dynamic range







Citiroc1A – block-schema



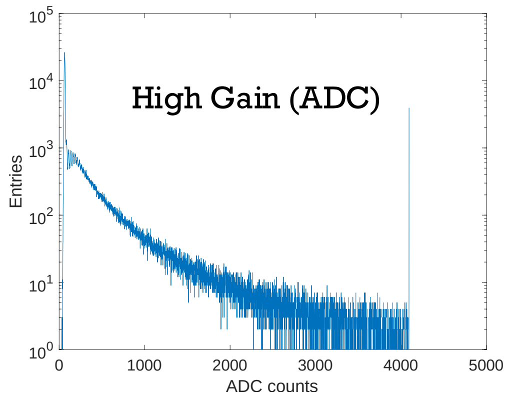
HG equalisation

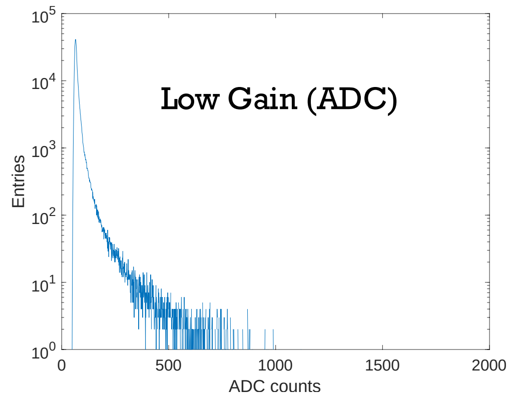
Dpp: used to convert ADC in Ph-e (monitored in all runs and for all SiPMs)

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

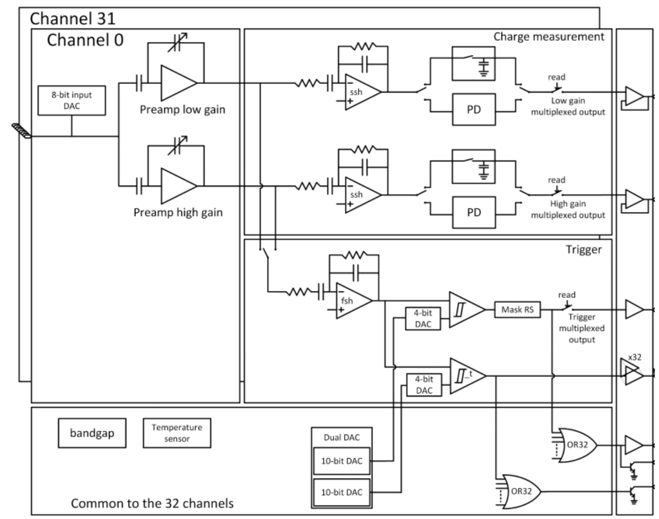
The importance of SiPM equalisation

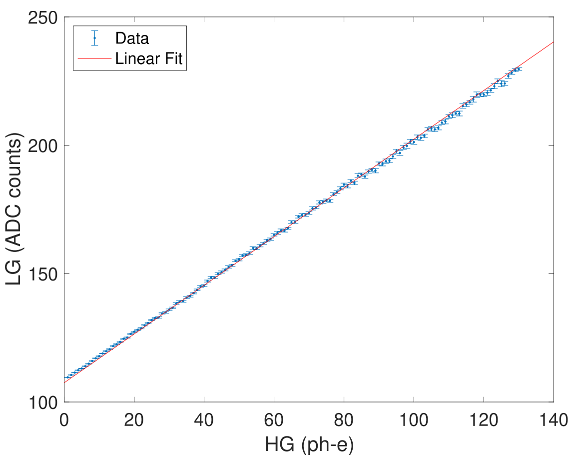
We need single photons resolution and large dynamic range

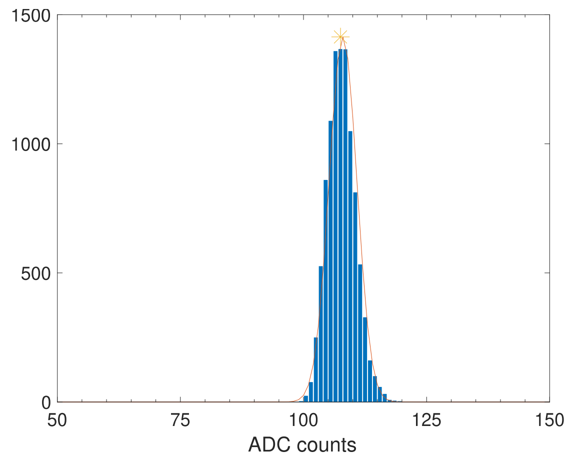




Citiroc1A – block-schema





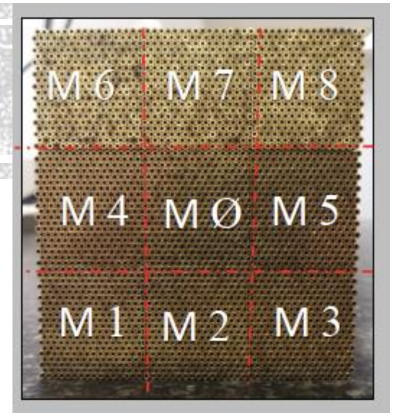


LG equalisation

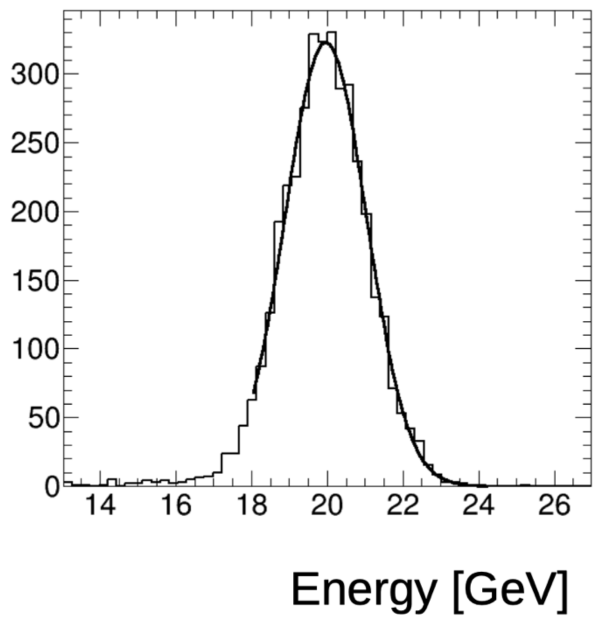
Slope of the correlation plot provides the ADC to Ph-e conversion factor

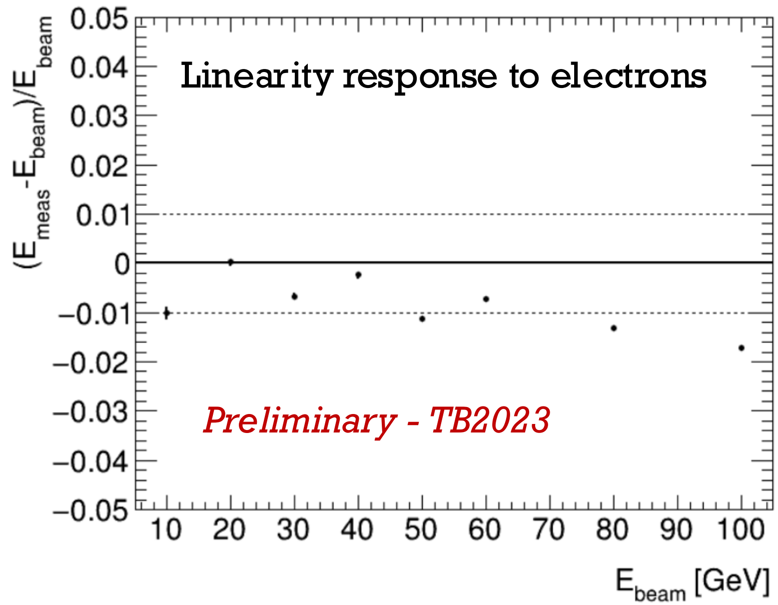
Pedestal width measured selecting noise events in the HG

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





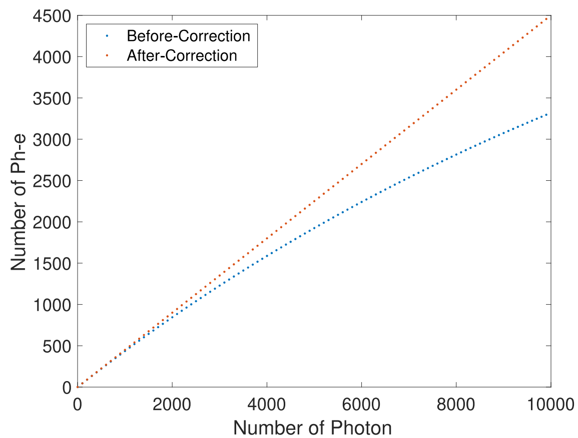
Pretty good linearity but never forget that SiPMs are digital sensors: the same cell cannot be fired twice

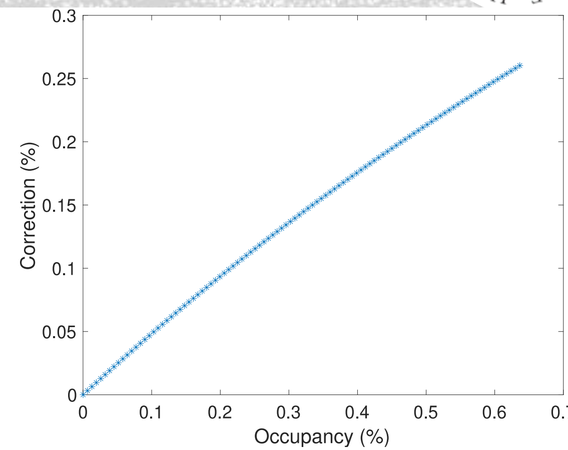
More on SiPM linearity

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

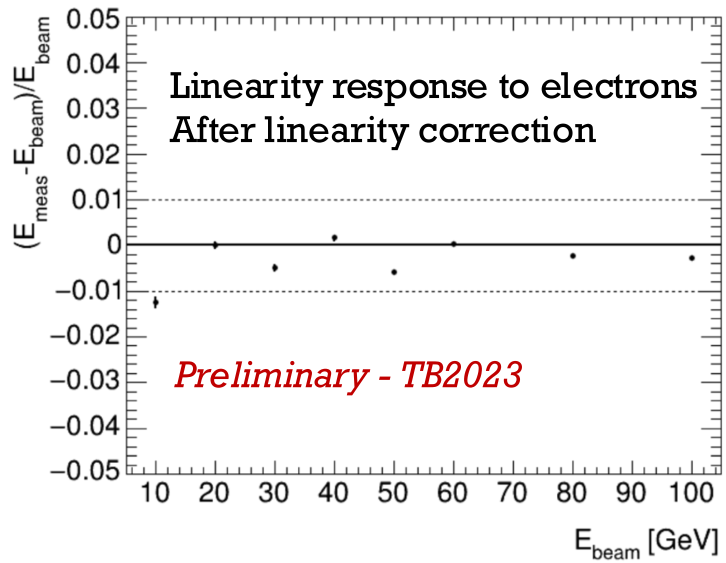
$$N_{\text{fired}} = N_{\text{cells}} \times \left[1 - \exp\left[-\frac{N_{\text{photons}} \times \text{PDE}}{N_{\text{cells}}}\right]\right]$$

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





Improved linearity after the correction



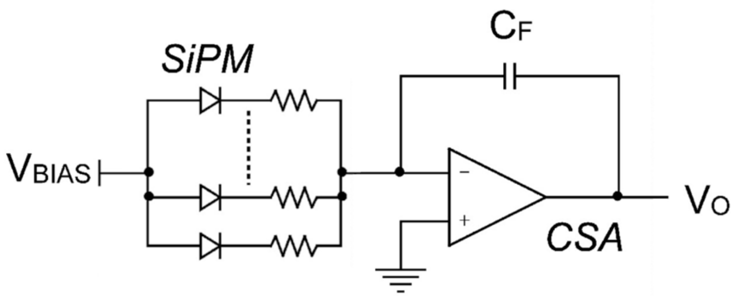
The take home message

DR High granularity modules have demanding and sometimes competing requirements:

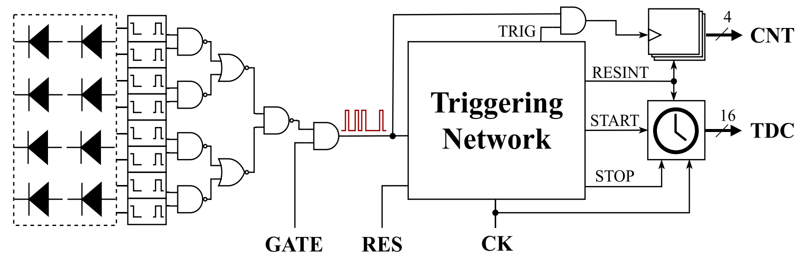
- SiPMs with:
  - High efficiency with single photon resolution
  - wide dynamic-range at fixed sensitive area to avoid non-linearity effects
- Readout coping with the SiPM dynamic range, preserving the single photon resolution
- Time resolution < 100ps to add longitudinal segmentation
- Signal grouping from SiPMs to reduce the number of channels to be read-out, knowing that:
  - It reduces the multi-ph quality and the timing performance
  - It requires that all SiPMs in the group must operate in linear regime: no-way to correct for non-linearity (they sampling different regions of the shower profile and are not uniformly illuminated)

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

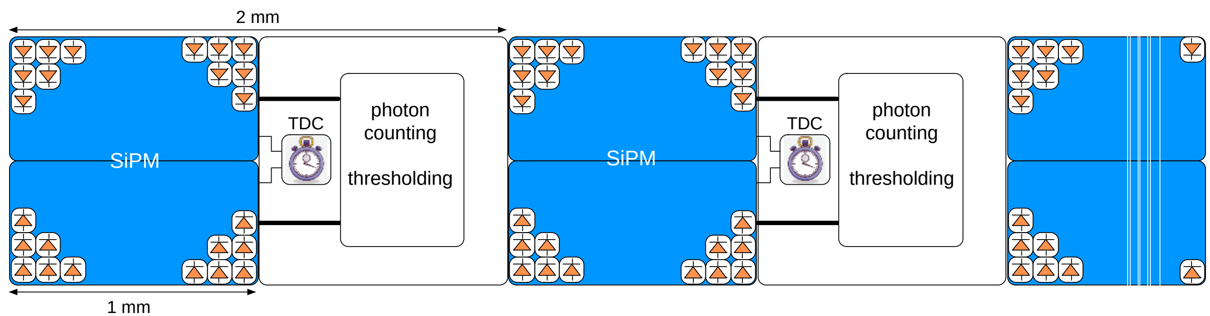
- SPAD array in CMOS technologies may offer the following benefits:
  - Front-end can be optimised to preserve signal integrity (especially useful for timing)
  - Easier linearisation and calibration – direct digital output vs digital/analog (including noise + non uniformity)/digital conversion
  - The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

dSiPM specifications

Requirements	Dual readout calorimetry
SiPM Unit area (mm^2)	1x1
Micro-cell pitch (um)	15-20
Macro-pixel area (μm^2)	500x500
PDE (%)	>20
DCR (kHz)	<100 kHz/mm^2
AP (%)	<1
Xtalk (%)	few
Trigger	external, self
Output data: light intensity	no. of fired cells in 1 or 2 time windows (10's of ns long)
Output data: time	time of arrival of the first photon in the window, possibly of the last photon (TOT)
Time resolution (ps)	<100
Module size and form factor	strip with 8 units (1mm x 16 mm), pitch of 2 mm
Connection	BGA

Demonstrator for DR calorimetry

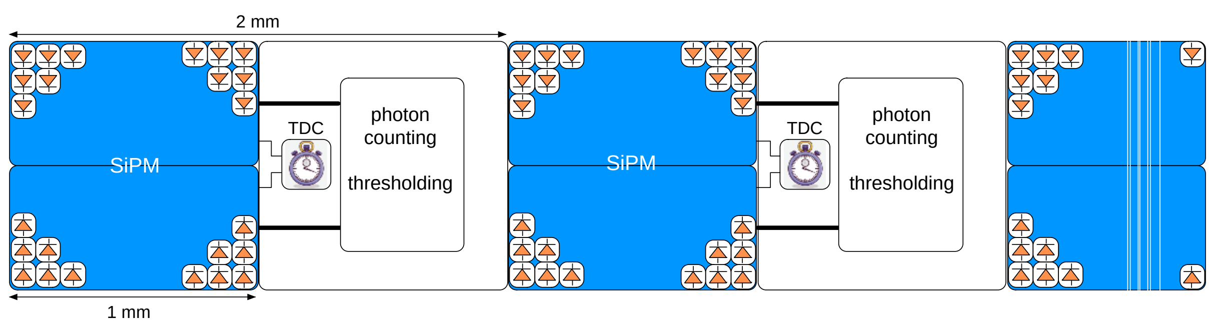
- Single building block of 8 dSiPM (1x1mm^2) and processing electronics in the common CMOS substrate
  - SPADs with minimal electronic circuits -> high fill-factor
  - The inter-dSiPM spacing is used to accommodate the processing electronics
  - Each mm^2 dSiPM will be subdivided in sectors, each served by dedicated mixed analogue and digital electronics to improve timing performance



Demonstrator for DR calorimetry

- Single building block of 8 dSiPM (1x1mm^2) and processing electronics in the common CMOS substrate
  - SPADs with minimal electronic circuits -> high fill-factor
  - The inter-dSiPM spacing is used to accommodate the processing electronics
  - Each mm^2 dSiPM will be subdivided in sectors, each served by dedicated mixed analogue and digital electronics to improve timing performance

- Processing electronics:
  - Fully digital output obtained through a completely digital processing chain (or, mixed analogue and digital approach, through current or charge integration and A/D conversion)
  - Time of arrival of the first bunch of photons and bunch duration with better than 100 ps resolution
  - Possibility of individual micro-cell enabling
  - Threshold adjustment capabilities for noise rejection
  - Asynchronous counting over a more than three decade wide dynamic range of simultaneously firing micro-cells (order of a few thousands, 15-20 μm pitch)



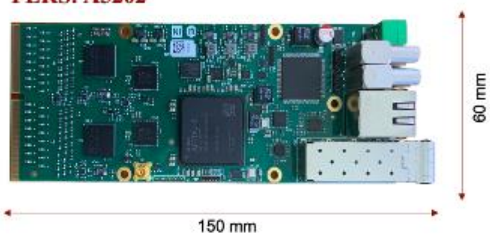
Summary

- The HiDRa collaboration is building a dual readout calorimeter large enough to contain hadronic showers, using a scalable and cost-effective solution for the next generation of detector concept (IDEA @ FCC-ee)
- The highly granular modules, equipped with SiPMs, set challenging requirements in terms of readout, calibration technique and linearity correction
- Although SiPMs are the baseline solution, monolithic CMOS SPAD array (dSiPM) may have a strong impact for this detector R&D
- If ASPIDES will succeed in its goal, we will have a demonstrator of interest to a broad community (i.e. calorimetry for high energy physics)

Backup

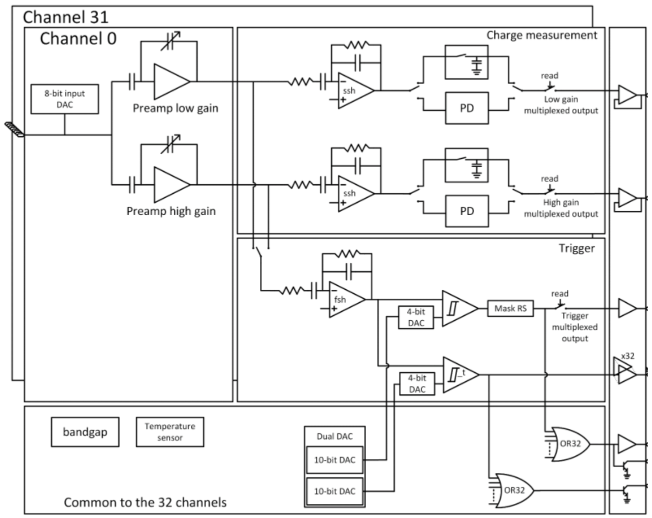
Integration and signal integrity

FERS: A5202

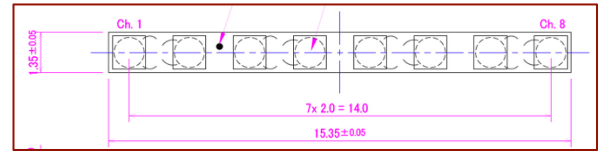


- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout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

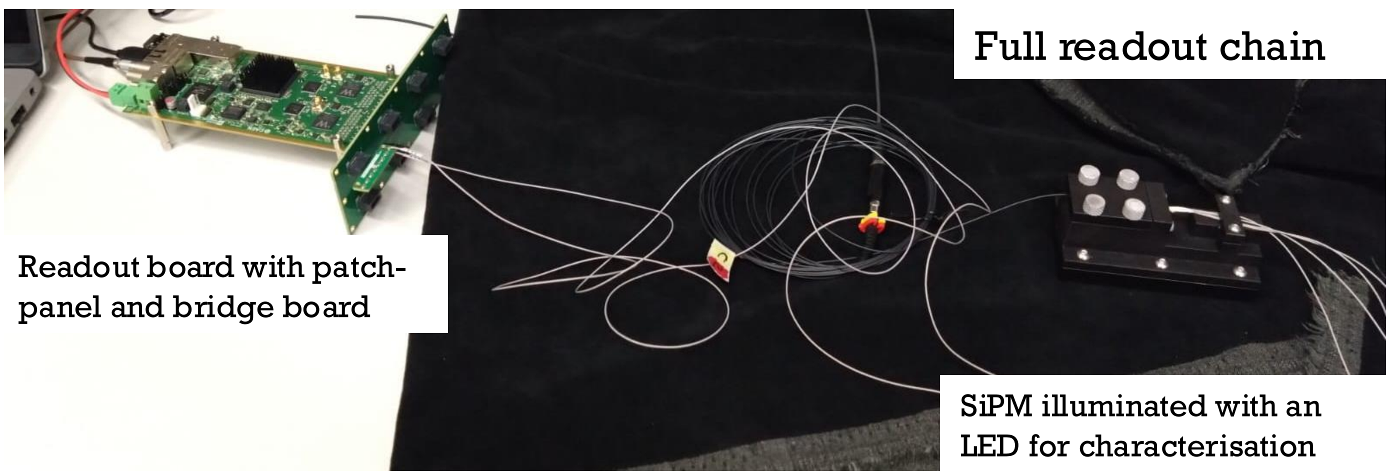
Citiroc1A – block-schema



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)



Full readout chain

Readout board with patch-panel and bridge board

SiPM illuminated with an LED for characterisation

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