

# CMS HGCAL

An overview of the CMS HGCAL

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# Outline

## About this talk

### **01 Introduction**

### **02 Silicon section of the HGCal**

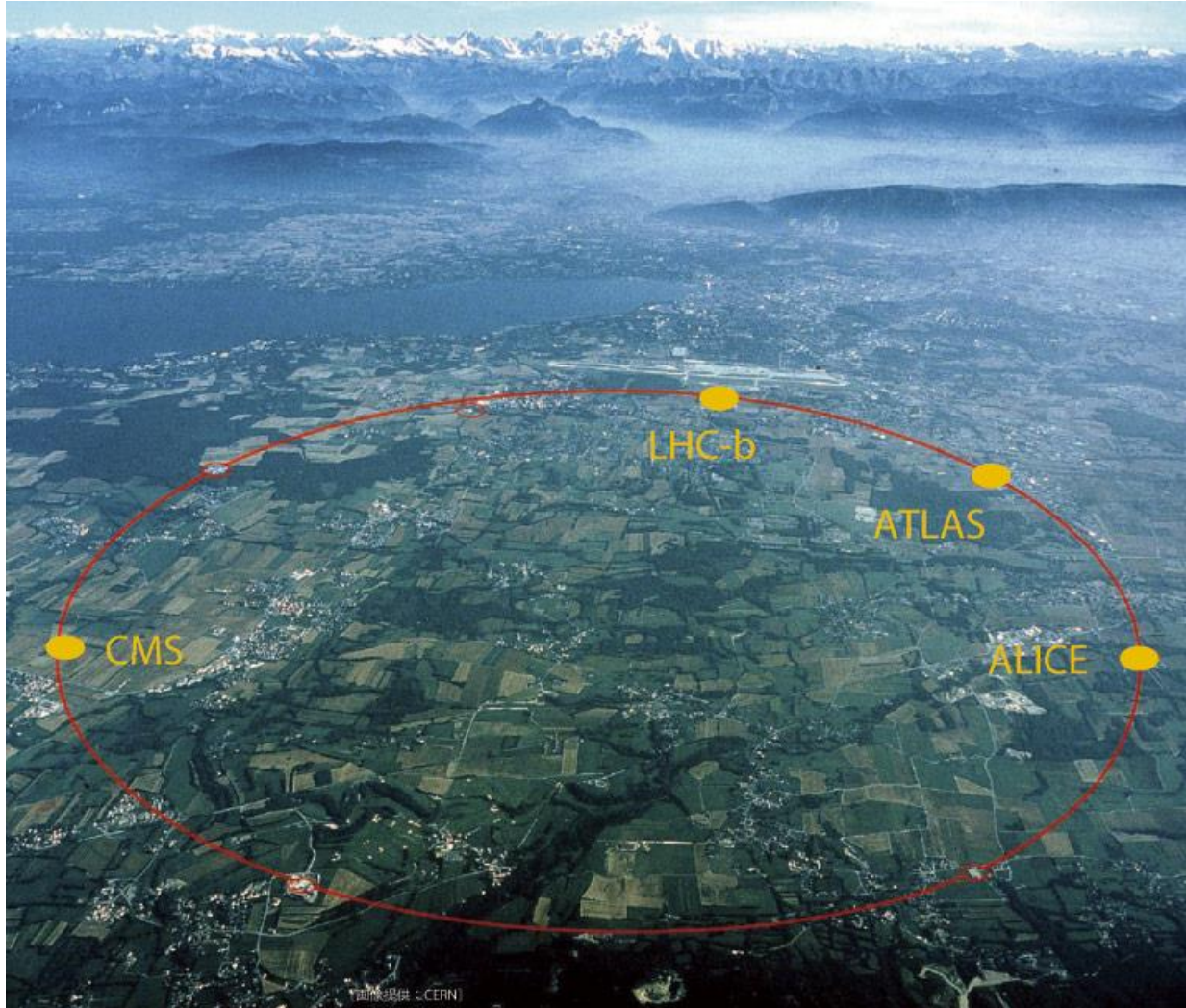
### **03 Scintillator section of the HGCal**

### **04 Summary**

# 01 Introduction

# The Large Hadron Collider (LHC) at CERN

## Basic information



- The **largest particle accelerator in the world**.
- Located **100 metres underground** at CERN with **27 km** superconducting magnet **ring**.
- **4 collision points** around the accelerator ring.
- **4 different particle detectors** in each collision point: **CMS, ATLAS, ALICE, and LHCb**.
- **Goal:** Standard model physics, the origin of mass, supersymmetry, dark matter, dark energy, matter v.s antimatter, quark-gluon plasma...etc.



# The Compact Muon Solenoid (CMS) detector

## Basic information

### CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 1\text{m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

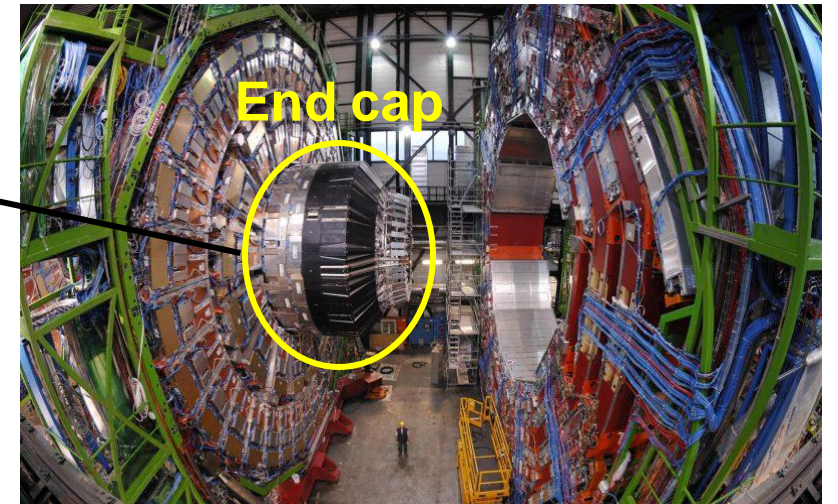
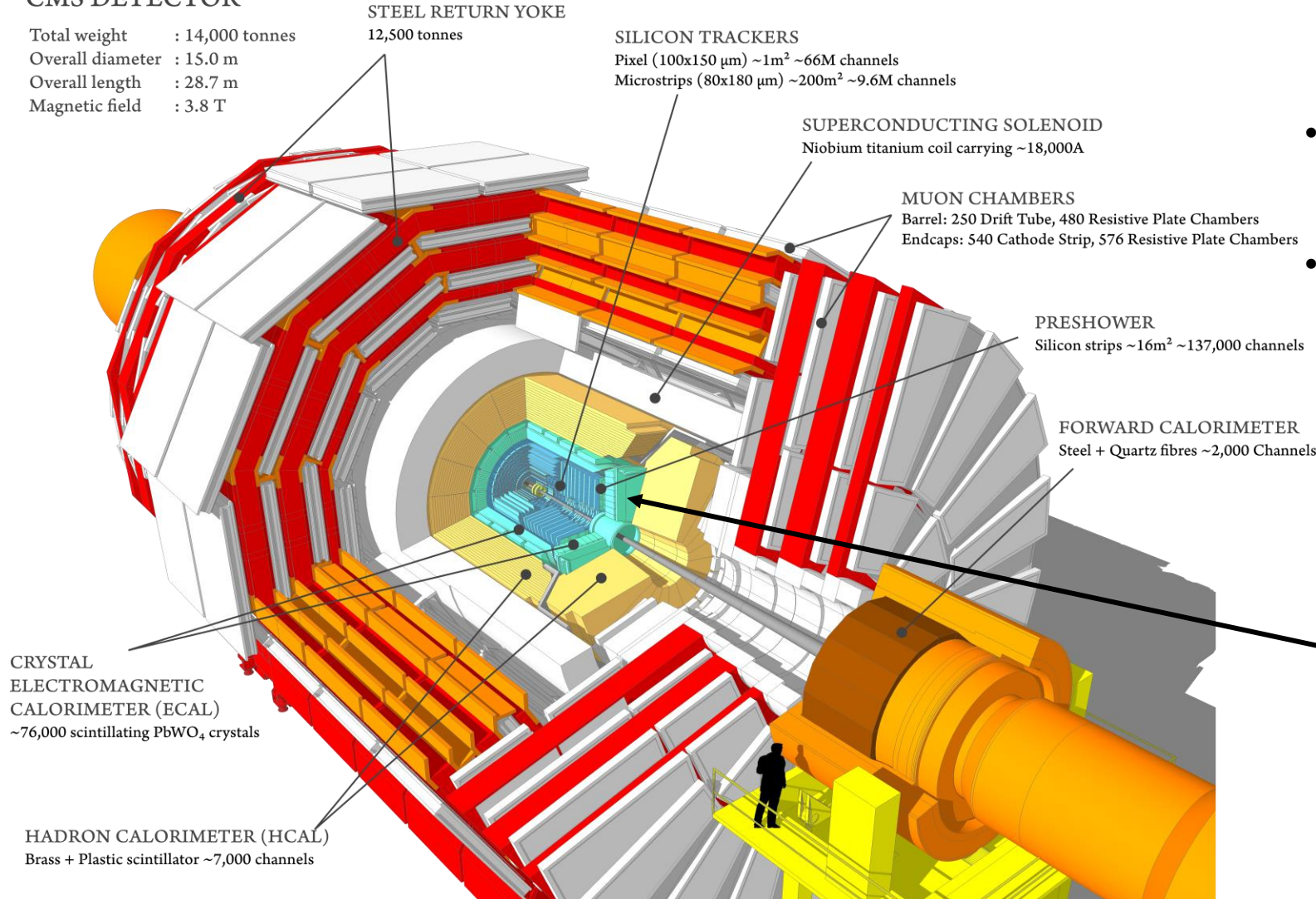
PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels

- Take "3D photographs" of particle collisions (up to 40 million times per second) in all directions.
- Weight 14000 tonnes. 15 metres high, 21 metres long.
- **Physics goal:** standard model, beyond standard model, Higgs boson mechanism, boost Higgs, dark matter, extra dimensions...etc.



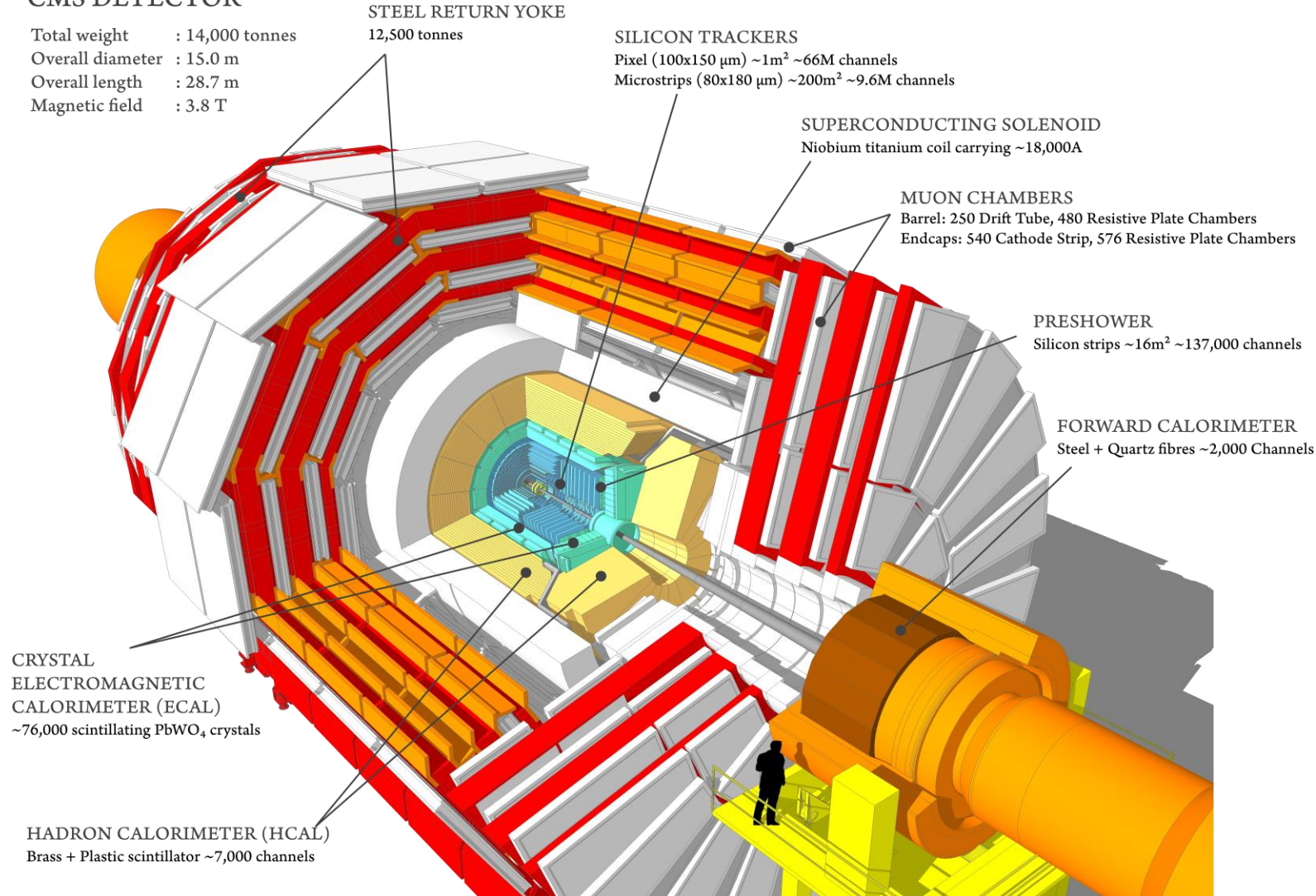


# The Compact Muon Solenoid (CMS) detector

## How it works.

### CMS DETECTOR

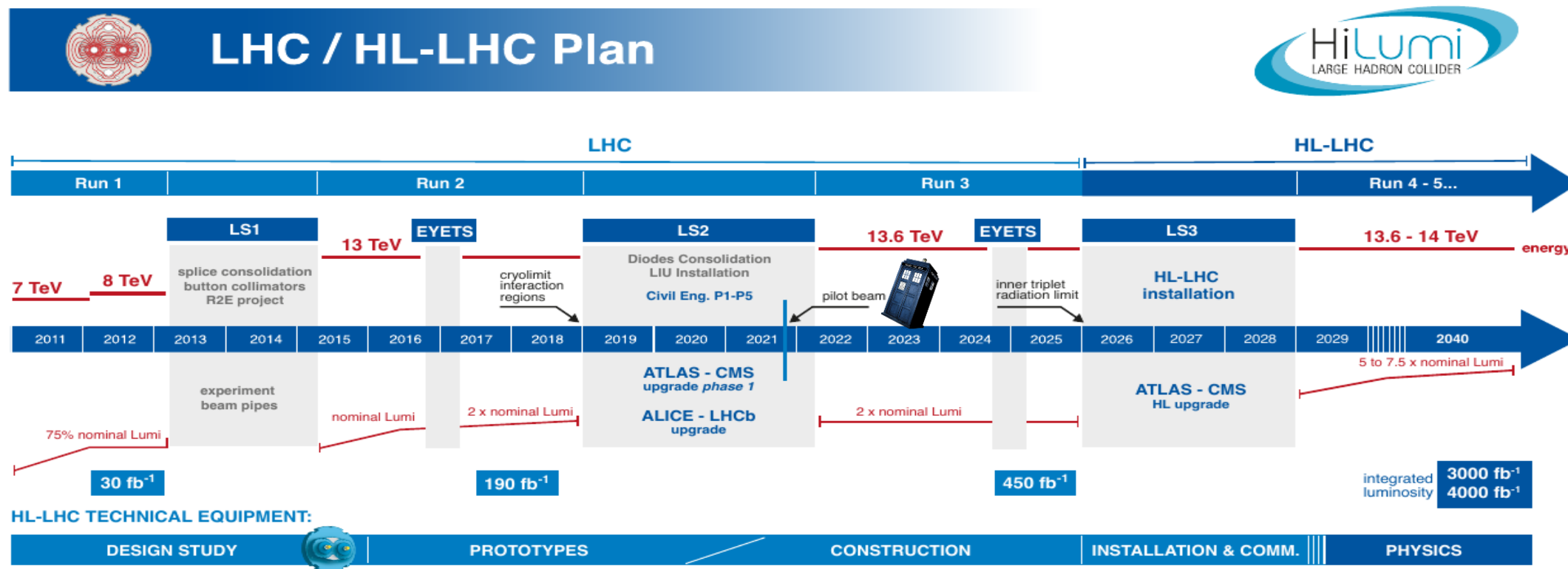
Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T



1. **Bending** the trajectories of charged **particles** (by using magnetic field  $\sim 4$  tesla): identify particle charge, measure particle momentum.
2. **Identifying tracks** of the bent charged particles (done by silicon tracker)
3. **Measuring energy** of particles produced in each collision: Electromagnetic Calorimeter (ECAL)  $\Rightarrow$  electrons, photons. Hadron Calorimeter (HCAL)  $\Rightarrow$  hadrons (quarks and gluons)
4. **Detect Muons**: can also measure its momentum by tracking devices and muon chambers.

# Schedule of the HL-LHC

## Plan for the next decays

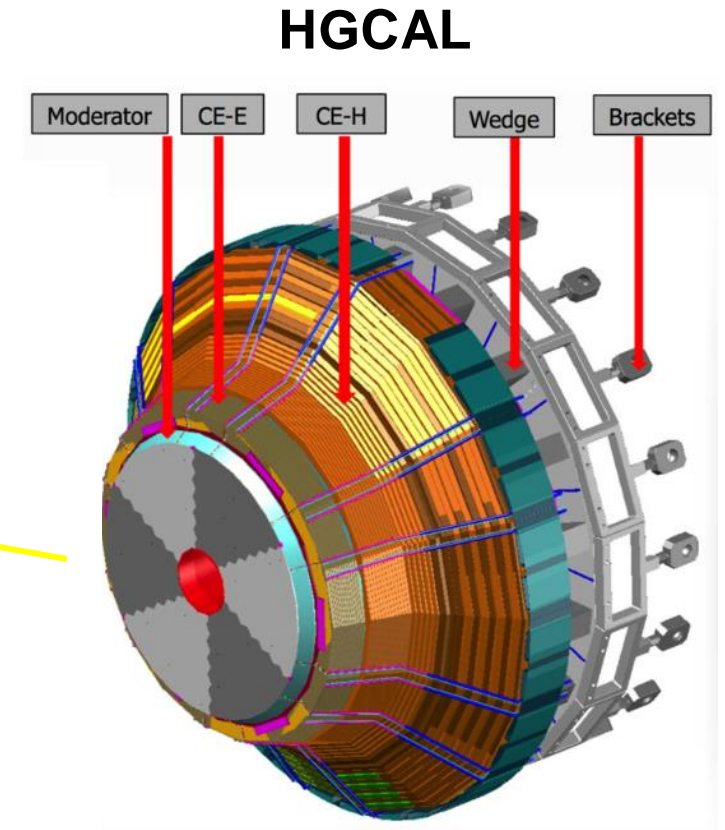
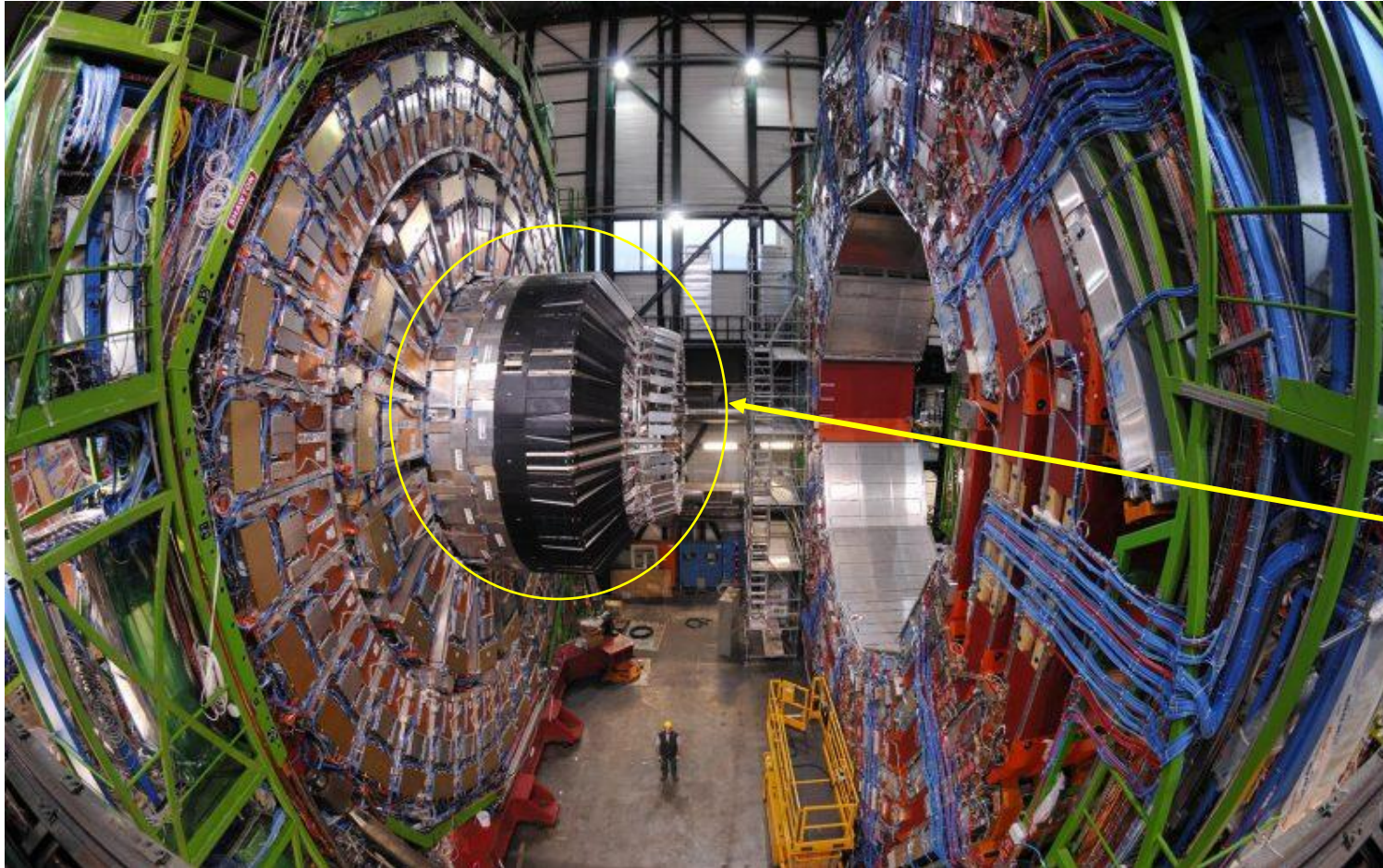


- Lowering, installation, and commissioning of the detector will be done during Long Shutdown 3 (LS3).
- Expected instantaneous luminosity =  $5 \times 10^{34}$  /cm<sup>2</sup>s, and pileup = 140 (can reach 50 % even higher)



# High Granularity Calorimeter (HGCAL)

What is HGCAL. Basic structure and purpose.



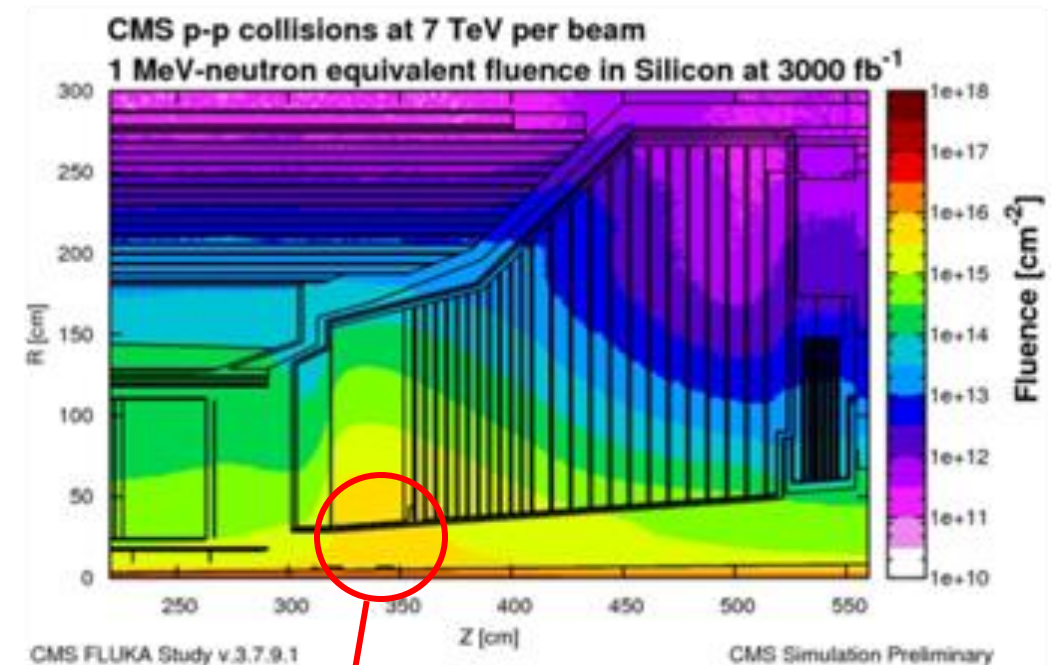
- As part of the CMS phase-II upgrade, HGCAL will replace **the current endcap** of the CMS detector in the **HL-LHC**.

# What is HGICAL, and why do we need it

What is HGICAL. Basic structure and purpose.

## What is HGICAL, and why do we need it

- It's a **5-D calorimeter** with high granularity which can measure energy deposition, time, and shower shape.
- It is designed to cope with the larger number of collisions per bunch crossing (**event pileup**) and **higher radiation dose** in HL-LHC.



Up to 2 MGy absorbed dose

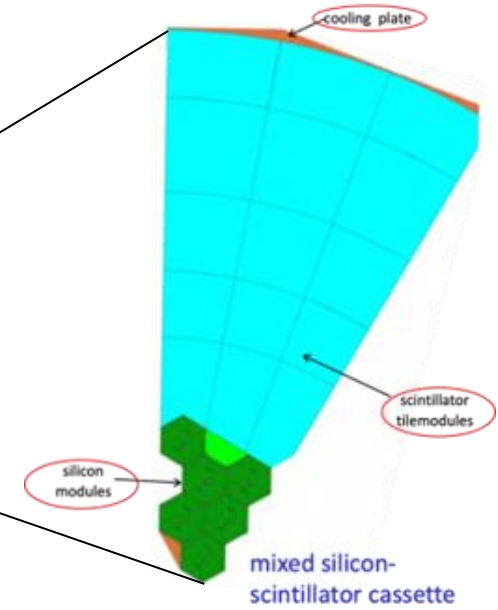
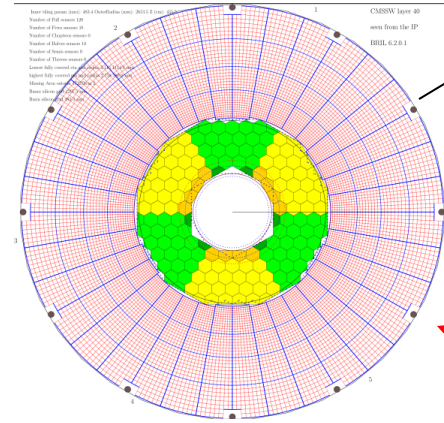


# Basic structure of the High Granularity Calorimeter (HGCAL)

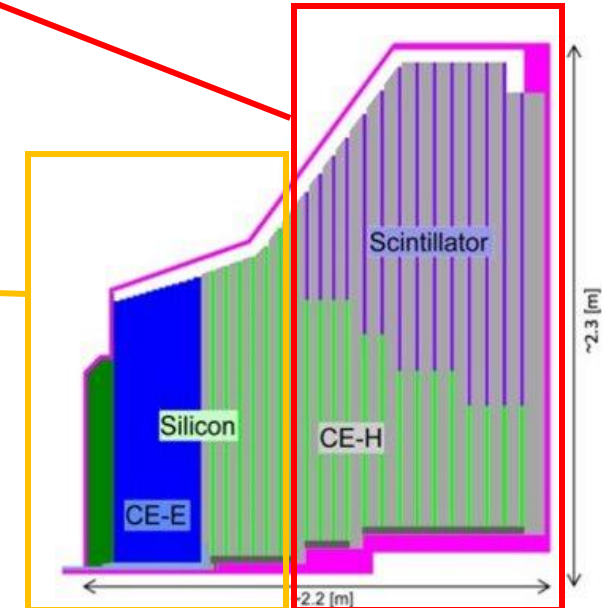
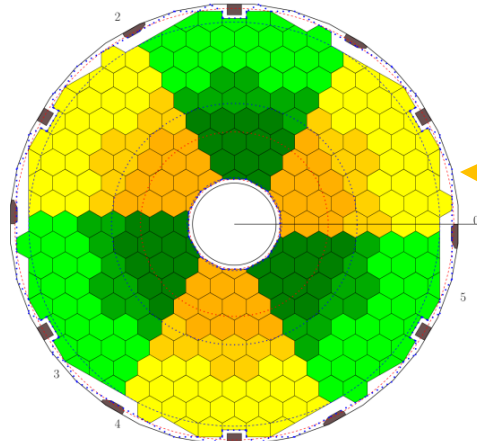
What is HGCAL. Basic structure and purpose.

- **Silicon section** (using silicon sensors): Cover the electromagnetic calorimeter (CE-E) and part of the Hadronic calorimeter (CE-H)
- **Scintillator section** (using SiPM-on-tile technology): Cover the CE-H where the expected end-of-life neutron fluence is less than  $5 \times 10^{13}$  n/cm<sup>2</sup>

Mix layer of silicon and scintillator section



Layer with only silicon section





# Basic structure of the High Granularity Calorimeter (HGCAL)

## Active elements and key parameters

### Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- “Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

### Key Parameters:

Coverage:  $1.5 < |\eta| < 3.0$

~215 tonnes per endcap

Full system maintained at  $-30^{\circ}\text{C}$

~620m<sup>2</sup> Si sensors in ~26000 modules

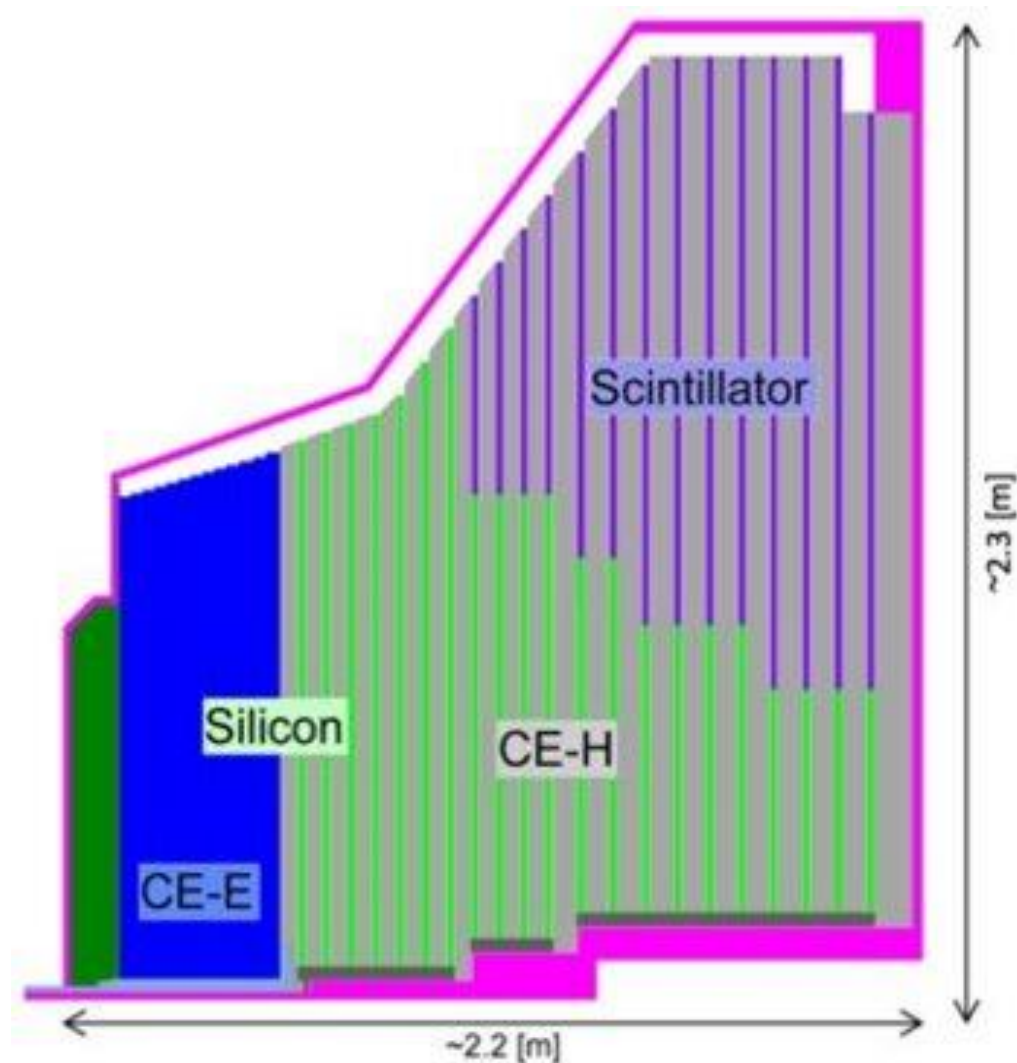
~6M Si channels, 0.6 or 1.2cm<sup>2</sup> cell size

~370m<sup>2</sup> of scintillators in ~3700 boards

~240k scint. channels, 4-30cm<sup>2</sup> cell size

Power at end of HL-LHC:

~125 kW per endcap



Electromagnetic calorimeter (CE-E): **Si**, Cu & CuW & Pb absorbers, 26 layers,  $27.7 X_0$  &  $\sim 1.5\lambda$

Hadronic calorimeter (CE-H): **Si** & **scintillator**, steel absorbers, 21 layers,  $\sim 8.5\lambda$

# What is HGCal, and why do we need it

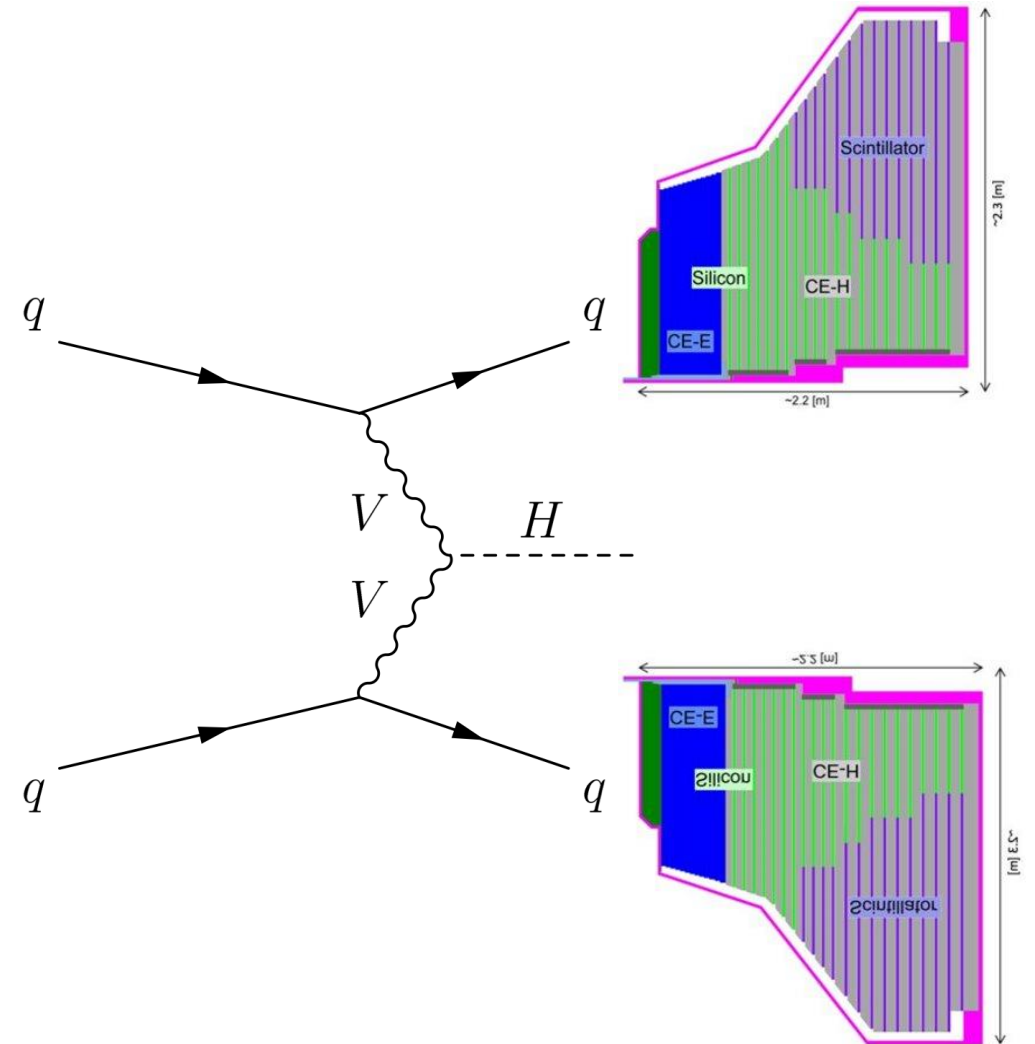
## Physics motivations

### Vector boson fusion (VBF)

- Two quarks from each of the LHC protons collide with each other. The quarks radiate off a heavy vector boson ( $W$  or  $Z$ ) and are deflected slightly from their original direction.
- The **particle jet of the deflected quarks** and the **heavy vector boson** can be detected by the HGCal.

### Quark-Gluon Discrimination

- The **high granularity** of HGCal can help improving **jet identification**.

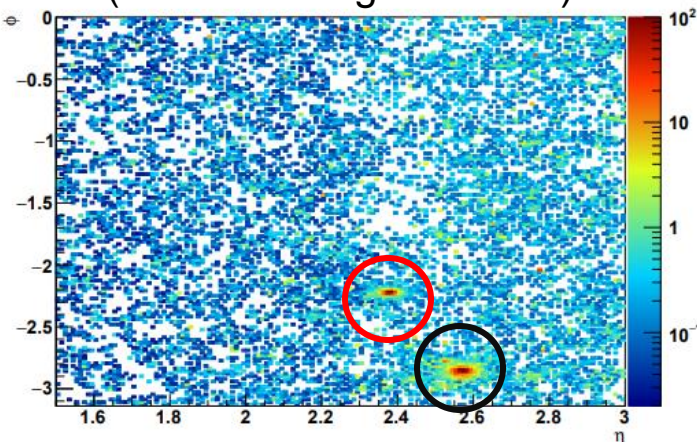


# What is HGCAL, and why do we need it

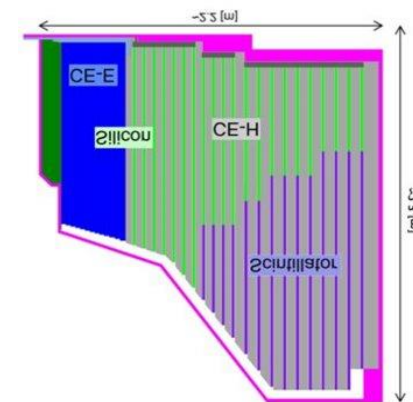
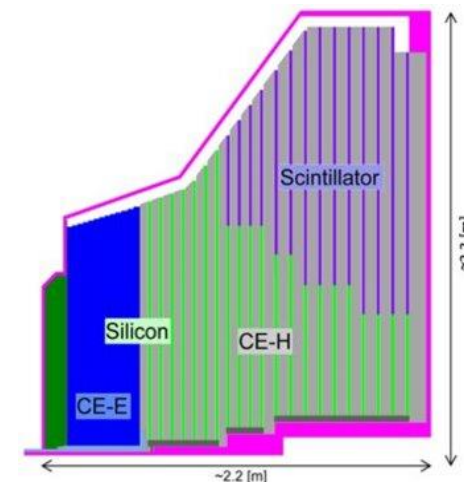
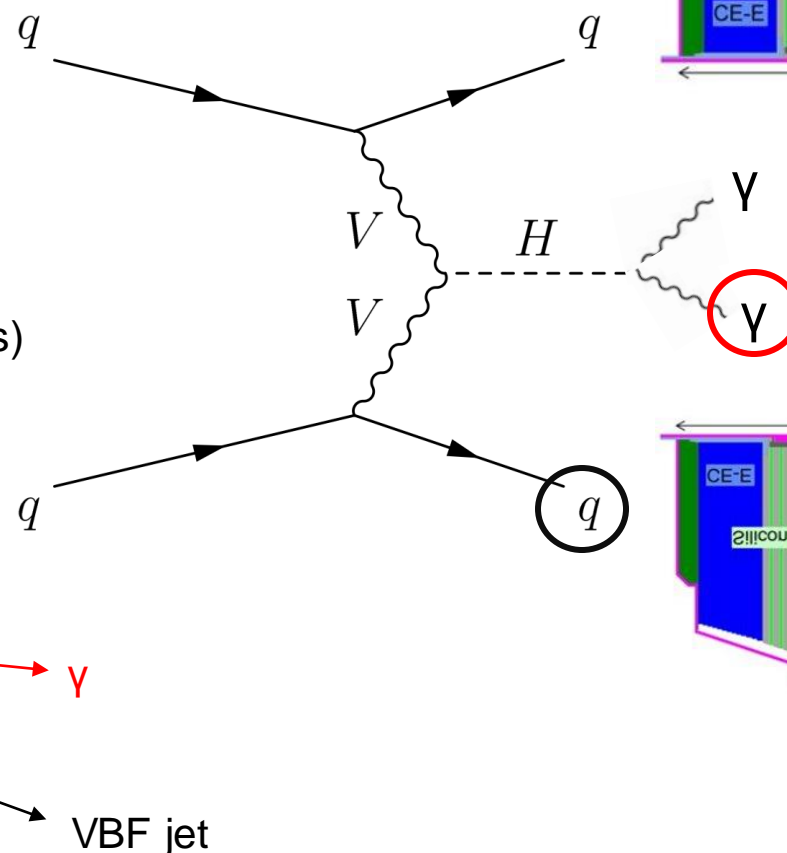
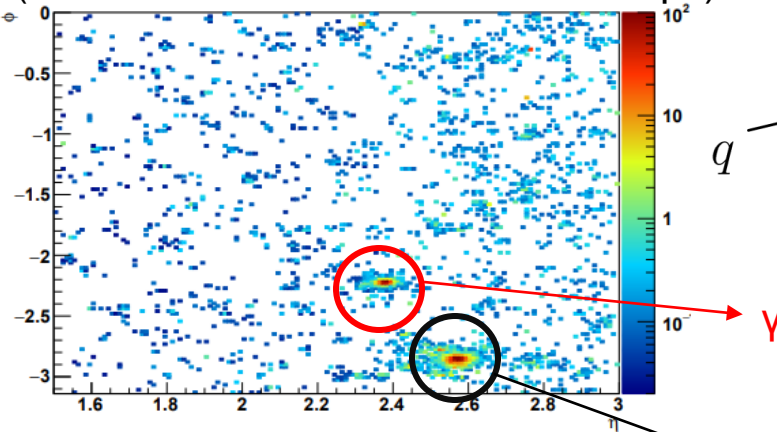
## The importance of precision about time and space

- With the **high granularity**, HGCAL will be able to identify **VBF jets**.
- The **pileup issue** can be greatly **improved** with good **timing resolution** (tens of picoseconds) of the HGCAL. (Ex: VBF  $H \rightarrow \gamma\gamma$ )

VBF  $H \rightarrow \gamma\gamma$   
(without timing selection)



VBF  $H \rightarrow \gamma\gamma$   
(select hits with time window  $< 90$  ps)

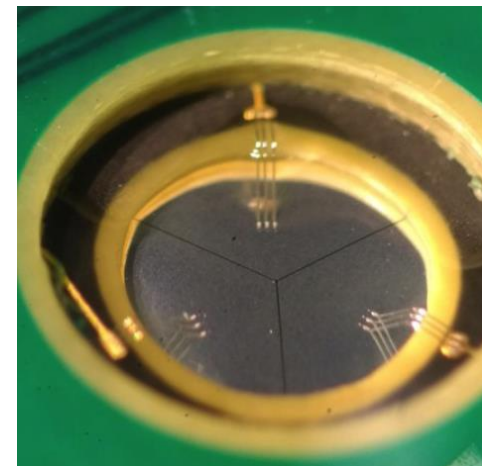
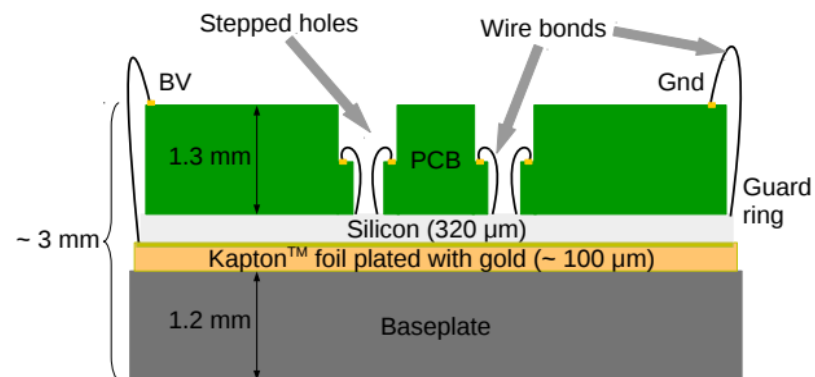


# 02 Silicon section of the HGCal

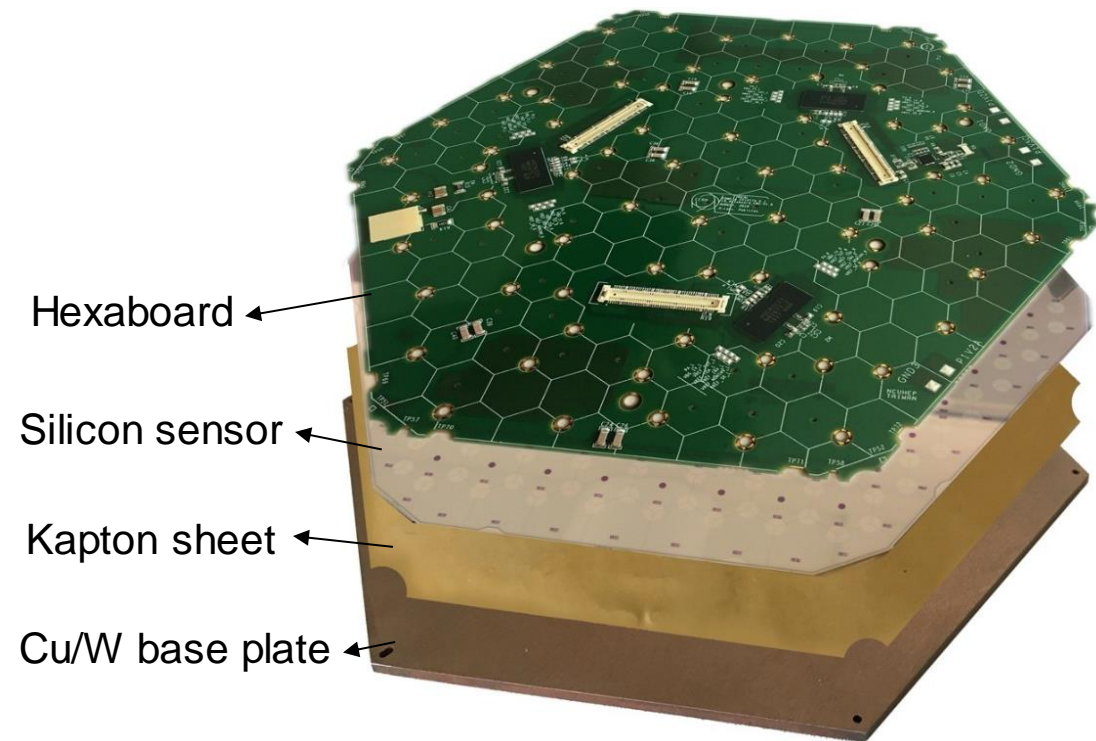
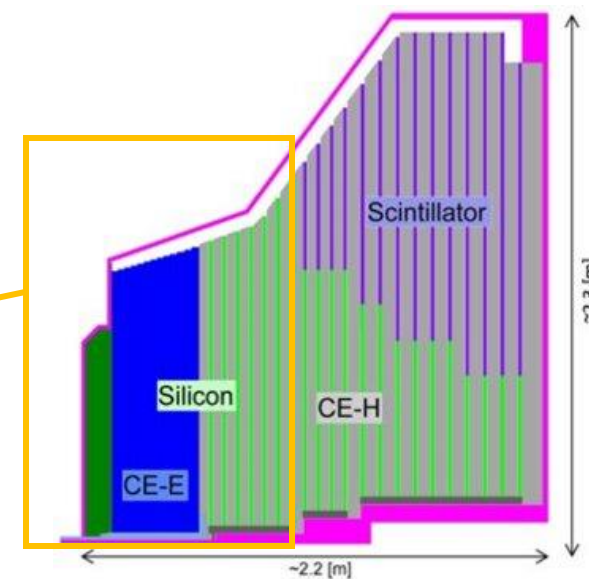
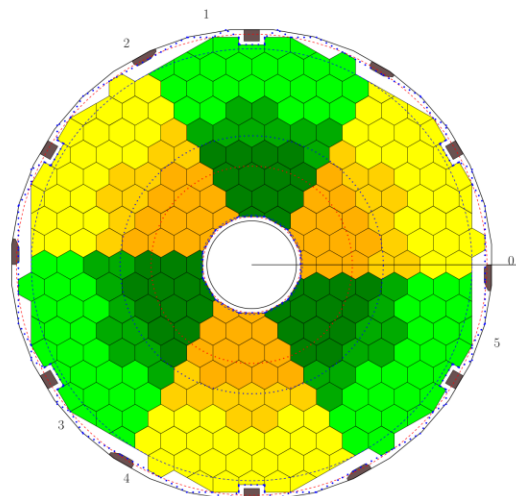
# Silicon module (hexaboard)

## Structure of the hexaboard

- The basic element in the silicon section of the HGCAL is called **hexaboard**.
- Silicon cell size: **0.5** (for **HD** hexaboard) and **1 cm<sup>2</sup>** (for **LD** hexaboard).
- Data readout by **HGCROC** chip.



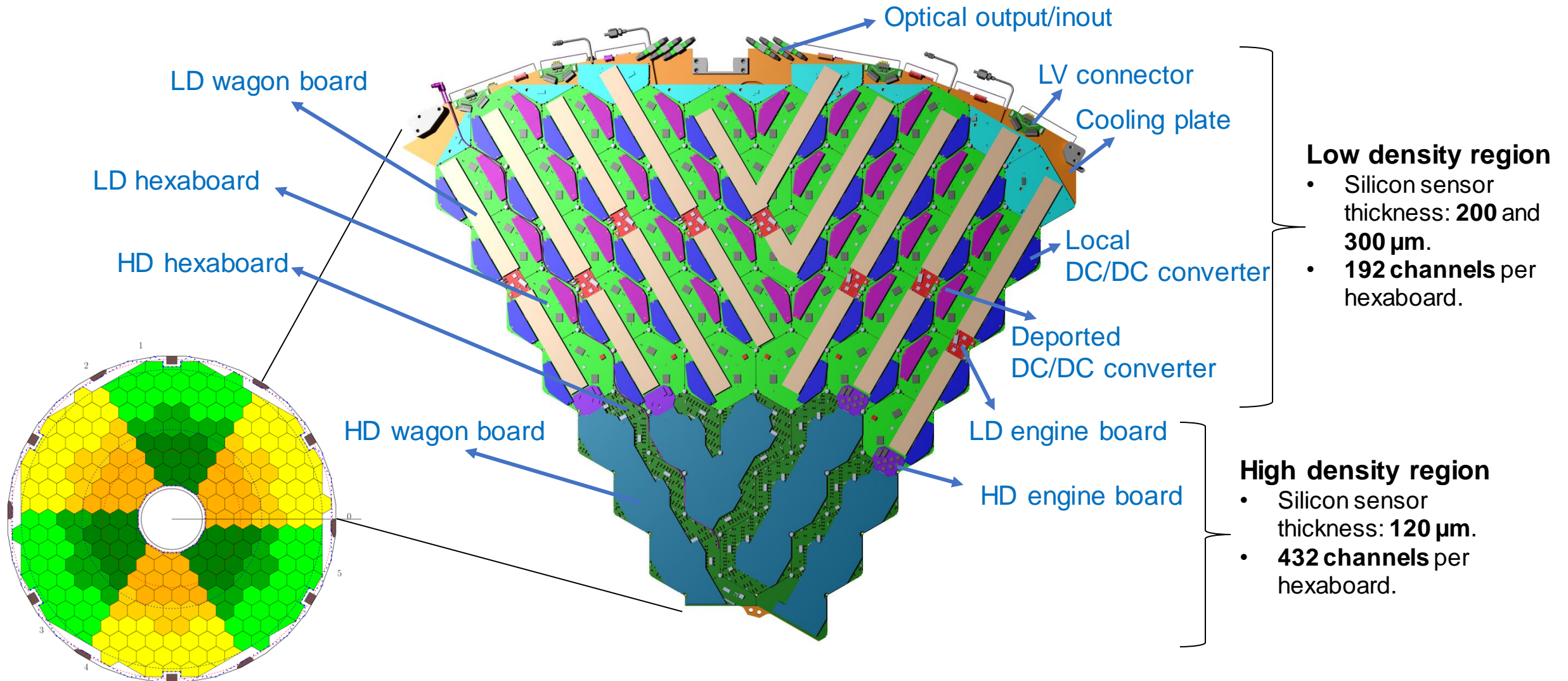
Layer with only silicon section





# A cassette in the silicon section

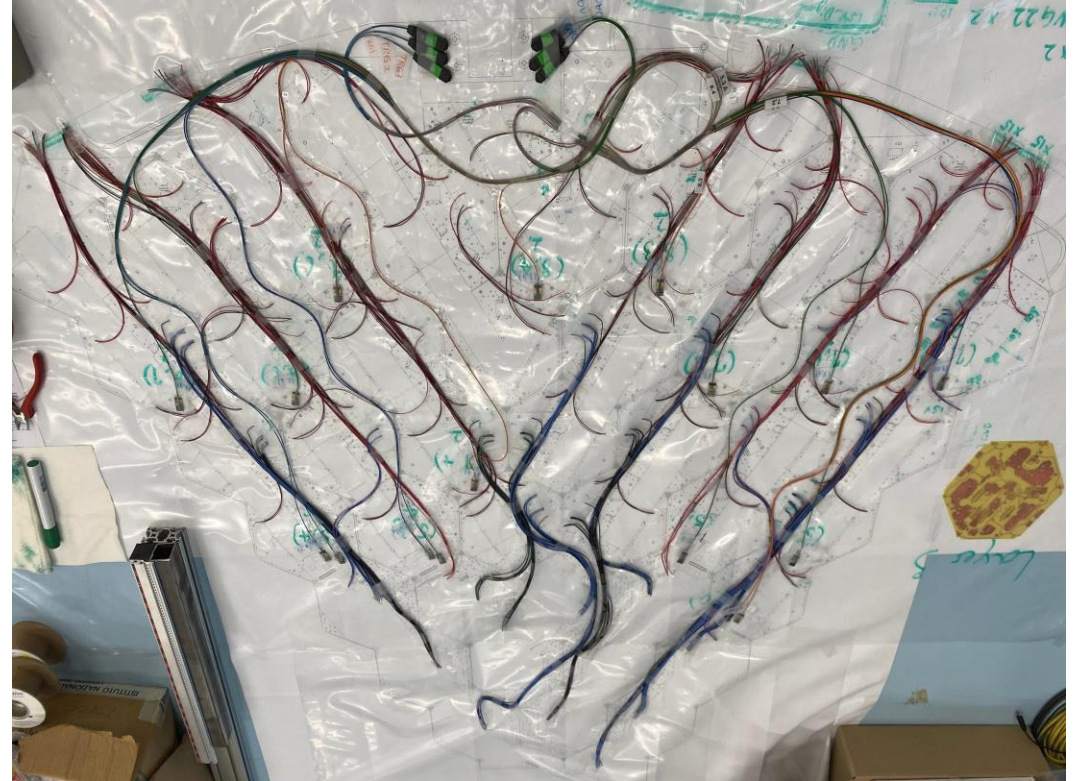
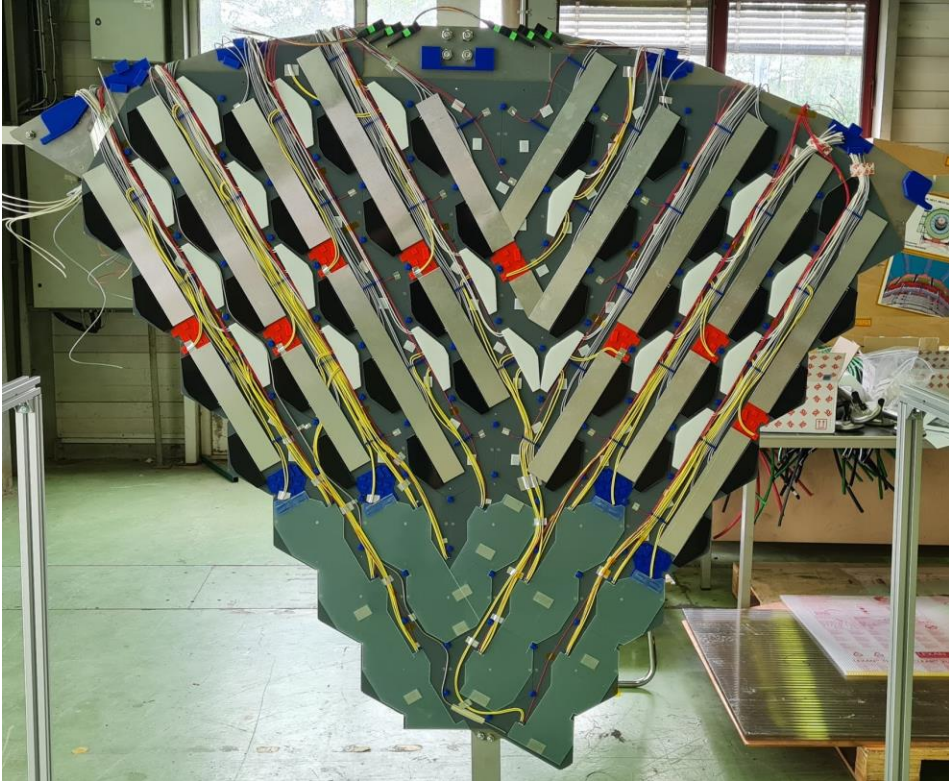
## Structure of the hexaboard





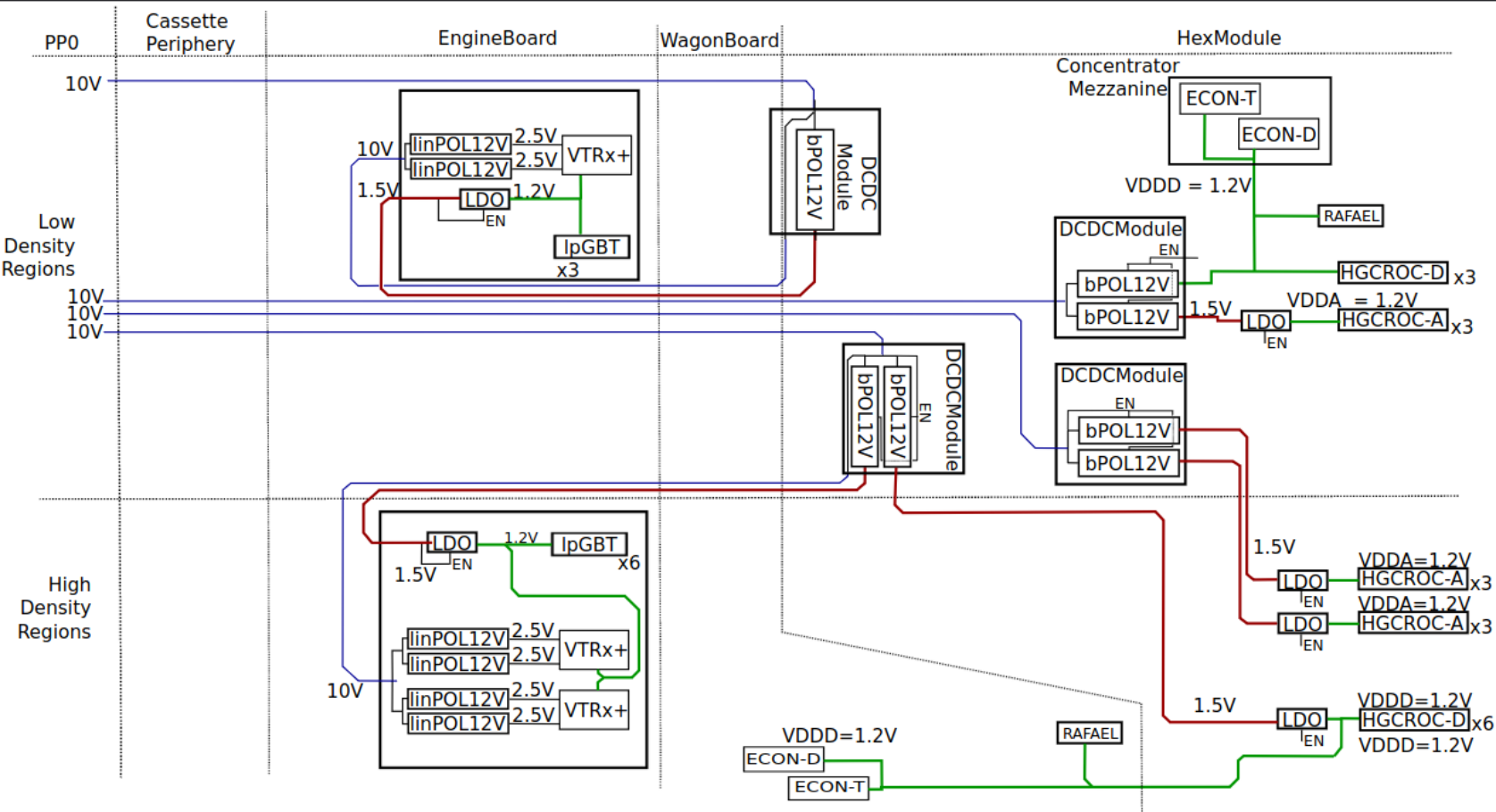
# A cassette in the silicon section

## Mockup cassette in the silicon section

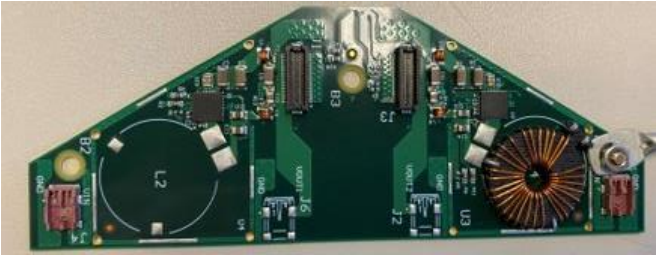


# Power tree of cassette

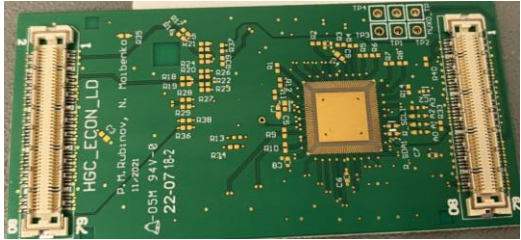
For the cassette with only hexaboards



DC/DC module



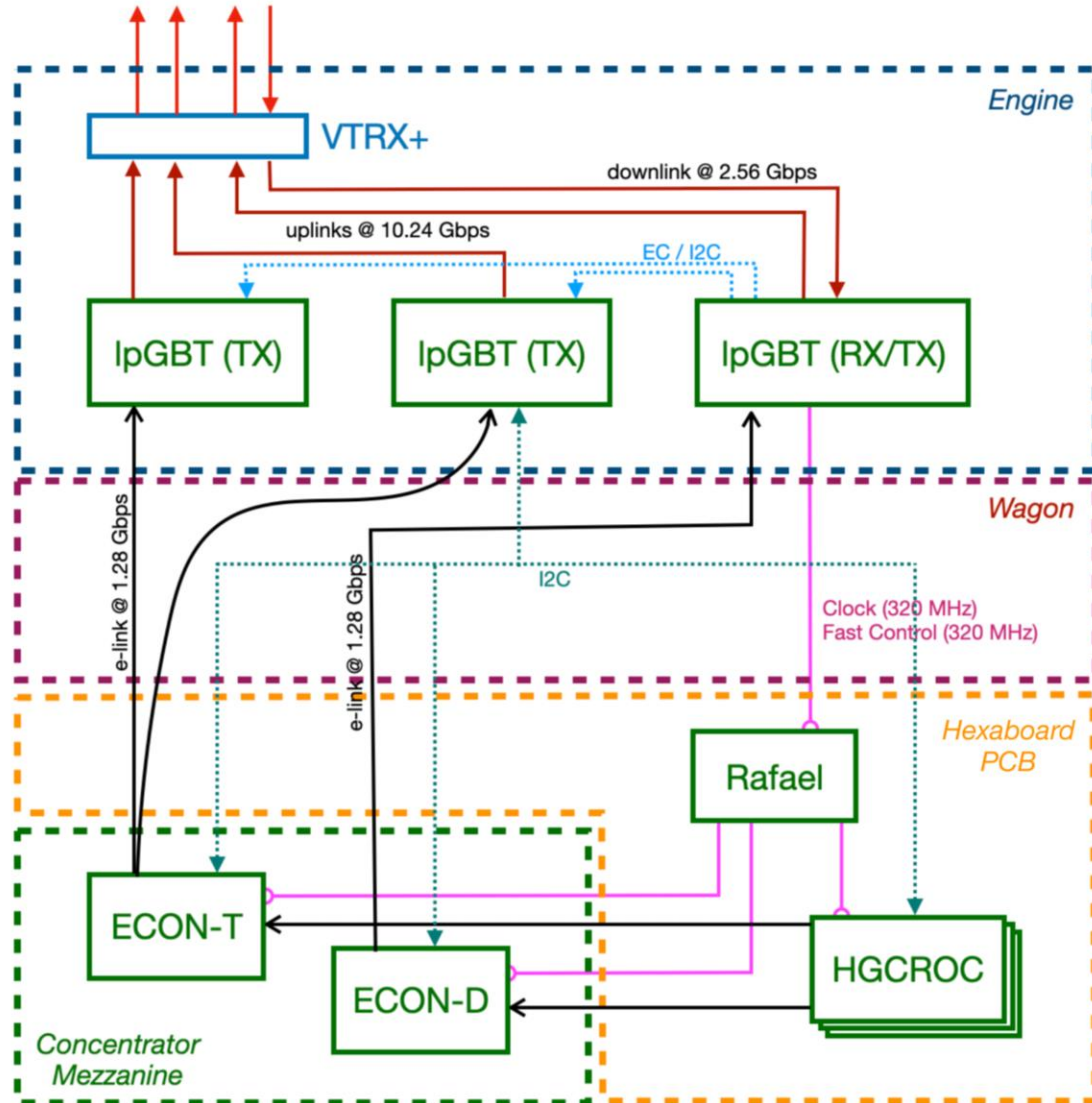
ECON mezzanine





# Front-end data acquisition (DAQ) system

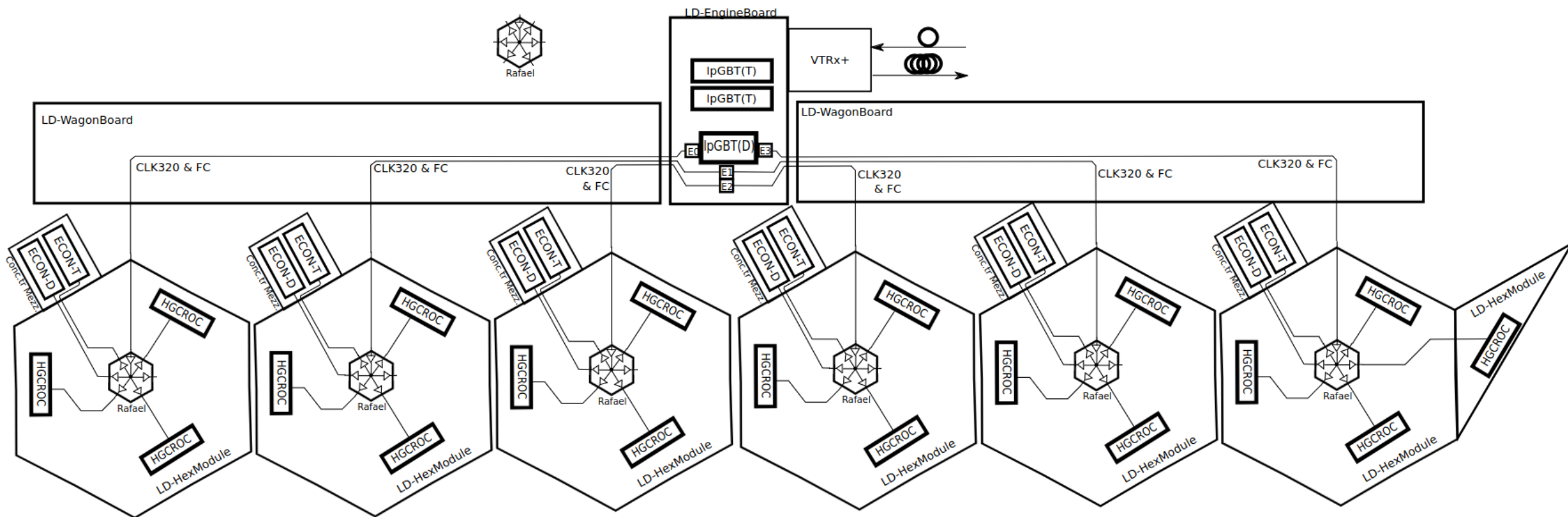
## Where the data go



- **HGCROC: Data readout chip.** There are 3 of it on the LD hexaboard, and 6 on the HD hexaboard. Receive and digitize signals coming from the silicon sensor.
- **ECON-T: Concentrator chip for trigger path.** Select and compress trigger data from the HGCROC. Trigger data transmission in 40 MHz.
- **ECON-D: Concentrator chip for DAQ path.** Channel alignment and zero suppression. Collect data from the HGCROC after level 1 trigger accept (L1A). DAQ data transmission in 750 kHz.
- **Rafael: fanout chip** for clock and fast control.
- **IpGBT: Send and receive data, clock, fast command** from versatile transceiver (VTRx+). Also responsible in sending **slow control** via I2C

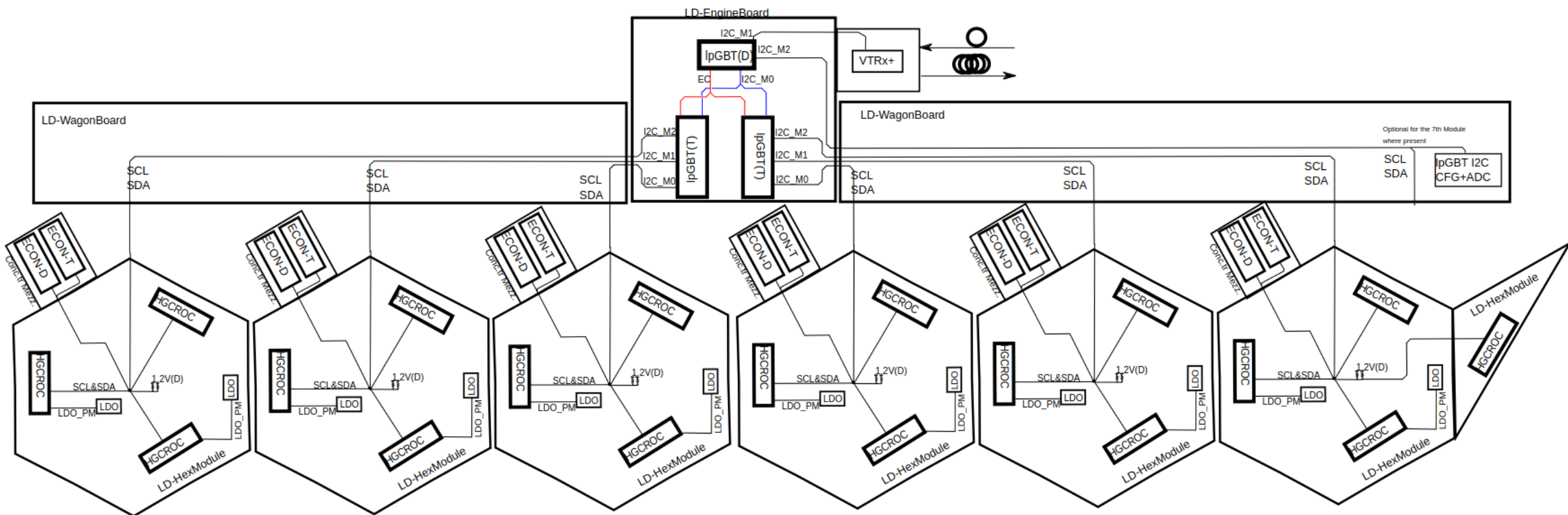
# Frontend data acquisition (DAQ) system

Fast command and clock for the LD hexaboard.



# Frontend data acquisition (DAQ) system

Slow control for the LD hexaboard.





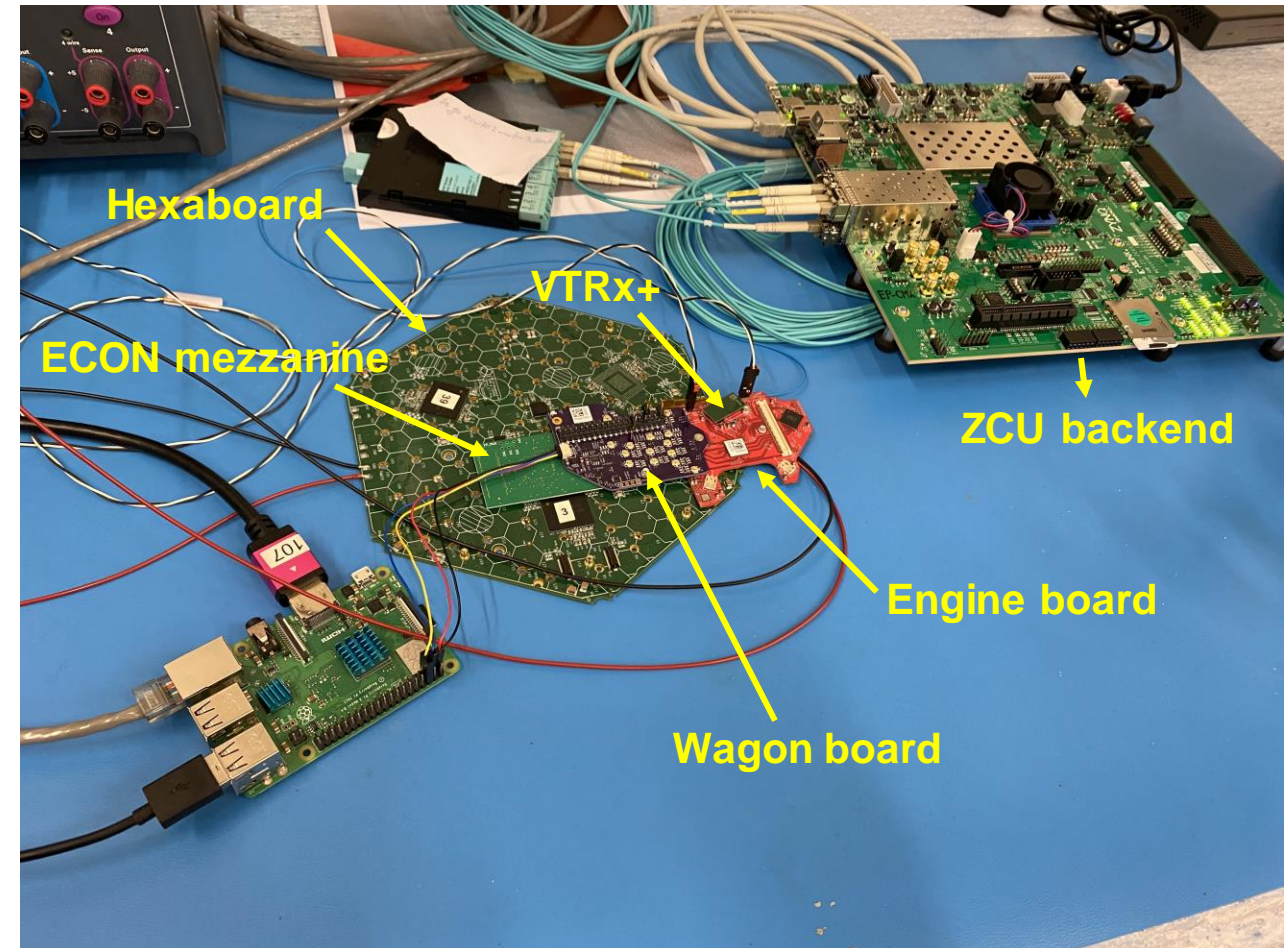
# System test for the LD hexaboard

## System test of the v3 hexaboard

- With **ECON mezzanine** (only equipped with ECON-T), **Wagon board**, **VTRx+**, mini backend (**zcu102**).
- Able to send **slow control**, **fast command**, and **read/write to registers** in the front end ASICs.
- Able to **transmit trigger** and **event data** from the HGCROC. (configured to send dummy data)



A successful I2C transaction between two front end ASIC

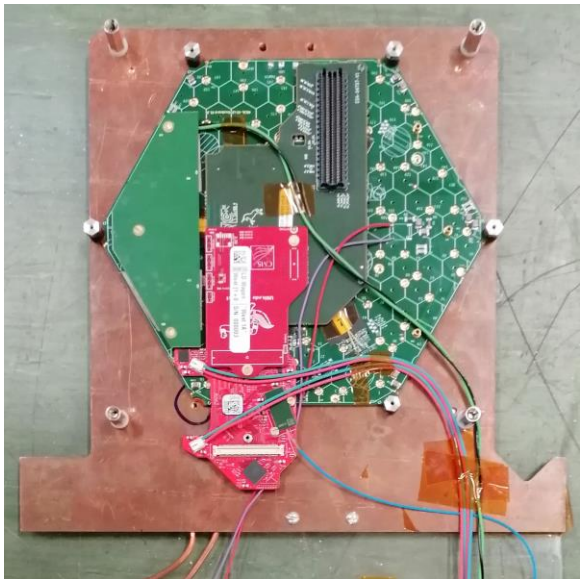




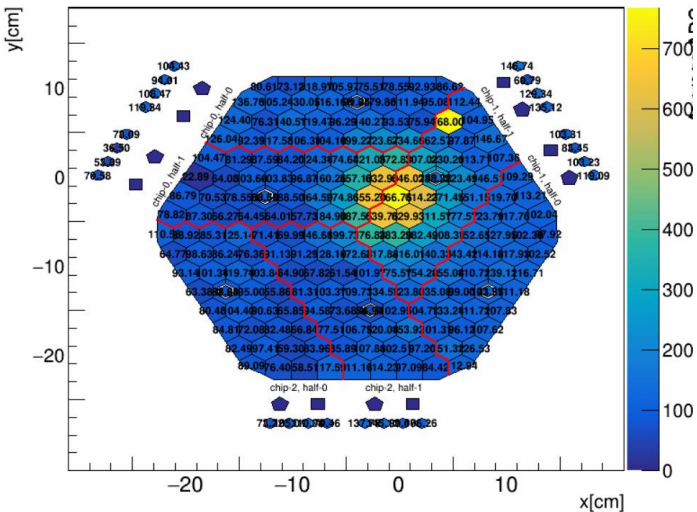
# Test beam at CREN in August 2023

## Test beam for hexaboard

Mounted hexaboard on a Cu cooling plate



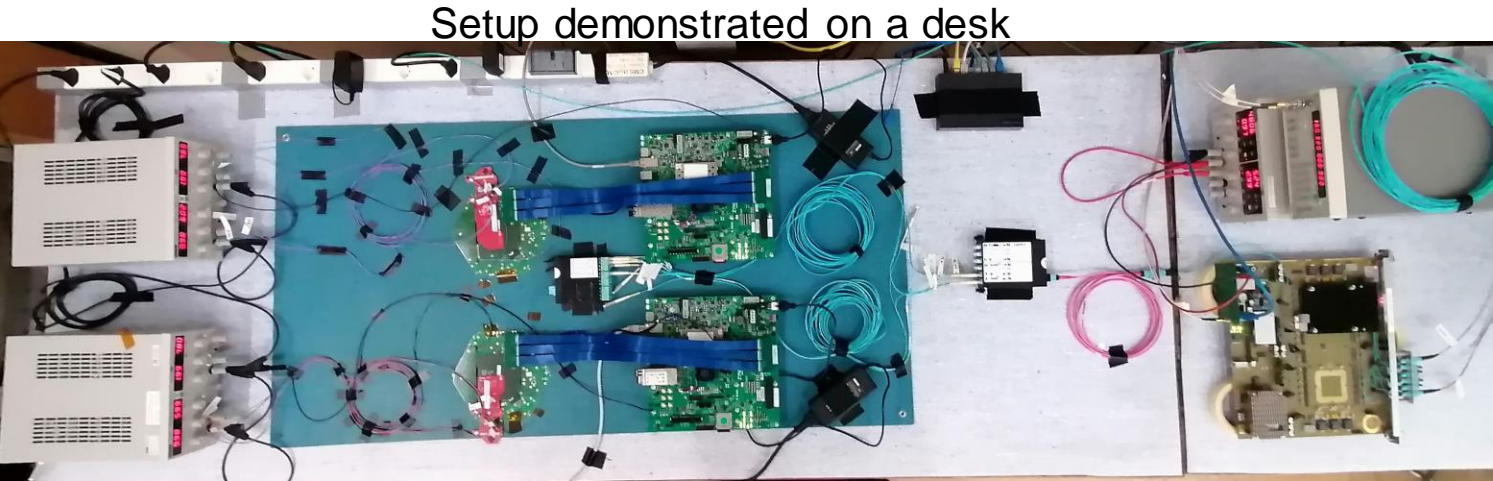
Successfully detect the beam



Front end setup



The group that make it happen!



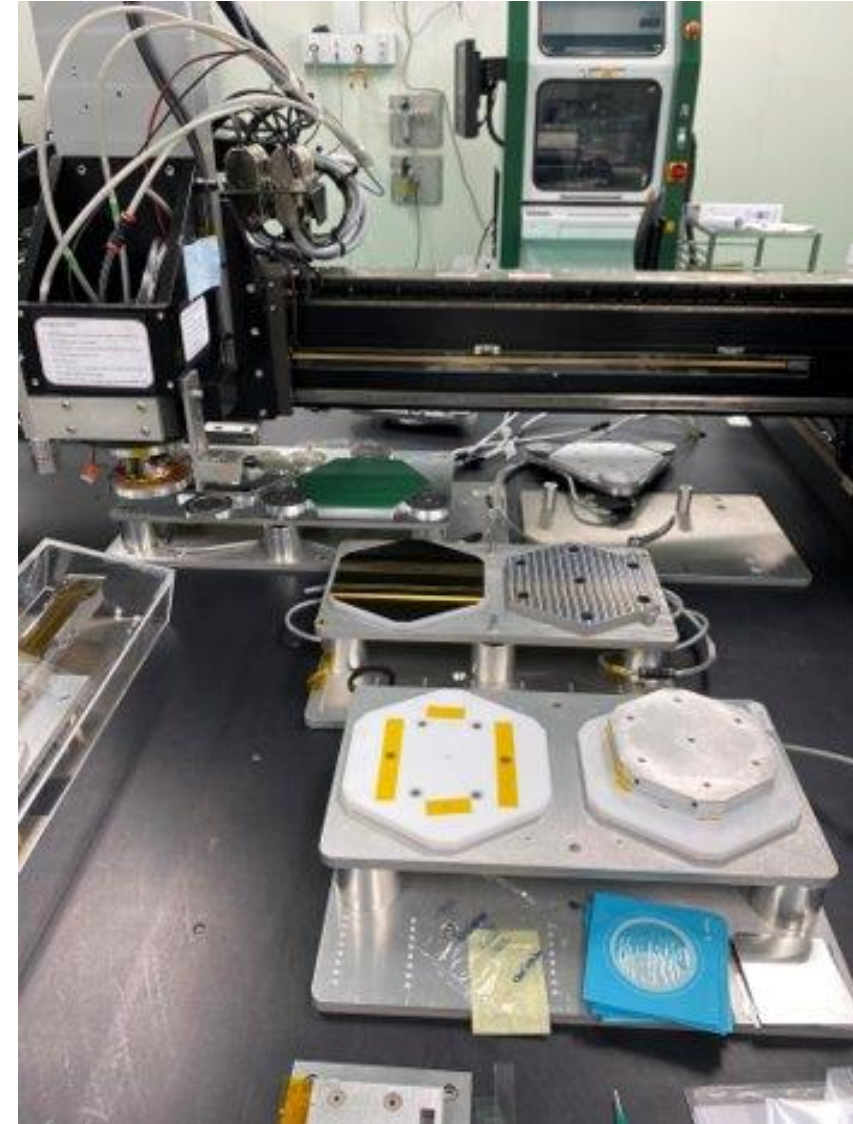


# Module assembly

## System test of the v3 hexaboard

- There are currently **6 module assembly centres (MAC)** for producing hexaboards.
- Video of the hexaboard module assembly procedure (from the NTU MAC in Taiwan):

<https://www.youtube.com/watch?v=f0fYa6sCFZY&t=407s>

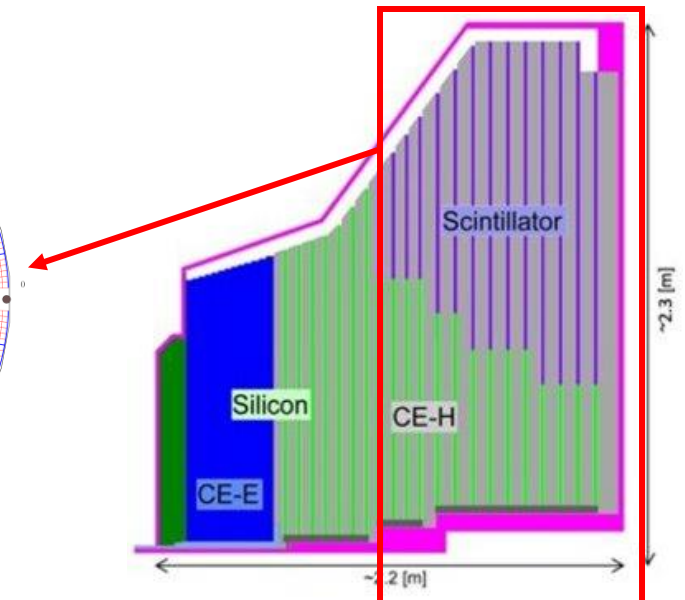
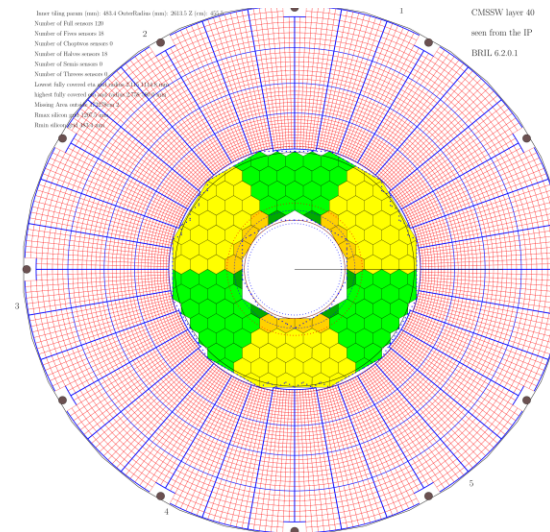
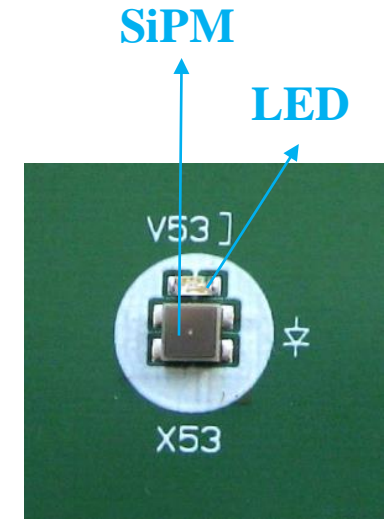
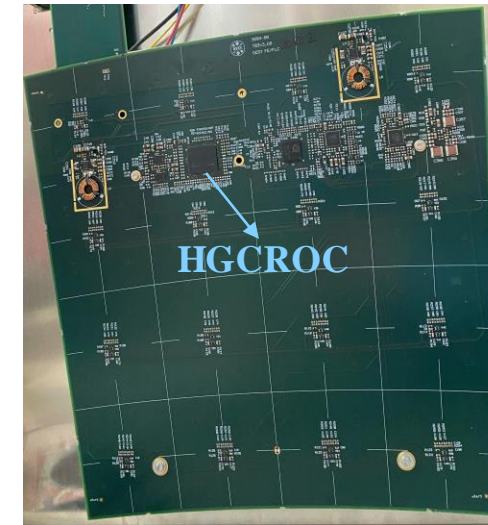
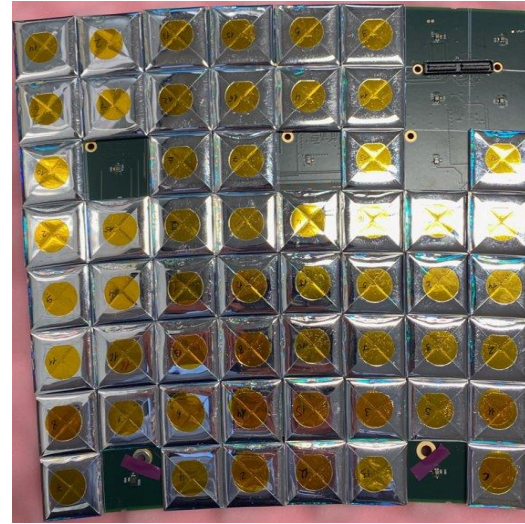


# 03 Scintillator section of the HGCal

# Tilemodule with SiPM-on-tile technology

## Components of a Tilemodule

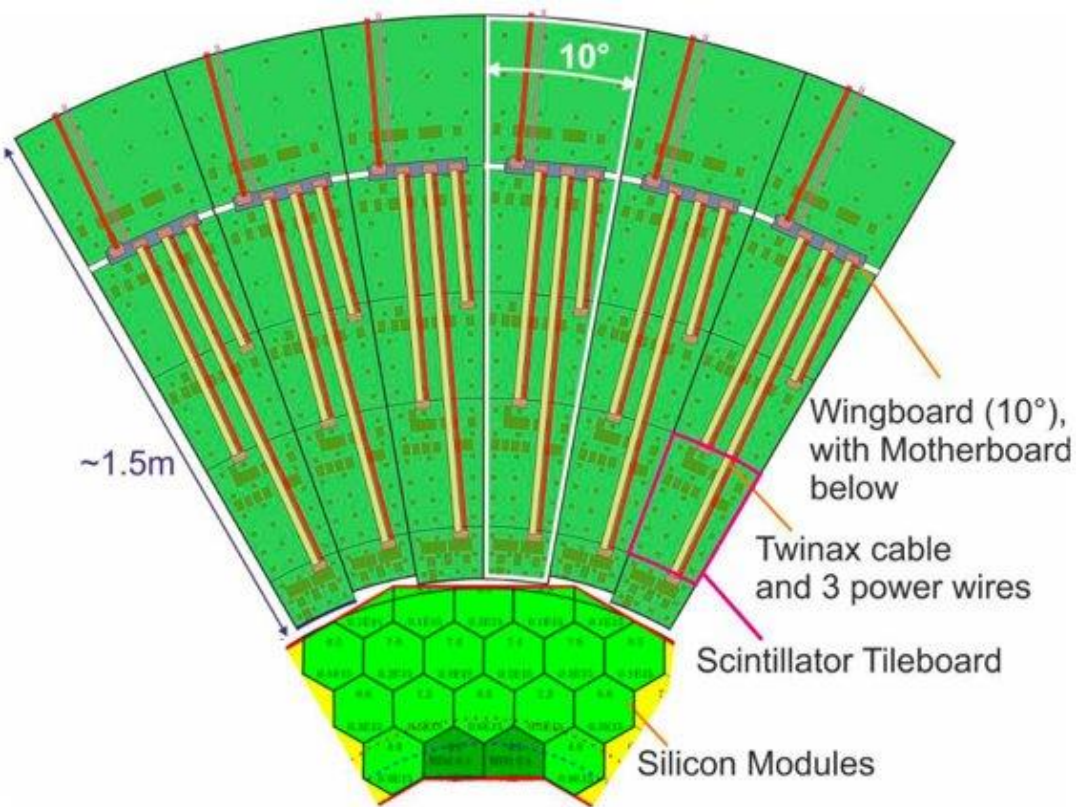
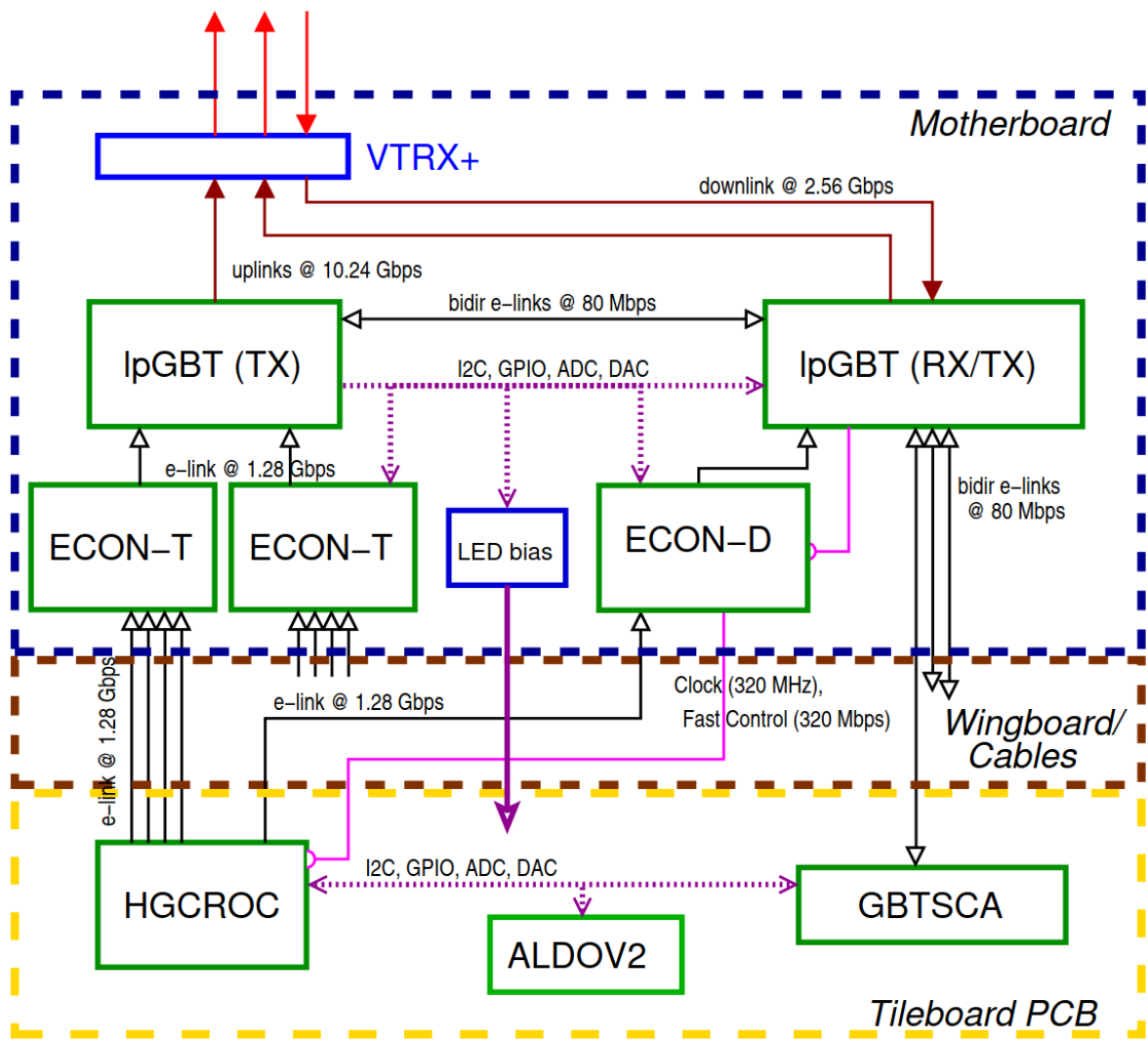
- A complete **Tilemodule** is a **basic unit** for particle detection in the **scintillator section** of the HGCAL.
- The Tilemodule includes **wrapped scintillator tiles**, **SiPMs**, **HGCROC**, **LED calibration system**, and other electronics.
- There are **240k channels** in the Scintillator part in the HGCAL.
- With scintillator **tile size**  $4 \sim 30 \text{ cm}^2$ , and **SiPM size**  $4 \text{ mm}^2$  and  $9 \text{ mm}^2$
- The HGCROC **readout 72 channels** from the Tilemodule.
- The HGCROC has **2 DAQ elinks** and **4 trigger elinks** (1.28 Gbps/elink) for data readback.





# Frontend data acquisition (DAQ) system

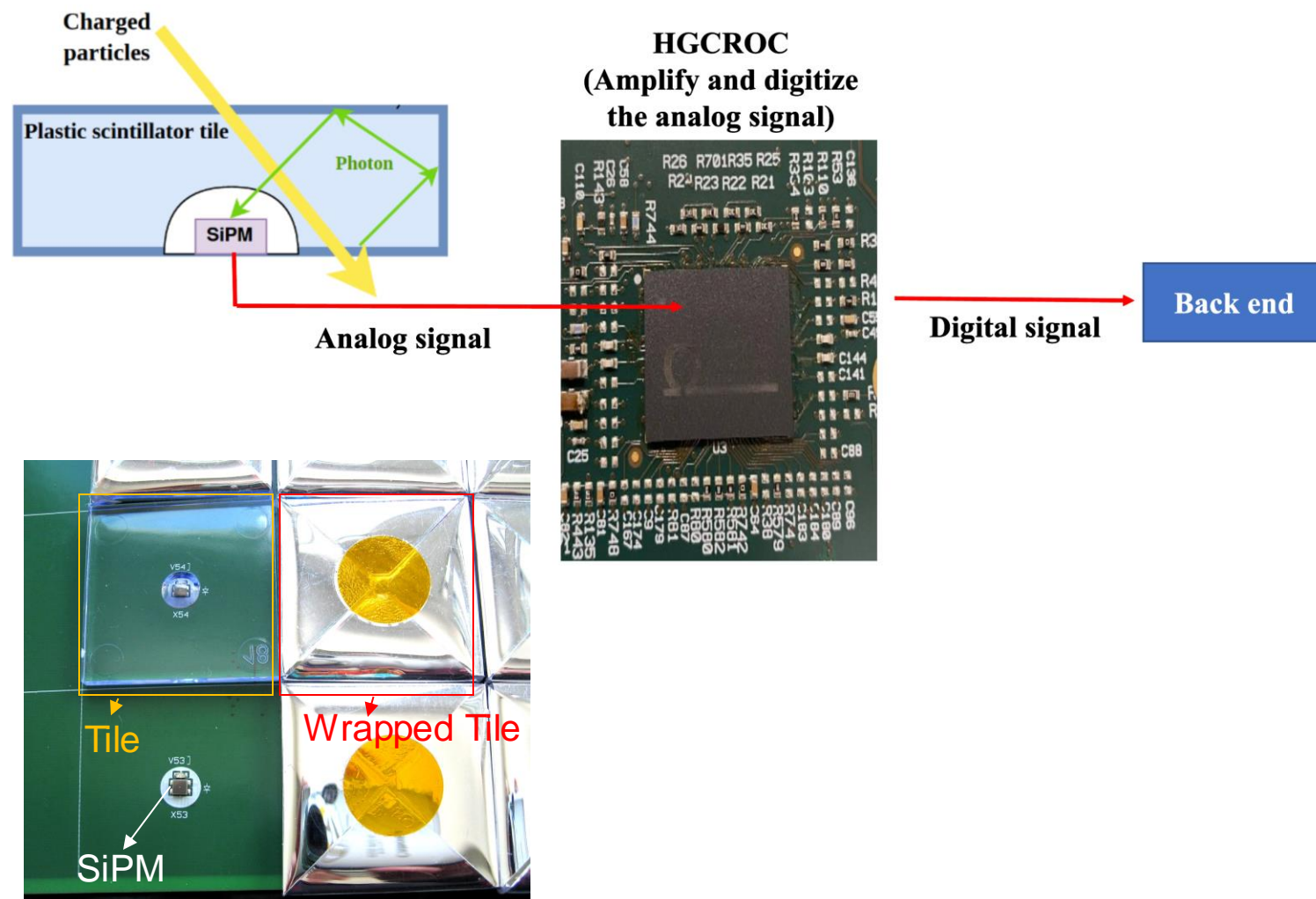
## Where the data go



# SiPM-on-tile technology in the scintillator section of HGCal

## Components, readout system

- The SiPM-on-tiles include **wrapped plastic scintillator tiles** and **silicon photomultiplier (SiPM)**
- Tiles are wrapped in reflective foil which can maximize the chance of light reaching the SiPM.
- **Smaller tile size and larger SiPM size can collect more light** to the SiPM.
- The **size of tiles are chosen for good S/N for MIP calibration** (needed until its end of life)
- SiPM can detect photons from the tiles.

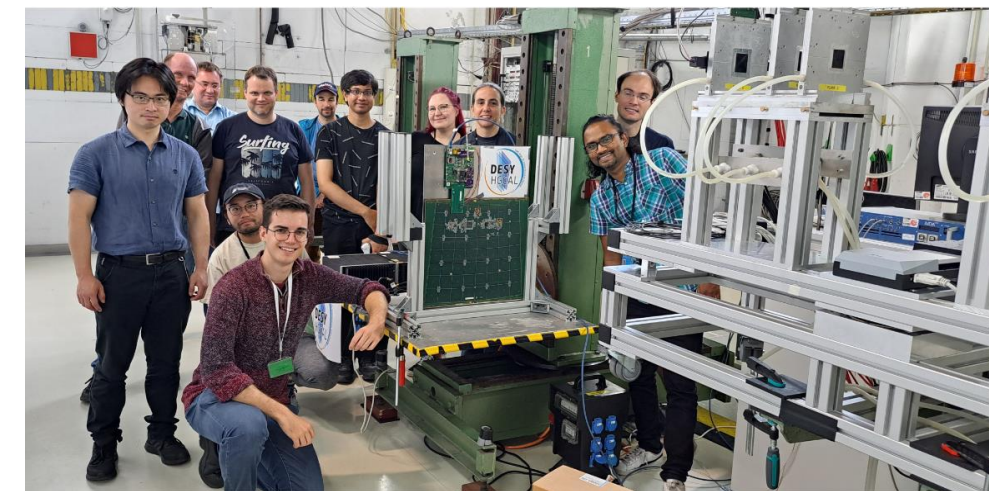
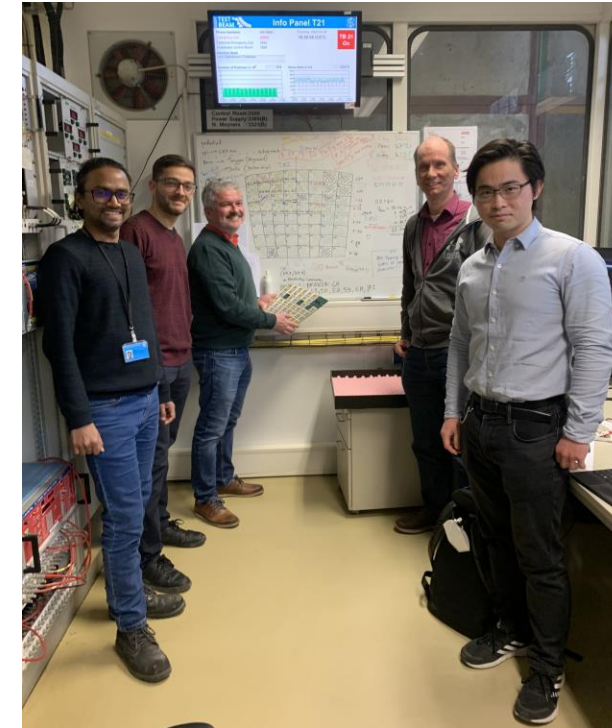
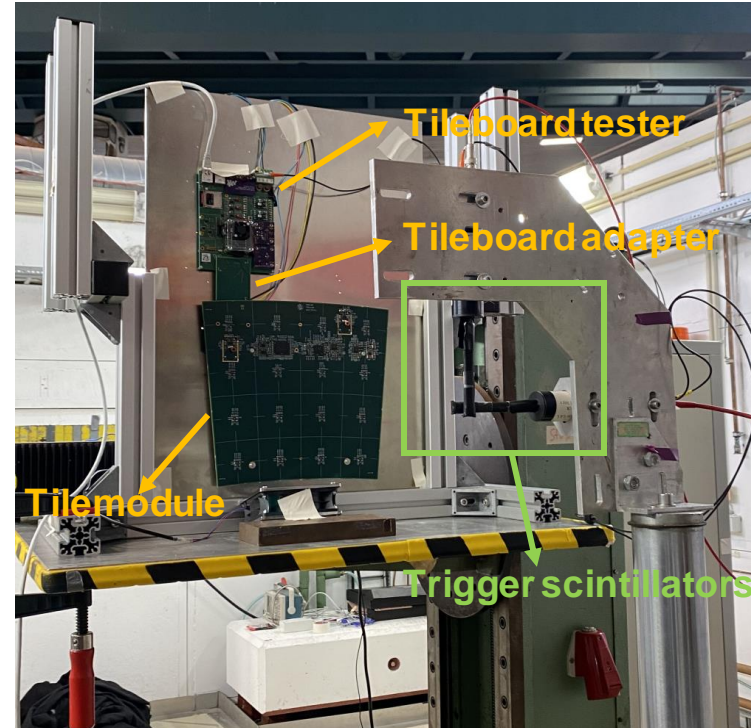




# Test beams of the Tilemodules at DESY

## Test beams that has been done at DESY

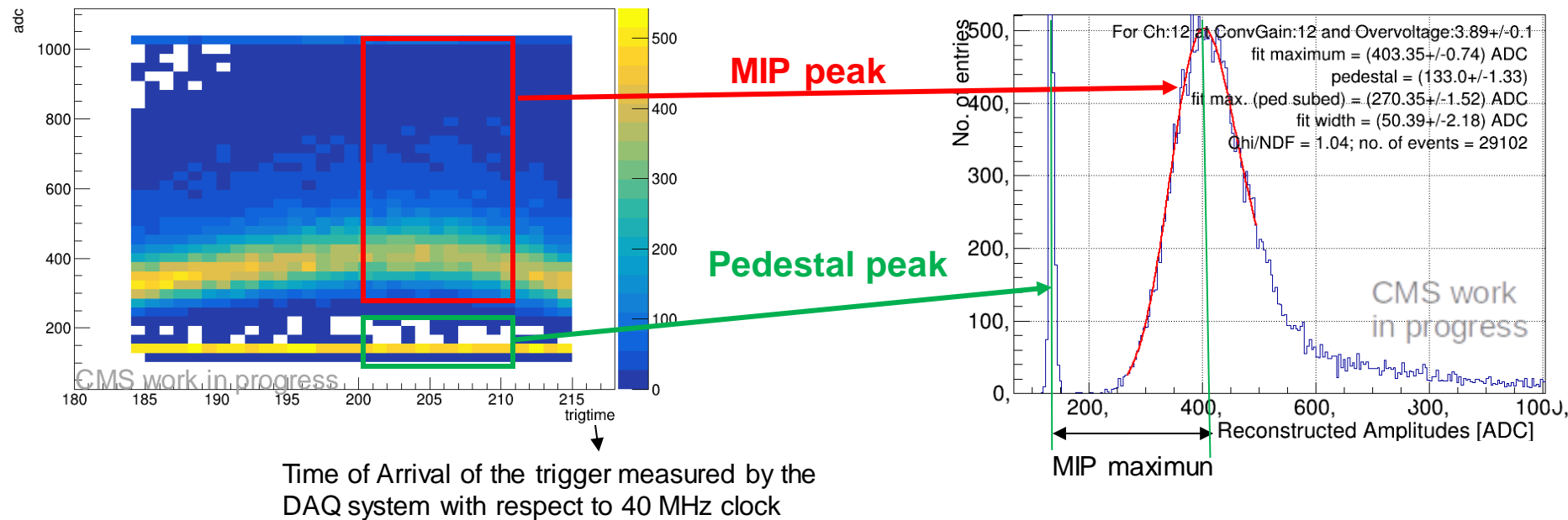
- **Validated** the performance of the **SiPM-on-tile** on **Tilemodules** with all the on-board electronics.
- Using **3 GeV electrons** at the DESY-II test beam facility.
- This includes:
  - Different **SiPM sizes**
  - Different **scintillator tile sizes**
  - Different **scintillator materials** produced using different **techniques**
  - **Irradiated** and **Non-irradiated** SiPMs



# Test beam of the Tilemodule at DESY

## Using pulse shape and trigger information for MIP extraction

- The HGCROC is designed to work in sync with the 40 MHz LHC clock.
- The DESY clock is asynchronous to this. Therefore the signal could come anytime within a clock cycle.
- The DAQ system also has an internal clock which measures the TOA measurement of the trigger with  $\sim 0.8$  ps resolution for each event. This trigtme information therefore can be used to reconstruct the pulse shape as seen in the plot below.
- The **MIP maximum** can be obtained by measuring the **peak** value of the MIP spectrum and then **subtracting the pedestal**.



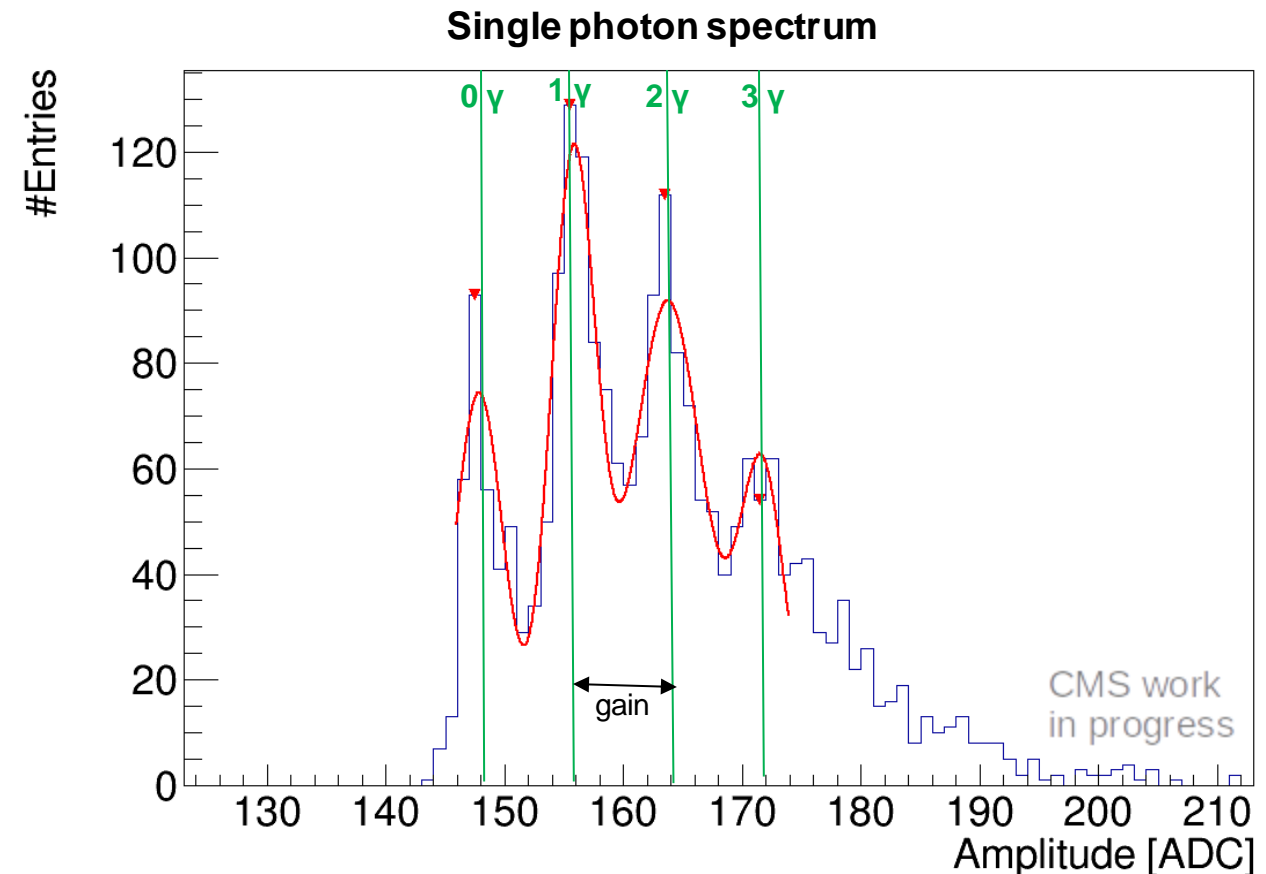
# Test beam of the Tilemodule at DESY

## Measure SiPM gain from single photon spectrum

- A **low intensity LED** is equipped **next to each SiPM** on the Tilemodule.
- Photons produce by the LED are captured by the SiPM.
- Sampled SiPM signals will produce a **Single Photon Spectrum (SPS)** with each peak corresponding to the **number of photons** detected by the SiPM.
- The **difference between two peaks** is defined as the **SiPM gain** in photon equivalent units (p.e.).

**Light Yield (number of photo-electrons captured):**

$$\text{Light Yield [p.e.]} = \frac{\text{MIP maxima [ADC]}}{\text{SiPM gain [ADC]}}$$

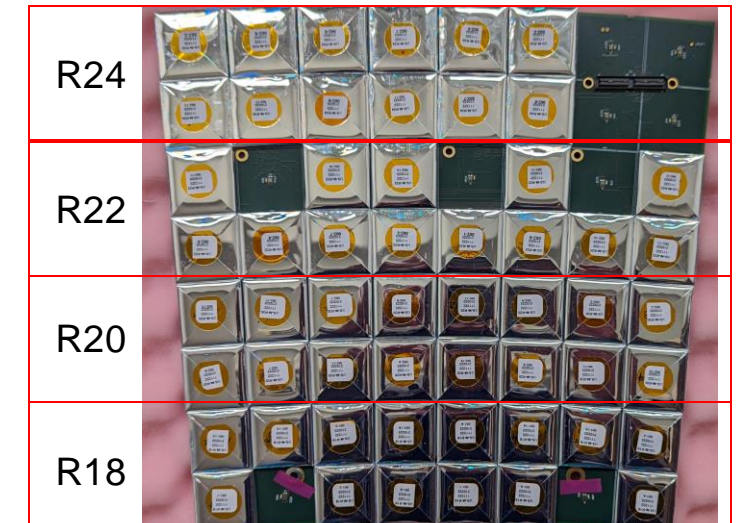
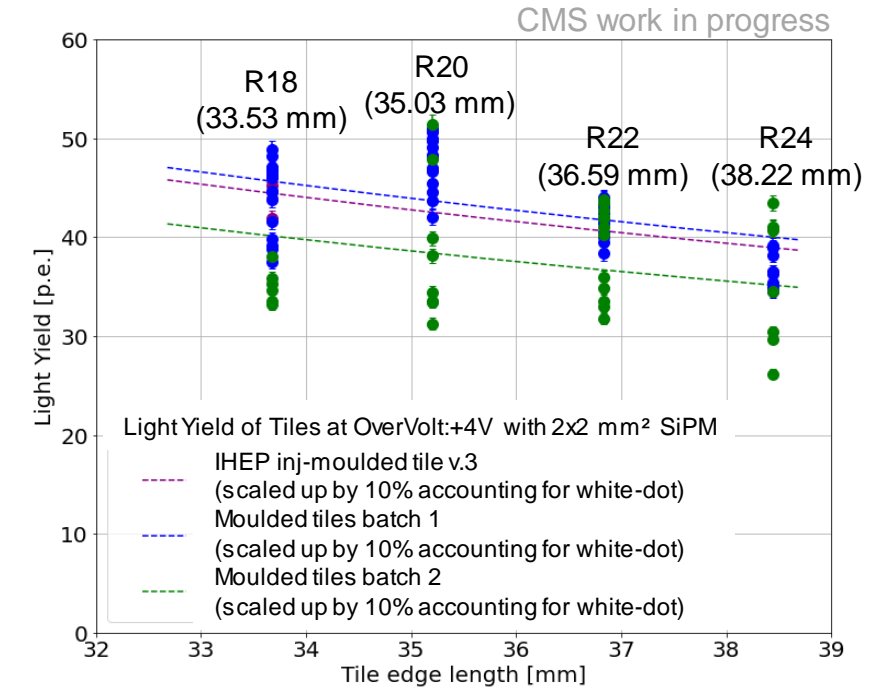




# Test beam of the Tilemodule at DESY

## Compare light yield measured from different type and size of tiles

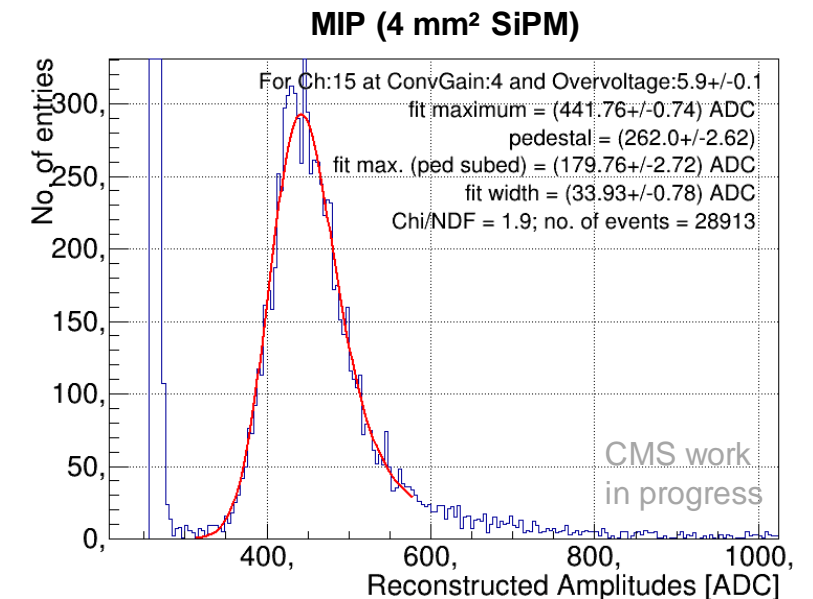
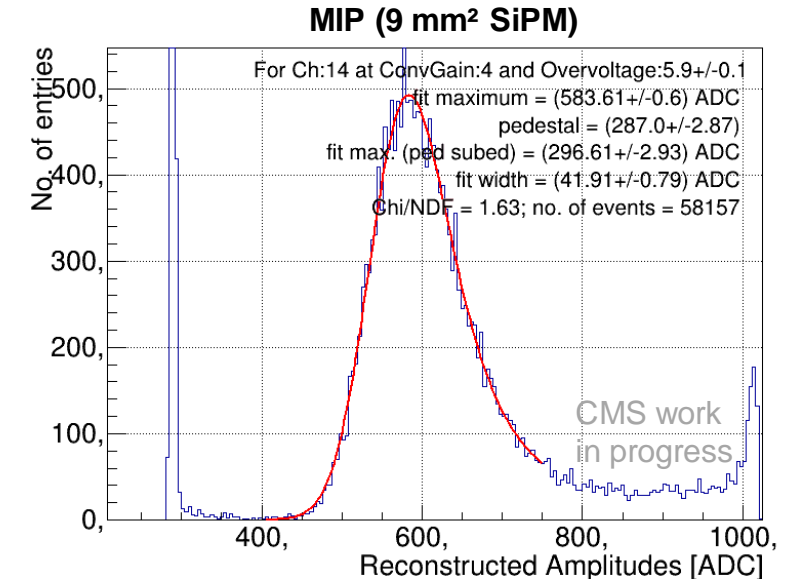
- There are **4 different size of tiles** on the Tilemodule tested.
  - 33.53 mm (R18), 35.03 mm (R20), 36.59 mm (R22), 38.22 mm (R24) side lengths.
- Light yield is inversely proportional to the squared root of the tile area, so **smaller tiles have a larger light yield**.
- The **moulded tiles batch 1** (made by the current producer) has a **light yield close to the IHEP inj-moulded tile v.3** (made by the previous producer, not available for tile production anymore).
- The three moulded tile batches use different **material compositions** which explain the **different light yields**.



# Test beam of the Tilemodule at DESY

## Different SiPM size (non-irradiated SiPM)

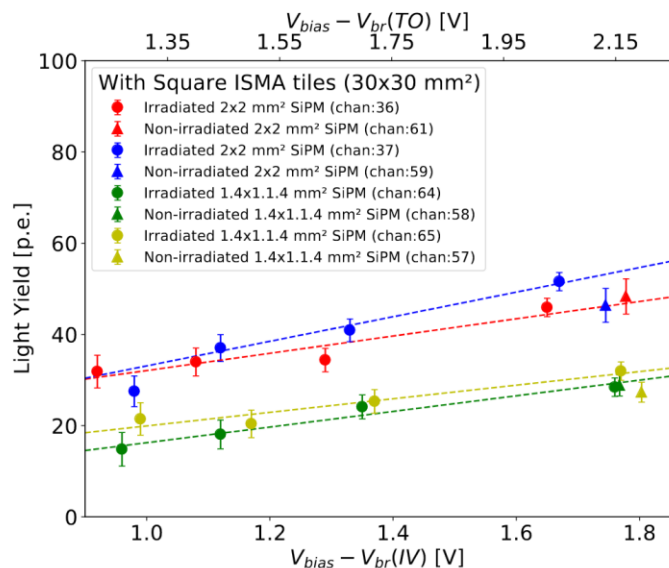
- Measure the **MIP** spectrum for **4 mm<sup>2</sup>** and **9 mm<sup>2</sup> SiPM** on the **mini Tileboard** with the same configuration and same type of tile (IHEP inj-molded v.2 tile).
- The **MIP maximum** for the **9 mm<sup>2</sup> SiPM** is **larger than** the **4 mm<sup>2</sup> SiPM**
- Apply **correction** to the **light yield** measured from 4 mm<sup>2</sup> and 9 mm<sup>2</sup> SiPM in Mini Tileboard
  - temperature correction (25°C)
  - over voltage correction (6 V)
- The **light yield** for **4 mm<sup>2</sup> SiPM** is **46.6 p.e.**
- The **light yield** for **9 mm<sup>2</sup> SiPM** is **106.8 p.e.**
- The **ratio** between 9 and 4 mm<sup>2</sup> SiPM is **2.29**, which is **close to the expected ratio**, of **2.25** (estimated from the size of the two SiPMs).



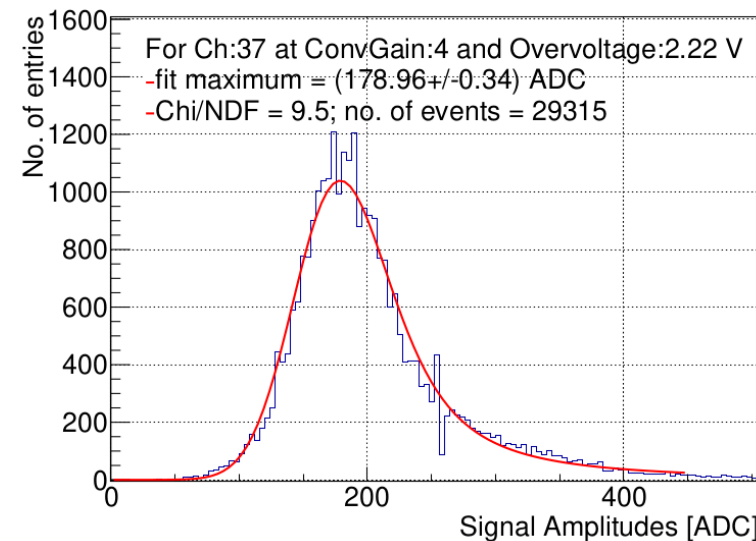
# Test beam of the Tilemodule at DESY

## Irradiated SiPMs

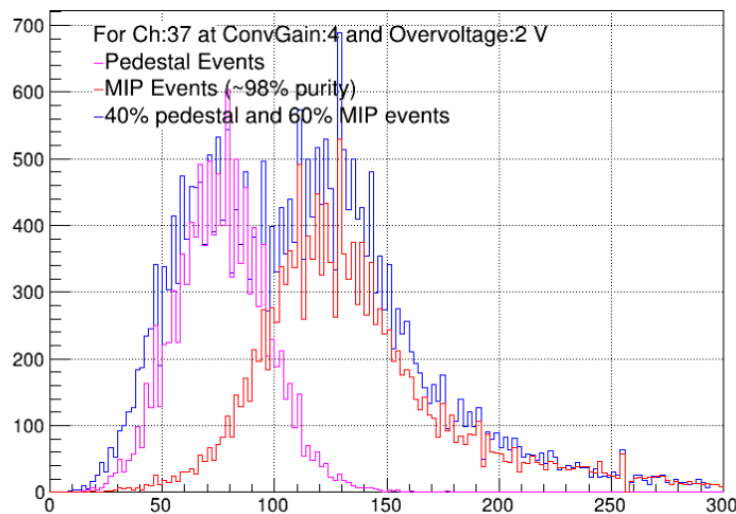
- In comparison with the non-irradiated SiPMs, the **pedestal** signal will be "**wider**" for the **irradiated SiPMs**.
- **Cannot easily separate the MIP peak and pedestal peak** with irradiated SiPMs.
- Need to adjust the beam line to hit in the middle of scintillator tile to mitigate data contamination from pedestal (try to aim all particles from the beam to reach the same tile).
- The light yield measured from irradiated and non-irradiated SiPM are similar.



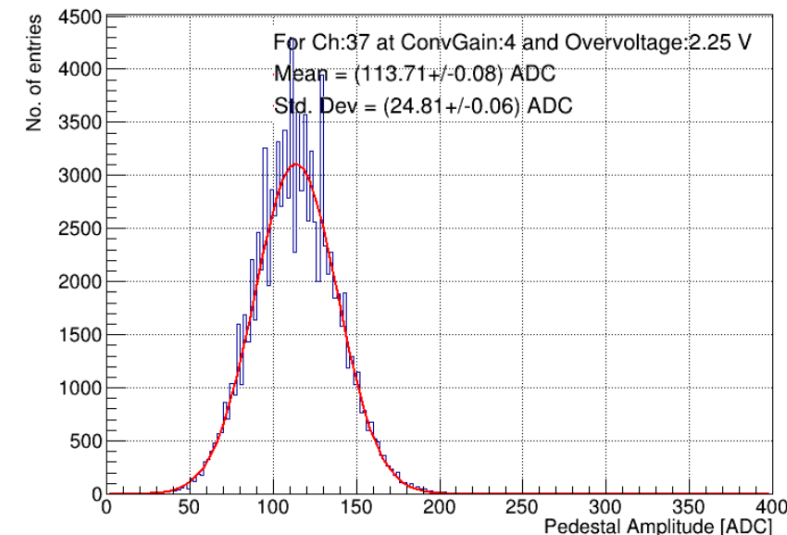
MIP data with beam directed hitting the SiPM area



Beam data with pedestal contamination



Data from pure pedestal without beam



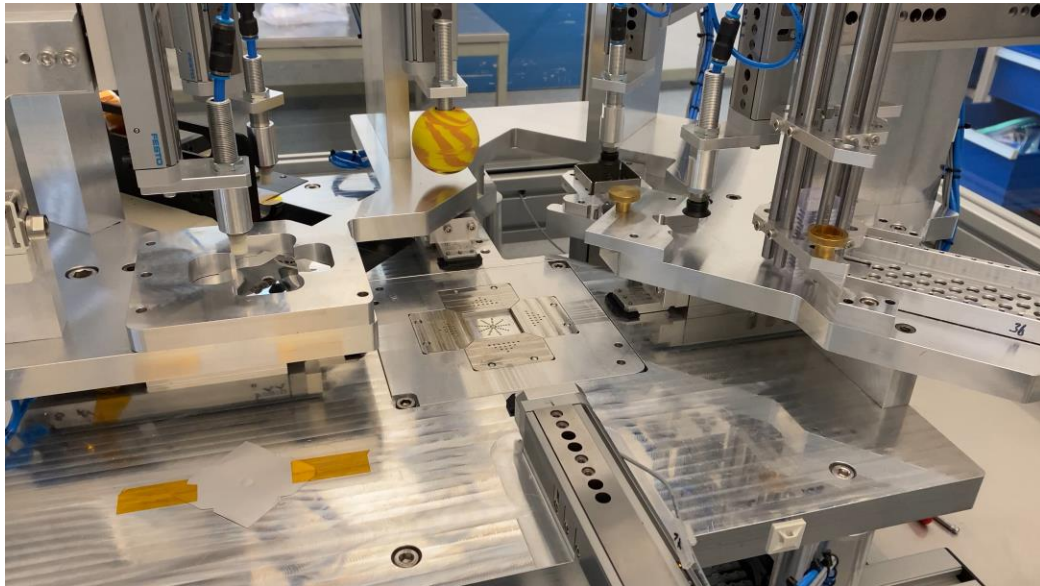


# Tilemodule assembly centre

## Tile wrapping and pick-and-place machine at DESY TAC

- The full production of the Tilemodules will start in 2024.
- There are currently two Tilemodule assembly centres (TAC). One of them is in DESY and the other is in Fermilab (FNAL).

Tile wrapping machine



Pick-and-place machine

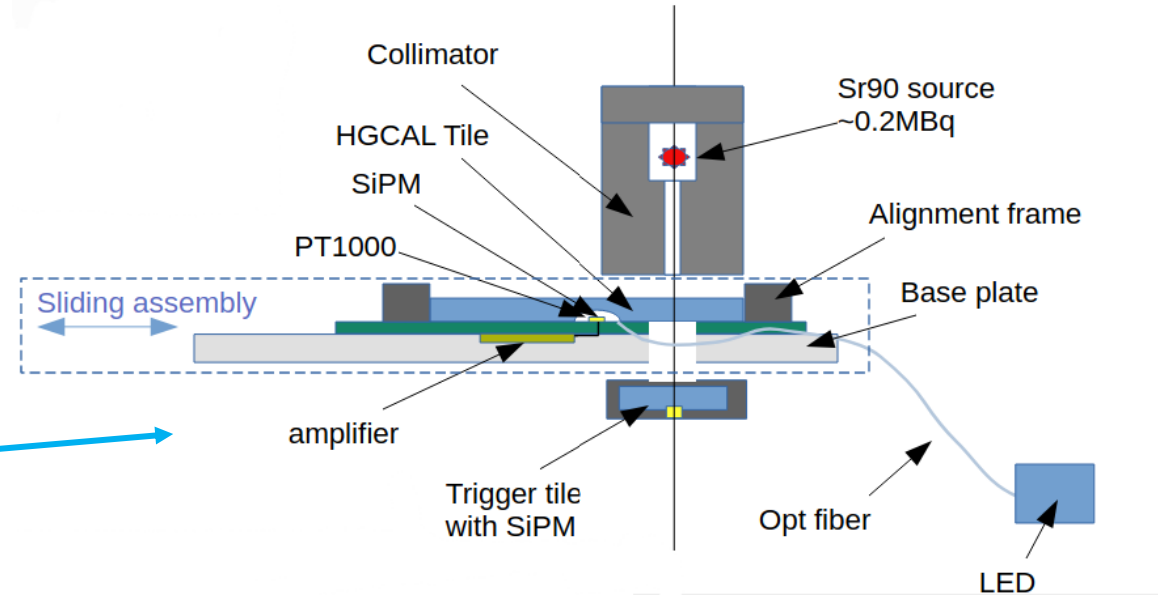
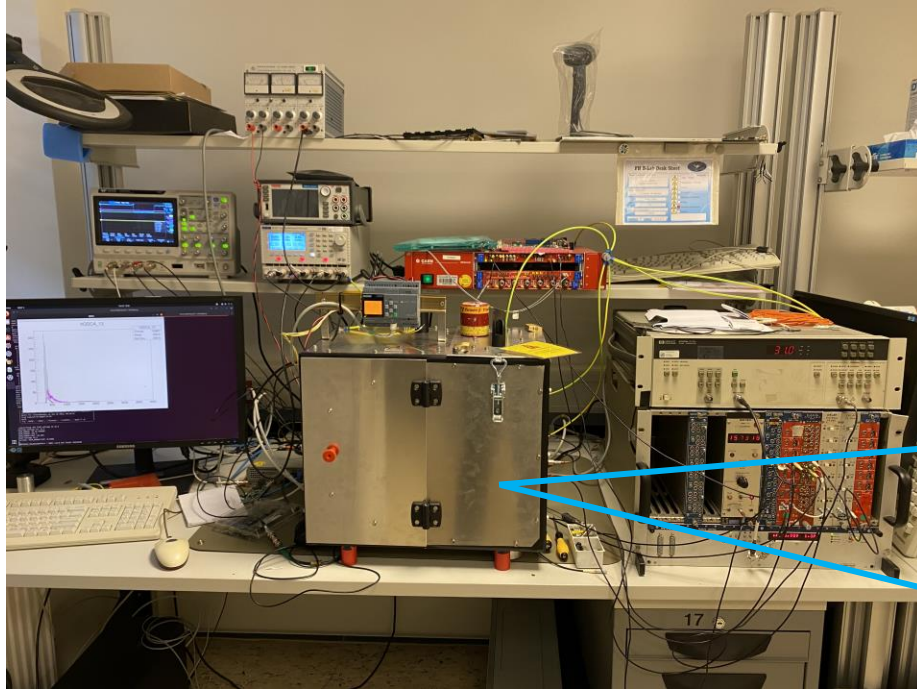


- Many setups have been developed for quality control.

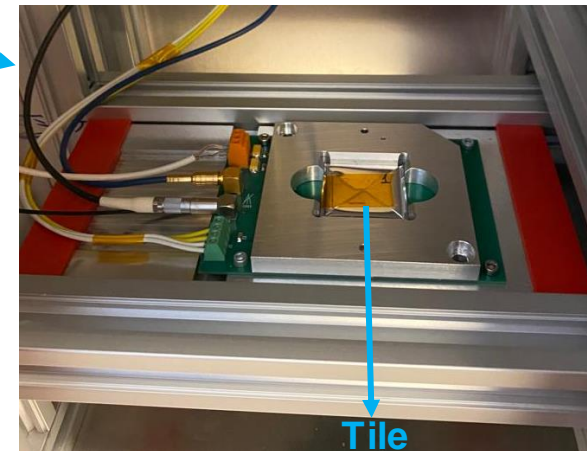
Videos taken in DESY TAC.

# Quality control for scintillator tiles

This is part of the quality control of the Tilemodule



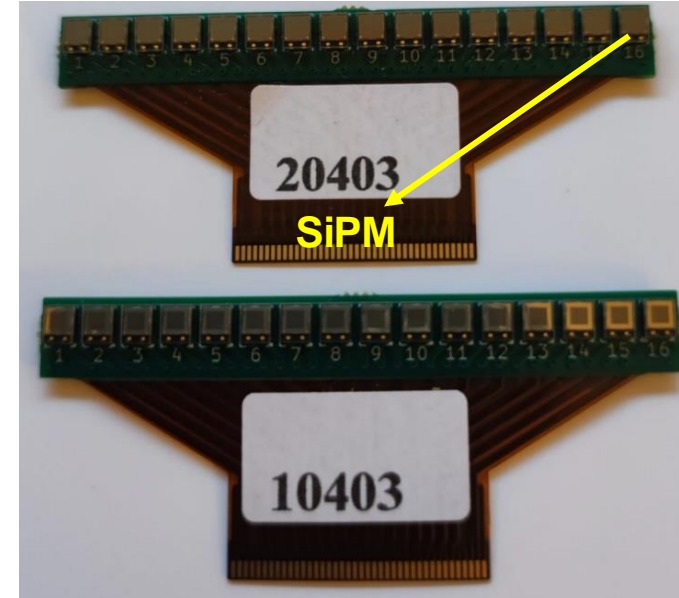
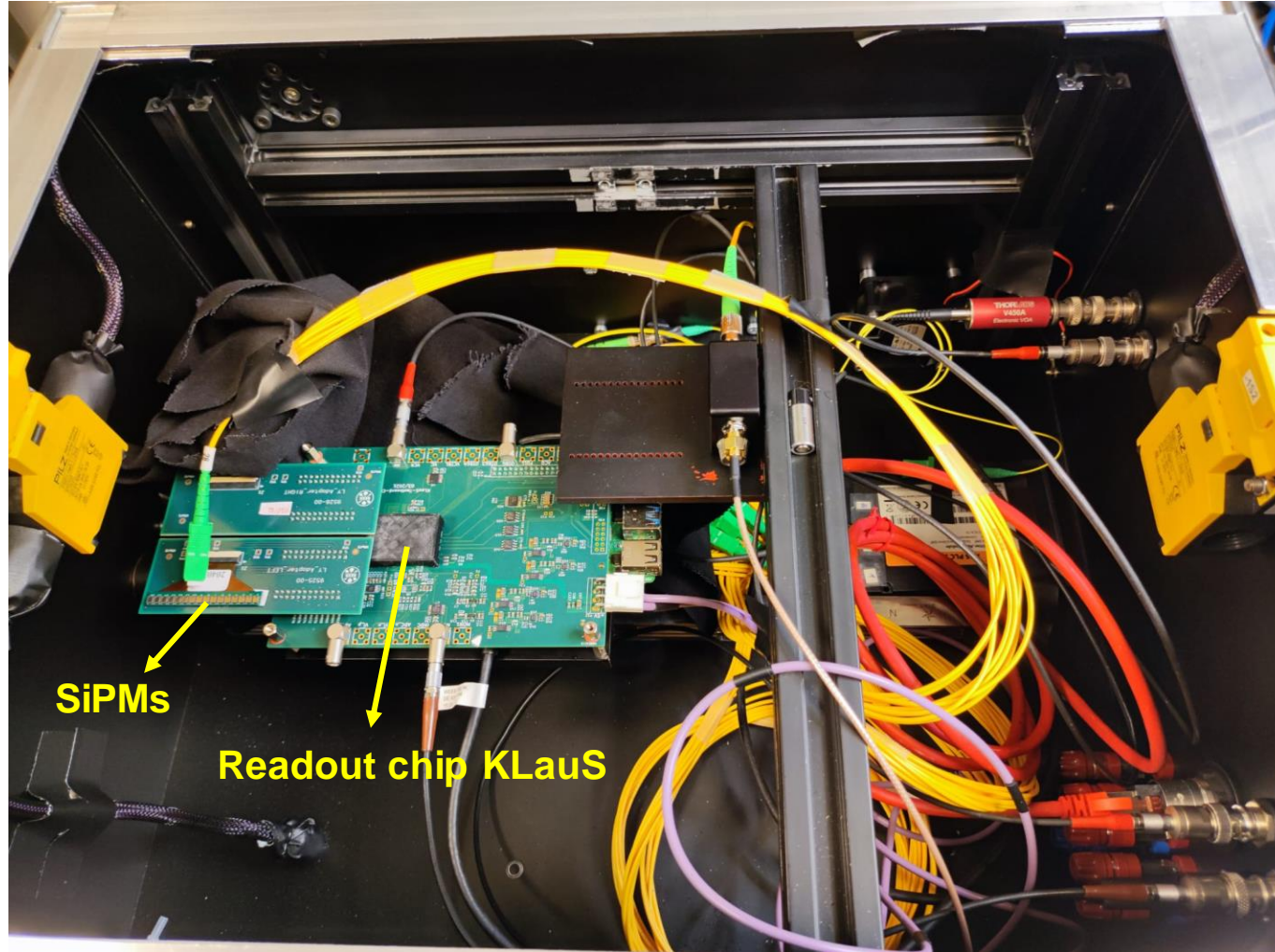
- Light yield test stand for scintillator tiles.
- Tested with **Sr90 source**.
- Measure **light yield** for quality control.
- Small fraction of tiles produced will be tested with this setup.





# Quality control for the SiPMs

This is part of the quality control of the Tilemodule

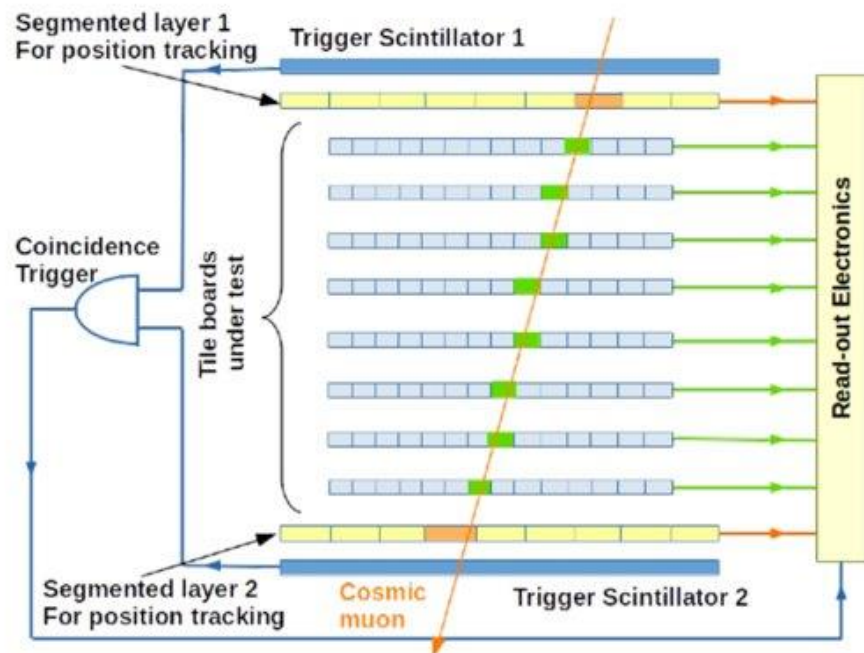


- Data readout by KLauS6-ASIC.
- Pulsed laser (510 nm at 40 mW) with optical attenuator and fibre splitter.
- Can measure **32 SiPMs** at the same time.
- Measure **SPS**.
- Study the **correlation** between **photon released** by the device and **photon detected** by the **SiPM** with high light intensity.

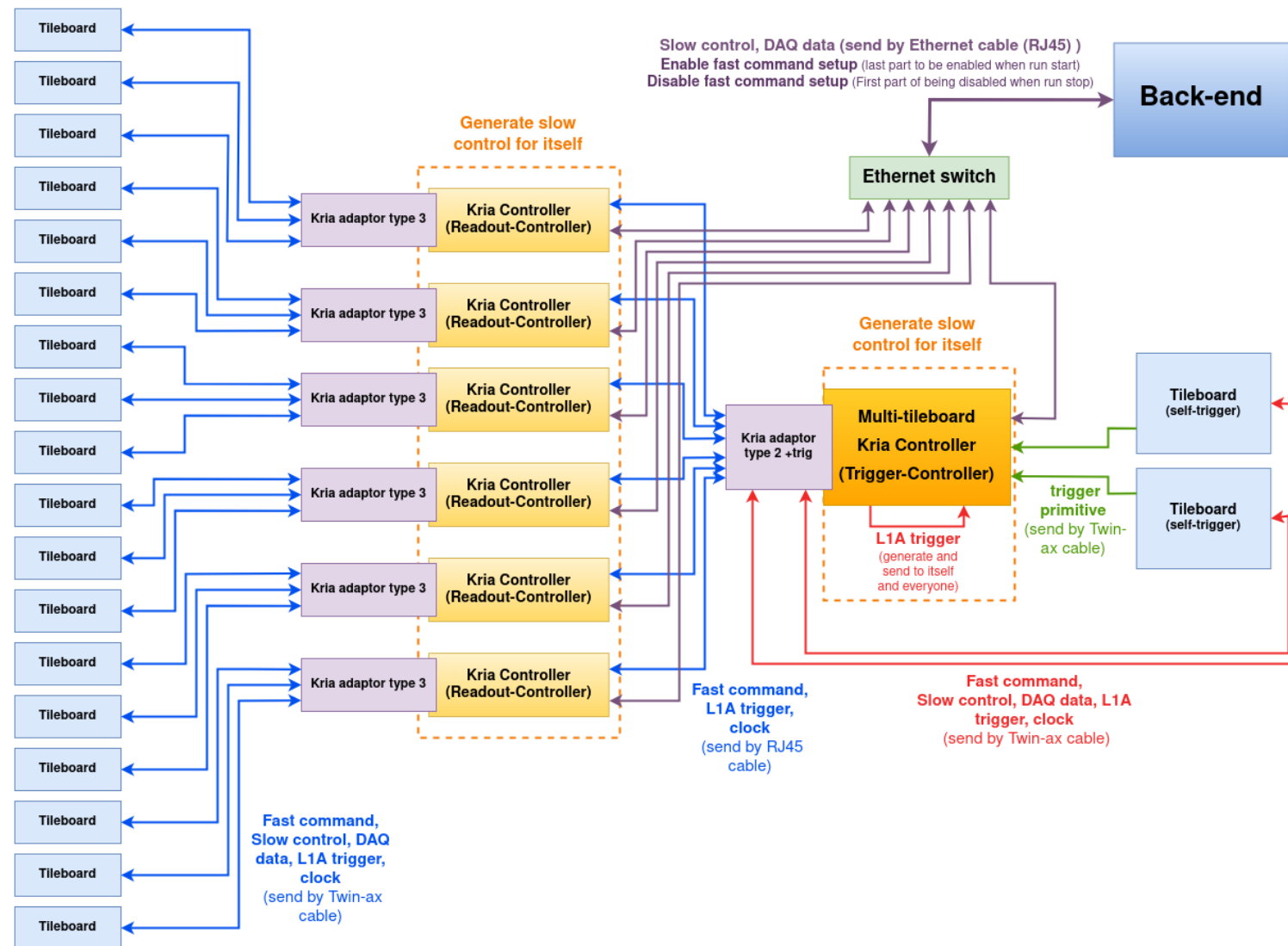


# Quality control for Tilemodules

Will be use in cosmic ray test stand and also a small EM stack in test beam for quality control.



- All Tilemodules produced will be tested with the **cosmic test stand**.
- Additionally, an **EM stack** with 15 Tilemodules will be built for **shower analysis** in test beam.



# Summary

# Summary

- HGCAL is a **5D imaging calorimeter** with **high granularity, precise timing resolution**. It can deal with **high pileup** issue and **high radiation level**. And will allow us for detailed studies of the Higgs boson, standard model and beyond standard model physics in the HL-LHC.
- The development and production of the CMS HGCAL is on track with the **final end caps** schedules to be **lowered** into the CMS cavern **in mid-2027**.
- There are many technological challenges in electronics, hardware, software, firmware, which make it an **exciting opportunity for an experimental physicist**.



# Thank you

## Contact

Deutsches Elektronen-  
Synchrotron DESY

[www.desy.de](http://www.desy.de)

Jia-Hao Li  
FTX group  
[jia-hao.li@desy.de](mailto:jia-hao.li@desy.de)

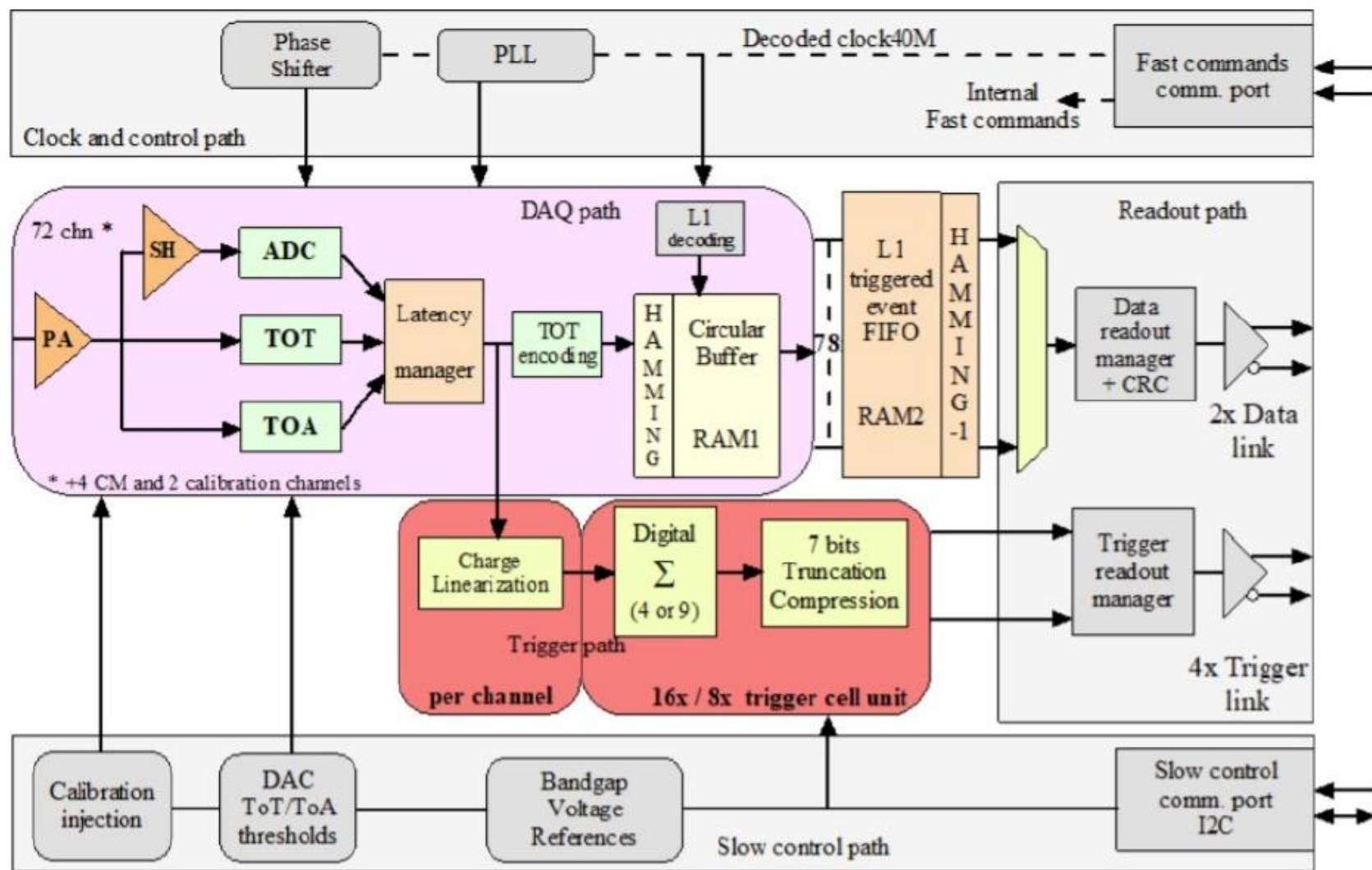
# Backup



# HGCAL readout chip (HGCROC)

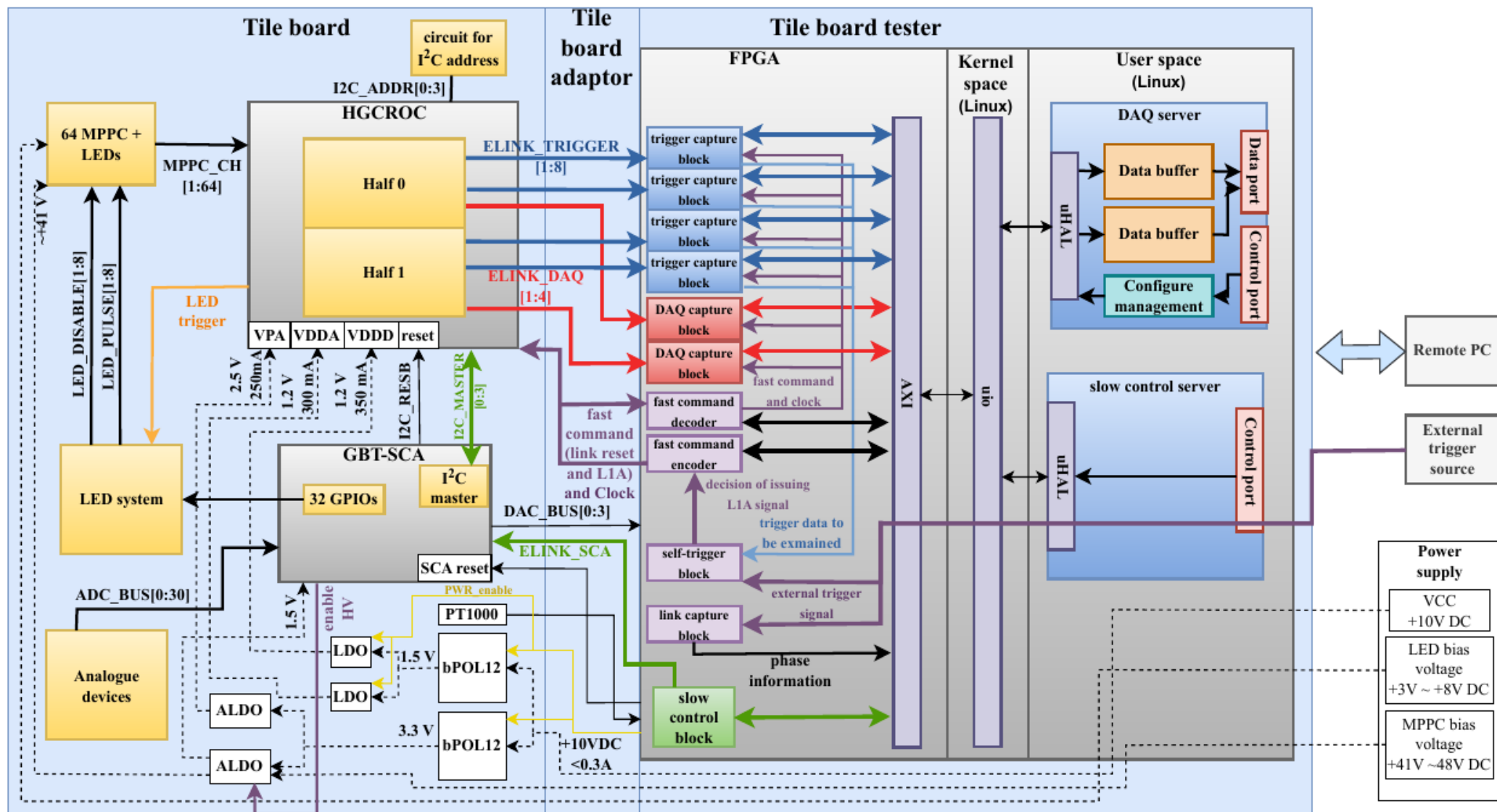
## Informatio about the data readout chip

- 72 active channels, 2 calibratin channels, and 4 common mode channels.
- Dynamic range  $\sim 0.2$  pC to 10 pC.
- Peaking time  $\sim 20$  ns.
- Linearity  $< 1\%$ .
- Energy measurement:
  - ADC 10-bit SAR, range 0  $\sim$  100 fC
  - TOT range 100 fC  $\sim$  10 pC, with bin size = 2.5 fC.
  - TOA: 10-bit TDC, LSB  $< 25$  ps, 25ns full range
- Data readout path: Latency up to 12.5  $\mu$ s. With 2 outputs in 1.28 Gbps.
- Trigger readout path: Latency up to 36 BX. With 4 outputs in 1.28 Gbps.
- 320 MHz clock.



# Single Tilemodule test system

## Block diagram

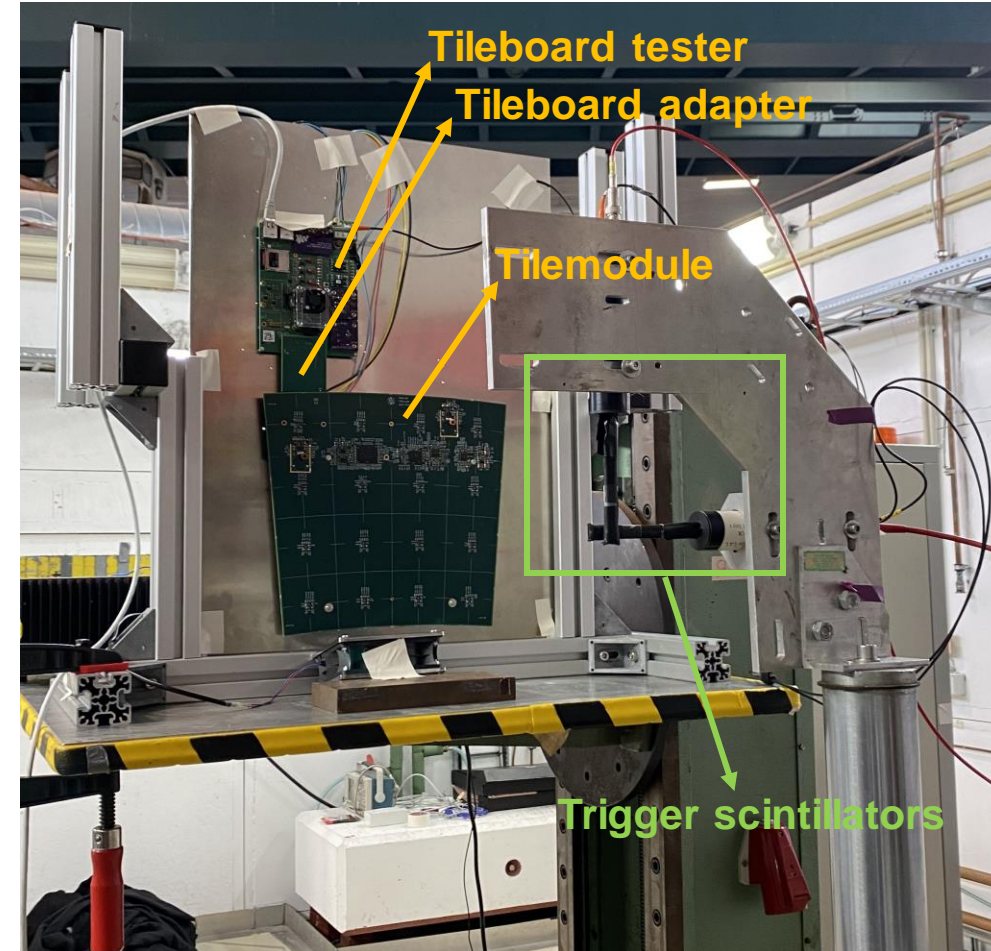


# Test beam of the Tilemodule at DESY in May 2023

## Test beam setup and goal

### Data taking

- Measure **MIP spectrum** by taking **100,000 events per channel** with **3 GeV electron beam**.
  - Signal responses from 3 GeV electrons are very similar to Minimum Ionizing Particles (MIPs)
  - Has been verified with muon beams of 120 GeV energy at CERN SPS
- Using the on-board LED system to measure single photon spectrum (**SPS**) by taking **3,000 events per channel**.





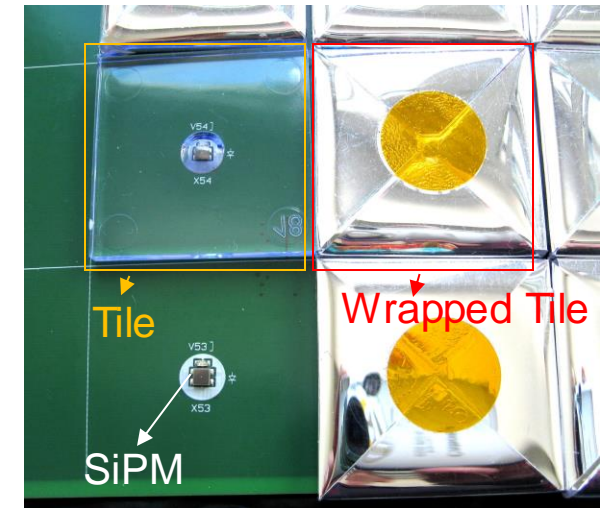
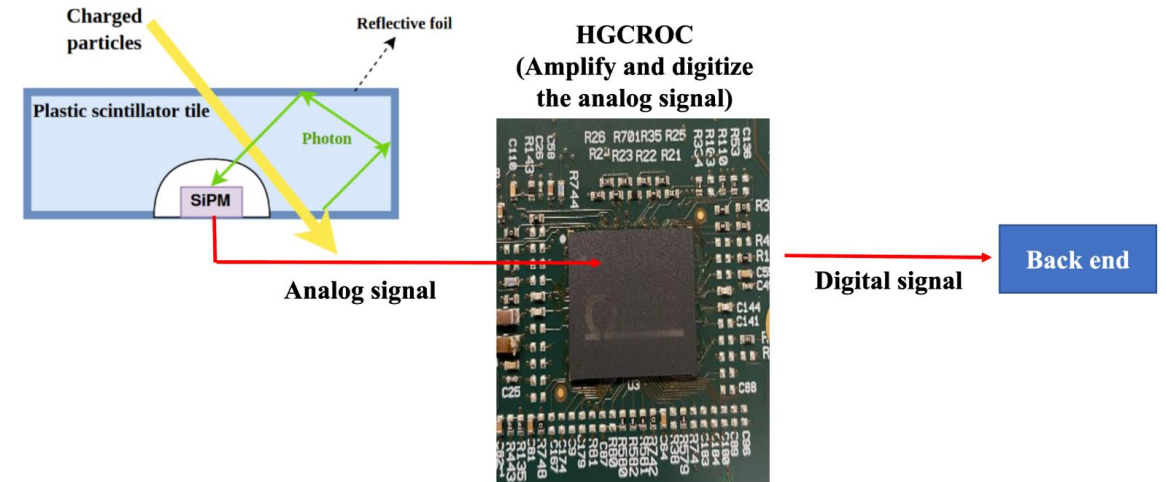
# Test beam of the Tilemodule at DESY in May 2023

## Test beam setup and goal

### Tiles and SiPMs to be examined

- There are 21 different sizes of tiles in 2 different materials.
- 2 different sizes of SiPM (4 mm<sup>2</sup> and 9 mm<sup>2</sup>)

To **decide which type** of **tiles** and **SiPMs** have the better performance to be used in the **HGCAL**. We need to do **test beam** for measuring and **comparing** the **light yield**.

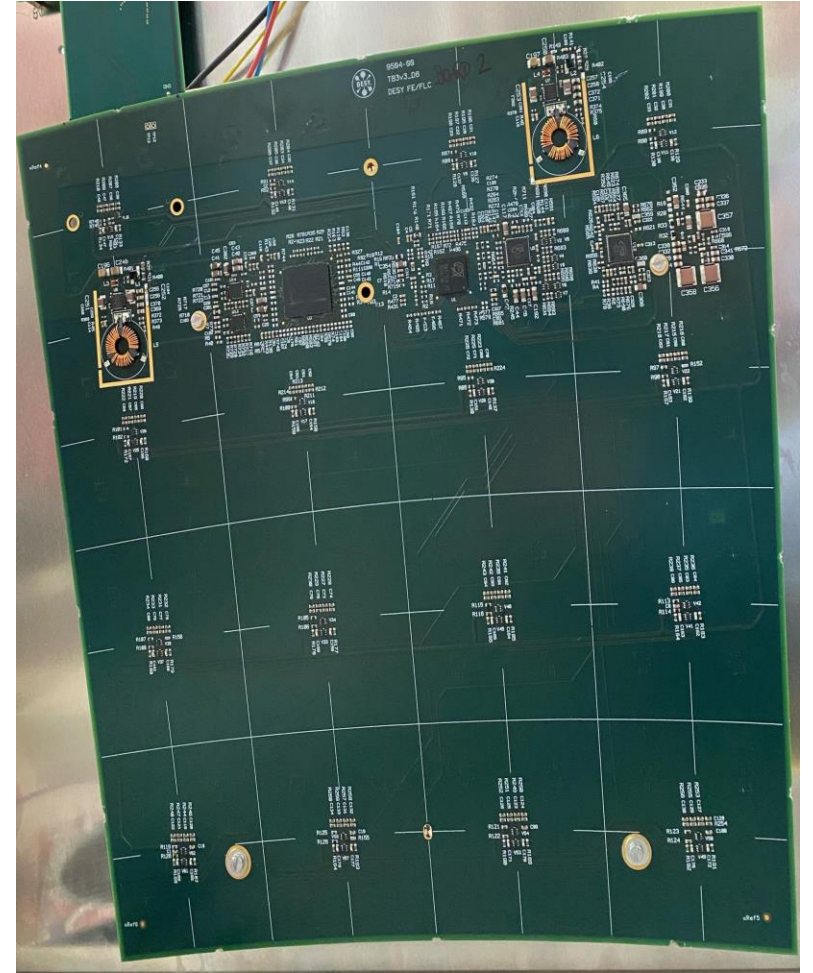


# Test beam of the Tilemodule at DESY in May 2023

The Tilemodule tested in the test beam

## Tilemodule v3

- Is the latest tileboard generation and is **very similar to the final version used in the HGCal**.
- **Will be used in the pre-series test**, including all quality control and quality assurance steps.
- Equipped with **SiPM** which has the **latest radiation hard package** and is **foreseen to be used in the final experiment**.



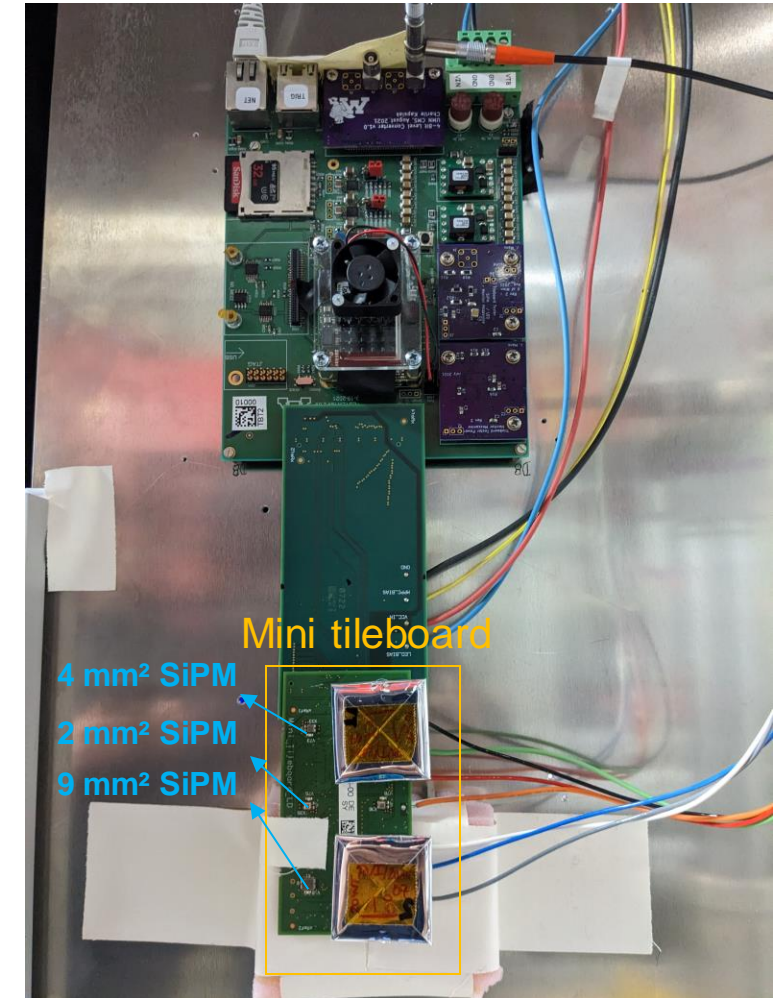
# Test beam of the Tilemodule at DESY in May 2023

## The Mini Tileboard tested in the test beam

- The mini Tileboard contains **6 SiPM channels**, **LED system**, **HGCROC**, and **slow control chip**.
- As it **does not have any power regulators**, all power are supplied externally.

## Main motivation

- The **size** of the mini Tileboard **can fit into most of the standard tubes used at irradiation facilities**.
  - This allows us to **test the radiation hardness of the whole module**.





# Test beam of the Tilemodule at DESY in May 2023

Two type of module were tested in the test beam

- **Tilemodules**



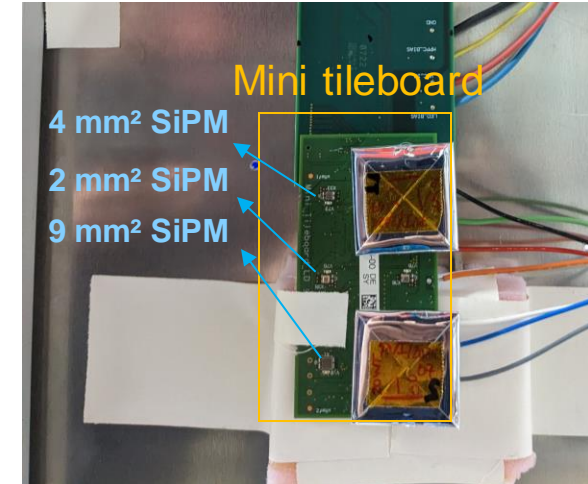
TB3 board 1  
equipped with **moulded tiles Batch 1**  
with pre-series 4mm<sup>2</sup> SiPMs



TB3 board 2  
equipped with **moulded tiles Batch 2**  
with pre-series 4mm<sup>2</sup> SiPMs

The **tiles** equipped here are **produced by the institute**  
**expected to make the final tiles** for HGCal.

- **Mini Tileboard**



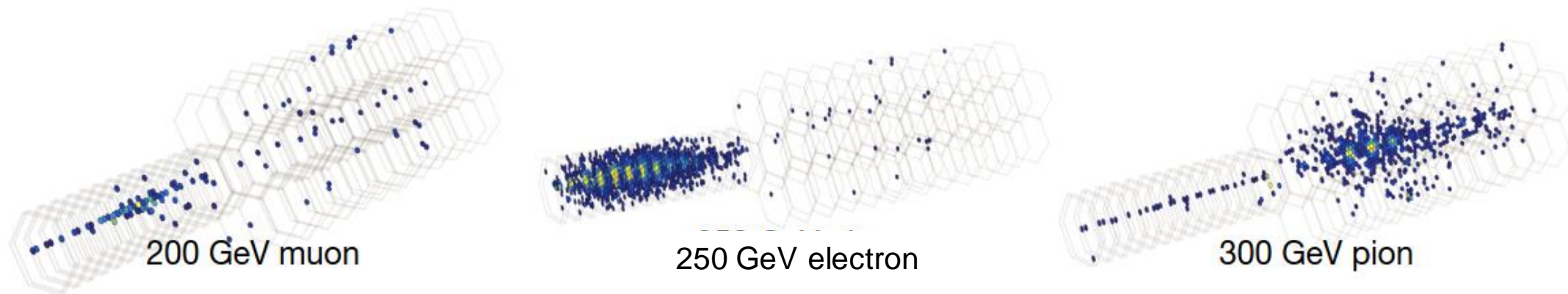
Mini Tileboard  
equipped with **IHEP v2 tiles**

with pre-series  
**4mm<sup>2</sup> SiPMs** and  
**9mm<sup>2</sup> SiPMs**

- All Tilemodules use a custom-made DAQ system which is driven by Zynq FPGA for data acquisition.

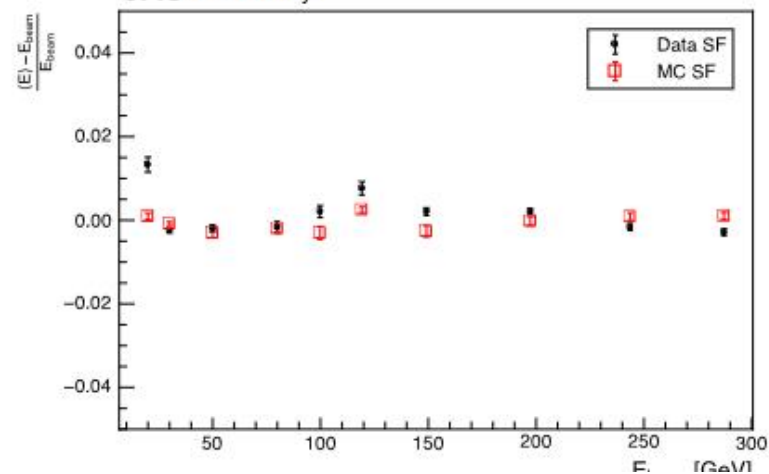
# Test beam in Oct 2018 at CREN

## Test beam for hexaboard

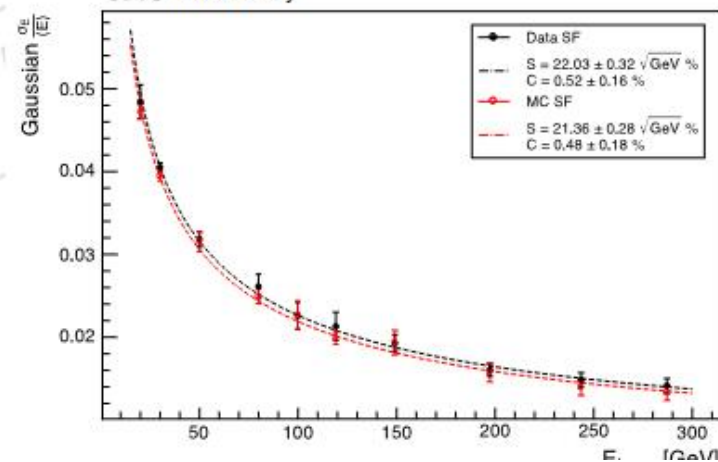


2018 TB results on positron energy linearity and resolution

CMS Preliminary



CMS Preliminary

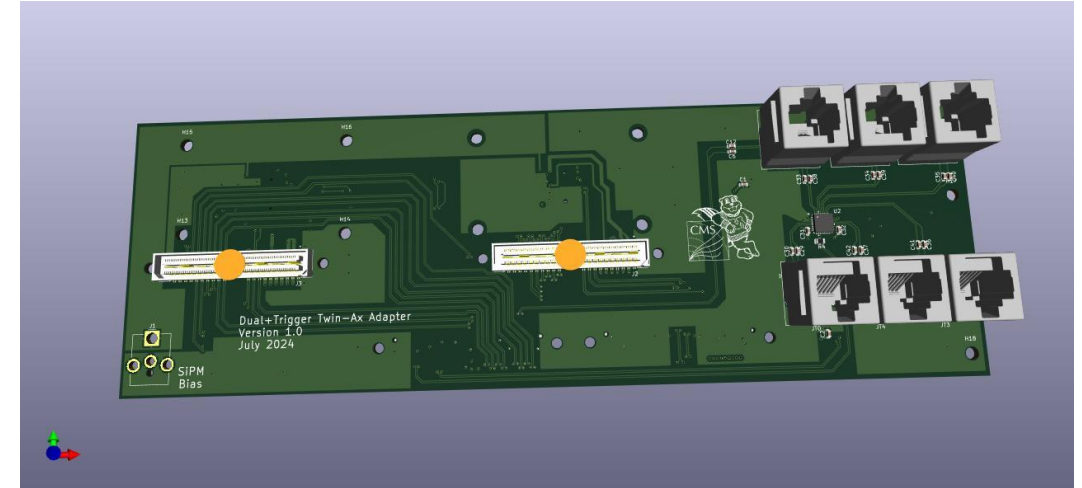


# Block diagram of the multi-Tilemodule test system

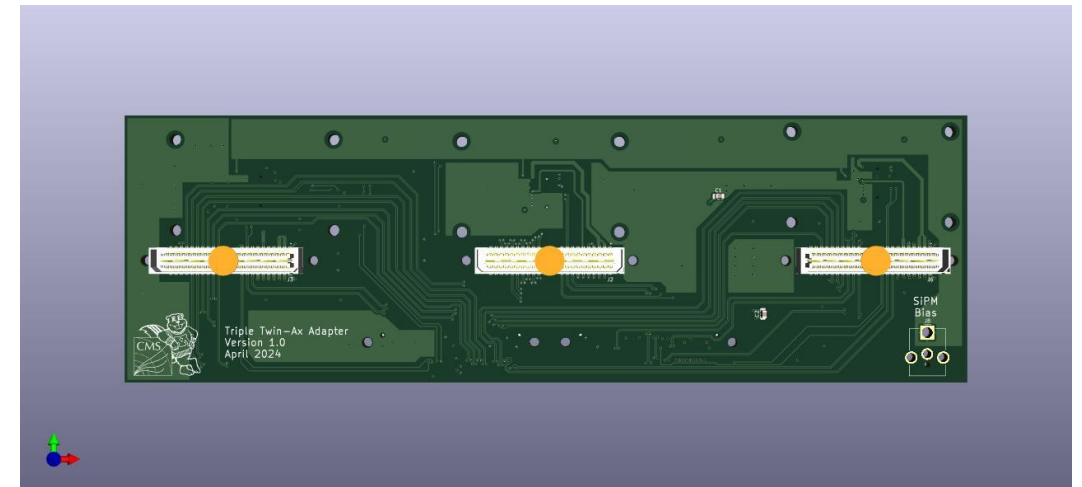
## Kria controllers

- **Trigger-Controller:**
  - is a **Kria controller** connected to a **Kria adaptor type "2 + trig"**
  - hosts 2 triggering Tilemodules by Twin-ax cable
  - drives up to 6 Readout-Controller by RJ45 cable
- **Readout-Controller:**
  - is a **Kria controller** connected to a **Kria adaptor type "3"**
  - can control up to 3 Tilemodules by Twin-ax cable
- Both of the Trigger and Readout-Controller are using the **same type of Kria Controller**. They use **different type of Kria adaptor** and **firmware**.

Kria adaptor type 2 + trig

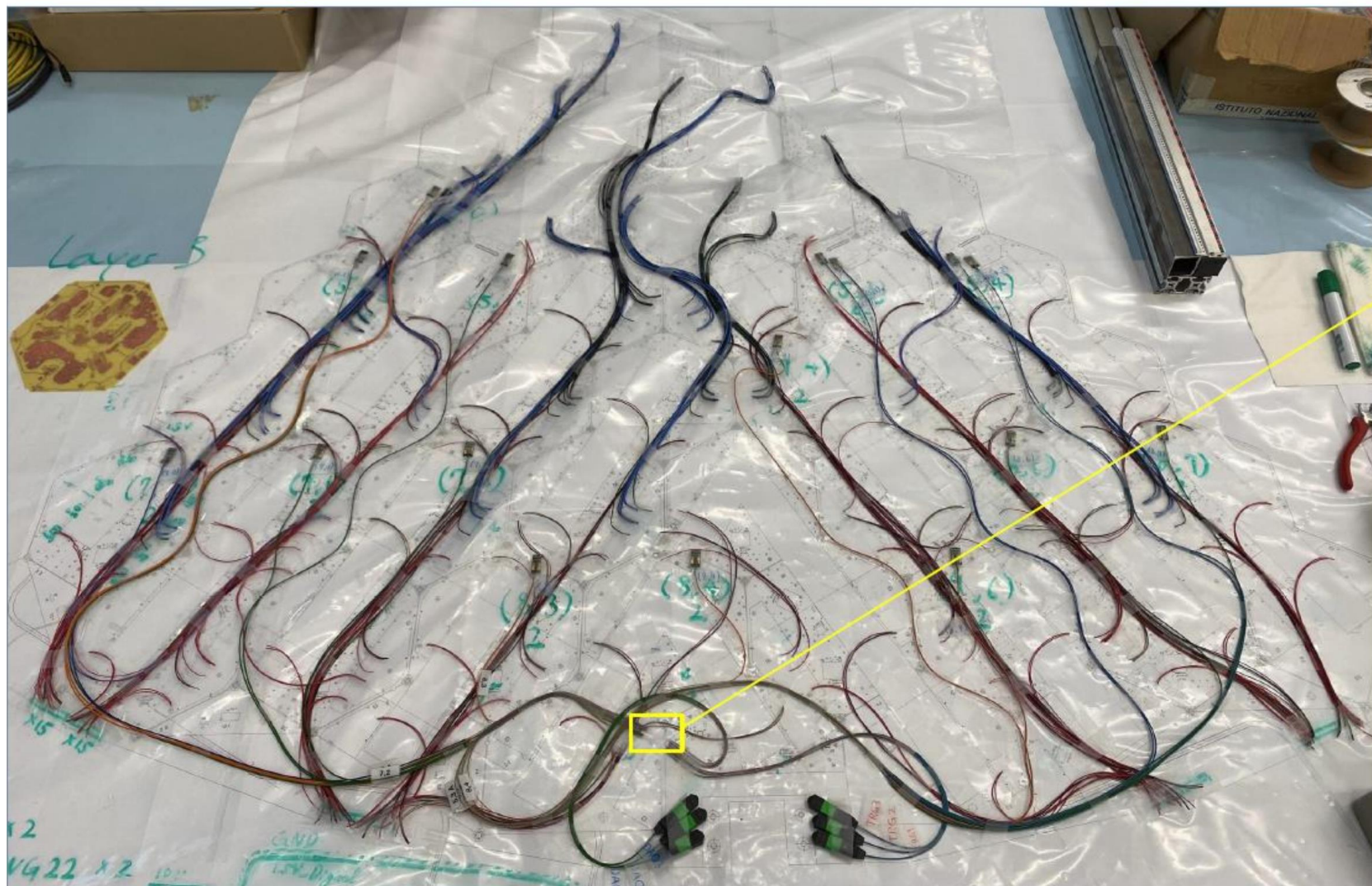


Kria adaptor type 3

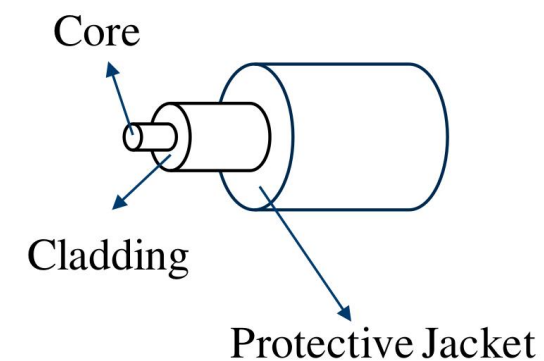




# Fibre splicing

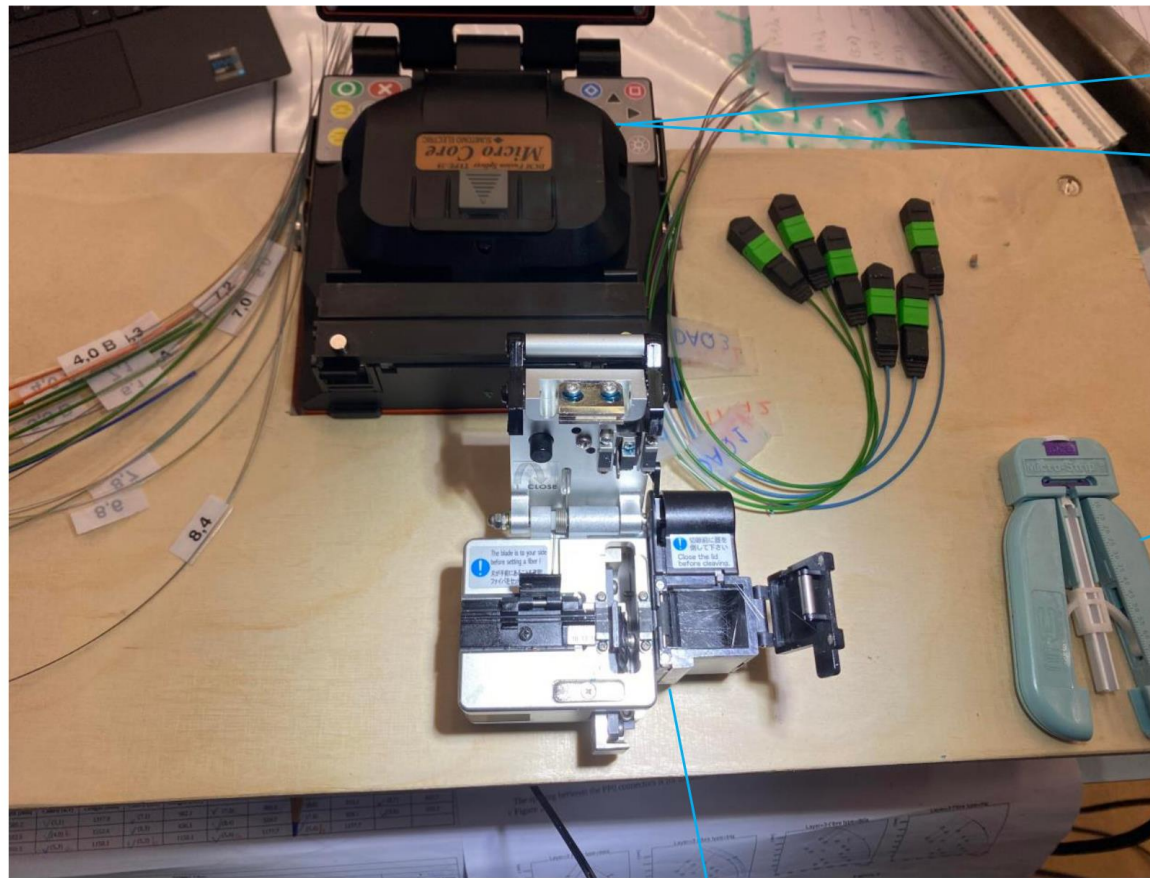


- All 72 splicing points are located in the same region.





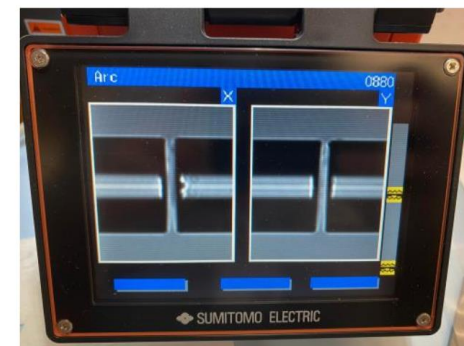
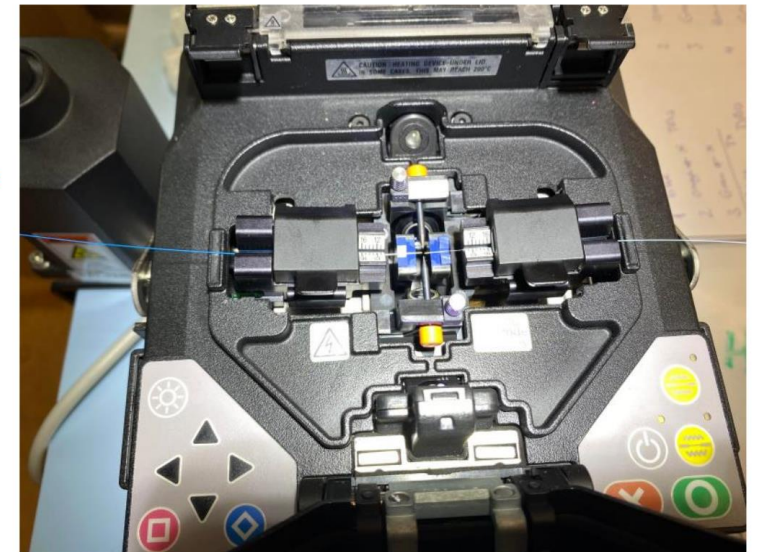
# Fibre splicing



Splicing machine

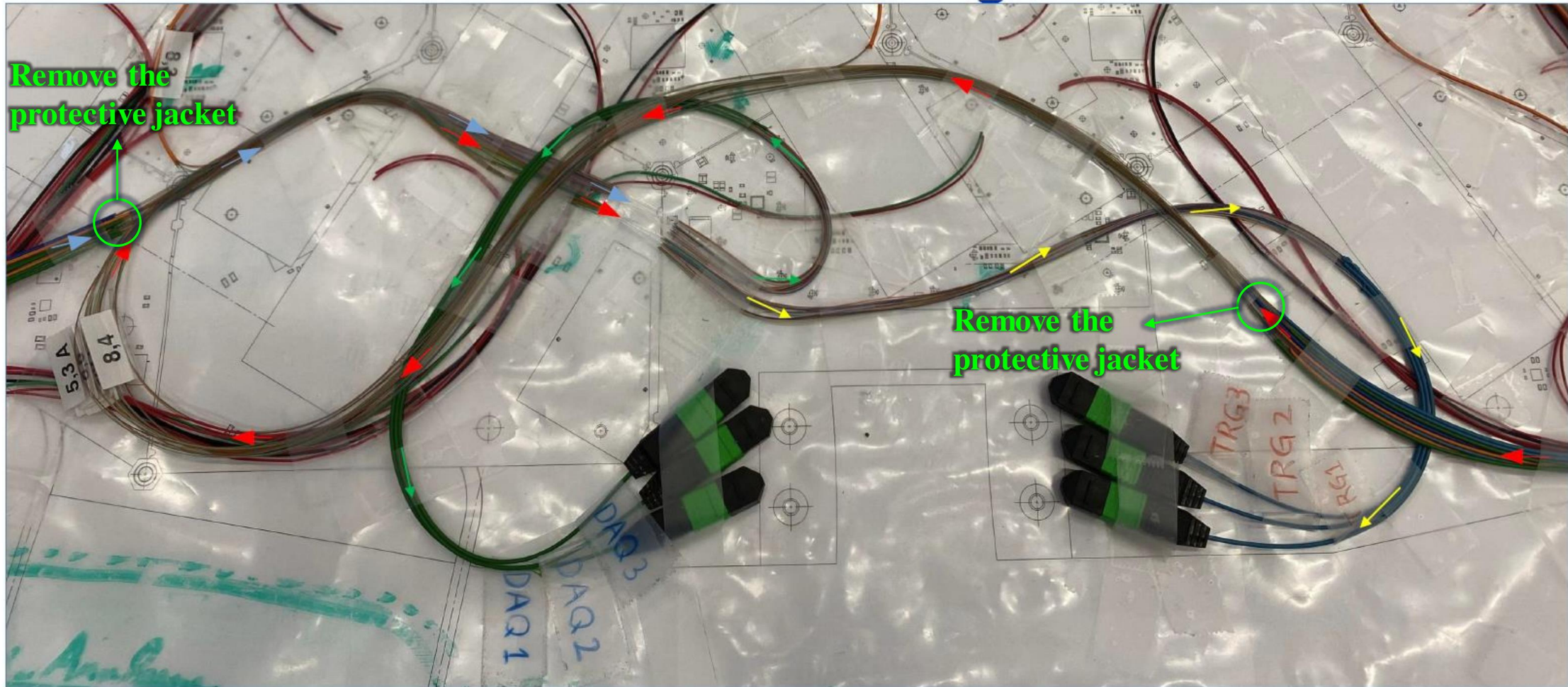
Remove the cladding

Fibre Optic Cleaver (Cut the core at 90 degree angle with smooth surface)





# Fibre splicing



- The light blue arrows indicate the fibres coming from the left side of the cassette. And the red arrows indicate the fibres coming from the right side.



# Terminology

## definition

- **SiPM gain:**

Charge amplification factor of the SiPM

$$\text{SiPM Gain} = \frac{(\text{Charge Collected per SPAD})}{(\text{Charge of an electron})}$$

- **Overvoltage (OV):**

Difference between bias and breakdown voltage

$$\text{Overvoltage} = (\text{Bias voltage}) - (\text{breakdown voltage})$$