CALICE Test Beam 2022 Results and Outlook

Yuichi OKUGAWA

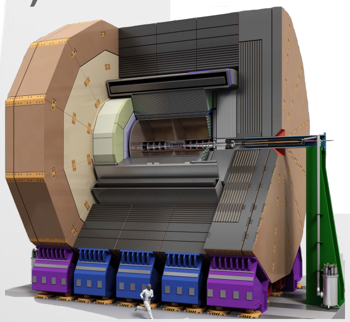
CEPC EU Workshop 2023
July 3-6, 2023

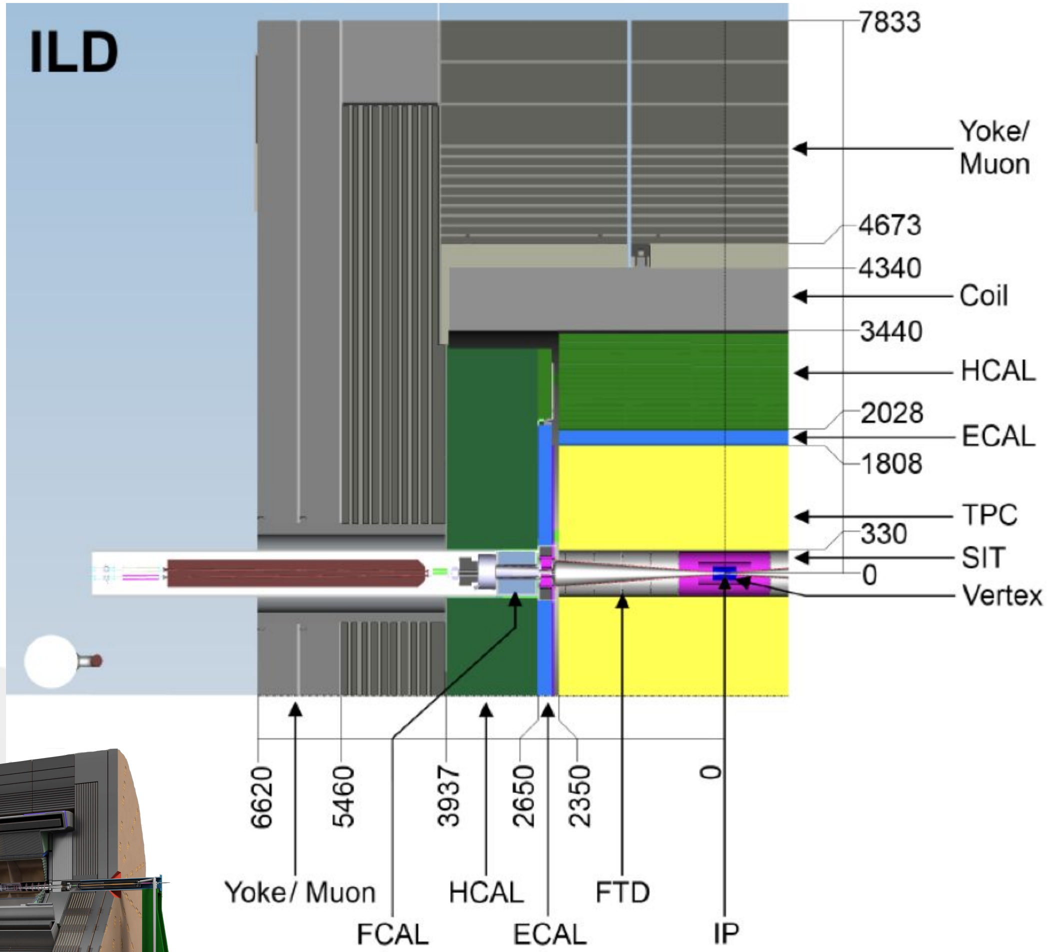
Affiliation:

In collaboration with:

International Large Detector (ILD)

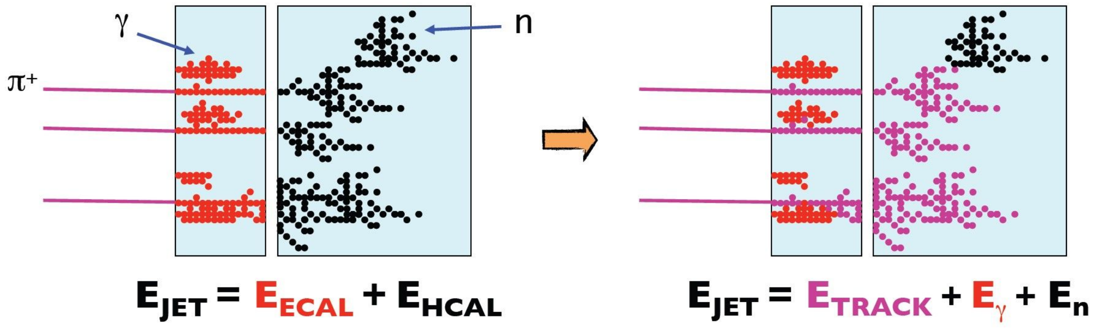
- Multi-purpose 4π detector designed for the ILC.
- Composed of multiple sub-detectors:
  - Vertex Detector (VTX)
  - Time Projection Chamber (TPC)
  - **Electromagnetic Calorimeter (ECAL)**
  - Hadronic Calorimeter (HCAL)
  - Muon Yoke
- Optimized for the application of **Particle Flow Algorithm (PFA)**



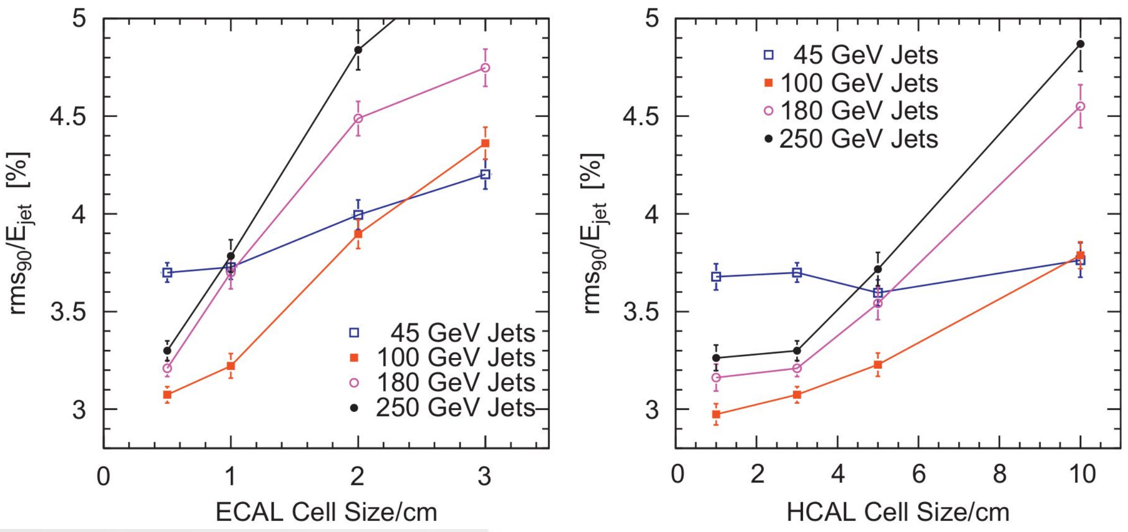


Particle Flow Algorithm (PFA)

- Jet composition
  - Photons: 27%
  - Charged Hadron: 63%
  - Neutral Hadron: 10%
- Energy depositions in the ECAL and HCAL are organized into topological clusters
- Requires highly granular calorimeters to differentiate particles.
- The ability to differentiate particles determines the jet energy resolution, σ / E_{jet}



S. Bilokin, 2018



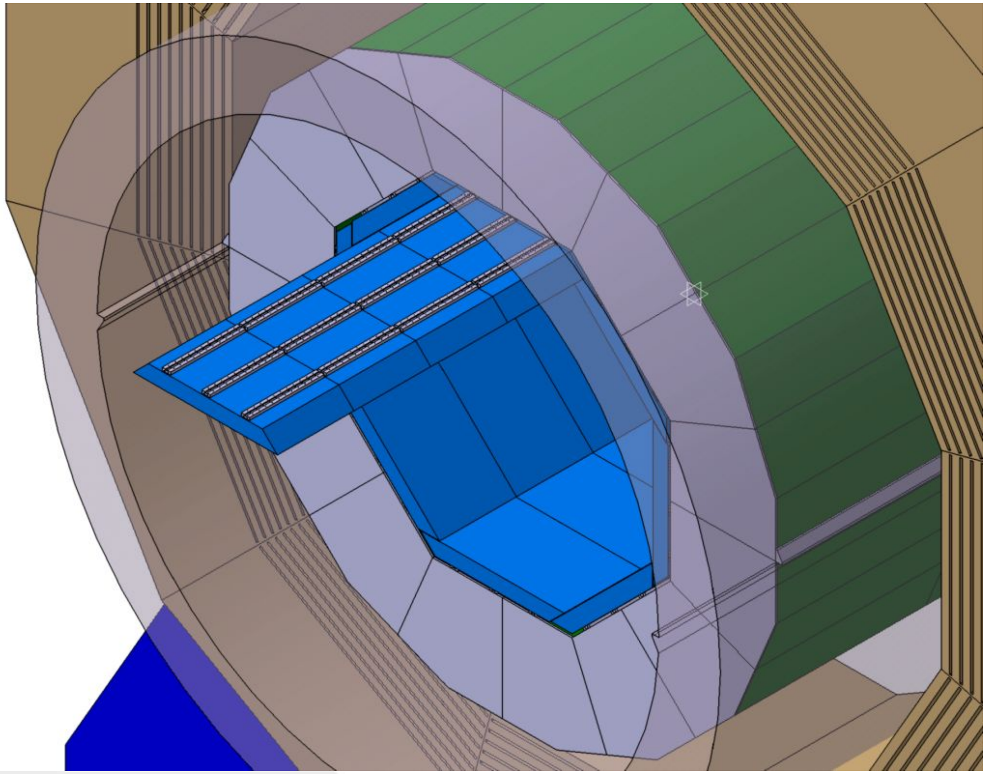
M.A.Thomson, 2009

PFA Requirements:

- Jet energy resolution 3-4%
- Excellent photon-hadron separation

ECAL Requirements:

- Extremely high granularity.
- Compact and hermetic (contained inside the magnetic coil)

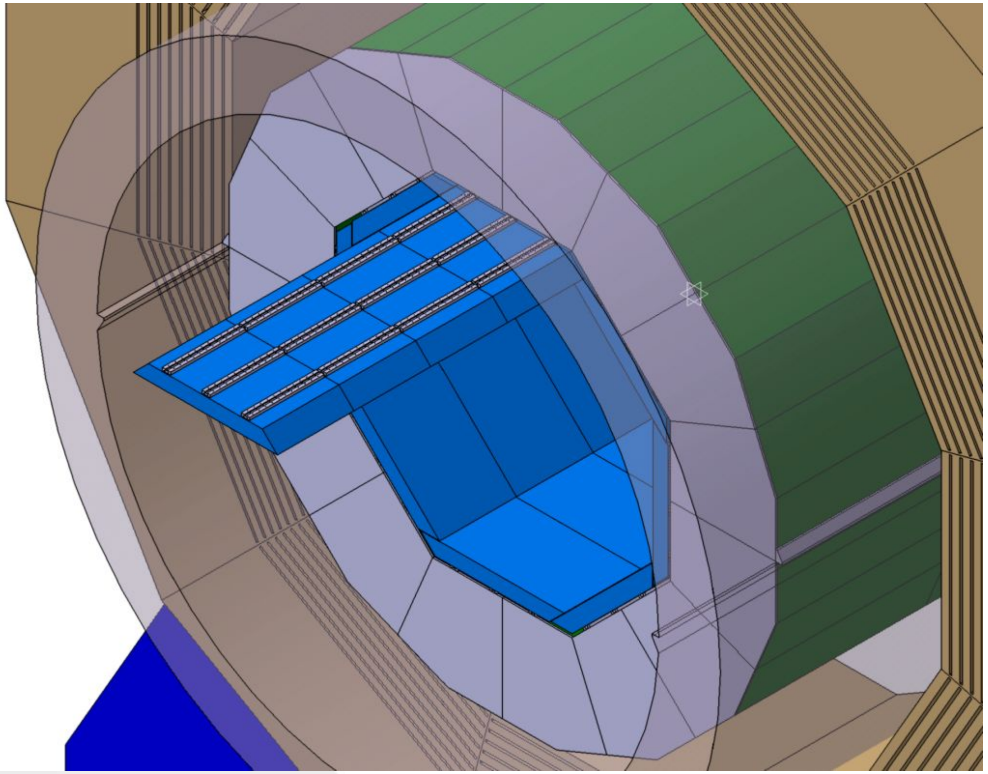


All future e+e- collider projects feature at least one detector concept with this technology

- Decision for CMS HGCAL based on CALICE/ILD prototypes

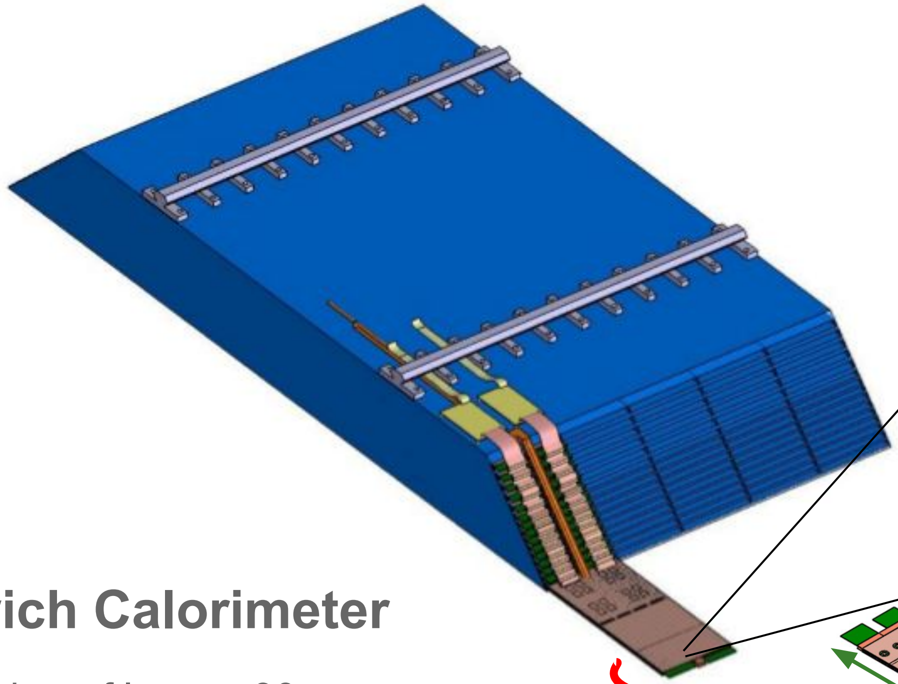
Technical Implementation:

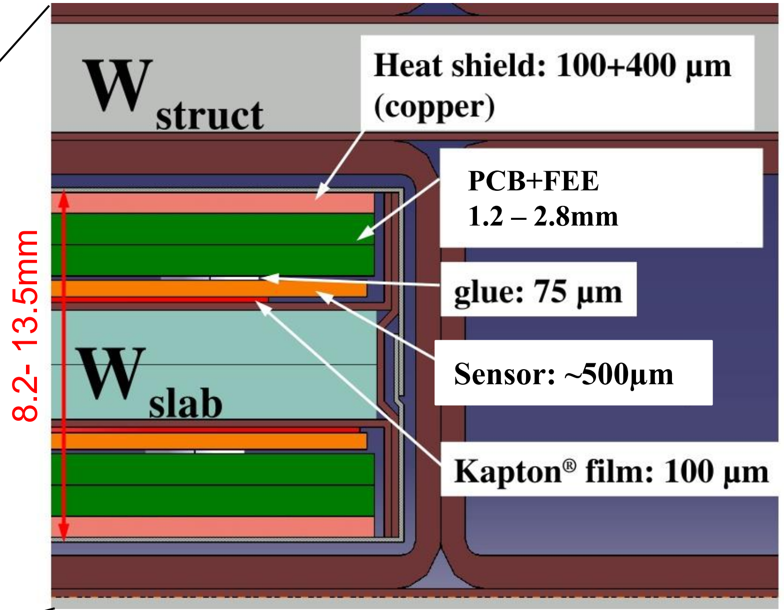
- Layer radius: 1808 mm < R < 2028 mm
- Tungsten (W) as an absorber material
  - X_0 = 3.5mm
    - A small radiation length to make ECAL as compact as $24X_0$ within 20cm
  - R_M = 9mm
    - A small Molière radius to better separate nearby showers
  - λ_I = 96mm → λ_I / X_0 = 27.5
    - Clearly distinguish electromagnetic showers from hadronic ones.
- Silicon (Si) as an active material
  - Pixels with high granularity
  - Excellent signal/noise ratio: 10 as design value

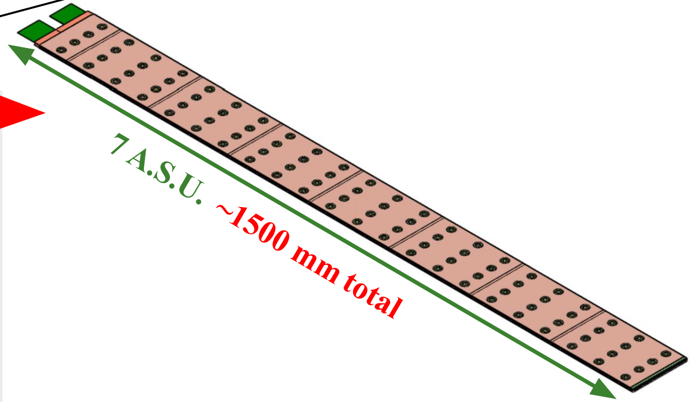


All future e+e- collider projects feature at least one detector concept with this technology

- Decision for CMS HGCAL based on CALICE/ILD prototypes





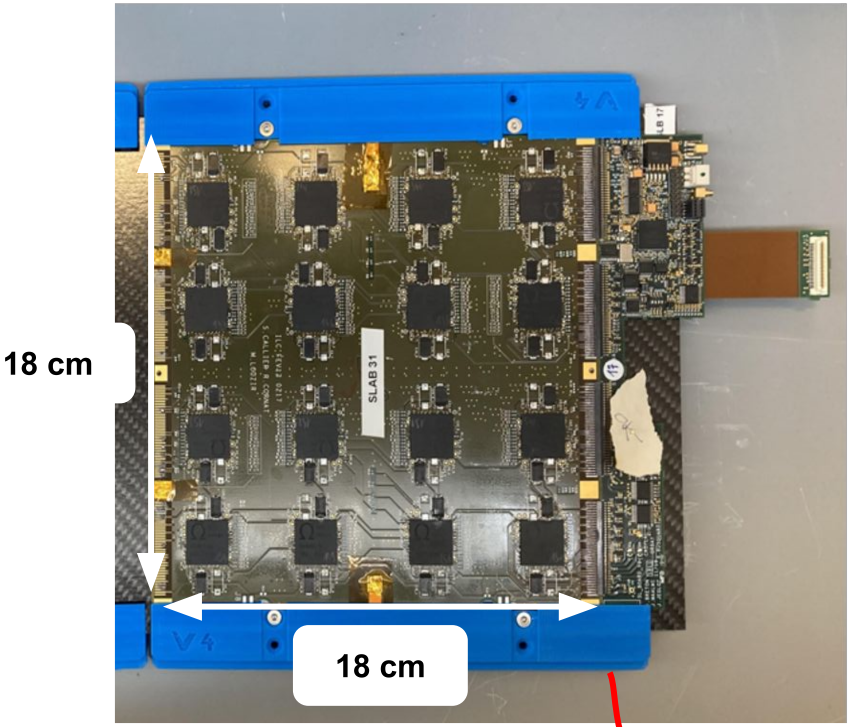


Sandwich Calorimeter

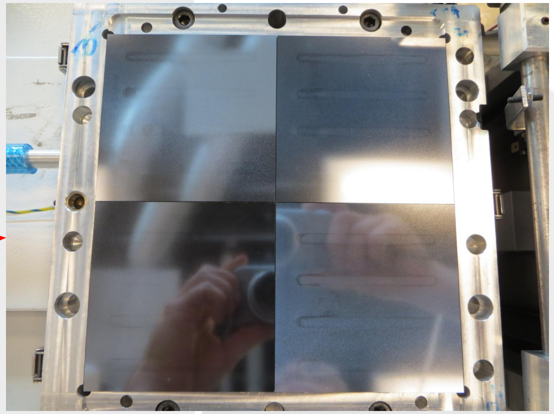
- Number of layers: 30
- Thickness: ~20 cm = 24 X_0/λ_I
- Pixel size: 5.5 x 5.5 mm^2
- Flat Kapton cable to fit trapezoidal structure

Active Sensor Unit (ASU) Structure

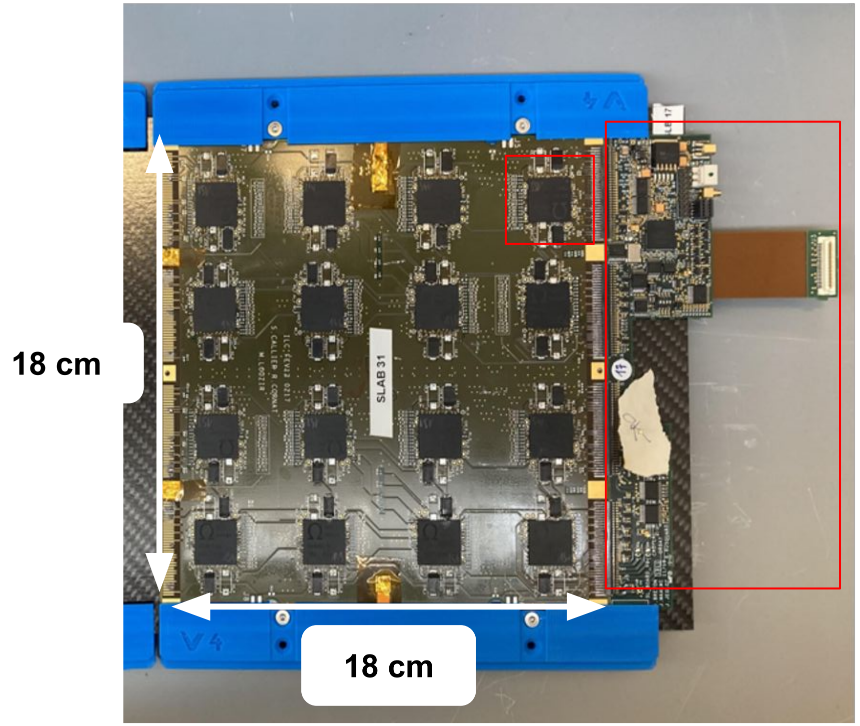
- ASICs + PCB + Si wafer + Copper/Kapton = ASU
- Developed by IJCLab, CERN, Kyushu, OMEGA, LLR, SKKU
- Composition:
  - 4 Si wafer plates / 1 ASU (= 1 wafer / 4 chips)
  - 16 chips / 1 ASU
  - 64 pixels / 1 chip
- High voltage will be provided through SL board, developed by IJCLab

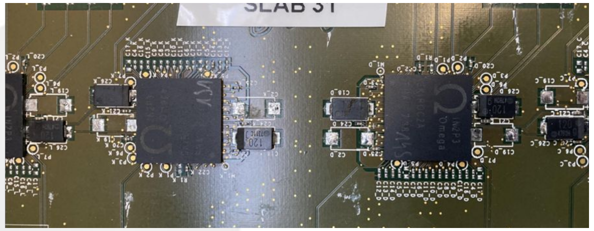


Behind



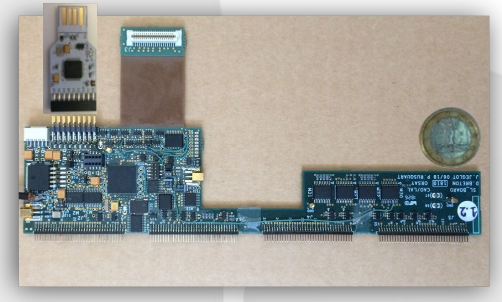
Si sensors glued onto PCB (LPNHE, IFIC)
Optimization of gluing (IJCLab)





ASIC SKIROC2(a)

- Silicon Kalorimeter Integrated Read-Out Chip
- Developed by OMEGA
- Wire bonded or in BGA package (IJCLab, LLR, Kyushu)



SL-Board

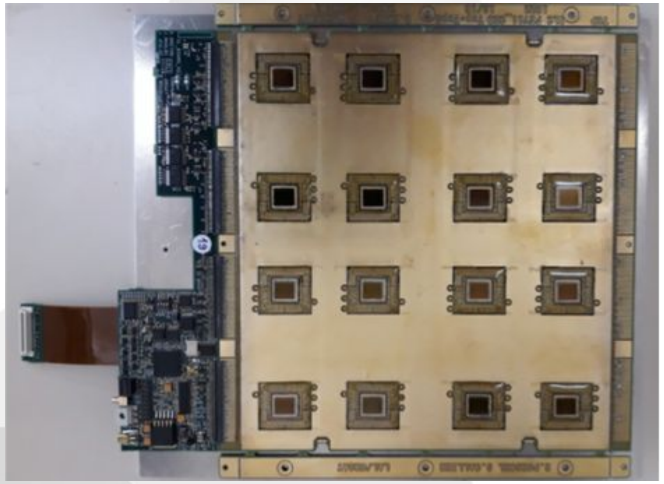
- Digital readout unit
- Configure firmware
- Low voltage supply
- Developed by IJCLab

PCB Variants

FEV10-12

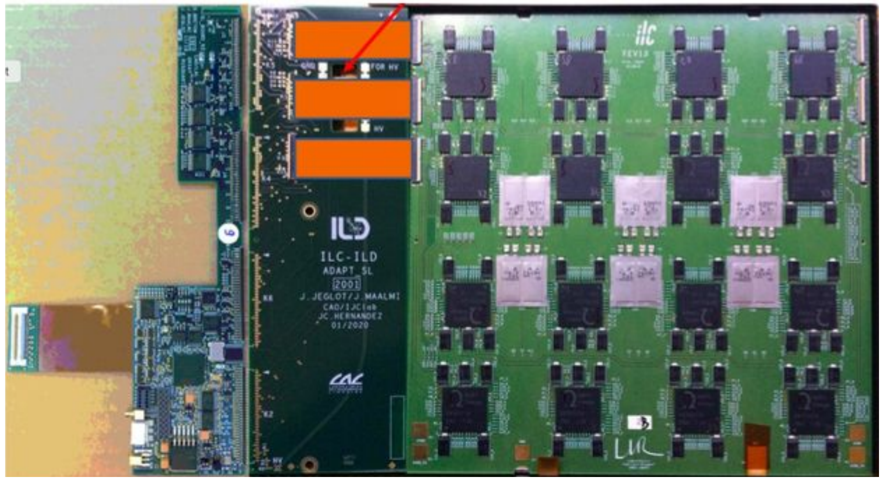
- ASICs in the BGA package
- Main “working houses” since 2014.

FEV_COB



- Chip On Board (COB)
- ASICs wire bonded in cavities.
- Thinner than FEV with BGA
- External connectivity compatible with BGA based FEV10-12

FEV13

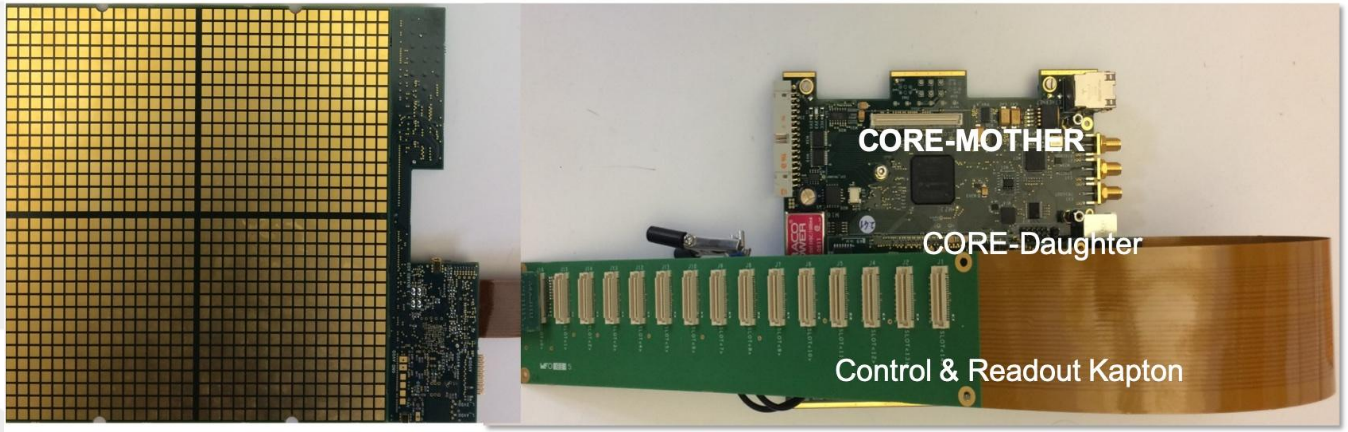


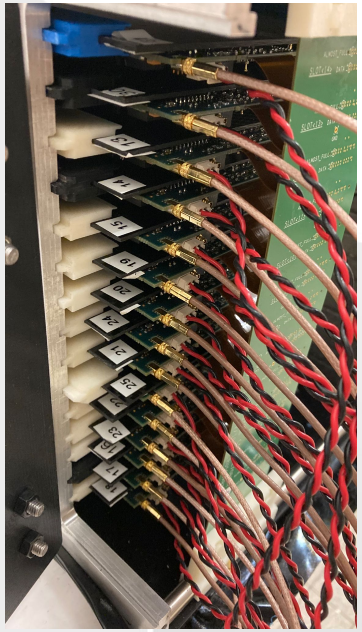
- ASICs based on BGA packaging
- Different routing than FEV10-12
- Different external connectivity

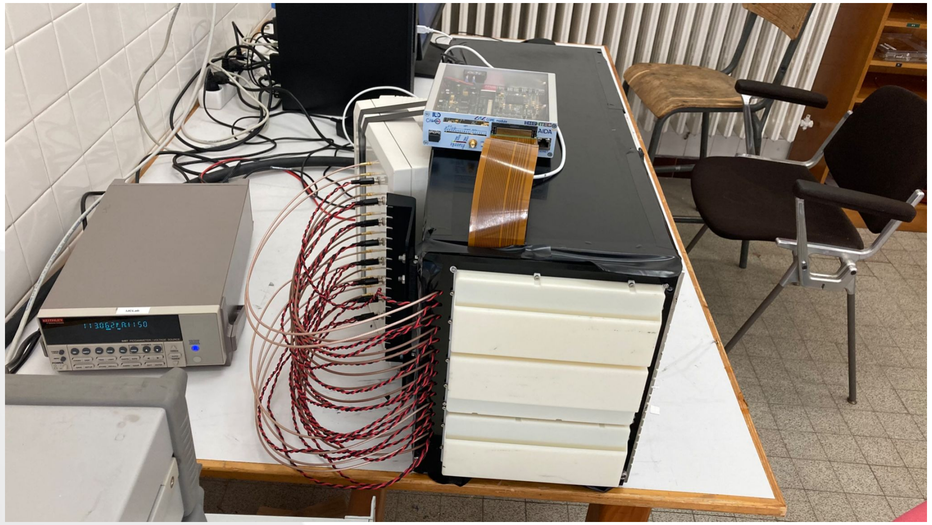
Implementation in the tight space

- “Dead space free” granular calorimeters put tight demands on compactness
- Current developments in for SiW-ECAL stacks 15 layers
- The layer density is close to what is requested by the ILD. Rest of 15 layers (30 layers in total) will fit between the stack shown on the right.
- Core module takes care of complete readout including the software
- Software also monitors the real-time beam status.

Complete readout system





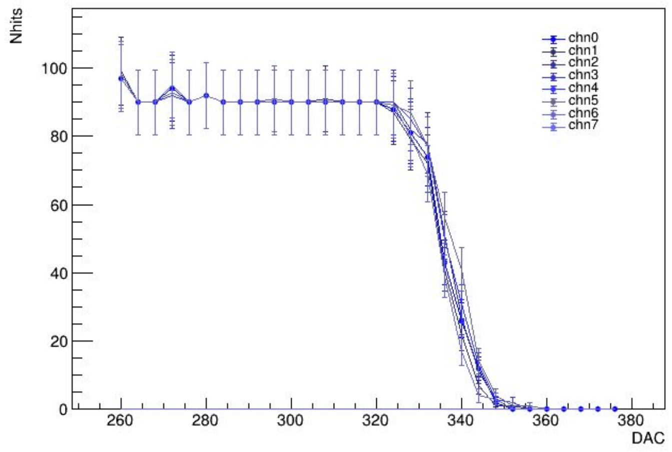


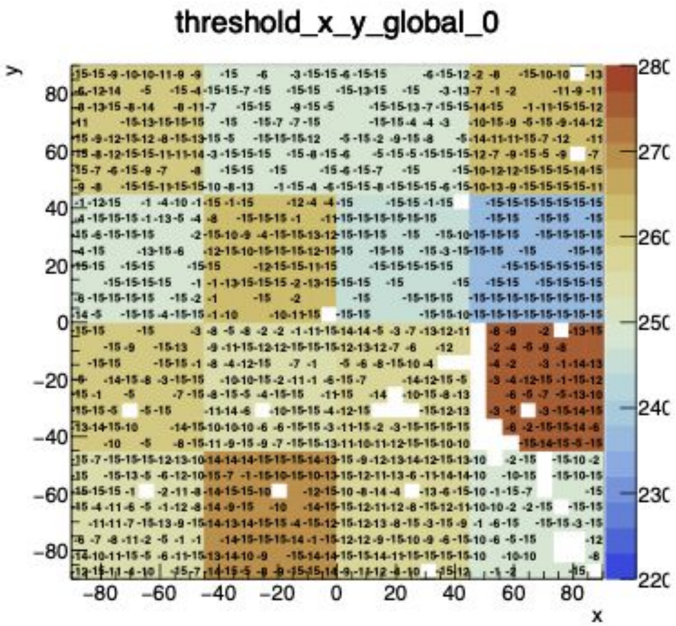
Calibration

Commissioning

- Calibration constants
    - Pedestal values
        - 15 layers / 16 chips / 64 channels / 15 SCA
    - +1 MIP scaling factor
    - x2 gains
    - 15 x 16 x 64 x (15+1) x 2 = 491,520 parameters

- Masking need to be done in order to silence the noisy cells.
- Multiple dry runs and cosmic ray runs were taken to filter out the defect cells.
- Detector signals come in form of electric pulses.
- DAC threshold determination were performed by injecting 1 MIP equivalent pulse and measuring the drop point for the hit counts.





Trail of R&D

Physics Prototype (2005 - 2010)

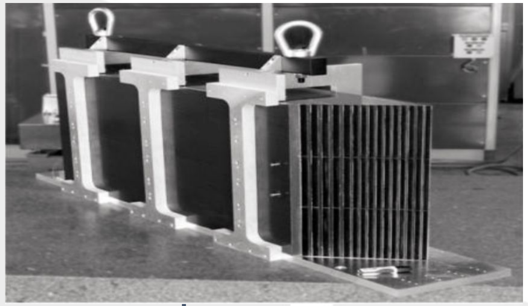
Proof of principle of granular calorimeters.
Large scale combined beam tests.

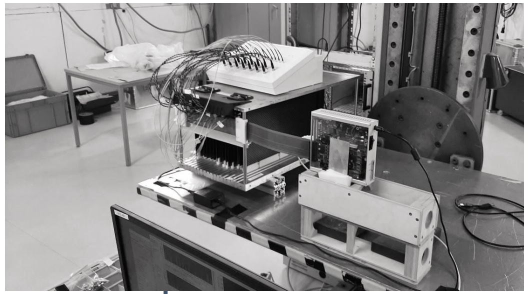
Technical Prototype (2010-)

Engineering challenges
High granularity, lower noise

15 layer assembly (2021-)

Further technical challenges with more realistic scenario using 15 layers (½ of real life ILD ECAL)



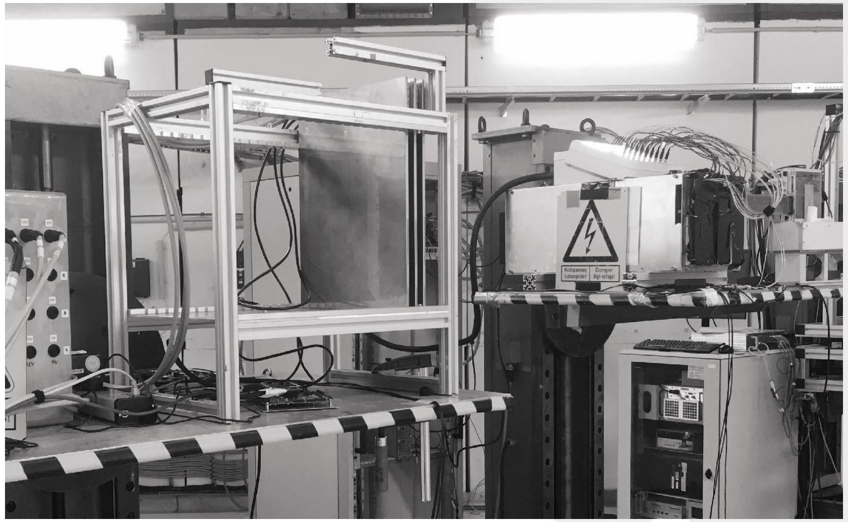


2005 2010 2021

Test Beam 2022

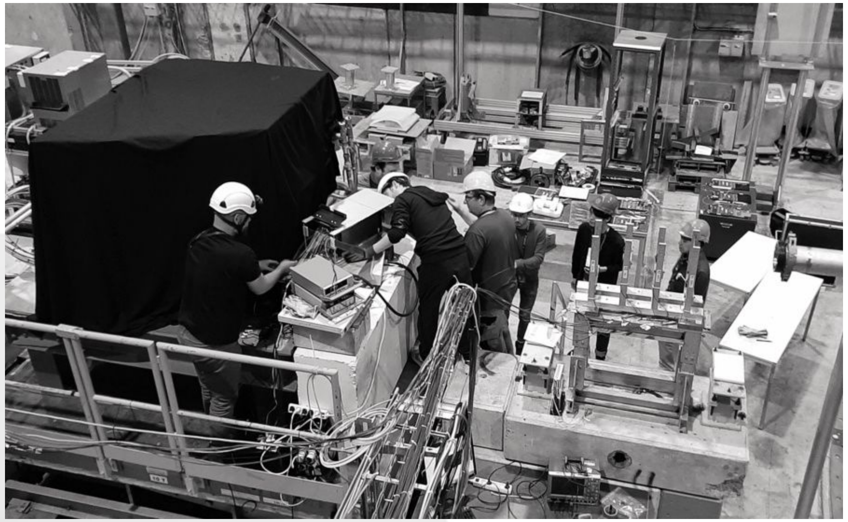
Test Beam March 2022 @ DESY

- Electron beam: 1-5 GeV
- First attempt conduct joint data taking with AHCAL group.
- Common data taking was performed.

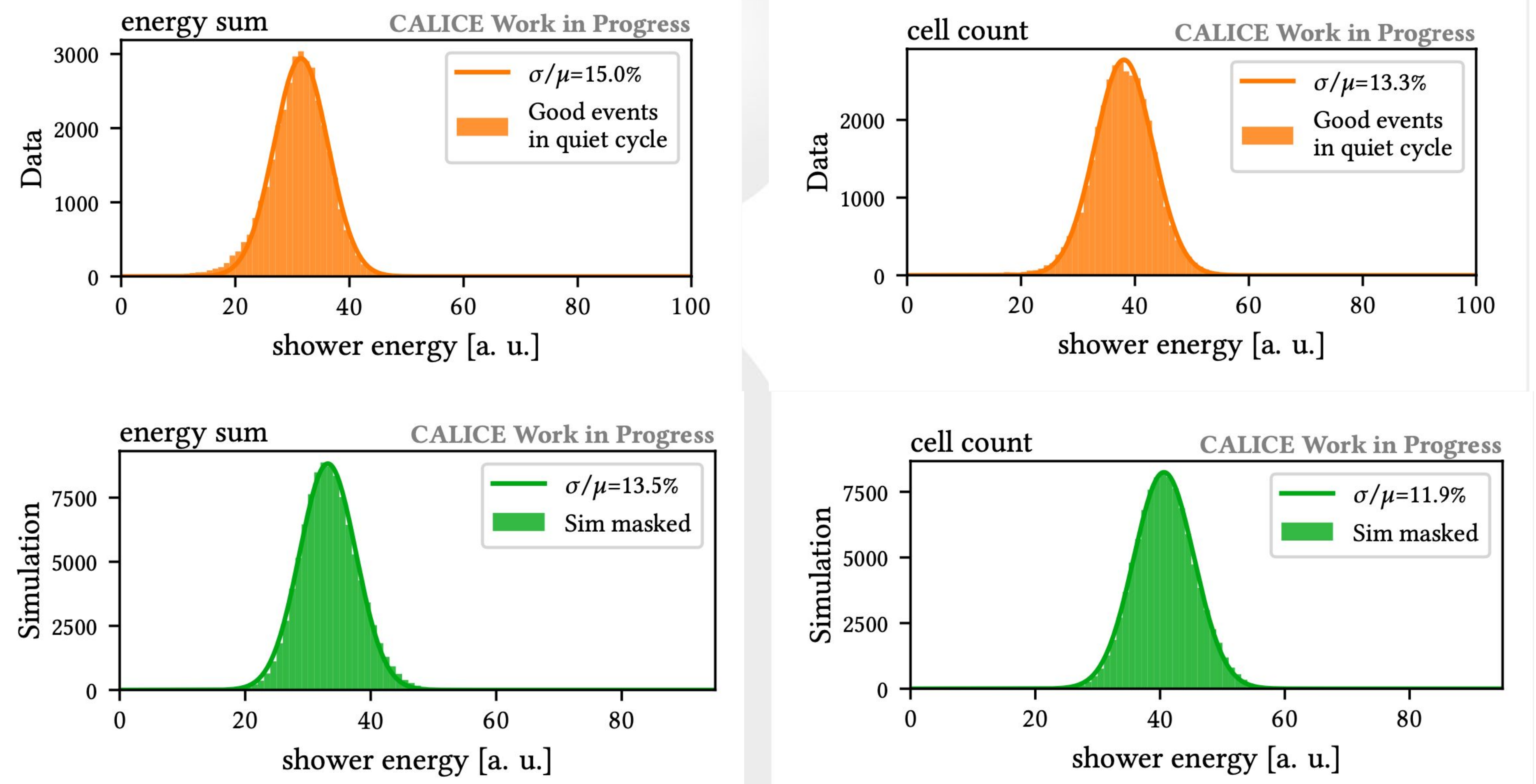


Test Beam June 2022 @ CERN

- Electron, muon, pion beam: 10-200 GeV
- Original plan was to use few new stabs to conduct the synchronization.
- Recycling old ASUs → 15 layer
- Disassembled and reassembled the old slabs.
- Successful synchronization of data recorded with SiW-ECAL and AHCAL



J. Kunath, F. Jimenez-Morales, SiW Ecal Analysis Meeting, 22/09/22



After proper filtering energy resolution in right ballpark for current prototype
Convergence in agreement data/MC

CERN Test Beam 2022-06

SiW-ECAL

- Sensors
  - 15 layers
  - 16 chips / layer
  - 64 channel / chip
  - **15 x 16 x 64 = 15,360 cells**
- Tungstens: up to 21 X_0
- Volume: 640 x 304 x 246 mm^3
- Commissioned 2020-2022
  - 4.5 x 10^5 calibration constants for one ASIC feedback capacitor setting.

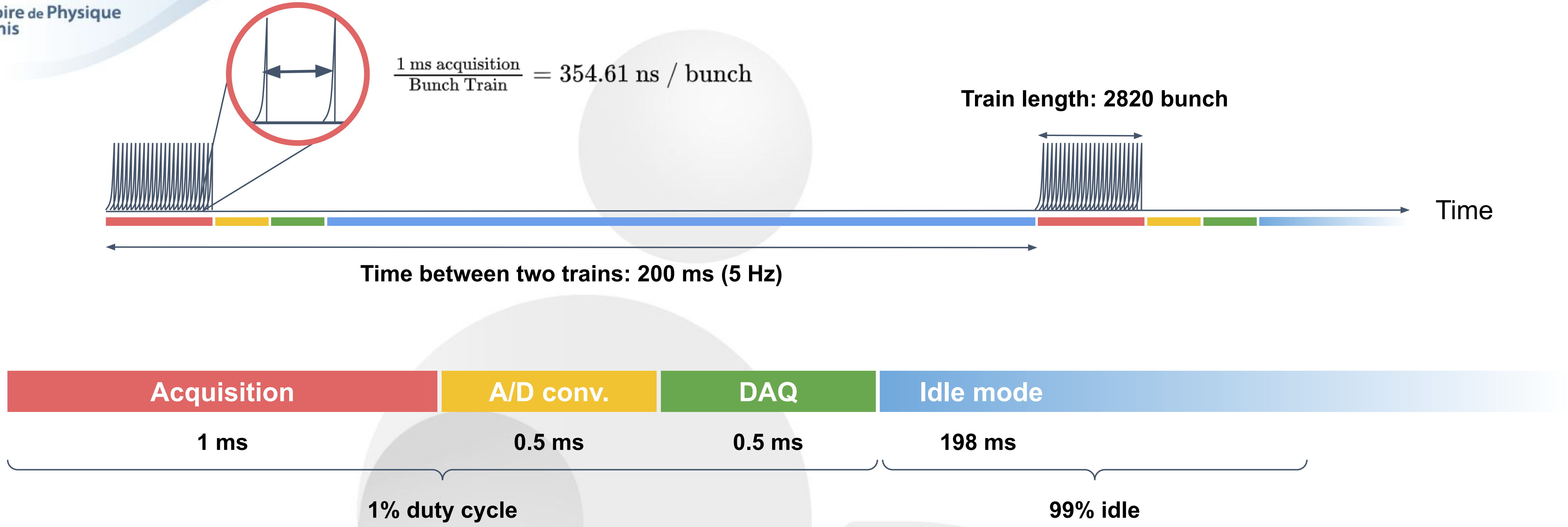
CERN SPS Beam

- Energies
  - e : 10, 20, 40, 60, 80, 100, 150 GeV
  - μ : 50, 150 GeV
  - π : 10, 20, 70, 100, 150, 200 GeV

Layer Setup

Layer	SLAB	SLBoard- ID	ASU type	wafer (um)	W (mm)	X0 cumulative
0	34	15	FEV13 K1	650	4.2	1.2
1	37	28	FEV13 D	650	4.2	2.4
2	36	18	FEV13 A	650	4.2	3.6
3	38	12	FEV13 C	500	4.2	4.8
4	35	16	FEV13 B	650	4.2	6.0
5	39	25	FEV13	500	4.2	7.2
6	29	22	COB	500	4.2	8.4
7	30	19	FEV12	500	4.2	9.6
8	33	20	COB	500	4.2	10.8
9	31	17	FEV12	500	5.6	12.4
10	19	13	FEV11	320	5.6	14.0
11	18	2	FEV11	320	5.6	15.6
12	23	6	FEV10	320	5.6	17.2
13	40	27	FEV13	320	5.6	18.8
14	17	10	FEV11	320	5.6	20.4

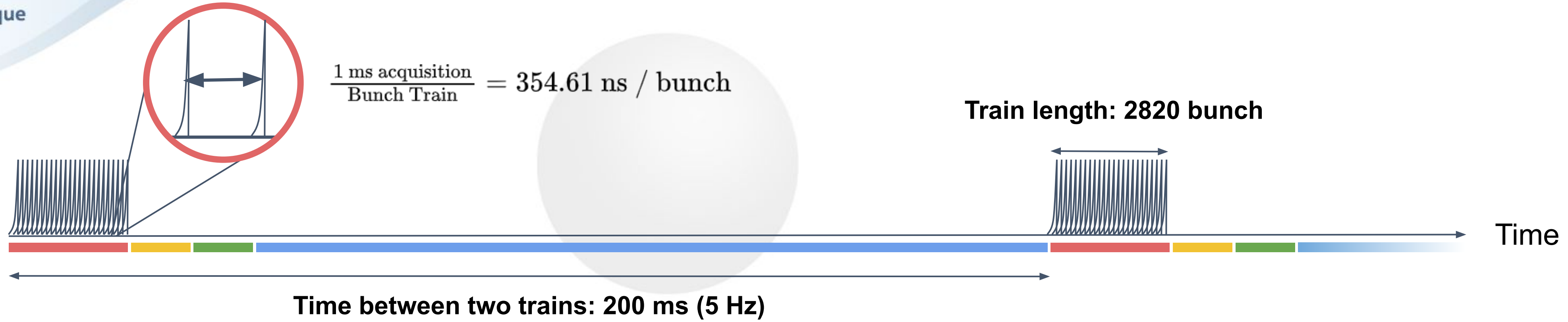
Beam Structure & Readout Cycle



ILC & ILD Setup

- ILC bunch trains come in frequency of 5 Hz. The time is synchronized between the beam and ILD.
- ILD will operate in **power pulsing mode**, where:
    - Electronics are switched on during > ~1 ms of bunch train and data acquisition.
    - Bias currents being shut down between the bunch trains.
- No active cooling necessary.

Beam Structure & Readout Cycle

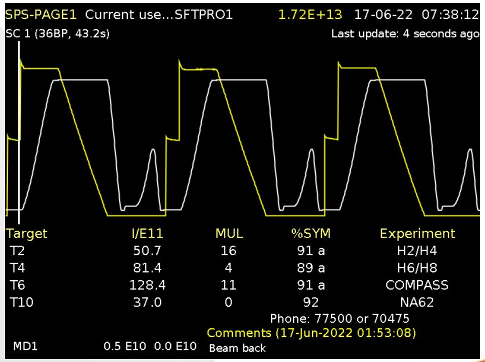


Acquisition	A/D conv.	DAQ	Idle mode
1 ms	0.5 ms	0.5 ms	198 ms

1% duty cycle **99% idle**

Test Beam Setup

- Beams will come in irregular rate.
- Clock was only synchronized between AHCAL and SiW-ECAL but not with the beam.
- Therefore power pulsing mode were not used during the test.
- The active cooling was applied with the ventilation of the air.

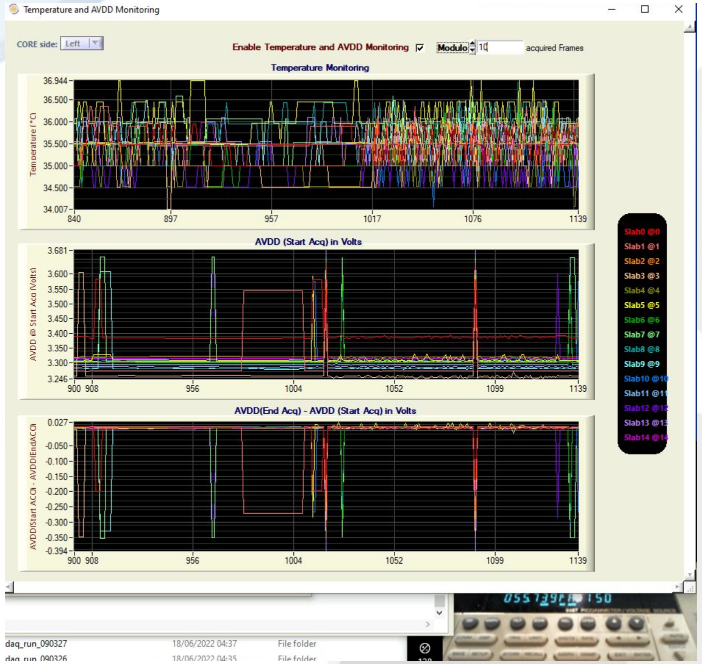


Online Beam Monitoring

Temperature

AVDD @ start acq.

AVDD
@ (start - end) acq.



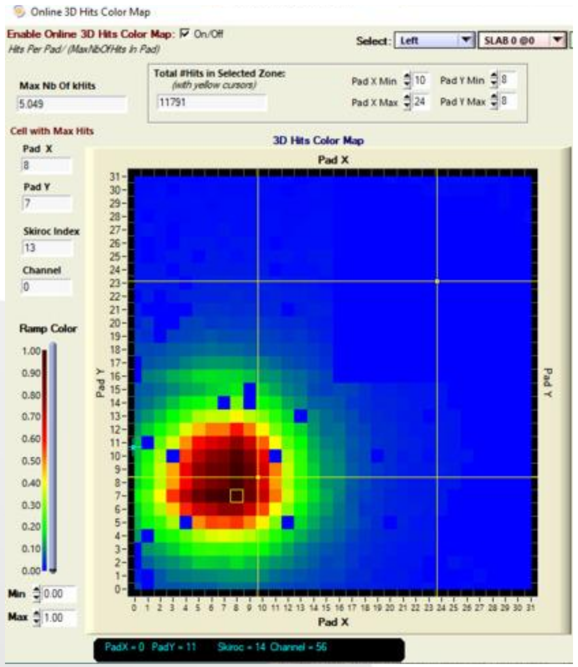
Temperature and Voltage Monitor

- Displays relative temperature inside the detector
- Monitors AVDD in volts to check the detector health

Efforts by Jihane & Dominique (IJCLab)

Beam Spot

- Displays hit maps for each layer.
- Allow for real-time beam and detector tuning
  - e.g. Adaquation of beam rates or thresholds



Clock Synchronization

- Clocks between ECAL and AHCAL need to be synchronized in order to conduct a common data taking.
- 40 MHz external clock sent from the Clock and Control Card (**CCC**), operated by the common DAQ system, **EUDAQ**.
- For each readout, Bunch Crossing ID (**BCID**) is assigned with recorded time stamp.

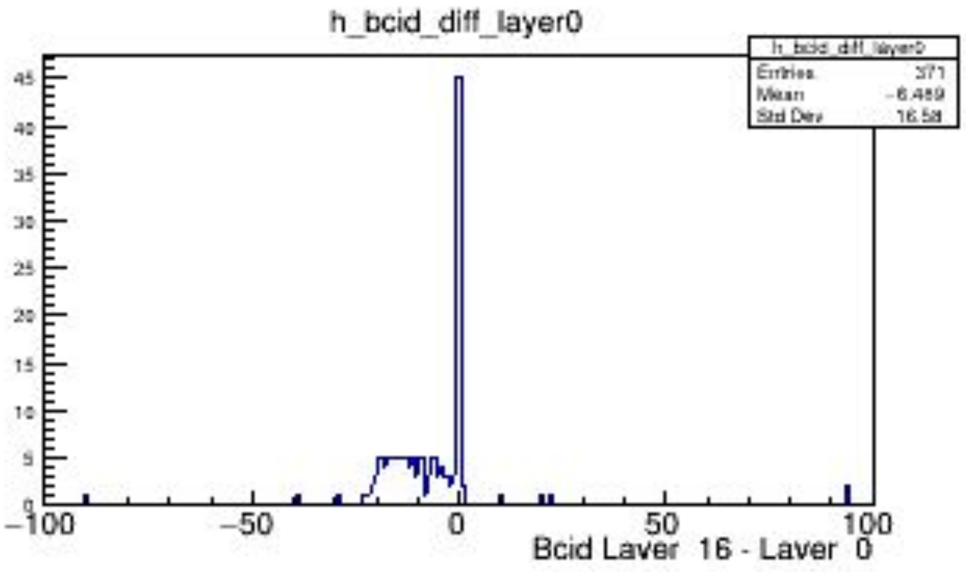


Fig. Difference between BCIDs in AHCAL and ECAL

Particle Identification

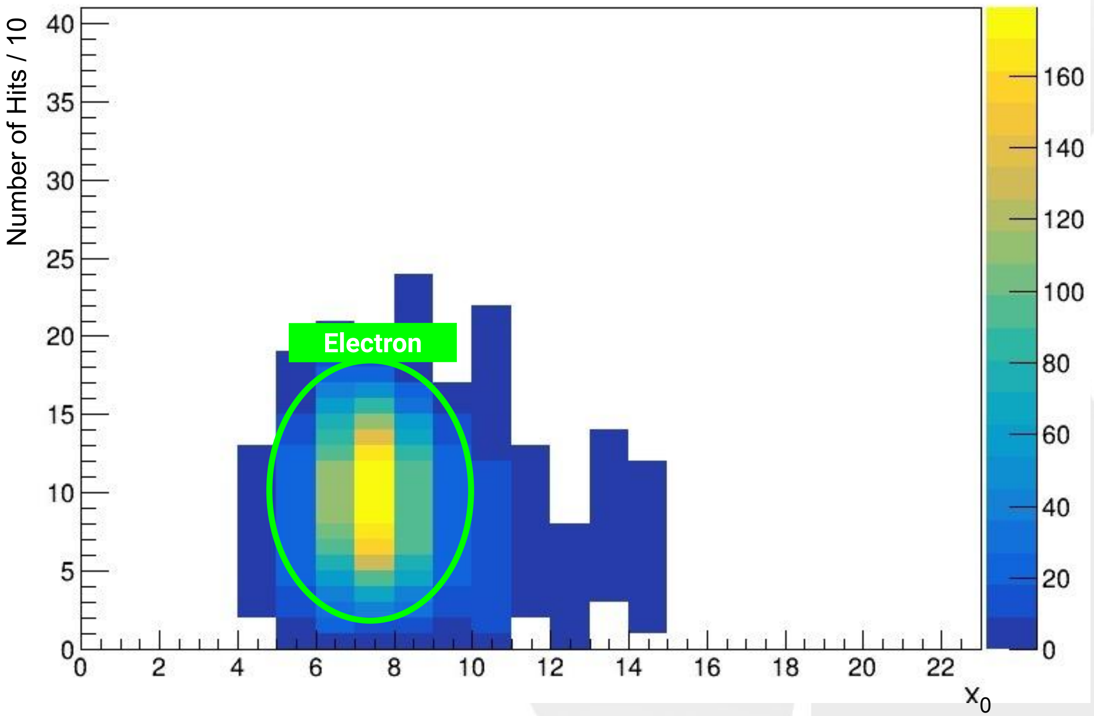


Fig. SiWECAL Electron 150 GeV

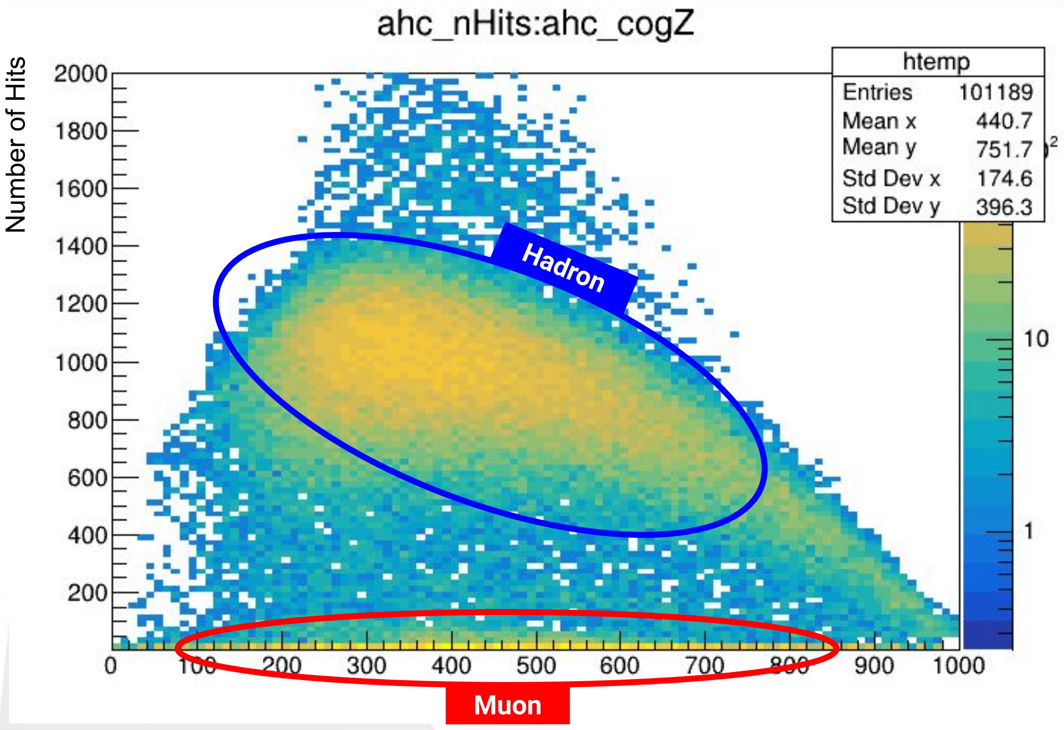


Fig. AHCAL Pion 200 GeV

Event Display

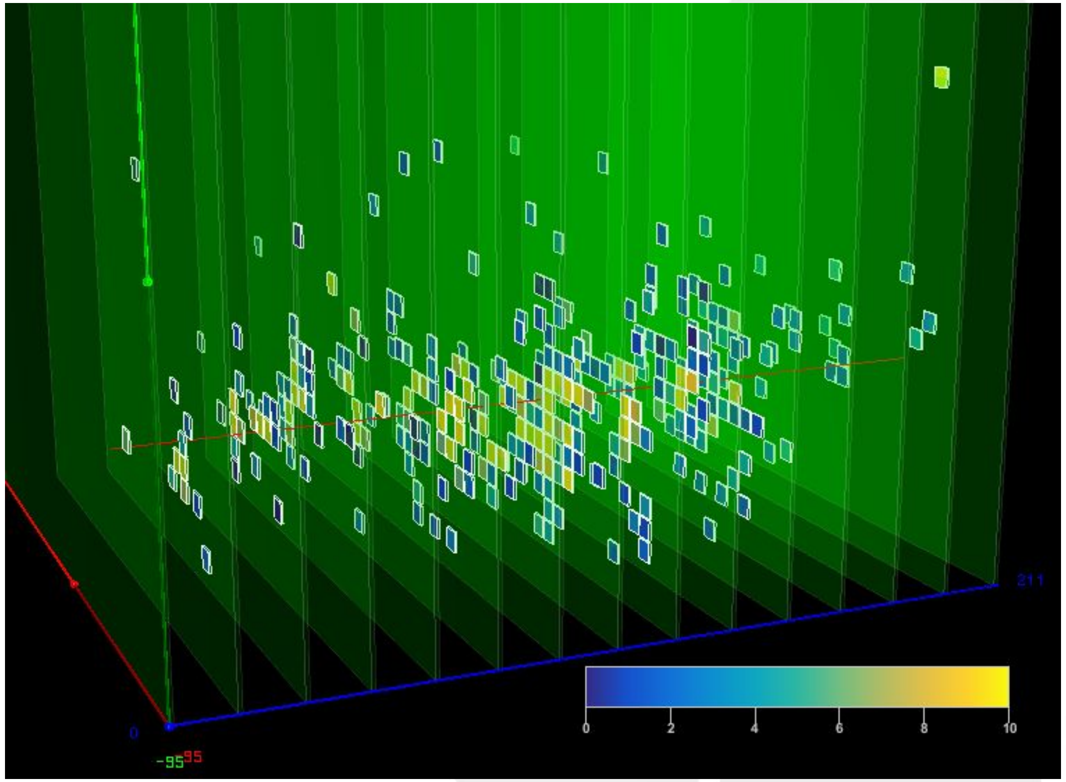


Fig. SiWECAL Electron 40 GeV

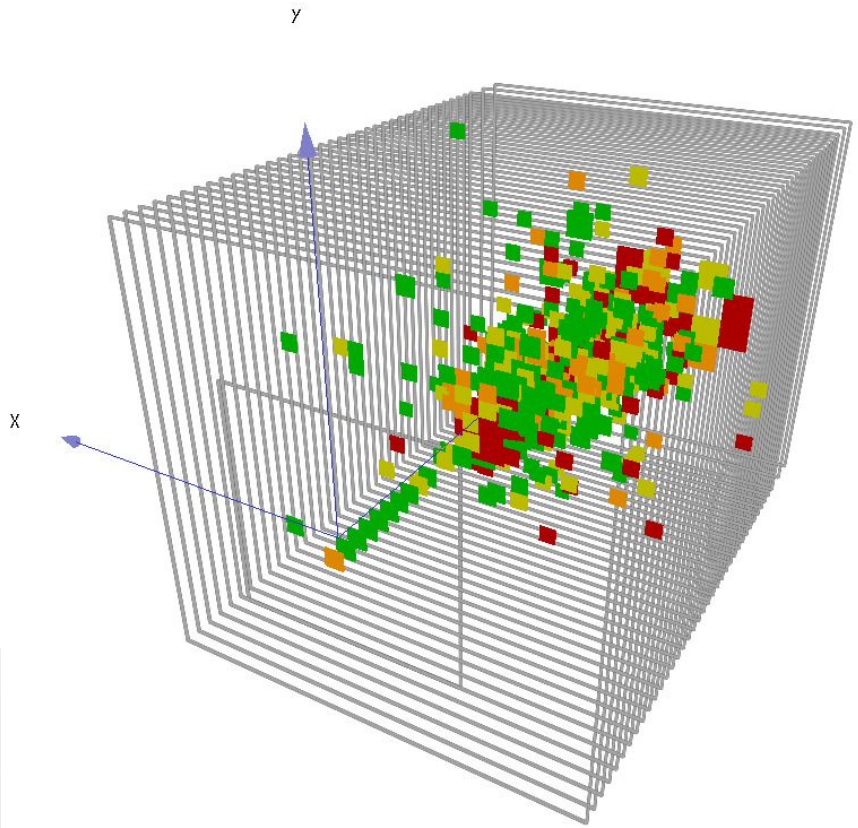
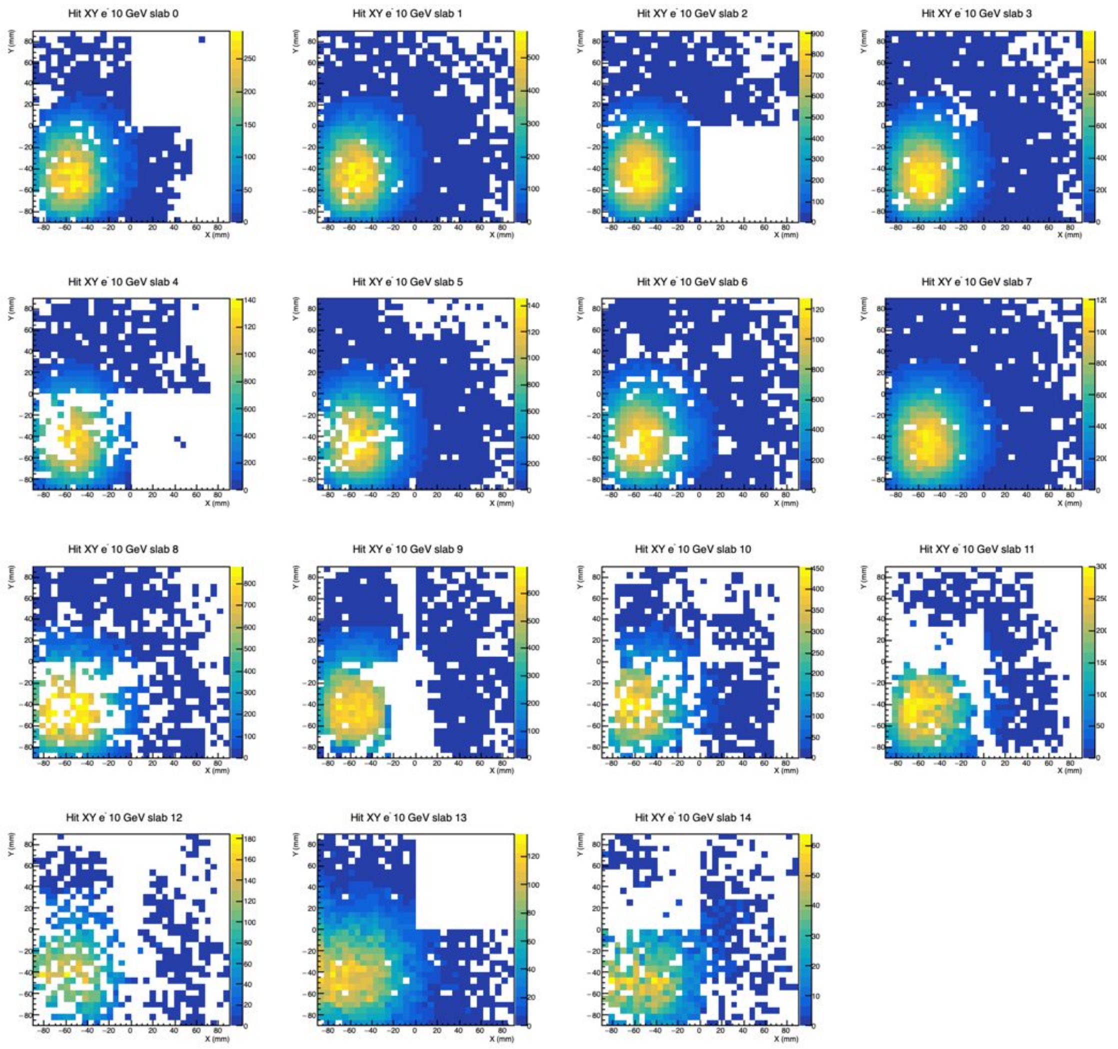


Fig. AHCAL Pion 106 GeV

Hit Quality Checks

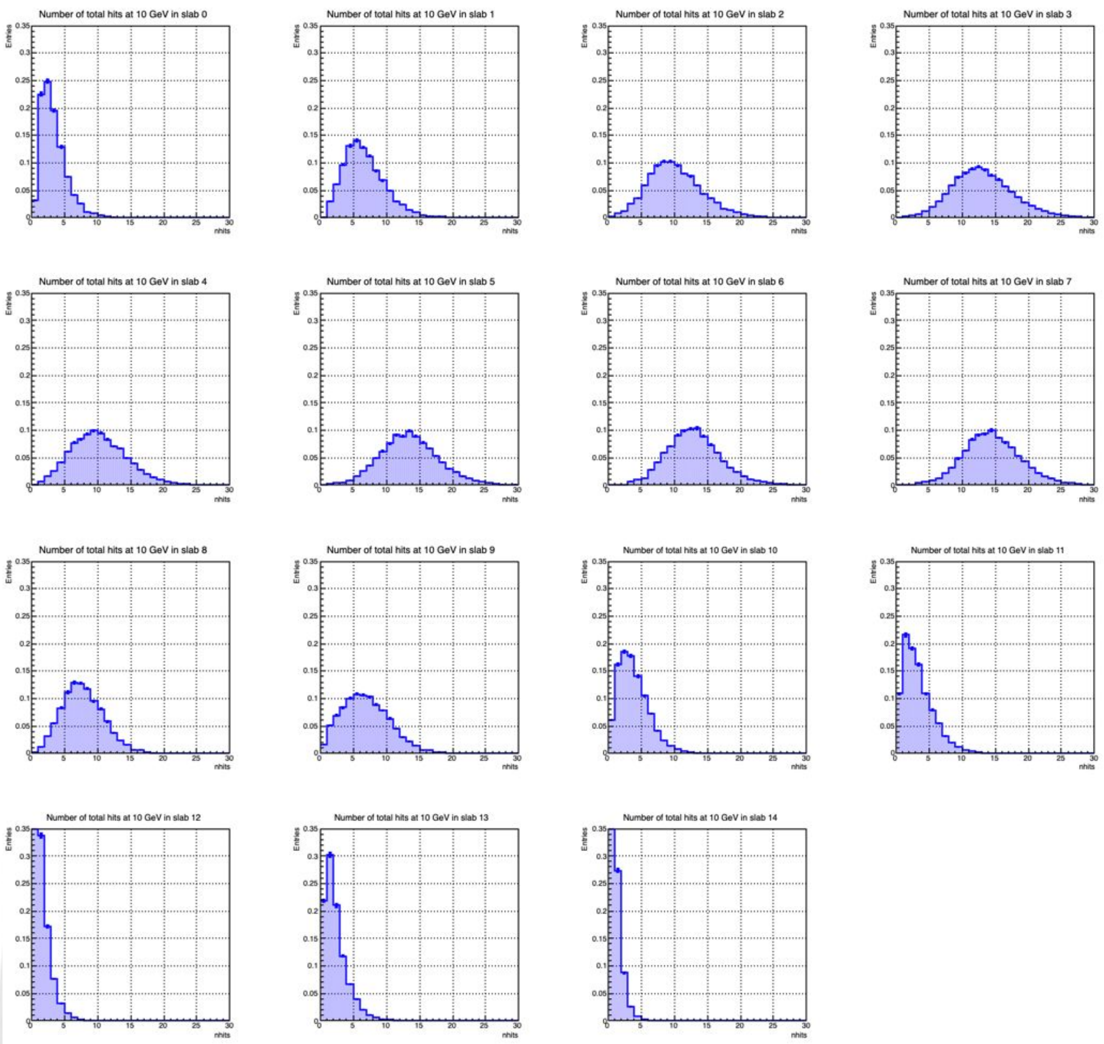
Hit Maps

- Hit distribution for the individual layer is mapped for one of the **10 GeV electron runs**, which was taken for 30 mins.
- The beam is shot at (x, y) = (-42, -42) mm.
- The beam axis position agrees with the position we observed in the online beam monitoring.
- The large square corresponds to the size of single wafer pad. Later we observed some wafer delamination, possibly due to the degrading in the glue.
- Noisy cells, along with the cells behind the delaminated wafers were masked.



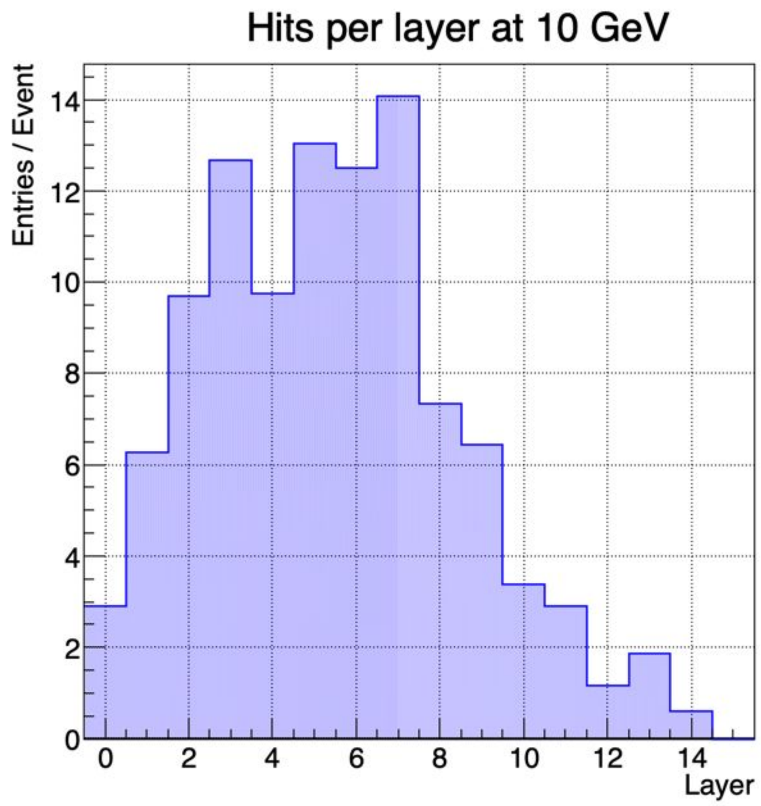
Hit Distribution

- Number of hits deposited to the individual layer is shown for the same run.
- The distribution is normalized the number of events recorded. (24k events)
- Required minimum of 12 layer coincidences for every events. Event selection efficiency: **46.4 %**.
- Hits with energy lower than 1 MIP was filtered.
- Shower maximum corresponds to slab 6 and 7.



Hits per Layer

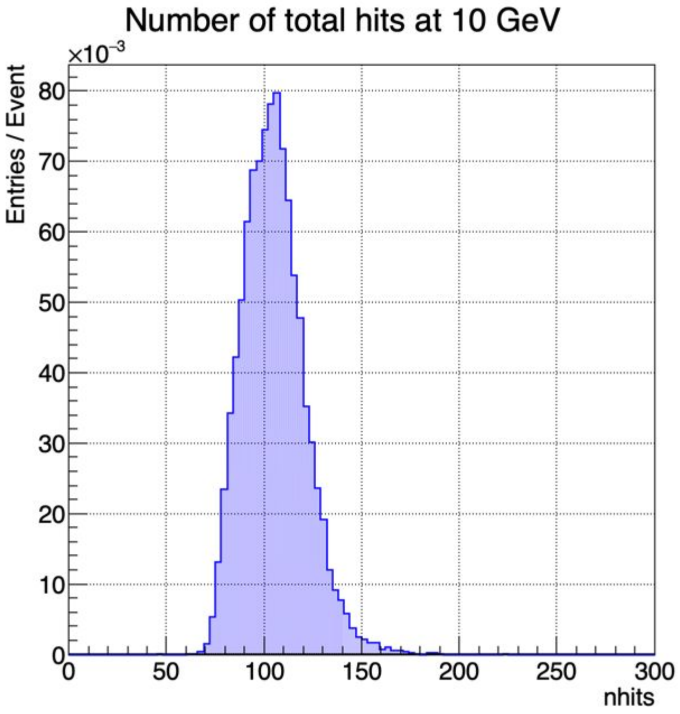
- Layer numbers of the deposited hits were plotted.
- The distribution should roughly correspond to the shower profile of the electron beam at 10 GeV.
- Shower maximum observed around slab 5-7.
- Some non-continuity in the distribution (e.g. layer 4), is caused by masking and wafer delamination, which leads to inability for the hit registration.



Hit Quality Checks

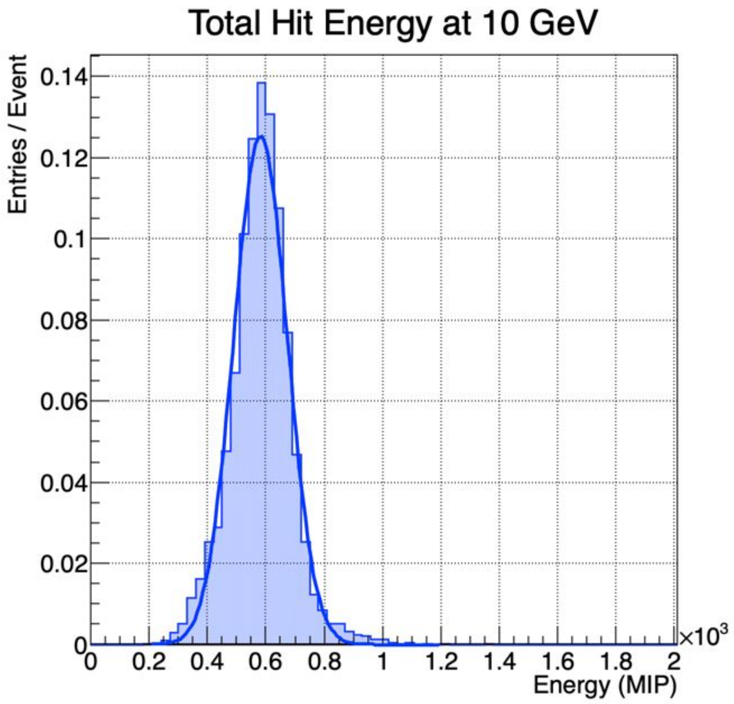
Total Hits

- Total hit plot has excellent distribution with peak at 115 hits.
- Short tail before the peak means there are small chances of missing hits from the EM shower.
- The tail on the higher end mostly likely originated from the electrical noises registered as hits, which can happen due to cross-talks between the circuits.



Energy

- Total hit energy is plotted as a unit of Minimum Ionization Energy (MIP)
- Gaussian peak at 580 MIPs
- Study using simulation is required to quantitatively understand the result.

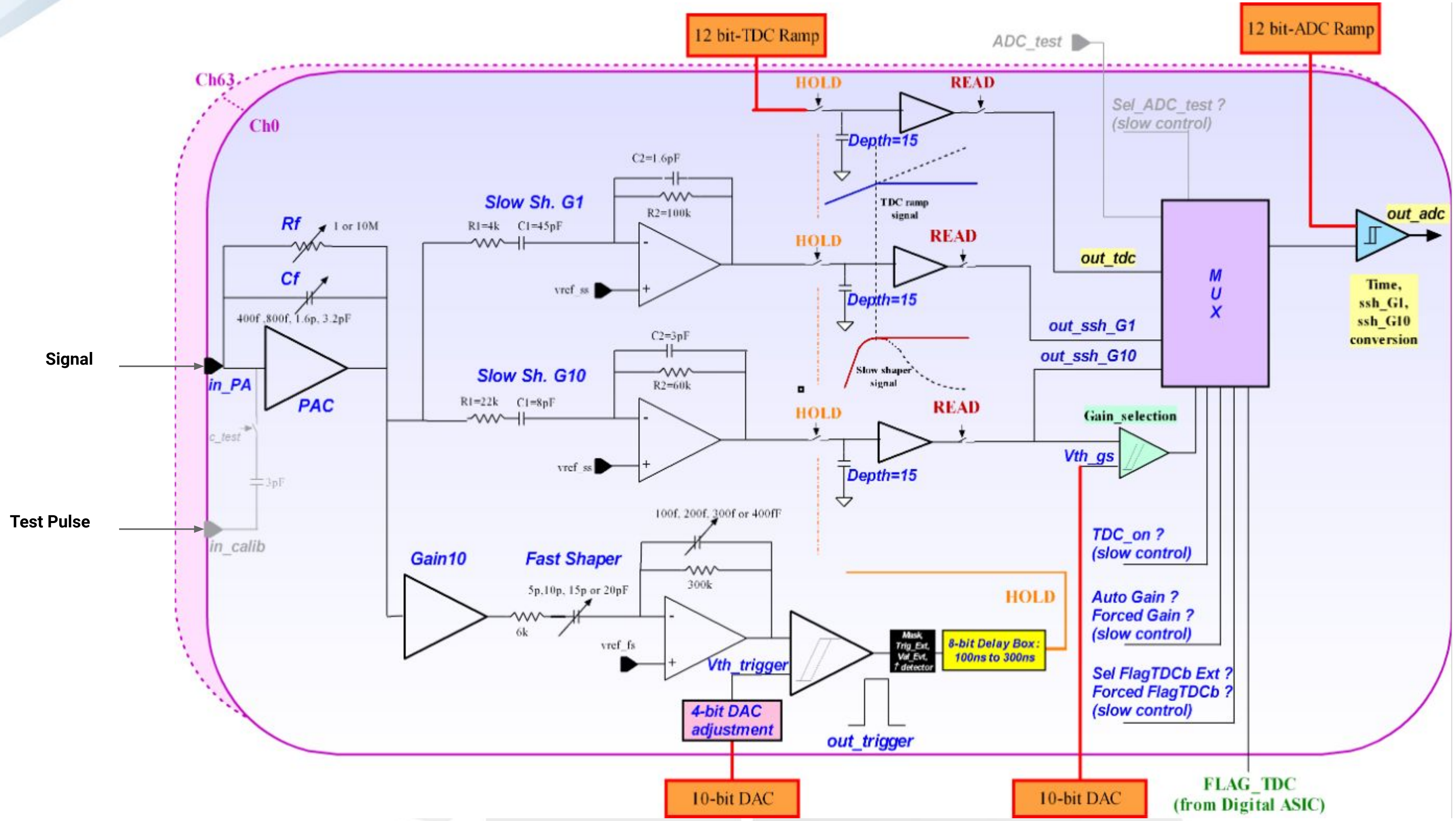


Summary and Outlook

- **Results from the Test Beam June 2022 @ CERN were presented.**
  - First successful operation using **15 layers** of ECAL, together with AHCAL.
    - Over 15,000 cells in total.
  - Clock synchronization with AHCAL data taking.
  - Difficulty in dealing with large amount of hits, especially at high energy.
  - Pilot study was performed with **10 GeV electron sample**.
- **Missing hits**
  - Some hits were missing from the data due to masking and wafer delamination.
  - Such effects gets involved at energies higher than 20 GeV.
- **Simulation analysis**
  - Simulation analysis is simultaneously performed to check the data quality.
  - The study is still undergoing.
- **Detector Development**
  - New PCBs for updated stack available. (Metrology and electrical tests currently conducted in-house)

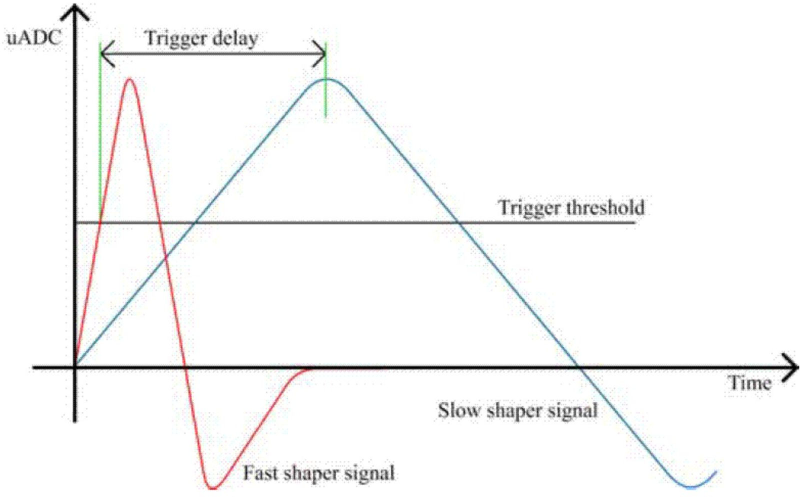
Backup

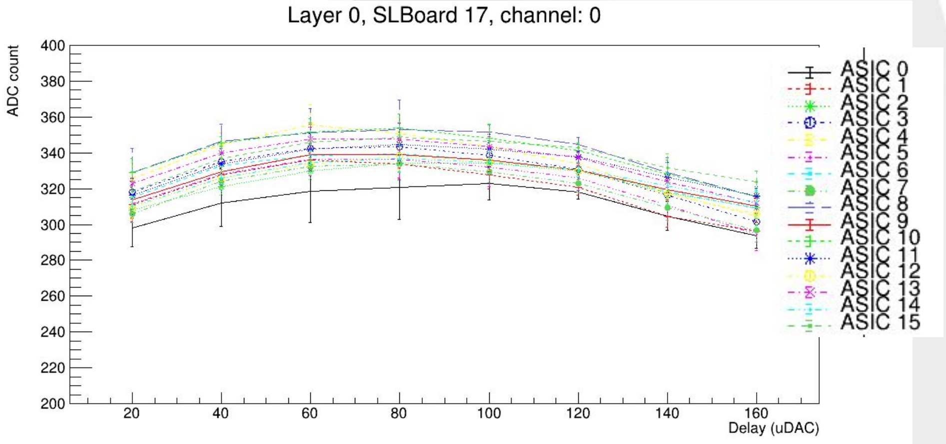
Electronic Circuit Layout for the SKIROC 2

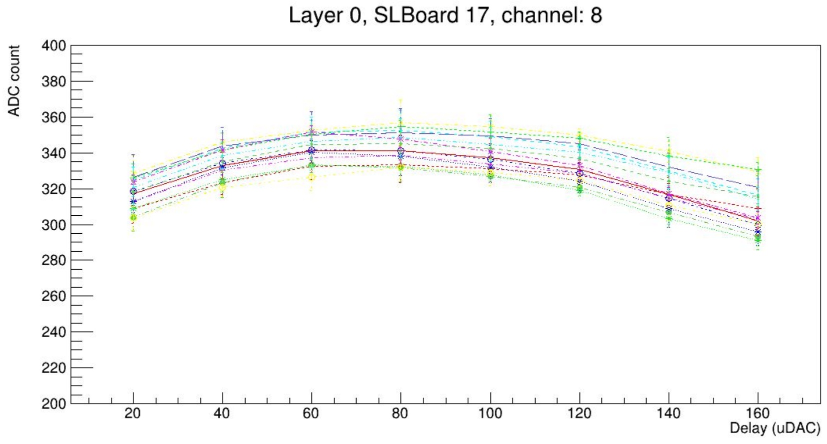


Hold Scan

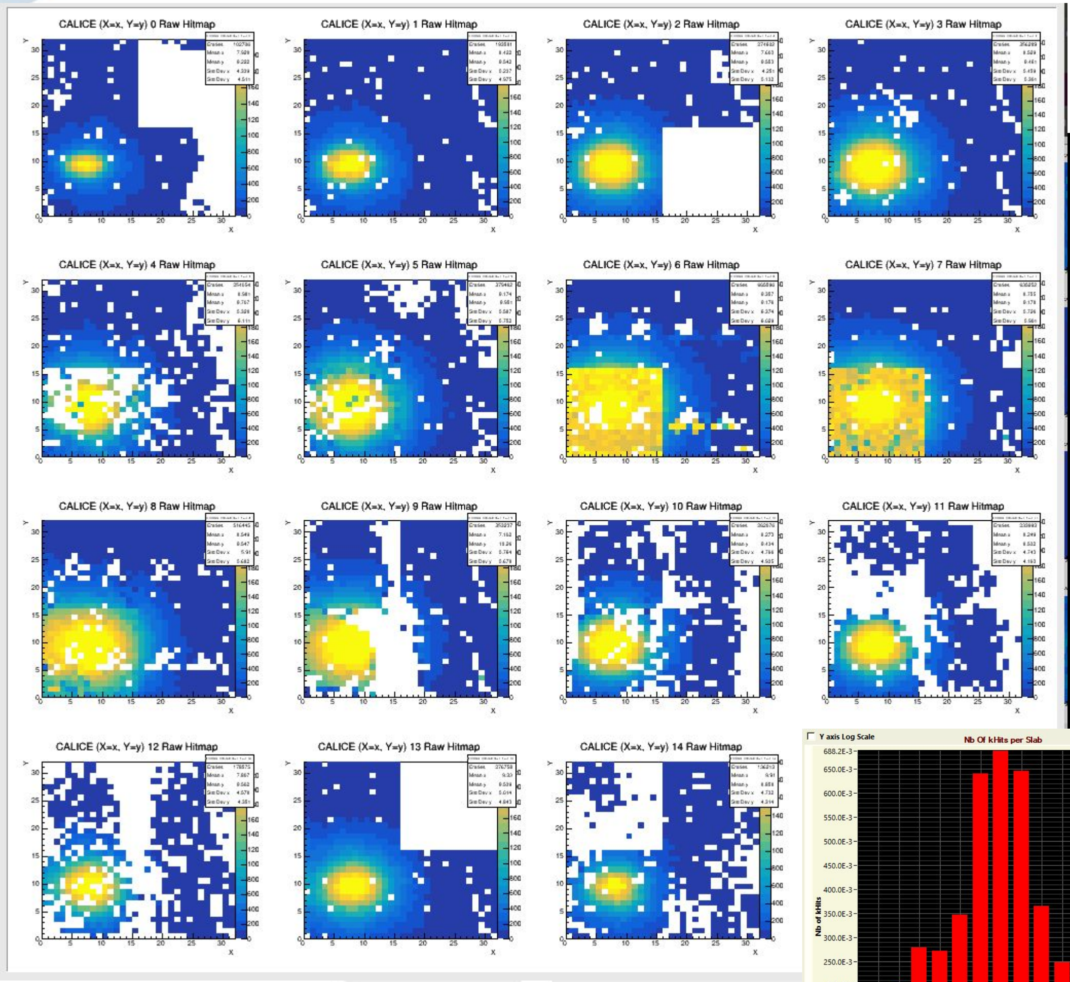
- Signal is needed to be read along the pulse that is generated by the slow shaper. This timing is managed by trigger delay.
  - Optimum trigger delay depends on the threshold.
- The delay-for-hold can be configured via DAQ software.
  - Inject the signal to row-by-row with signal amplitude of 1.2V
  - Hold scan was performed from the range of 20-160 in steps of 20.

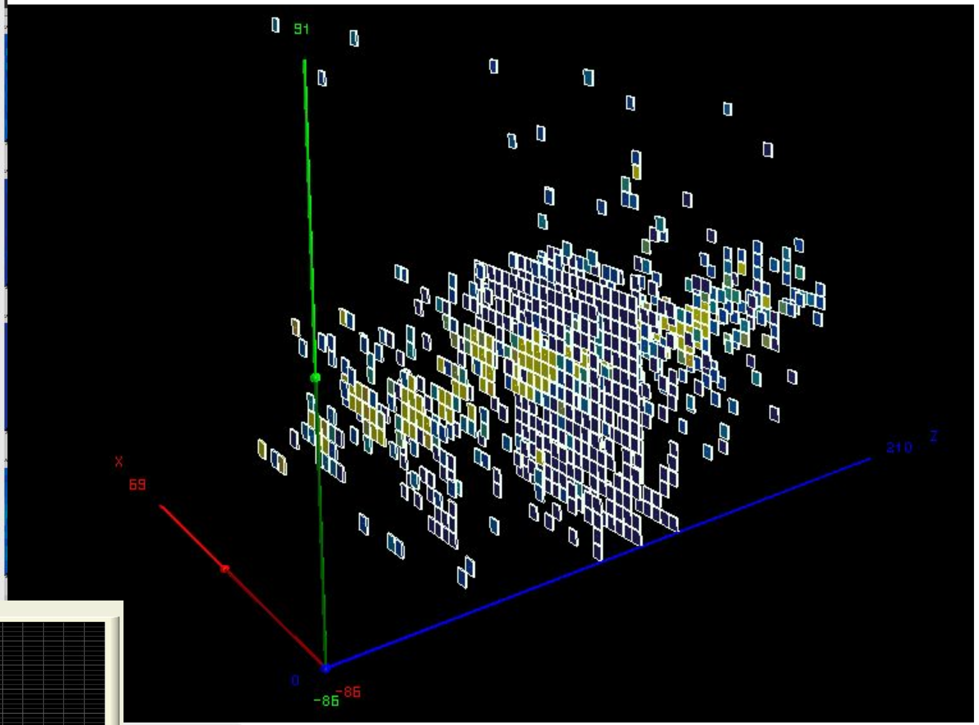


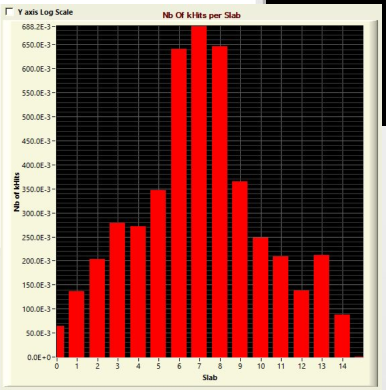




Wafer Delamination







Particle Identification

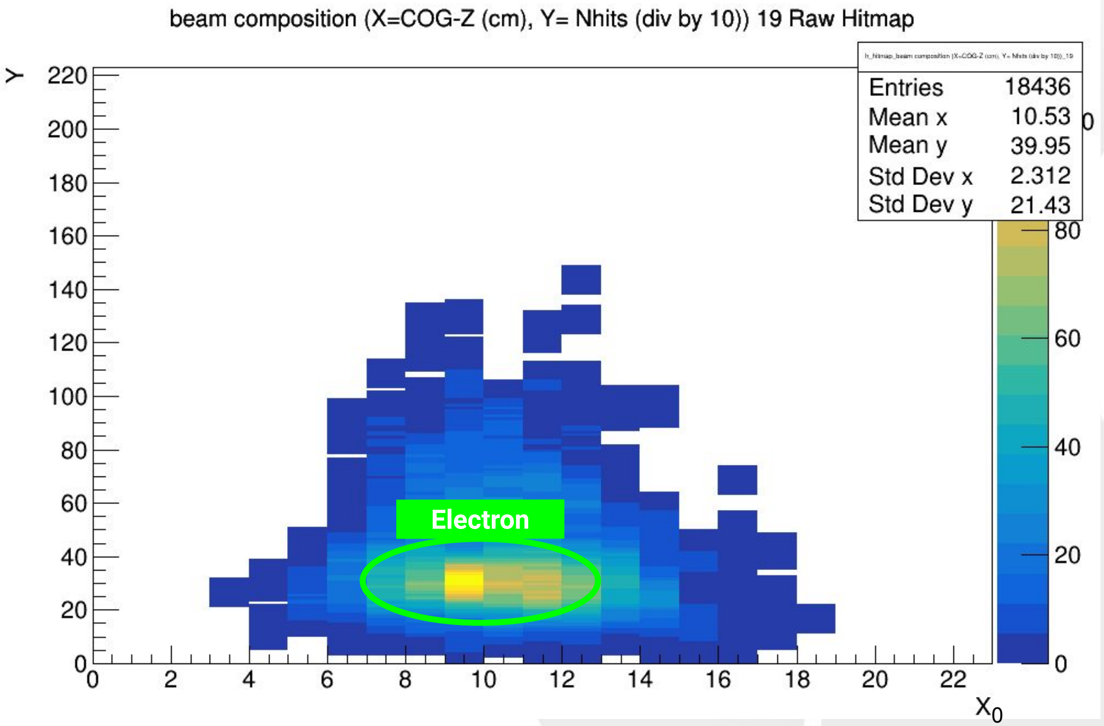


Fig. SiWECAL Electron 150 GeV

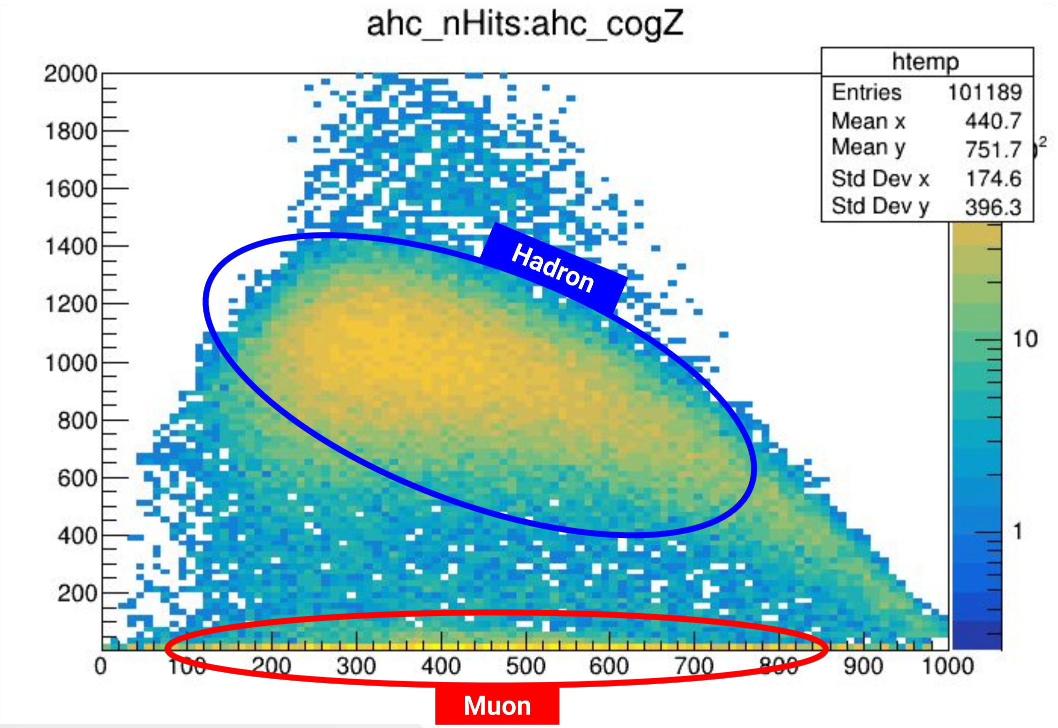
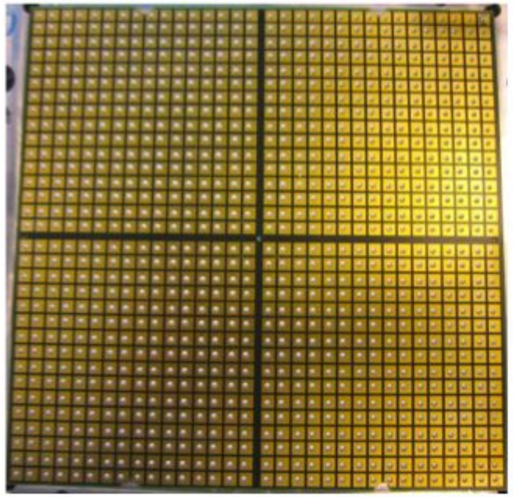


Fig. AHCAL Pion 200 GeV

Wafer Delamination



Metrology and PCB Deformation

- Setup of a device to measure the flatness of the PCB at different stages
- PCBs will be out into cabling machine and dimensions will be monitored before and afterwards

Glue – Alternative agents and procedures

- After discussion with Astronomy Institute of Paris and Epotek
- Test glue of type H20E as alternative to Epotek J2189
  - Should have higher mechanical stability
- Use EPOTEK 301-2 as underfill for mechanical stabilisation (proposal of Epotek)
  - This underfill has low viscosity that ensures mechanical stability by capillary effect
  - First tests carried out – Stay tuned for results
- Alternative proposal EPOTEK 353ND-T
  - Epoxy for gluing electrical component, could be used to stabilise glued sensor at sensor boundaries
  - Data sheet in backup

  Further alternatives will be studied

Pull tests

- IJCLab will prepare pull tests in order to get a quantitative picture of the mechanical stability of the glue
- Maybe in combination with C2N – A CNRS Institute specialised for materials

New FE boards

LLR, IJCLab, LPNHE, OMEGA

Improvements:

- Power distributions
  - Local power regulation
  - Local High Voltage filtering & Supply
- Signal distribution (buffering), data paths
- Monitoring (single ID, temp, probe analogue line)
- ASIC shielding/routing

Status:

- pre-version 2.0 tested, minor corrections needed
  - Noise uniformity dramatically improved (ex: outliers in thr. / 20 !)
- version 2.1 produced, … in metrology
  - before cabling, 2nd metrology, gluing, …
  - All material available : ASICs being tested