Progress towards large ultra-granular Silicon-Tungsten electromagnetic calorimeters

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université PARIS-SACLAY GRADUATE SCHOOL Physique
P2I Physique des deux Infinis

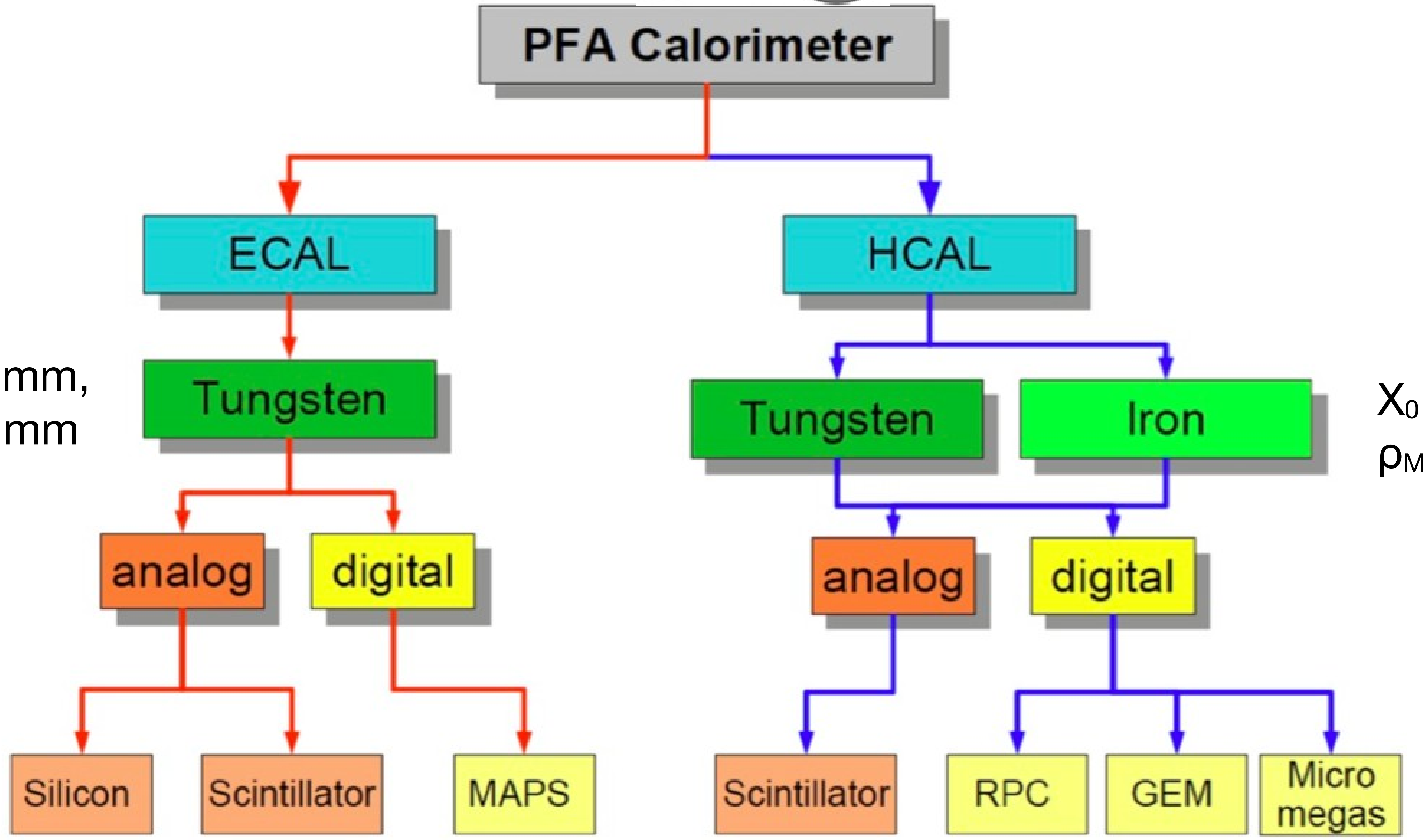
On behalf of the CALICE Collaboration

LCWS 2023 – SLAC May 2023

Supported by AIDA innova

Calorimeters for PFA

Mainly organised within the CALICE Collaboration



X_0 ~ 3 mm, ρ_M ~ 9 mm

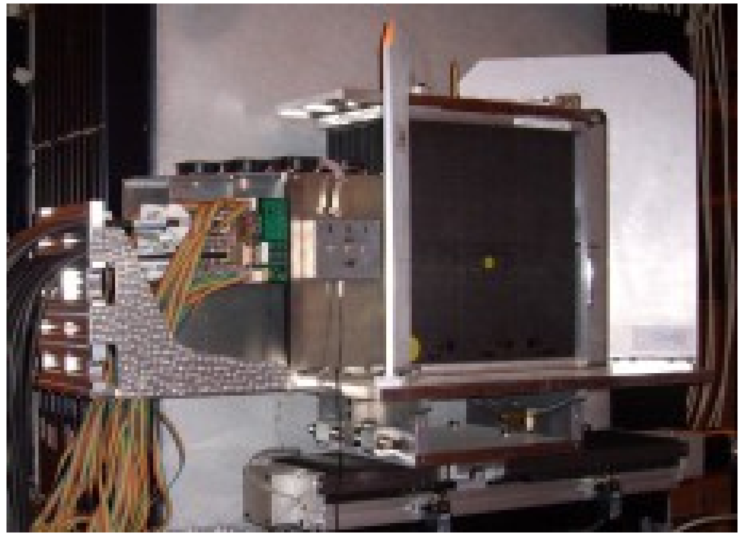
X_0 ~ 20 mm, ρ_M ~ 30 mm

All projects of current future high energy colliders propose highly granular calorimeters

Steps of R&D

Physics Prototype

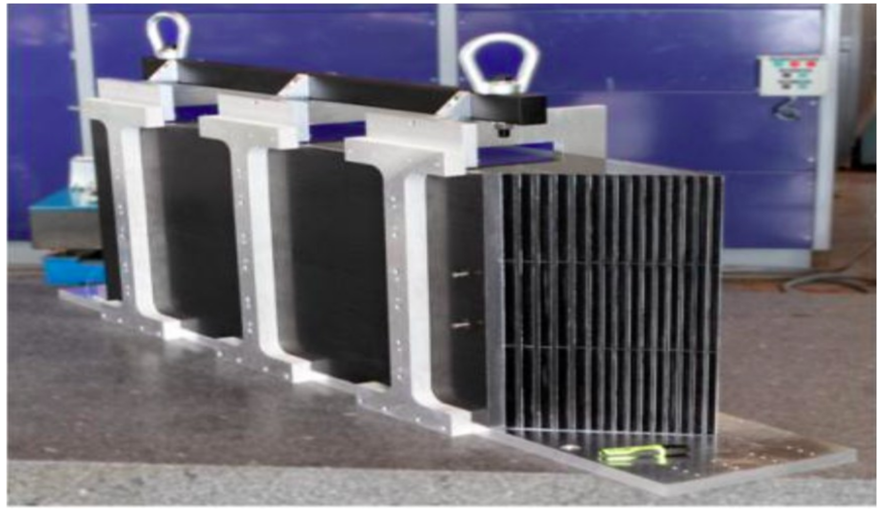
2005 - 2011



Proof of principle of granular calorimeters
Large scale combined beam tests

Technological Prototype

2010 - ...

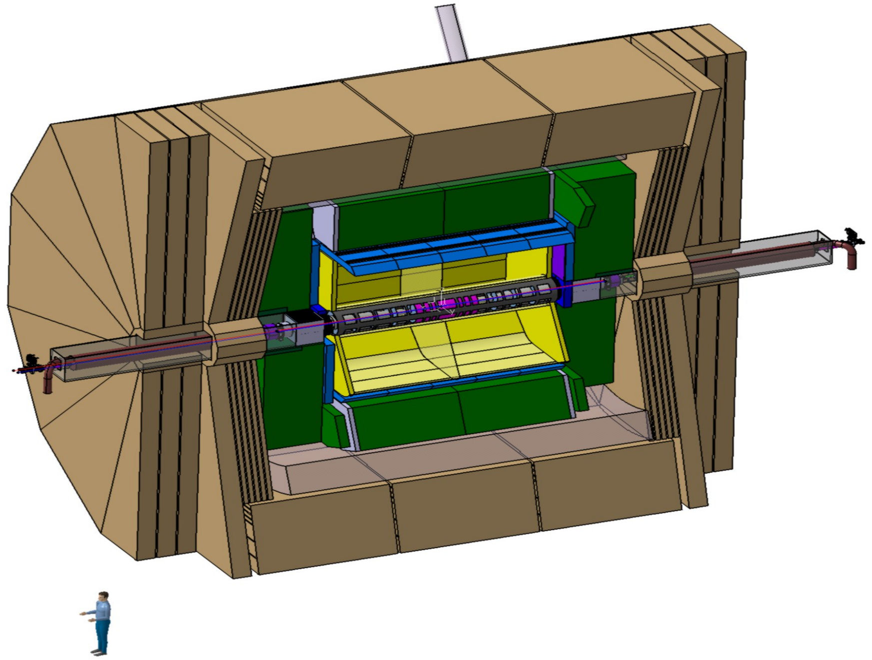


Engineering challenges

Higher granularity

Lower noise

LC detector

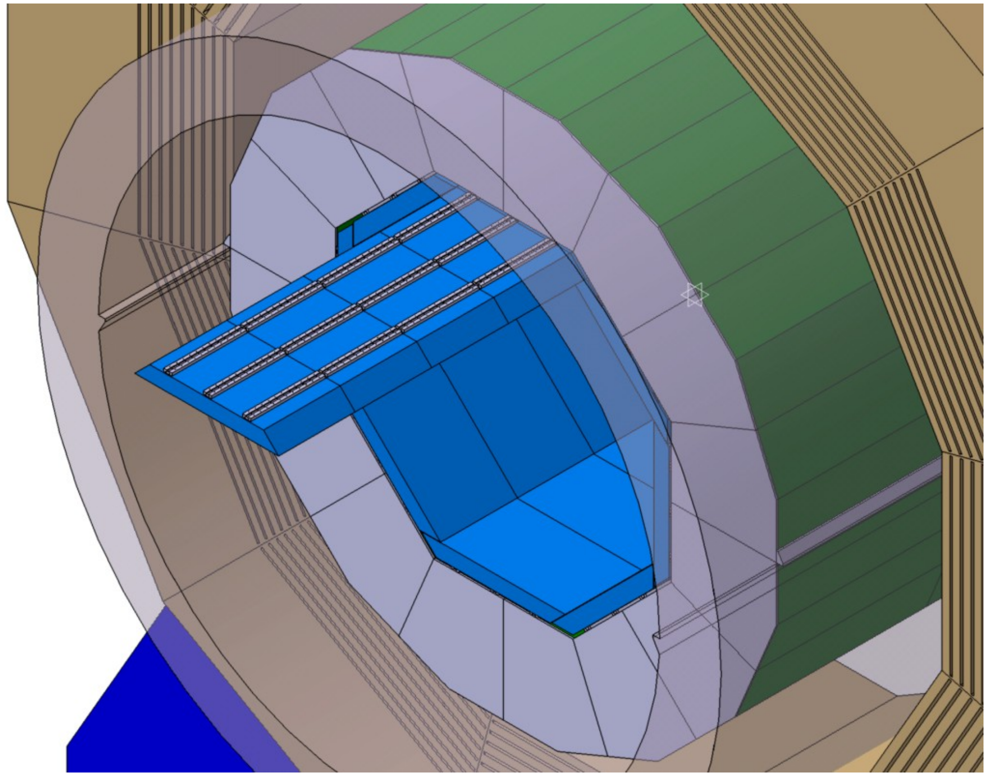


The goal
- Typically 10^8 calorimeter cells

Compare:
- ATLAS LAr ~10^5 cells
- CMS HGCAL ~10^7 cells

Silicon Tungsten electromagnetic calorimeter

Optimized for Particle Flow: Jet energy resolution 3-4%, Excellent photon-hadron separation



The SiW ECAL in the ILD Detector

- O(108) cells
- “No space”
=> Large integration effort

Basic Requirements:

- Extreme high granularity
- Compact and hermetic
- (inside magnetic coil)

Basic Choices:

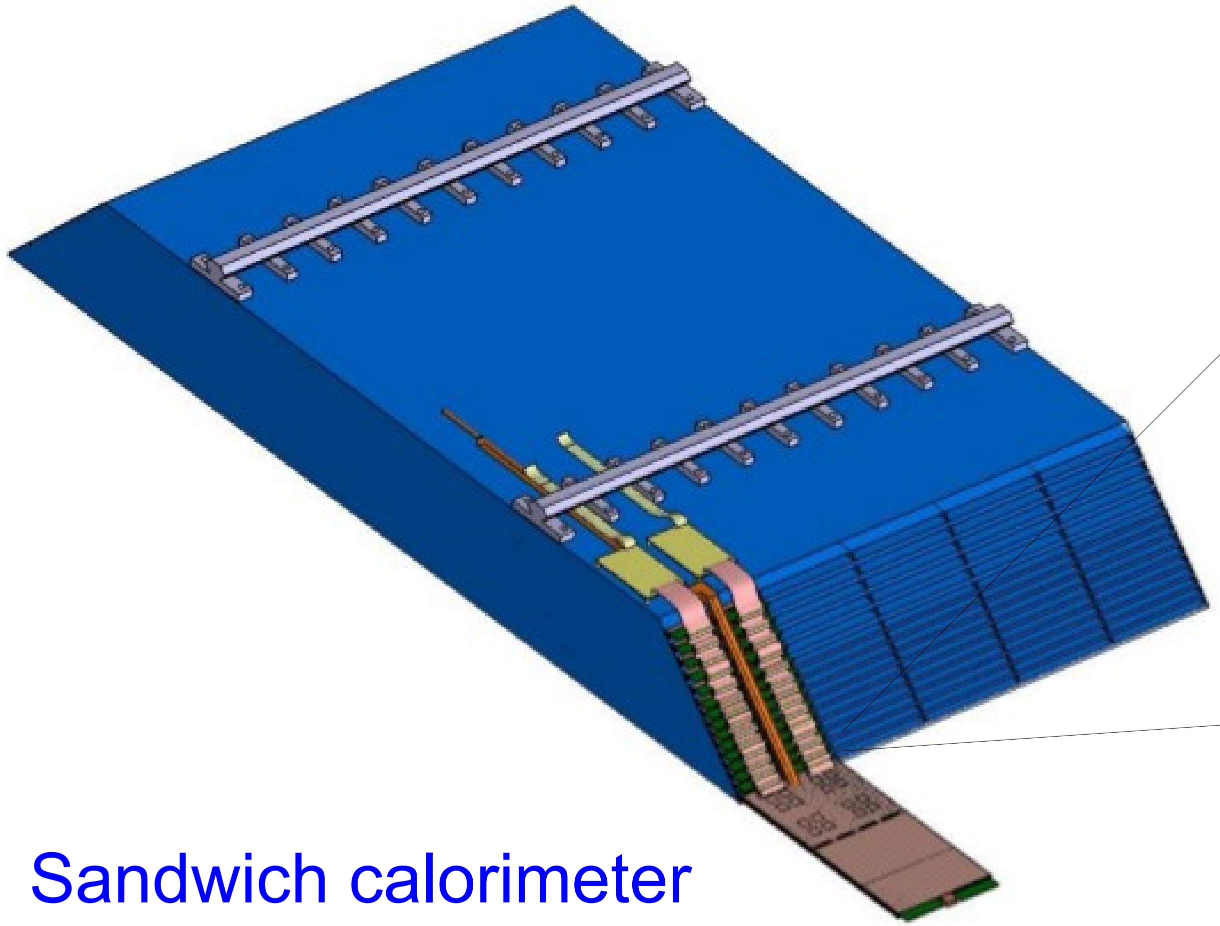
- Tungsten as absorber material
  - X_0=3.5mm, R_M=9mm, λ_I=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisationRobust technology
  - Excellent signal/noise ratio: 10 as design value

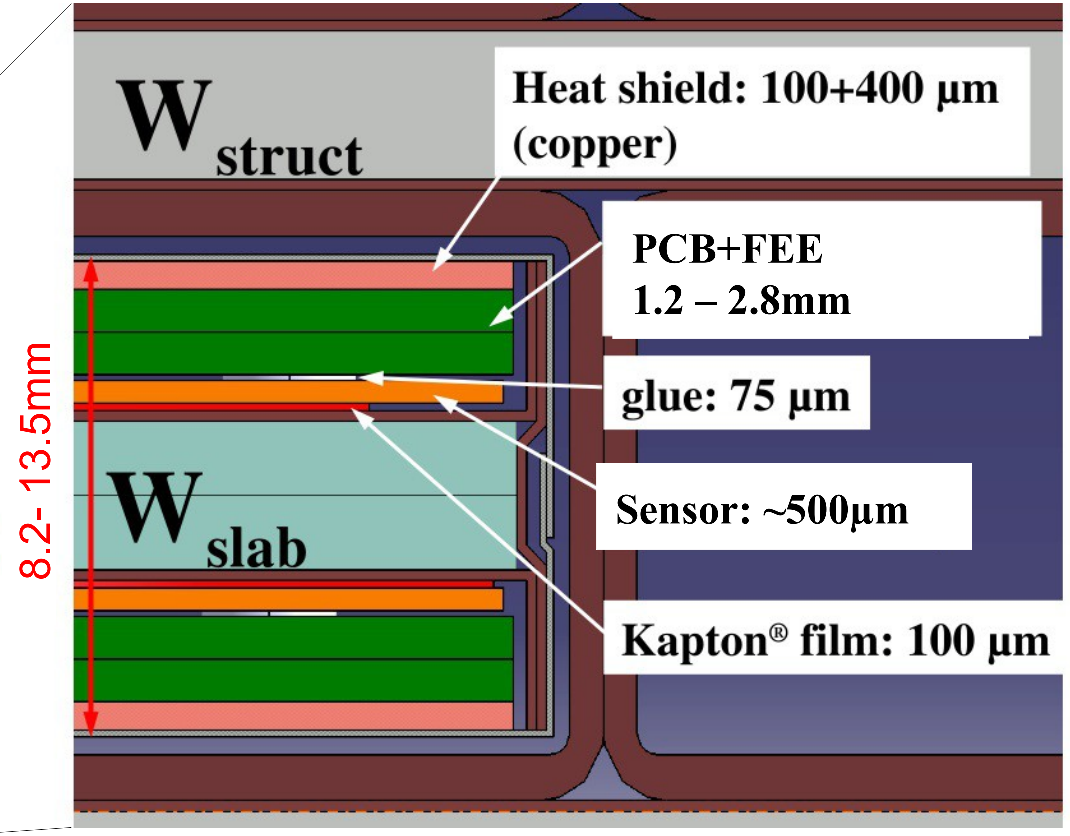
All future e+e- collider projects feature at least one detector concept with this technology

•Decision for CMS HGCAL based on CALICE/ILD prototypes

Silicon Tungsten electromagnetic calorimeter – Example ILD

Ecal alveolar structure



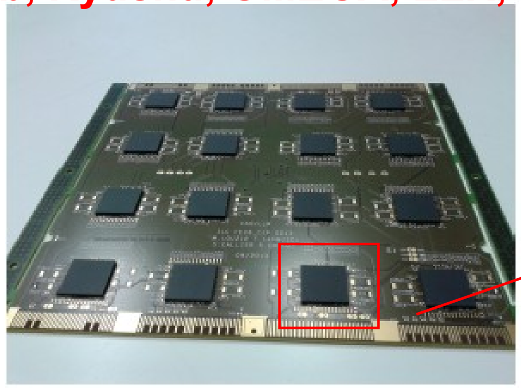


Sandwich calorimeter
26 layers (+/- 4)
Thickness: ~20cm, 24 $X_0/1\lambda_I$
Pixel size ~5x5 mm^2
Expected elm. energy resolution 15-20%/√E

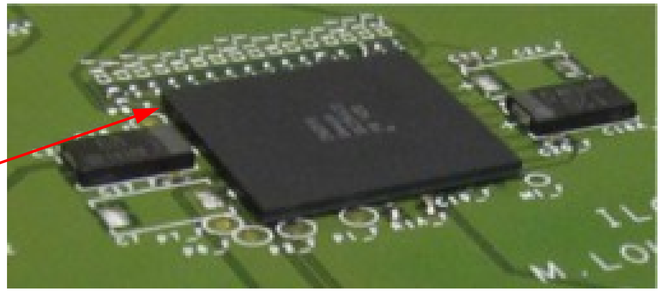
- Two layers within 13mm max.
- Key feature: Embedded electronics

SiW Ecal Technological prototype – Elements of (long) layer

ASIC+PCB+SiWafer
=ASU
Size 18x18 cm^2
(IJCLab, Kyushu, OMEGA, LLR, SKKU)

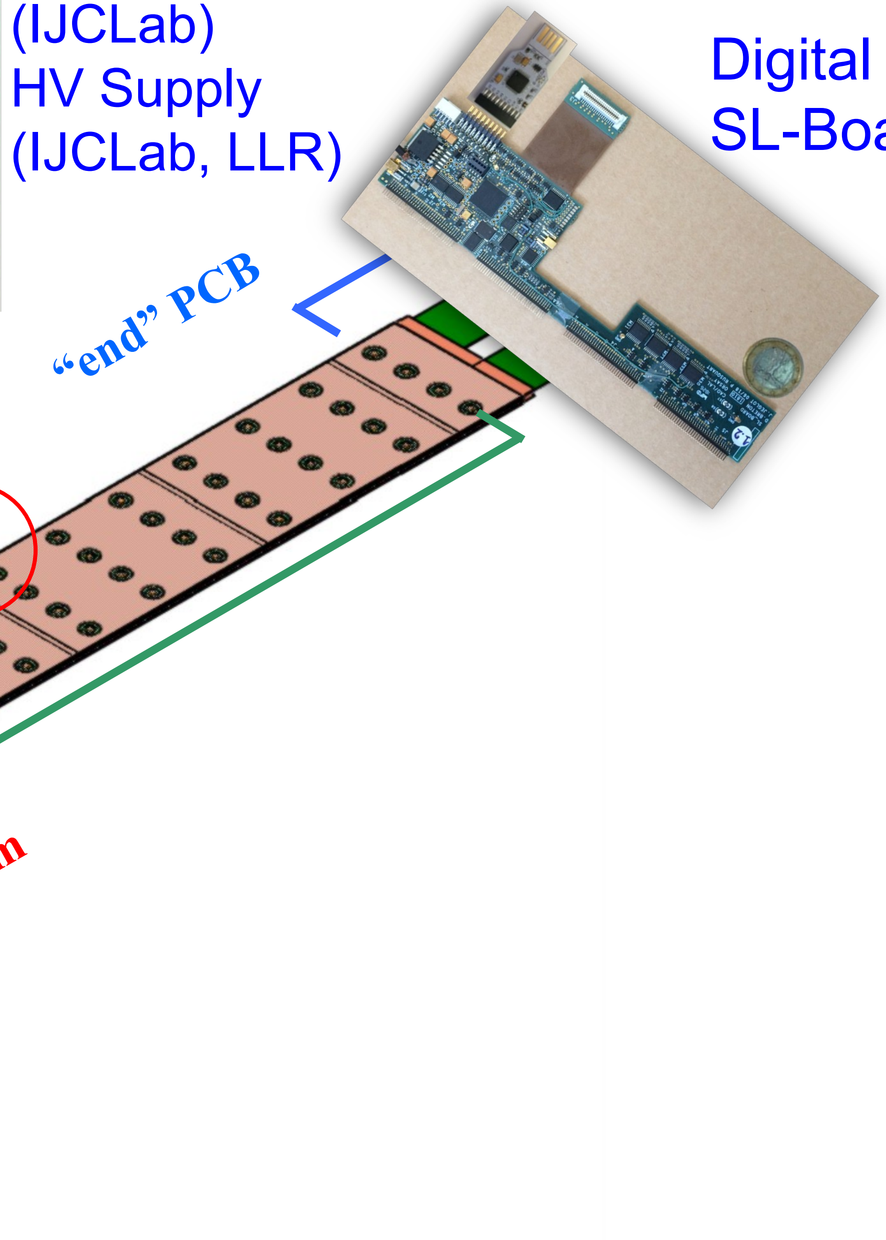
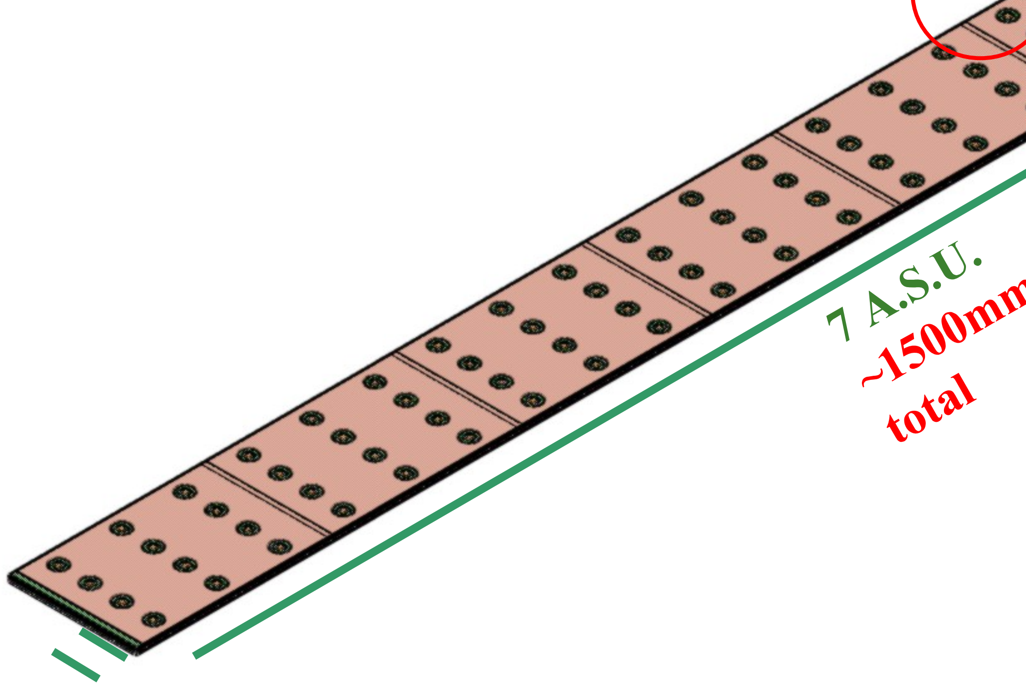


ASIC SKIROC2(a)
(OMEGA)
Wire Bonded or
In BGA package
(IJCLab, Kyushu, LLR)

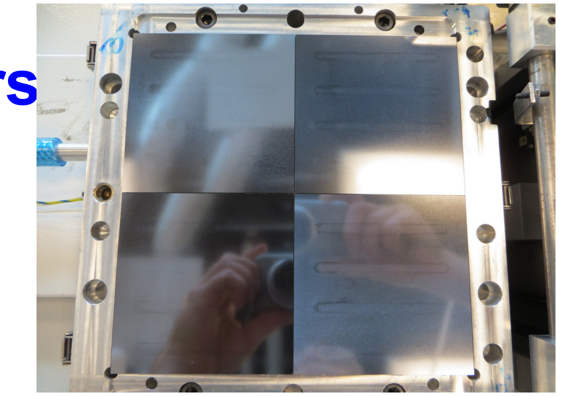


Interconnection
(IJCLab)
HV Supply
(IJCLab, LLR)

Digital readout
SL-Board (IJCLab)

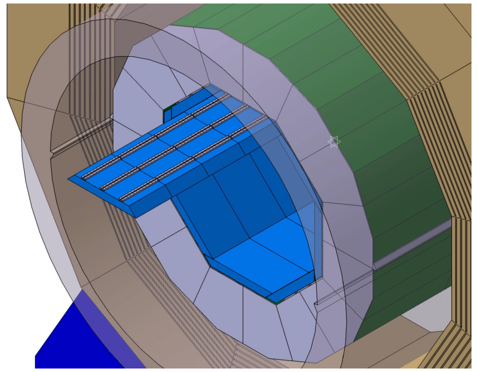



Si Sensors
glued
onto PCB
Pixel size
5.5x5.5 mm^2
(LPNHE, IFIC)

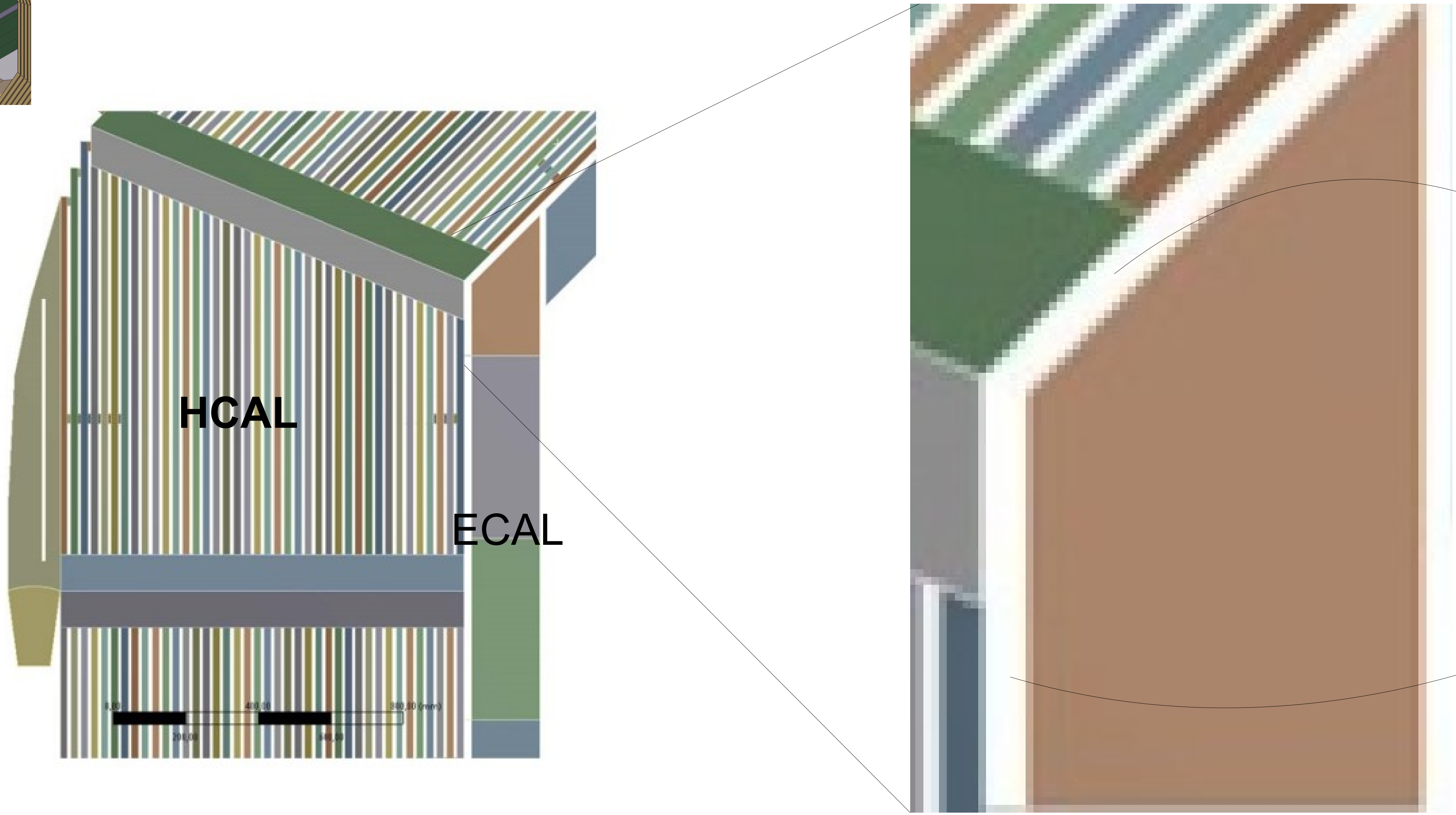


The beam test set ups comprised mainly **short layers** consisting of one ASU and a readout card each

Requirements on compactness



- Successful application of PFA requires calorimeters to be inside the magnetic coil
  => Tight lateral and longitudinal space constraints



40-70mm for services as readout, cooling and power

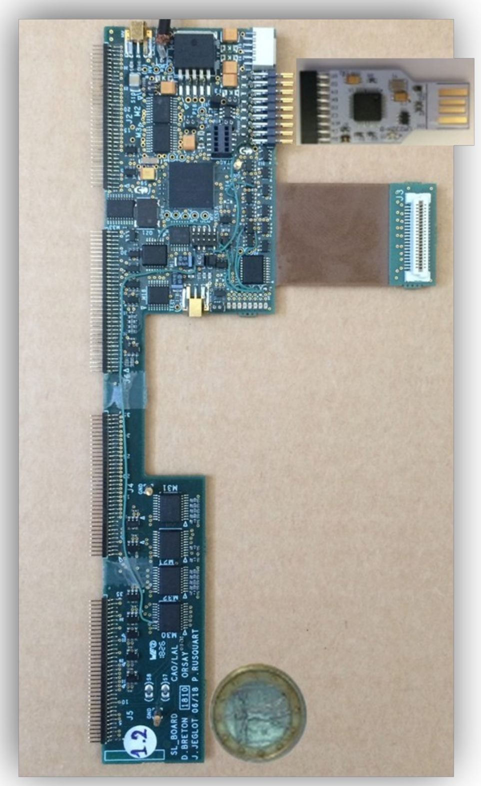
~200mm for up to 30 layers with 10-20 kcells each

Calorimeter has to be conceived as one device with electromagnetic and hadronic sections

7

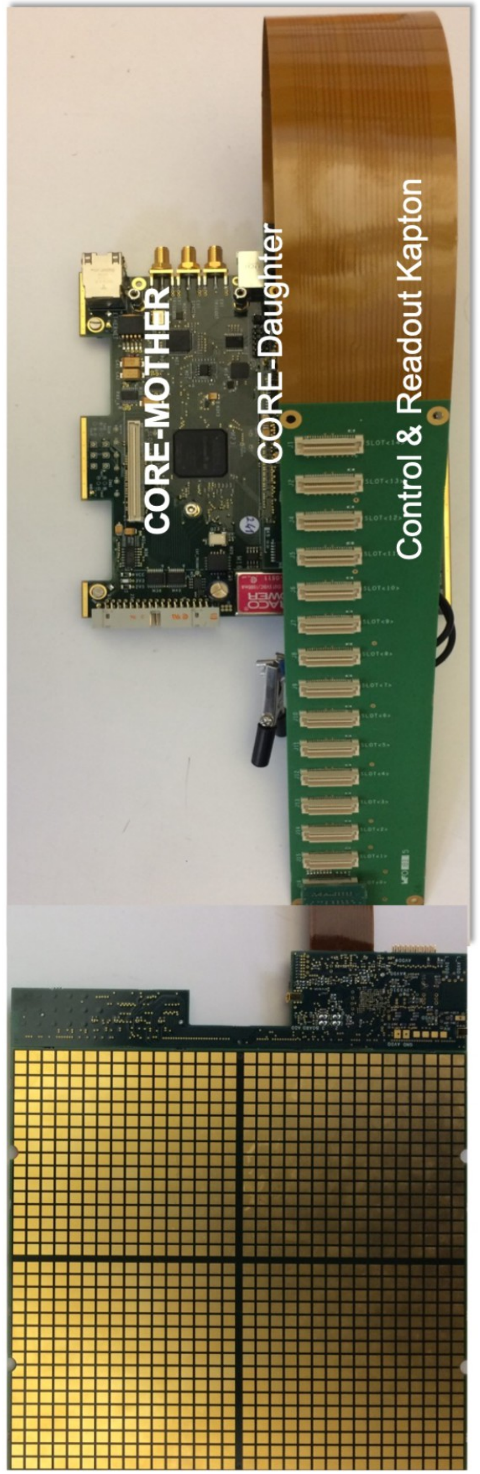
Compact readout

Current detector interface card (SL Board) and zoom into interface region

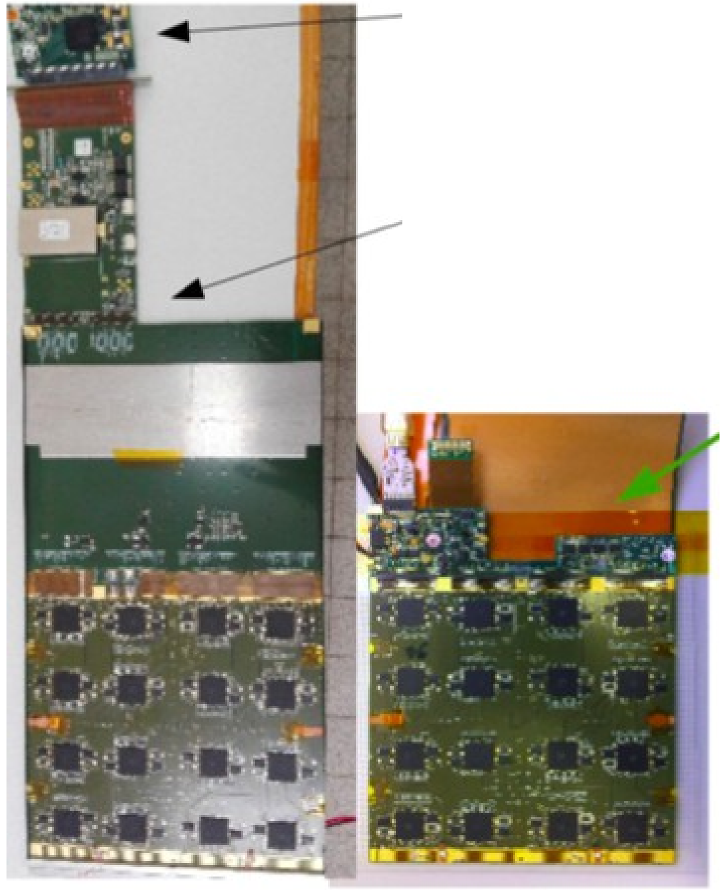


SL Board

Complete readout system



For reference
Comparison old/new r/o system



"Dead space free" granular calorimeters put tight demands on compactness

- Current developments in for SiW ECAL meet these requirements

System allows to read column of 15 layers <-> to be expected in ILD

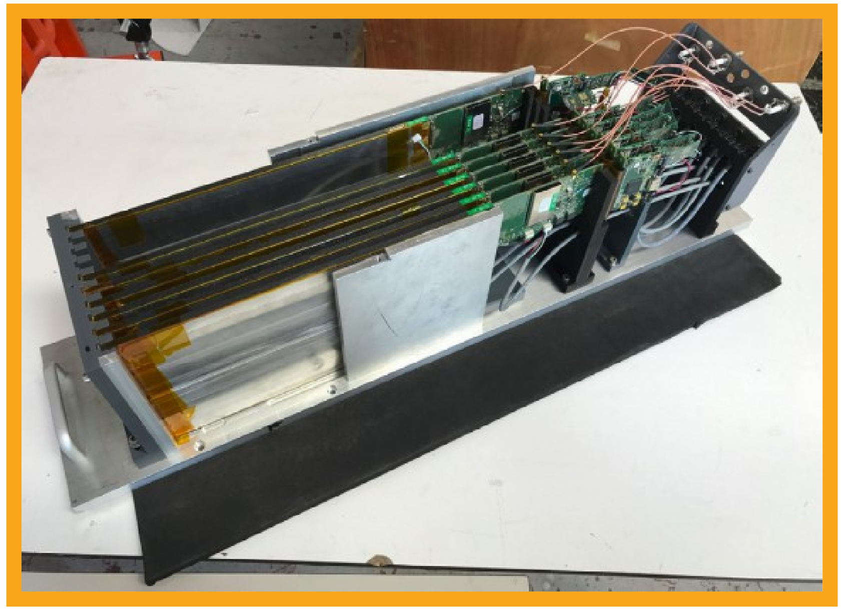
- Important that full readout system goes through scrutiny in beam tests

Readout piloted by performant firmware

Deliverable of AIDA-2020 and HIGHTEC

SiW ECAL Technological Prototype – Development phases

≤ 2018



Up to 7 short layers (18x18x0.5cm^3)

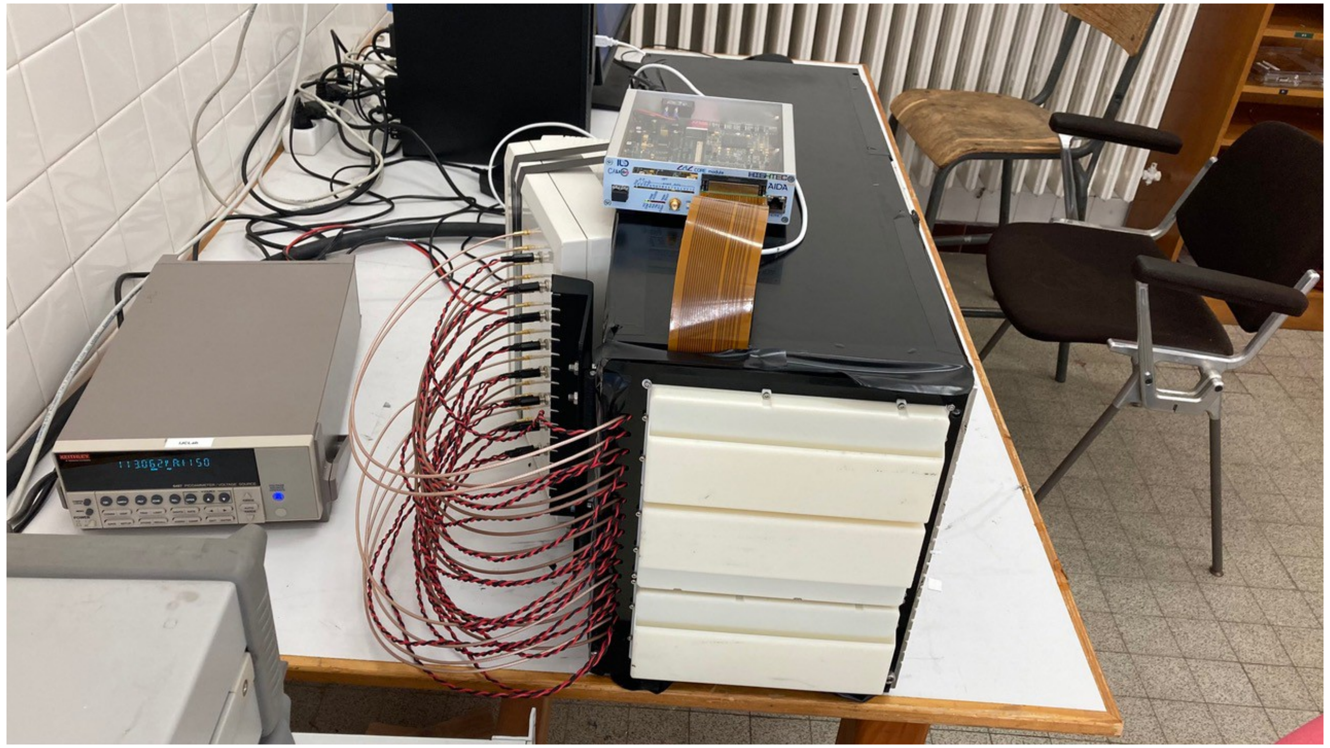
- Up ~10 X_0

1024 channels per layer => 7186 cells

Technical tests at “MIP level”

First version of r/o system

> 2018



15 short layers equivalent to 15360 readout cells

- Partially by ***recycling*** of ASUs from earliear stacks
- Up to 21 X_0

Overall size 640x304x246mm^3

Flexible mechanical structure to adapt to beam conditions

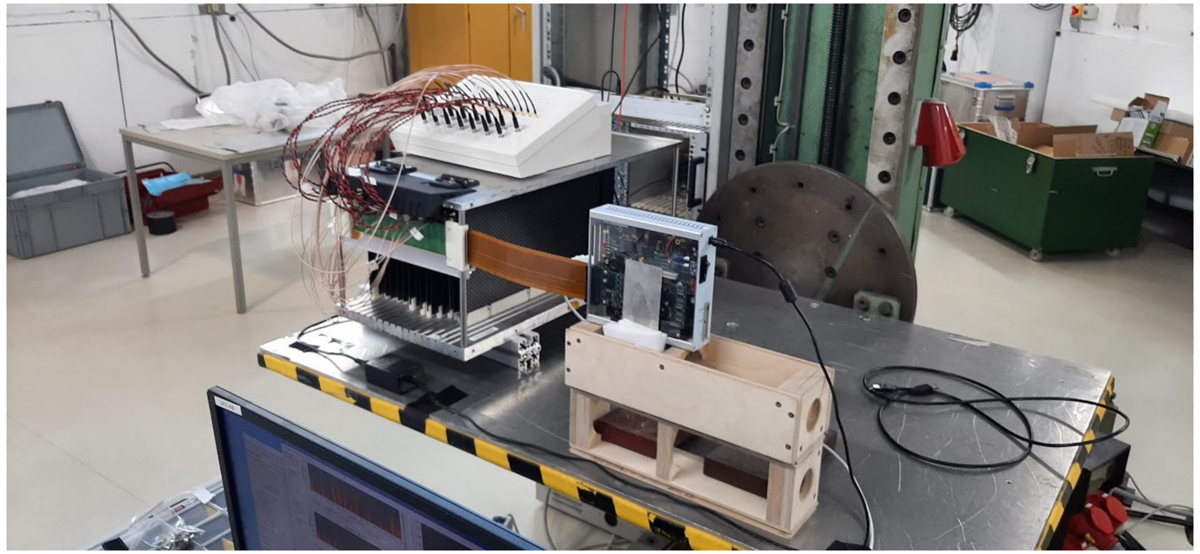
Commissioned 2020-2022

- ~450000 calibration constants for one ASIC feedback capa setting

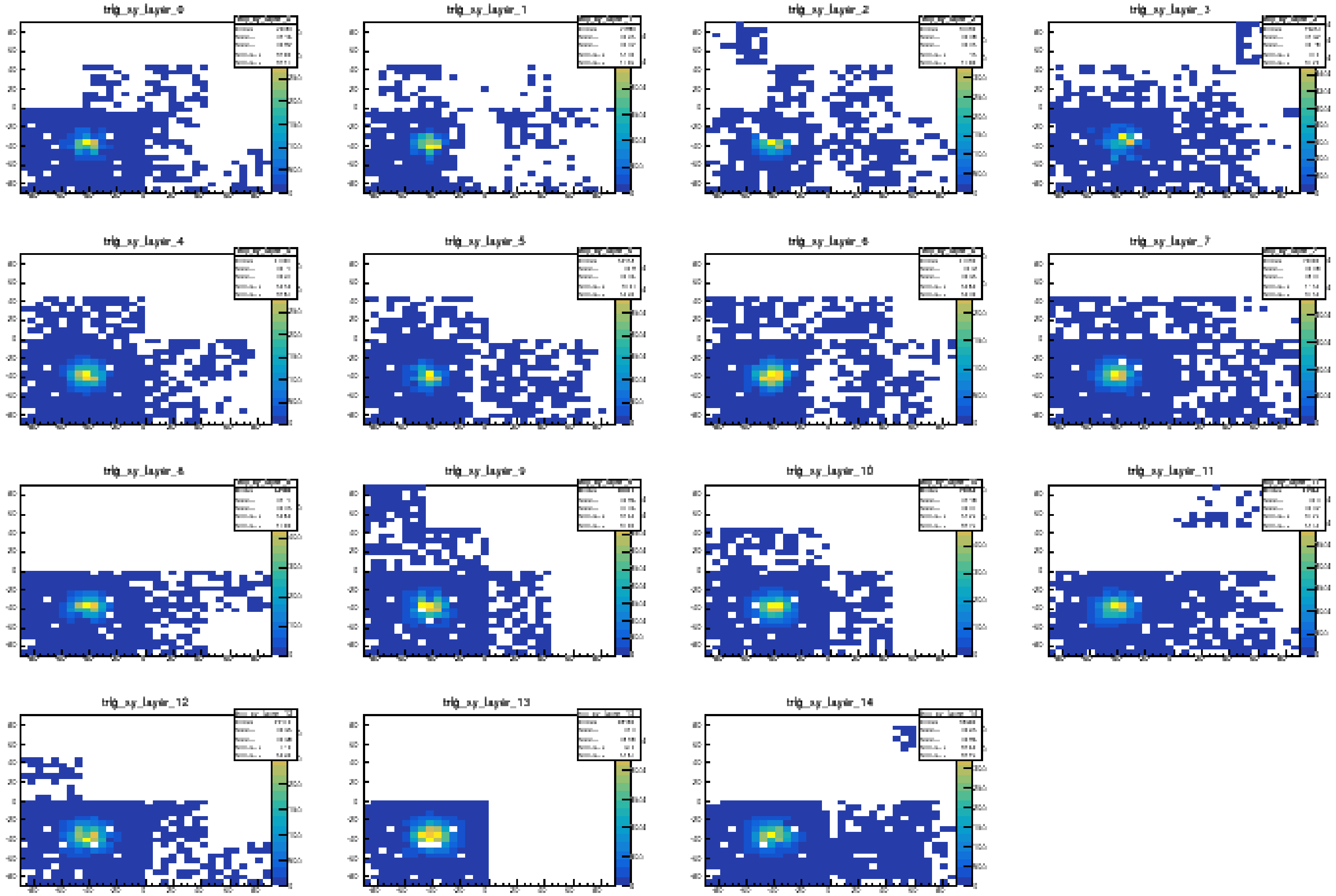
Testbeams (finally) in November 2021 and during 2022

SiW-ECAL in beam test @ DESY

Detector Setup



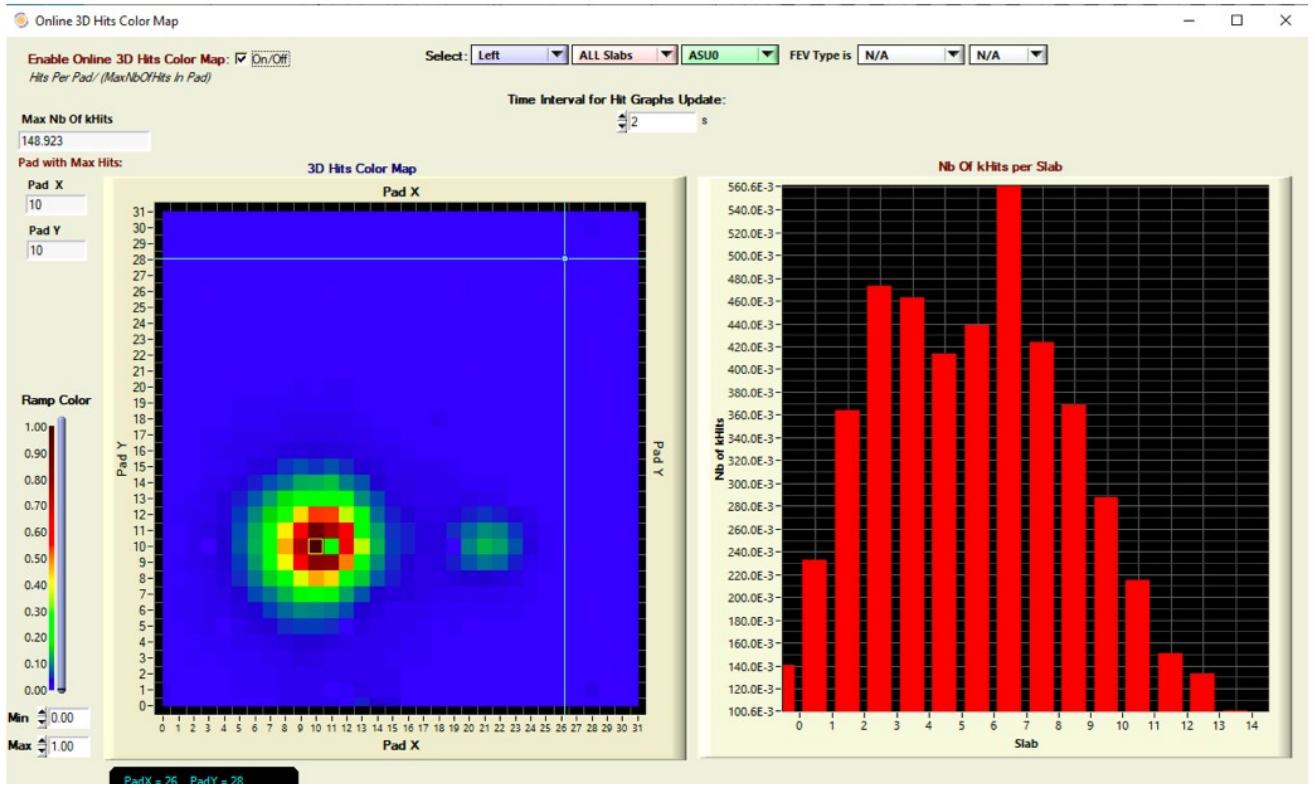
Detector in beam position



Beam spot in 15 layers

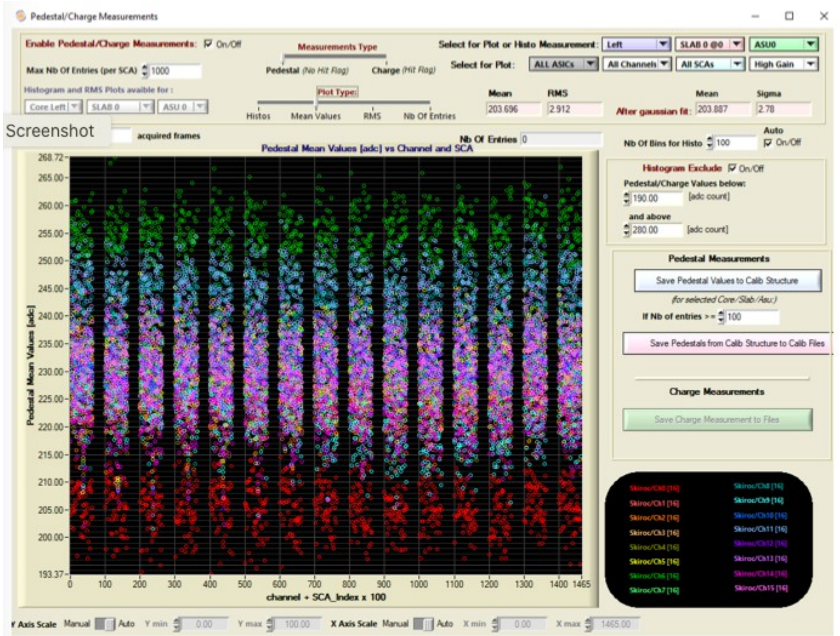
SiW-ECAL Beam test – Online Monitoring

Jihane Maalmi, CALICE Meeting Valencia



Online Hit Maps and shower profiles

Allow for real time beam and detector tuning
  e.g. Adaptation of beam rates or thresholds



Further online tools

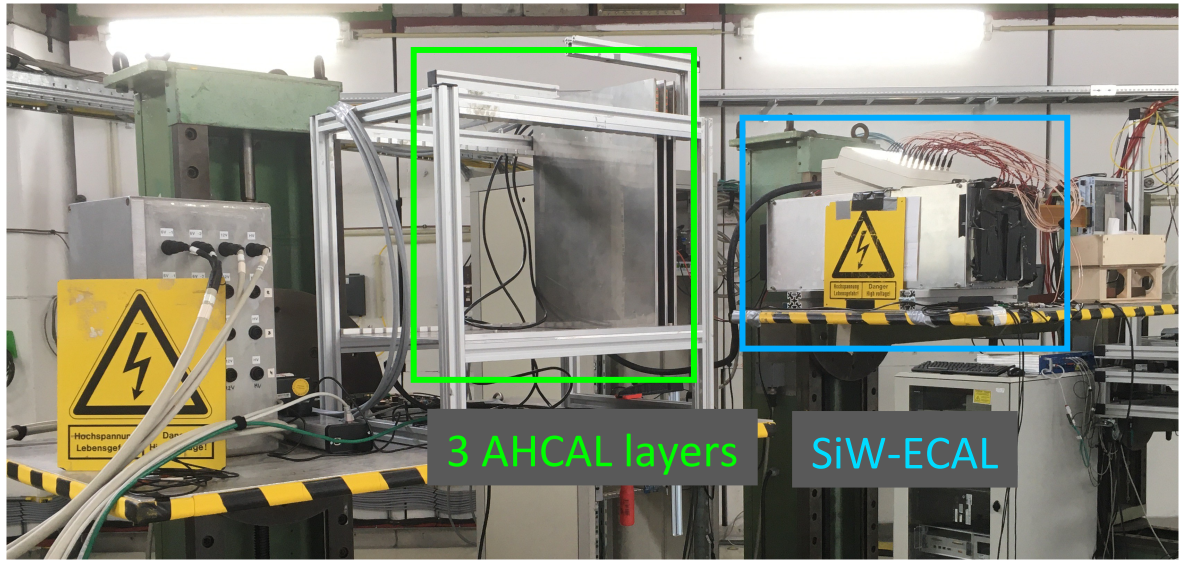
Pedestal measurement and subtraction
Charge measurement and histogramming
MIP gain correction

These are just a few examples from the powerful online suite

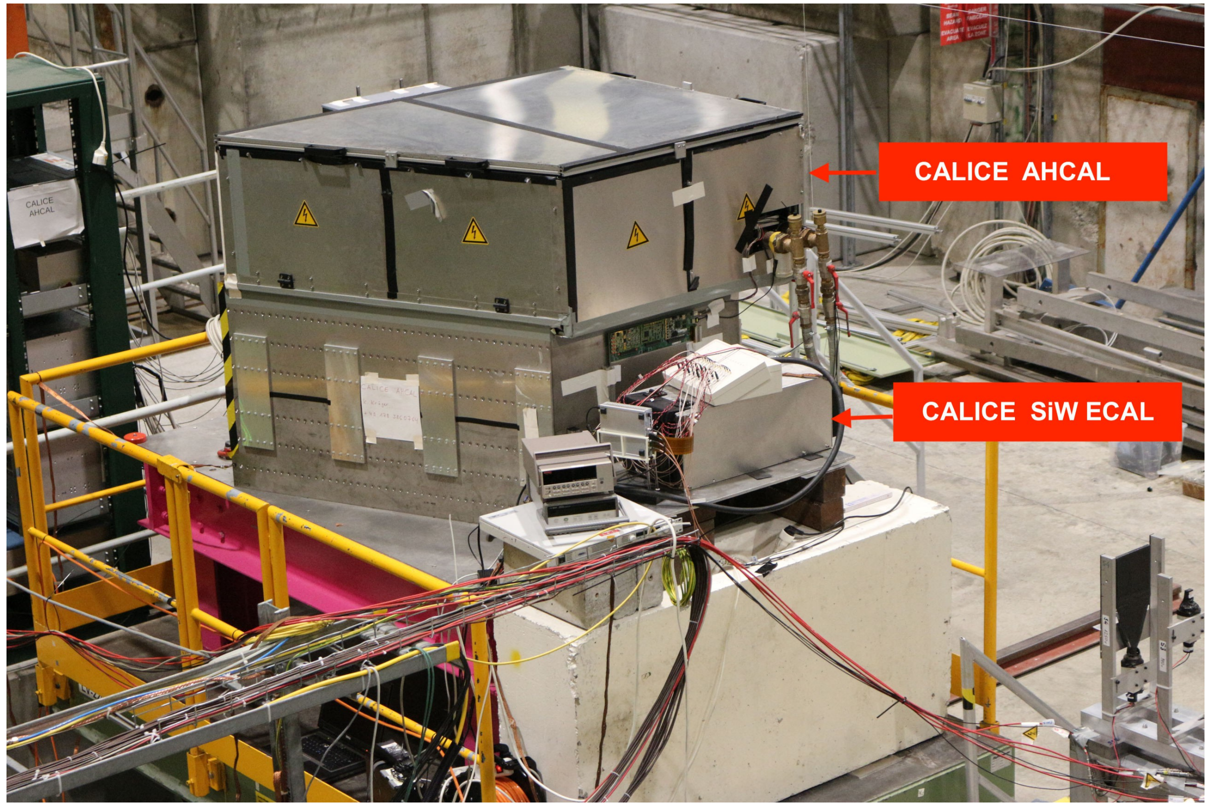
Common developments

CALICE meets DARK MATTER LAB

SiW-ECAL + AHCAL DAQ test @ DESY in March 2022



Common setup at CERN June 2022



15360 + 22000 (full analogue) readout cells

Successful synchronisation of data recorded with SIW-ECAL and AHCAL

- First step of ***knowledge transfer*** on compact readout system to AHCAL → AIDA innova

Common running makes full use of EUDAQ tools (developed within European projects)

Common data anlalysis ongoing

Correlation

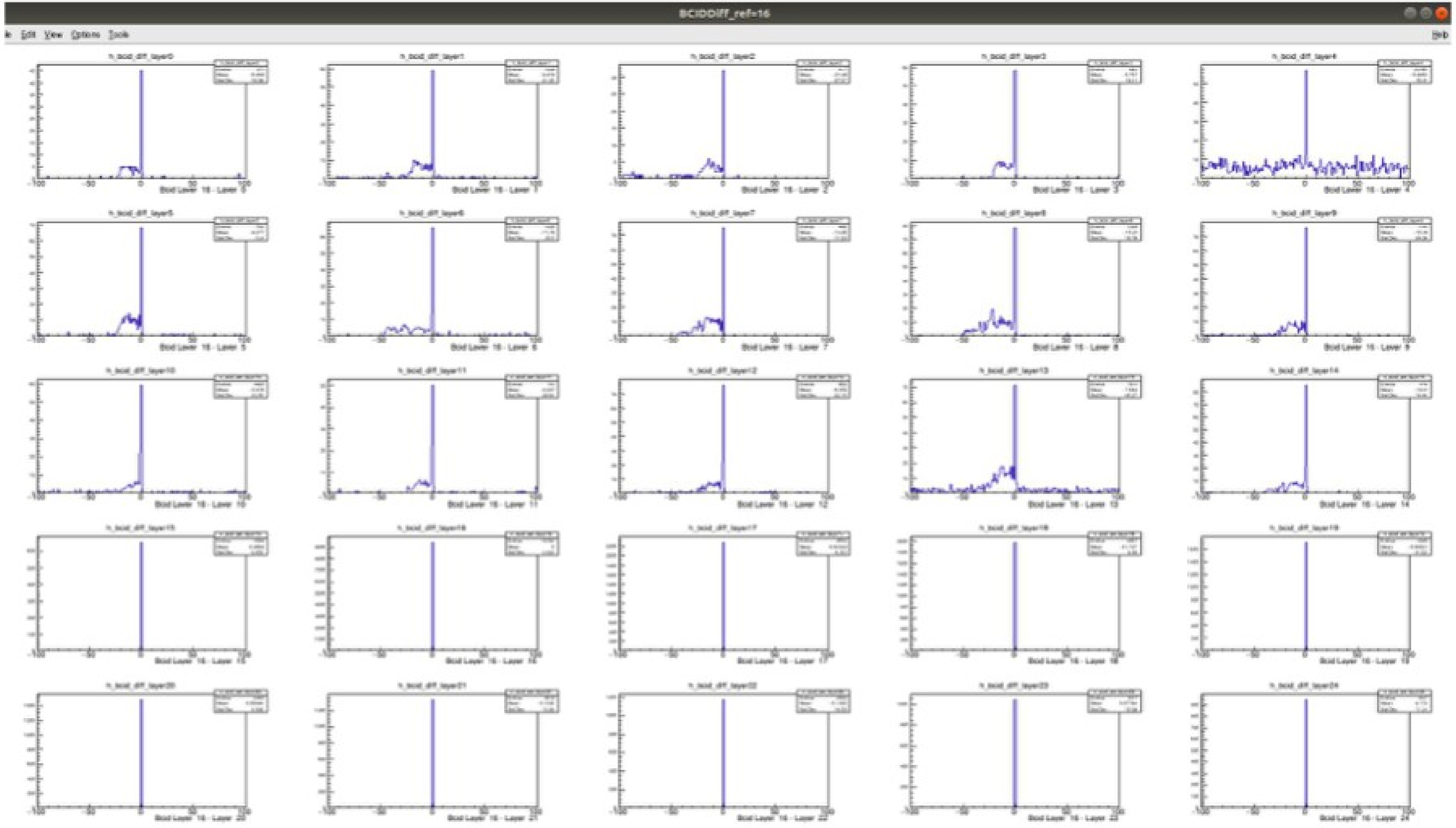
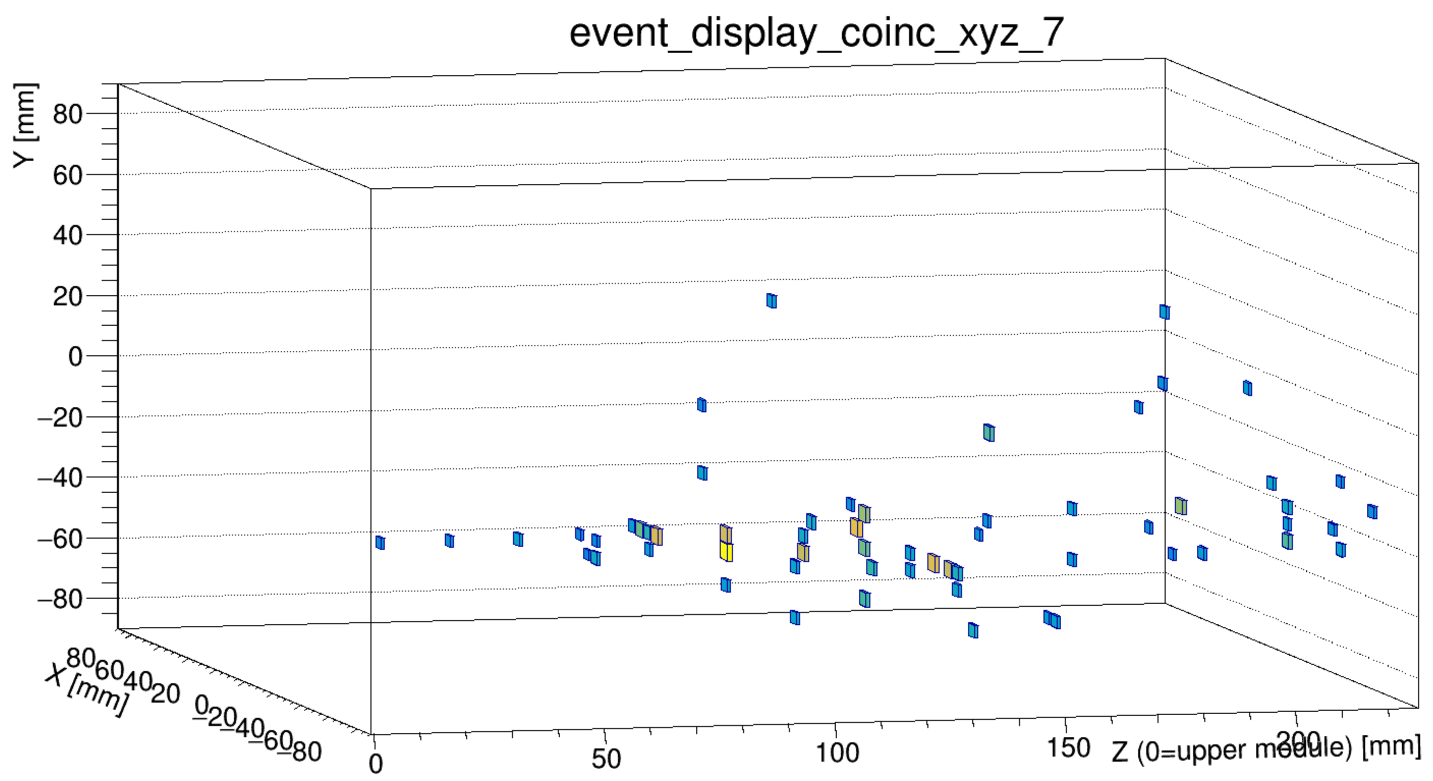


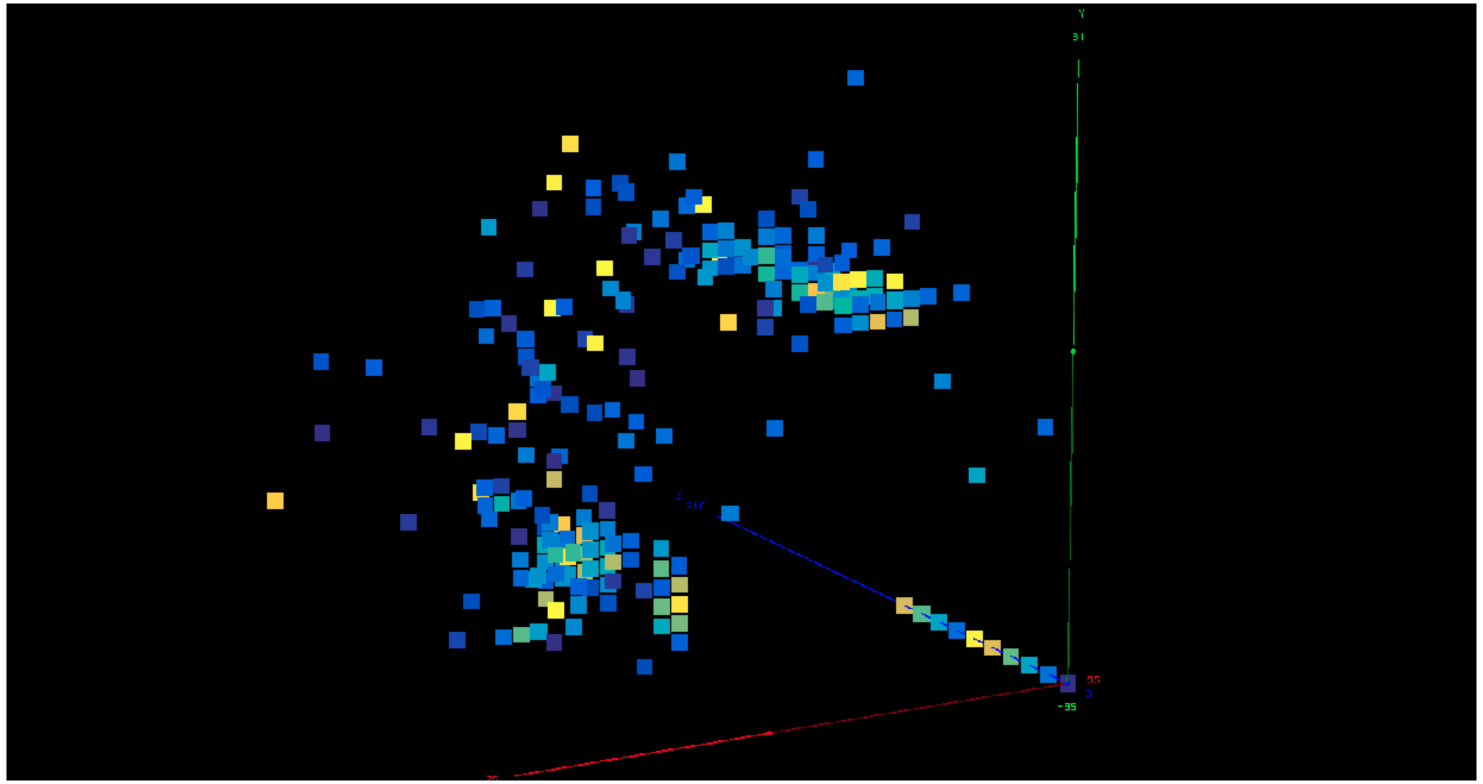
Fig. Difference between BXID in the readout cycle.

SiW-ECAL Beam tests 2022 – Onlline/Offline Event Displays

First contained electron showers since physics prototype (2011)



J. Kunath (LLR)



Y. Okugawa (IJCLab)

Clear showers measured during beam test campaigns

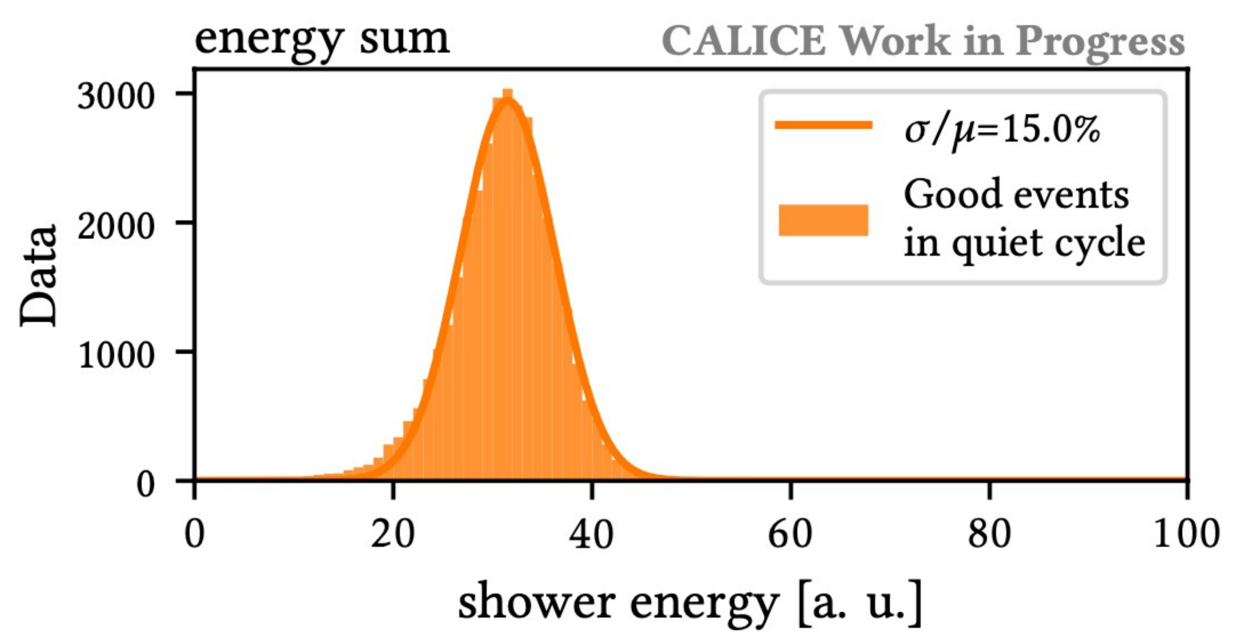
- Requires full event reconstruction
- These (and more) "high level" views are available already while a run is going on

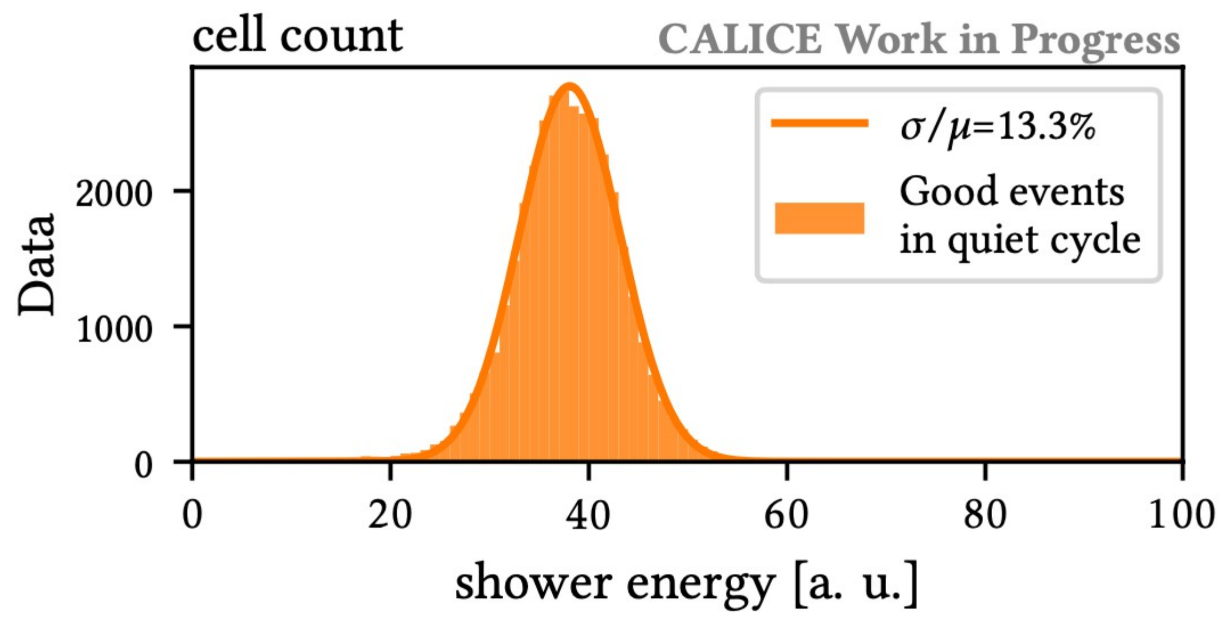
"Particle separation continued"

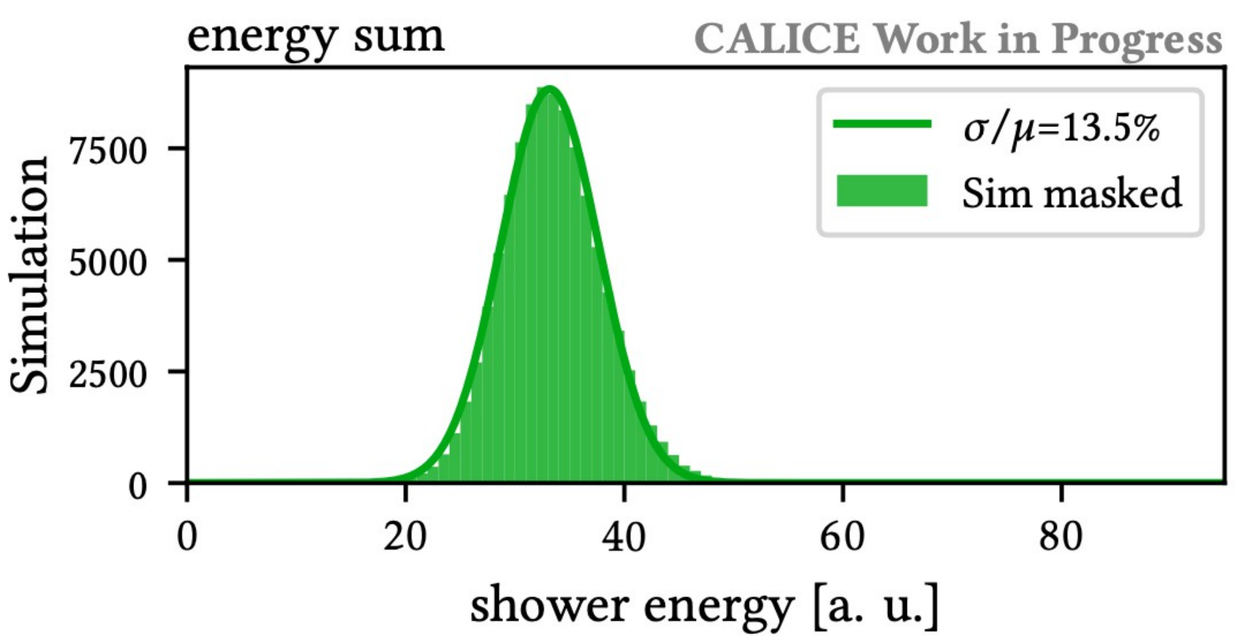
- Two electrons "seen" in 20 GeV e- run at CERN

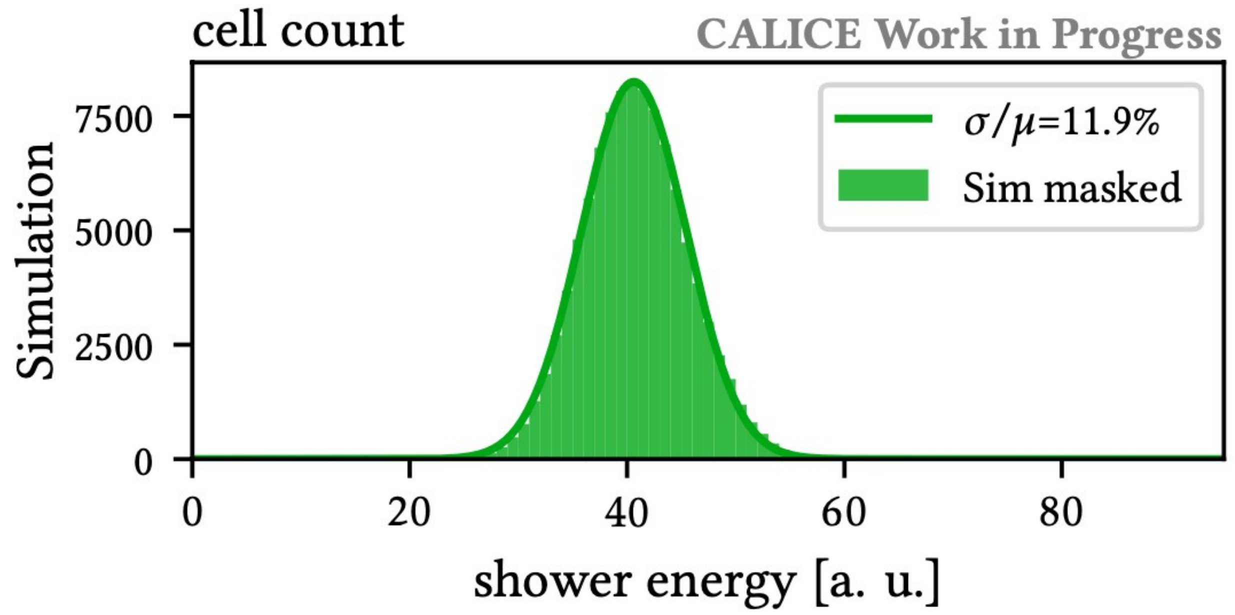
Hot news - First results from DESY beam test 03/22

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





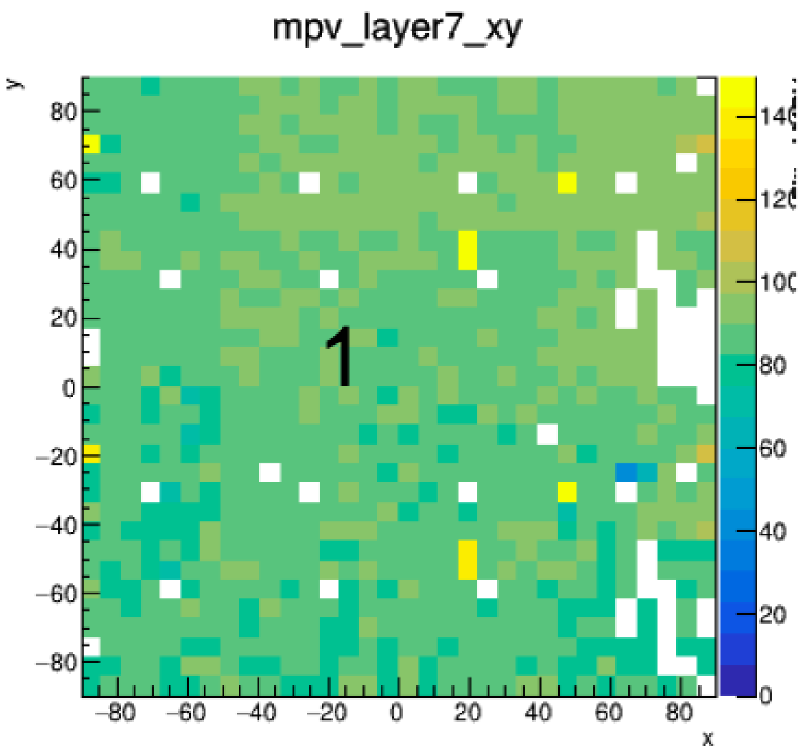


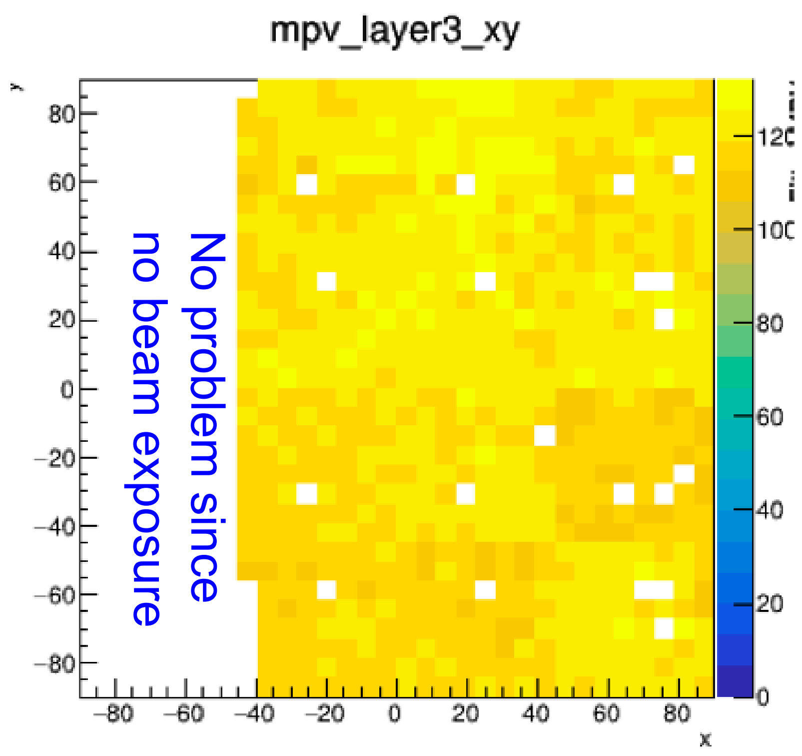


After proper filtering energy resolution in right ballpark for current prototype
Convergence in agreement data/MC

SiW-ECAL Beam test 2022 – Further observations

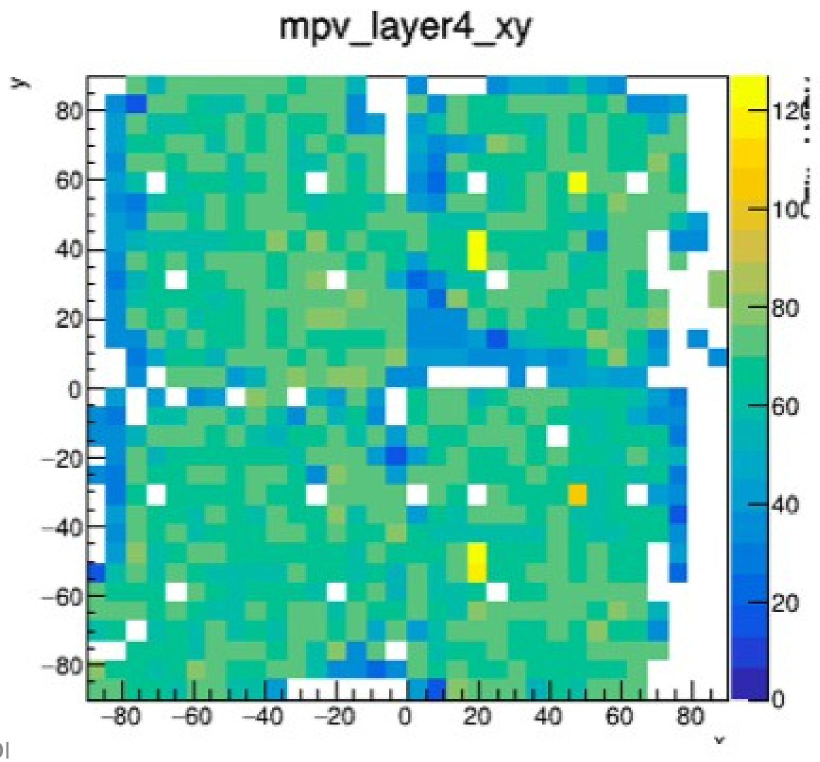
Adrian Irles





We have good layers ...

- Homogeneous response to MIPs over layer surface
- \> 90% efficiency for MIPs
- Here white cells are masked cells due to PCB routing
  - understood and will be corrected



... and not so good layers

Inhomogeneous response to MIPs

- Partially even no response at all, in particular at the wafer boundaries
- Not seen in 2017, degradation observed during 2018/19
- To be understood, ***will require dedicated aging studies***

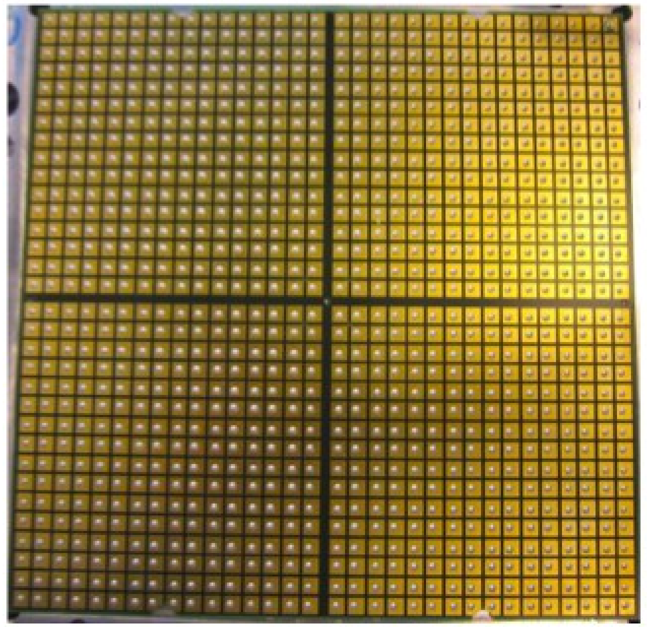
Since Summer 2022 access to the different stages of the ASICs

- => analogue probes, <u>major</u> debugging tool

Sensor Delamination – Overview on Actions at IJCLab

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

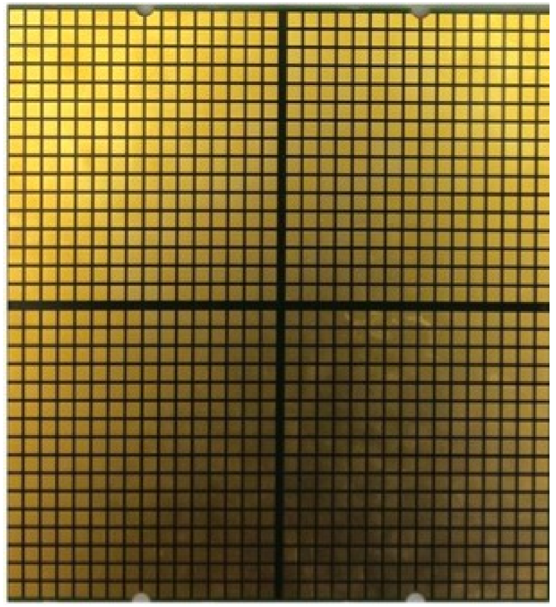
Pull tests

- 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

PCB Mechanical Monitoring – Planned Steps

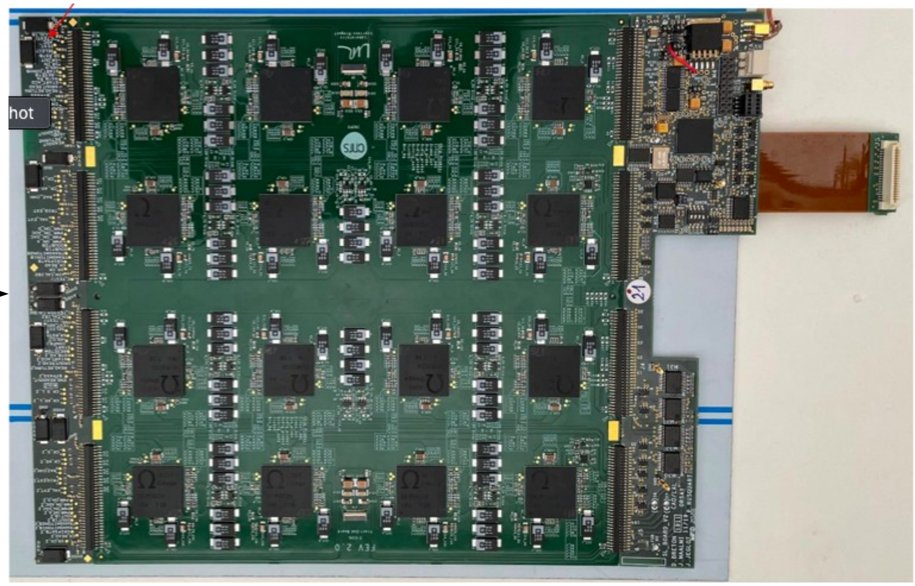
IJCLab Cabling workshop

Uncabled PCB



Measurement before cabling

Cabled PCB

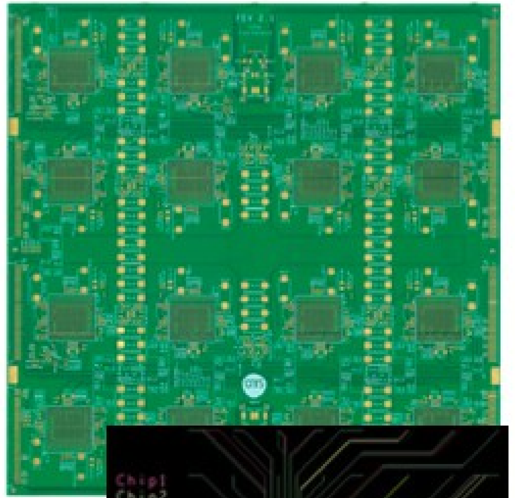


Measurement after cabling

- Control and measure the PCB before and after cabling for deformations
  - Shipping to e.g. IFIC for sensor gluing
  - ==> Set up of a logistics chain

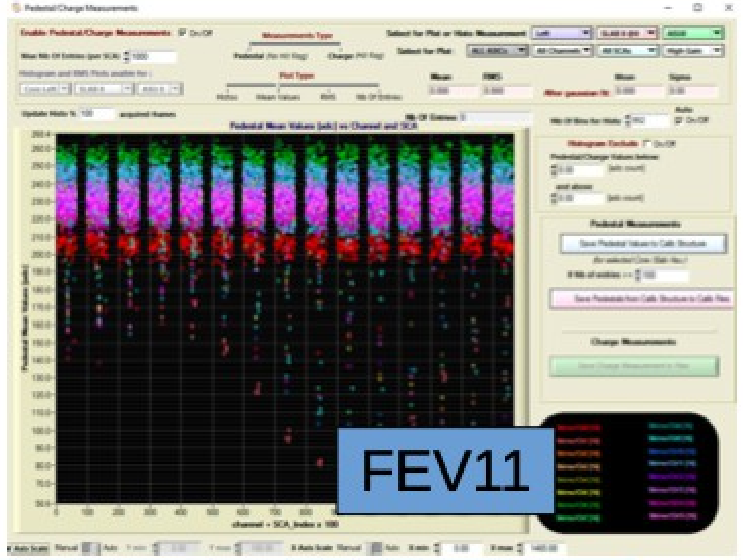
New FE boards

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

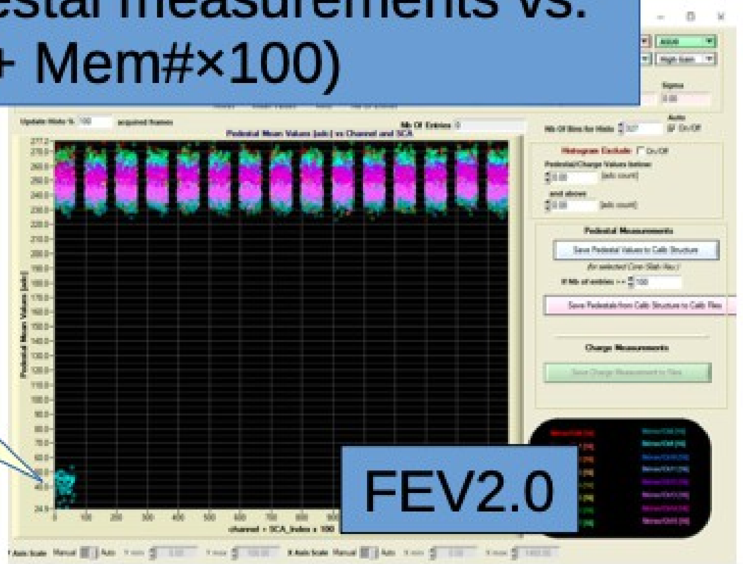


Pedestal measurements vs. Ch# + Mem#×100)

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

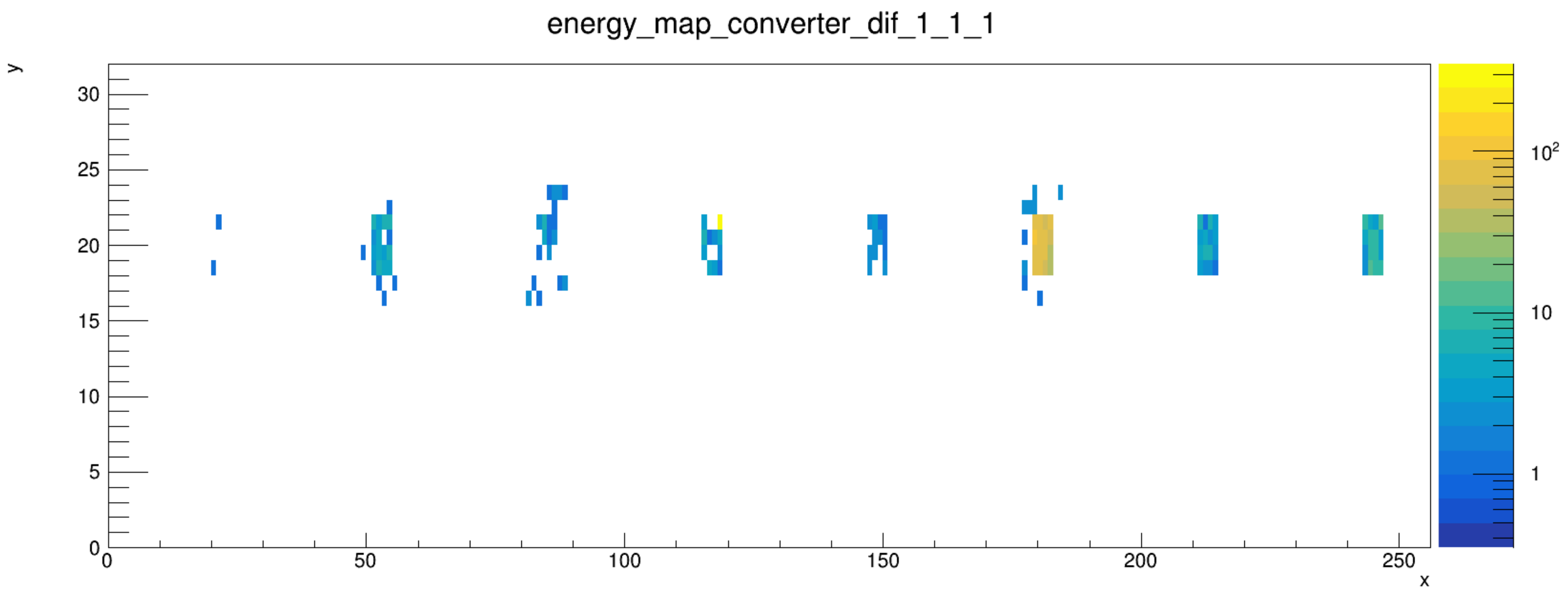
SIngle channel → the fault on the ASIC/packaging

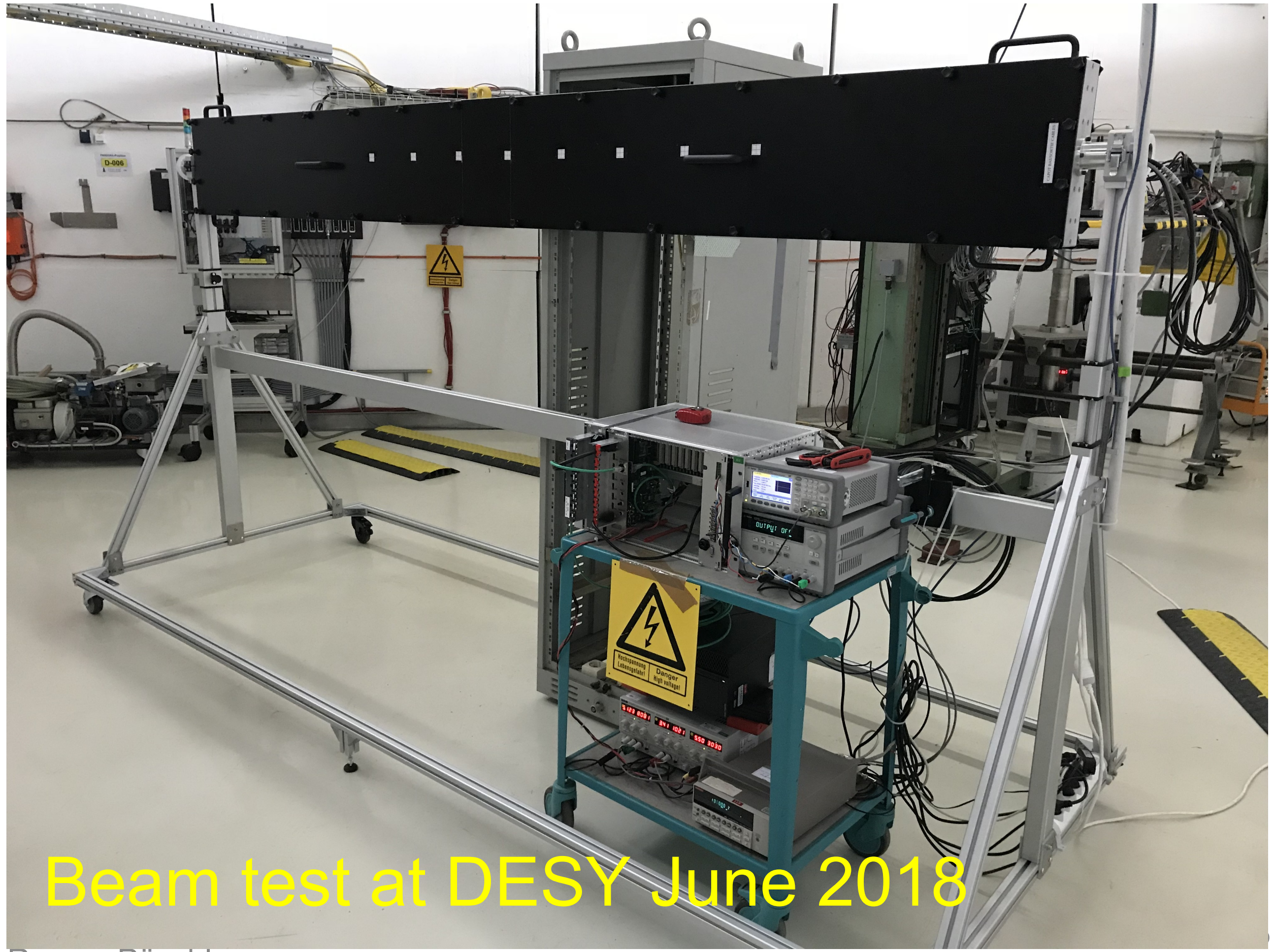


Goal: build 15 layer stack for 2024 based on these Boards

(One of) Next step(s) – Slab long

Chain of
8 detection elements
~2m



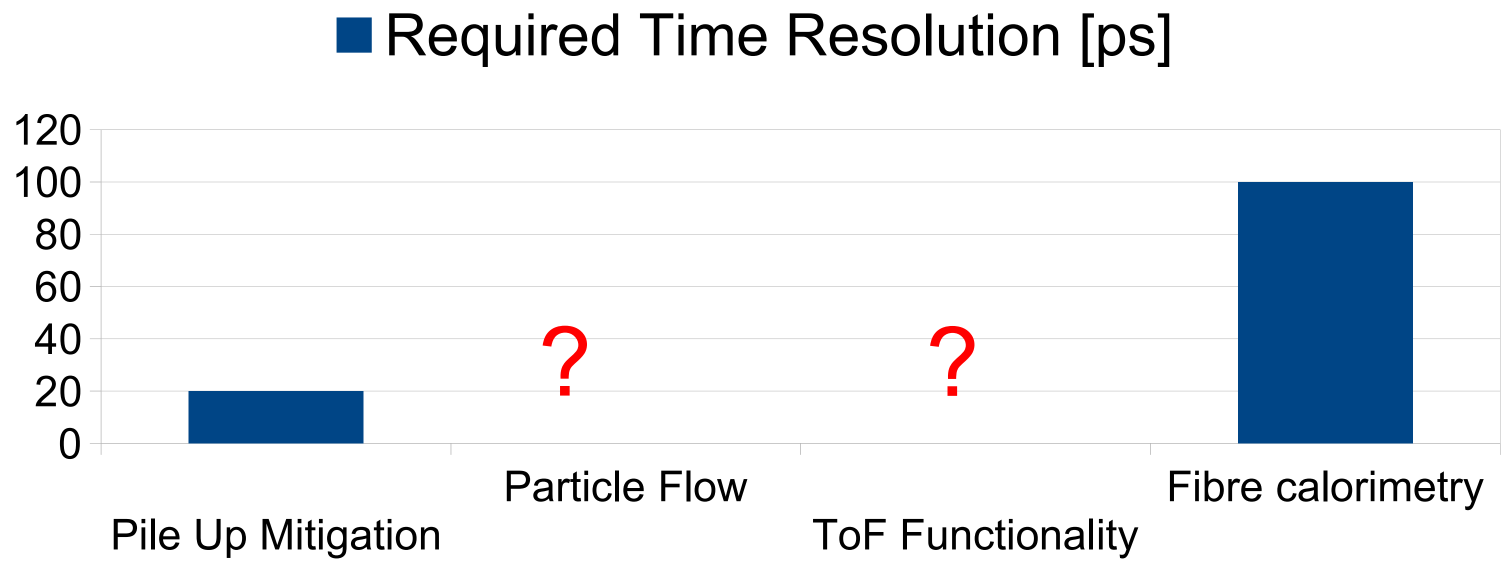


Encouraging results in first beam test in 2018

- Issues with signal drop towards extremities
- Long slab studies vital for all future applications

Timing ?

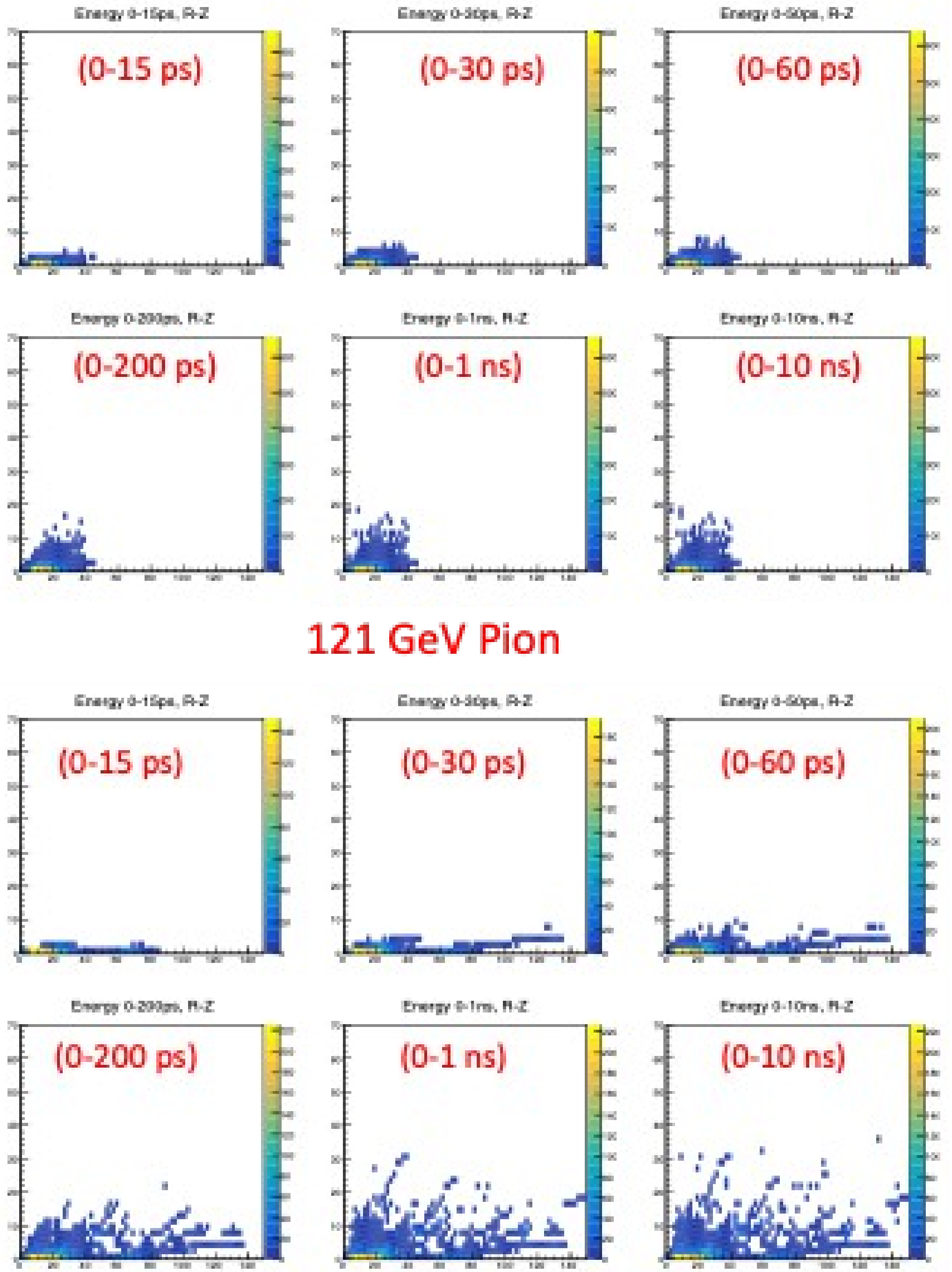
- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters

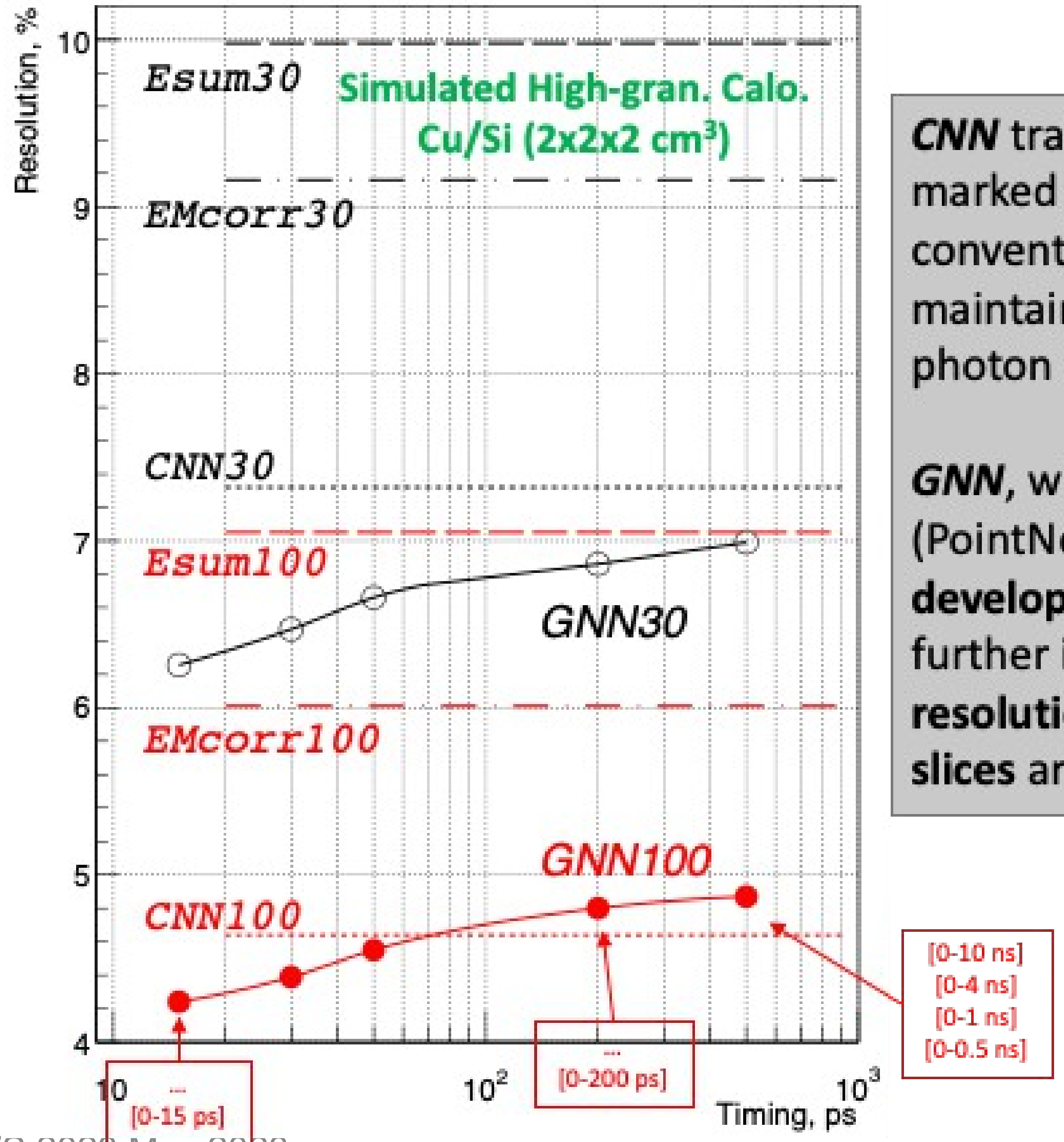


- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

Timing in calorimeters

Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance $\sigma(E)/E$





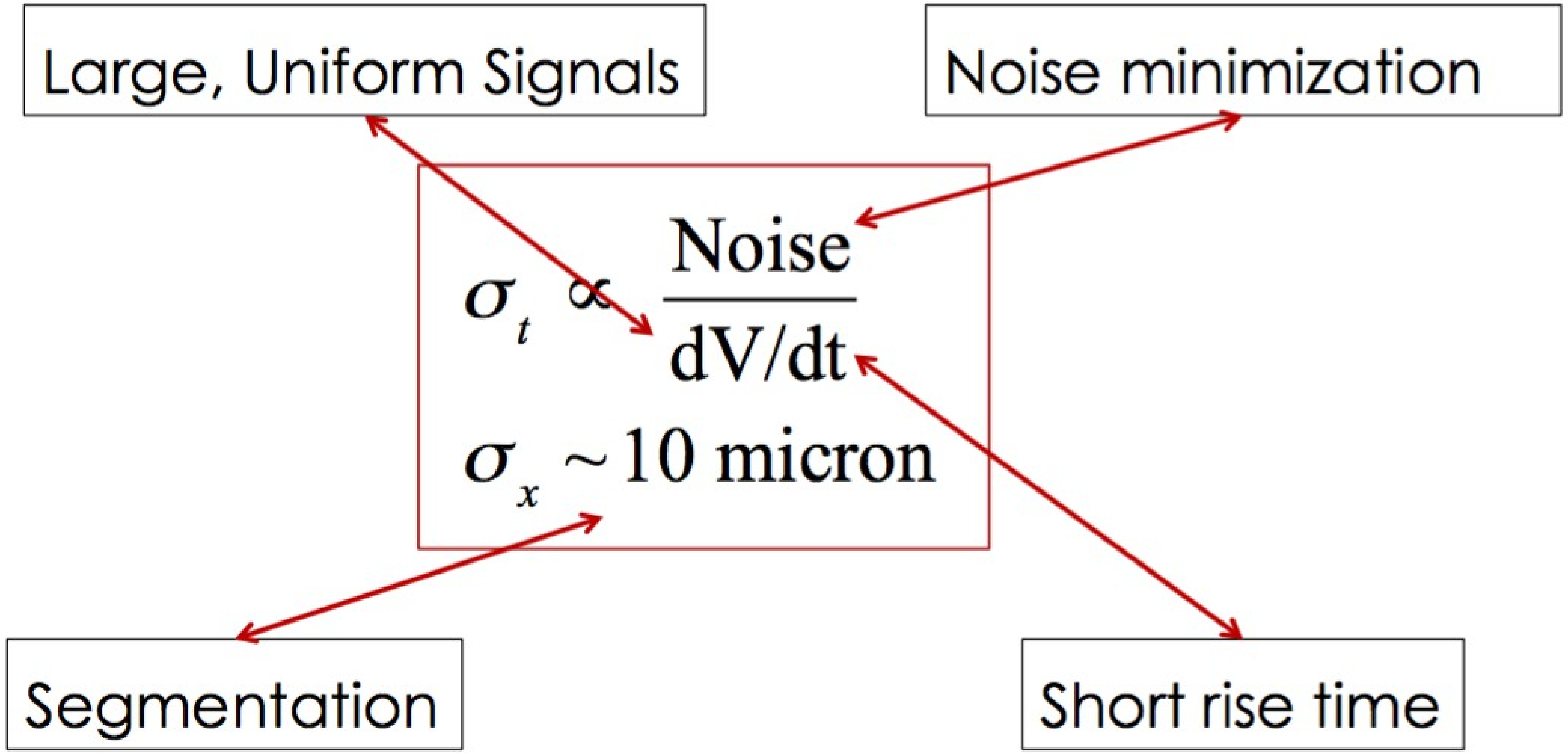
CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

GNN, with edge convolution (PointNet), **with shower development timing information** further **improves energy resolution** when **shorter time slices** are included

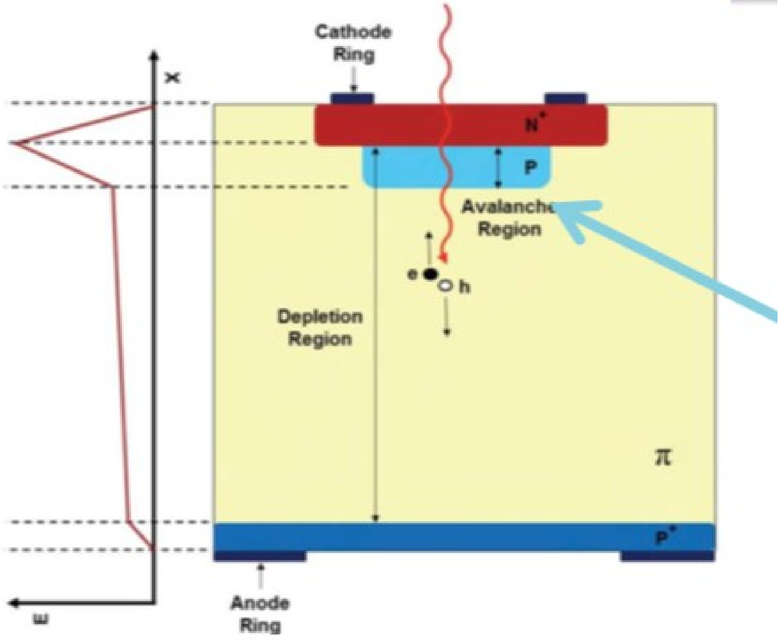
arxiv:2108.10963

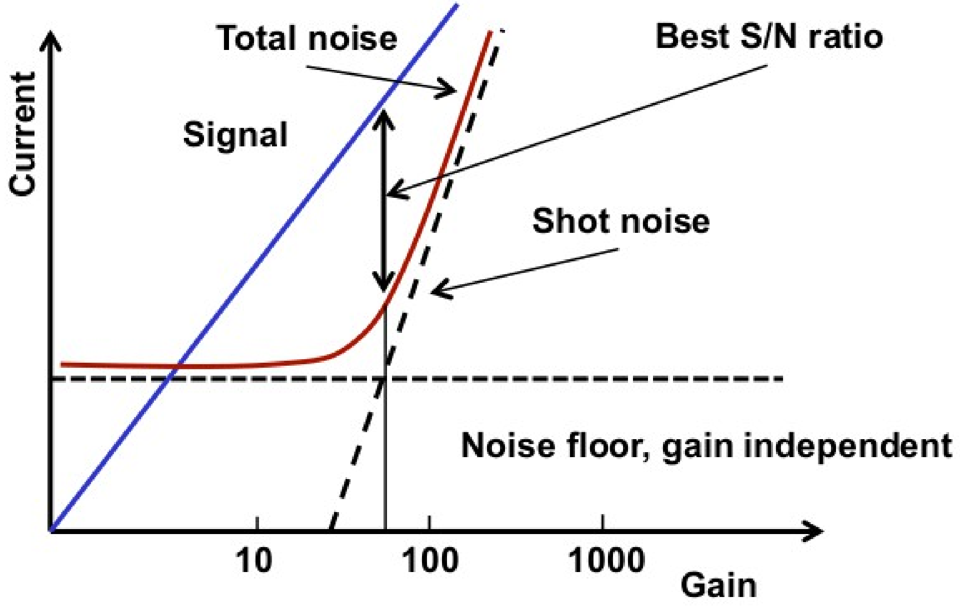
New Trends Timing

Pioneered by LHC Experiments, timing detectors may require adaptation for LC Experiments



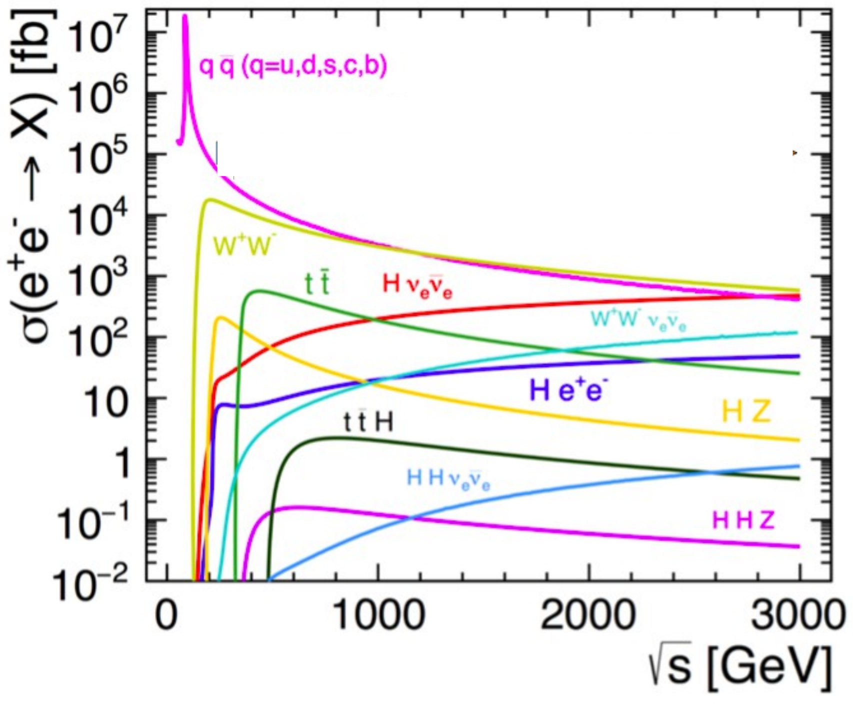
LGAD

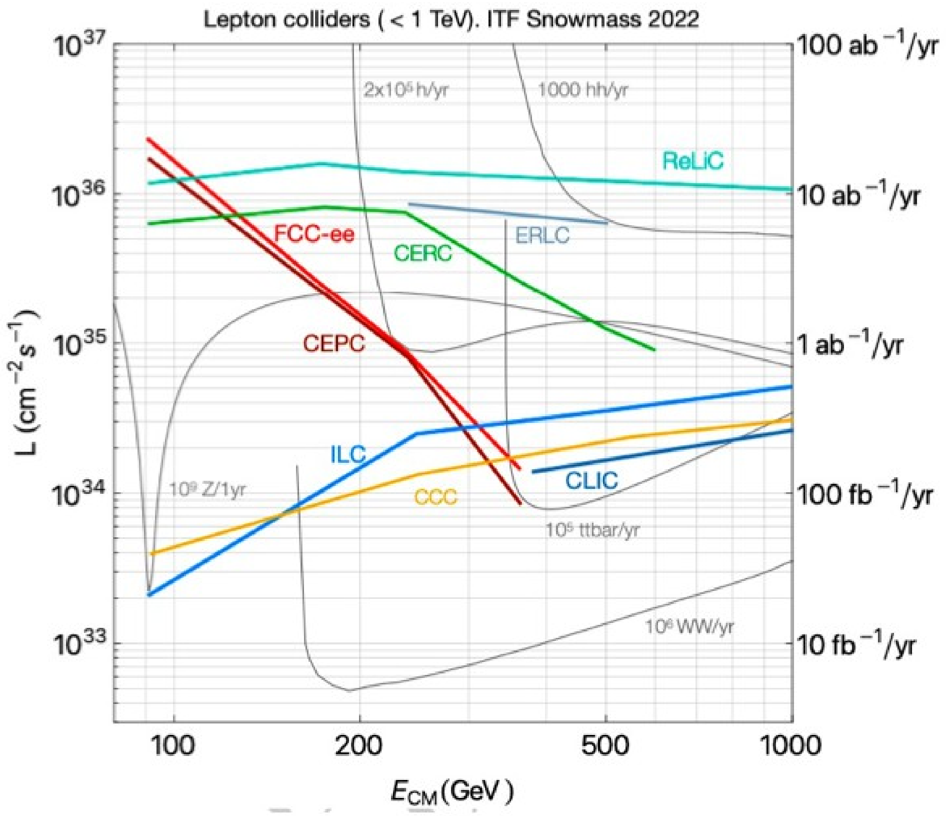




- Better dV/dt by “active” Si diodes ? => Low Gain Avalanche Detectors
  - LGADs applied for ATLAS HGTD and CMS ETD
  - Expect time resolution σ_t ~ 30-50ps
- Integration of LGADs into calorimeter volume may be one of the roads to follow

Future direction of R&D - Impact of event rates





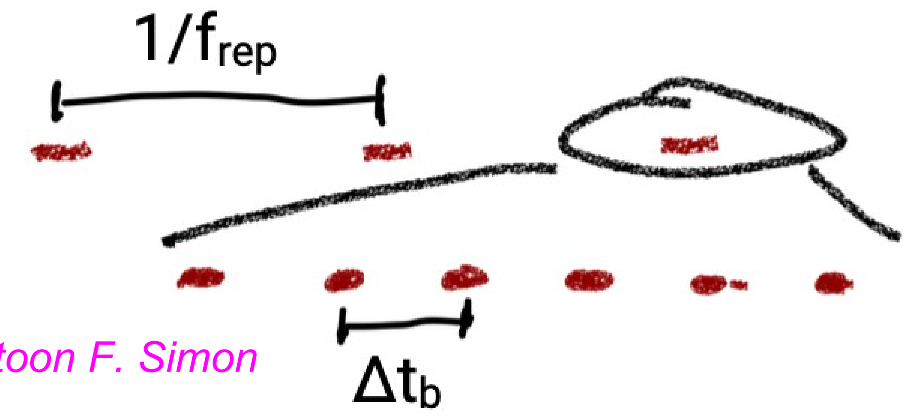
High energy e+e- colliders:

- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole

- Event and data rates have to looked at differentially
  - In terms of running scenarios and differential cross sections
  - Optimisation is more challenging for collider with strongly varying event rates
    - Z-pole running must not compromise precision Higgs physics

Operation mode- pulsed or continous

- Linear Colliders operate in bunch trains



Cartoon F. Simon

CLIC: Δt_b ~ 0.5ns, frep = 50Hz

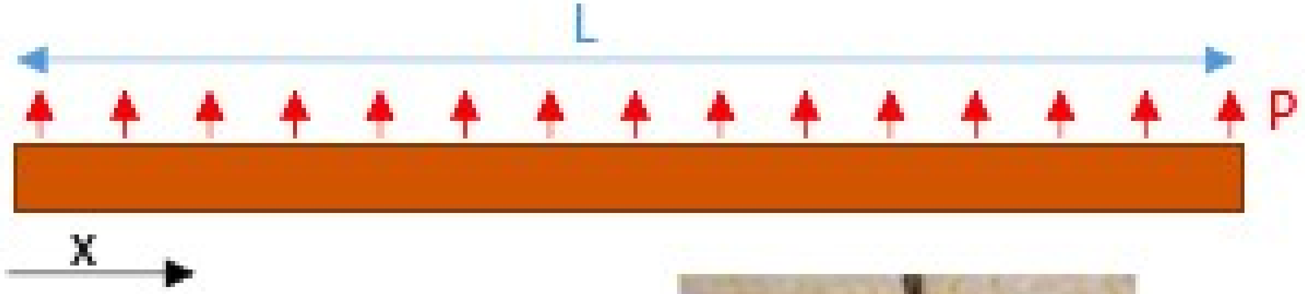
ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design
- Have to avoid large peak currents
- Have to ensure stable operation in pulsed mode

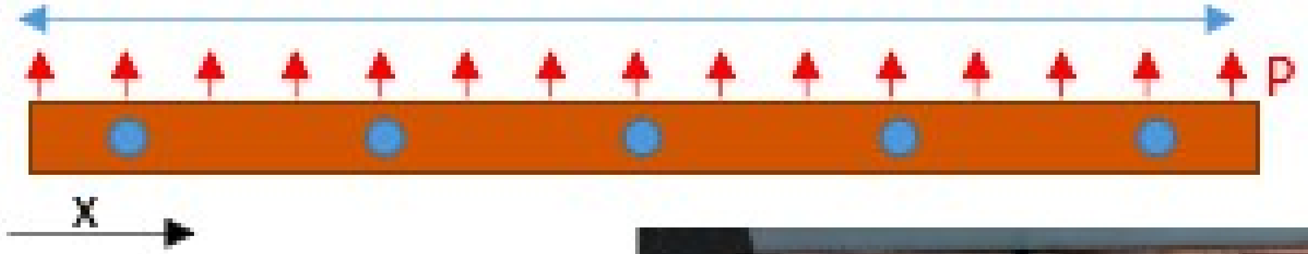
- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in "continuous" mode
  - Tendency: Avoid/minimise active cooling in also continuous mode

Active cooling?

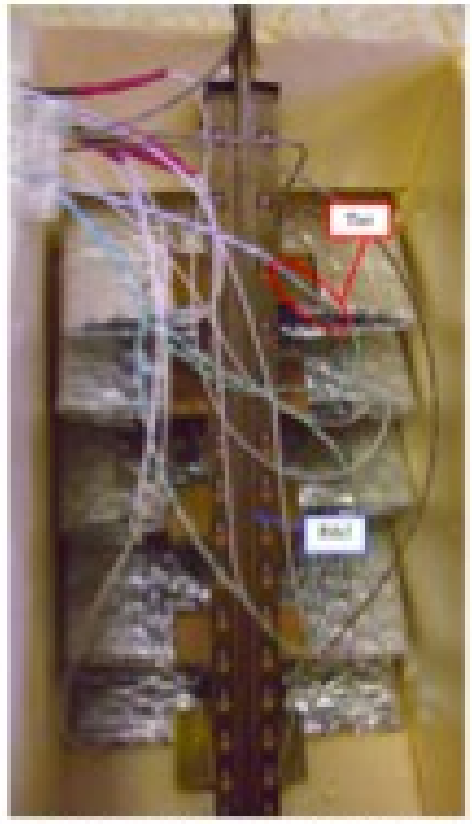
Passive cooling



Active cooling

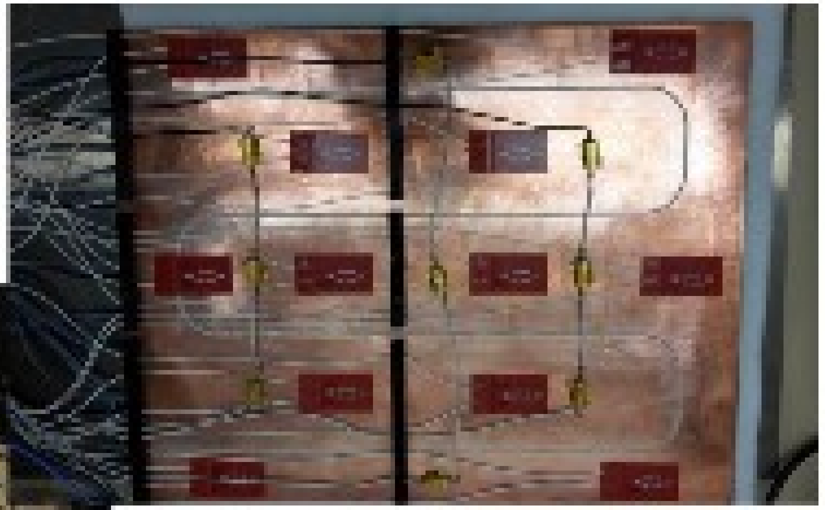


Passive cooling ramp example



Passive cooling ramp set up test

Active cooling set up test with water at room temperature

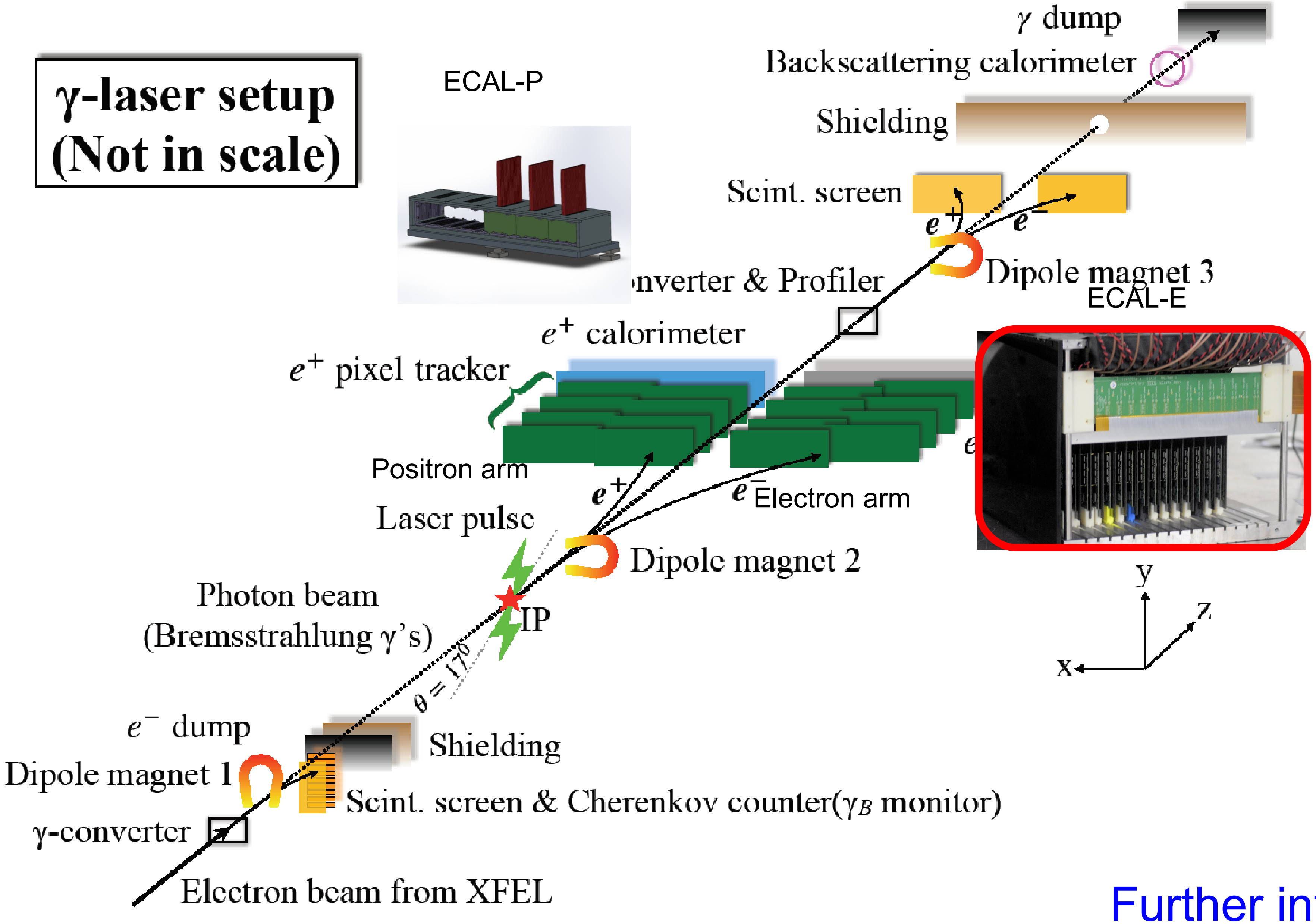


Active cooling test layout (400mm x 300mm x 3mm thick copper plate with 1,800 pipes embedded)

Cooling needs may be enhanced due to precision timing and will most likely be unavoidable at circular colliders

"Early Applications" of CALICE Technologies - LUXE

Laser Und Xfel Experiment – QED in extreme fields



CALICE meets LUXE

Granular calorimeters in positron and electron arms of spectrometer

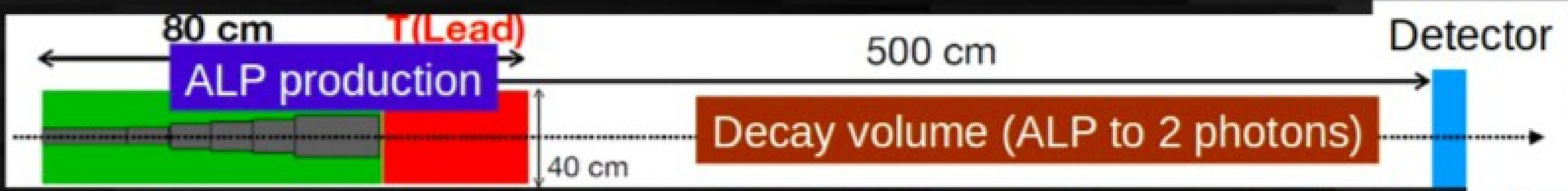
- Our focus ECAL-E
- Main application electron measurement of Breit-Wheeler process in γ-laser setup
- Could also be used in early LUXE phase in case of delays of ECAL-P
  - Dark photon search next to γ dump could be further option
- Ideal application(s) of CALICE SiW Ecal technological prototype

Further interest by dark photon experiments EBES (KEK) and Lohengrin (Uni Bonn)

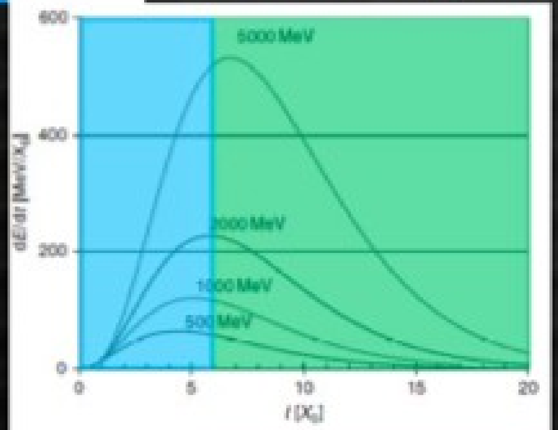
“Early Applications” of CALICE Technologies - EBES

EBES (Eletron Beam-dump Experiment at SY3)

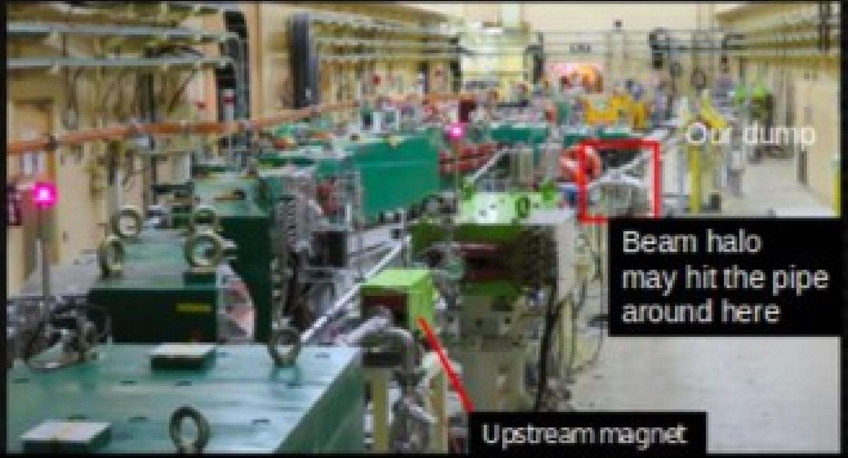
- Sub-GeV ALP (Axion-Like Particle) produced at beam dump of KEK Linac switching-yard (SY) 3 (7 GeV e^- / 4 GeV e^+) decaying to 2 photons
- Combination of 5 SiW-ECAL layers and PbO Cherenkov calorimeters



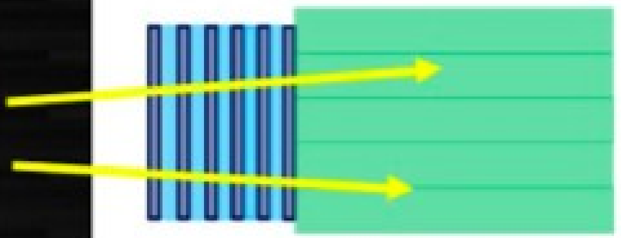
2 photon clusters should be seen as ALP signal



Pilot run at SY3 in July 2022



Huge background from upstream seen shielding being developed
→ Second run later 2023



Summary and conclusion

- Two beam tests campaigns in 2021 and 2022
  - ... partially in combination with CALICE AHCAL
  - Data analysis is still ongoing
  - See also Adrian's talk on Chip-On-board PCBs

- CALICE SiW ECAL is about to reply to conclusions from 2021/22 beam test campaigns

- Understanding and remedying of observed sensor delamination
  - Independent of application in future projects
  - One study ongoing with underfill agent and epoxy with better mechanical properties
  - Further solutions will have to be studied and evaluated
  - Need a conclusion this year in order to move on

- New PCB designed and meanwhile manufactured
  - Basis for revised 15 layers stack => Gearing up for next beam test campaign in 2024
  - Will be important step towards readiness for linear collider detector construction

- Precious feedback from LHC Upgrades for future steps
  - System integration, timing, active cooling

- Application in small scale experiments (BES, LUXE, Lohengrin)

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Backup

The roadmap document(s)

- ECFA R&D Roadmap
  - CERN-ESU-017 https://cds.cern.ch/record/2784893
  - 248 pages full text and 8 page synopsis

- Endorsed by ECFA and presented to CERN Council in December 2021

The Roadmap has identified

- General Strategic Recommendations (GSR)
- Detector R&D Themes (DRDT) for each of the taskforce topics
- Concrete R&D Tasks

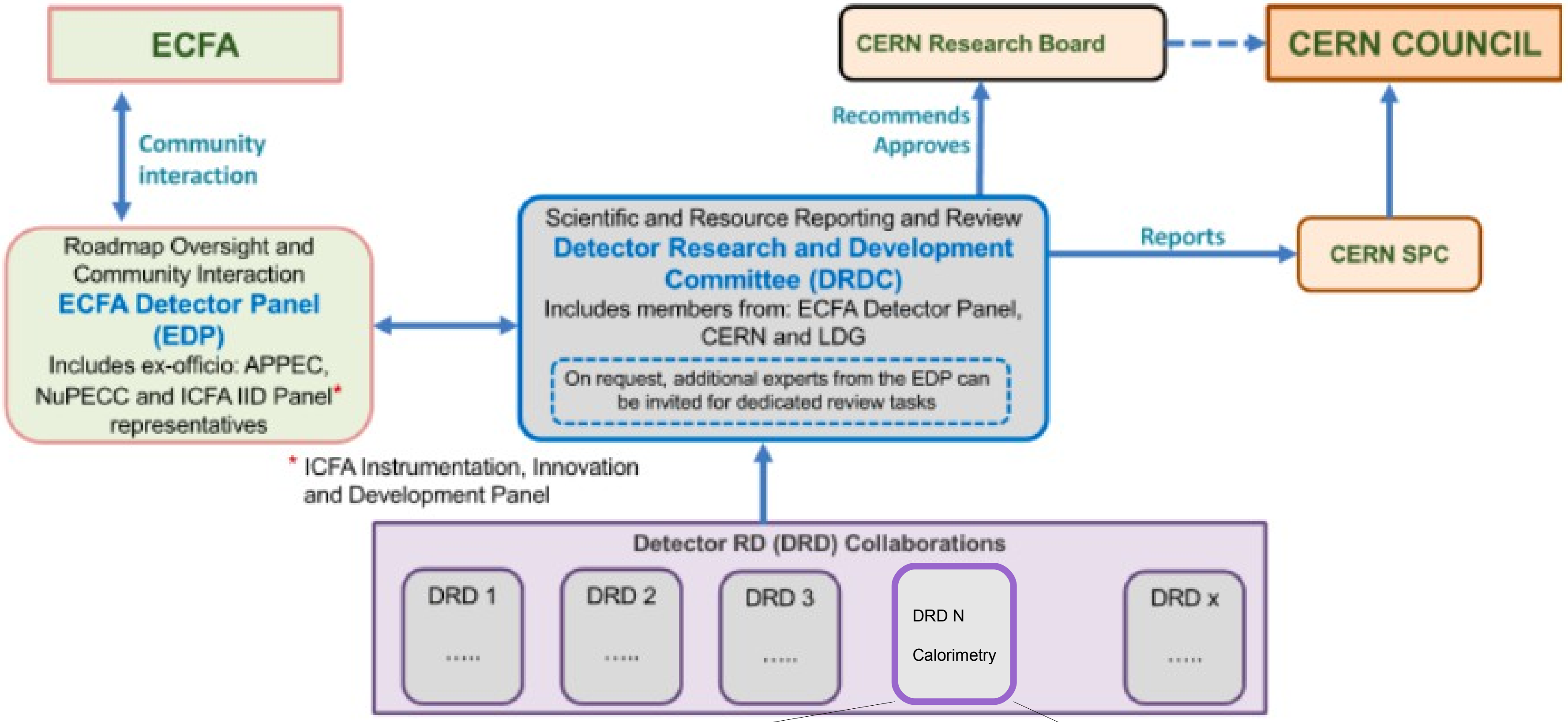
- Timescale of projects as approved by European Lab Director Group (LDG)

Guiding principle: Project realisation must not be delayed by detectors

Toward DRD Calorimetry

Proposed organisation scheme :

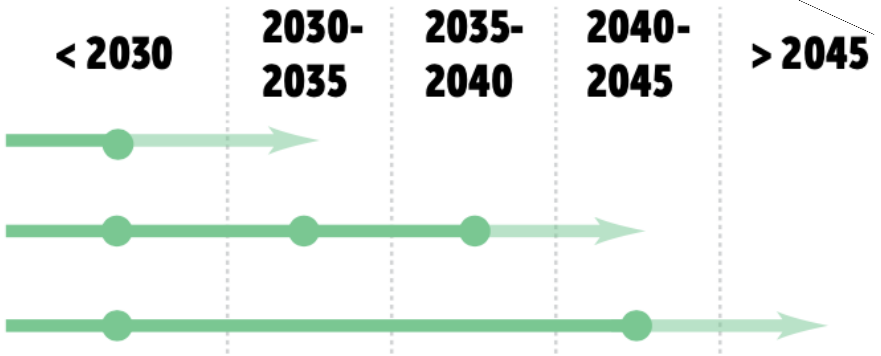
Endorsed by CERN Council in Sept. 2022



Research themes calorimetry:

Calorimetry

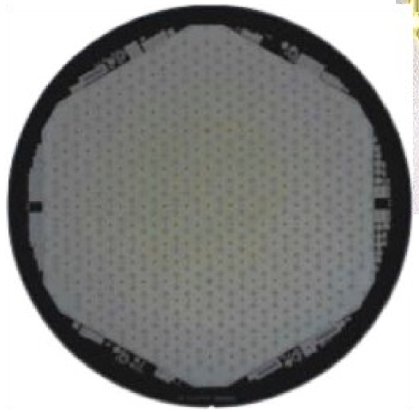
- **DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
- **DRDT 6.2** Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
- **DRDT 6.3** Develop calorimeters for extreme radiation, rate and pile-up environments

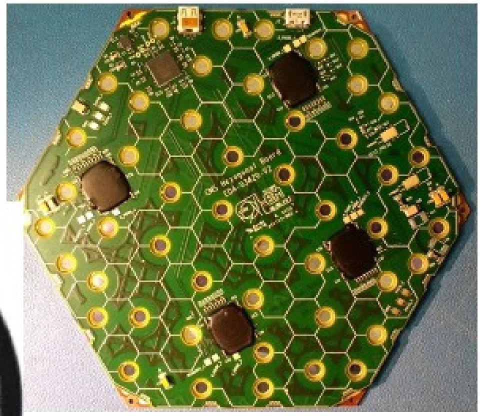


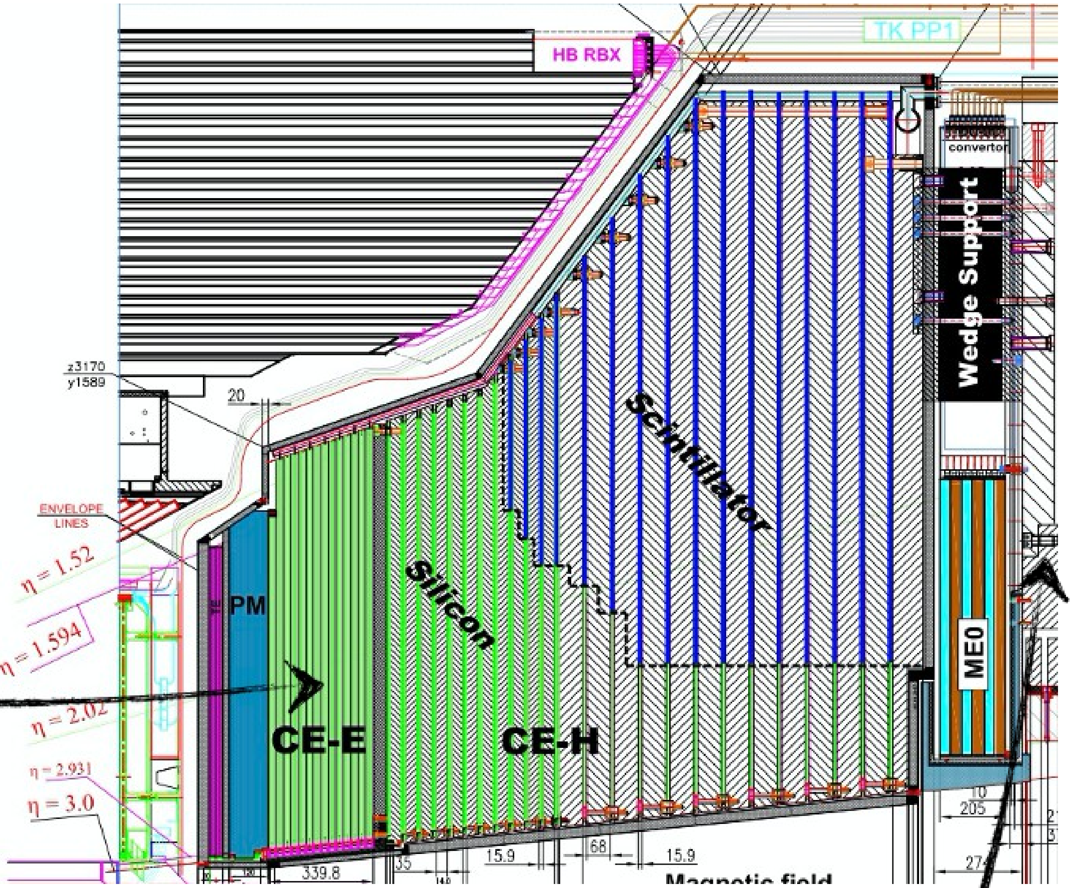
HL-LHC Upgrades

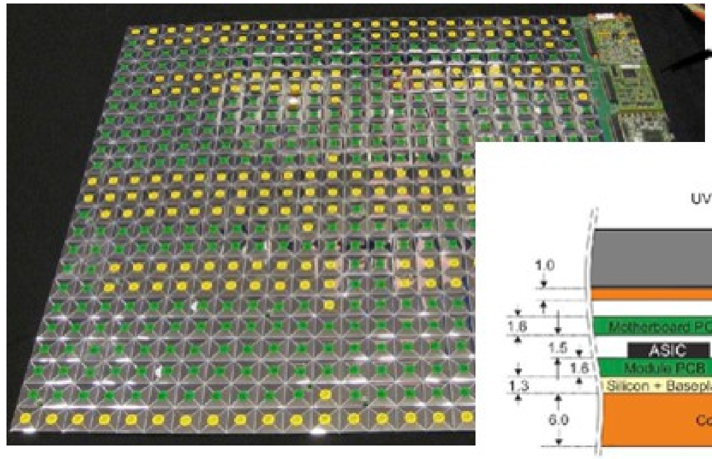
- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

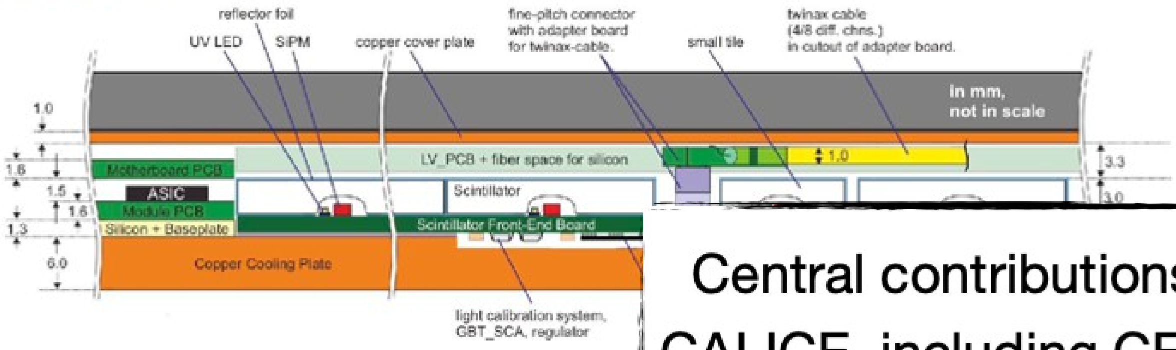
Most prominent: The CMS Endcap Calorimeter Upgrade HGCal









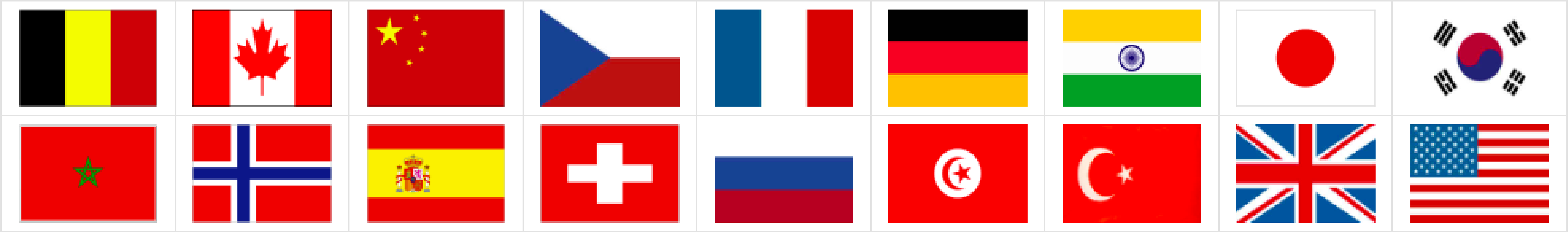


Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

F. Simon

The CALICE Collaboration

Calorimeter R&D for large imaging calorimeters

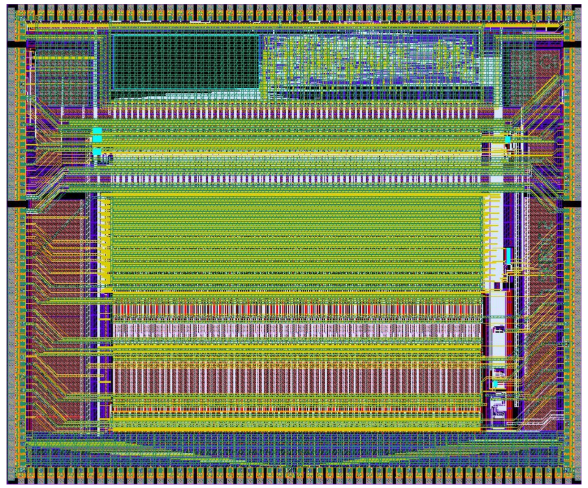


~270 physicists/engineers from 62 institutes and 18 countries from 4 continents

- Integrated R&D effort
- Acceleration of detector development due to *coordinated* approach
- MOU 2005
  - IN2P3 among founding members, first Spokesperson Jean-Claude Brient

ASICs – The “ROC Family”

SKIROC
(for SiW Ecal)



SiGe 0.35µm AMS,

Size 7.5 mm x 8.7 mm, 64 channels

High integration level

(variable gain charge amp,

12-bit Wilkinson ADC, digital logic)

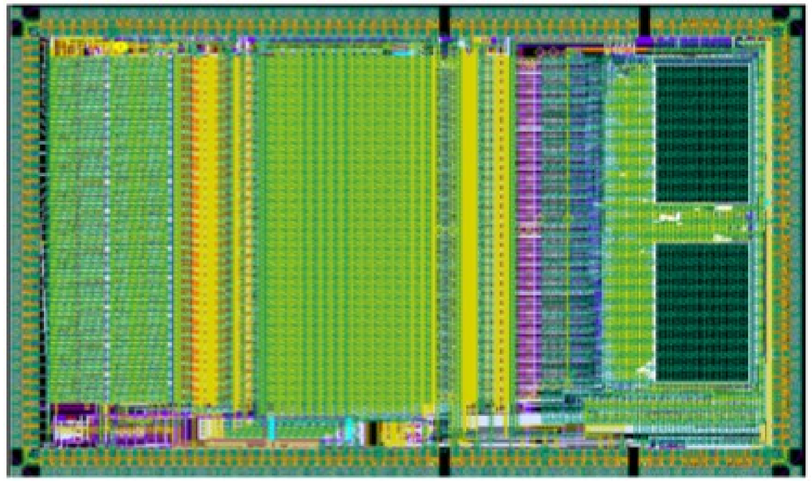
Large dynamic range (~2500 MIPS)

low noise (~1/10 of a MIP, 400 fC)

Auto-trigger at ½ MIP

Low Power: (25µW/ch) power pulsing

SPIROC
For optical readout, Tiles + SiPM



Variant of SKIROC

36 channels, 15 bit readout

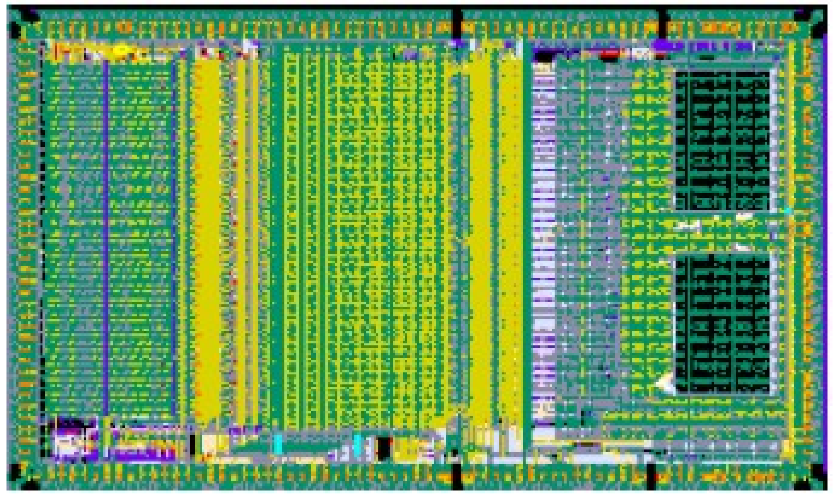
Auto-trigger down to ½ p.e,

80 fC for G=1x10^6

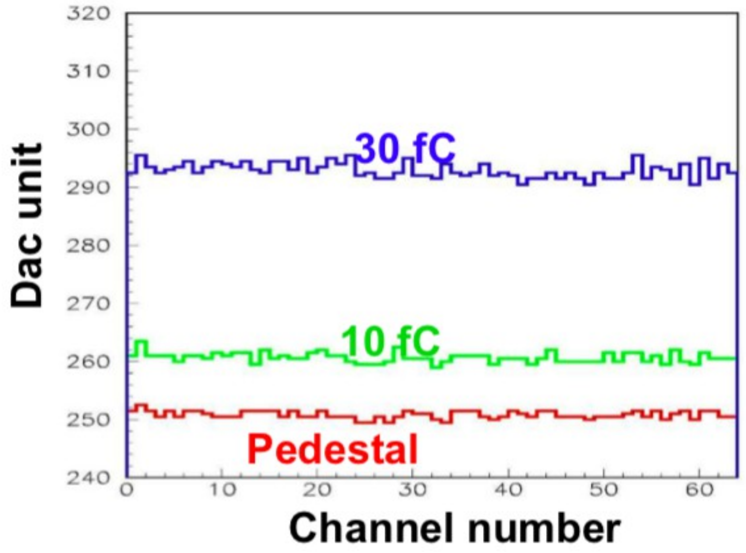
Timing to ~ 1ns

Low Power: (25µW/ch) power pulsing

HARDROC
For gaseous r/o - GRPC



64 Channels with three thresholds



Power pulsing

Variant for Micromegas: MICROROC

Towards Implementation of DRD Calorimetry

- **Entry point, "DRD Calo indico page": https://indico.cern.ch/event/1213733/**
  - Information on important events and access to relevant documents
  - Note also the Q&A Doc
  - 227 people from four regions registered so far

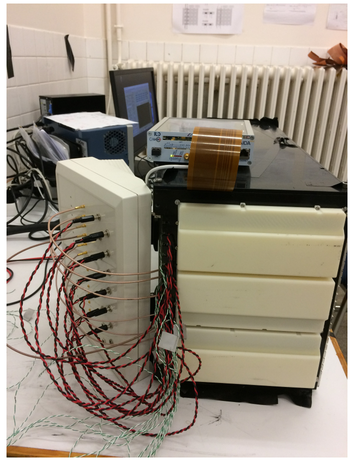
- 1st Community Meeting 12/1/23
  - https://indico.cern.ch/event/1212696/

- Proposal phase until 1st of July 2023
  - **Input-proposals until latest 1st of April 2023**
  - 2nd Community Meeting 20th April at CERN
    - https://indico.cern.ch/event/1246381/
    - Summary of input-proposals (w/o disclosing confidential information)
    - Presentation/discussion of organisation of DRD Calorimetry (with focus on scientific aspects)
      - Guidance by existing R&D collaborations

  - Input-proposals will be condensed into a DRD on Calorimetry proposal until (around) 1st of June 2023
    - Further iteration with stakeholders, community and higher level bodies

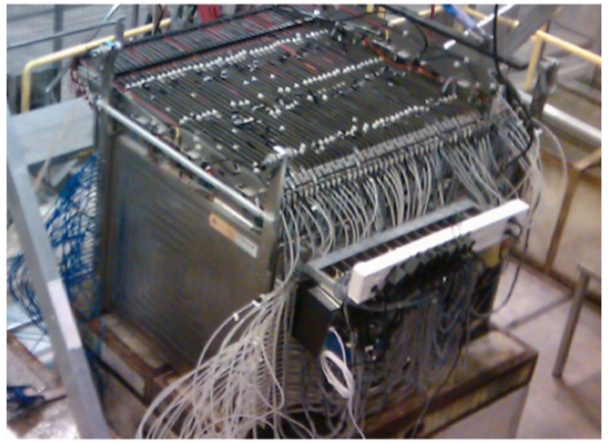
CALICE (Technological) Prototypes

ScECAL



SiECAL

AHCAL



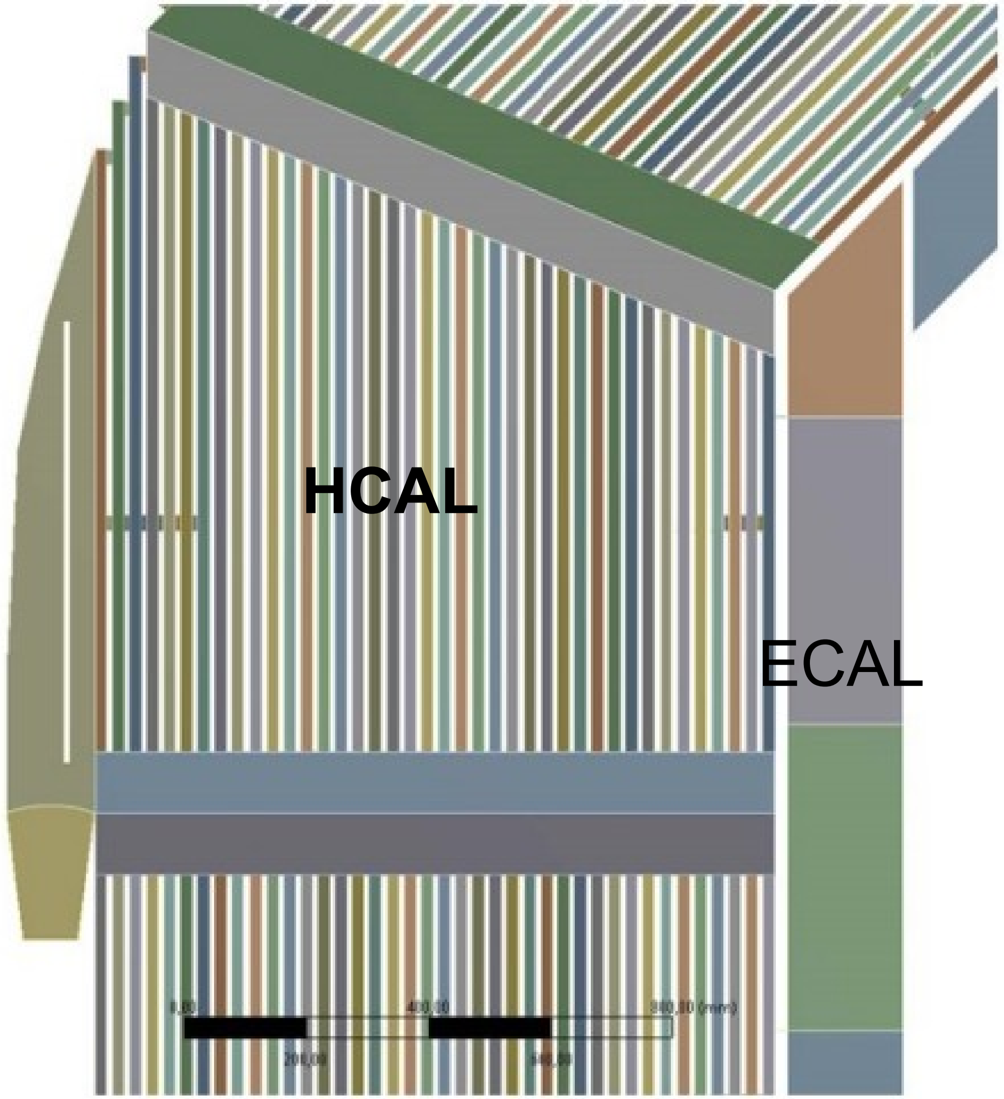
SDHCAL

Name	Sensitive Material	Absorber Material	Resolution	Pixel size/mm^3	~Layer size**/cm^3	~Layer depth/X_0	~Layer depth/λ_I	# of Pixels/ layer	# of layers	Comment
ScECAL	Scintillator	W-Cu Alloy	Analogue, 12bit	5x45x2	23x22x0.5	0.73	0.03	210	32	2x16 x and y strips
SiECAL	Si	W	Analogue, 12bit	5.5x5.5x 0.3 (0.5, 0.65)	18x18x 0.24 (- 0.63)	0.6-1.6	0.02-0.06	1024	≥22	Can be run in different configs.
AHCAL	Scintillator	Fe*/W	Analogue, 12bit	30x30x3	72x72x2/ 1.4	1/2.9	0.11	576	38	Running with Fe and W
SDHCAL	Gas	Fe*	Semi-digital 2bit	10x10x6	100x100x 2.6	1.1	0.12	9216	48	

*Stainless Steel

**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)

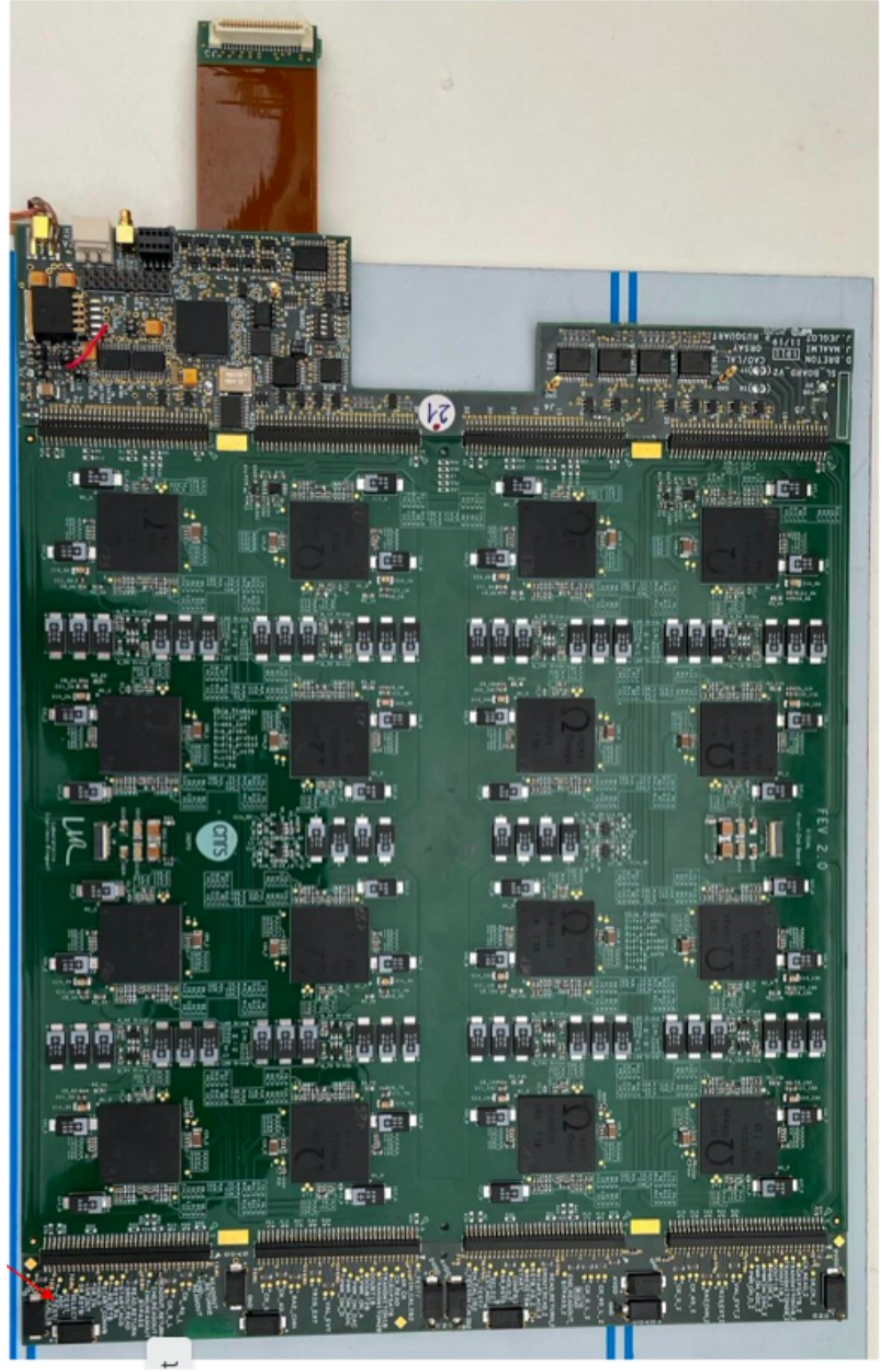
ILD concept and highly granular calorimeters



- ILD is particle flow detector
  - Implies goal to measure every particle of hadronic final state
  - Key components for PFA are highly granular calorimeters
- Calorimeter options in ILD
  - Silicon-Tungsten Ecal
    - 26-30 layers
    - Cell size 5.5x5.5mm^2, layer depth 0.6-1.6 X_0
  - Scintillator-Tungsten Ecal
    - 30 layers
    - Strip size 5x45 mm^2, layer depth 0.7 X_0
  - Analogue Hcal
    - 48 layers
    - Scintillating tiles: 30x30mm^2, layer depth 0.11λ_I
    - Absorber stainless steel
  - Semi-Digital Hcal
    - 48 layers
    - GRPC: 10x10mm^2, layer depth 0.12 λ_I
    - Absorber stainless steel

SiW ECAL PCB - New FEV 2.1

LLR, IJCLab, LPNHE, OMEGA



Improved Layout

- Better shielding of AVDD and AVDD PA plans and minimisation of cross-talk between inputs and digital signals.

Power Pulsing Mode: new philosophy

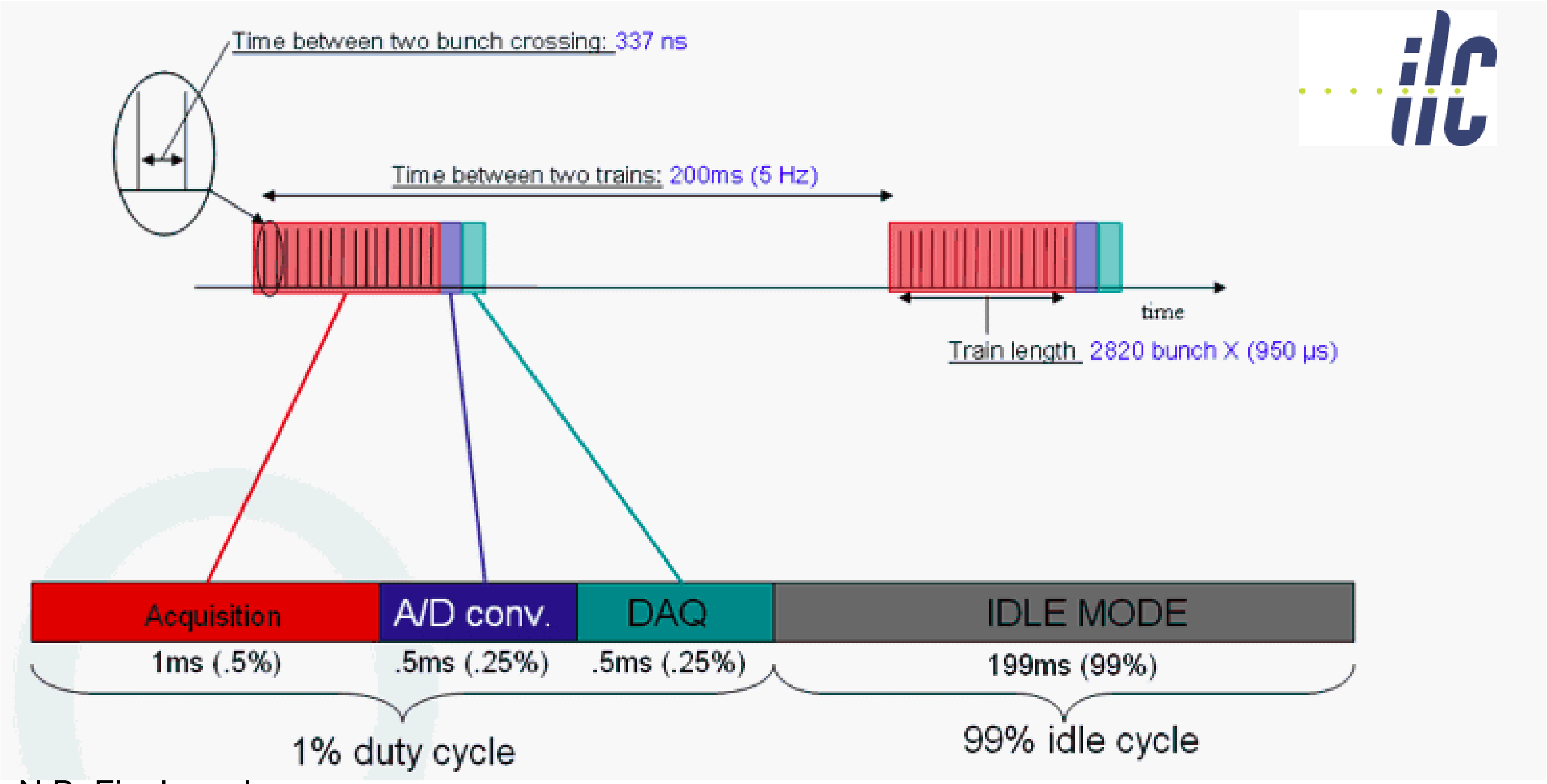
- limiting the current through a layber (current limiter present on the SL Board) to:
  - avoid driving high currents through the connectors and makes the current peaks **local** around the SKIROCs chips
  - avoid voltage drop along the slab
  - ensure temperature uniformity
- Large capacitors with low ESR for **local** energy storage (around each SKIROC chip)
- Generate **local** power supply with LDO (Low Drop Out) to avoid voltage variations

- 25 PCBs delivered beginning of March 2023

This board will enable us to finish the ongoing R&D, join the LUXE Experiment (see later) and be ready in case of ...

Beam Structure and Detector Operation

- Linear collider beams come in bunch trains
  - CLIC: repetition frequency 50 Hz, ILC: repetition frequency 5 Hz (minimum)



N.B. Final numbers may vary

- Power pulsing of electronics:

- Electronics switched on during > ~1ms of bunch train and data acquisition
- Bias currents shut down between bunch trains

Exploiting beam structure can/will lead to power economic operation of linear collider detectors

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[GeV]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

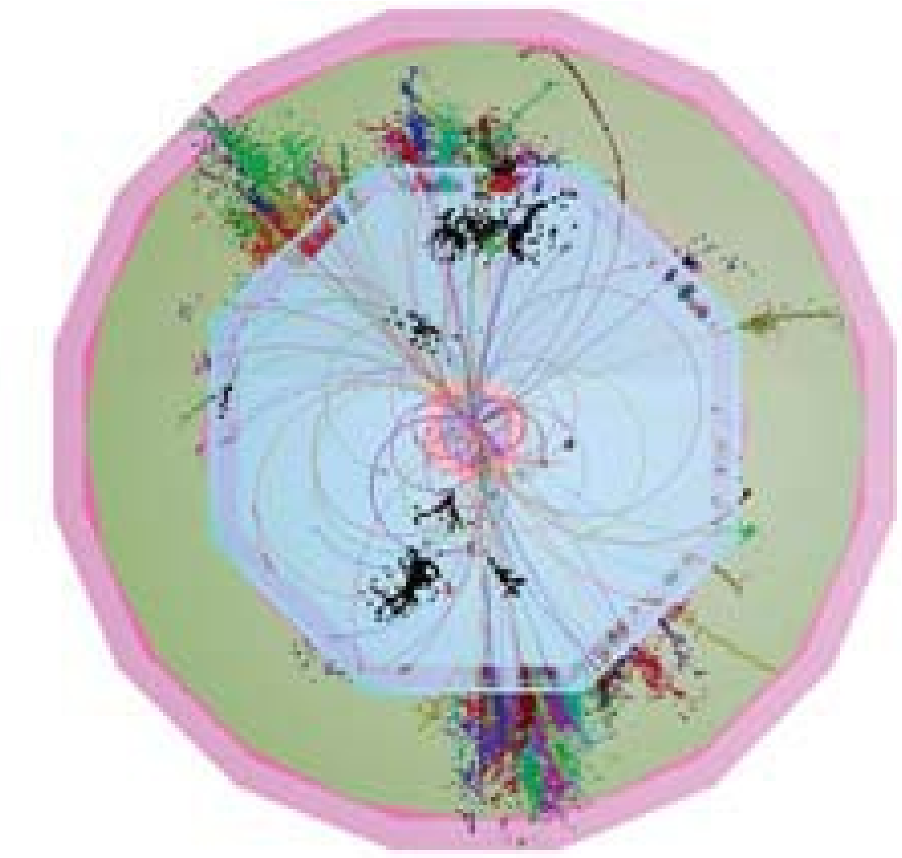
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : $\theta_{min} = 5$ mrad

(for events with missing energy e.g. SUSY)



Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp

ee->bb at 250 GeV

Efficiency of selection for $e^-_L e^+_R \to X$ [%]							
	$X = q\bar{q}$ ($E_\gamma < 35\,GeV$)			$X = q\bar{q}$ ($E_\gamma > 35\,GeV$)			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ (uds)	$q\bar{q}$ (udscb)	$X = ZZ$	$X = WW$	$X = HZ$
No cuts	100%	100%	100%	100%	100%	100%	100
Cut 1	84.5%	84.9%	86.4%	6.7%	12.3%	11.7%	12.6
+ Cut 2	82.8%	82.0%	80.3%	1.2%	12.1%	11.1%	11.8
+ Cut 3	72.1%	71.7%	71.3%	0.7%	2.5%	5.0%	4.5
+ Cut 4	71.5%	71.1%	70.7%	0.7%	1.6%	3.6%	3.8
Efficiency of selection for $e^-_R e^+_L \to X$ [%]							
	$X = q\bar{q}$ ($E_\gamma < 35\,GeV$)			$X = q\bar{q}$ ($E_\gamma > 35\,GeV$)			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ (uds)	$q\bar{q}$ (udscb)	$X = ZZ$	$X = WW$	$X = HZ$
No cuts	100%	100%	100%	100%	100%	100%	100
+ Cut 1	84.1%	85.2%	86.5%	7.0%	12.5%	12.6%	12.4
+ Cut 2	82.6%	82.2%	81.1%	0.7%	12.3%	11.8%	11.8
+ Cut 3	71.6%	72.3%	72.2%	0.4%	2.5%	5.6%	1.8
+ Cut 4	71.1%	71.6%	71.6%	0.4%	1.7%	4.3%	1.6

Table 3: Cut flow for the signal and background events.

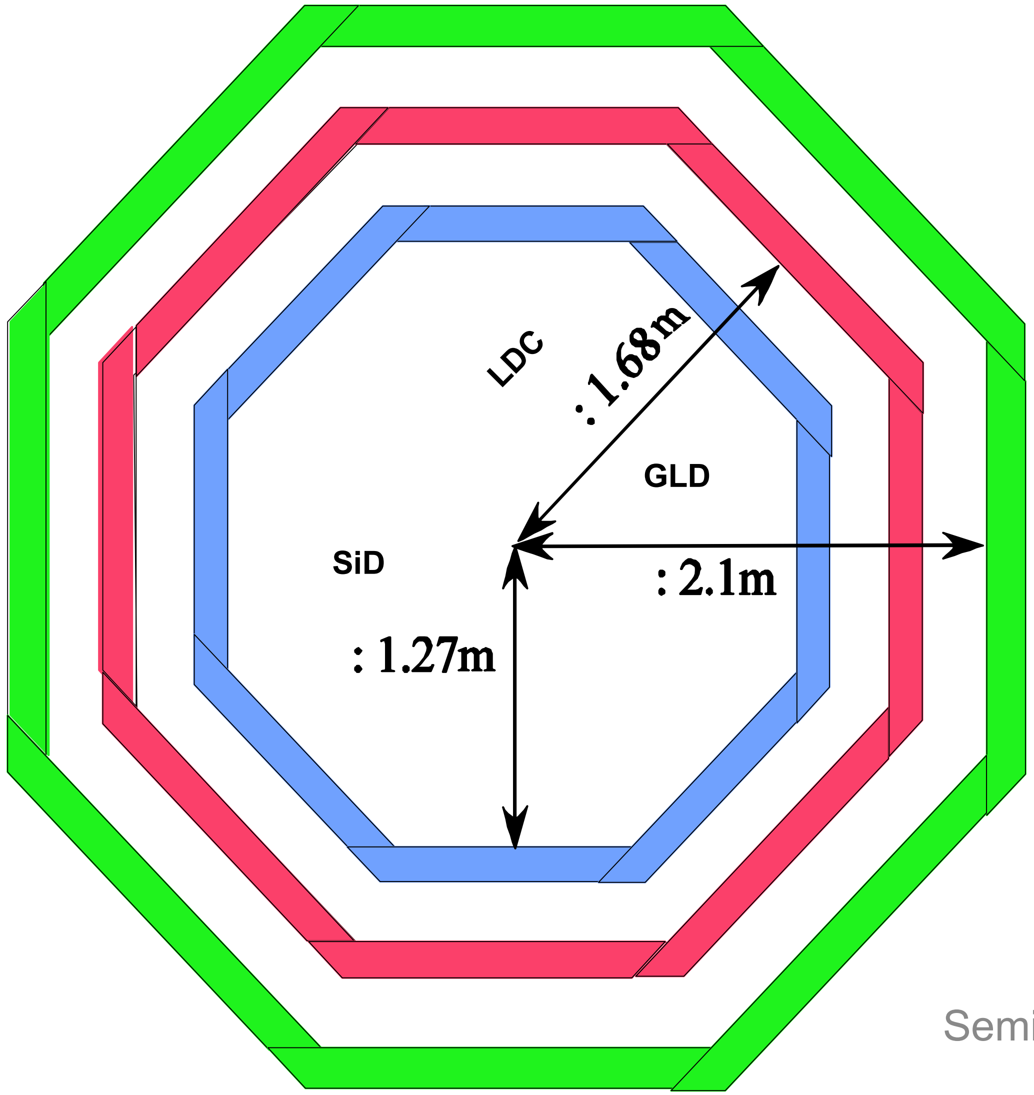
- Cut 1: Photon veto based on acolinearity
- Cut 2: Photon veto based on ISR photon reconstruction in detector volume

ILD concept and highly granular calorimeters

Concepts currently studies differ mainly in SIZE and aspect ratio

Relevant: inner radius of ECAL: defines the overall scale

ECAL end-view



- Figure of merit (ECAL):

  Barrel: $B R_{in}^2 / R_m^{effective}$

  Endcap: "B" $Z^2 / R_m^{effective}$

  R_{in} : Inner radius of Barrel ECAL

  Z : Z of EC ECAL front face

- Different approaches

  SiD: $\mathbf{B}\ R_{in}^2$

  LDC: $B\ R_{in}^2$

  GLD: $B\ \mathbf{R}_{in}^2$