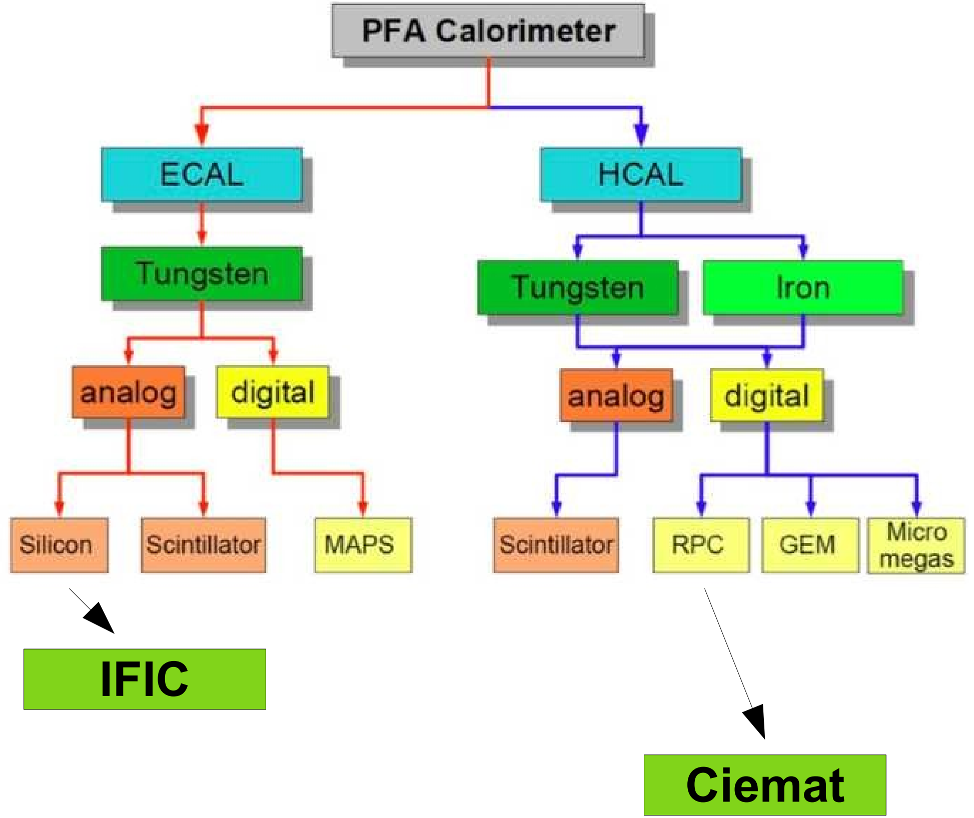
CALICE activities at IFIC

DRD T6: Calorimetry

Adrián Irles
AITANA group at IFIC – CSIC/UV

The CALICE Collaboration

High Granular Calorimetry for Particle Flow: Pioneered by the CALICE Collaboration



More than 300 physicists/engineers from ~60 institutes and 19 countries coming from the 4 regions (Africa, America, Asia and Europe)

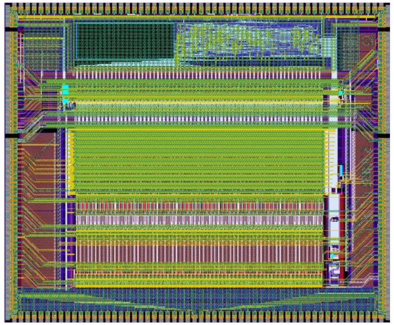
Most projects of current and future high energy colliders propose highly granular calorimeters

PFA calorimetry is not only a quest on high jet energy resolution but on a deep understanding of shower developments

Technological premises

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)

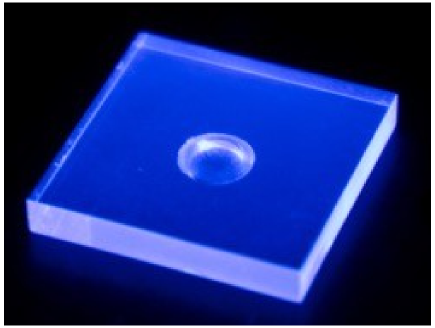


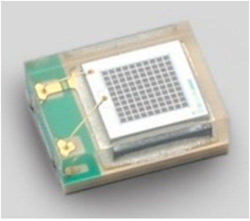
Size 7.5 mm x 8.7 mm, 64 channels

- **Analogue measurement**
- **On-chip self-triggering**
- **Data buffering**
- **Digitisation**
  ... all within one ASIC

- **Common developments on different CALICE projects**

Miniaturisation of r/o devices





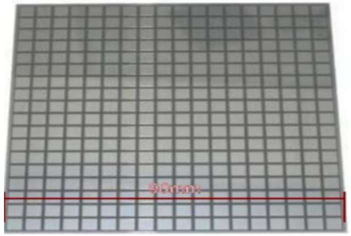
- Small scinitllating tiles
- (Low noise) SiPMs

Power pulsed electronics
to reduce power consumption…
Compactness –> no space left for active cooling systems

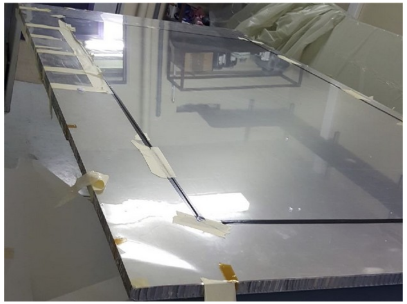
Self trigger of individual cells below MIP level

Large surface detectors

Si Wafer



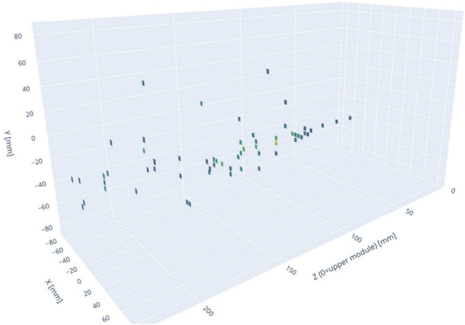
RPC layers

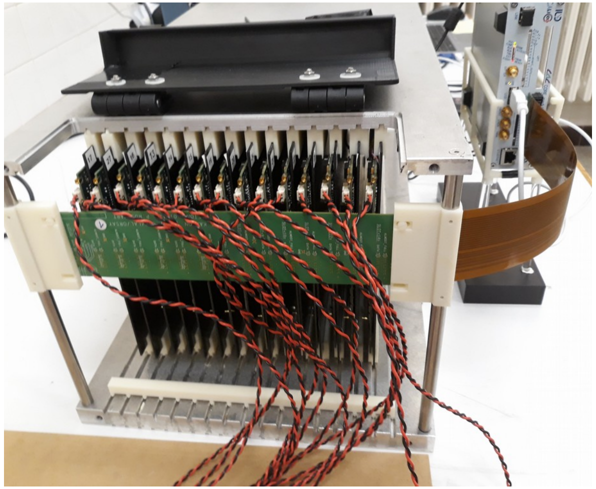


Many things that look familiar to you today were/are pioneered/driven by CALICE

SiW-ECAL CALICE prototype (current version)

SiW-ECAL
- **15 layers 18×18 cm²**
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm³
- **15k channels**





In process to be rebuilt + upgraded + extended + "compacted"

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
LLR
LPSC Grenoble
LPNHE PARIS
OMEGA Microelectronics
cnrs IN2P3 Les deux infinis

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
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Since 2020

九州大学 KYUSHU UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO

A SiW-ECAL full size prototype milestone

- A main **DRD6 milestones/deliverables** will be the construction of **full size prototypes** of high granular with fully embedded sandwich **ECAL and HCAL *à la CALICE*** & **common beam tests**
  - 24-30 X_0 + 4-5λ

- ~2030-40: **Higgs Factories – Particle Flow** Calorimeters
  - **PF calorimetry**: up to about **O(10^8) readout cells** for barrel calorimeters (SiW-ECAL case)
  - **Linear** colliders (**low rates** favoring self-trigger and low consumption electronics through **power-pulsing**)
  - **Circular** colliders (**higher rates**, specially running at Z-pole, challenging the power consumption budgets and/or the cooling needs)

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- **Other applications** in the short term (i.e. ~2026)
  - For example: **LUXE** (featuring two silicon-tungsten highly granular and compact ECALs (CALICE and FCAL adaptations). XFEL pulsed electron beam (as ILC)

Technological challenges (some)

Current prototyping phase

- Integration (including integration with AHCAL)
- Low consumption requirements
- Very dense PCBs with fully embedded readout electronics
- Large surface sensors
- Highly specific ASIC developments (but with lots of commonalities for different projects)
  - ASIC design and production for prototyping → not only for the final detector.
- **Sensor-PCB integration**
  - **Maximizing compactness (minimal moliere radius)**

Longer term

- Sensor development (low noise, timing, CMOS development for calorimetry, etc)
- Adaptation to other concepts with higher rates and/or radiation levels
- Integration aspects (cooling, mechanics, etc)

Technological challenges (some)

IFIC

- ▶ Co-responsible of beam test preparation & commissioning, data taking and analysis.
- ▶ Co-responsible of module integration (sensor to readout modules – PCBs)
  - For the two calorimeters to be built for LUXE (and DRD)
- ▶ Including
  - R&D and durability tests on gluing (conductive epoxy)
  - Other approaches (anysotropic film, ...)
  - QA of assembled modules
- ▶ In collaboration with IN2P3 laboratories form Ile de France and Tel Aviv institutions (Weizman, TAU), Kyushu Univ. and DESY

- ▶ **Sensor-PCB integration**
  - **Maximizing compactness (minimal moliere radius)**

CALICE - IFIC

Timeline

- ▶ IFIC joined CALICE in 2020 (A. Irles)
  - (before, A. Irles was member of CALICE since 2015, first AHCAL in DESY later SiWECAL in LAL-IJCLab)
- ▶ IFIC organized the CALICE Collaboration Meeting 2021 https://agenda.linearcollider.org/event/9571/
  - And the SiW-ECAL meeting
- ▶ IFIC joined LUXE experiment in 2022 (A. Irles)
  - Plans to use to ECALs, both based in CALICE/FCAL prototypes

Collaboration with international partners

- DESY, IN2P3, KEK... via **CALICE**
- DESY, Tel Aviv, Weizzman, Krakow Univ... via **LUXE**
- CiEMAT via CALICE and a joint **Proyecto Nacional** (IFIC-CiEMAT)

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CALICE - IFIC

Person power / budget

- **A. Irles (CIDEGENT-** 01/2021-12/2024**)**
  - **+ 1 student** (CIDEGENT, CALICE+ILC, until 12/2024)
  - **+ 1/3 mechanical engineer**
  - + support from IFIC electronic and mechanic services
- Planes Complementarios
  - A. Irles and M. Vos, project for R&D on conductive gluing and detector assembly at IFIC (CALICE -LUXE)
  - **1 Postdoc (starting ~May 2023)**
- Plan Nacional: approved a joint application IFIC-CIEMAT with a Work Package on high granular calorimetry
- Support from the Prometeo (2022-2024) of the group
  - **at least 1 PhD student (starting June 2023)**

More info

- Jornadas IFIC L7: Advanced instrumentation and computing in fundamental physics
  - https://indico.ific.uv.es/event/6899/contributions/19784/attachments/10689/14496/CALICE_LUXE_IFIC_v2.pdf
- Second community meeting 20/04/2023 at CERN
  - https://indico.cern.ch/event/1246381/

DRD TF6

Implementation of TF6 https://indico.cern.ch/event/1213733/

- Team:
  - **Roberto Ferrari (INFN-Pavia, co-convener)**
  - **Roman Pöschl (CNRS/IN2P3/IJCLab, co-convener)**
  - **Felix Sefkow (DESY, member of coordination group)**
  - Martin Aleksa (CERN)
  - Etiennette Auffray-Hillemanns (CERN)
  - Dave Barney (CERN)
  - Tommaso Tabarelli de Fatis (University and INFN Milano-Bicocca)
  - Gabriella Gaudio (INFN-Pavia)
  - Frank Simon (KIT/MPP)

DRD T6 proposal team

- First community meeting, 12/01/2023 at CERN
  - https://indico.cern.ch/event/1212696/
  - A. Irles presenter: *Sandwich calorimeters with fully embedded electronics: ECAL section*
- Second community meeting 20/04/2023 at CERN
  - https://indico.cern.ch/event/1246381/
- **Proposal submission open** in the indico (abstract system). **Deadline 24th March**

Proposal team

- **Track 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters**
  - A Irles (IFIC), Frank Simon (KIT), Jim Brau (University of Oregon), Wataru Ootani (University of Tokyo)
- Track 2: Liquified Noble Gas Calorimeters
  - Martin Aleksa (CERN), Nicolas Morange (IJCLab), Marc-André Pleier (BNL)
- Track 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
  - Etiennette Auffray (CERN), Gabriella Gaudio (INFN-Pavia), Macro Lucchini (University and INFN Milano-Bicocca), Philipp Roloff (CERN), Sarah Eno (University of Maryland), Hwidong Yoo (Yonsei University)

DRD T6 proposal team

Proposal team

- **Track 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters**
  - A Irles (IFIC), Frank Simon (KIT), Jim Brau (University of Oregon), Wataru Ootani (University of Tokyo)

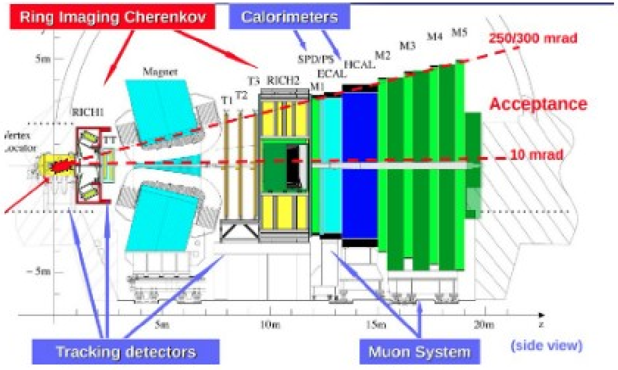
- Proposal team is in charge of encourage (strongly) merging proposals if made by single insitutes.
- Prototype delivery and common beam test (ECAL+HCAL) are expected as milestones/deliverables
  - 3-5 years
- Transversal R&D (less experiment oriented) is also expected
- Long term wishes (sensor development, ASIC development, etc).
  - Synergies with other DRDT.

ECFA

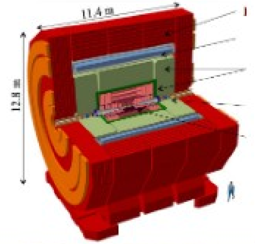
(Main) Target Projects of Detector R&D

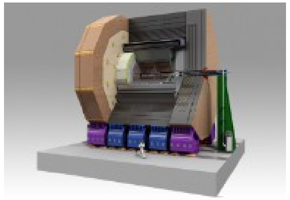
European Strategy Update

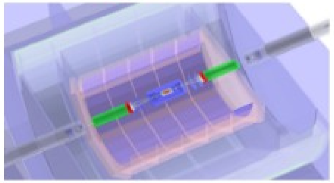
HL-LHC after LS4

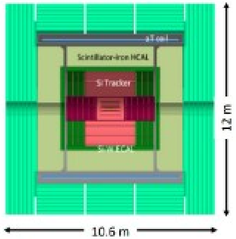


Higgs Factories

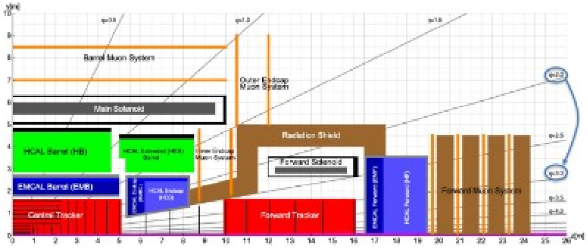




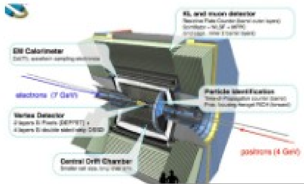


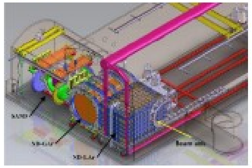


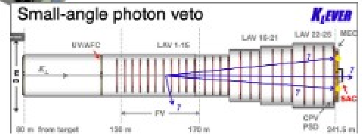
Future hadron colliders (including eh colliders)



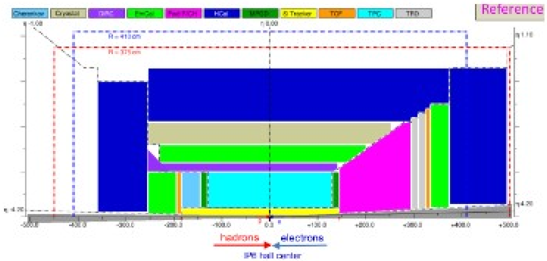
SuperKEKB, DUNE ND and Fixed Target



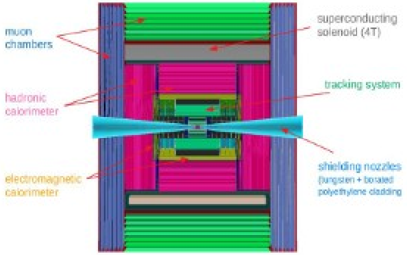




EiC



Muon Collider



Detector R&D Roadmap Implementation – Calorimeter Community Meeting

5

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ECFA

Review Input Sessions – Overview Table

European Strategy Update

Project	~Earliest Start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2045	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2045	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	"continous"		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

In most of the cases final choices have still to be made

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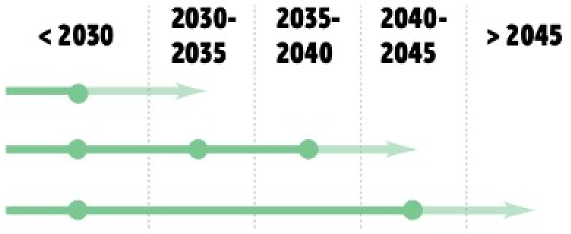
Future Facilities and DRDT for Calorimetry

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



- The DRDT and the provisional time scale of facilities set high-level boundary conditions
  - See next slide for detailed R&D tasks
- Both as well as the GSR should be taken into account when formulating the R&D proposal(s)

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On the proposals

- Proposal Team: In first approach the TF6+ Task Force
- Stakeholders: Existing R&D Collaborations and communities in coordination with the corresponding funding agencies

- There exists already a draft of guidelines for the input-proposals and the final proposal
  - The following is oriented at this draft
  - The draft is still open for comments and modification, please provide feedback

- Input-proposals: Content
  - Brief description of R&D project including a reference to the roadmap
  - Where applicable a sketch of synergies inside and outside of DRD Calorimetry
  - “External needs” like test facilities, software framework etc.

- Input-proposasl: Important Formalities
  - Set of tables on R&D projects with Deliverables (and most likely Milestones)
  - A list of interested institutes associated with the R&D projects (confidential information)
    - This can be European and also Non-European Groups
  - An overview on (eventually) existing and needed resources (confidential information)
    - Again can cover European and non-European resources
  - The length of these input-proposals should be of the order of 5-10 pages

- Proposal with plans and general overview on resources (20 pages for DRD Calorimetry)

Thanks to Y. Benhamou, V. Boudry, J. Liu, Y. Liu, W. Ootani, R. Poeschl, T. Suehara, and more for the material in these slides

Back-up slides

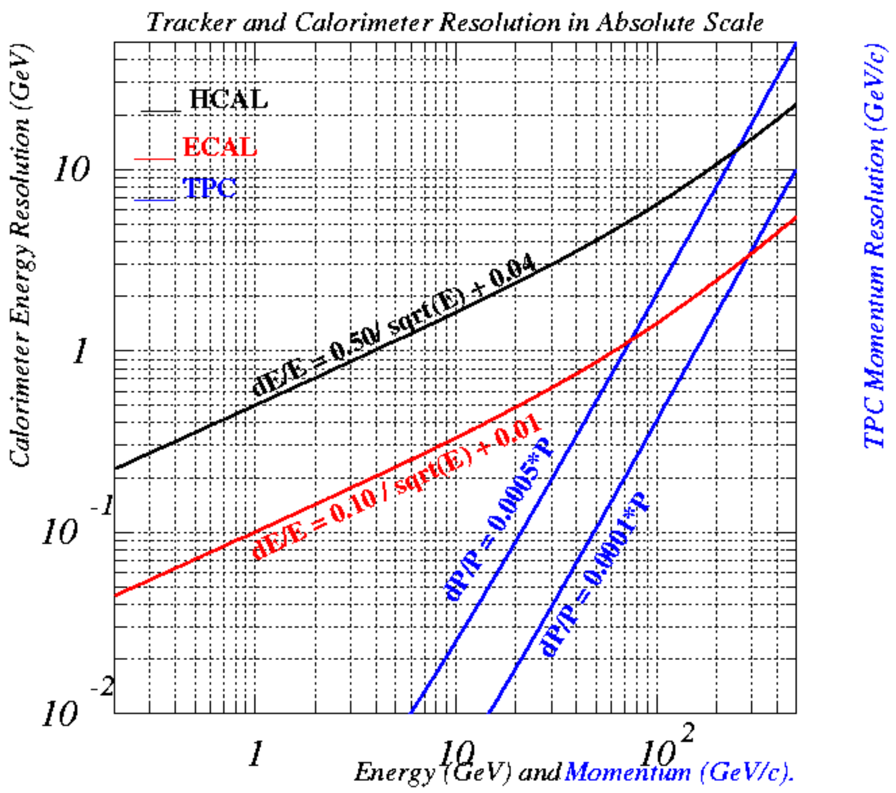
High Granular Calorimetry IFIC: 2021-2022

- Test Beam Campaign 2021-2022
- Publications & conferences
  - CALICE publications
  - ICHEP 2022 → *CALICE Imaging Calorimeters: A Review and New Results* (Parallel talk)
  - CALOR 2022 → *Performance at testbeam andsimulation of the CALICE SiW ECAL prototype* (Plenary)
  - ILCX2021 → *ILD: status, concrete R&D and long-term wishes* (Plenary talk)
  - EPS-HEP 2021 → *Implementation of large imaging calorimeters* (Parallel talk)
  - HEP 2021 (IAS Program on High Energy Physics) → *Status of PFA Calorimeter R and D.* (Parallel talk)
- The publication of the ECFA Detector R&D Roadmap is followed by the creation of Detector R&D (DRD) Collaborations, notably of the DRD Calorimetry
  - Implementation of TF6 (Calorimetry) https://indico.cern.ch/event/1212696/
  - A. Irles: *Sandwich calorimeters with fully embedded electronics - Electromagnetic Section*

Tentative roadmap

- **2023-2024 Beam tests** of updated **power pulsed** systems
  - Large scale multilayer calorimeters
- **2023-2025 Simulation studies** for hardware specifications for **high-rate Higgs Factories and timing**
- **2025-2027**
  - Other applications – i.e. **LUXE**
  - **Prototypes and combined beam tests** implementing high-rate Higgs Factories specifications?

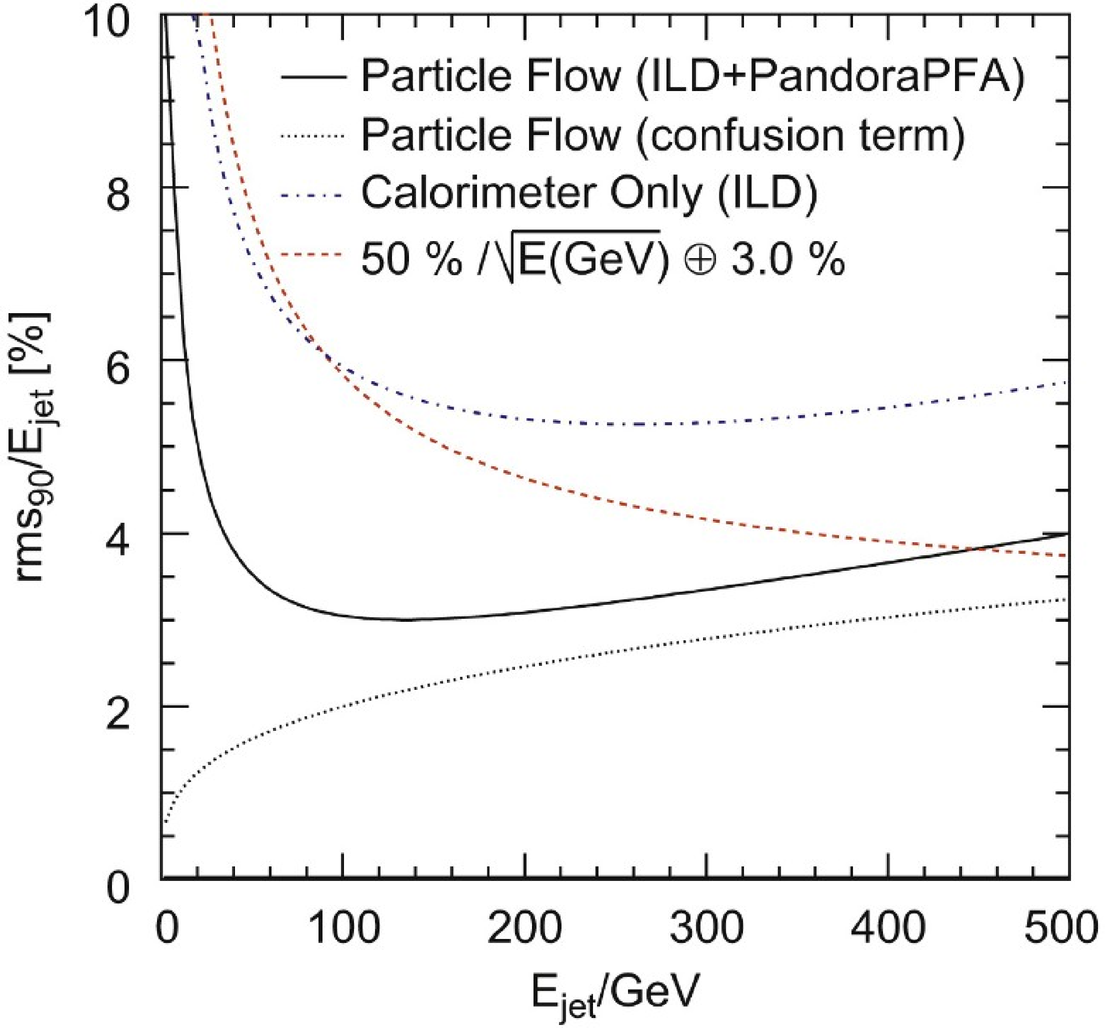
Jet energy resolution: how to improve it?



In a "typical jet" the energy is carried by

- **Charged particles ($e^{\pm}$, $h^{\pm}$, $\mu^{\pm}$): 65%**
  - Most precise measurement by **Tracker**
- **Photons: 25%**
  - Measurement by Electromagnetic Calorimeter **(ECAL)**
- **Neutral Hadrons: 10%**
  - Measurement by Hadronic Calorimeter **HCAL** and ECAL

Jet Energy Resolution



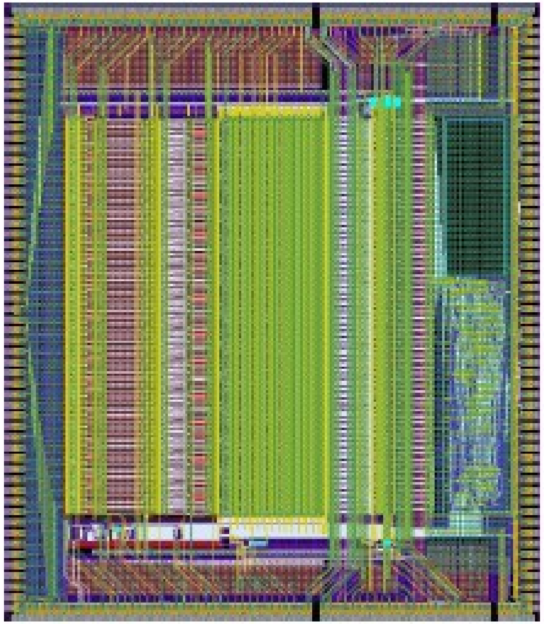
The path to Large Scale prototypes

- **Ongoing R&D** phase with the goal of **the construction of multilayer scale ECAL (and HCAL) PF prototypes**
  - With **high granularity** (up to 5x5mm^2)
  - **Extreme compactness** to ensure the smallest moliere radius
  - Fully implementing **power pulsing**!
  - To be tested in **beam facilities** in order to ensure a proper integration/interplay of the two sections (ECAL+HCAL) which is **crucial for PFA**
- **Adaptation** of the concepts to **different projects**
  - Lineal-vs-circular → low or high rates → Power pulsing or not, self trigger or not
  - e+e- vs hadron → no strict radiation hardness requirement vs the opposite
  - First phase of simulation studies required.
- Application of **new ideas**

Very Front End electronics

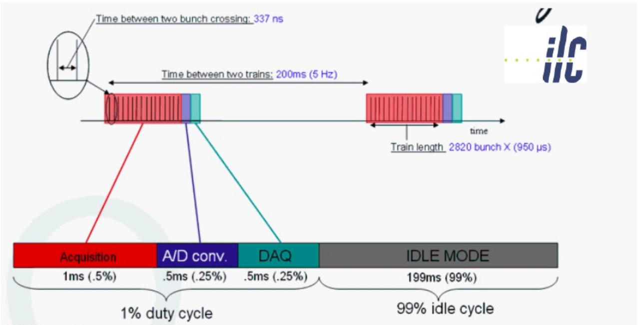
▶ **SKIROC and SPIROC** (SiW-ECAL and SC-ECAL)

- **Large dynamic range and low noise**
- **Dual readout: high and low gain plus TDC**
- **Auto-trigger at ~0.5 MIP**
- Low Power: (25µW/ch) **power pulsing:** switch off electronics bias currents during bunch trains



▶ **Common efforts in CALICE**

- Designs by Omega of ASICs for AHCAL, SDHCAL, ECAL with same readout scheme and basic features
- Also other independent developments (KlauS – for AHCAL)

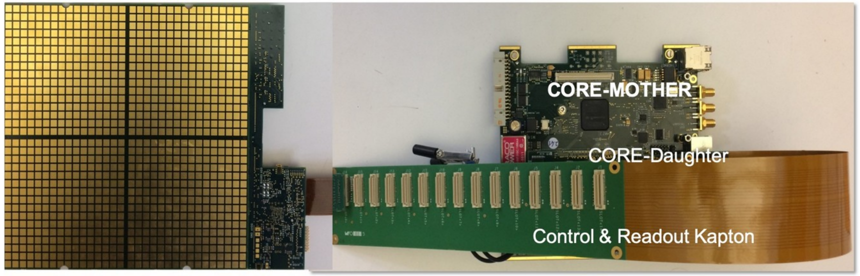


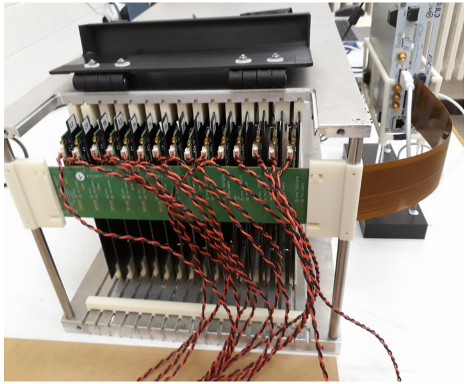
N.B. Final numbers may vary

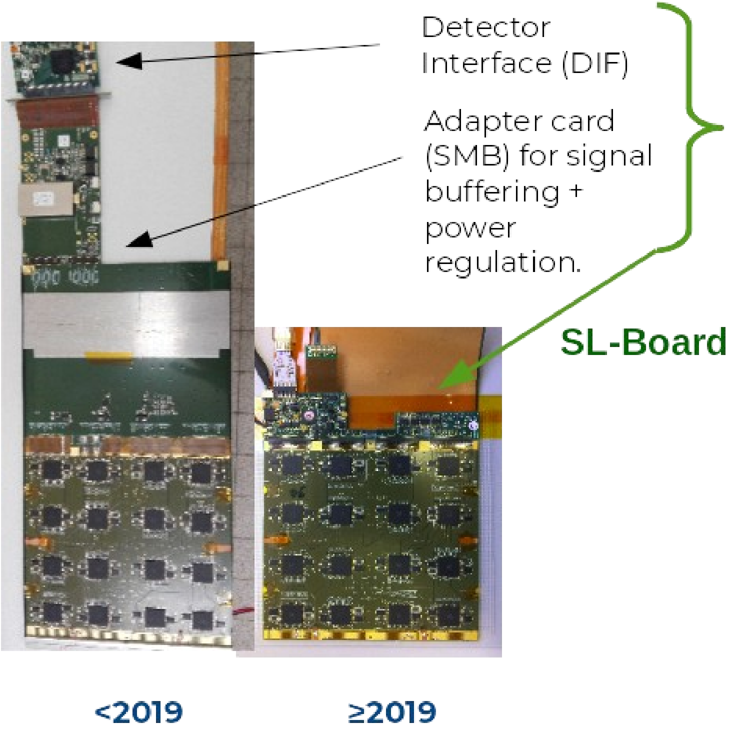
Microelectronics

Ultra Compact Readout & Open challenges

- ▶ Ultra compact DAQ developed to match testbeam requirements (100% occupancy) and ILD conditions (including compactness requirements)
  - Will be used for LUXE
- ▶ Dedicated developments and R&D would be needed for different projects
  - Higher rates (Z-pole), higher radiation (hadron machines)







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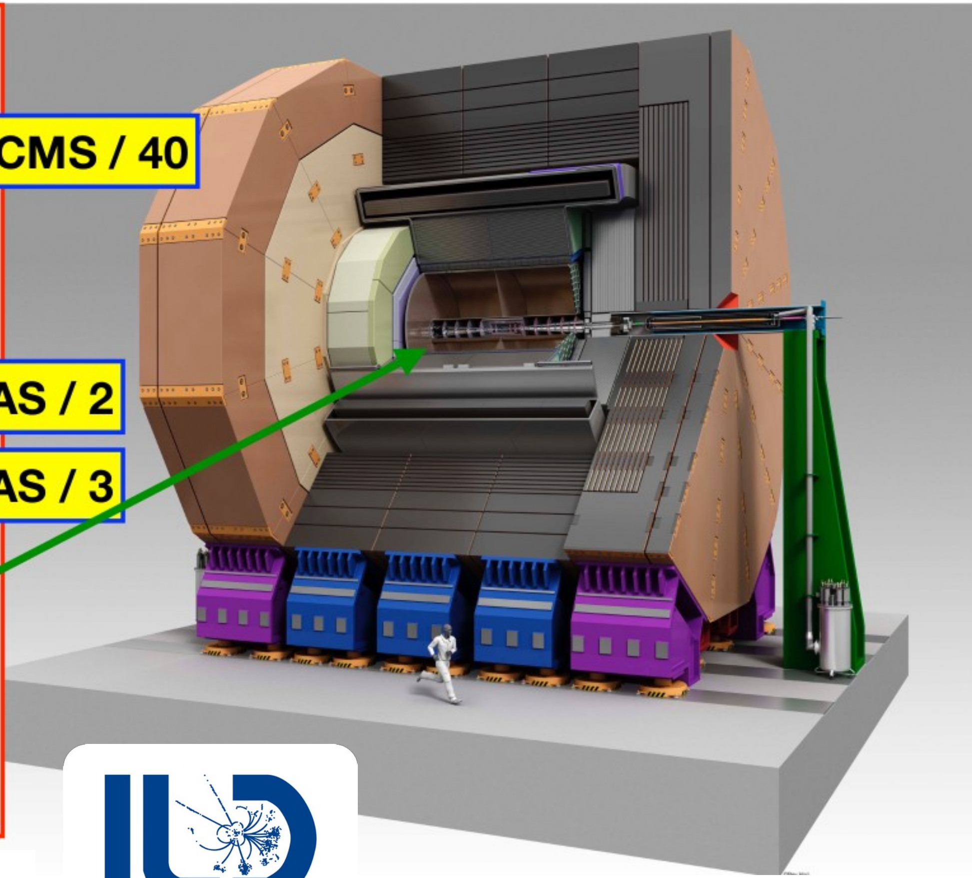
International Large Detector (a PFA detector)

From key requirements from **physics**:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \text{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** (H → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** (H → invisible) 3-4%
- **hermeticity** (H → invis, BSM) θ_{min} = 5 mrad

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



ILD

ilc

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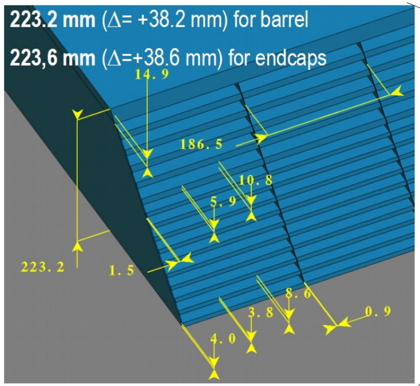
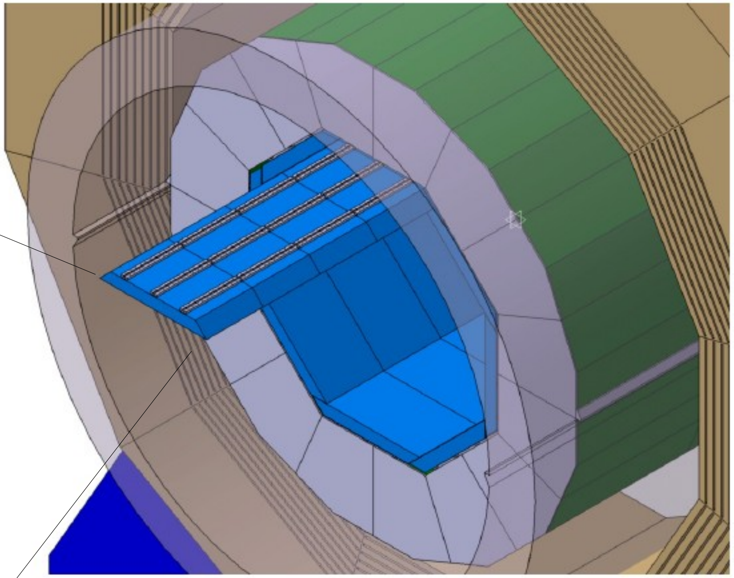
SiW-ECAL for future LC

- **Tungsten** as absorber material
  - **Narrow showers**
  - Assures **compact** design
  - Low radiation levels forseen at LC
  - X_0=3.5 mm, R_M=9mm, l_L=96mm

- **Silicon** as active material
  - Support **compact** designs
  - Allows **pixelisation**
  - **Robust technology**
  - **Excellent signal/noise** ratio





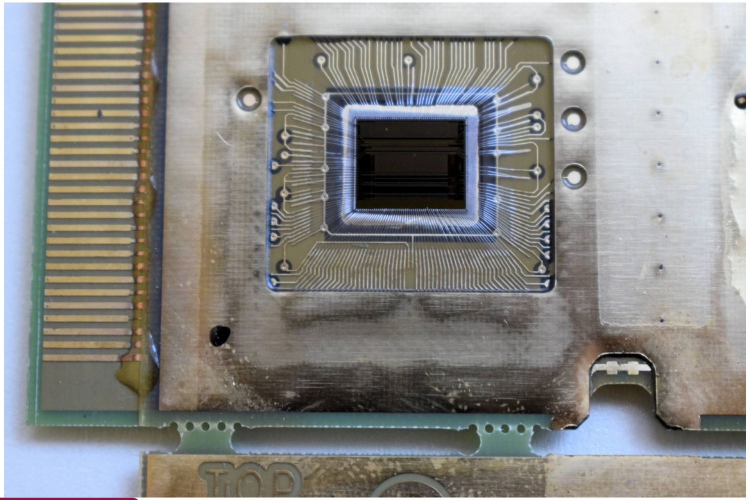
The SiW ECAL in the ILD Detector

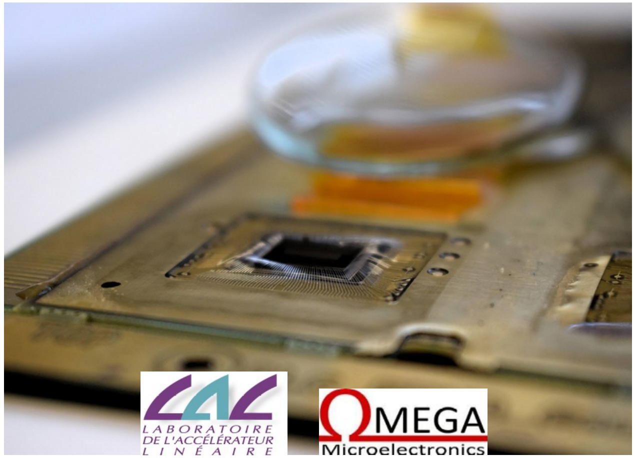
The **SiW ECAL R&D** is tailored to meet the specifications for the **ILD** ECAL **baseline** proposal

IFIC INSTITUT DE FÍSICA CORPUSCULAR

Ultra thin PCBs

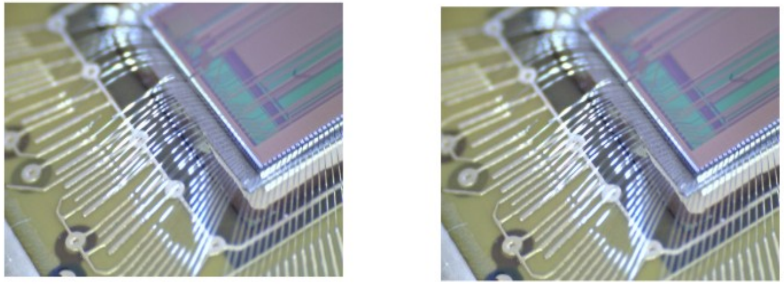
- **PCB with naked die placed in carved cavities and wirebonded to the board**
- Very thin board ~1.2mm (ILD requires 1.8mm for board and comp.)
  - 10 layers (+ gnd cupper layer)
  - To be compared with 2.8-3mm of the FEV10-13
  - but they include BGA SKIROCs and extra components as decoupling capacitances...!!





LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
ΩMEGA Microelectronics
SUNGKYUNKWAN UNIVERSITY(SKKU) EOS CORPORATION

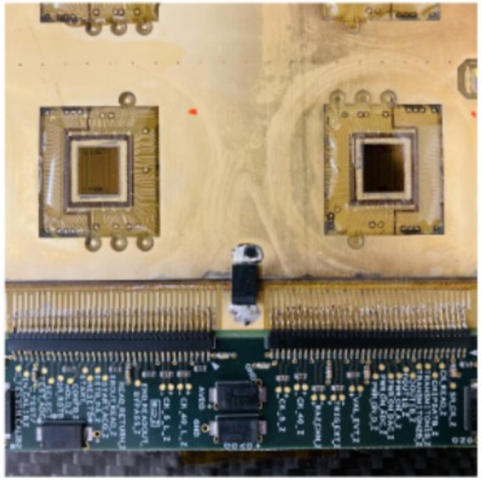
Zoom into ASIC cavities

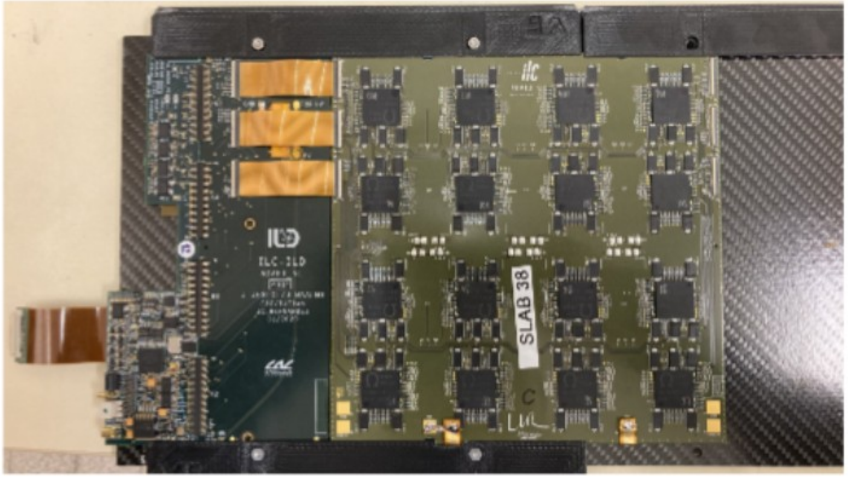


Before application of epoxy

After application of epoxy

Ultra thin PCBs

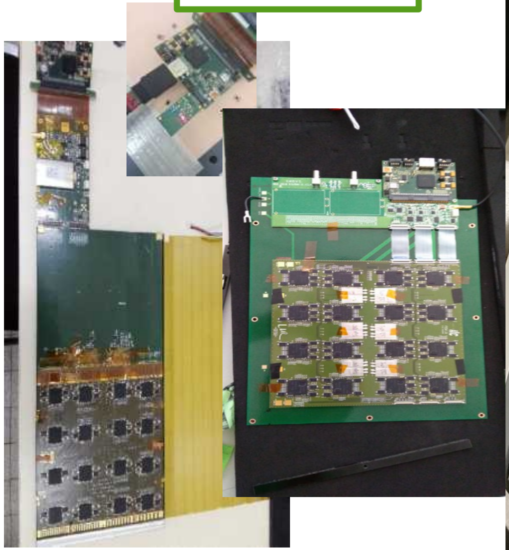


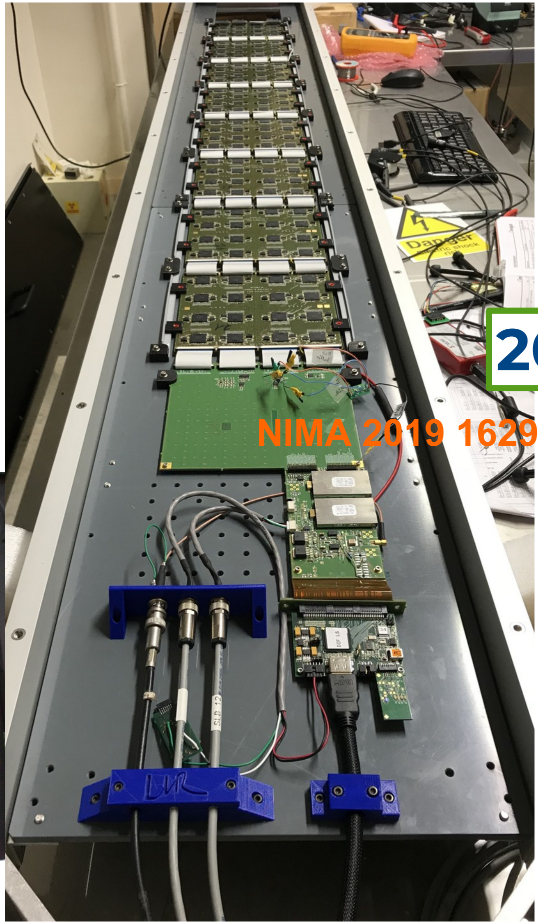


Technological prototype: time travel

2010-2015

2010-18





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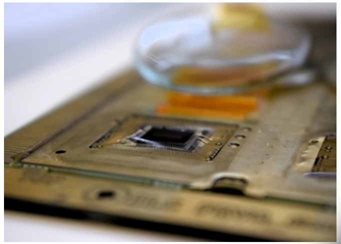
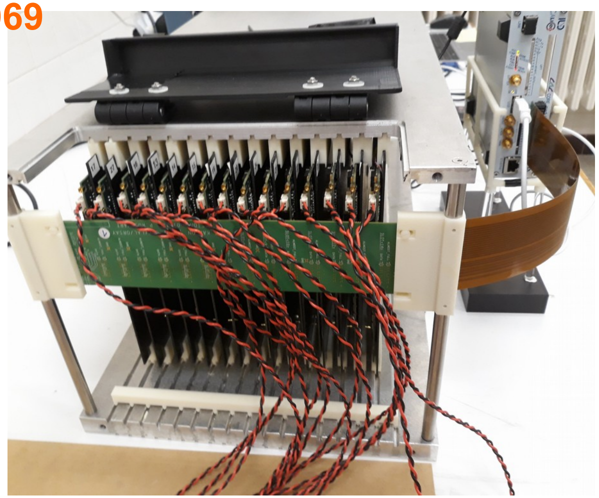
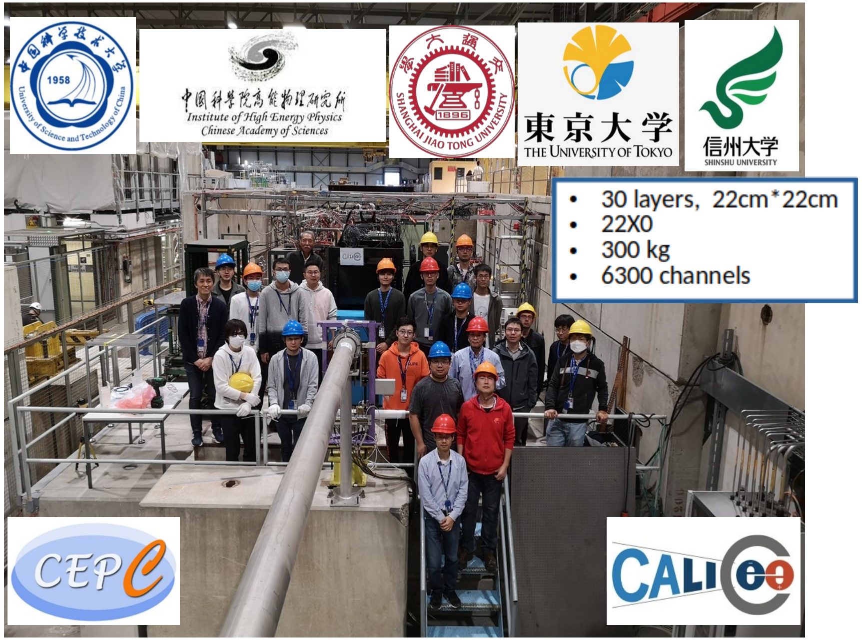




Large scale prototypes and common beam tests

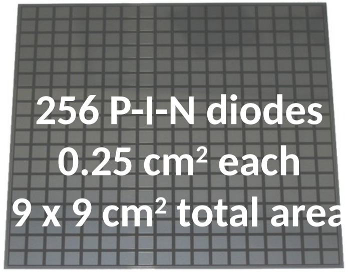


- ▶ Common ECAL+AHCAL beam tests with **high energy beams** are mandatory
  - At Europe, only at CERN. Available during LS3 ?
- ▶ **Test of the technology & study of the PFA performance** and deep understanding of shower developments
- ▶ Requires also **common developments** on **software**: common DAQ, simulations, Geant4 , event model, high level reconstruction tools
  - Not covered in this talk

Readout Modules

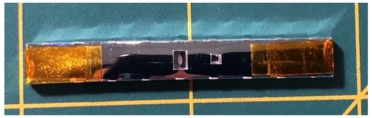
The core of the prototypes are the readout modules entities, consisting of:

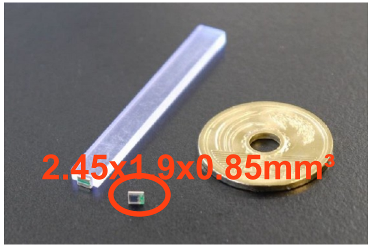
- ▶ **VFE** (ASICS, common developments within CALICE)
- ▶ **PCBs**
  - Very dense PCBs with up to 1024 channels + extra components for power pulsing and noise filtering in 18x18cm^2
- ▶ **Active material**
  - **Large surface silicon sensors** (9x9cm² directly **glued** to the back of the PCB) → **SiW-ECAL (CALICE)**
  - Large surface silicon sensors (8” wafers wire-bonded through PCB holes) → **CMS-HGCAL**
  - **Scintillator** strips individually wrapped connected to **SiPM** → **Sc-ECAL (CALICE)**



EUDET layout

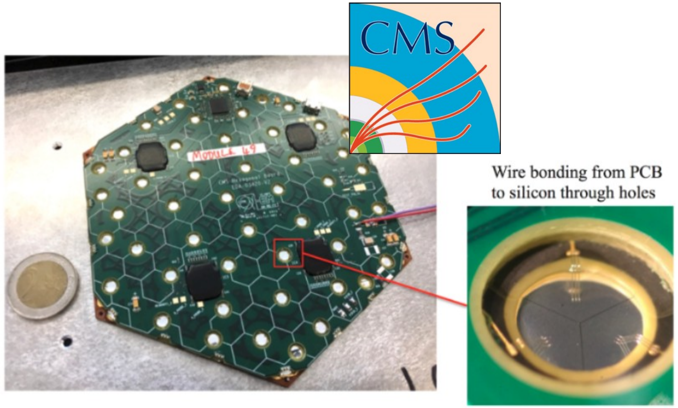
Prototype from Hamamatsu





PCBs

- Very dense **PCBs:**
  - i.e. at SiW-ECAL they are known as featuring 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm^2 board



CMS HGCAL Hexaboard

Wire bonding from PCB to silicon through holes

SiW-ECAL current prototype solution.

Meets industry requirements → bulky components **compromise compactness**

Chip-On-Board solution (R&D phase, tested recently in beam test)

The **most compact solution**… but no space for required components (i.e. for power pulsing)

Open challenges (very-front-end)

- ASICs for prototyping are already available

Near Future (~1-5years):

- Plans: how to implement high precision timing? (keeping low power budget)
  - Current TDC allows for ~ns timing measurements → to be further characterized and tested in beam test
  - New ideas associated to R&D on sensors

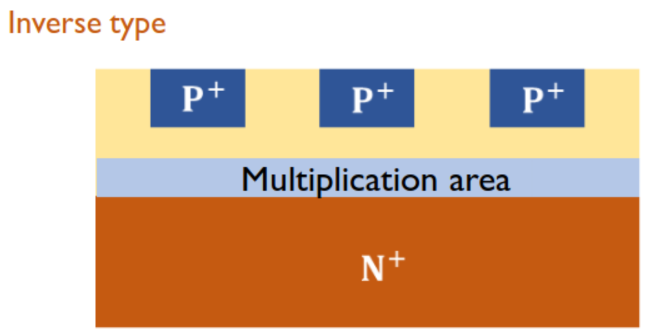
Mid/Long Term → Next Generation ASICs

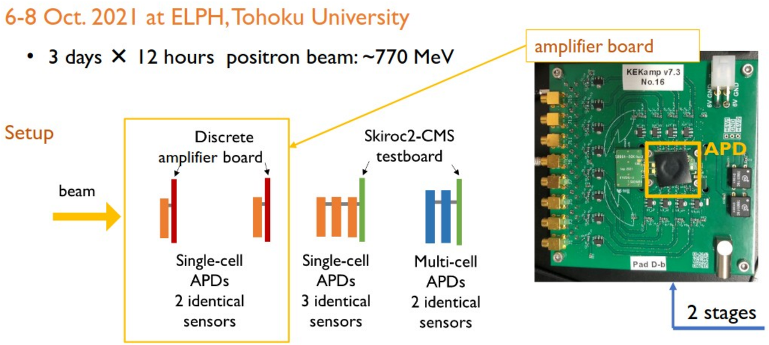
- design / performance goals are highly **experiment dependent**
  - However, **low consumption** is seek for all of them (even if active cooling systems are foreseen).
- **Adaptation to circular e+e-** machines with higher rates:
  - Interplay with forward calorimetry developments (where the rates are relatively high even at linear colliders)
  - Externally trigger? Low consumption without powerpulsing?
- For **hadron** machines, **radiation** issues become relevant again: **where can we irradiate large surface detectors?**
- High processing speed, high data compression, etc.
  - “adding software” into the front end (neural networks)

Open challenges (silicon sensors)

- **Highly integrated silicon sensors** → CMOS, ultragranular option, fully digital (see **T. Peitzmann talk**)
- How to implement **timing**?
  - **APD**, **LGADs**, (**thin** sensors with **gain**)
  - Newer options SPAD (avalanche diode with geiger-mode gain, can be monolithic)
  - Require **dedicated electronics** → **challenge** on the **power** management
- **Thicker** sensor → **larger charge S/N**
- Integration of larger surface **8" sensors**
  - Experience from **HGCAL**
- Strengthen synergies with industry.

LGAD (Low Gain Avalanche Detector)



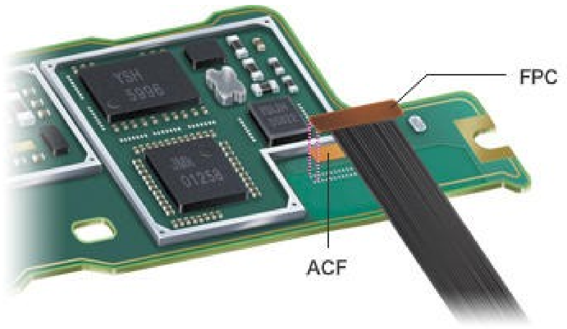


Open challenges (Silicon-PCB integration)

Near Future

▶ Current technological prototype solution for sensor-PCB connection is based on epoxy-silver glue.

- Mechanical strength, industrialization, durability… to be studied.
- Silver → may be an issue on high radiation environments



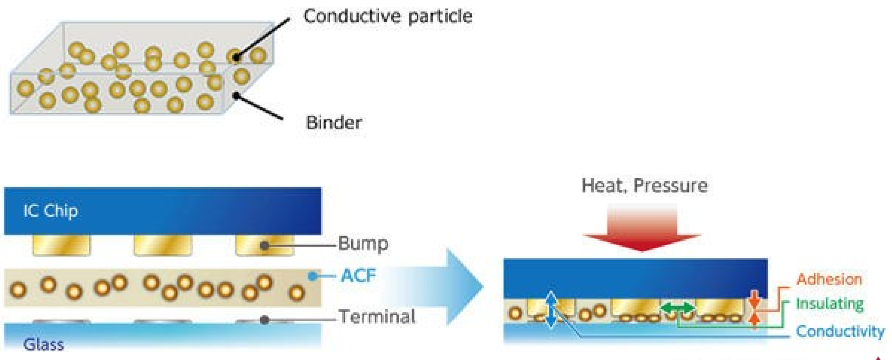
▶ R&D Alternative solutions:

- through-hole wire bonding (à la HGCAL → limits the extreme high granularity goals of PF ECALs)
- Check what the industry is doing (smartphones, LCD screens, etc)

  → Anysotropic Conductive Films, Micropearls… (investigated also in the context of LUXE)

▶ Similar issues are to be investigated about the interconnection of the (PCB+Silicon) to absorber/mechanics

- Independently of the active material (Si or Sc)



LUXE (Laser Und XFEL Experiment)

TDR to appear in 2023
Operation from 2025-2032 (+x)

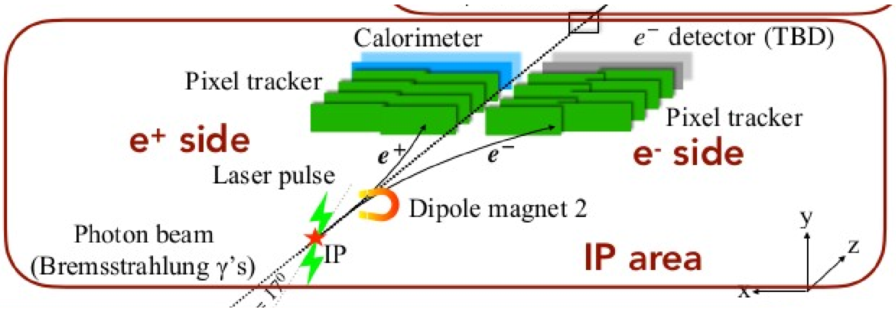
Positron and electron detection systems

Positron detection system proposal
Based on a pixel tracker + ECAL-p based on FCAL prototypes of LumiCal

But using CALICE-Hammatsu sensors

High Granular Calorimetry

Electron detection system proposal
Based on a pixel tracker + SiW-ECAL of CALICE (15 layers with modified/extended geometry)



Positron and electron detection systems

Positron detection system proposal
Based on a pixel tracker + ECAL-p based on FCAL prototypes of LumiCal

using “CALICE sensors”

High Granular Calorimetry

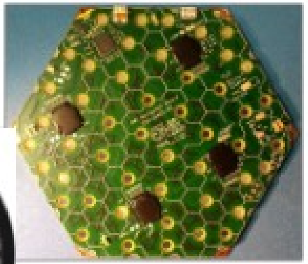
Electron detection system proposal
Based on a pixel tracker + SiW-ECAL of CALICE (15 layers with modified/extended geometry)

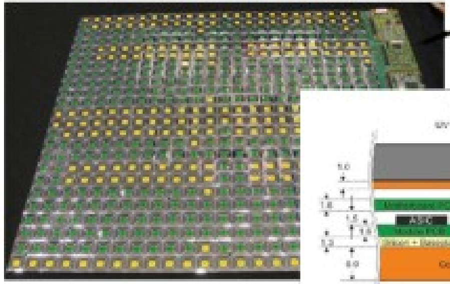
Two detectors of the **scale of CALICE prototypes** running in **real experiment conditions.**
Integration challenge: Very thigh compactness requirements

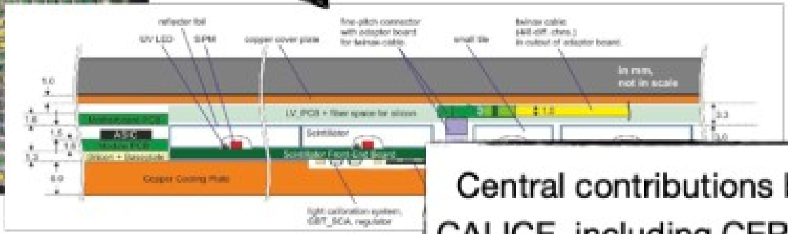
“Spinoffs” of CALICE R&D I: CMS HGCAL

- 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



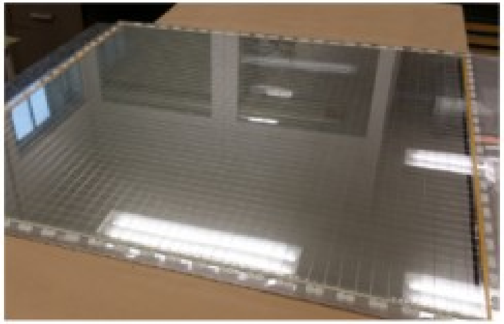


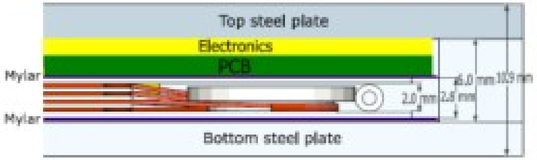


Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

The next decade: ps timing in calorimeters

Pioneered by LHC Experiments, timing detectors are/will be also under scrutiny by CALICE Groups

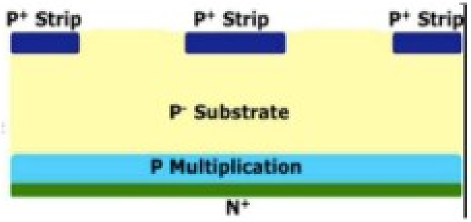




Under development:
GRPC with
PETIROC

- < 20ps time jitter
- Developed for CMS Muon upgrade

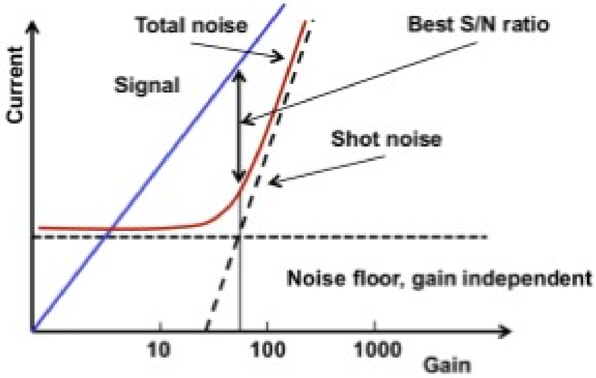
Inverse APD as LGAD?



Inverse APD
by Hamamatsu

Gain ~ 50

Theory says, need comparatively small amplification



- Shot noise may be limiting factor
- Expect interesting comparison between inverse APD and LGAD as e.g. used by ATLAS
- Not that Members of CALICE are also members of ATLAS-HGTD

Expect interesting results on timing detectors from CALICE in coming years


TOUTES DIRECTIONS
AUTRES DIRECTIONS