Sandwich calorimeters with fully embedded electronics: EM barrel calorimeters

ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

AITANA MATTER AND TECHNOLOGY

Outline

1 Particle Flow calorimetry: CALICE

2 Multi layer high granular ECAL prototypes

- SiW-ECAL
- Sc-ECAL

Open Challenges

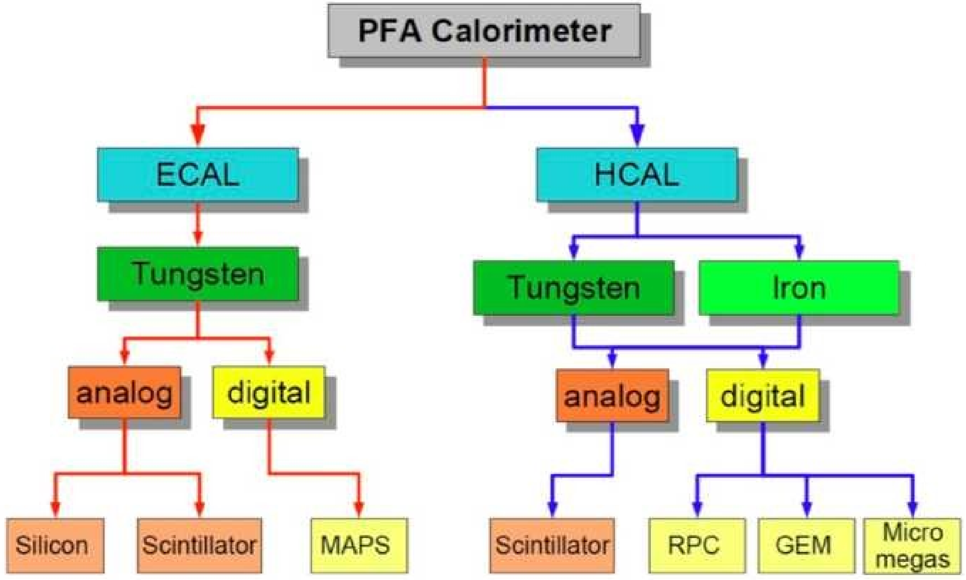
1

Particle Flow calorimetry

High granular calorimetry

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

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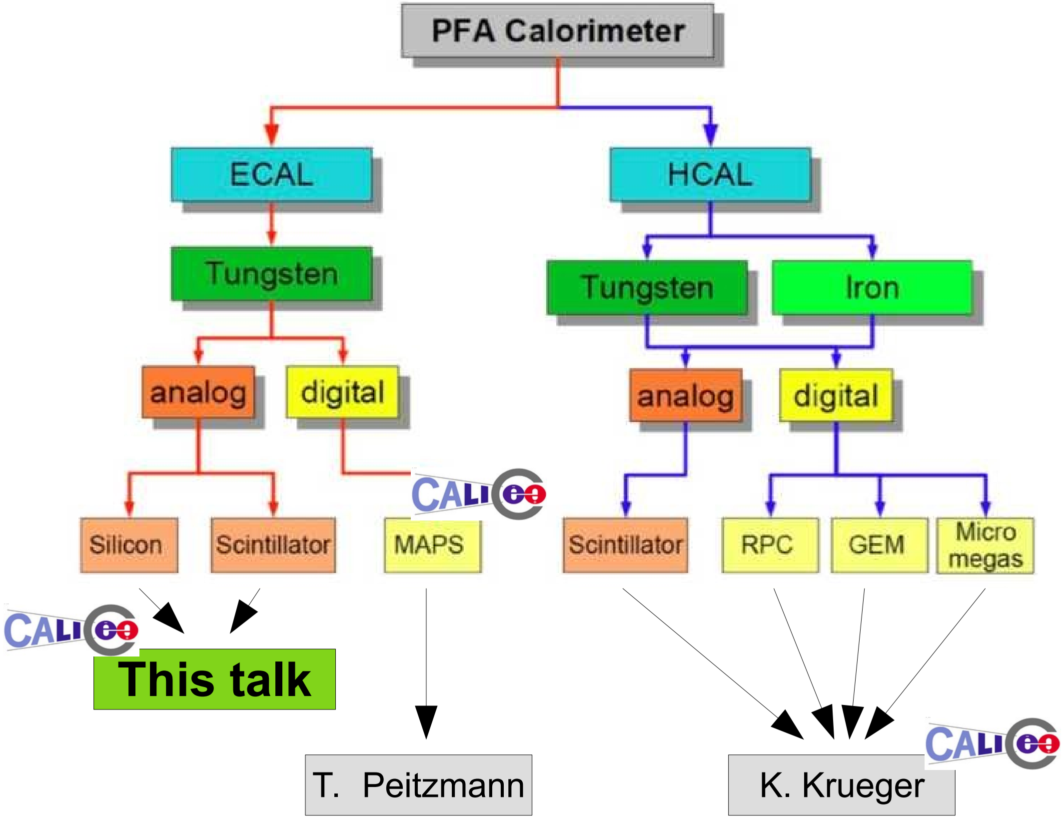

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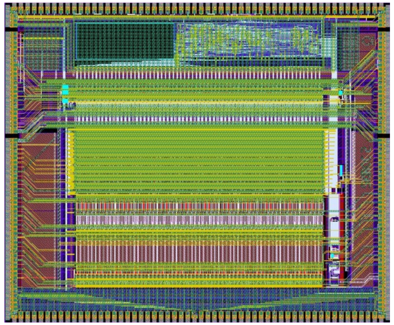
Technological premises

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)

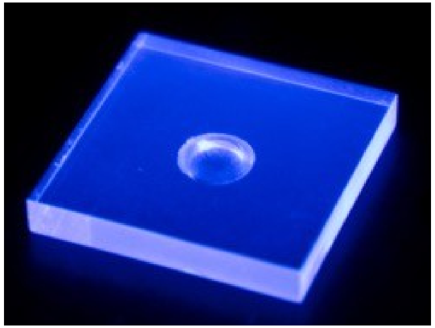


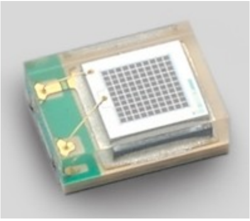
Size 7.5 mm x 8.7 mm, 64 channels

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

- **Common developments on different CALICE projects**

Miniaturisation of r/o devices





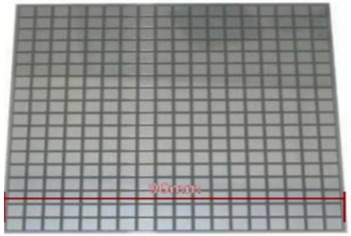
- Small scinitllating tiles
- (Low noise) SiPMs

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

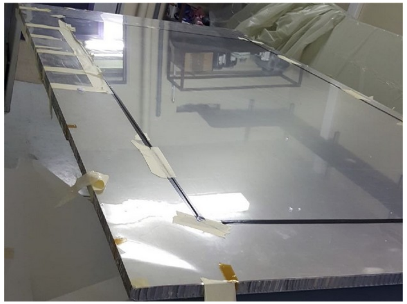
Self trigger of individual cells below MIP level

Large surface detectors

Si Wafer



RPC layers

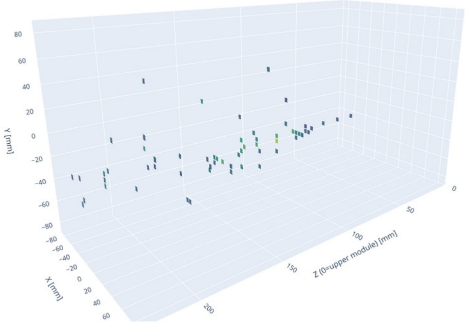


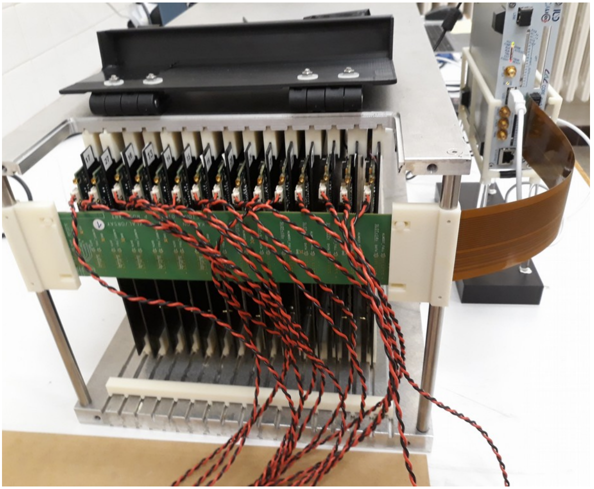
Many things that look familiar to you today were/are pioneered/driven by CALICE

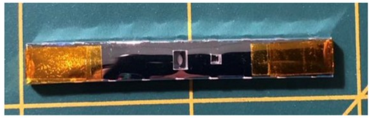
Sc-ECAL and SiW-ECAL CALICE prototypes

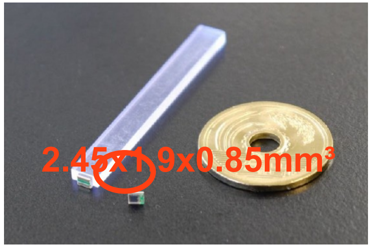
SiW-ECAL

- **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**







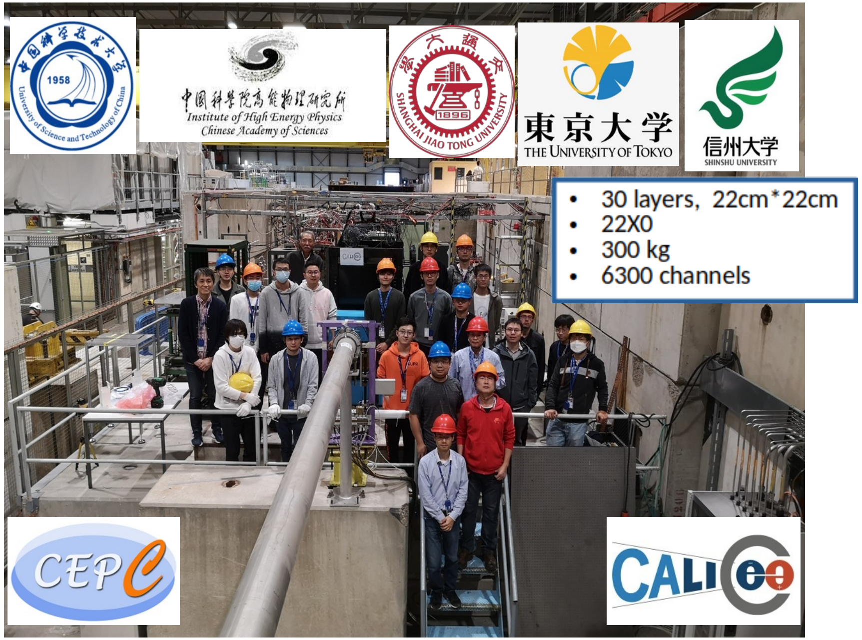


- 30 layers, 22cm*22cm
- 22X0
- 300 kg
- 6300 channels

The sensitive layer is composed of **210 plastic scintillator strips**. The strip size is
5 mm x 45 mm x 2 mm³.
Each scintillator is coupled with a SiPM at the bottom

Effective granularity of 5x5mm²
(but with x10 less channels) → relevant for power consumption control

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

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Constructing large scale PF ECAL calorimeters: **R&D challenges ahead us**

*Disclaimer: for lack of time and personal bias I will emphasize the SiW-ECAL wherever the SiW-ECAL and Sc-ECAL share commonalities

What for?

- **HL-LHC Upgrade** of existing detectors
  - ALICE FoCAL pixel calorimeter
  - HGCAL with high granular Si and SC calorimeter systems
- **Other applications** in the short term (i.e. 2025-2026)
  - For example: **LUXE** (featuring two silicon-tungsten highly granular and compact ECALs (CALICE and FCAL adaptations). XFEL pulsed electron beam (as ILC)
- Mid-term: **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)
- **Longer term**
  - **Muon** colliders and/or **Hadron-hadron** machines (high rates and high **radiation** environments)

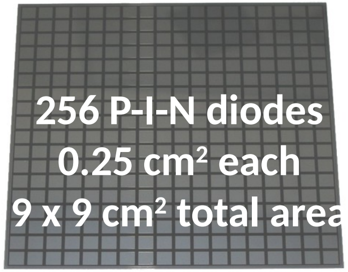
The path to Large Scale prototypes

- **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**

Readout Modules

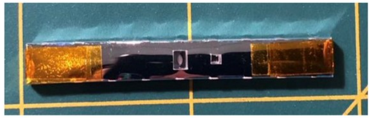
The core of the prototypes are the readout modules entities, consisting of:

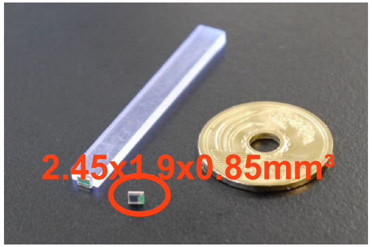
- **VFE** (ASICS, common developments within CALICE)
- **PCBs**
  - Very dense PCBs with up to 1024 channels + extra components for power pulsing and noise filtering in 18x18cm^2
- **Active material**
  - **Large surface silicon sensors** (9x9cm² directly **glued** to the back of the PCB) → **SiW-ECAL (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





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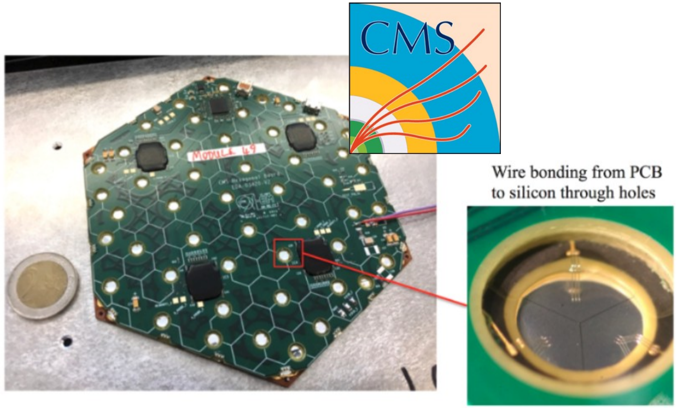
PCBs

▶ 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)

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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

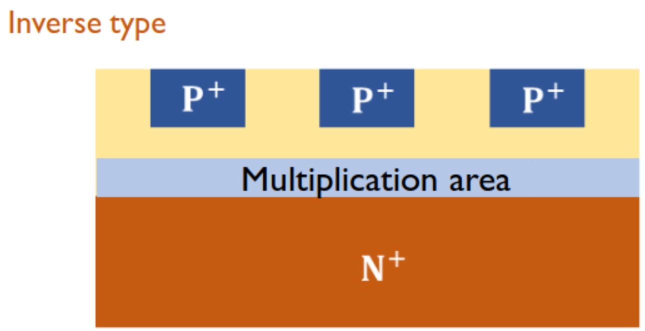
Mid/Long Term → Next Generation ASICs

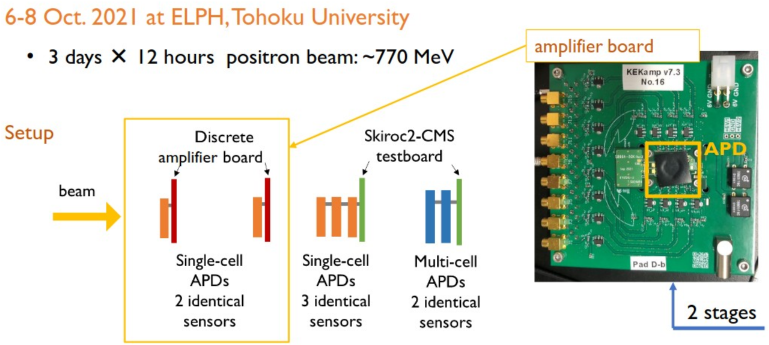
- design / performance goals are highly **experiment dependent**
  - However, **low consumption** is seek for all of them (even if active cooling systems are foreseen).
- **Adaptation to circular e+e-** machines with higher rates:
  - Interplay with forward calorimetry developments (where the rates are 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)



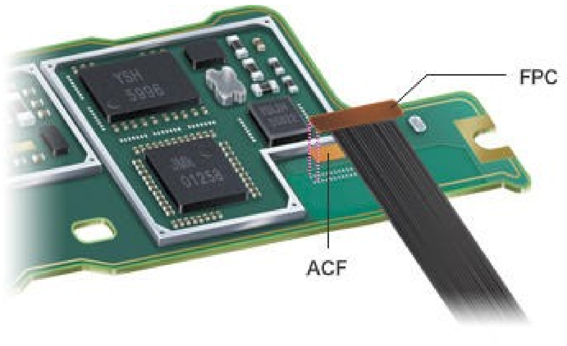


Open challenges (Silicon-PCB integration)

Near Future (~5 years)

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

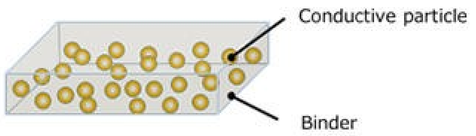
- Mechanical strength, industrialization, durability… to be studied.
- Silver → may be an issue on high radiation environments



▶ R&D Alternative solutions:

- through-hole wire bonding (à la HGCAL → could limit 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

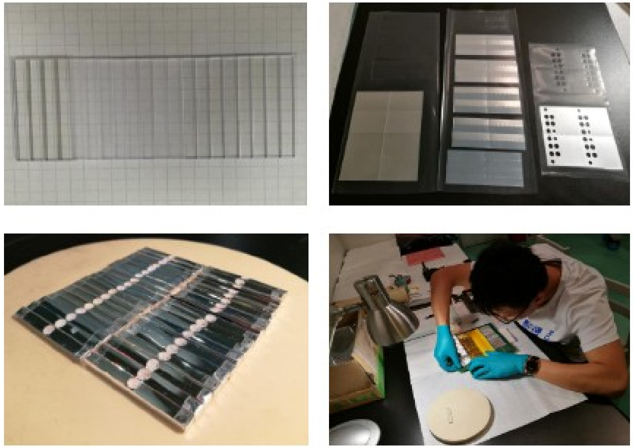
- Independently of the active material (Si or Sc)

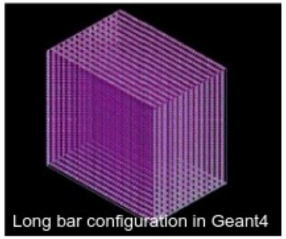
Open challenges (Scintillators/SiPMs)

Ongoing and Near Future (~5 years)

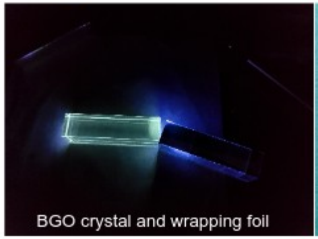
- Engineering work for **large scale production**
  - Injection moulding, automated assembly, system for QC/QA
- **Improvement of timing** performance with **dedicated timing layers** ~10ps
  - Scintillator tile + larger SiPM with high light yield → better time resolution
  - Cherenkov detector based on RPC-GasPM (New R&D)
- **R&D on new materials:**
  - High Granular Crystal Calorimetry

Strip wrapping and assembly on EBU was done by hand (Shanghai Institute of Ceramic)

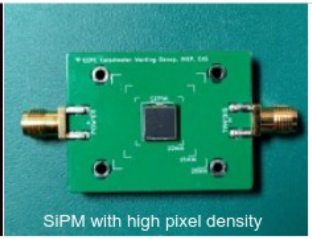




Long bar configuration in Geant4



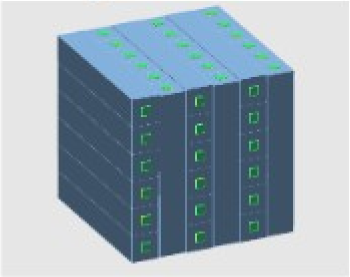
BGO crystal and wrapping foil

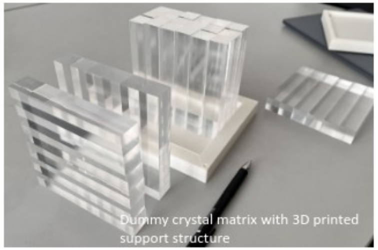


SiPM with high pixel density

SiPM readout electronics

Single EM module





Dummy crystal matrix with 3D printed support structure

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Open challenges (PCBs)

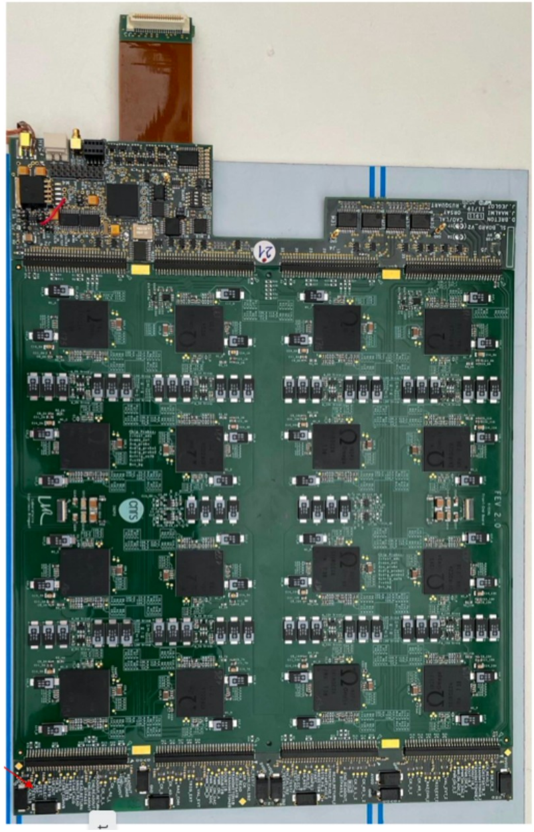
R&D happens in close communication with concept groups

Near Future (~1-3years)

- **R&D iterations** for PCB design optimization for **testbeam** and other applications
- **Compactness** requirements:
  - Going **thinner** → challenge for very complex PCBs
  - **Thinner passive components** → needed for all, but key for power pulsing operation
- R&D on high **reliability** connectors/components → its importance is sometimes underestimated

Mid/Long Term Future

- **Adaptation** to different experiments (higher rates, higher radiation damage)
- **Industrialization**, mass production.
- Obtain **Quality Assurance** competences → in synergy with industry and other DRD
- For **hadron machines**, radiation issues become relevant again: where can we **irradiate large surface** detectors?



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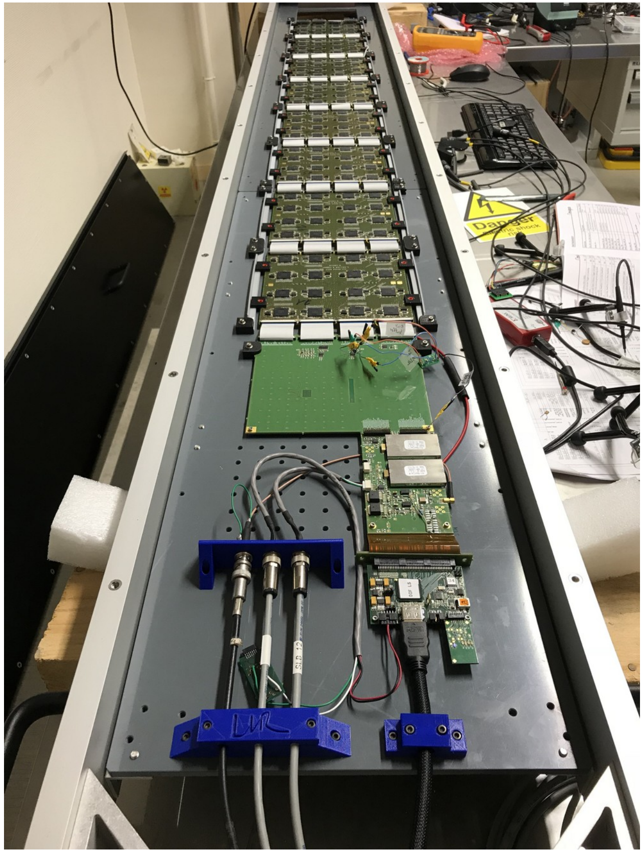
Full length modules & Open challenges



- Already an **existing prototype** (2m) for SiW-ECAL
  - Non compact mechanics
  - Not optimized for power pulsing
  - New prototype to be built with the new design of **PCB optimized for power pulsing** (with local storage of power)
- **Power pulsing is a particular challenge for long layers**
  - Build long layers as exercise to solve other issues for this type of detectors (connectors, signal processing)
- What about for **high rate circular colliders**?
  - These machines **require**, in the next 2-3 years, dedicated **simulation studies** before **hardware requirements** can really be formulated (CEPC may accelerate this process)

Mechanics / Cooling & Open challenges

▶ **Compactness** requirements on ECAL for PFA are very strict

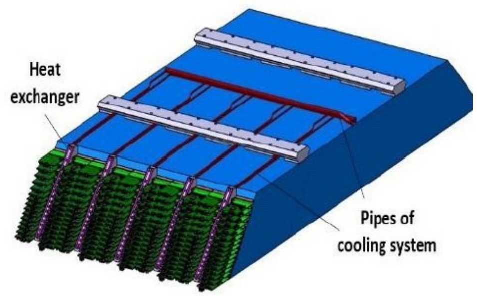
- Very little space for services / DAQ
- Cooling system developed for ILD → SiW-ECAL readout electronics designed accordingly

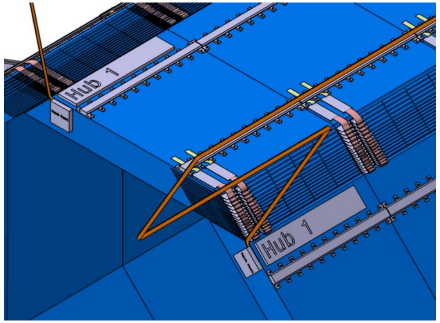
Near Future (1-5years)

▶ **Study** the impact of **“extra” cooling to cope** with **high rates** from other experiments (or with very demanding timing requirements).

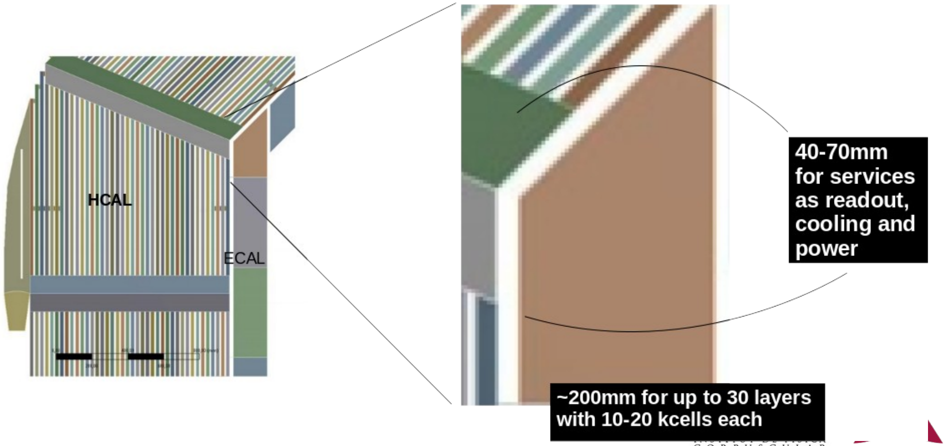
- **Simulation** and **integration studies**
- still, the goal should be to perform R&D on low consumption electronics

Zoom into ILD Ecal barrel





- Total average power consumption 20 kW for a calorimeter
- system with 10^8 cells*
  - Only possible through PP



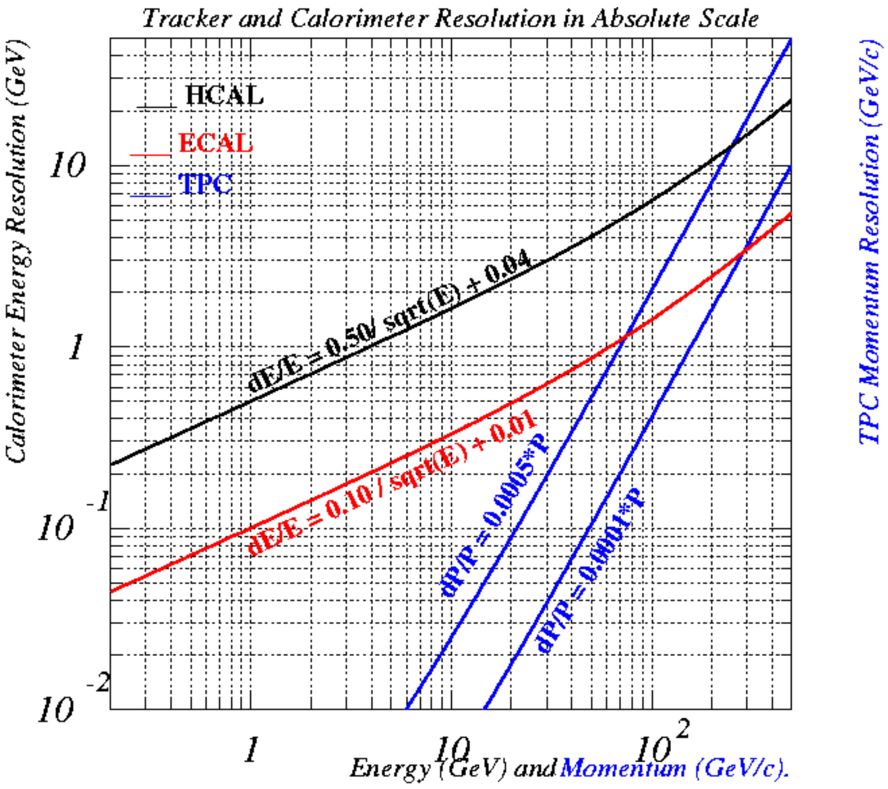
Tentative roadmap

- **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?

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

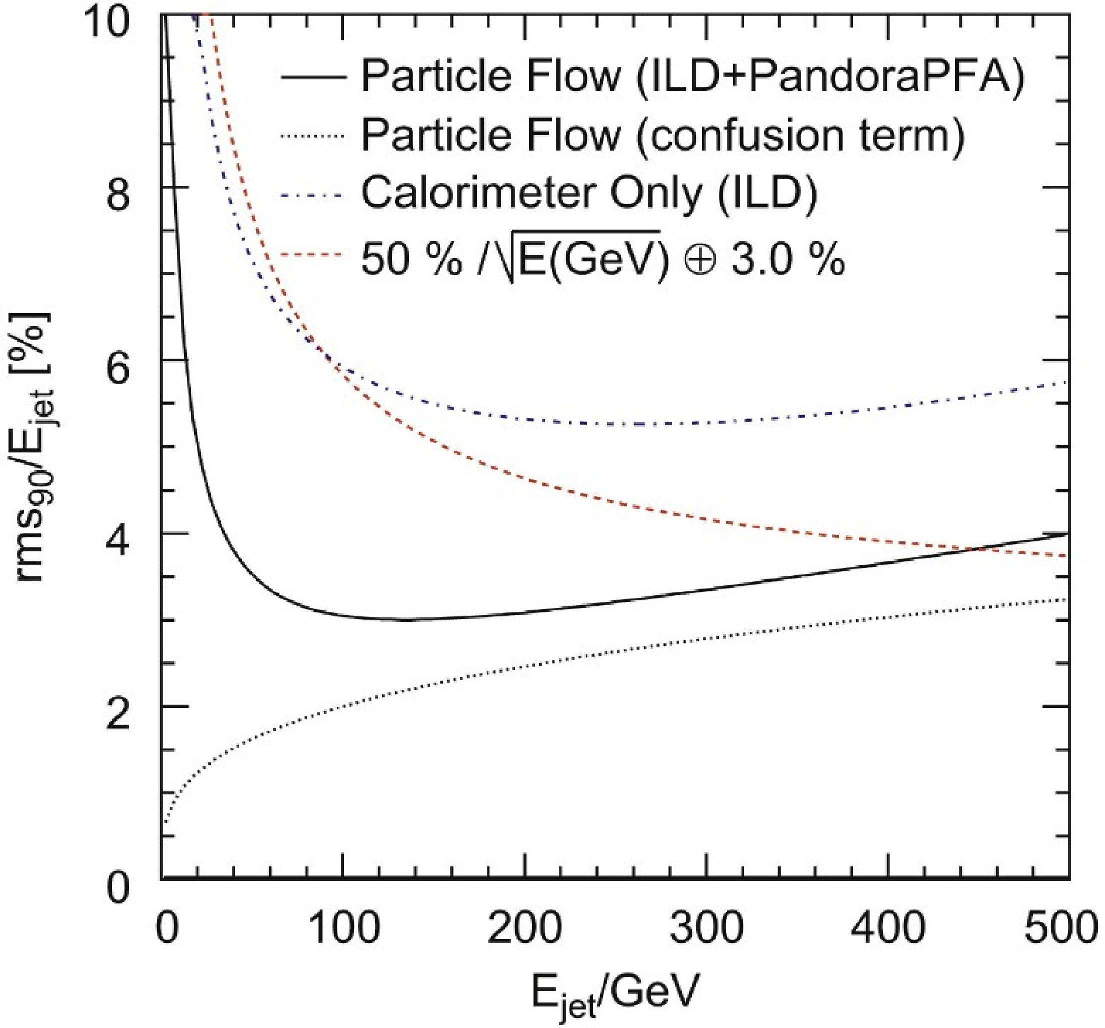
Jet energy resolution: how to improve it?



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



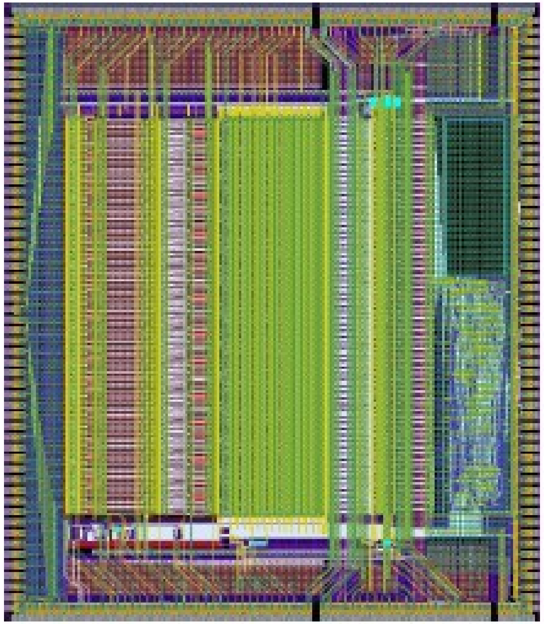
Very Front End electronics

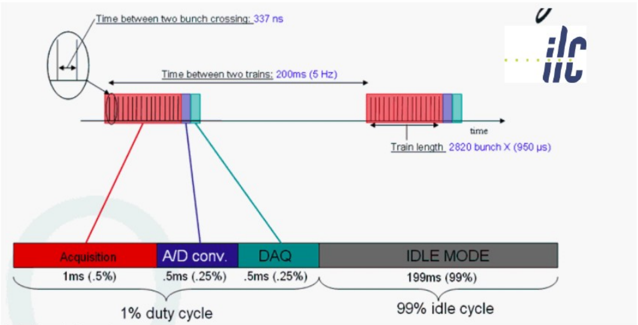
▶ **SKIROC and SPIROC** (SiW-ECAL and SC-ECAL)

- **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

ΩMEGA Microelectronics

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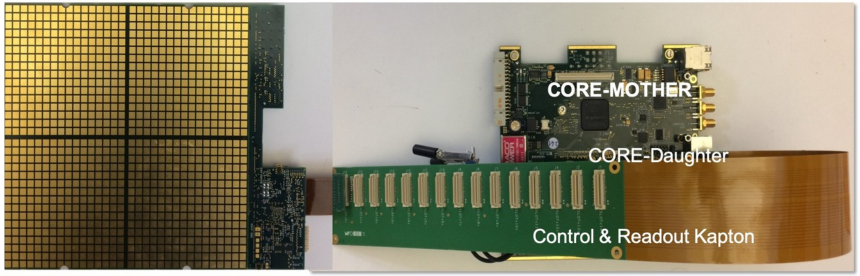
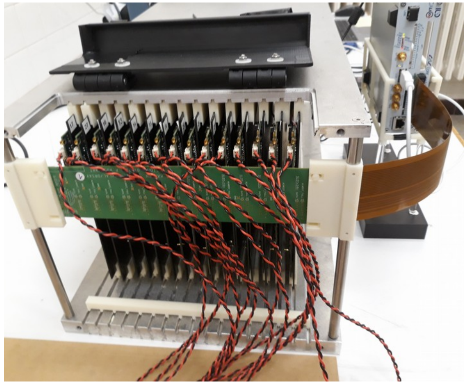
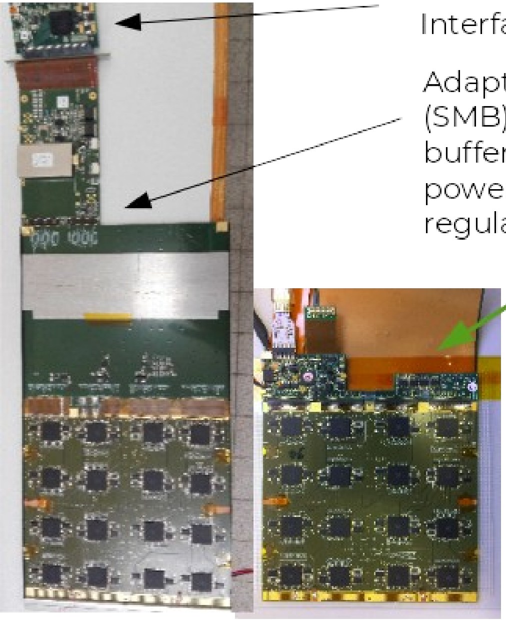
Ultra Compact Readout & Open challenges

- ▶ 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)







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** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad

To key features of the **detector**:

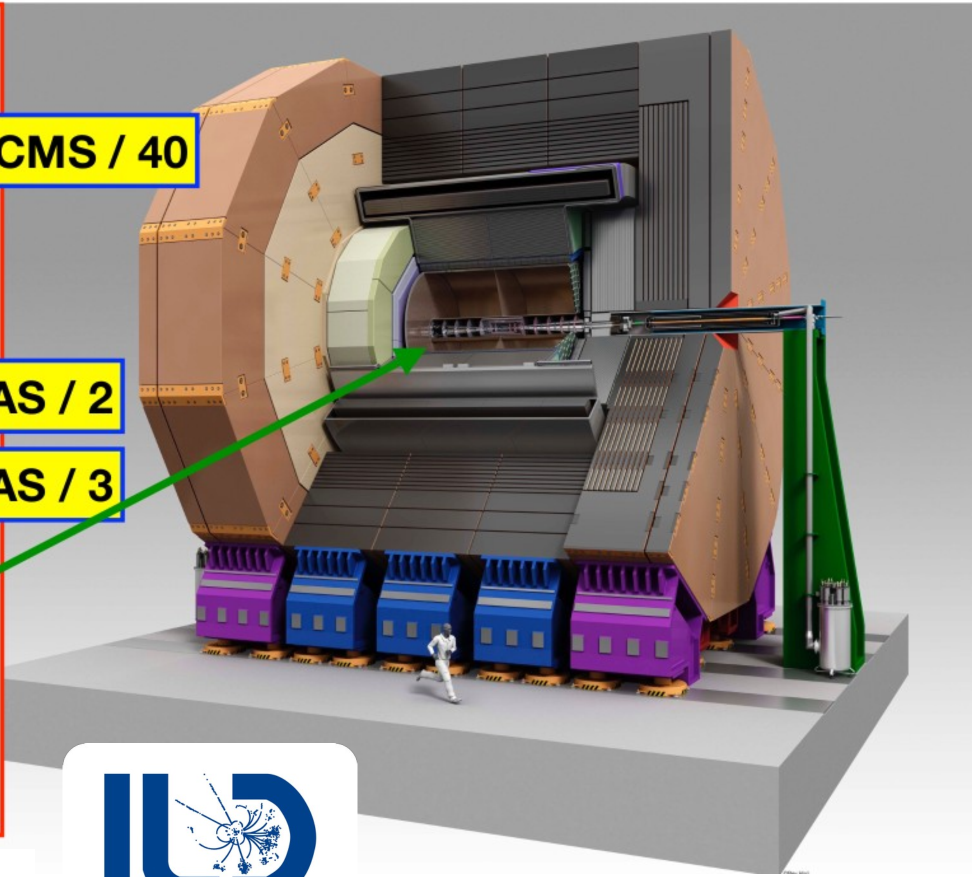
- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow

≈ CMS / 40

≈ CMS / 4

≈ ATLAS / 2

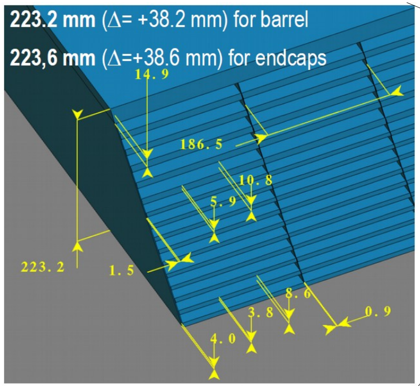
≈ ATLAS / 3

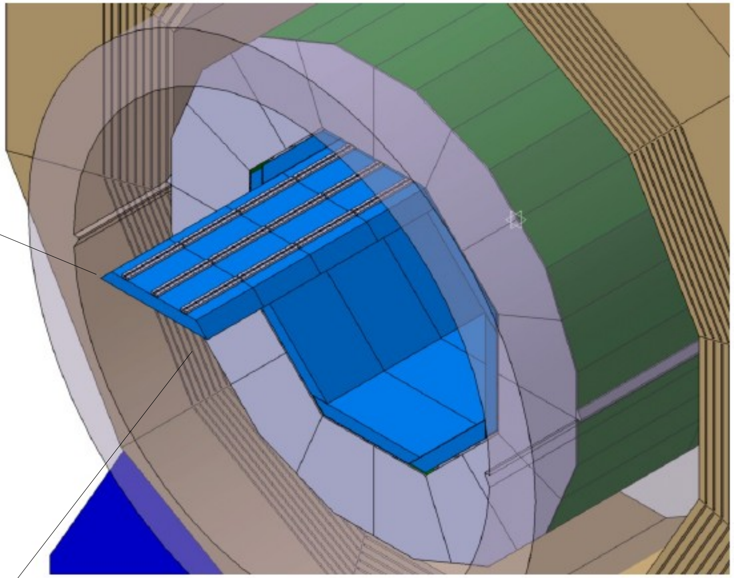


SiW-ECAL for future LC

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

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



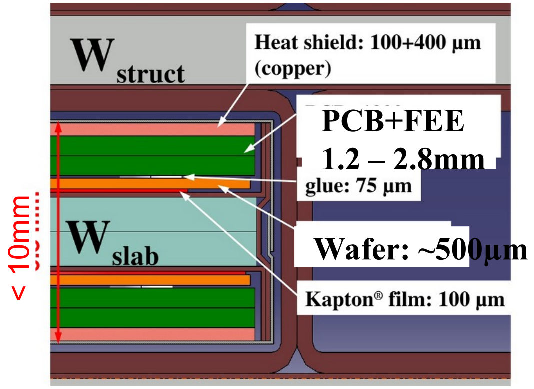


The SiW ECAL in the ILD Detector

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

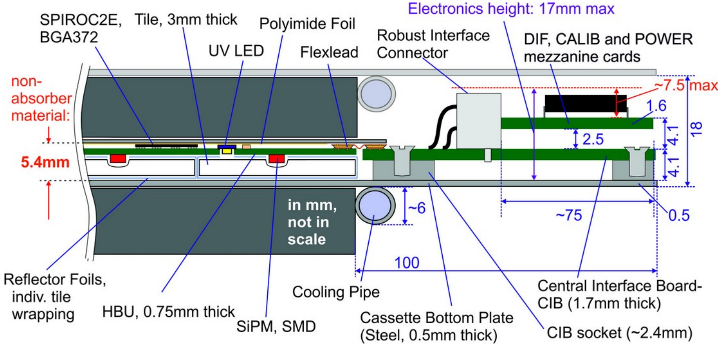
Technological solutions for final detector I

SiW Ecal



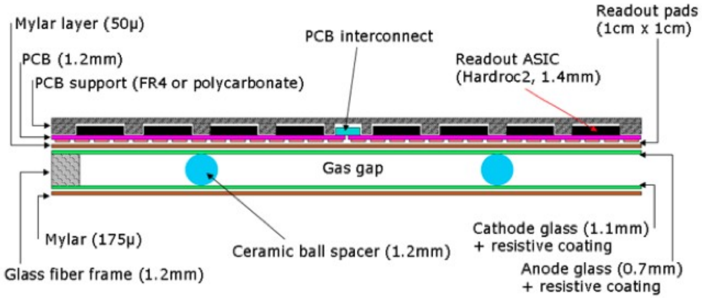
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

No drawback for precision measurements *NIM A 654 (2011) 97*

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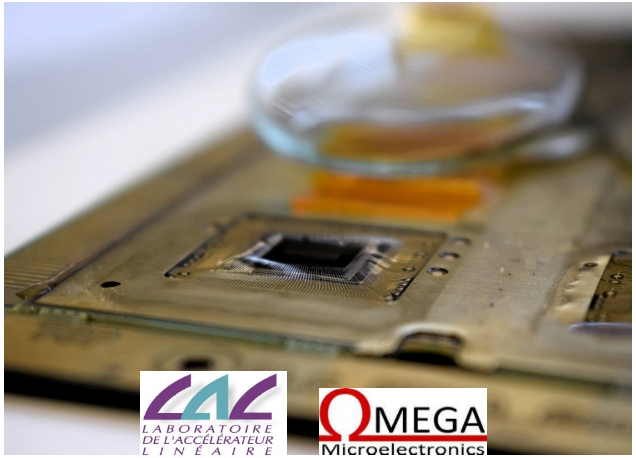
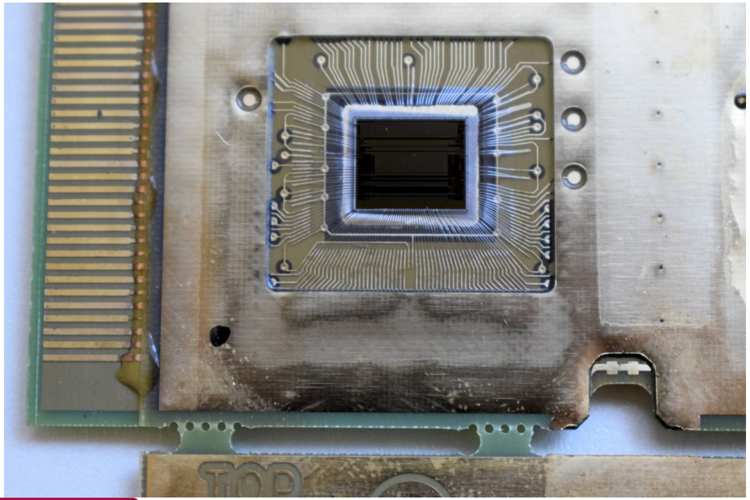
Ultra thin PCBs

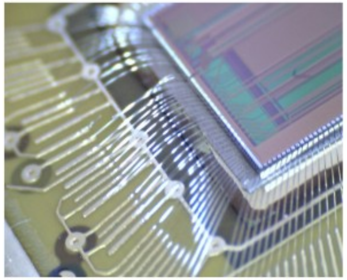
- **PCB with naked die placed in carved cavities and wirebonded to the board**
- Very thin board ~1.2mm (ILD requires 1.8mm for board and comp.)
  - 10 layers (+ gnd cupper layer)
  - To be compared with 2.8-3mm of the FEV10-13
  - but they include BGA SKIROCs and extra components as decoupling capacitances…!!



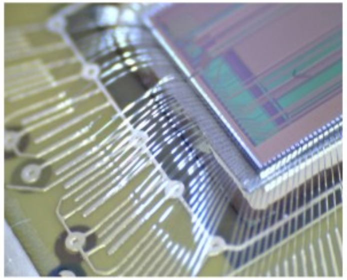


SUNGKYUNKWAN UNIVERSITY(SKKU) EOS CORPORATION

Zoom into ASIC cavities



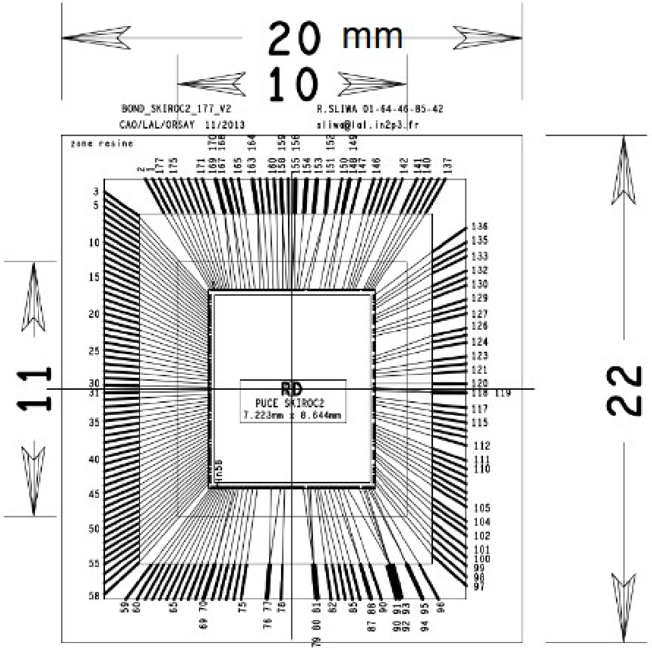
Before application of epoxy



After application of epoxy

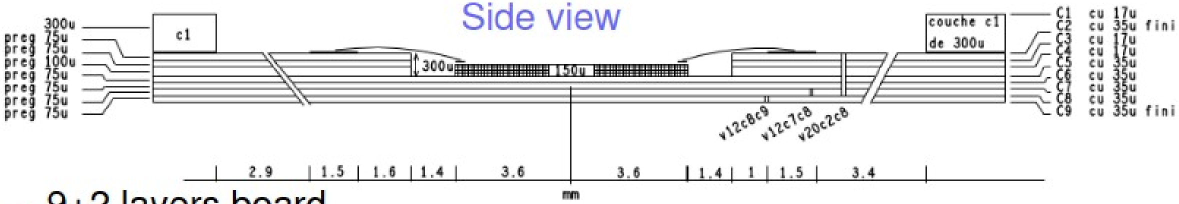
FEV11_COB – Some Technical Details

Bonding scheme

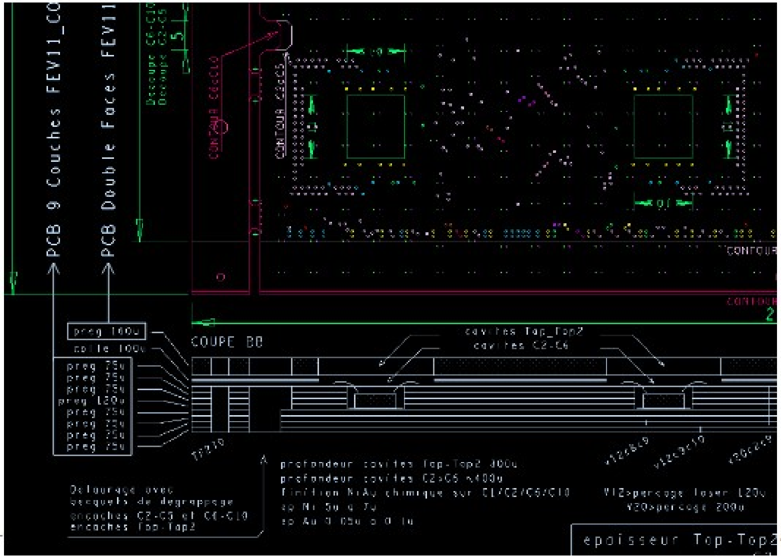


- ~177 Bonding wires
- Bonding by CERN Bondlab
- Regular exchange allowed to iron out early shortcomings

Side view



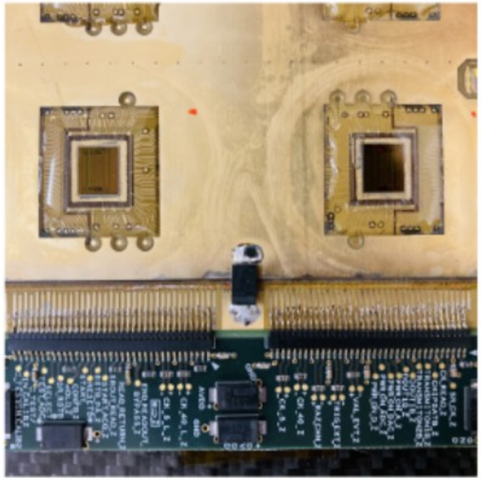
- 9+2 layers board
- Overall height ~1.2mm
- ASICs buried in cavities to ensure overall flatness
  - Need to make sure that bonding wires don't pass board surface

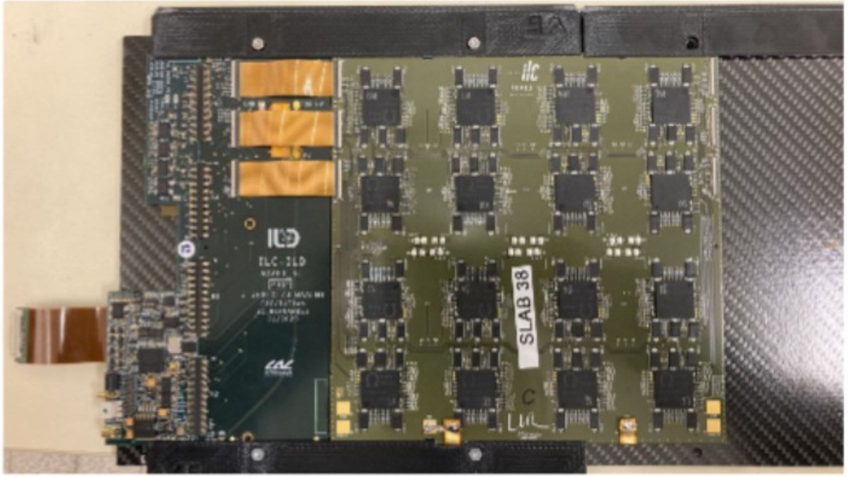


Stephane Callier

CALICE Meeting Oct'22 @ IJCL

Ultra thin PCBs





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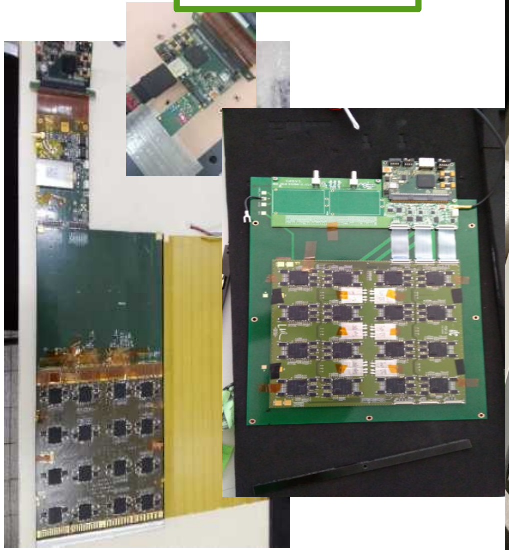
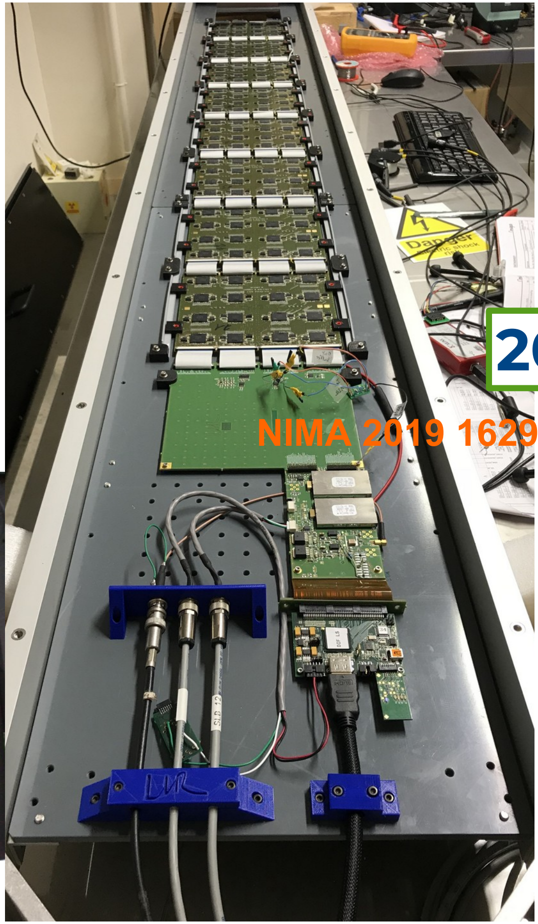
Technological prototype: time travel

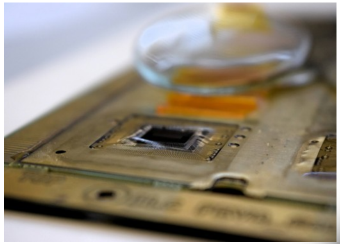
2010-2015

2010-18

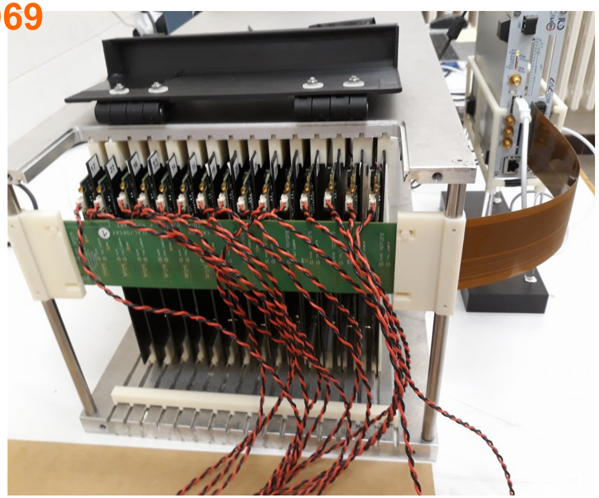




NIMA 2019 162969



2018-22



LUXE (Laser Und XFEL Experiment)

LUXE (Laser Und XFEL Experiment)

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

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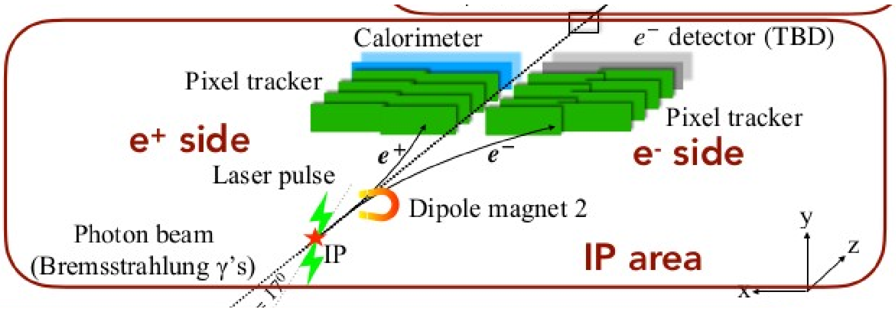
Positron and electron detection systems

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)



IFIC INSTITUT DE FÍSICA CORPUSCULAR

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

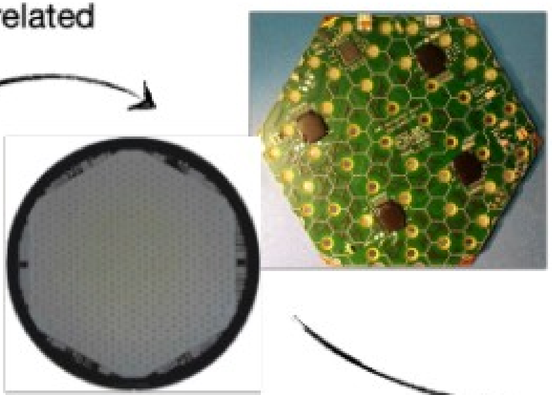
Electron detection system proposal
Based on a pixel tracker + SiW-ECAL of CALICE (15 layers with modified/extended geometry)

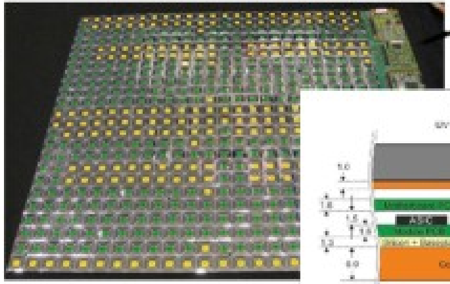
Two detectors of the **scale of CALICE prototypes** running in **real experiment conditions.**
Integration challenge: Very thigh compactness requirements

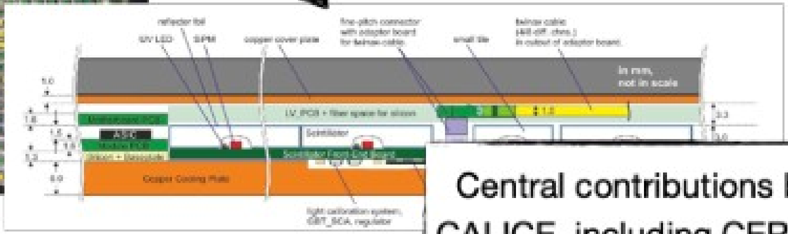
“Spinoffs” of CALICE R&D I: CMS HGCAL

- 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



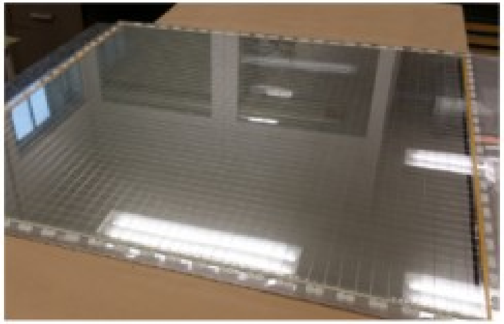


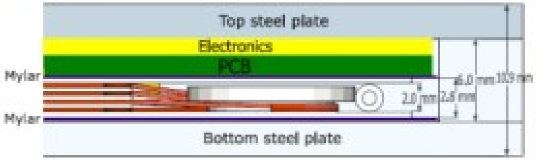


Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

The next decade: ps timing in calorimeters

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

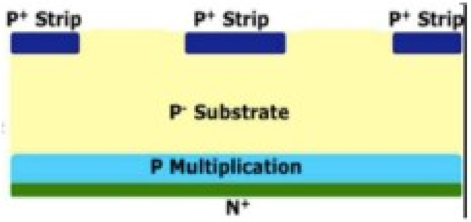




Under development:
GRPC with
PETIROC

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

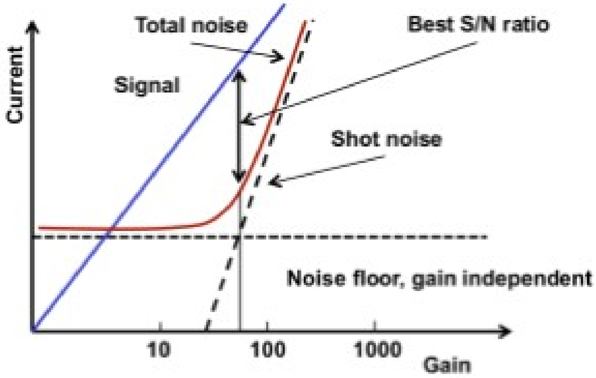
Inverse APD as LGAD?



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