CALICE Imaging Calorimeters: A Review and New Results

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on behalf of the CALICE Collaboration

IFIC
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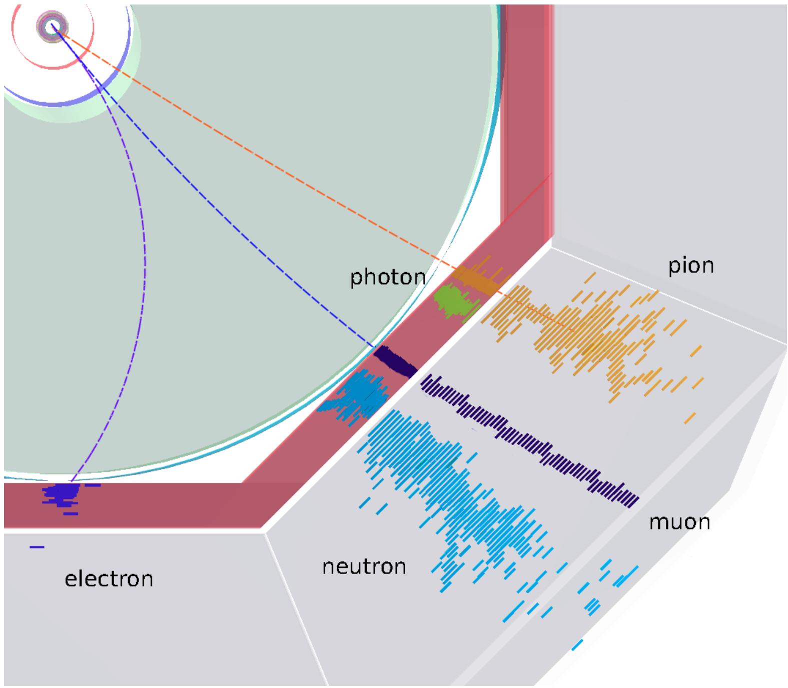
CALICE

ICHEP 2022 BOLOGNA

ICHEP 2022 XLI International Conference on High Energy Physics Bologna (Italy)

6 13 07 2022

Particle Flow Algorithms



Calorimetry requiremetns (some)
Ultracompactness: small Molière radius of calorimeters to minimize shower overlap
Extreme high granularity

Concept

- Base the measurement on the subsystem with best resolution for a given particle type (and energy)
- Separation of signals by charge and neutral particles in the calorimeters
- **Maximal exploitation** of precise **tracking** measurement
  - **“no” material in front of calorimeters**
- Single particle separation

(some) Challenges

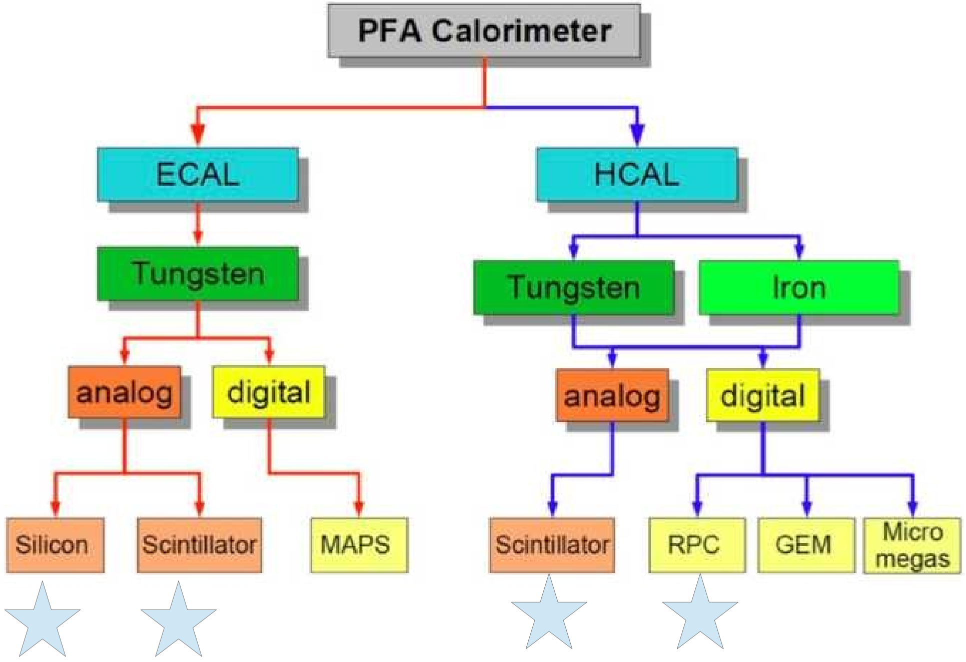
- Complicated topology by (hadronic) showers
- Overlap between showers compromises correct assignment of calorimeter hits

  –> Confusion term

  - Need to minimize this term as much as possible

Particle Flow Calorimetry R&D

Mainly organised within the CALICE Collaboration



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

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

Particle Flow Calorimetry TODAY

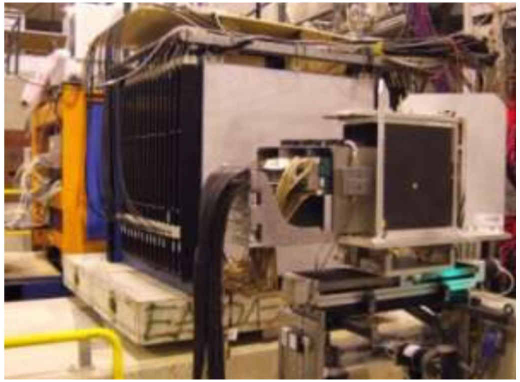
17:00

CALICE Imaging Calorimeters: A Review and New Results	*Adrian Irles*
Bologna, Italy	17:00 - 17:15
Hadronic Energy reconstruction in highly granular calorimeters	*Imad Laktineh*
Bologna, Italy	17:15 - 17:30
Advanced reconstruction and simulation techniques for highly granular calorimeters	*Fabricio Jimenez Morales*
Bologna, Italy	17:30 - 17:45

CALICE – History and steps

Physics Prototypes

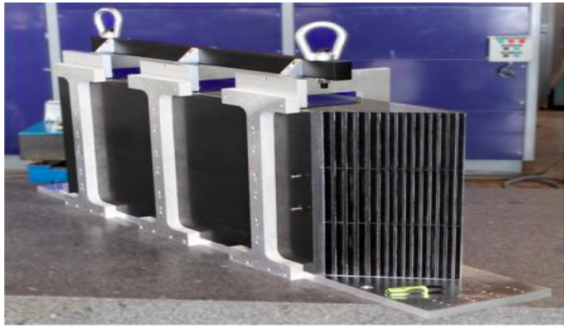
2003 - 2012



- Proof of principle of PFA calorimeters
- Large scale combined beam tests
- Validation of G4 Physics lists

Technological Prototypes

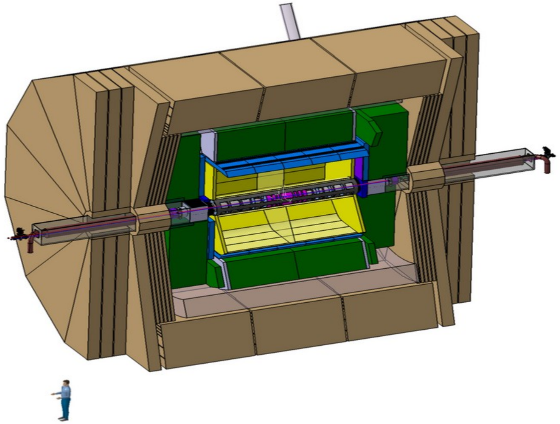
2010 - ...



Engineering challenges

This talk

Detectors (e.g. LC's)



- Goal: ~10^8 calorimeter cells

  to compare:

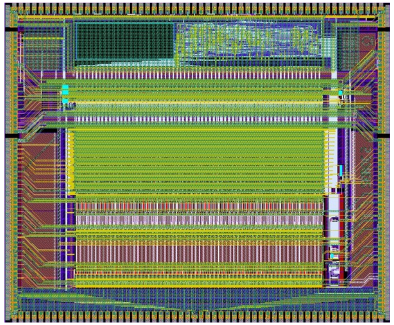
  ATLAS LAr ~ 10^5 cells

  CMS HGCAL ~10^7 cells

Technological premises

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)



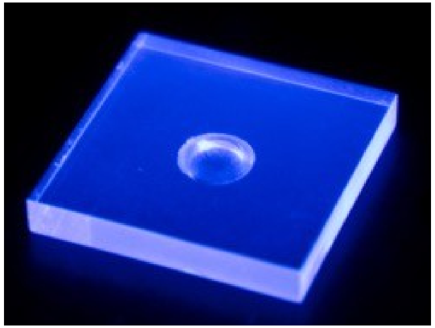
Size 7.5 mm x 8.7 mm,

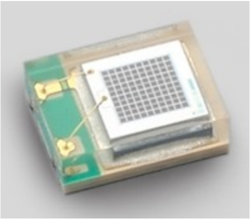
64 channels

- **Analogue measurement**
- **On-chip self-triggering**
- **Data buffering**
- **Digitisation**

... all within one ASIC

Miniaturisation of r/o devices



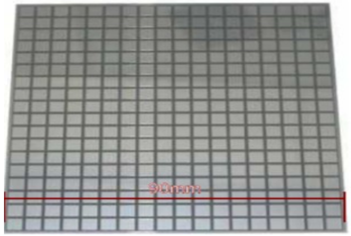


- Small scinitllating tiles
- (Low noise) SiPMs

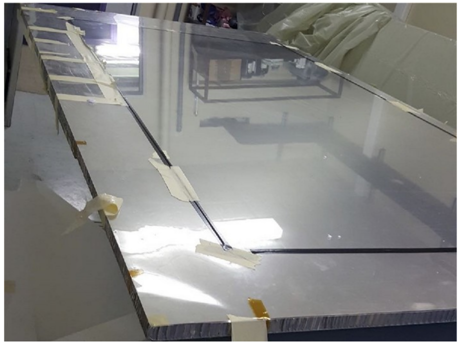
Power pulsed electronics
to reduce power consumption…
Compactness –> no space left for active cooling systems

Large surface detectors

Si Wafer



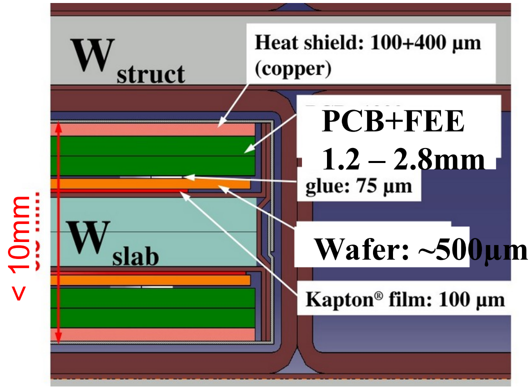
RPC layers



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

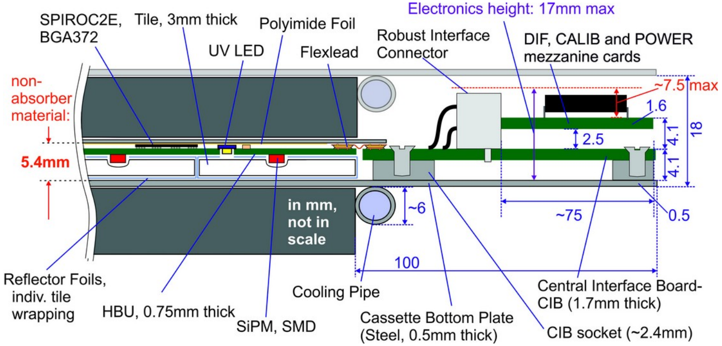
Technological solutions for (almost) final detector

SiW ECAL



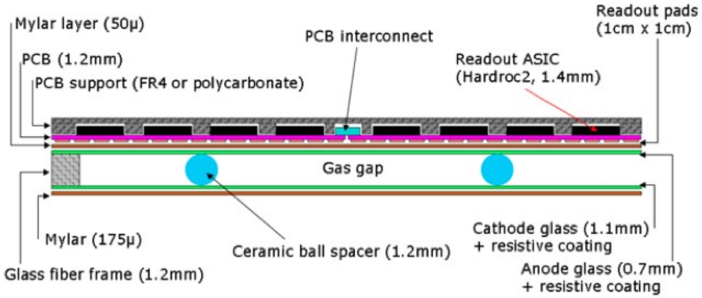
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Scintillator tiles/strips + SiPM
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gas RPCs
Typical segmentation: 1x1cm^2

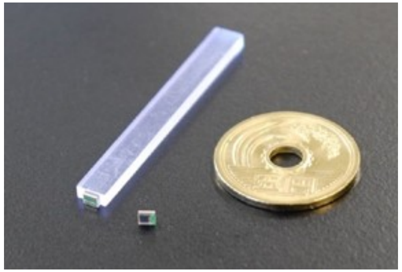
Integrated front end electronics

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

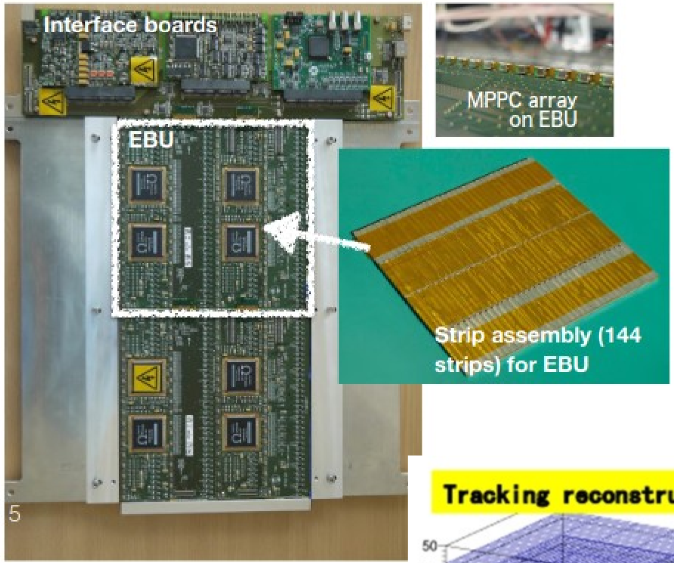
Self triggered readout.
with sub-MIP thresholds (high S/N ~ 10)
and >99% hit efficiency detection

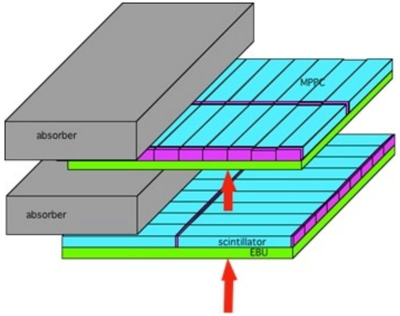
CALICE Sc-ECAL

A 32-layer prototype is under construction in China.
Option for CEPC and ILC electromagnetic calorimeters.

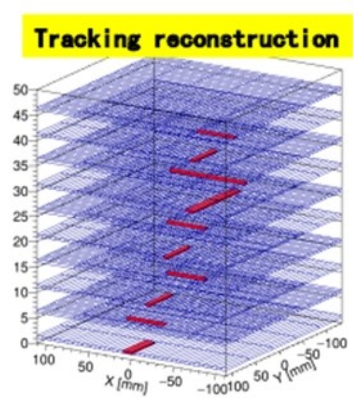


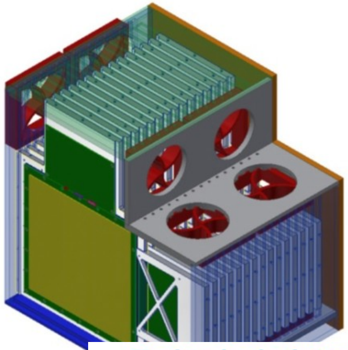
45×5×2mm^3 scintillator strips
2.45×1.9×0.85 mm^3 SiPM



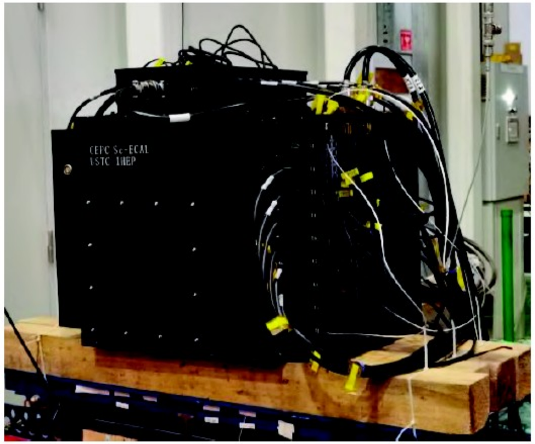


Strips could be read at both ends of longer strips
to increase accuracy and provide redundancy.





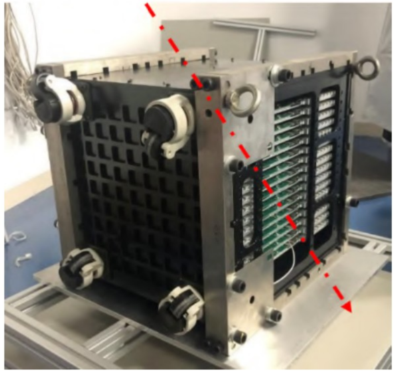
- **Technological prototype: full layer**
  - **Joint R&D with CEPC-ECAL group**
  - Scintillator strip ($45 \times 5 \times 2\ \mathrm{mm}^3$) with SiPM
  - 32 layers, $\sim 23.4\, X_0$
  - 210ch /EBU



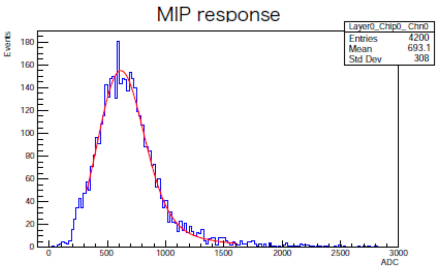
Cosmic stand

- ▶ No beam test performed yet due to pandemic
  - Sc-ECAL/CEPC-AHCAL combined test beam at CERN SPS in October 2022
- ▶ Long cosmic ray run (~3 month)
  - MIP calibration
  - Stability test
  - Performance study
  - Detection efficiency, position resolution
  - Study with cosmic-ray induced shower

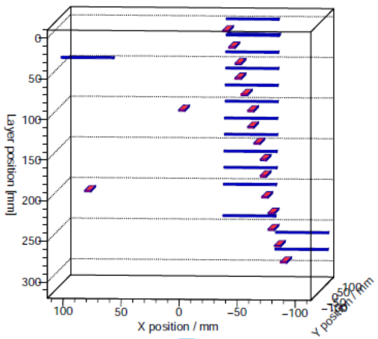
Prototype rotated by 90° for cosmic-ray test



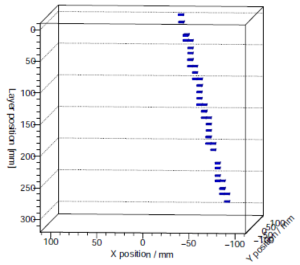
Cosmic ray tracks



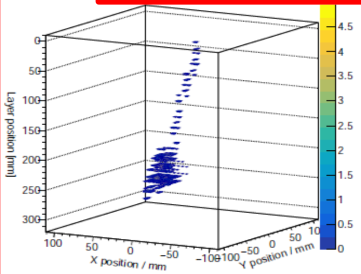
CR event display

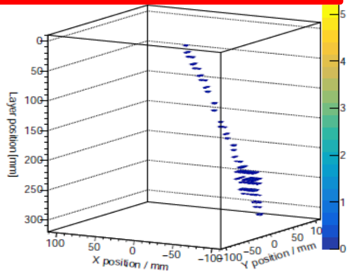


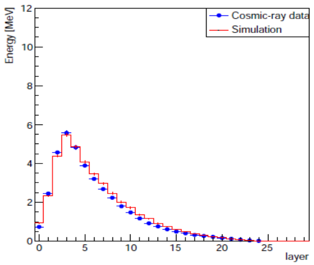
CR event display with hit reconstruction

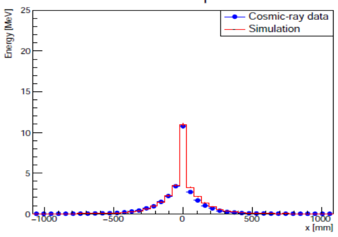


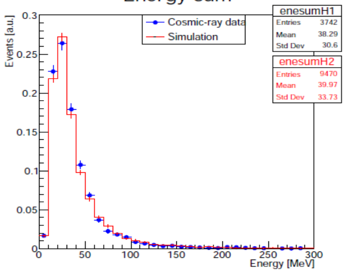
Cosmic ray induced showers



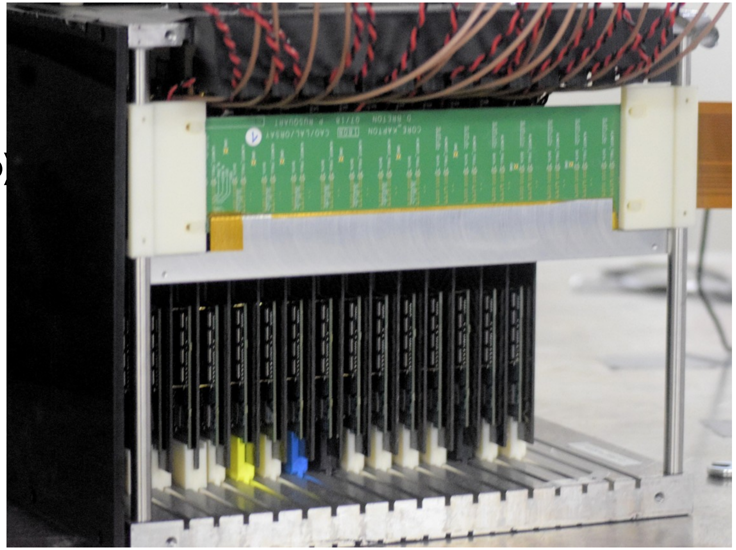








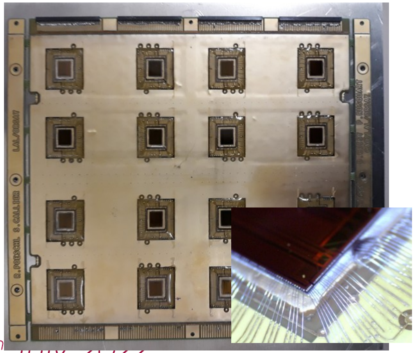
CALICE SiW-ECAL

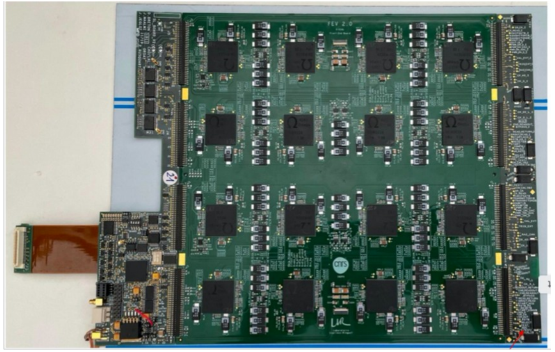


- new technological prototype with tungsten absorber
  - Si pads: 5 × 5 mm² (ILD design)
  - 15 modules layers × 1024 channels/layer ≈ **15000 cells (~as LHC-exp)**
  - TB at DESY and CERN 2022 (with AHCAL)
- All components designed to fit the requirements of a Lepton Collider Detector
  - Ultra compact digital readout systems
  - Same granularity as ILD

- Very dense **PCBs *aka* FEV** with 1024 readout channels (with digital, analogue, clock signals) in a 18x18

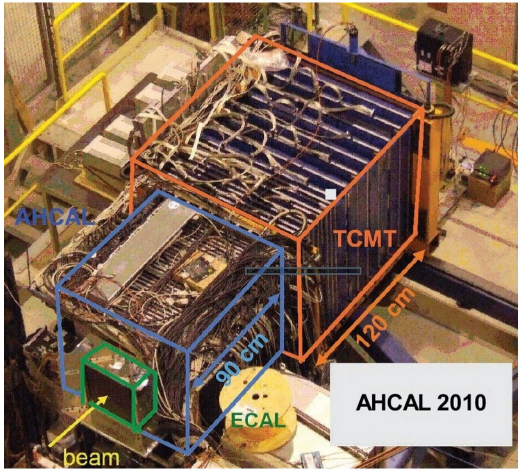
FEV10-12



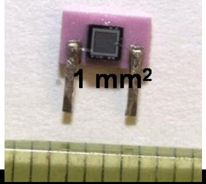


Highly compact objects with minimal space for the components needed to assure the integrity of the signals & a **proper power management**

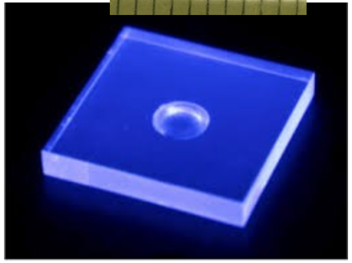
CALICE – Analogue HCAL



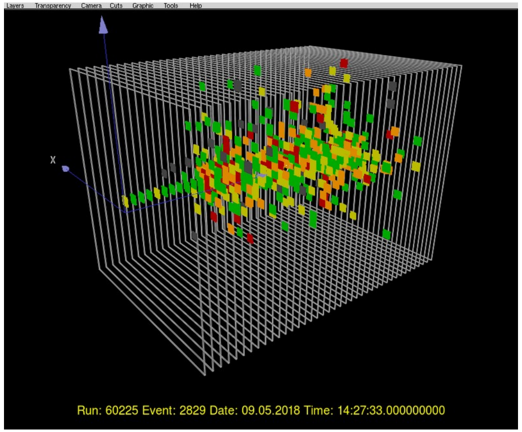
38 layers
72×72×2.5 cm^3 / layer
22,000 tiles



SiPM under the tiles
for better uniformity
and light collection

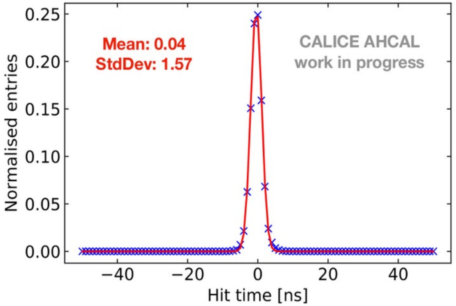


3x3cm^2 tiles



each cell also provides
time information with
~1ns resolution

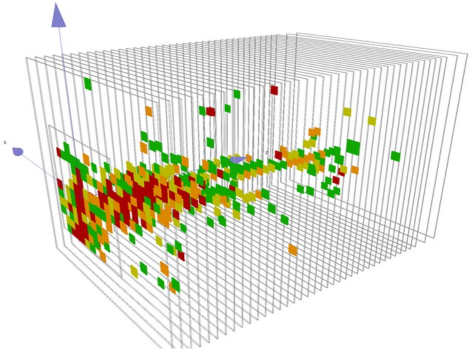
a true 5D "pixel" detector: x,y,z,E,t

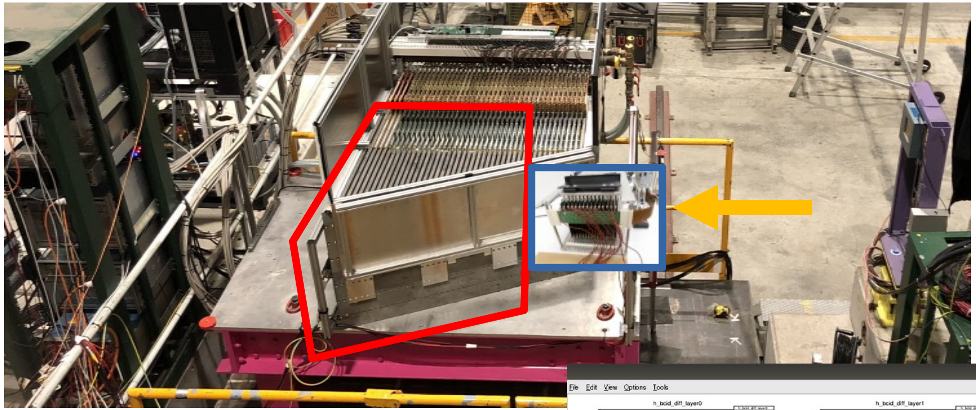


Intensive beam test campaigns in the last years, including **combined with CMS-HGCAL and SiW-ECAL**

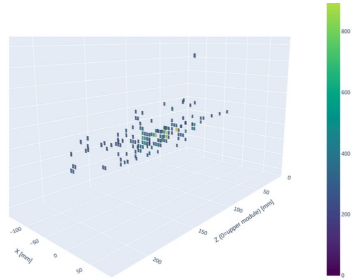
Common beam test CERN SPS 06/2022

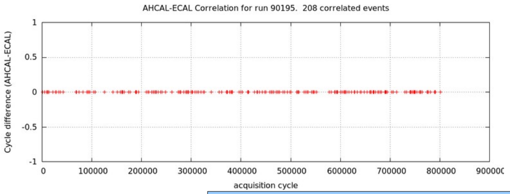
AHCAL :
- **38 layers 72×72 cm²**
- 3×3 cells scintillator + SiPM
- 1.7 cm Stainless Steel (~4λ)
- **6t, 1×1×1.5 m³**

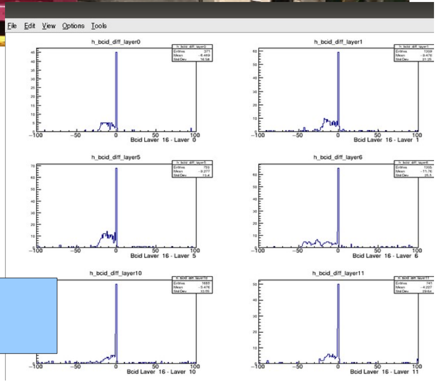




SiW-ECAL
- 15 layers 18×18 cm²
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm³







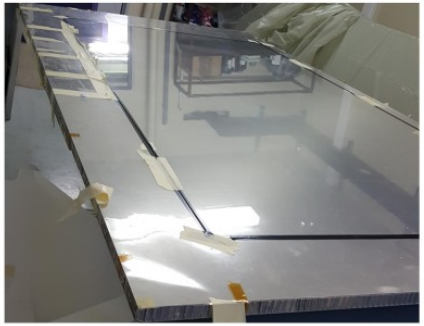
Synchronization checked online

- ▶ Master Clock (from CCC AHCAL). Busy signals. Common Acq-Windows with a fixed Offset in clock.
- ▶ System controlled by EUDAQ 2
  - Online event building and EUDAQ monitoring tools.
  - Common tools for analysis are work in progress.

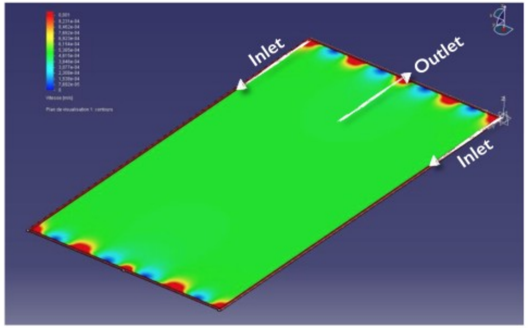
Muons (150GeV), electrons (10-100GeV) and pions (10-150GeV)

Semi Digital-HCAL

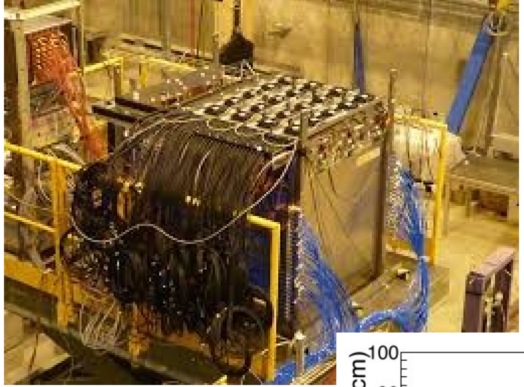
2 m^2 RPC assembled

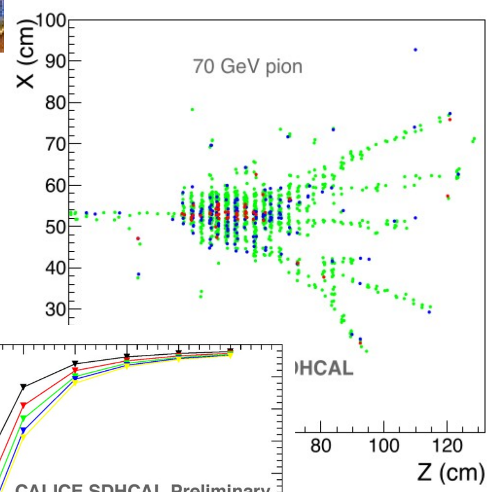


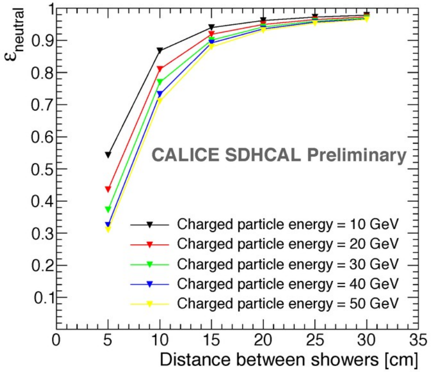
Scalable gas distribution



- 48 layers × 28 mm, also made of glass RPC.
  - 96 × 96 channels per layer, i.e.
  - ~440000 1×1 cm^2 readout channels.
- Semi digital readout
  - 3 tunable energy thresholds – 0.1MIP -5 MIP - 15 MIP
  - thresholds coded into 2 bits → pads with few, many or lots of hits.
- Optimize hadronic shower reconstruction via choice of thresholds.
- Better linearity response, improved energy resolution.



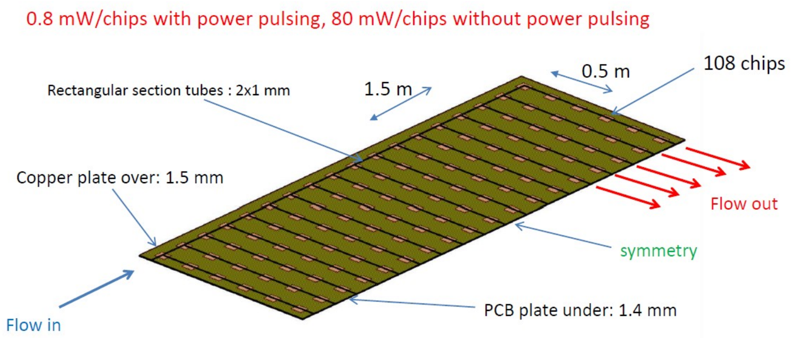


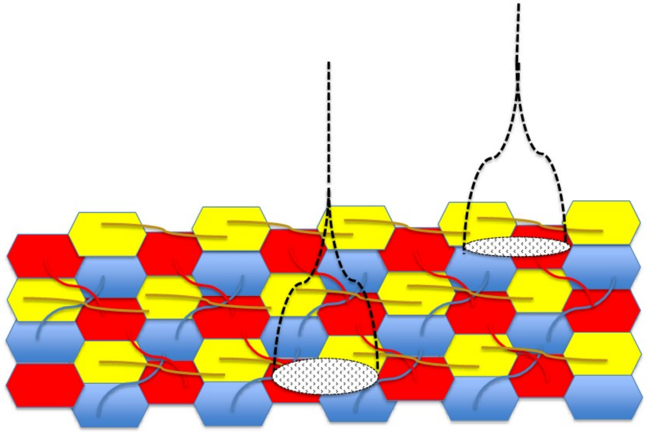


Semi Digital-HCAL

▶ Circular colliders (CEPC) expect power consumption 100-200 times larger than ILC

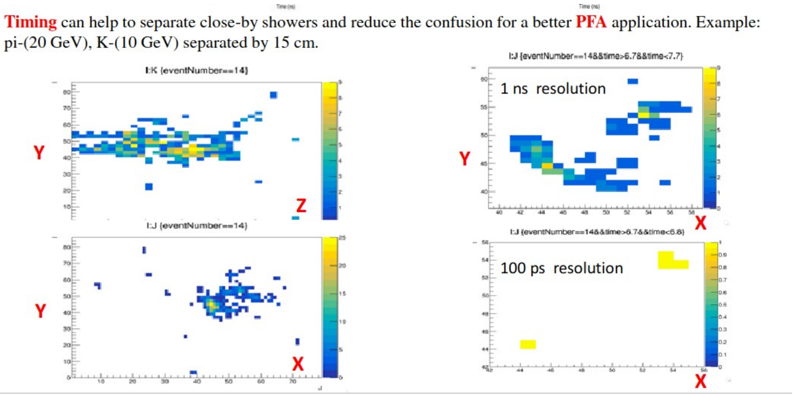
- Active cooling needed (water cooling using cooper pipes)
- and/or new readout schemes as woven strips (Work in progress)





▶ Investigating timing using **MultiGAP RPC**

- 4-5 gaps of 250 μm each can provide 100 ps time resolution

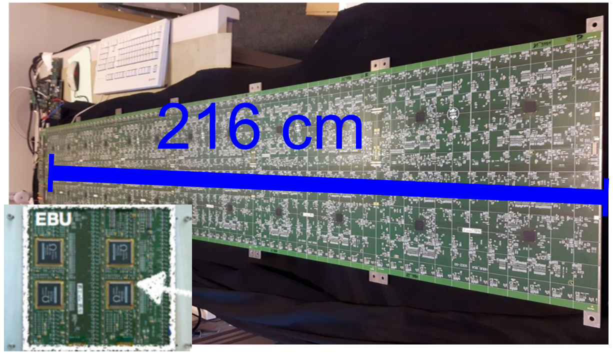


Realistic detector dimensions: long layers

SiW-ECAL

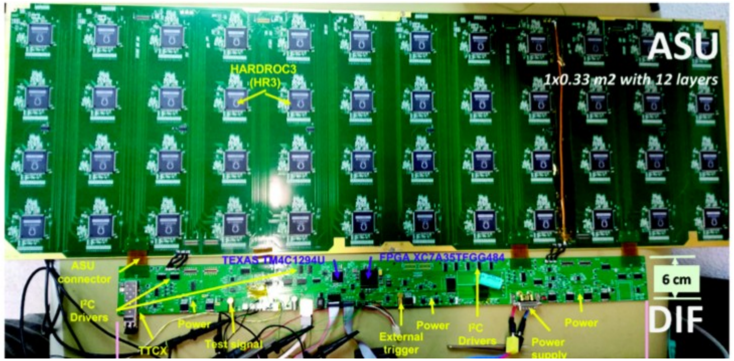
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm^2

Analogue-HCAL and Sc-ECAL



Scintillator tiles/strips + SiPM
Typical segmentation: 3x3cm^2

Semi-digital HCAL

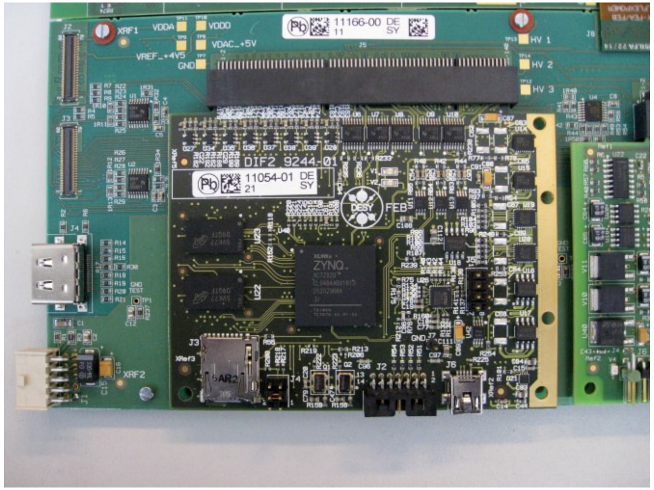


Gas RPCs
Typical segmentation: 1x1cm^2

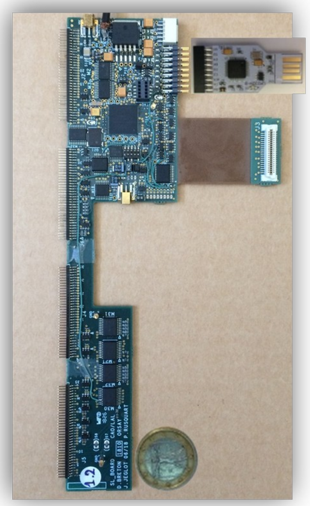
- Realistic detector dimensions
  - Structures of up to 3m in length (more than 10000 cells)
  - With compact external components
- Challenge for the power pulsing techniques (for the power consumption management)

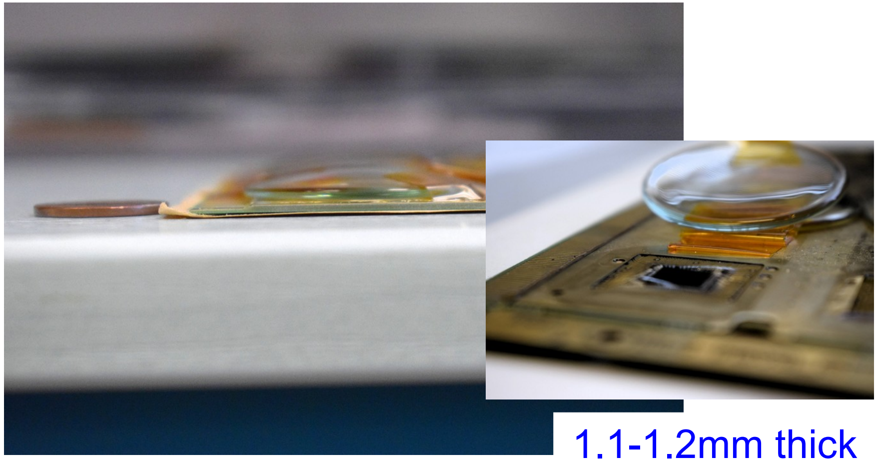
Realistic detector dimensions: ultra compact layers

Current detector interface card - AHCAL



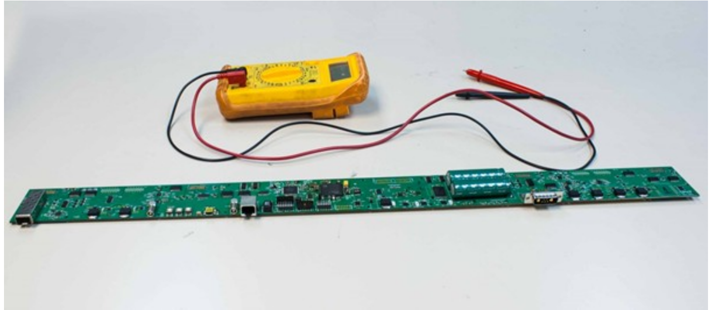
Current detector interface card and thin detection unit – SiW ECAL





1.1-1.2mm thick

Current detector interface card - SDHCAL



- “Dead space free” granular calorimeters put tight demands on compactness
- Current developments within CALICE meet these requirements
  - Unique successes in worldwide detector R&D
- Can be applied/adapted wherever compactness is mandatory
- Components will/did already go through scrutiny phase in beam tests

Summary and more

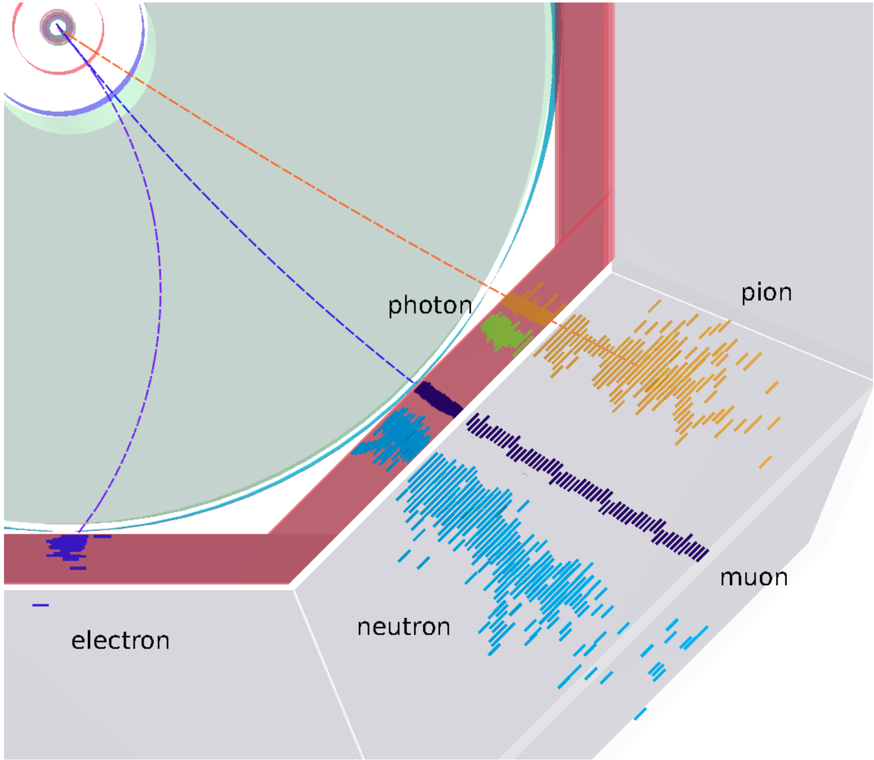
- We are in a **very exciting moment for the PFA calorimeters prototyping**
  - High level integration (meeting the very tight technical requirements of the future colliders)
  - Discussed projects are near (or already) in the phase of building large scale (~m^3) technological prototypes.
  - Proven stable operation of prototypes in beam test: **common test beams campaigns restarted in 2022**
- **Looking forward for a lepton collider soon!**

Many other topics could not be covered in this talk but you may find some extra material in the back up slides

- **CALICE R&D inspired CMS high granularity solution HGCAL**. Common testbeams with the AHCAL prototype.
- **Further spin-offs:** LUXE, ALICE FOCAL, DUNE ND, Belle II Claws
- **New ideas/technologies being explored**
  - **high precision (ps) timing** calorimeters?
  - New sensors ideas (MAPS, LGADs, etc)
  - Dual readout & high granularity
- Original target of the CALICE calorimeters were the linear colliders but **the generic concept is also applicable to circular colliders**

Back-up slides

Particle Flow Algorithms



Concept

- ▶ Base the measurement on the subsystem with best resolution for a given particle type (and energy)
- ▶ Separation of signals by charge and neutral particles in the calorimeters
- ▶ Single particle separation

Challenges

- ▶ Complicated topology by (hadronic) showers
- ▶ Overlap between showers compromises correct assignment of calorimeter hits

  –> Confusion term

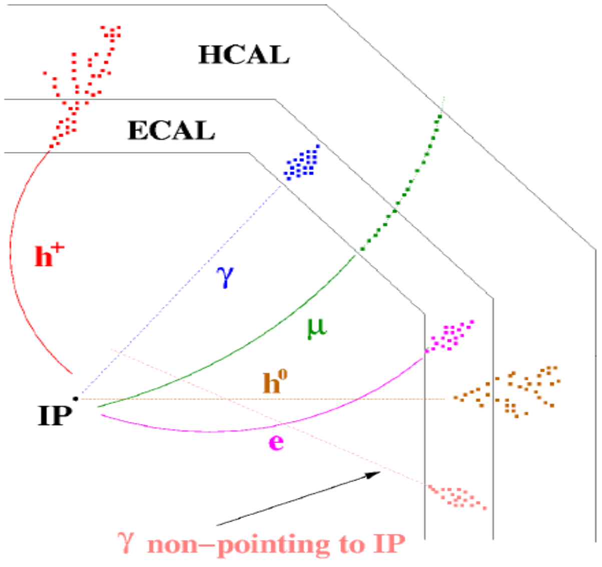
- Need to minimize this term as much as possible

Requirements for PFA oriented detectors

Jet energy measurement by measurement of **individual particles**

Maximal exploitation of precise **tracking** measurement

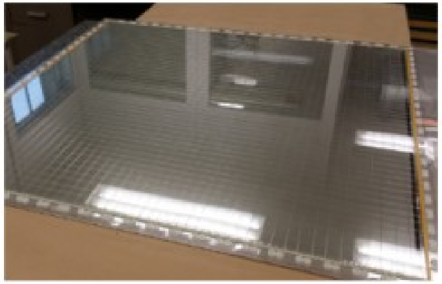
- large radius and length
  - to separate the particles
- large magnetic field
  - To increase separation of neutral/charged particles at calorimeters
  - to suppress very large, low-momentum beam-related backgrounds"
- **“no” material in front of calorimeters**
  - Low material budget on the tracker + stay inside coil + **no active cooling systems** (linear colliders, circular colliders impact to be understood)
- **Ultracompactness:** small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers
- **And fast timing calorimeters**

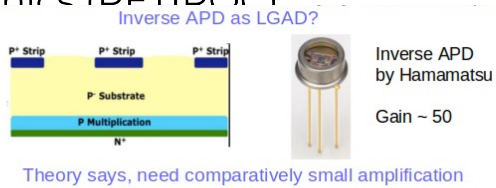


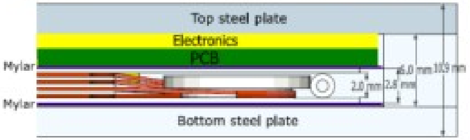
New Kids in the Block

A 5th dimension: time

- ▶ **O(ns) with "standard" Si/Sc** sensors and integrated readout electronics (to separate slow and fast shower components)
- ▶ **O(50ps)** with ultra-fast silicon sensors: **Inverse APD, LGAD, etc**
- ▶ **O(20ps) with GRPC** and dedicated electronics (PETIROC). Developped for CMS muon upgrade

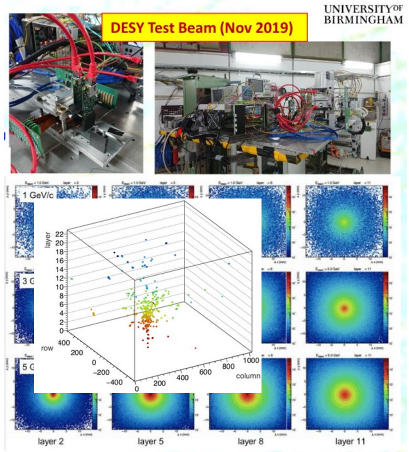






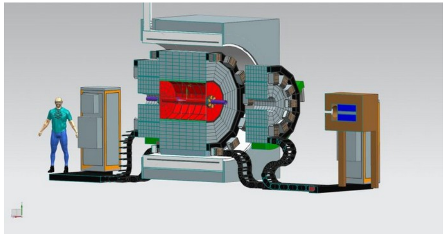
DECAL/MAPS

- ▶ **Ultra granular calorimeter** under consideration for ALICE (and also SiD-ILC, FCC-hh…)
- ▶ TestBeams in 2019-20-21
  - 24 layers, 48 **ALPIDE** sensors, 24M pixels



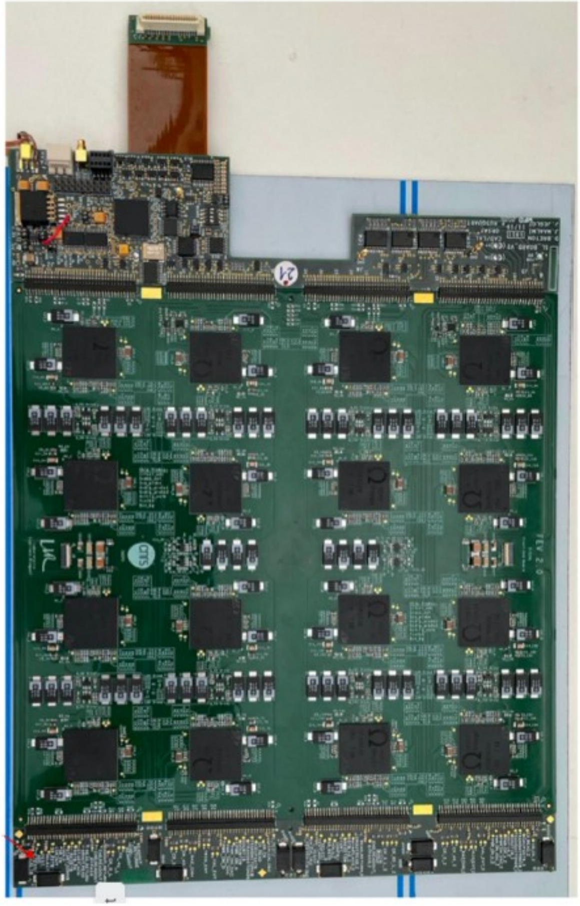
Dual + PFA calorimetry

- ▶ **ADRIANO2 (REDTOP)** merges the benefits of a dual-readout and of a CALICE-type calorimeter,
  - Plastic scintillator + heavy dense glass (only senstite to charged particles fast detector)
  - Fast detectors (80ps)

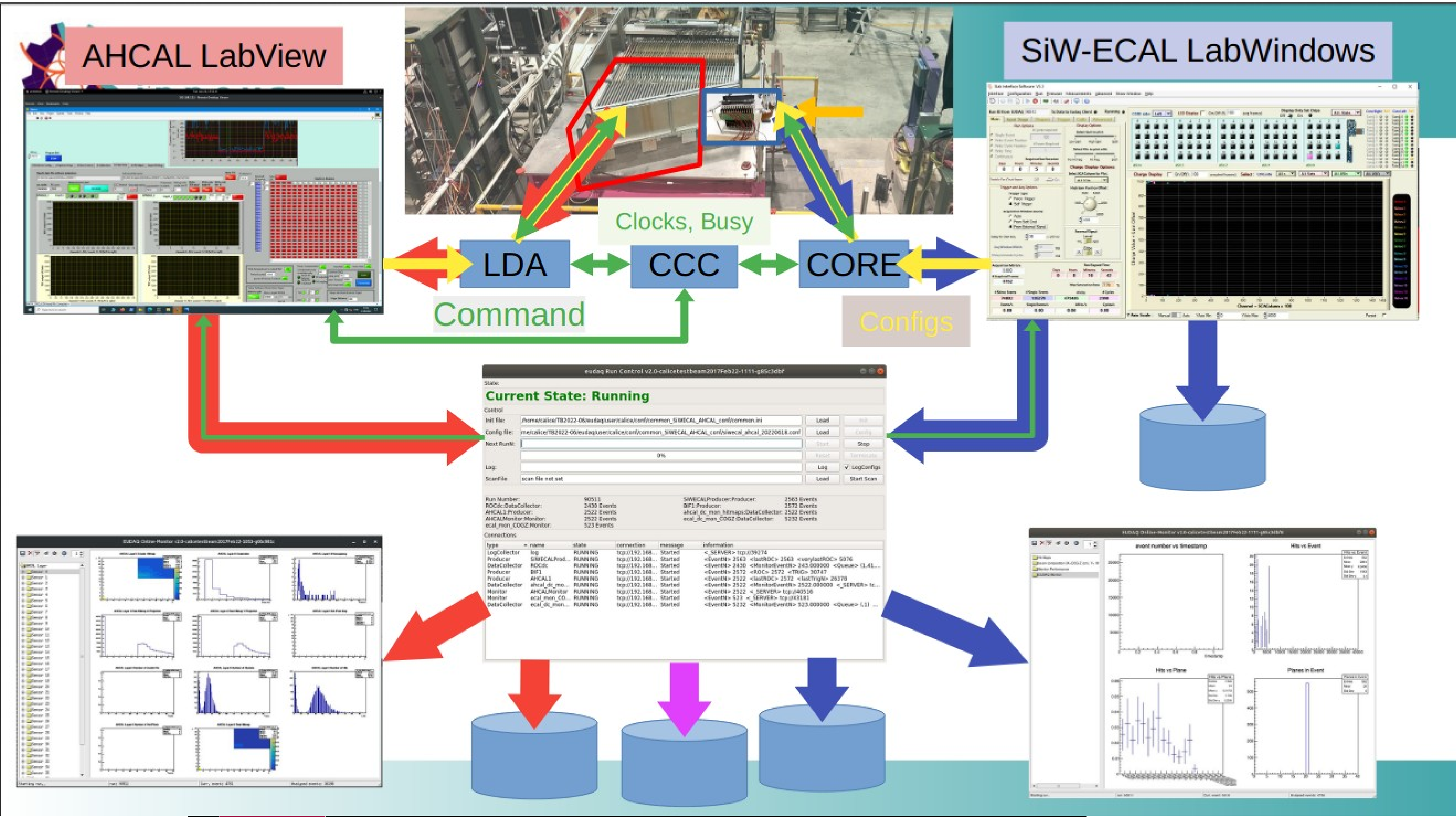


New PCB – FEV2.x

LLR, IJCLab, LPNHE, OMEGA

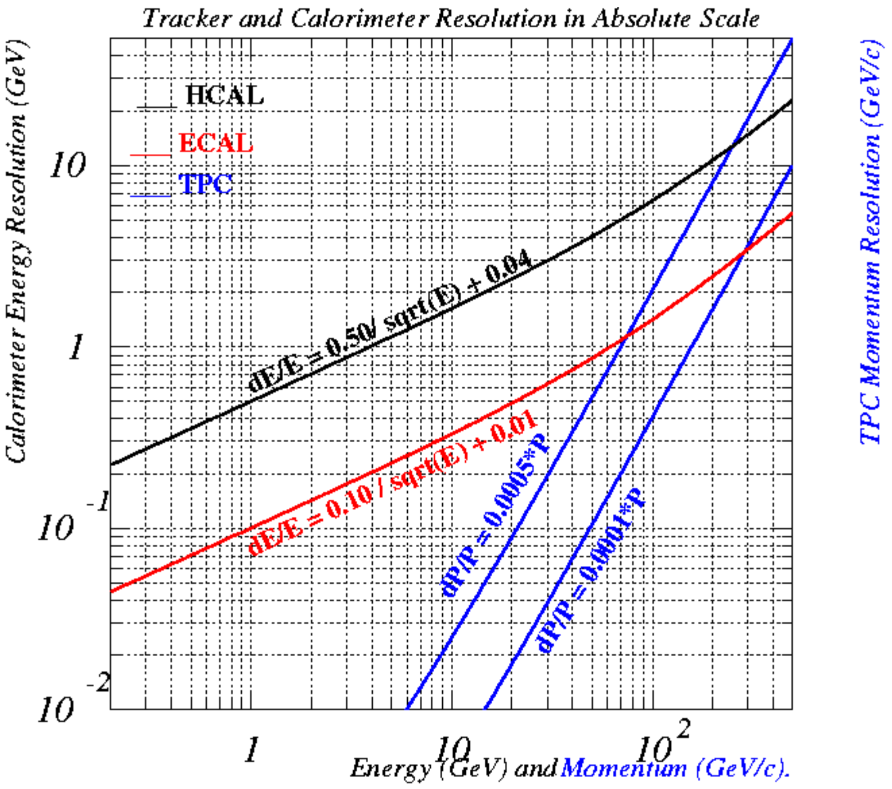


- Improved Layout
  - Better shielding of AVDD and AVDD PA plans and minimisation of cross-talk between inputs and digital signals.
- Power Pulsing Mode: new philosophy
  - limiting the current through the Slab (current limiter present on the SL Board) to:
    - avoid driving high currents through the connectors and makes the current peaks **local** around the SKIROCs chips
    - avoid voltage drop along the slab
    - ensure temperature uniformity
  - We add large capacitors with low ESR for **local** energy storage (around each SKIROC chip)
  - Generate **local** power supply with LDO (Low Drop Out) to avod voltage variations
- Clean clock distribution all over the slab
  - for Slow Control and Readout Clocks
- Parallel configuration and readout over 2 partitions.
- Driving high voltage up to 350V for 750µm wafer (via the ASU connectors)
  - Adding a filter for each wafer HV and limit the current in case of wafer failure



AHCAL LabView
SiW-ECAL LabWindows
Clocks, Busy
LDA
CCC
CORE
Command
Configs
Current State: Running

Jet energy resolution



$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

Lepton Collider goal is around *dE_{jet}/E_{jet}- 3-4%*
(e.g. 2x better than ALEPH)

In a "typical jet" the energy is carried by

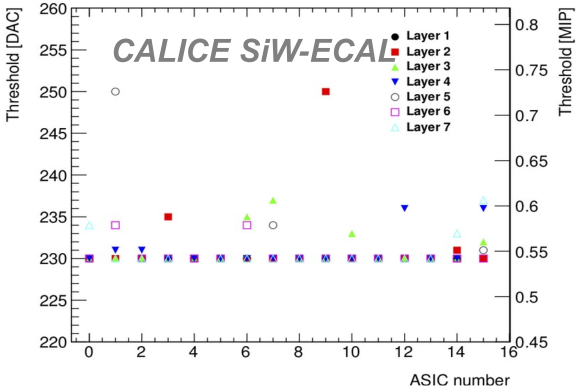
- ▶ **Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$): 65%**
  - Most precise measurement by **Tracker**
- ▶ **Photons: 25%**
  - Measurement by Electromagnetic Calorimeter **(ECAL)**
- ▶ **Neutral Hadrons: 10%**
  - Measurement by Hadronic Calorimeter **HCAL** and ECAL

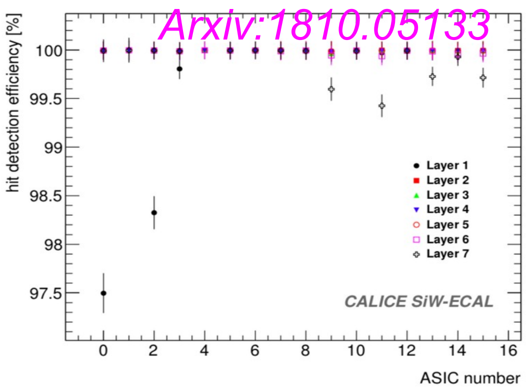
Particle Flow Algorithm

- ▶ Choose the best information in our detector

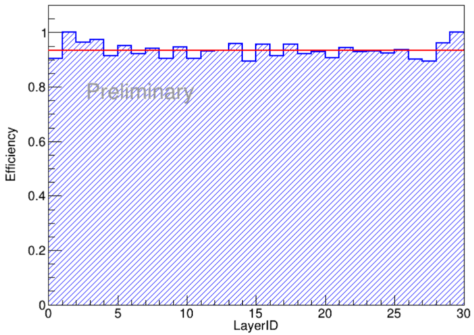
performance at MIP level

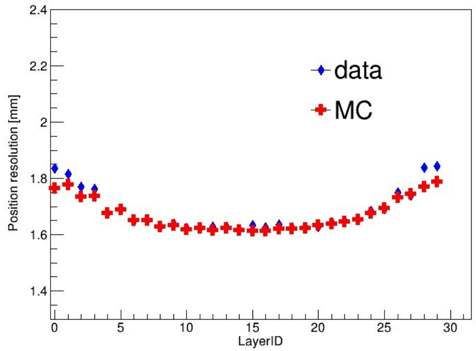
Trigger thresholds uniform at around 1/2 MIP





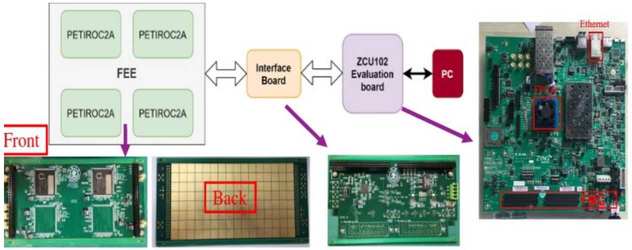
MIP Detection efficiency ~100%





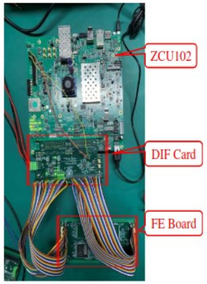
PFA requires small pixel size, large segmentation and pattern at low energy:
a) Access to small signals -> Low self-trigger thresholds (with zero supression and high S/N ~10 at MIP)✔
b) Tracking in calorimeters -> High MIP detection efficiency ✔

First step towards transforming SDHCAL into T-SDHCAL



- Front-End Electronics for MRPC readout with high timing resolution
- The system includes a front-end board (FEB), a detector interface card (DIF) and a data acquisition system(DAQ) based on ZCU102.

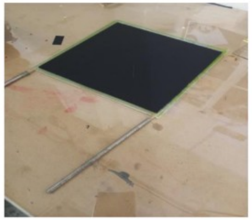
Test System and Setup



First step towards transforming SDHCAL into T-SDHCAL

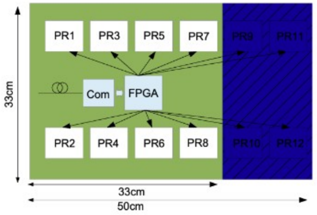
New and easy way of construction MRPC

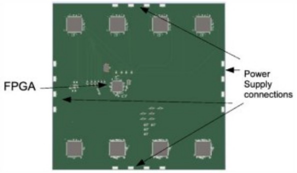
Using thin spacers made of mylar+double face



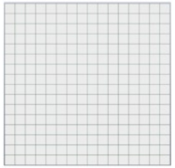
Large timing PCB

- Board with 8 (could be extended to 12) Petircoc2B ASICs
- Pads 2cm x 2cm, 256 channels
- Local FPGA (Xilinx Spartan-6 TQFP) embedded on board





Top view



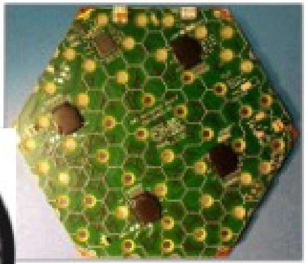
Bttom view

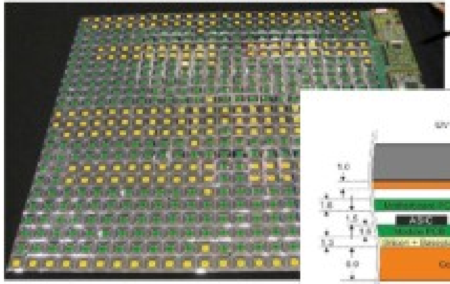
I. Laktineh

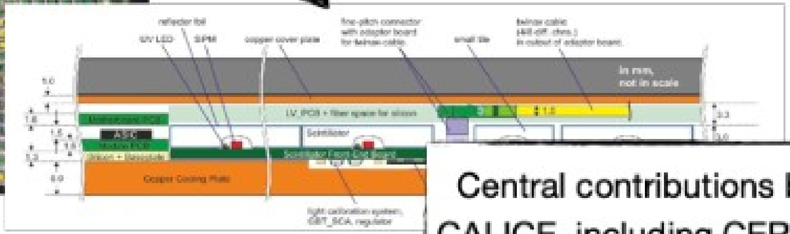
Spinoffs of CALICE R&D I: CMS HGCAL

- 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







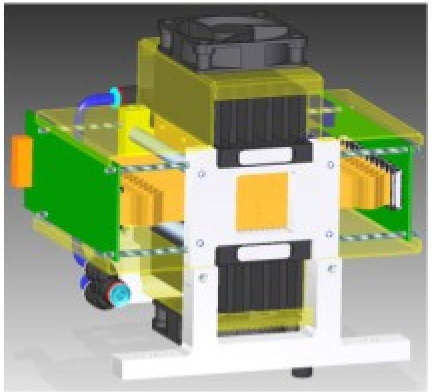
Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

Spinoffs of CALICE R&D II

FOCAL MAPS ECAL:
Ultrahigh granular calorimeter is under consideration for ALICE (and also SiD-ILC, FCC-hh...)

Numbers for FOCAL assuming ≈ 1m² detector surface

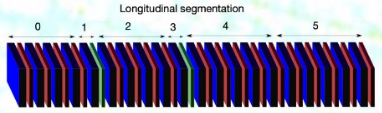
	LG	HG
pixel/pad size	≈ 1 cm²	**≈ 30x30 µm²**
total # pixels/pads	≈ 2.5 x 10^5	**≈ 2.5 x 10^9**
readout channels	≈ 5 x 10^4	**≈ 2 x 10^6**



- Recent Testbeams with
- MIMOSA for HG
- Prototype with ALPIDE under construction

▶ TestBeam in Nov2019 & Feb2020

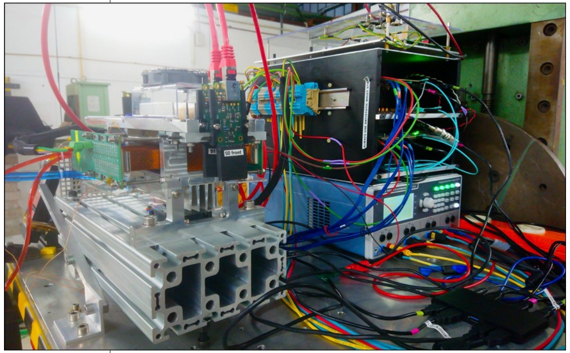
- 24 layers,
- 48 ALPIDE sensors,
- 24M pixels
- Electron/positron, E = 1.0 - 5.8 GeV



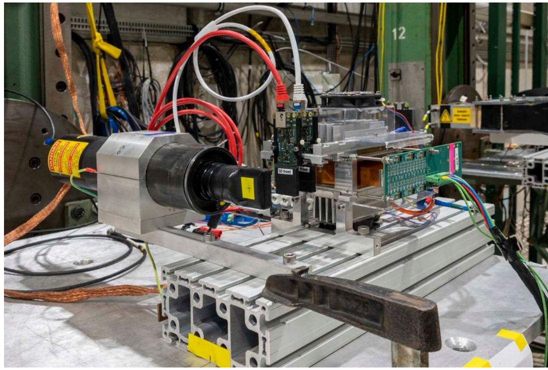
New ALPIDE CMOS sensor based 3cm×3cm area 24 layer stack

▶ H6 test beam SPS (Sept./Oct. 2021)

- Mixed beam, E = 20 - 80 GeV

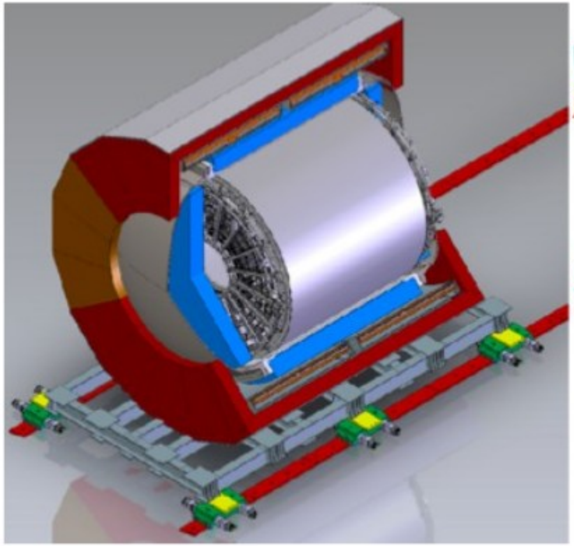


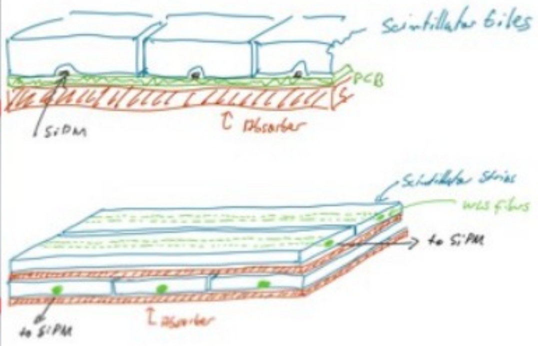
DESY



SPS

Spinoffs of CALICE R&D III

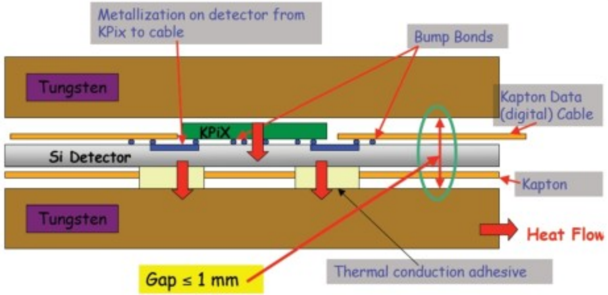




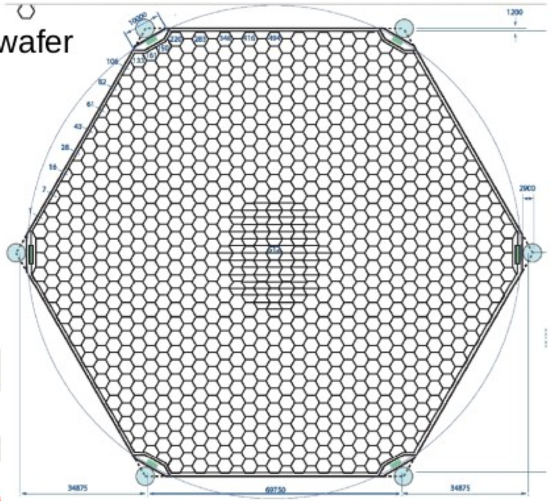
- SiPM-on-Tile and scintillator strips as active material for DUNE Near Detector
- Similar requirements on compactness as lepton collider detectors
  - Study of adaptation of CALICE technologies ongoing
  - Including first discussions on engineering level

SiD – Si-W ECAL

Design configuration: "(20+10)", i.e.
20 thin W layers (2.5 mm)
10 thick W layers (5.0 mm)
+ 30 Si layers



6" wafer

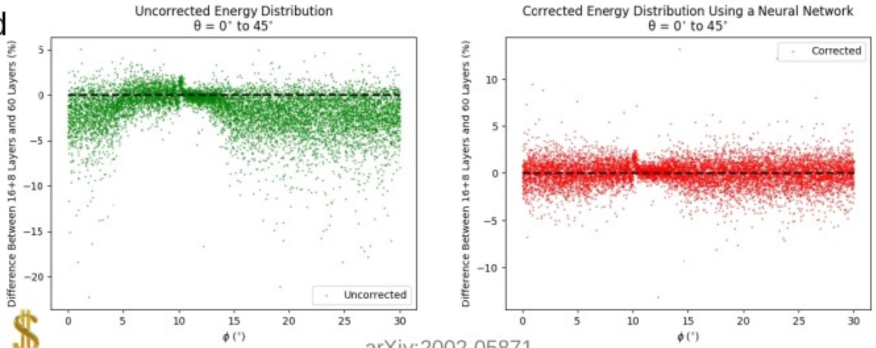


arXiv:1306.8329 - ILC TDR 4: Detectors

Energy leakage of electromagnetic particles estimated by analyzing the patterns in total energy deposition in each layer using neural networks.

(18+6) vs (60+0) GEANT4 models, with:
- energies range: 20 – 300 GeV
- incidence angles θ = 0° - 45°
- azymuthal angles ϕ = 0° - 30°

Design performance possible with 16+8 configuration: $



arXiv:2002.05871

Common beam tests

SiW ECAL/SDHCAL (2018)

CALICE meets CMS

Common beam tests since 2017

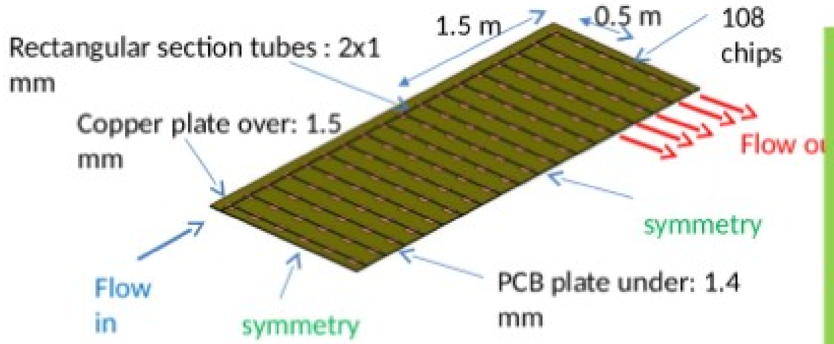
- Common beam tests benefit from common approach within CALICE
- But also from wider networking activities such as EUDAQ2 of AIDA2020
- More common beam tests to come after CERN shutdown

Some challenges at Circular Colliders

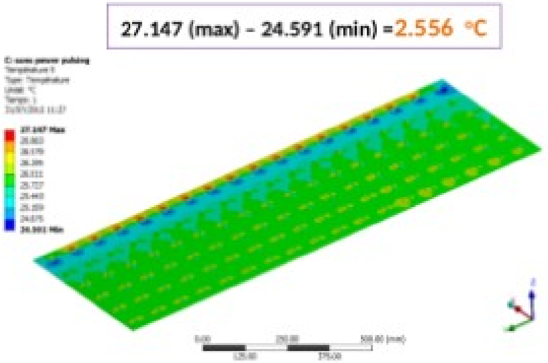
Power pulsing at LC <-> No power pulsing at Circular Colliders => Strong heat dissipation

Example:

CALICE SDHCAL



- A water-based cooling system inside copper tubes in contact with the ASICs to absorb excess heat.
- Temperature distribution in an active layer of the SDHCAL.



Water cooling : h = 10000 W/m²/k

Thermal load : 80 mW/chip

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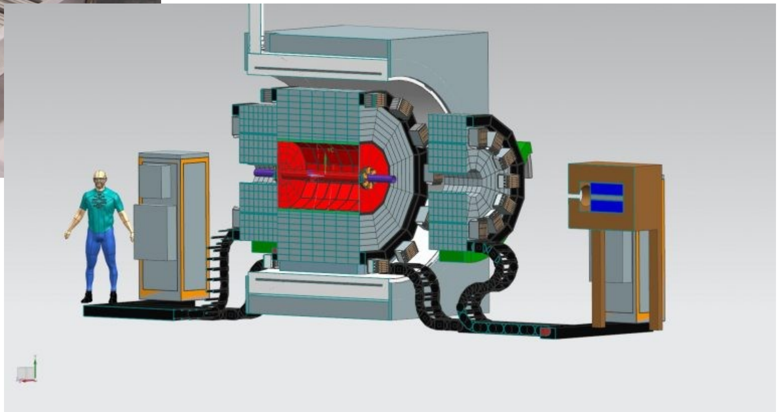
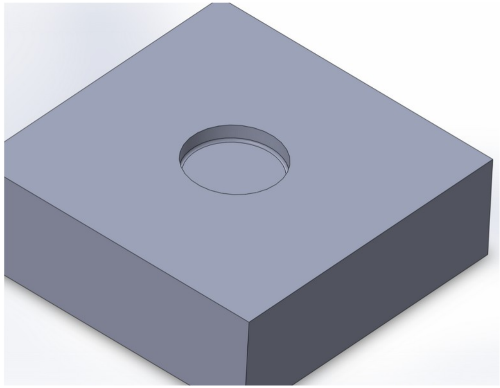
Dual & high granularity (and timing) calorimetry

- See Cristal Calorimetry talks from yesterday.
- Another example: ADRIANO2 calorimeter (REDTOP detector)

ADRIANO2 merges the benefits of a dual-readout and of a CALICE-type calorimeter, creating the base for a new generation of high-performance detectors.

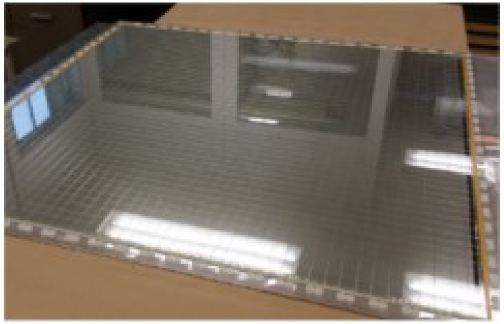
- Active mat.1: Plastic scintillator
- Active mat.2: heavy dense glass (only sensible to charged particles via Cherenkov rad). Fast detectors !
- Another example: ADRIANO2 detector

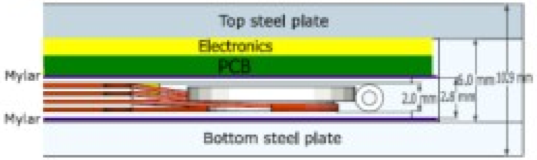




The next decade: ps timing in calorimeters

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

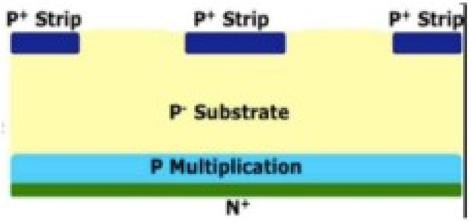




Under development:
GRPC with
PETIROC

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

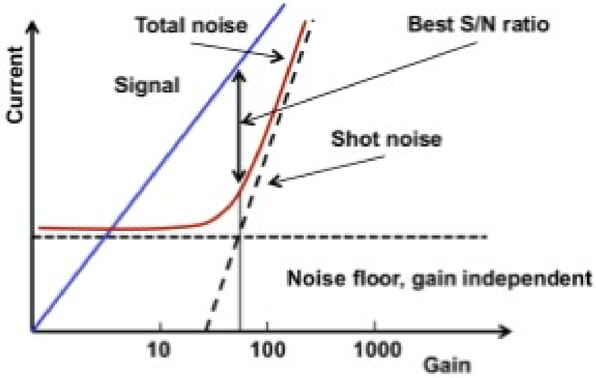
Inverse APD as LGAD?



Inverse APD
by Hamamatsu

Gain ~ 50

Theory says, need comparatively small amplification

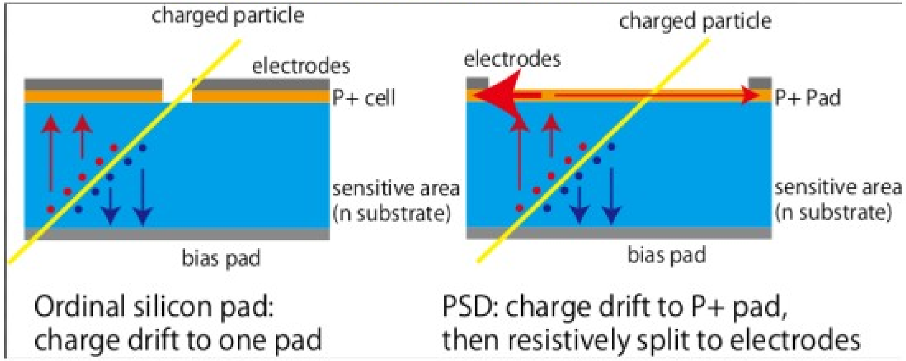


- Shot noise may be limiting factor
- Expect interesting comparison between inverse APD and LGAD as e.g. used by ATLAS
- Not that Members of CALICE are also members of ATLAS-HGTD

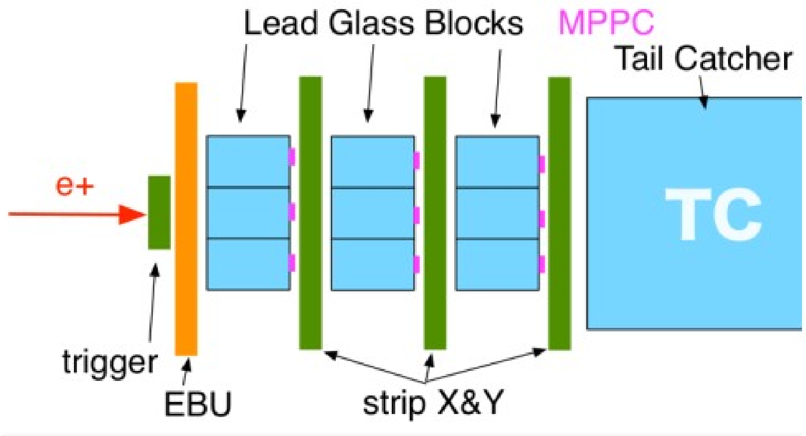
Expect interesting results on timing detectors from CALICE in coming years

R&D on materials

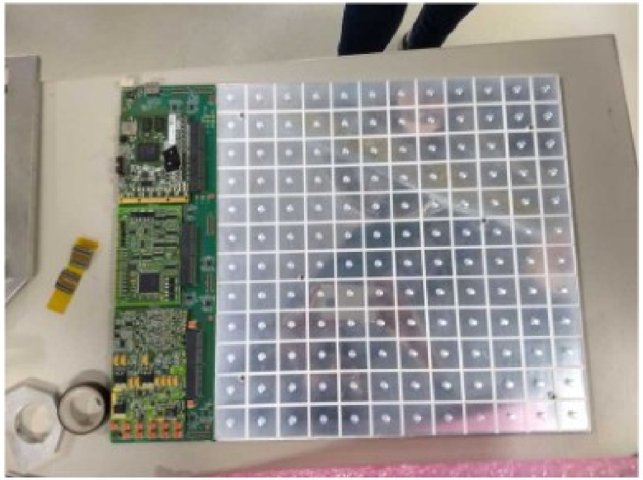
Position Sensitive Devices



Prototype of Crystal calorimeter



Megatiles for scintillator based calorimeters



- Tests in lab ...
- ... but also in beam tests
  - Megatiles and LG-Calo in 2019

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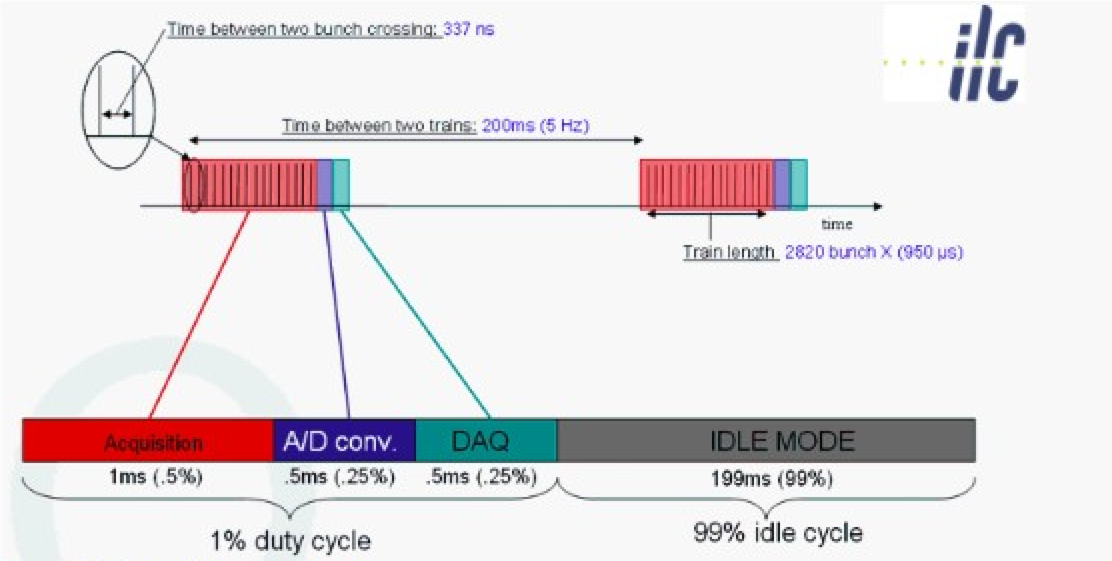
Power pulsing



N.B. Final numbers may vary

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

Mastering of technology is essential for operation ofILC detectors