# Technological Prototypes and Result Highlights of Highly Granular Calorimeters

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on behalf of CALICE collaboration

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July $6^{th}$ 2017

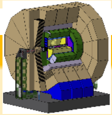
## CALICE collaboration

- 57 institutes, 17 countries (4 continents), $\sim$ 336 members.
- Goal : Research and development of highly granular calorimeters for future lepton colliders.

## Particle Flow Algorithm (PFA)

- ILC physics program requires W/Z$\rightarrow q\bar{q}$ mass separation.
- $\Rightarrow$ jets resolution better than $\sim 3-4$ % $\sim 30\%/\sqrt{E}$.
- Use optimal sub-detector for jet energy estimation :
  tracker ($\sim$ 60%), ECAL ($\sim$ 30%), HCAL ($\sim$ 10%).
- Separate energy depositions from close-by particles :
  high granularity is key point.

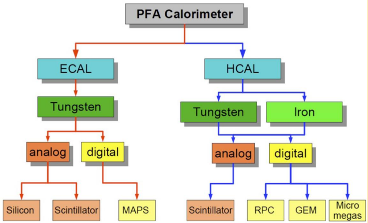
## High granularity calorimeters : ILD baseline example



ECAL 29 layers, 2 to 4 mm thick, $5 \times 5$ mm$^2$ cells.

HCAL 48 layers, 25 mm thick, $30 \times 30$ mm$^2$ cells.

## CALICE calorimeters




## Tungsten for ECAL

- lateral separation : $R_M = 9$ mm
- compactness : $X_0 = 3.5$ mm
- electromagnetic-hadronic shower separation : $\frac{\lambda_I}{X_0} = 27.4$

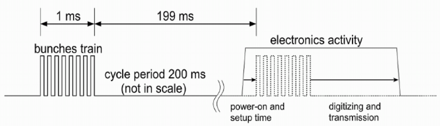
## Physics prototypes

High granularity is achievable, can read the number of channels (DHCAL $>$ 0.5 million channels), can reconstruct energy with the data (it is a calorimeter)

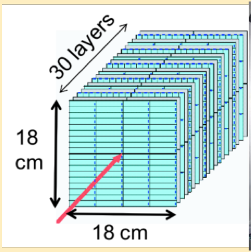
## Technological prototypes

Scalable, buildable, insertable in a ILC-like detector. Embedded electronics

- Based on ROC chips from OMEGA group (HARDROC3, SKIROC, SPIROC, ...)
- Can store event (analogical or digital) for later readout.
- Power-pulsing to reduce consumption to a level compatible with no cooling.

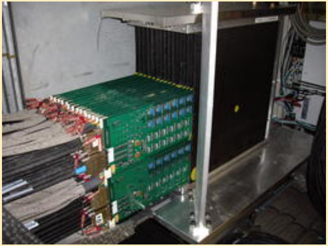


## Scintillator Strip W-ECAL Physics prototype




- 30 layers, 3.5 mm thick W + 3 mm thick scintillator.
- strip $10 \times 45$ mm$^2$, alternating orthogonal orientation (effective cell size $10 \times 10$ mm$^2$).
- 2 readouts with/without wavelength shifting fibre.
- bunch of 9 strips read by Multi Pixel Photon Counter (with 1600 pixels).

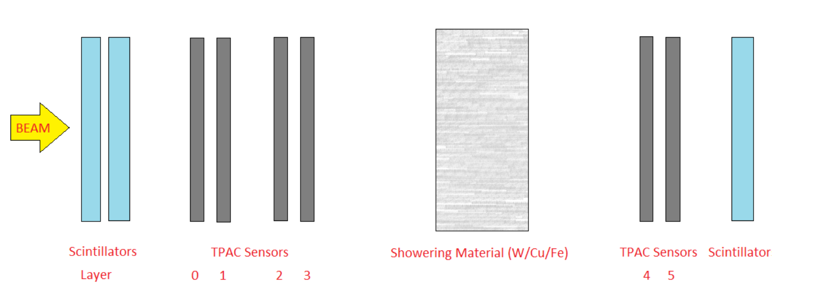
## Silicon W-ECAL Physics prototype



- 30 layers, W-thickness increasing (1.4 mm, 2.8 mm, 4.2 mm)
- 525 $\mu$m thick Si-wafer, $10 \times 10$ mm$^2$ pads in $62 \times 62$ mm$^2$ modules with 0.5 mm guard rings
- $3 \times 3$ modules per layer, $18 \times 18$ cm$^2$ active area.

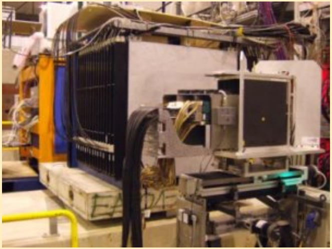
## Digital ECAL , proof of principle

- MAPS (Monolithic Active Pixel Sensor) TPAC sensor
- $168 \times 168$ pixel grid, cell size is $50 \times 50 \mu m^2$




- 4 beam upstream sensors for tracking
- # of hits in downstream sensors depends on absorber length in $X_0$ and electron beam energy.

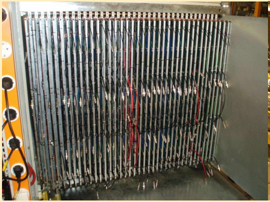
## Scintillator HCAL (AHCAL)

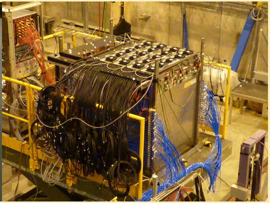


Physics prototype

- 38 layers, Fe or W absorber, 5 mm thick scintillator tiles.
- Tiles size from $30 \times 30$ mm$^2$ in central area to $120 \times 120$ mm$^2$ in outer area.
- Active area $90 \times 90$ cm$^2$
- Tiles read by 16-bit ADC.

## Gaseous HCAL (DHCAL and SDHCAL)



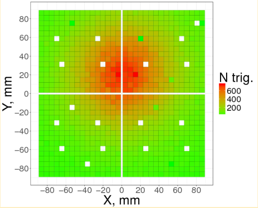


DHCAL physics and SDHCAL technological prototypes

- 3 mm thick Glass Resistive Plate Chamber as active detectors
- 50 (SDHCAL)/54 (DHCAL) layers (20 mm thick Steel plate + 6 mm GRPC+embedded electronics)
- $1 \times 1$ m$^2$ active area.
- Cell size defined by electronic readout : $10 \times 10$ mm$^2$ readout pads, $96 \times 96$ pads per m$^2$.
- 1-bit (Digital HCAL) or 2-bit (Semi Digital HCAL) readout.

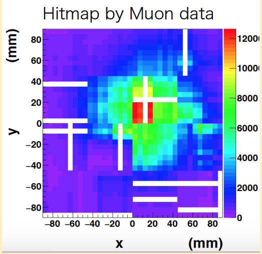
## SiW ECAL technological prototype

- Embedded electronics with SKIROC chips reading 4 sensors.
- Silicon sensor of 256 pixels $5.5 \times 5.5$ mm$^2$, 12 bit ADC per pixel.
- Segmentation of the guard rings
- Irradiation tests (Si OK for 50 years of ILC)
- 10 layers build.



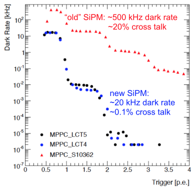

## Scintillator-W ECAL technological prototype

- Thinner strips (2 mm, even 1 mm), $45 \times 5$ mm$^2$ strips, effective cell size $5 \times 5$ mm$^2$
- No wavelength-shifting fibre, strips and Surface Mounted (SMD)-SiPM with 10000 pixels directly mounted on the PCB.
- Improved strips uniformity.
- New Strip Splitting Algorithm to extract cell information from strips.



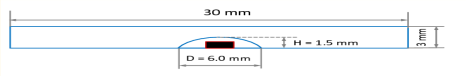
## SiPM

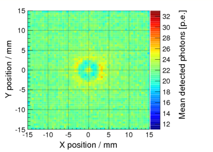
- Embedded PCB with SMD-SiPM read by SPIROC.
- Low noise new generation SiPM

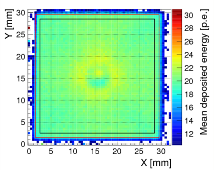



## Scintillator tiles

Tiles with optimized dome shape cavity, wrapped in reflective foil.

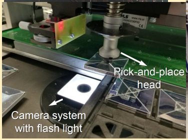


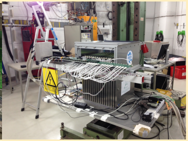




## Mass production with pick and place machine

- small stack with 15 layers build and tested.
- large stack ( $\sim$1 m$^3$, 160 boards for 40 layers) to be completed by the end of this year.

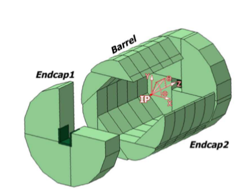


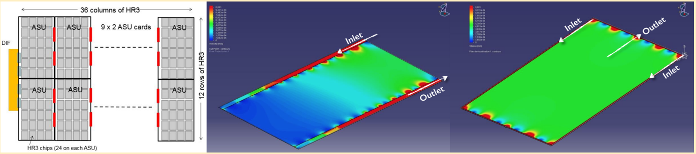



## The ILD HCAL "Videau" geometry requires GRPCs of various lengths (up to 3 m)

Design and construction of length-scalable GRPC+electronics :

- HARDROC3 (HR3) chips : zero suppression, extended dynamic range, ...
- New Active Sensor Unit (readout pads and HR3) daisy chained, $1 \times \frac{1}{3}$ m$^2$.
- One Detector InterFace board per chamber any size, with parallel I2C link communication.
- redesigned gas distribution



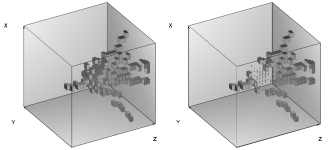

## Mechanical structure : steel plates production and assembly

- Industrial production by roller levelling up to $1 \times 3$ m$^2$ (flatness $< 1$ mm)
- Electron beam welding at CERN

## Physics prototype energy resolution

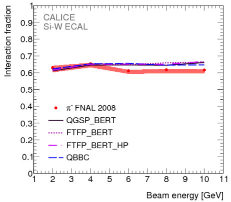
Si-W ECAL $\frac{(16.5 \pm 0.2)\%}{\sqrt{E}} \oplus (1.9 \pm 0.2)\%$

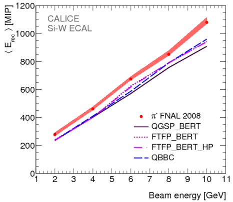
Scintillator ECAL $\frac{\left(13.2^{+0.2}_{-1.7}\right)\%}{\sqrt{E}} \oplus \left(3.7^{+0.5}_{-3.7}\right)\%$

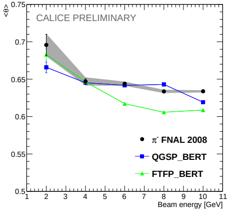


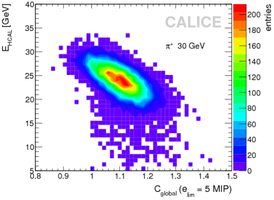

## Test of hadronic interaction in Si-W ECAL

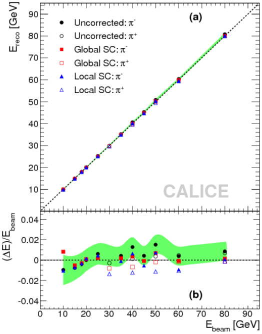
Detection of pion interaction from evolution of energy deposition per layer (efficiency range from 60% for 2 GeV $\pi^+$ to 93% for 10 GeV $\pi^+$) , reconstruction of tracks emerging from pion interaction $\Rightarrow$ test of GEANT4.



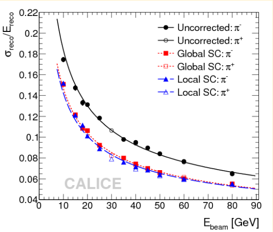





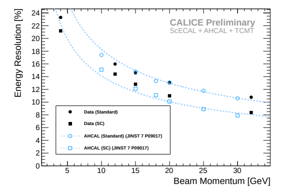

## Software compensation (electromagnetic fraction)

- AHCAL energy response linear
- High energy density in electromagnetic part of hadronic shower
- Derive energy correction based on local cell energy density or global based on mean cell energy density in shower.




| $\frac{\sigma_{reco}}{E_{reco}}$ | stochastic | constant | noise |
|---|---|---|---|
| Uncorrected | $(57.6 \pm 0.4)\%$ | $(1.6 \pm 0.3)\%$ | 1.8% (fix) |
| Global SC | $(45.8 \pm 0.3)\%$ | $(1.6 \pm 0.2)\%$ | 1.8% (fix) |
| Local SC | $(44.3 \pm 0.3)\%$ | $(1.8 \pm 0.3)\%$ | 1.8% (fix) |

## Combined Scintillators ECAL + AHCAL physics prototype test beam

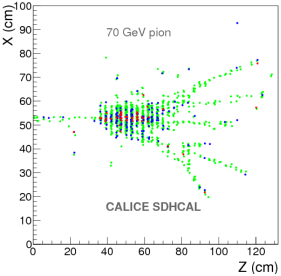


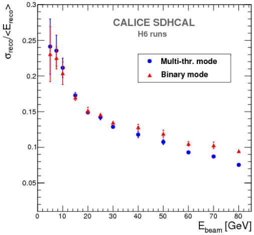
## Energy reconstruction in digital hadronic calorimeters

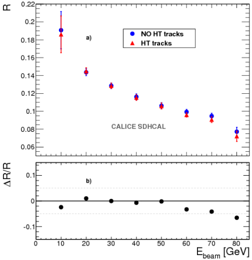
- Linear function of the number of hits ⇒ Overcompensating response (non linear)
- Quadratic function the number of hits ⇒ Linear response
- Modulating response depending on the threshold crossed ⇒ partial correction related to electromagnetic fraction ⇒ improved resolution

## Extra corrections

- Correct for recovery time in data
- Modulating response depending hits is in tracks (Hough Transform).



## Particle Flow Algorithms

**Pandora** Most mature, optimized for ILD baseline cell size (Scintillator ECAL and AHCAL), designed for analogue device.

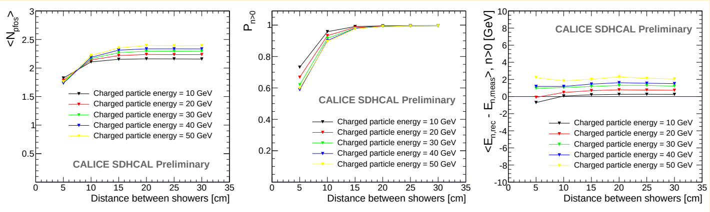
**ArborPFA** Use PandoraSDK, designed for SDHCAL, small cell size.

**GARLIC** Si-W ECAL optimised EM shower reconstruction.

## Test PFA separation power

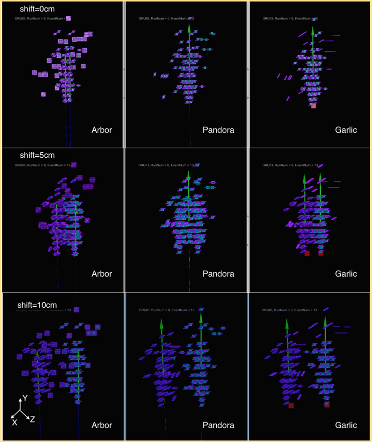
- Combine 2 single particle showers from test beam data in one event.
- Emulates neutral hadron by removing hits corresponding to the incoming track.

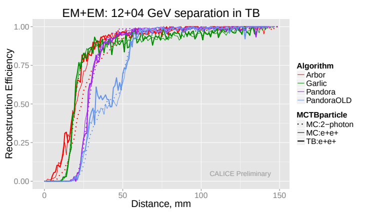
## $h^+ - h^0$ separation in SDHCAL with ArborPFA ($h^0$ at 10 GeV)

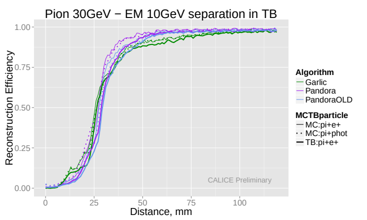


# Combined Scintillator ECAL-AHCAL separation

## Overlay two 4 GeV $e^+$



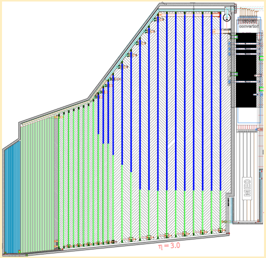



LHC phase II upgrades need to cope with high luminosity, higher pile-up.
High granularity can help

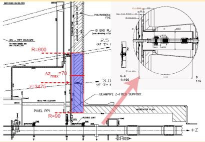
## CMS HGCAL

- High Granularity CALorimeter
- High (resp low) level radiation sectors inspired from CALICE SI-W ECAL (resp Scintillator ECAL and AHCAL) technology



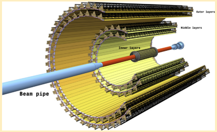

## ATLAS HGTD

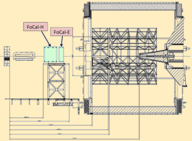
- High Granularity Timing Detector
- Inspired from CALICE SI-W ECAL technology




## ALICE ITS and FOCAL

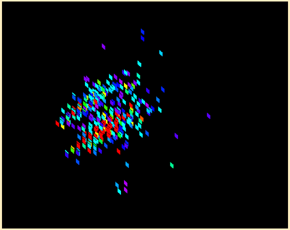
- Common team CALICE DECAL MAPS/ ALICE FOrward CALorimeter.
- Development in synergy with ITS tracker upgrade.



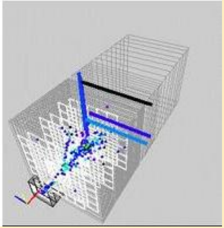



- CALICE collaboration is developing highly granular calorimeters designed for particle flow paradigm.
- Detector concepts validated with physics or technological prototypes.
- Moving towards scalable and buildable devices for ILC detectors.
  - baseline cell size, automated scintillator mounting, expandable GRPC design, ...
- Testing Particle Flow concept on real data.
- CALICE technologies are inspiring HL-LHC experimental upgrades.
- Unprecedented spatial (and time) view of showers gives input to simulation models.

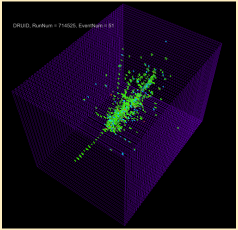
### Si W Ecal e+$\gamma$



### AHCAL

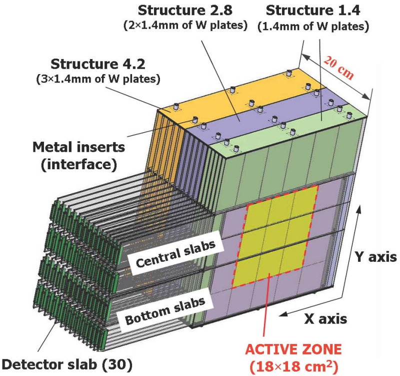


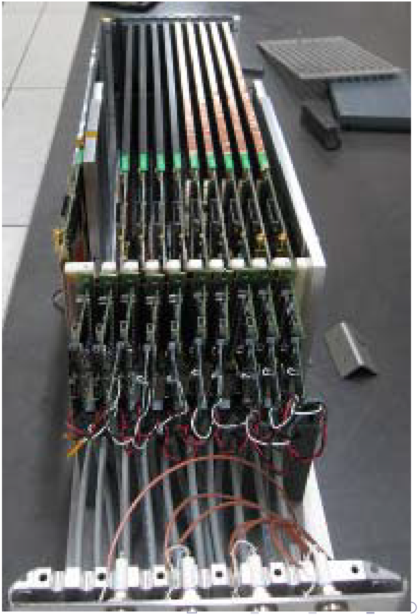
### SDHCAL

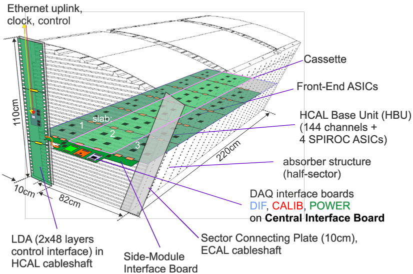


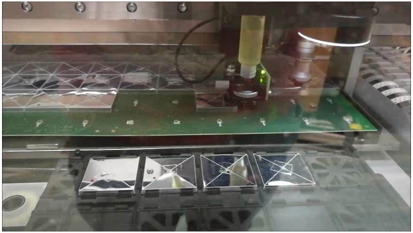
Thanks for your attention

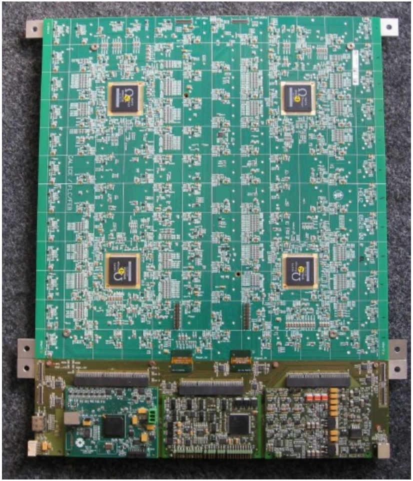
# Backup

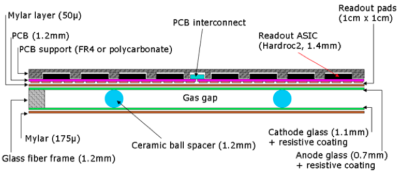

Structure 2.8
(2×1.4mm of W plates)
Structure 1.4
(1.4mm of W plates)
Structure 4.2
(3×1.4mm of W plates)
20 cm
Metal inserts
(interface)
Central slabs
Bottom slabs
Y axis
X axis
Detector slab (30)
ACTIVE ZONE
(18×18 cm²)




Ethernet uplink,
clock, control
Cassette
Front-End ASICs
HCAL Base Unit (HBU)
(144 channels +
4 SPIROC ASICs)
absorber structure
(half-sector)
DAQ interface boards
DIF, CALIB, POWER
on Central Interface Board
Sector Connecting Plate (10cm),
ECAL cableshaft
Side-Module
Interface Board
LDA (2x48 layers
control interface) in
HCAL cableshaft
slab:
1
2
3
110cm
10cm
82cm
220cm





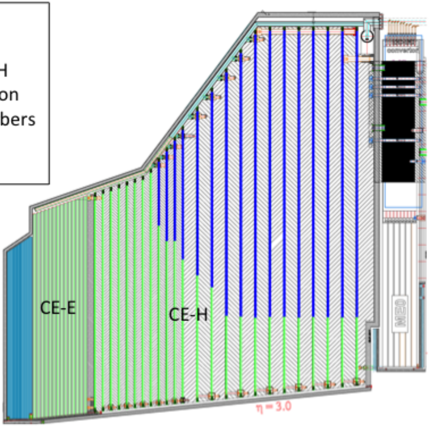

Mylar layer (50µ)
PCB interconnect
Readout pads
(1cm x 1cm)
PCB (1.2mm)
PCB support (FR4 or polycarbonate)
Readout ASIC
(Hardroc2, 1.4mm)
Gas gap
Mylar (175µ)
Ceramic ball spacer (1.2mm)
Cathode glass (1.1mm)
+ resistive coating
Glass fiber frame (1.2mm)
Anode glass (0.7mm)
+ resistive coating

**Active Elements:**

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

**Key Parameters:**

- EC covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap




Electromagnetic calorimeter (**CE-E**): Si, Cu & CuW & Pb absorbers, 28 layers, 25 $X_0$ & ~1.3$\lambda$

Hadronic calorimeter (**CE-H**): Si & scintillator, steel absorbers, 24 layers, ~8.5$\lambda$