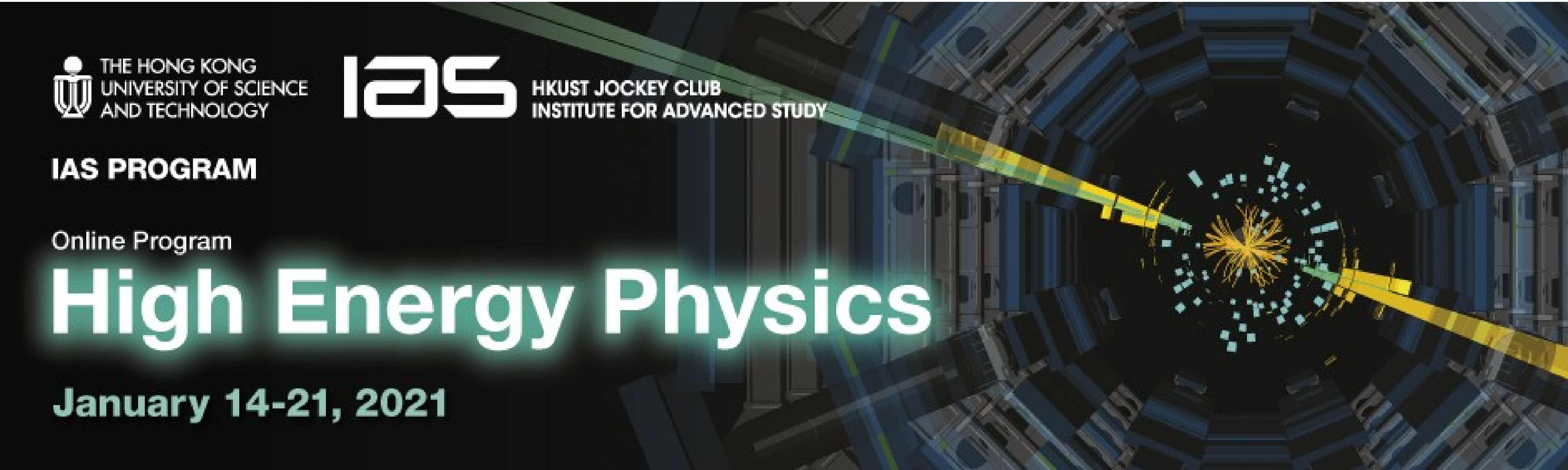
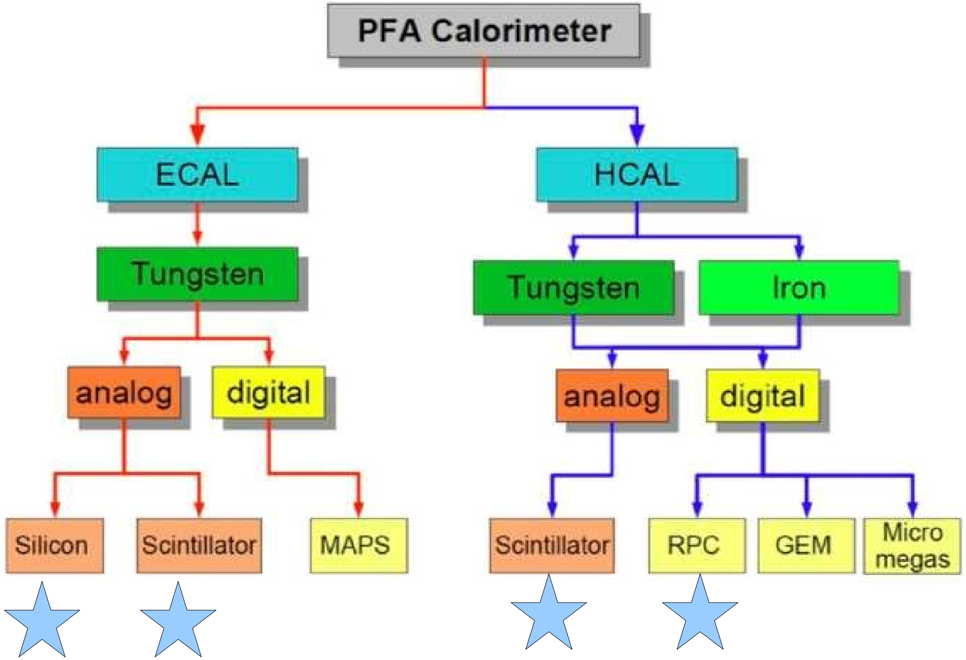
Status of Particle Flow Algorithms (PFA) Calorimeter R&D

Adrián Irles on behalf the **CALICE Collaboration**
IFIC (UV/CSIC)



Particle Flow Calorimetry R&D

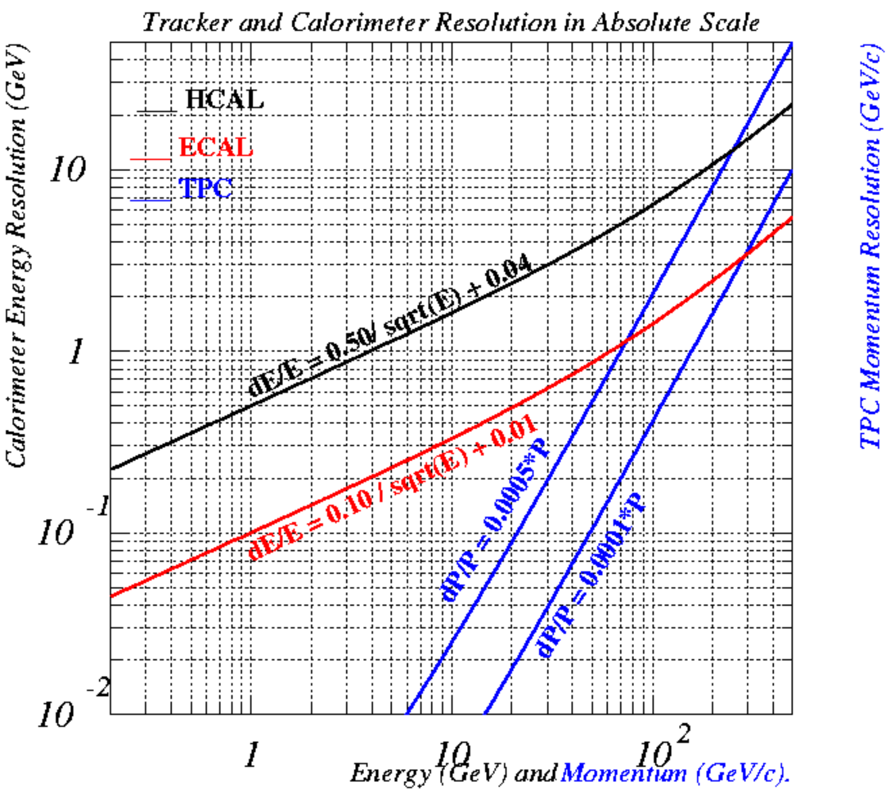
Mainly organised within the CALICE Collaboration



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

Jet energy resolution



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

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

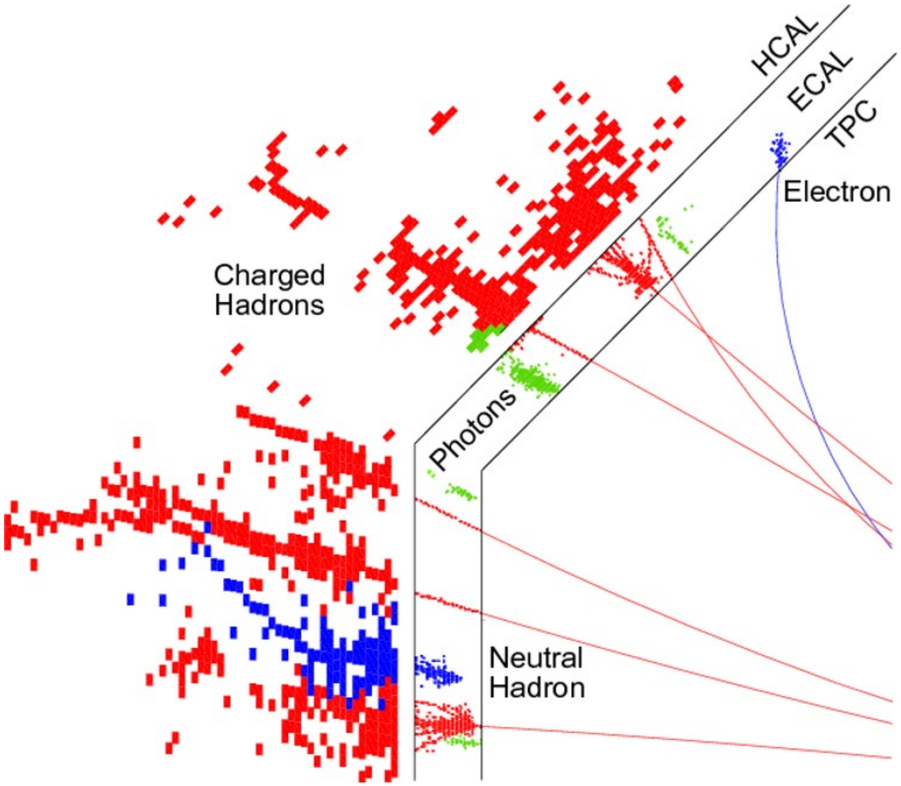
In a "typical jet" the energy is carried by

- ▶ **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

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

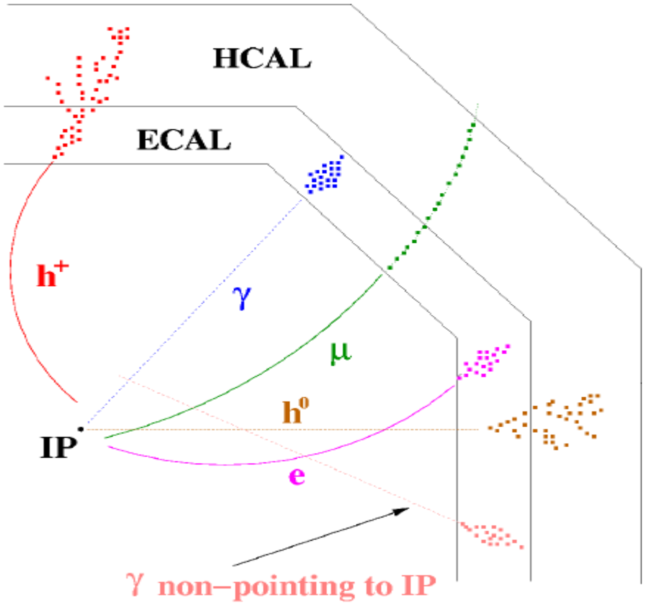
- Need to minimize this term as much as possible

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
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers
- And fast timing calorimeters

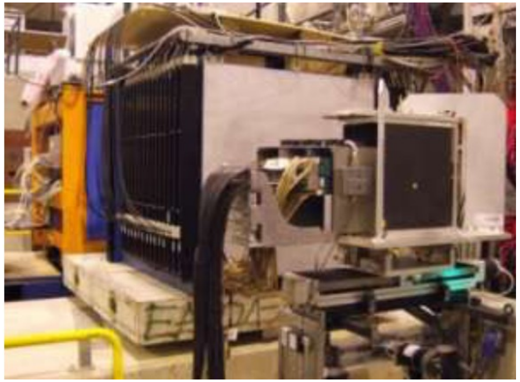


Particle flow as privileged solution for experimental challenges
=> Highly granular calorimeters!!!
Emphasis on tracking capabilities of calorimeters

CALICE – History and steps

Physics Prototypes

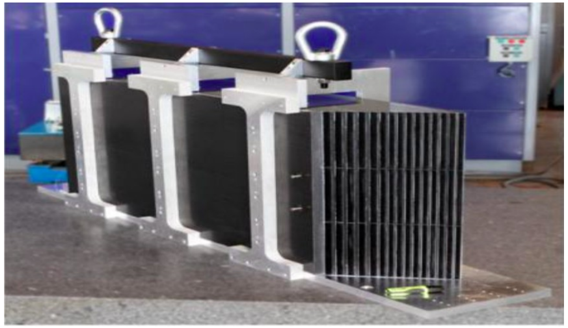
2003 - 2012



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

Technological Prototypes

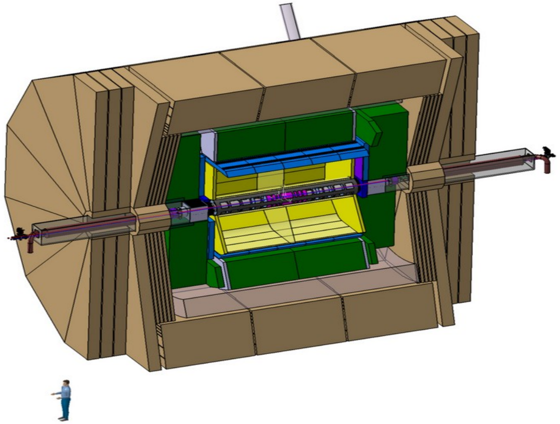
2010 - ...



Engineering challenges

This talk

(LC) detector



- Goal: ~10^8 calorimeter cells

  to compare:

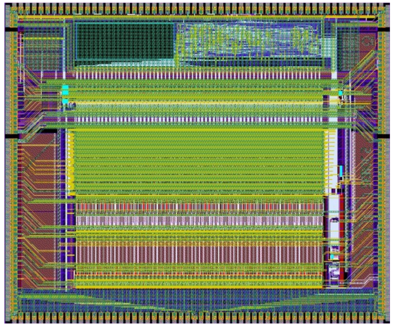
  ATLAS LAr ~ 10^5 cells

  CMS HGCAL ~10^7 cells

Technological premises

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)



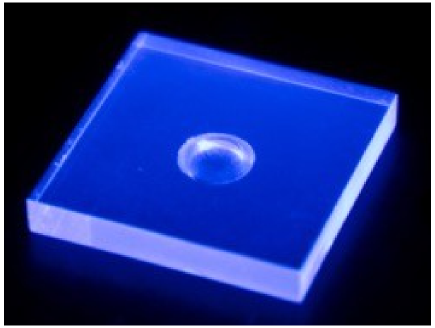
Size 7.5 mm x 8.7 mm,

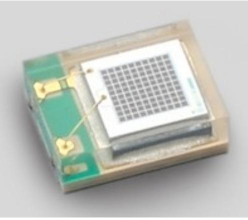
64 channels

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

... all within one ASIC

Miniaturisation of r/o devices



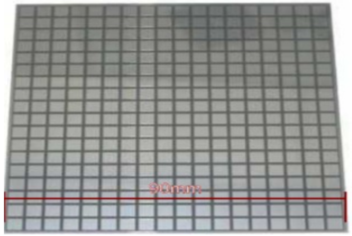


- Small scinitllating tiles
- (Low noise) SiPMs

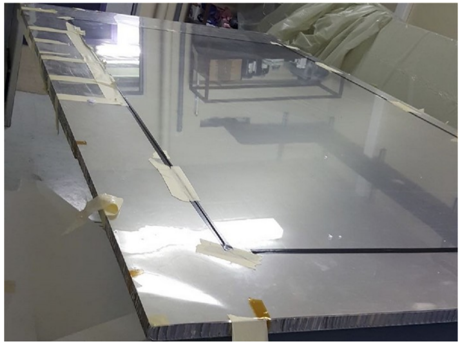
Power pulsed electronics
to reduce power consumption…
Compactness –> no space left for active cooling systems

Large surface detectors

Si Wafer



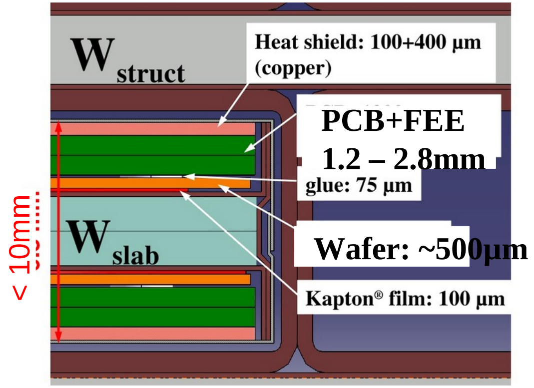
RPC layers



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

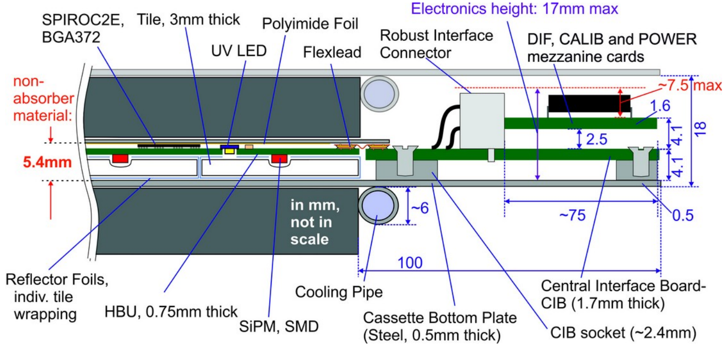
Technological solutions for final detector I

SiW Ecal



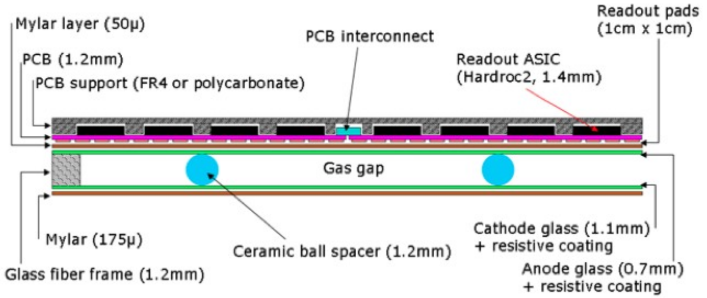
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



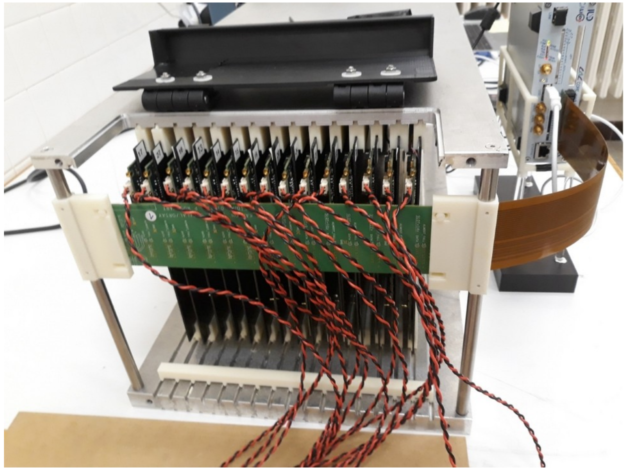
Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

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

CALICE SiW-ECAL

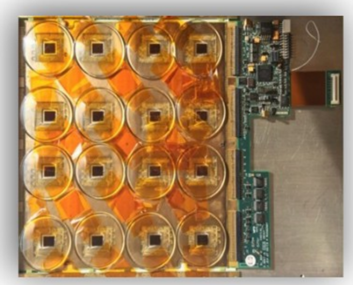
- ▶ new technological prototype with tungsten absorber
  - Si pads: 5 × 5 mm^2 (ILD design)
  - 15 modules layers × 1024 channels/layer ≈ **15000 cells (~as CMS)**
  - going to test beams again in 2021 (DESY)
- ▶ All components designed to fit the requirements of a Lepton Collider Detector
  - Ultra compact digital readout systems
  - Same granularity as ILD



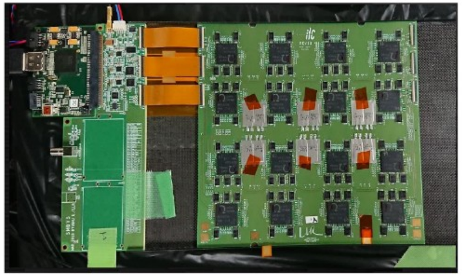
▶ Very dense **PCBs *aka* FEV** with 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm board

FEV10-12

FEV_COB

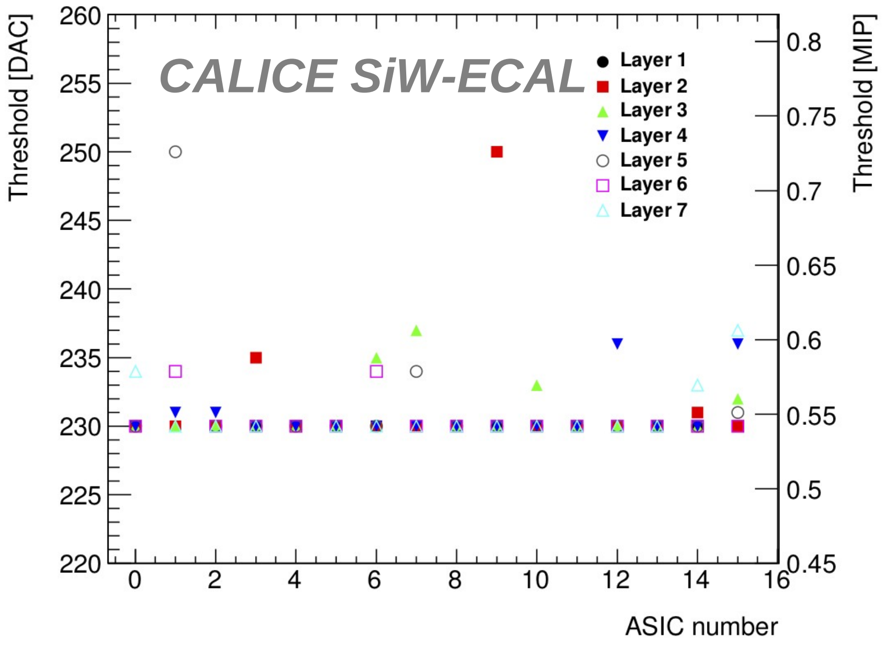


FEV13

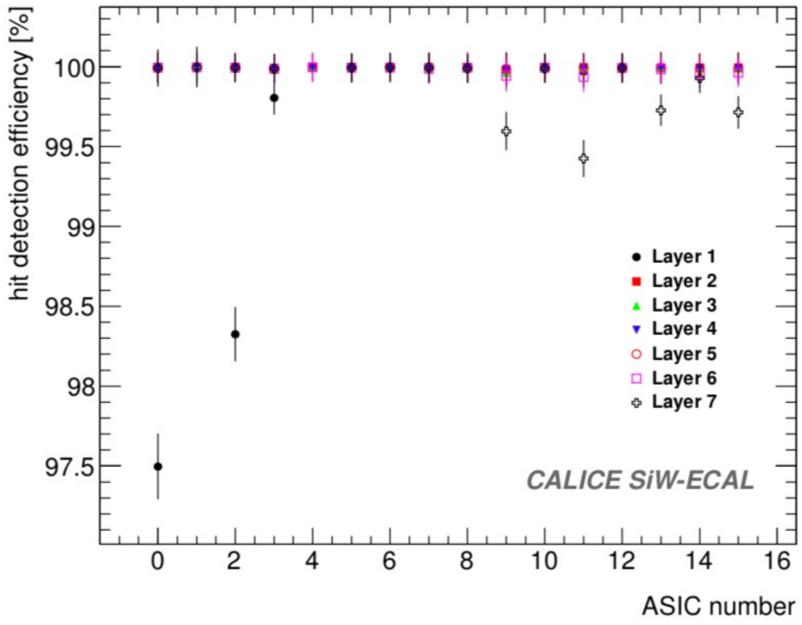


Highly compact objects with minimal space for the components needed to assure the integrity of the signals & a proper power management

CALICE SiW-ECAL: performance at MIP level



Arxiv:1810.05133



Trigger thresholds uniform at around 1/2 MIP

MIP Detection efficiency ~100%

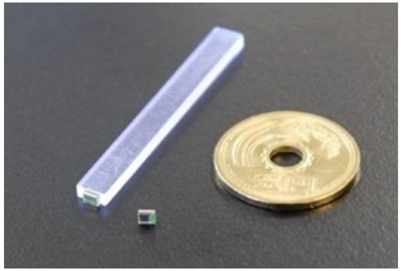
PFA requires small pixel size, large segmentation and pattern at low energy:

a) Access to small signals -> Low self-trigger thresholds (with zero supression and high S/N ~10 at MIP)✔

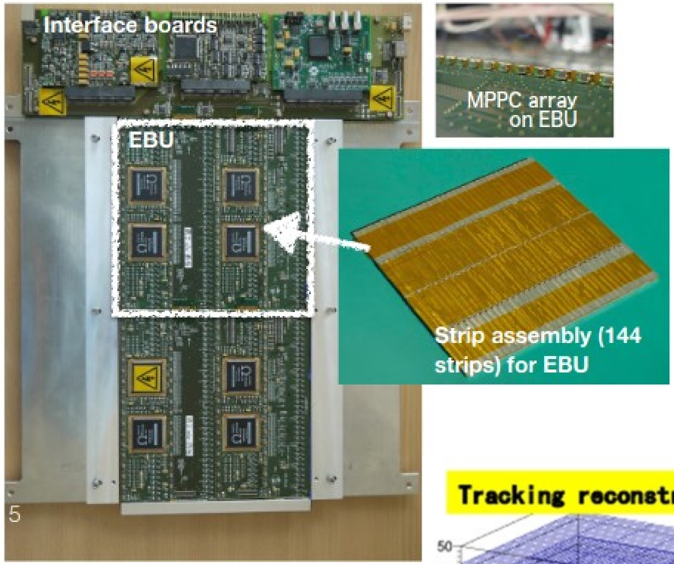
b) Tracking in calorimeters -> High MIP detection efficiency ✔

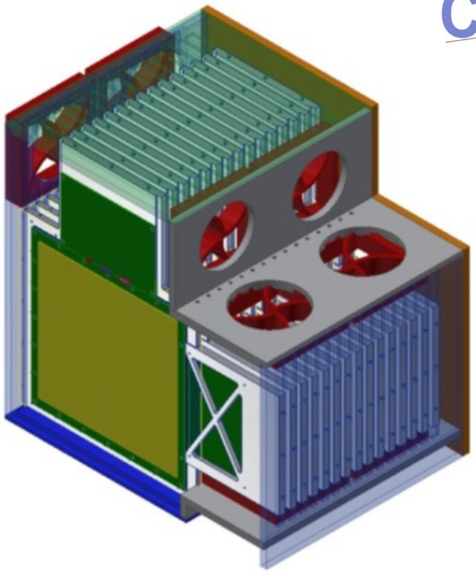
CALICE Sc-ECAL

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

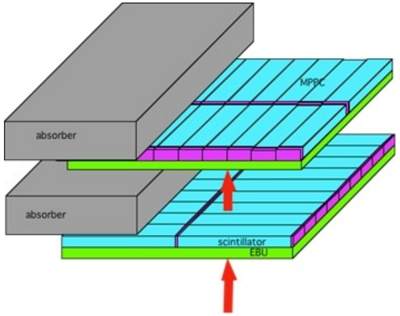


45×5×2mm^3 scintillator strips
2.45×1.9×0.85 mm^3 SiPM

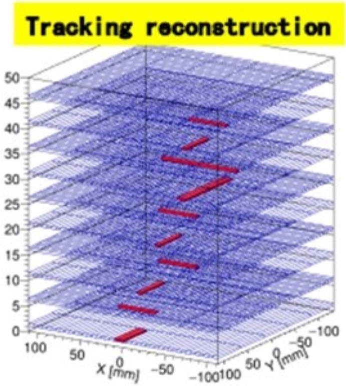


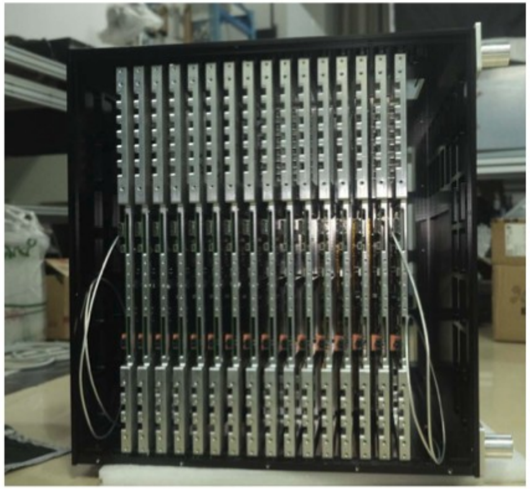


Test beams at DESY early 2021

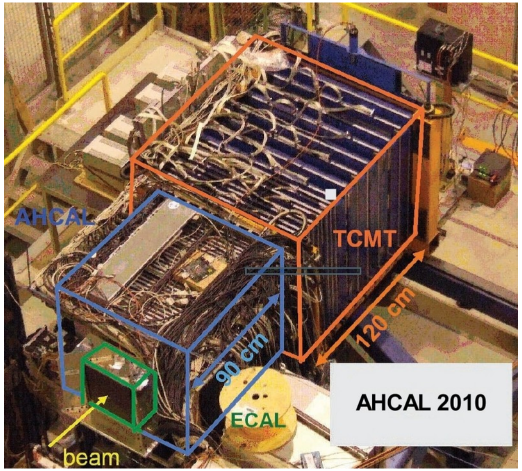


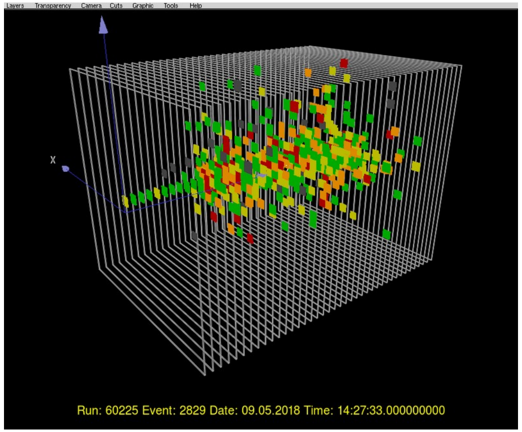
Strips could be read at both ends of longer strips
to increase accuracy and provide redundancy.





CALICE – Analogue HCAL

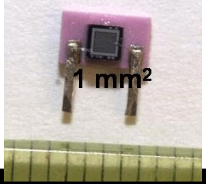


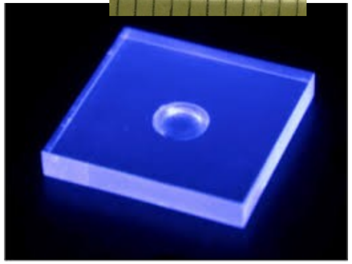


38 layers
72×72×2.5 cm^3 / layer
22,000 tiles

SiPM under the tiles
for better uniformity
and light collection

3x3cm^2 tiles



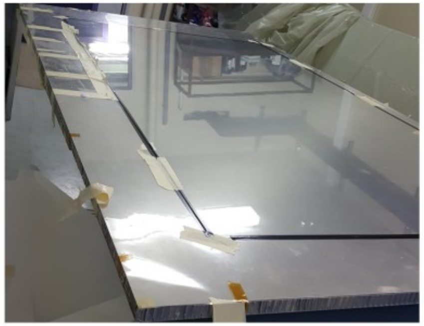


each cell also provides
time information with
~1ns resolution

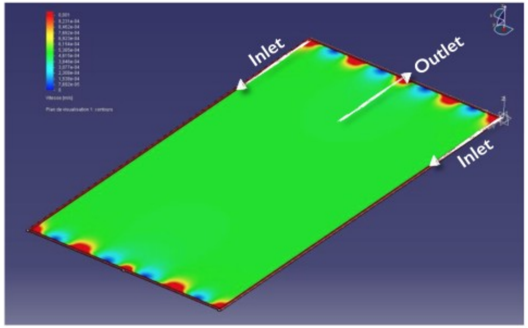
a true 5D "pixel" detector: x,y,z,E,t

Semi Digital-HCAL

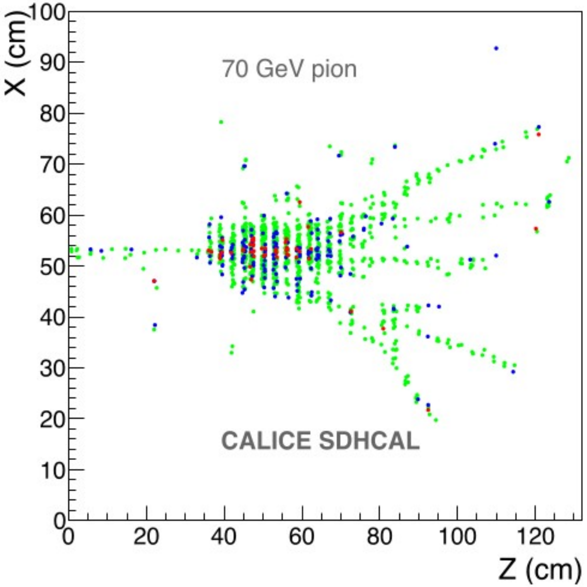
2 m^2 RPC assembled



Scalable gas distribution



- ▶ 48 layers × 26 mm, also made of glass RPC.
  - 96 × 96 channels per layer, i.e.
  - ~440000 1×1 cm^2 readout channels.
- ▶ Semidigital 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.

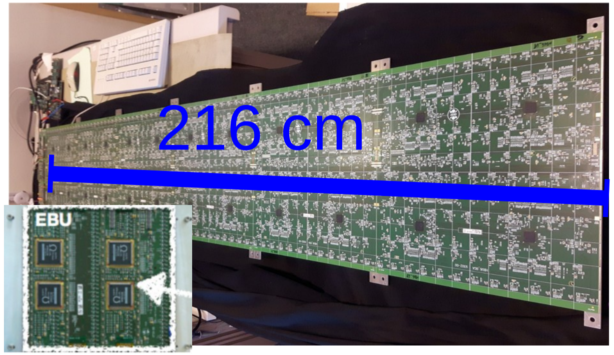


Technological solutions for final detector II

SiW Ecal

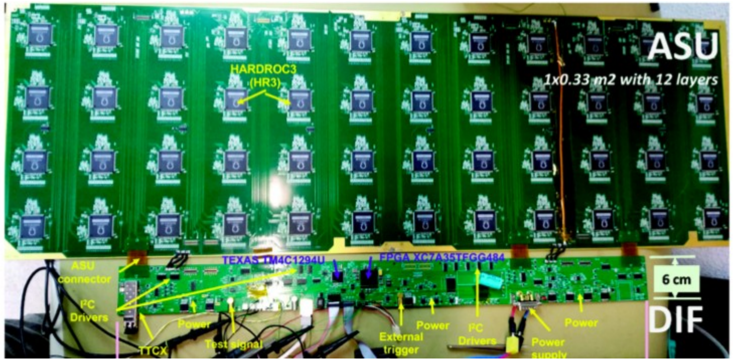
Semi-conductor readout

Analogue Hcal and Scintillator Ecal



Optical readout

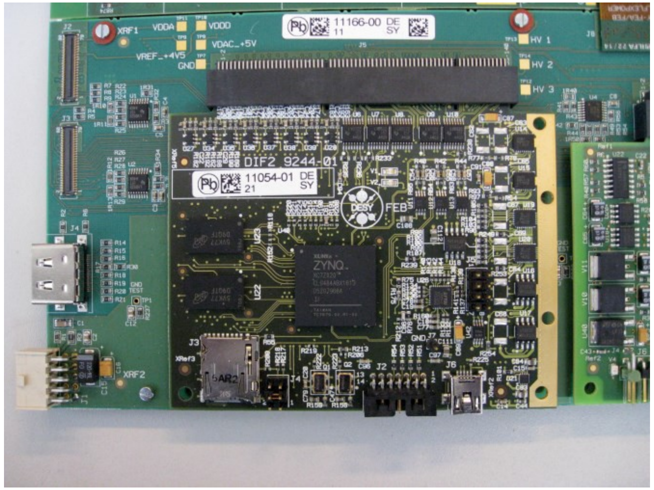
Semi-digital Hcal



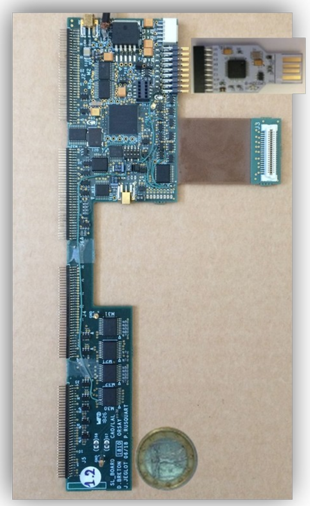
- Realistic detector dimensions
  - Structures of up to 3m in length (more than 10000 cells)
  - With compact external components
- Challenge for the power pulsing techniques (for the power consumption management)

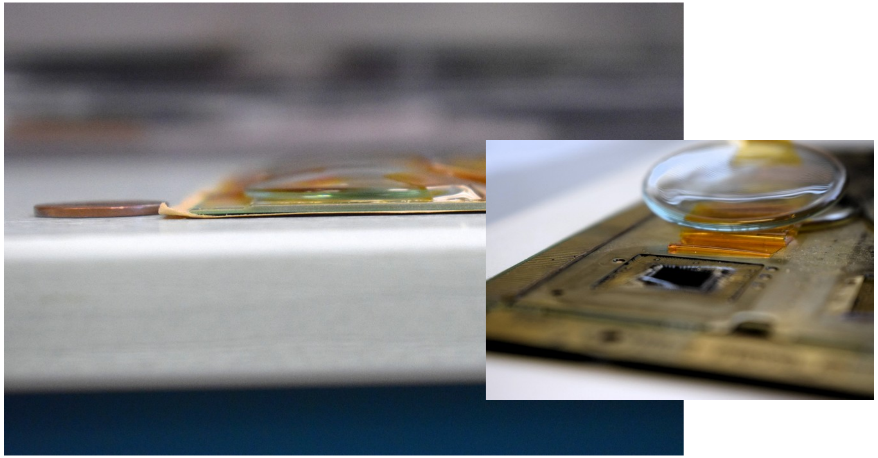
Technological solutions for final detector III

Current detector interface card - AHCAL

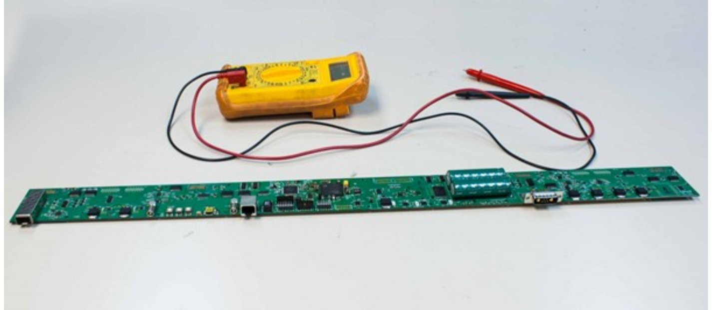


Current detector interface card and thin detection unit – SiW Ecal



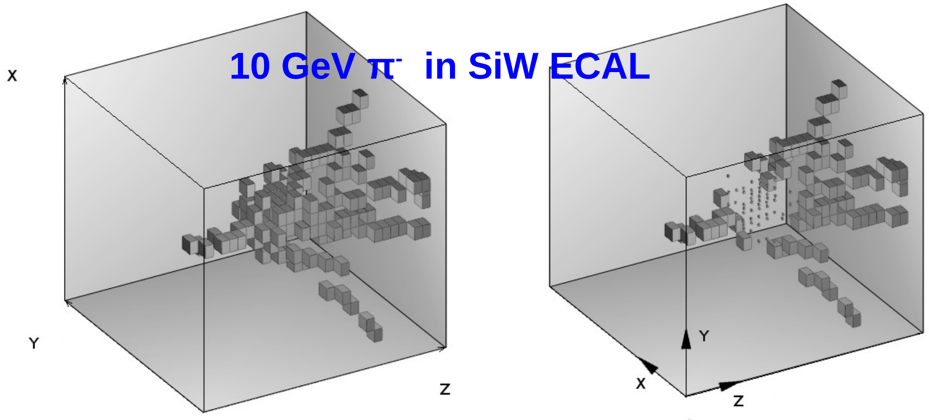


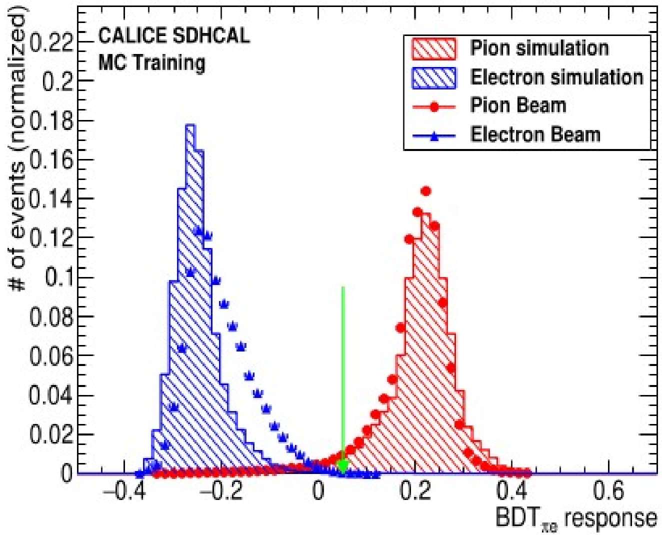
Current detector interface card - SDHCAL



- "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

High granularity calorimeters: more than “only” PFA





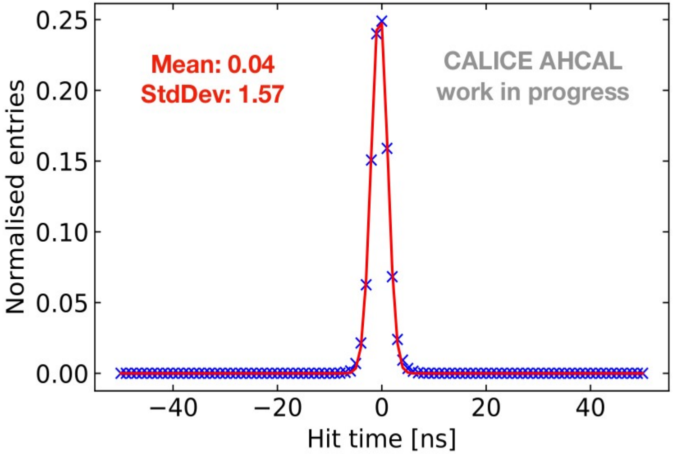
- **study of first hadronic interaction in the SiW-ECAL** (physics prototype)
  - NIM A 937 (219) 41-52

- **SDHCAL** using 6 variable discriminnating **BDT for Particle Identification** [JINST 15 (2020) P10009]

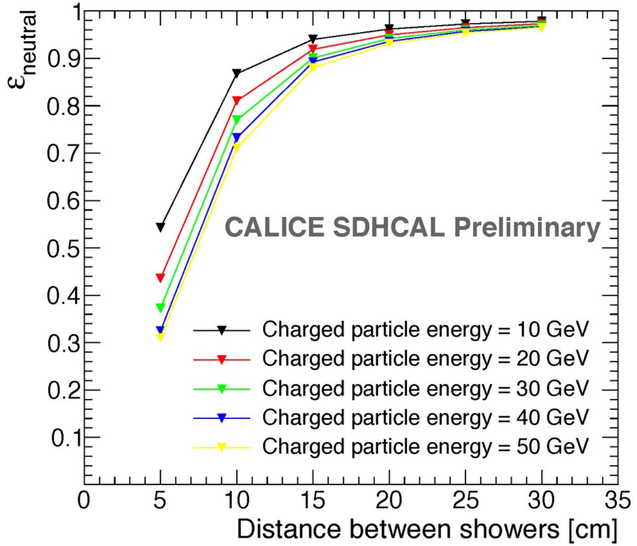
The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

High granularity calorimeters: more than “only” PFA

Clock frequency 5 MHz,
Powering pulsing



- Hit time resolution: Results from **2018 beam test** of **AHCAL** with muons
  - Encouraging results (1-2 ns resolution)
  - Distinction between slow and fast components in the showers (neutral vs charged)



- **SDHCAL**: Separation of 10 GeV between neutral hadron and charged hadron [CALICE-CAN-2015-001]
  - More than 90% efficiency and purity for distances ≥ 15 cm

The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

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 to start in 2021-22**
- **Looking forward for a lepton collider soon!**

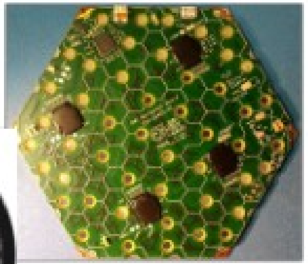
Many other topics could not be covered in this talk but you may find some extra material in the back up slides

- **CALICE R&D inspired CMS high granularity solution HGCAL**. Common testbeams with the AHCAL prototype.
- **Further spin-offs**
  - ALICE FOCAL, DUNE ND, Belle II Claws
- Optimization and **development of different PF algorithms** (Pandora, Arbor, April, Garlic…)
  - Detector performance comparisons require also high level of PF algorithm developments.
- **Other technological solutions** (i.e. SiW-ECAL for SiD detector)
- **The next decade: high precision (ps) timing** calorimeters?
- Original target of the CALICE calorimeters were the linear colliders but **also** they are *directly* applicable to **circular colliders**

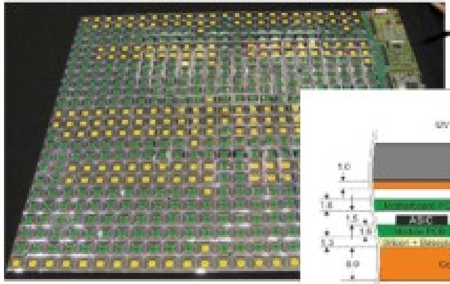
Back-up slides

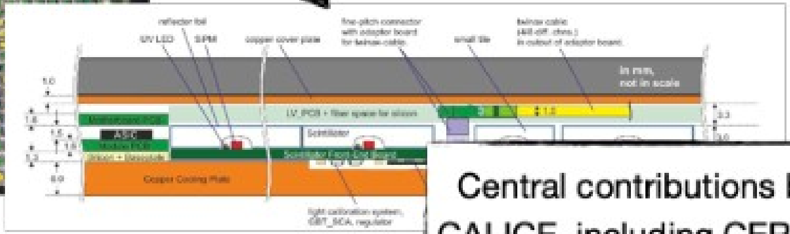
Spinoffs of CALICE R&D I: CMS HGCAL

- 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.

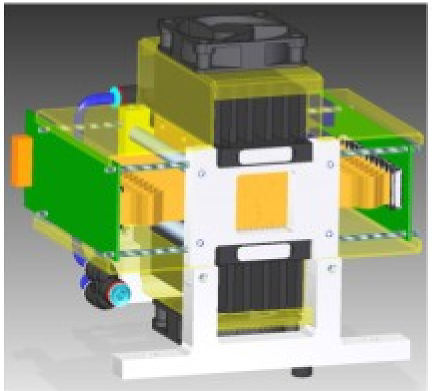
Spinoffs of CALICE R&D II

FOCAL MAPS ECAL:

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

Numbers for FOCAL assuming ≈ 1m² detector surface

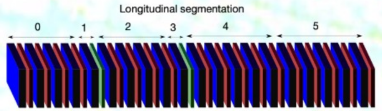
	LG	HG
pixel/pad size	≈ 1 cm²	**≈ 30x30 μm²**
total # pixels/pads	≈ 2.5 x 10^5	**≈ 2.5 x 10^9**
readout channels	≈ 5 x 10^4	**≈ 2 x 10^6**



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

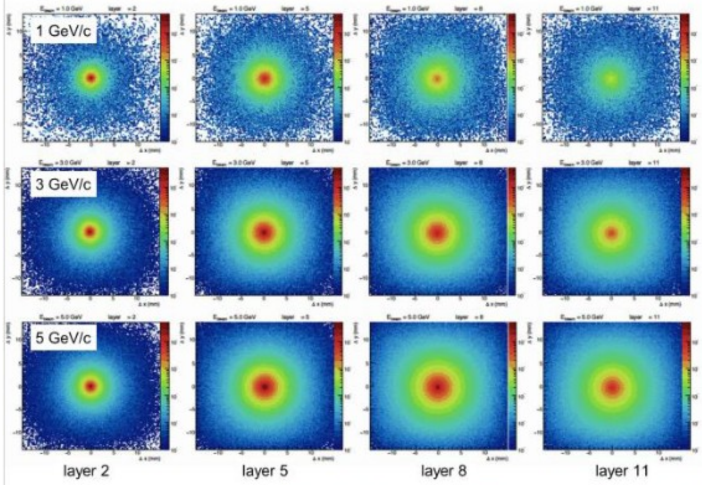
▶ TestBeam in Nov2019 & Feb2020

- 24 layers,
- 48 ALPIDE sensors,
- 24M pixels

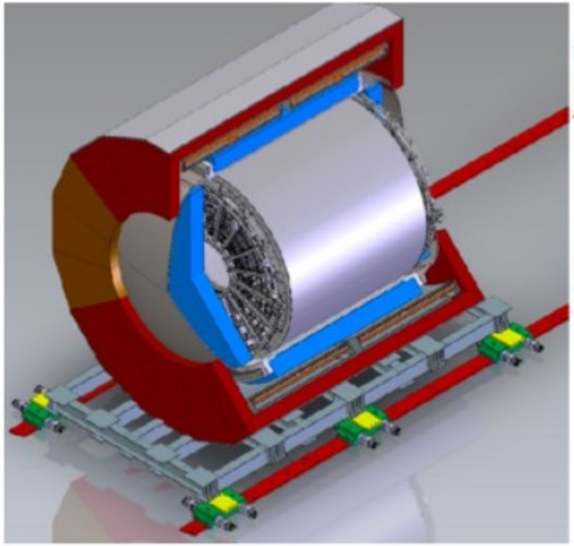


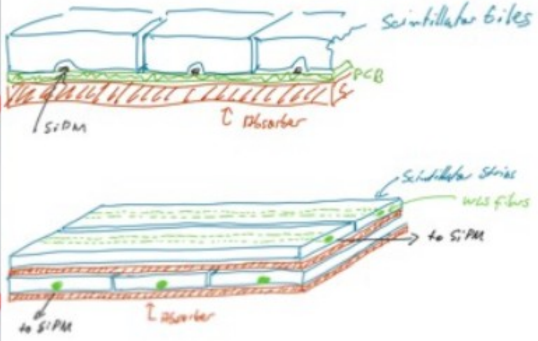
New ALPIDE CMOS sensor based 3cm×3cm area 24 layer stack

UNIVERSITY OF BIRMINGHAM



Spinoffs of CALICE R&D III



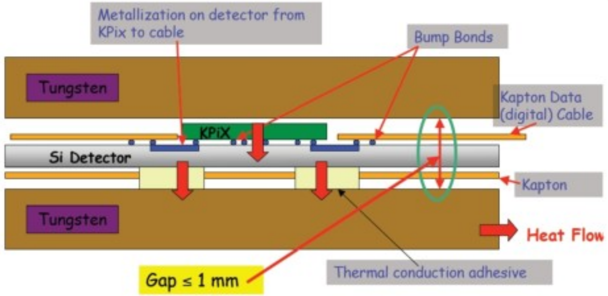


- SiPM-on-Tile and scintillator strips as active material for DUNE Near Detector
- Similar requirements on compactness as lepton collider detectors
  - Study of adaptation of CALICE technologies ongoing
  - Including first discussions on engineering level

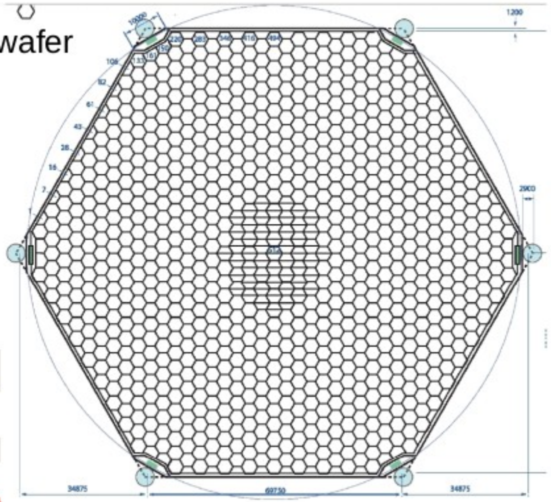
SiD – Si-W ECAL

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

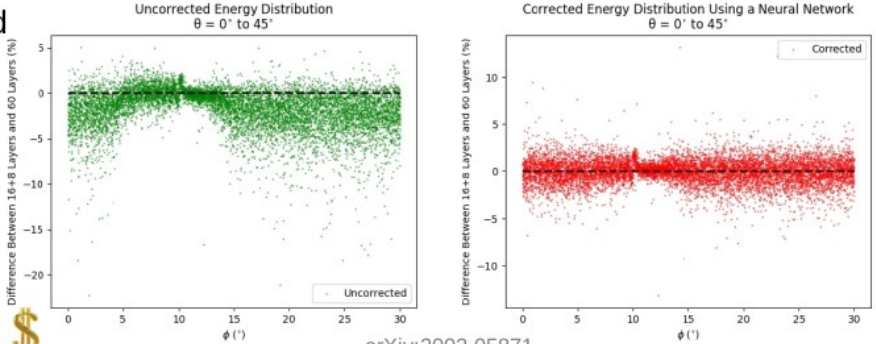


arXiv:1306.8329 - ILC TDR 4: Detectors

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 $\theta = 0° - 45°$
- azymuthal angles $\phi = 0° - 30°$

Design performance possible with 16+8 configuration: $

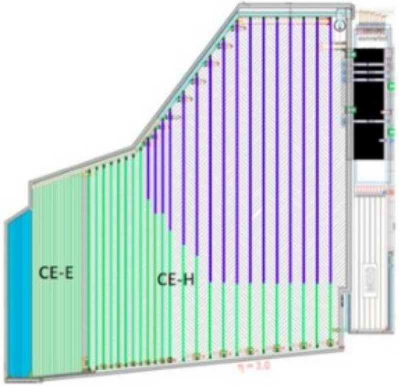


arXiv:2002.05871

SiW ECAL/SDHCAL (2018)

CALICE meets CMS

Common beam tests since 2017



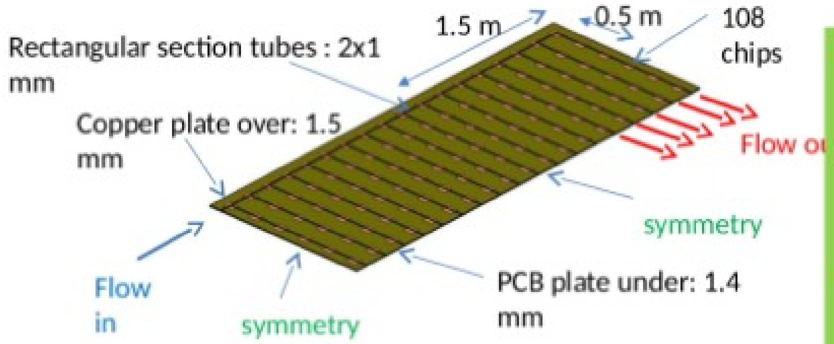
- Common beam tests benefit from common approach within CALICE
- But also from wider networking activities such as EUDAQ2 of AIDA2020
- More common beam tests to come after CERN shutdown

FCC Week – November 2020 22

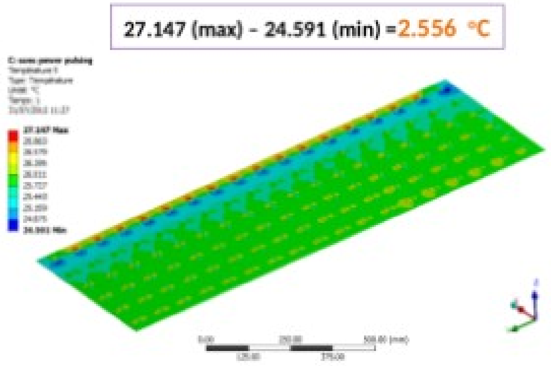
Power pulsing at LC <-> No power pulsing at Circular Colliders => Strong heat dissipation

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

8

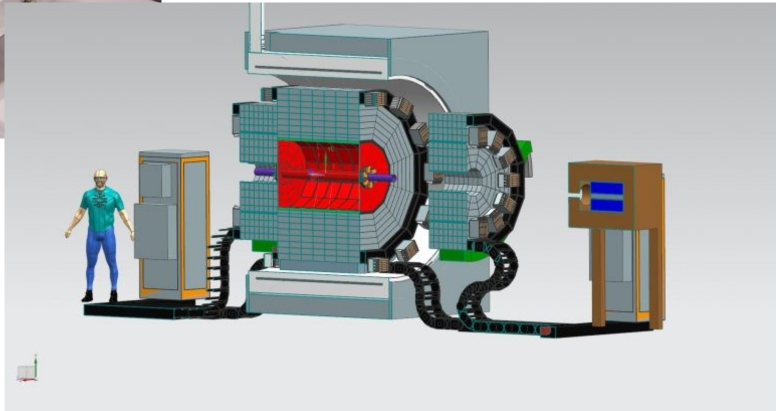
CEPC Xtal Calo Workshop – July 2020 33

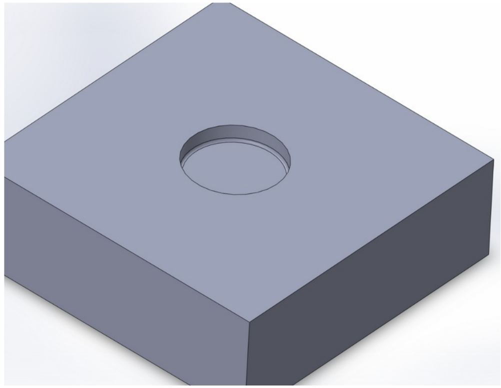
Dual & high granularity (and timing) calorimetry

- 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.

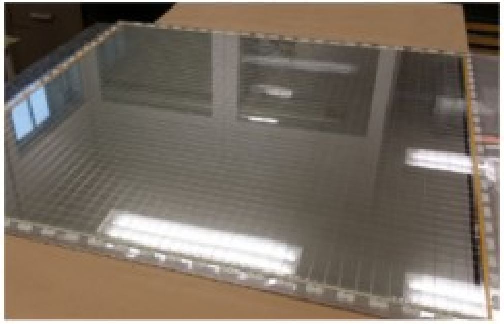
- Active mat.1: Plastic scintillator
- Active mat.2: heavy dense glass (only sensible to charged particles via Cherenkov rad). Fast detectors !
- Another example: ADRIANO2 detector





The next decade: ps timing in calorimeters

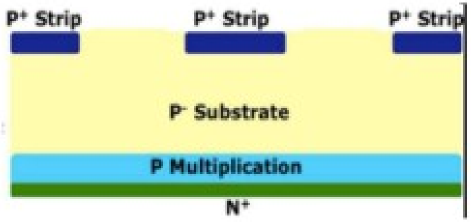
Pioneered by LHC Experiments, timing detectors are/will be also under scrutiny by CALICE Groups



Under development:
GRPC with
PETIROC

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

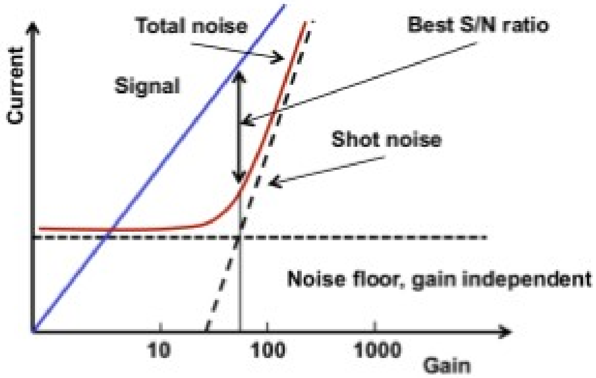
Inverse APD as LGAD?



Inverse APD
by Hamamatsu

Gain ~ 50

Theory says, need comparatively small amplification

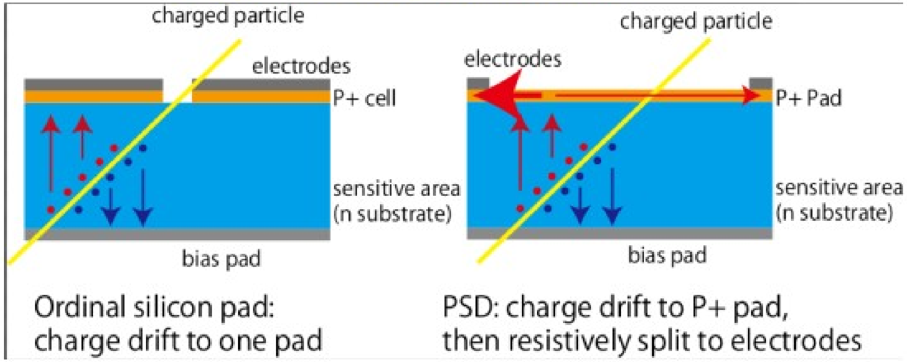


- Shot noise may be limiting factor
- Expect interesting comparison between inverse APD and LGAD as e.g. used by ATLAS
- Not that Members of CALICE are also members of ATLAS-HGTD

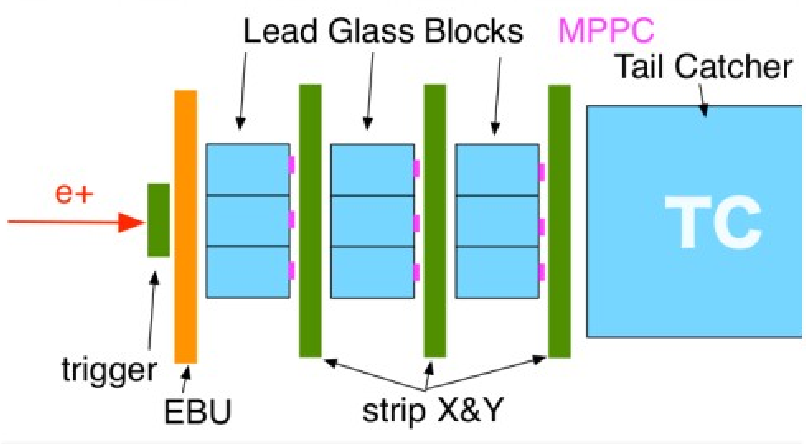
Expect interesting results on timing detectors from CALICE in coming years

R&D on materials

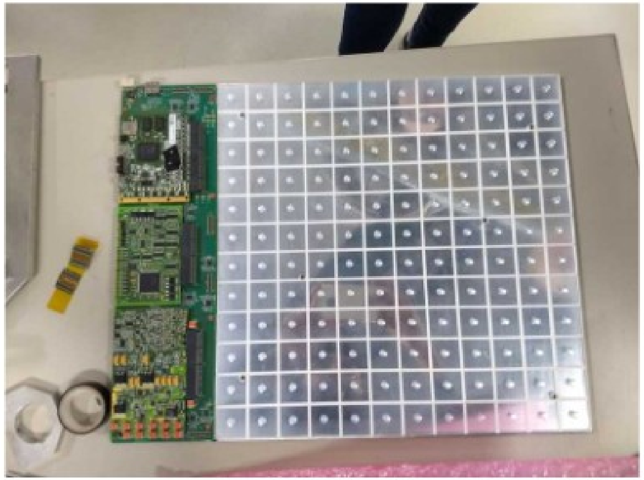
Position Sensitive Devices



Prototype of Crystal calorimeter



Megatiles for scintillator based calorimeters

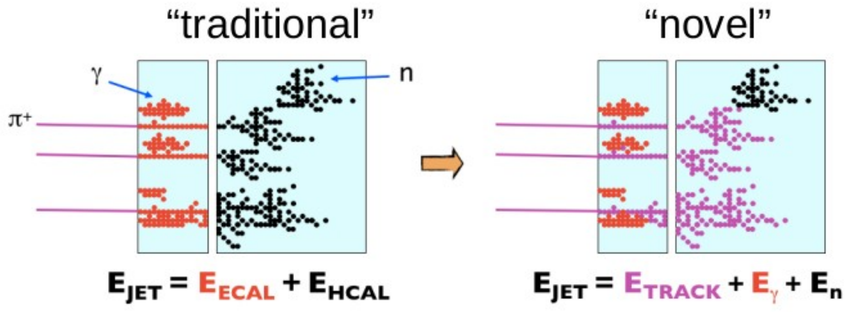


- Tests in lab ...
- ... but also in beam tests
  - Megatiles and LG-Calo in 2019

CEPC Xtal Calo Workshop – July 2020 23

Pandora PFA

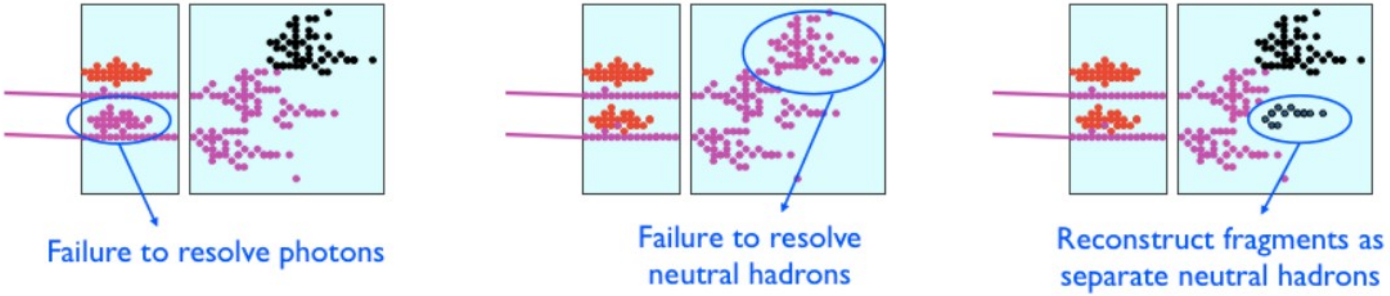
M. Thomson, J.B. Marshall
Cambridge LC Group



A PFA is a set of algorithms for pattern recognition and particle reconstruction.

arXiv:1308.4537

However, there might be *confusion* in particle reconstruction, such as:

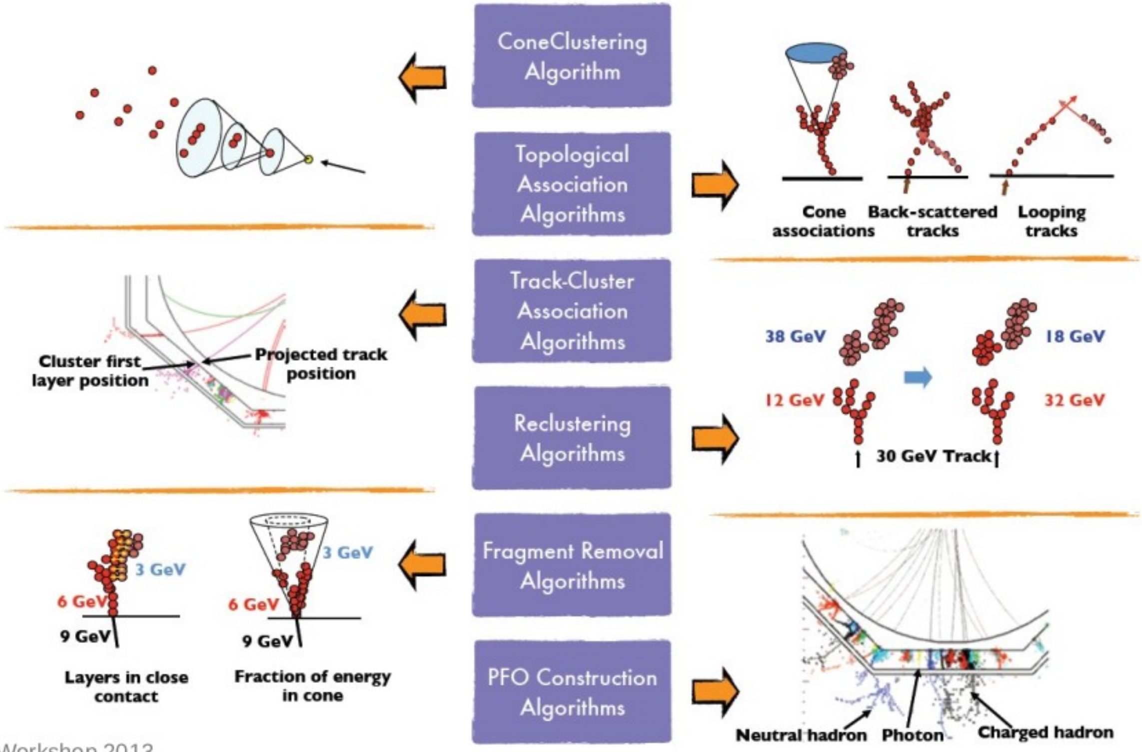


Hence constraints on both calorimeters and software.

2020.10.21 F.Corriveau (IPP/McGill) - AWLC 2020 - Particle Flow Calorimetry 15

Pandora PFA - Approach

“Implement a large number of ‘decoupled’ pattern-recognition algorithms, each of which looks to reconstruct specific particle topologies, whilst carefully avoiding causing confusion”



CLIC Workshop 2013

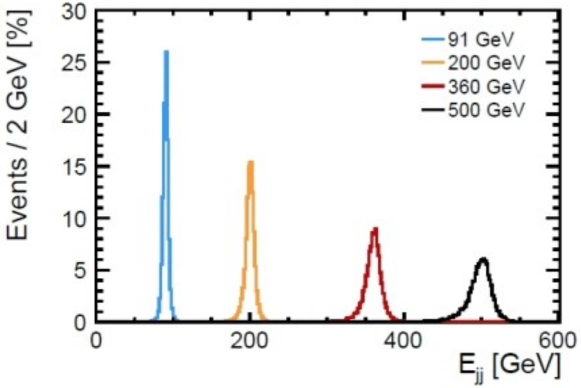
working outwards
↓
topological merging
↓
tracker-calorimeter
↓
improve match
↓
neutral vs charged
↓
particle flow objects
↓
particle identification

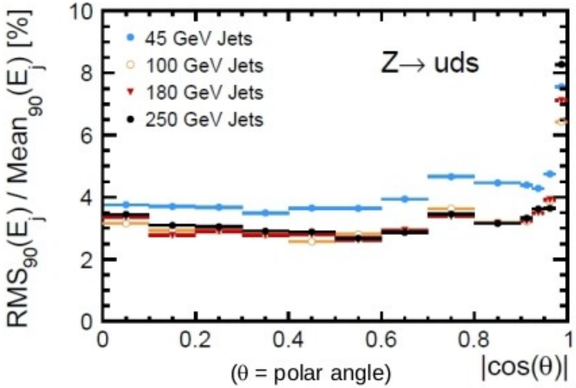
2020.10.21 F.Corriveau (IPP/McGill) - AWLC 2020 - Particle Flow Calorimetry 16

Pandora PFA - Performance

ILC: Tested with ILD-model Monte-Carlo Z'→jj events produced at rest at 4 energies

arXiv:1308.4537





100-250 GeV jets:
resolution ~constant (barrel)

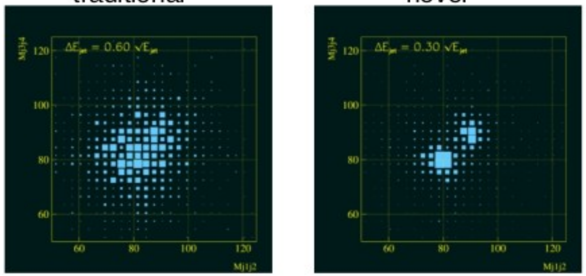
45 GeV jets:
limited by intrinsic term

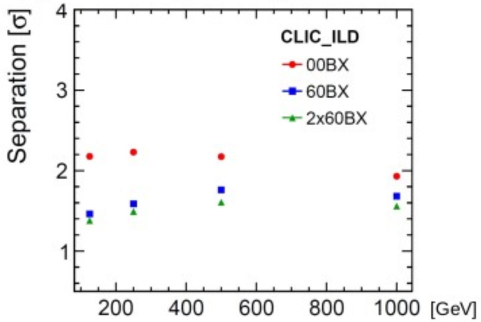
high energy jets:
limited by confusion term

PFA robust *wrt* shower parameters

CLIC (higher energies and larger backgrounds): e.g. W vs Z separation ($\not{p}_T$, PID)

"traditional" "novel"





$e^+e^-\to WW\to \mu\nu qq$
$e^+e^-\to ZZ\to \nu\nu qq$
W/Z energies: 125-1000 GeV
overlaid $\gamma\gamma\to$hadrons background
(BX=beam crossing)

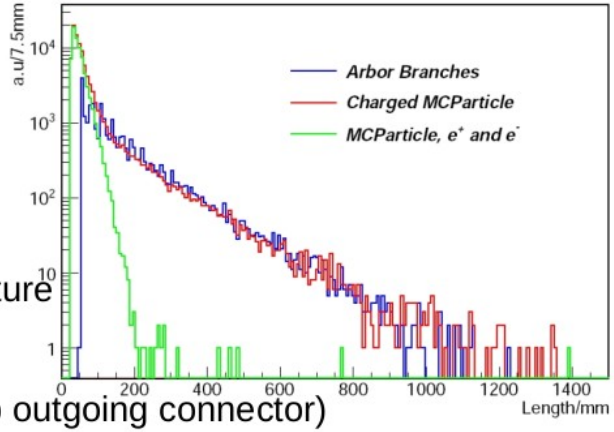
2σ separation without background
~1.7σ with 60BX background

CLIC Workshop 2013

Arbor PFA

Shower development topology in an imaging calorimeter reminds of a tree structure.

Step 1: initial hit cleaning if necessary (e.g. noise)
close pairs of hits are connected
a connector is the outgoing vector between them

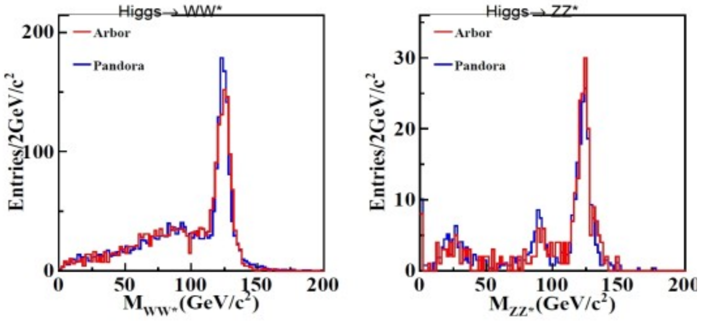


Step 2: a reference direction calculated from a hit position
and the directions of its outgoing connectors
the most likely incoming connector is kept → tree structure
this structure can be iterated. Tree means no loop.

Step 3: some hits are seeds (no ingoing connector) or leafs (no outgoing connector)
tracing from leaf to seed → branches → tree
ideal case, a tree = a particle shower
intuitive, effective is separating nearby showers

The algorithm is next applied to jets

Reconstructed energy for e.g. Higgs decay events
Jet energy resolution comparable to Pandora's



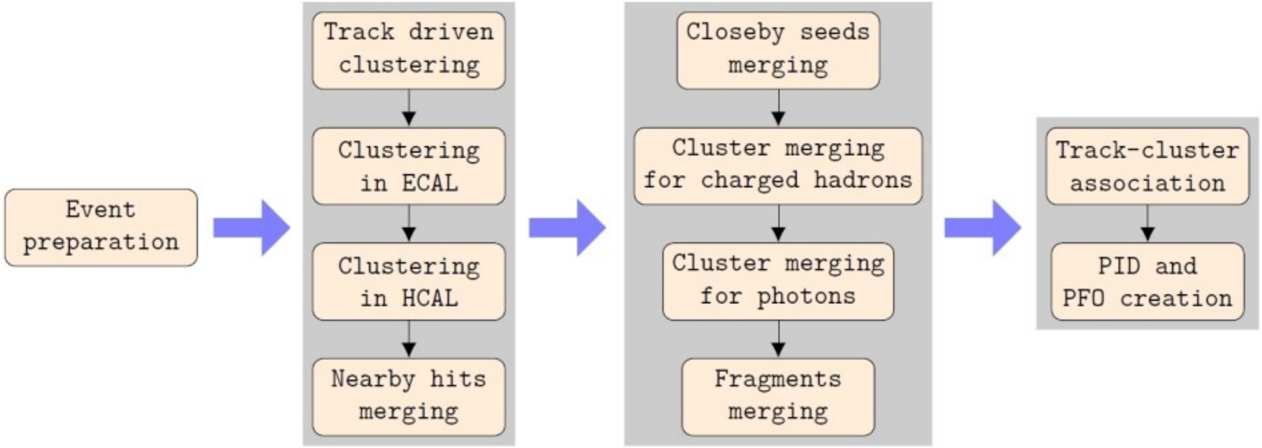
arXiv:1403.4784

APRIL: Algorithm for Particle Reconstruction at ILC from Lyon

APRIL ≈ Arbor PFA with modified cluster merging for SDHCAL

(Pandora PFA assumes linear responses as in AHCAL case)

SDHCAL energy reconstruction: $E_{reco} = \alpha_1 N_1 + \alpha_2 N_2 + \alpha_3 N_3$
where N_i are the number of hits for each threshold

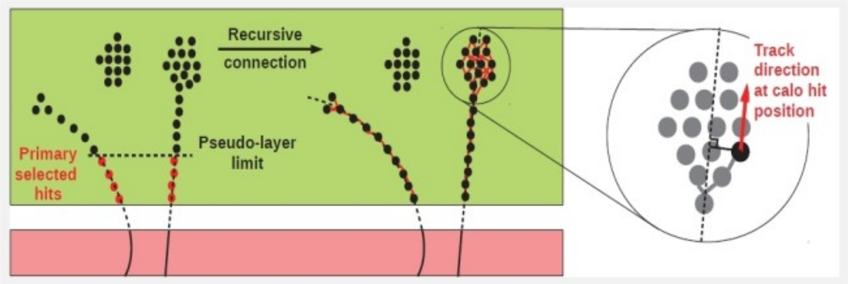


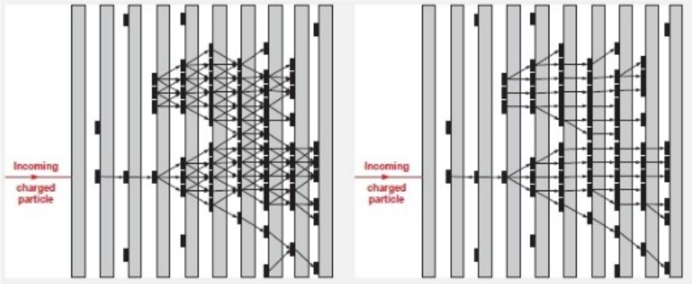
CHEF 2019

2020.10.21 F.Corriveau (IPP/McGill) - AWLC 2020 - Particle Flow Calorimetry 25

APRIL

Tracks: 1) clustering done by Arbor with parameters set to avoid big clusters
2) remaining hits merged by efficient Nearest Neighbour clustering (mlpack)
3) keep only one backward connection per hit (minimal angles × distance)





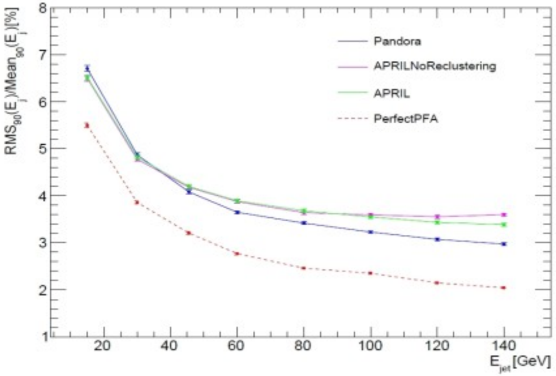
Clusters: 1) cluster merging similar to above hit clustering
2) function of cluster orientations and distances
3) (work in progress, e.g. splitting/reclustering)

Results: jet energy resolution in barrel at M_Z

APRIL: 4.2% → competitive with Pandora (<60 GeV)

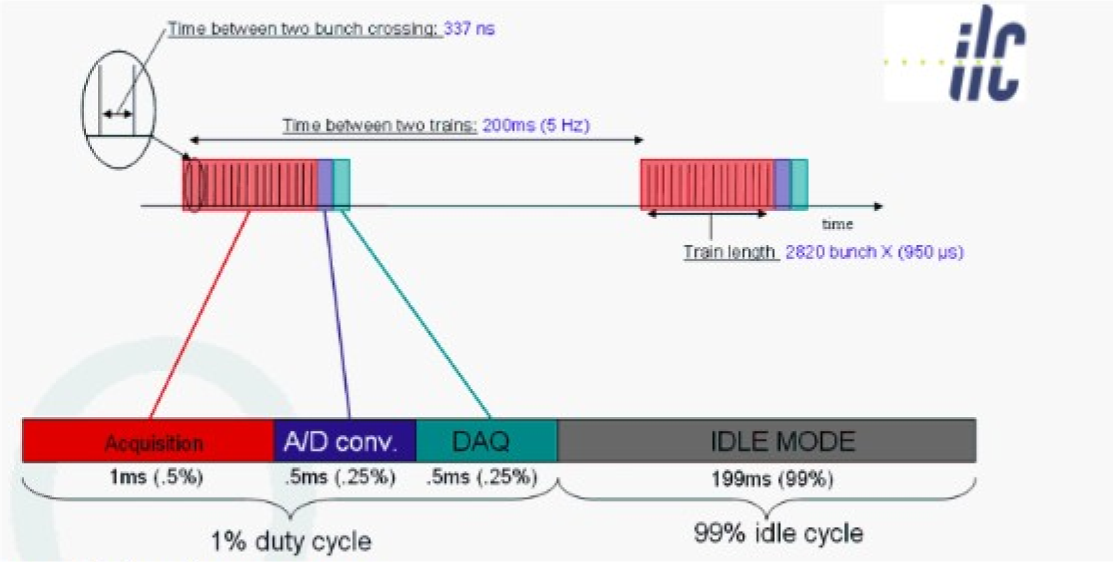
Pandora: 4.1%

"ideal PFA": 3.3%



CHEF 2019

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