DRD6-WP1
Sandwich calorimeters with fully embedded electronics

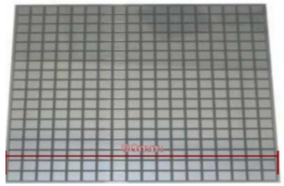
Adrián Irles for the DRD6-WP1
AITANA group at IFIC – CSIC/UV

High Granularity Calorimetry concept

- ▷ **R&D and proof of concept lead by the CALICE and FCAL collaborations**
- ▷ **Exported to HL-LHC** Upgrade of existing detectors (ALICE FoCAL pixel calorimeter, HGCAL with high granular Si and SC calorimeter systems)
- ▷ **Adapted to lower energy** experiments
  - Strong-Field QED experiments (LUXE)
  - Dark Photon, ALPs Experiments (LUXE-NPOD, EBES -KEK, Lohengrin - Bonn,...)

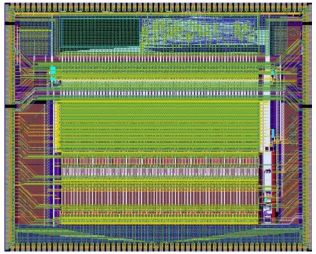
Large surface detectors

Si Wafer



Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)



Achieved milestones in the past: FCAL, CALICE (and CALICE+CMS) beam tests campaign of large size prototypes

Sandwich calorimeters with fully embedded electronics

IFIC INSTITUT DE FÍSICA CORPUSCULAR

General approach:

- Highly granular calorimeters as integrated systems - but often still with separate requirements and correspondingly separate technological solutions for electromagnetic and hadronic sections.

Overarching goals:

- Establish (where not existing already) large-scale prototypes that allow to demonstrate the technologies, both stand-alone and in combined tests of different electromagnetic and hadronic sections.

High-level structure: Tasks covering technology areas

- Task 1.1: Highly pixelised electromagnetic section
- Task 1.2: Hadronic section with optical tiles
- Task 1.3: Hadronic section with gaseous readout

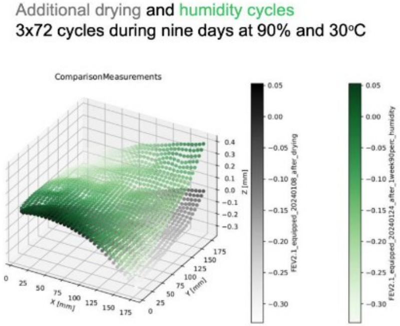
1.1. Pixelated ECAL

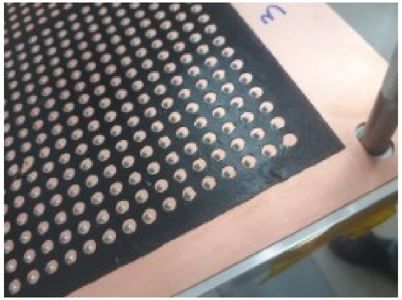
IFIC INSTITUT DE FÍSICA CORPUSCULAR

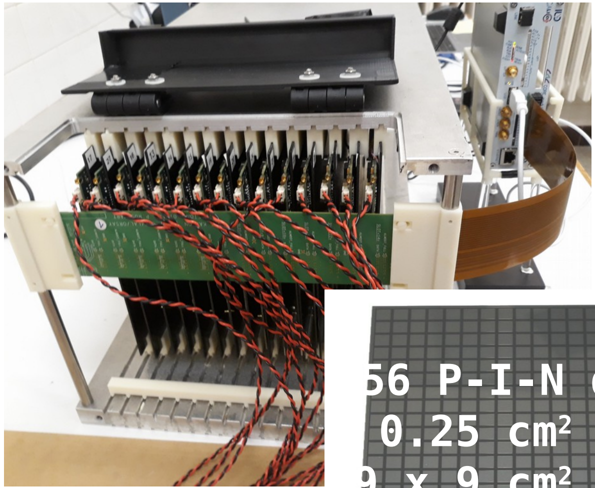
Task/Subtask	Sensitive Material/ Absorber	DRDTs	Target Application	Current Status
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.1: SiW-ECAL	Silicon/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.1.2: Highly compact calo	Solid state (Si or GaAs)/ Tungsten	6.2	e^+e^- collider forward part	Prototypes with non-optimised sensors, Sensor optimisation and data transfer studies ongoing
Subtask 1.1.3: DECAL	CMOS MAPS/ Tungsten	6.2, 6.3	e^+e^- collider central detector. Future hadron collider	Prototypes with non-optimised sensors, Sensor optimisation ongoing
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed

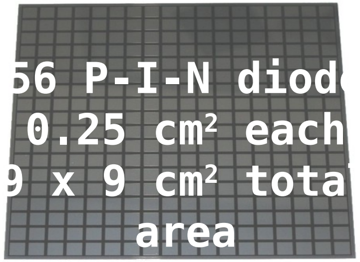
SiW-ECAL

SiW-ECAL (<2020)
- **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**
- **Sensor delamination issues**







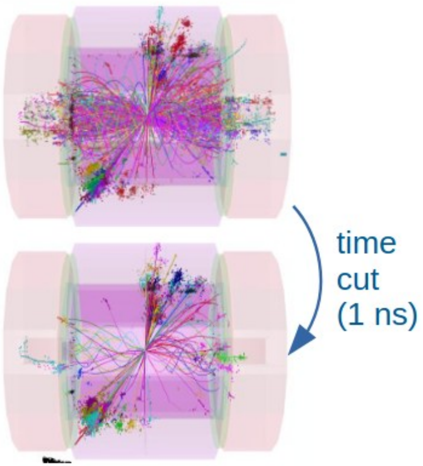


EUDET layout

Prototype from Hamamatsu

SiW-ECAL (ongoing)
- Goal 15 layers 18×18 cm²
- **New PCB generation & ASICs**
- **R&D on optmized hybridization**
- **Ongoing studies on requirements for Circular Colliders:**
  - \- high fluxes
  - \- cooling
- **5d calorimetry**

Cleaning of Events

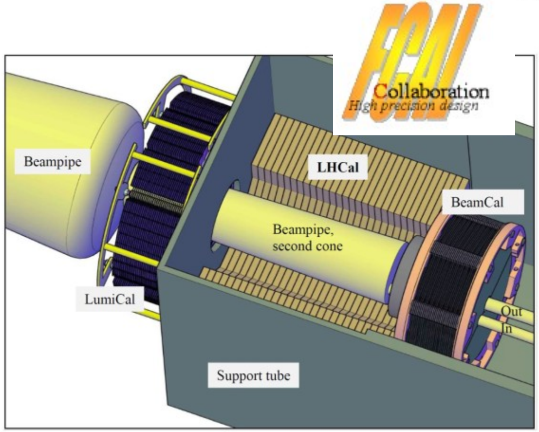


[CLIC CDR: 1202.5940] adapted from L. Emberger

Forward Calorimetry (extreme compactness)

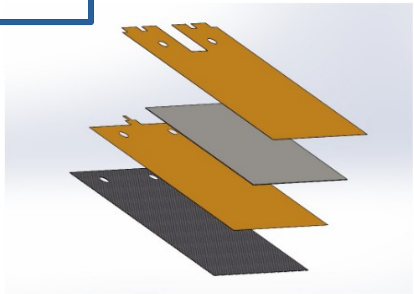
IFIC INSTITUT DE FÍSICA CORPUSCULAR

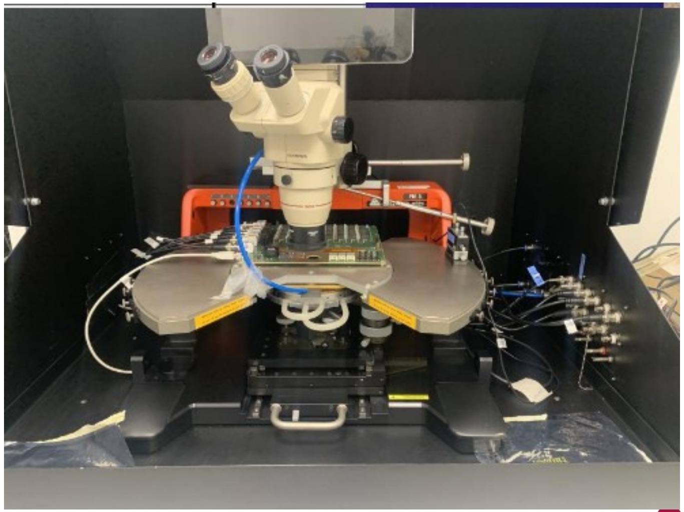
- ▷ LumiCal for precise luminosity measurement (Counting Bhabhas)
- ▷ BeamCal for fast luminosity measurement (using beamstrahlung)
- ▷ Technology choice: Si or GaAs/W sandwich calorimeters
- ▷ 1 X0 absorber thickness per layer, 20 (30) layers in ILC (CLIC)
  - Optimal geometries for FCC being studied
- ▷ Recent progress:
  - investigation of new GaAs sensors with integrated signal routing → similar signal size to silicon sensor
  - **FLAMe and FLAXE ASICS** development and production (ongoing)



Production of a large scale prototype (adapted to LUXE)

- ▷ Large sensors (9x9cm²) and **flexible PCBs (compact calo)**
- ▷ **Material budget, thickness:**
  - **Total bellow 1mm**
  - 200um CF + 320um sensor
  - ~500um for fanout + HV kapton + 3 layers of glue/Adhesive





Slide from K. Krueger

DRD6 – high granular silicon ECALs

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

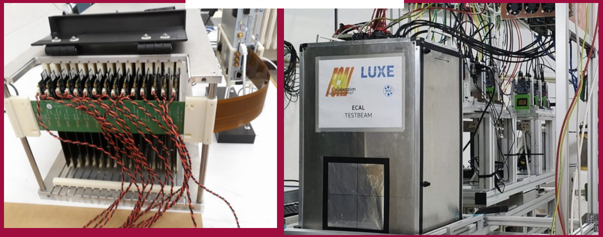
Barrel ECAL:
Similar design in:

(linear collider)
CLICdetector, ILD, SiD

(circular collider)
CLD, ILD, CepC

Electron Calo for LUXE

LUXE



CALICE -type calorimeter

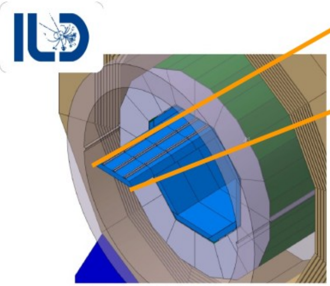
FCAL-type calorimeter

Froward LumiCAL:
Similar design in:

(linear collider)
CLICdetector, ILD, SiD

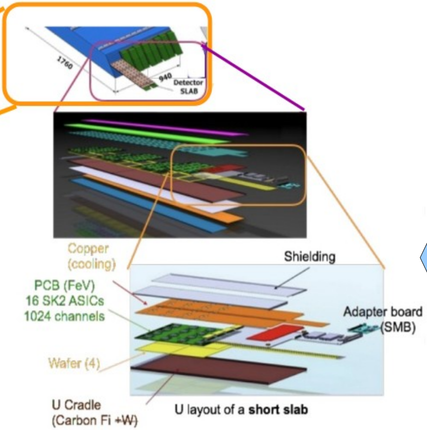
(circular collider – with adaptations)
ILD, CEPC,..

Positron Calo for LUXE



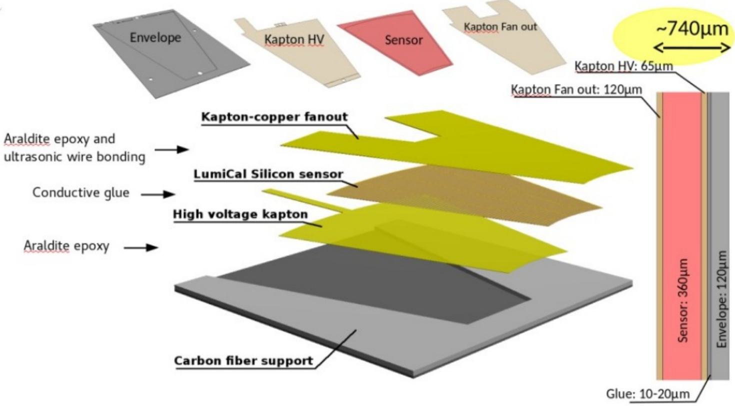
The SiW ECAL in the ILD Detector

SiW Ecal



R&D on sensor hybridization

IFIC
INSTITUT DE FÍSICA CORPUSCULAR



IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
LLR
九州大学 KYUSHU UNIVERSITY
KEK High Energy Accelerator Research Organization
東京大学 素粒子物理国際研究センター International Center for Elementary Particle Physics The University of Tokyo
CERN
cnrs IN2P3 Les deux infinis
LPNHE PARIS
ΩMEGA Microelectronics

TEL AVIV UNIVERSITY אוניברסיטת תל-אביב
UNIVERSITAS VARSOVIENSIS
AGH
DESY.
ISS INSTITUTE OF SPACE SCIENCE A subsidiary of INFLPR

Digital ECAL based on MAPS

IFIC INSTITUT DE FÍSICA CORPUSCULAR

▷ Primary experimental context: ALICE FOCAL, Higgs Factories

▷ A MAPS-based digital Silicon-Tungsten ECAL,

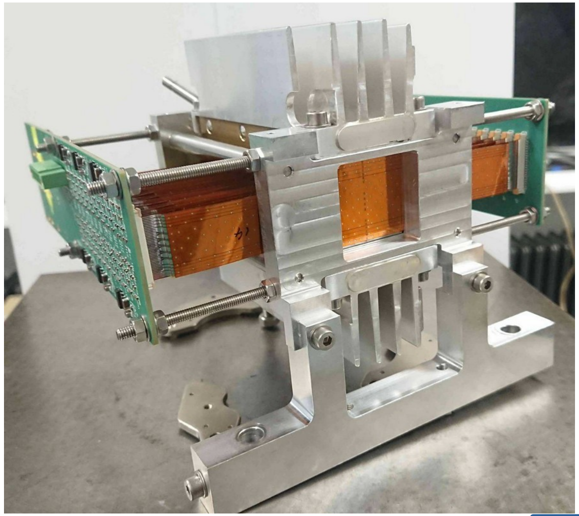
- EPICAL: building on current DECAL and EPICAL projects, partially integrated in CALICE in the past
- NAPA-p1 at SLAC – (cooperation with CERN) sensor development

24 layers with each
- 3 mm W absorber
- 2 ALPIDE CMOS sensors
(NIM A, 845:583–587, 2017)

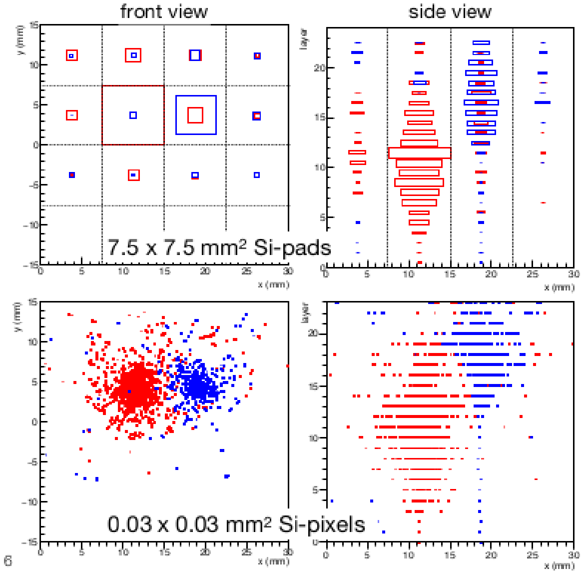
29.24 x 26.88 µm² pixel size

active cross section 3 x 3 cm²

compact design: expect $R_M \approx 11$ mm



EPICAL-2



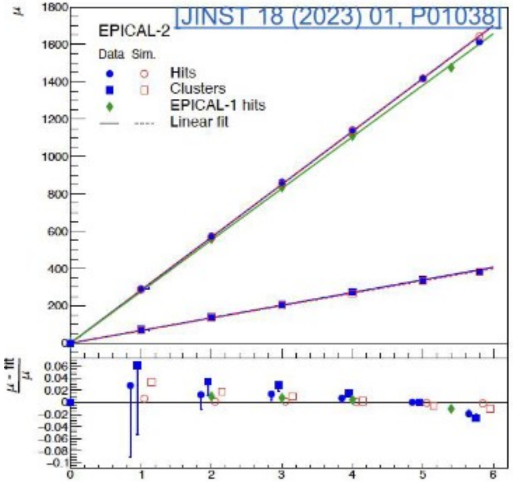
At an advanced phase of proof-of-principle: small prototypes

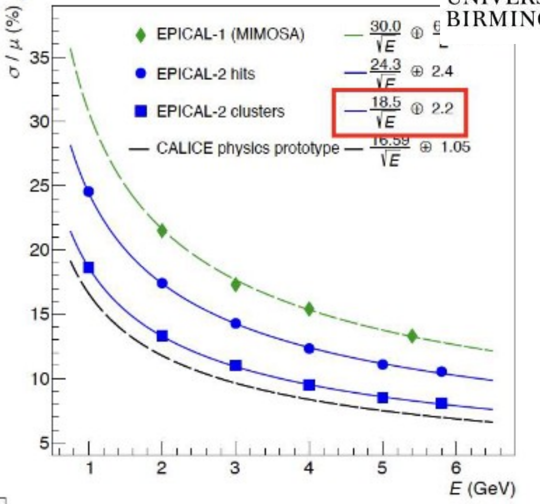
Digital ECAL based on MAPS

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

UNIVERSITY OF BIRMINGHAM

Calorimetric performance





hits	a (%)	b (%)	c (%)
data	24.30 ± 0.03	2.41 ± 0.08	-
sim (E_{spread} = 0)	21.27 ± 0.06	2.30 ± 0.16	-
sim (E_{spread} = 158 MeV)	21.58 ± 0.25	1.8 ± 0.5	15.1 ± 0.4
clusters	a (%)	b (%)	c (%)
data	18.54 ± 0.02	2.17 ± 0.05	-
sim (E_{spread} = 0)	14.10 ± 0.04	2.52 ± 0.07	-
sim (E_{spread} = 158 MeV)	14.57 ± 0.21	1.96 ± 0.26	14.93 ± 0.23

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b \oplus \frac{c}{E/\mathrm{GeV}}$$

- Good standard performance
- Better resolution from clusters
- Uncertainties in beam energy spread

Nigel Watson / Birmingham LCWS 2023 18-May-2023 14

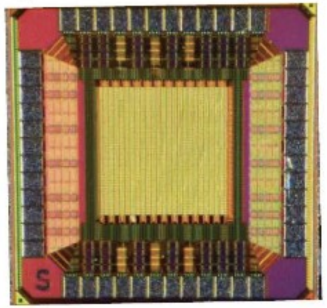
DRD6 Collaboration Meeting

SLAC NATIONAL ACCELERATOR LABORATORY

NAPA-p1 at SLAC

	Specification	Simulated NAPA-p1
Time resolution	1 ns-rms	0.4 ns-rms ✓
Spatial Resolution	7 µm	7 um ✓
Noise	< 30 e-rms	13 e-rms ✓
Minimum Threshold	200 e-	~ 80 e- ✓
Average Power density	< 20 mW/cm^2	0.1 mW/cm^2 for 1% duty cucle ✓

The chip was received at SLAC in September 2023



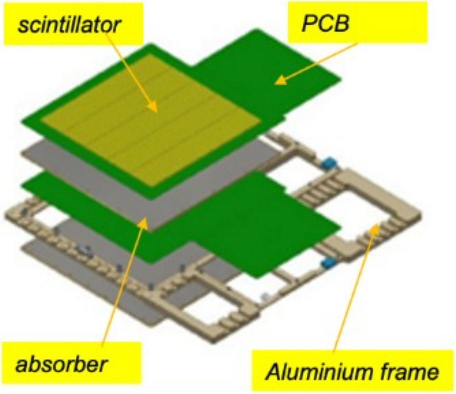
Microscope photo of NAPA-p1

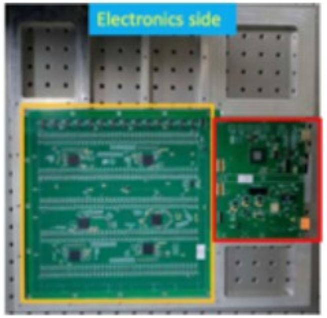
Acknowledgement: CERN WP 1.2 for the excellent cooperation: NAPA-p1 uses the pixel masked developed and optimized by CERN, and was fabricated in a shared run led by CERN

Scintillator ECAL

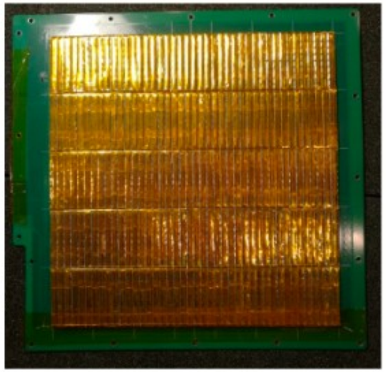
Technological Prototype

- ScW-ECAL **technological prototype**
  - Full layers (32 layers)
    - Detection layer of 210×225mm^2 with 210 scintillator-strips
      - 30 layers with single SiPM readout
      - 2 layers with double SiPM readout
    - Absorber plate (3.2mm-thick 15%-85% Cu-W alloy)
    - Total material thickness $23.4\,X_0$

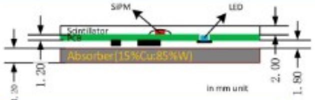




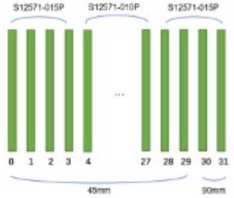
Detection layer on EBU



Scintillator-SiPM readout scheme



Sensitive layer arrangements



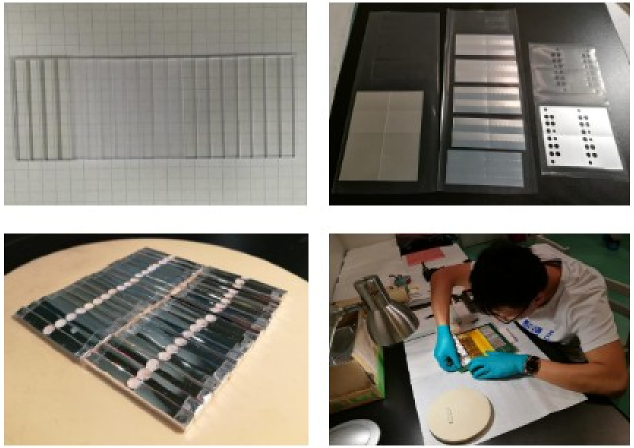
TestBeam Campaigns at CERN 2023
(results to be discussed in next DRD6 meeting)

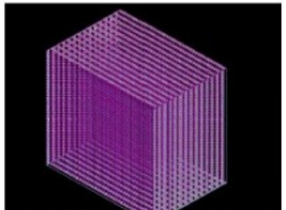
Scintillator ECAL

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

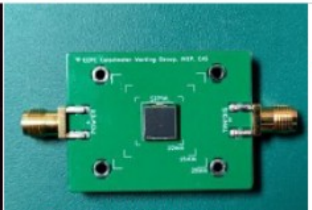
Strip wrapping and assembly on EBU was done by hand (Shanghai Institute of Ceramic)





Long bar configuration in Geant4

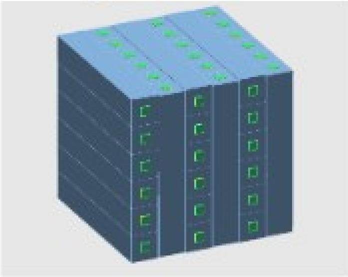
BGO crystal and wrapping foil

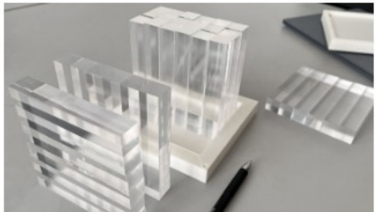


SiPM with high pixel density

SiPM readout electronics

Single EM module





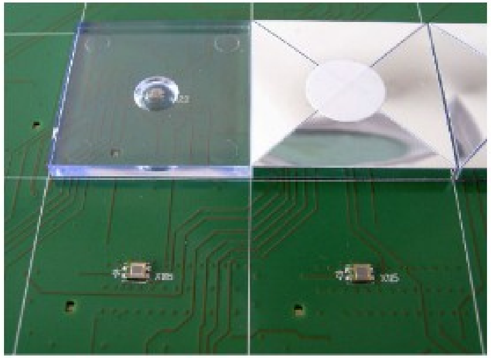
Dummy crystal matrix with 3D printed support structure

1.2. HCAL with optical tiles

Task 1.2: Hadronic section with optical tiles				
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/ Steel	6.2	e^+e^- collider central detector	Material studies and specifications for prototypes

AHCAL

- ▷ Main experimental context: Higgs Factories
- ▷ SiPM-on-tile / steel HCAL
  - Builds on CALICE AHCAL Technological Prototype
- ▷ Main R&D topics:
  - Extension of current detector concept to circular colliders with continuous readout
  - evaluate consequences of higher data rate
  - re-evaluate need for cooling
  - re-optimisation of detector to ensure optimal performance while respecting new constraints
- ▷ Corresponding hardware development: ASICs (KLAuS, OMEGA), HBU and interfaces, mechanical and thermal design; scintillator geometry
- ▷ First layers for new system design in 2026, EM stack with ~15 layers ~ 2029



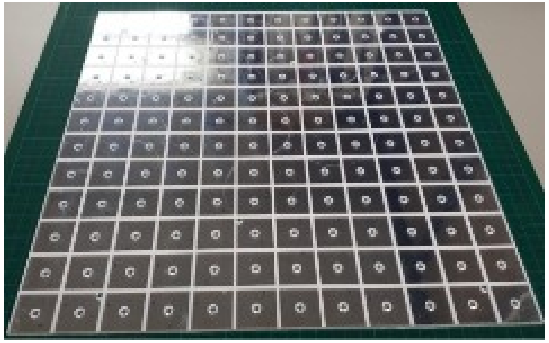
Design, Construction and Commissioning paper:

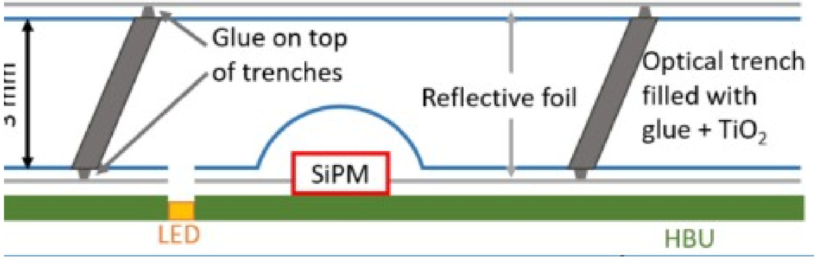
JINST 18 (2023) 11, P11018

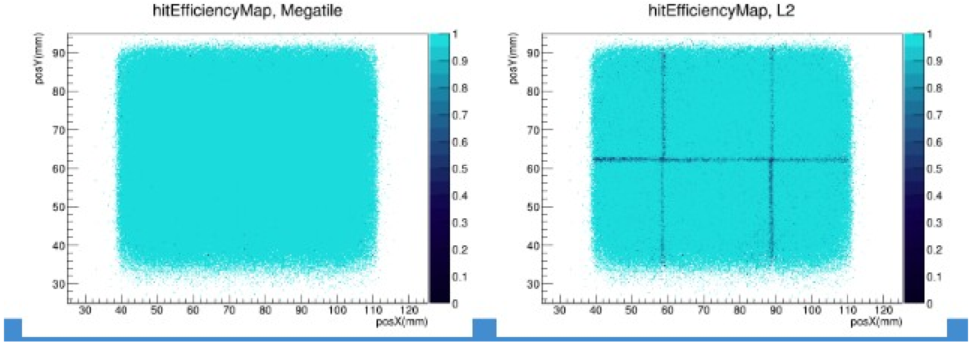
AHCAL

▷ Megatile Design

- Large scintillator plate with optically separated trenches filled with reflective TiO2
- Plate wrapped in reflective foil
- Pro: Easier assembly; no dead areas
- Con: Not fully light tight



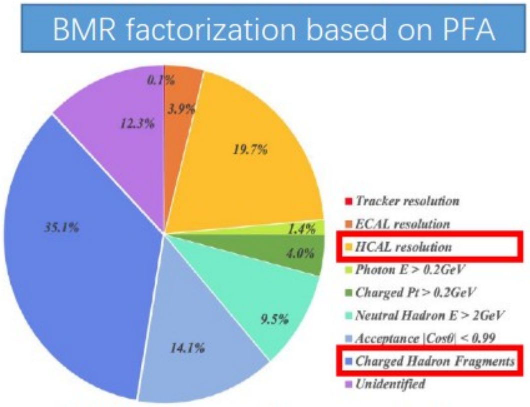




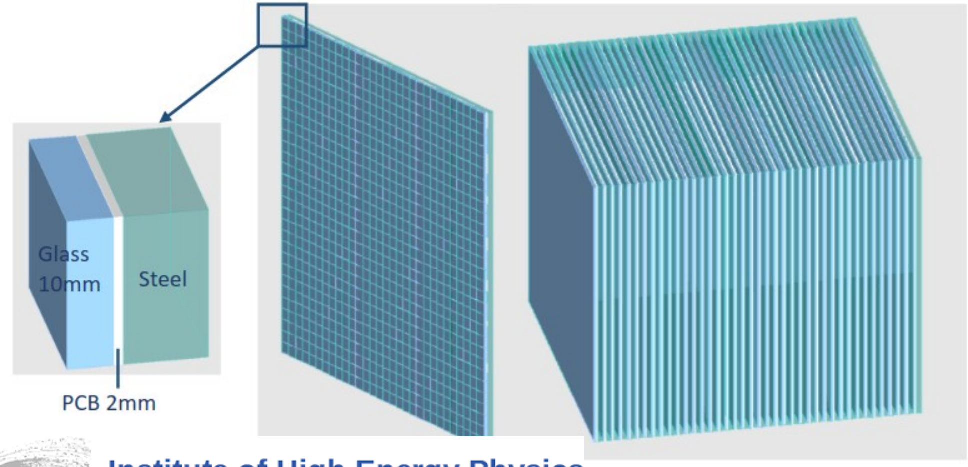
First Look at Efficiency

ScinGlass HCAL

- ▷ A variation of the CALICE AHCAL concept: Using glass scintillator tiles instead of plastic
  - Increased sampling fraction - with the potential for improved energy resolution
- ▷ Main R&D directions:
  - R&D of scintillator material - main targets: high density, high light yield, low cost
  - Simulation studies of hadronic performance: single particles, jets
  - Development of modules: setup for characterization; EM prototype ~2025; HCAL prototype ~ 2027



BMR=Boson Mass resolution



Institute of High Energy Physics
Chinese Academy of Sciences

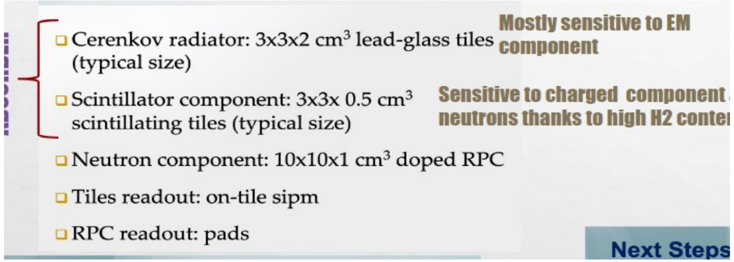
1.3. gaseous HCAL

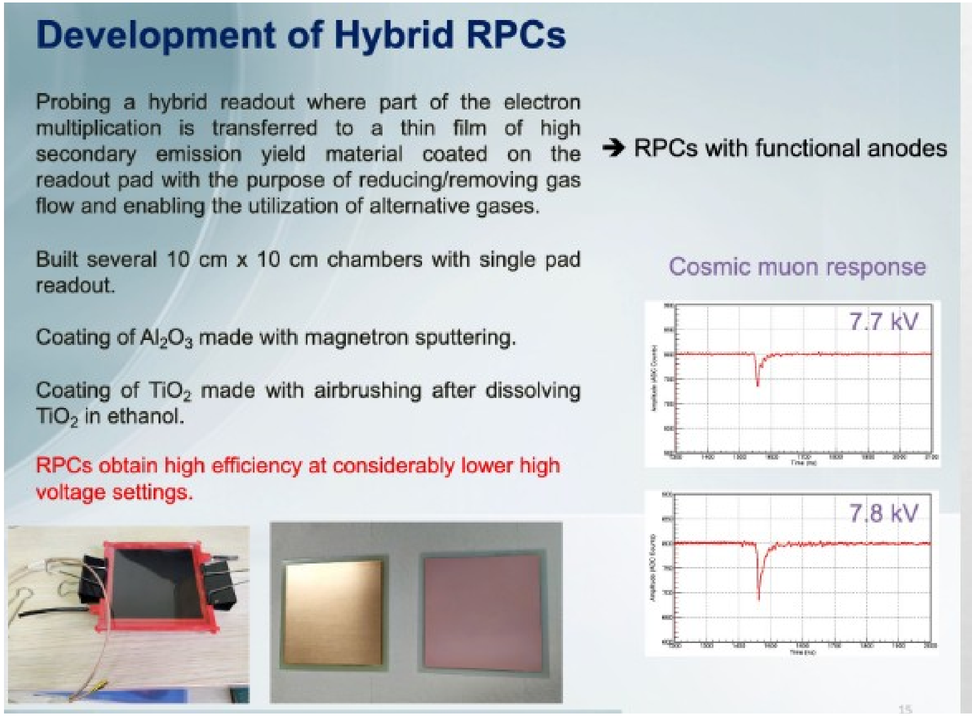
IFIC INSTITUT DE FÍSICA CORPUSCULAR

Task/Subtask	Sensitive Material/ Absorber	DRDTs	Target Application	Current Status
Task 1.3: Hadronic section with gaseous readout				
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/ Steel	6.2, 6.3	$\mu^+\mu^-$ collider central detector	Small prototype for proof-of-principle, Lateral and longitudinal extension envisaged
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers +Scintillating plastic tiles/ Heavy Glass	6.1, 6.2, 6.3	e^+e^- collider central detector BSM searches in MeV-GeV range	RPC, Scintillating Tiles advanced status, R&D on heavy glass needed

ADRIANO3

- ▷ Extension of ADRIANO2 (for REDTOP)
- ▷ Three-readout modes with 5D shower measurement, disentangling the neutron component of the shower.
- ▷ Key R&D goals
  - optimization of the construction technique in terms of: light yield, RPC efficiency, timing resolution, and cost
  - Test layers in 2024, small-scale prototype 2025
  - Larger-scale prototype 2026-2027
- ▷ Plans to use ultrafast ASICs for RPC readout





Multipattern Gas Detector

MPGD prototypes

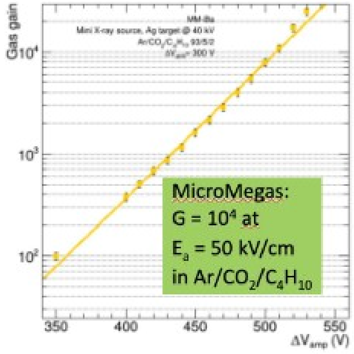
Prototypes produced and tested within **RD51 common project**:

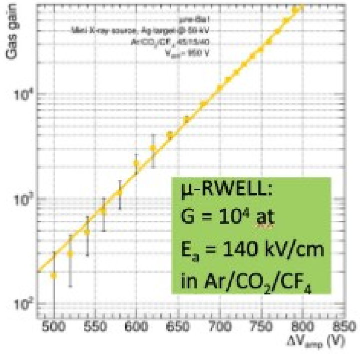
- 7 μ-RWELL
- 4 MicroMegas
- 1 RPWELL

Detector design:

- Active area 20×20 cm^2, pad size 1×1 cm^2
- **Common readout** board

Prototype characterization performed in all the laboratories





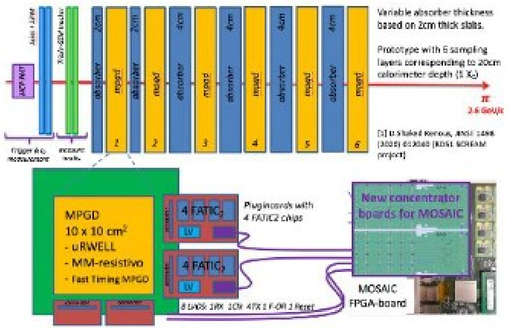
Development of Resistive MPGD Calorimeter with timing measurement (2021-2023)

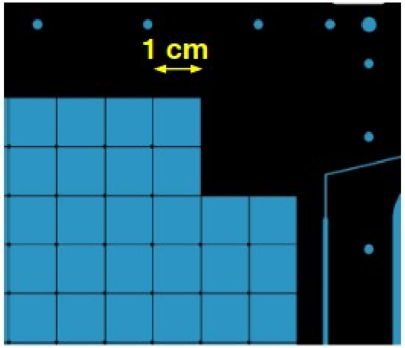
RD51 Institutes:

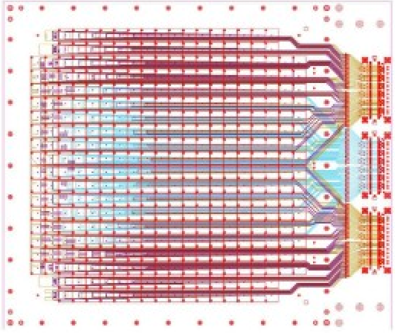
1. *INFN sez. Bari, contact person: piet.verwilligen@ba.infn.it*
2. *INFN sez. Roma III, contact person: mauro.iodice@roma3.infn.it*
3. *INFN LNF Frascati, contact person: giovanni.bencivenni@lnf.infn.it*
4. *INFN sez. Napoli, contact person: massimo.dellapietra@na.infn.it*

\+ Weizmann Institute of Science

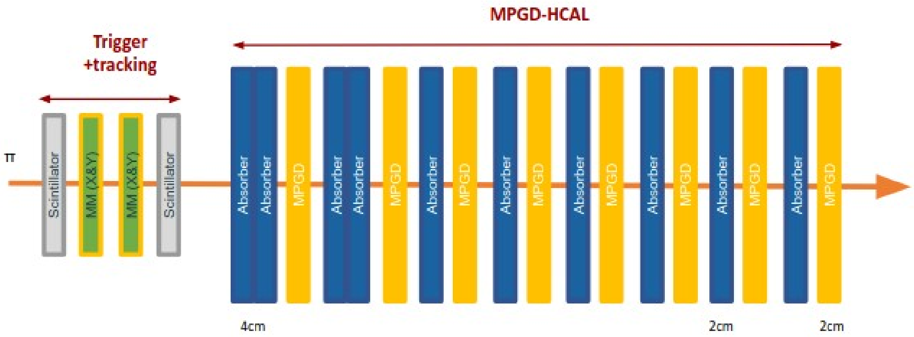
Design of MPGD-based HCAL cell

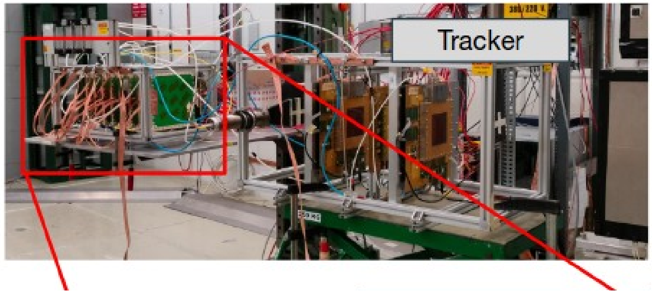






Multipattern Gas Detector





▷ Development of MPGD-HCAL ongoing in simulations and hardware

- Tested 12 MPGDs and small cell calorimeter within RD51 common project

Plans for 2024-2025

▷ Consolidating results with present prototypes in two test beams in 2024:

- SPS: full efficiency Vs HV curve, response uniformity
- PS: test of a fully equipped 8 MPGD layers prototype

▷ Construction and test of 4 large detectors (50×50 cm 2)

- Results to be discussed in next DRD6 meeting

T-SDHCAL

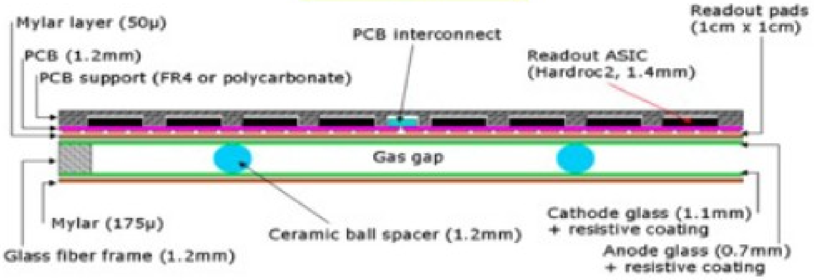
IFIC INSTITUT DE FÍSICA CORPUSCULAR

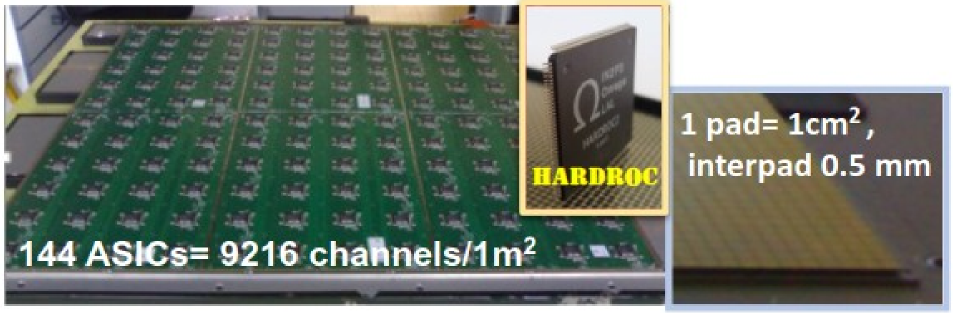
SDHCAL - Semi-Digital Hadronic CALorimeter

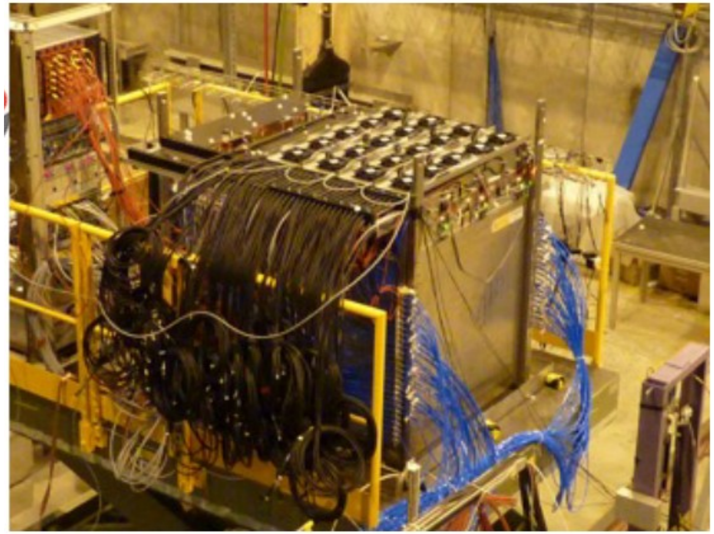
Sampling calorimeter:

Absorber: Stainless Steel + Detector: Glass Resistive plate Chambers

GRPC Sketch





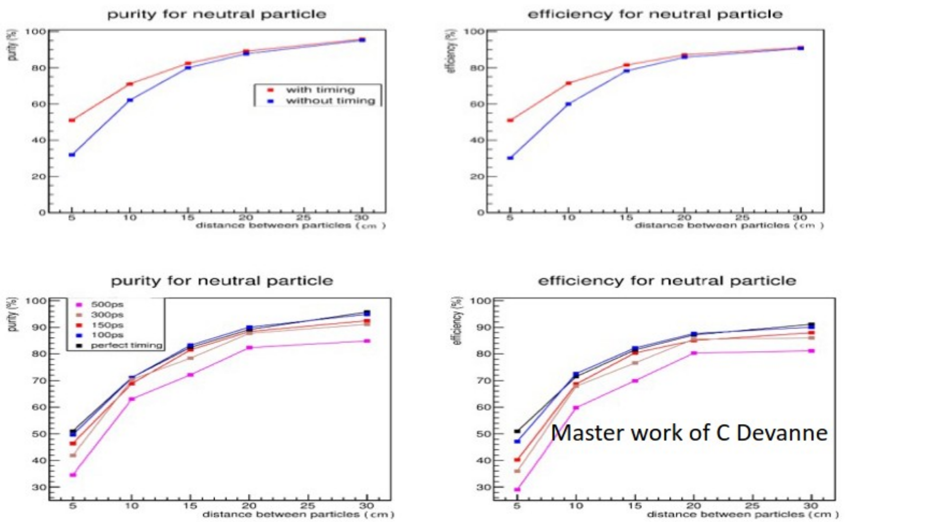


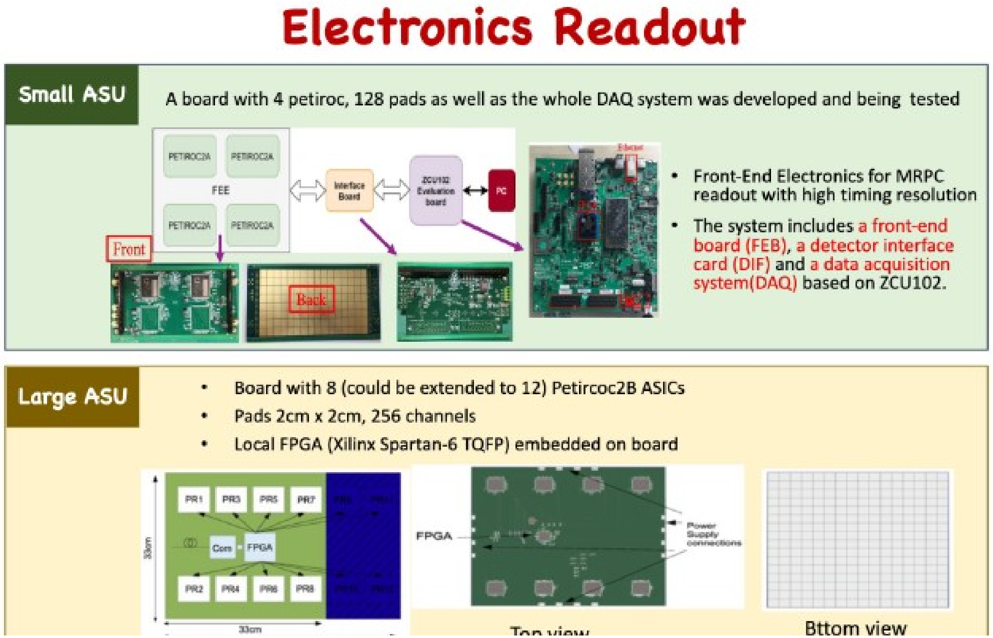
- 48 layers ($\sim 6\lambda_I$)
- 1 cm x 1 cm granularity
  3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

Published: JINST 10 (2015) P10039

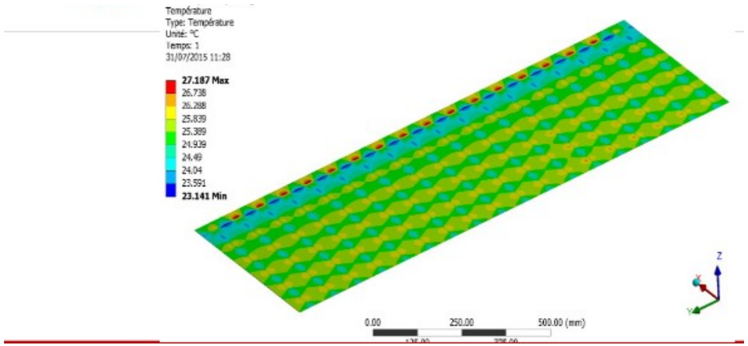
T-SDHCAL

Including time information in the simulation to separate hadronic showers (10 GeV neutral particle from 30 GeV charged particle) using techniques similar to ARBOR's ones.





- ▷ **Timing studies → 5d Particle Flow**
  - **MultiGap glass RPC**
- ▷ **Electronics : from SDHCAL to T-SDHCAL**
- ▷ Cooling (adaptations to CC)



thanks

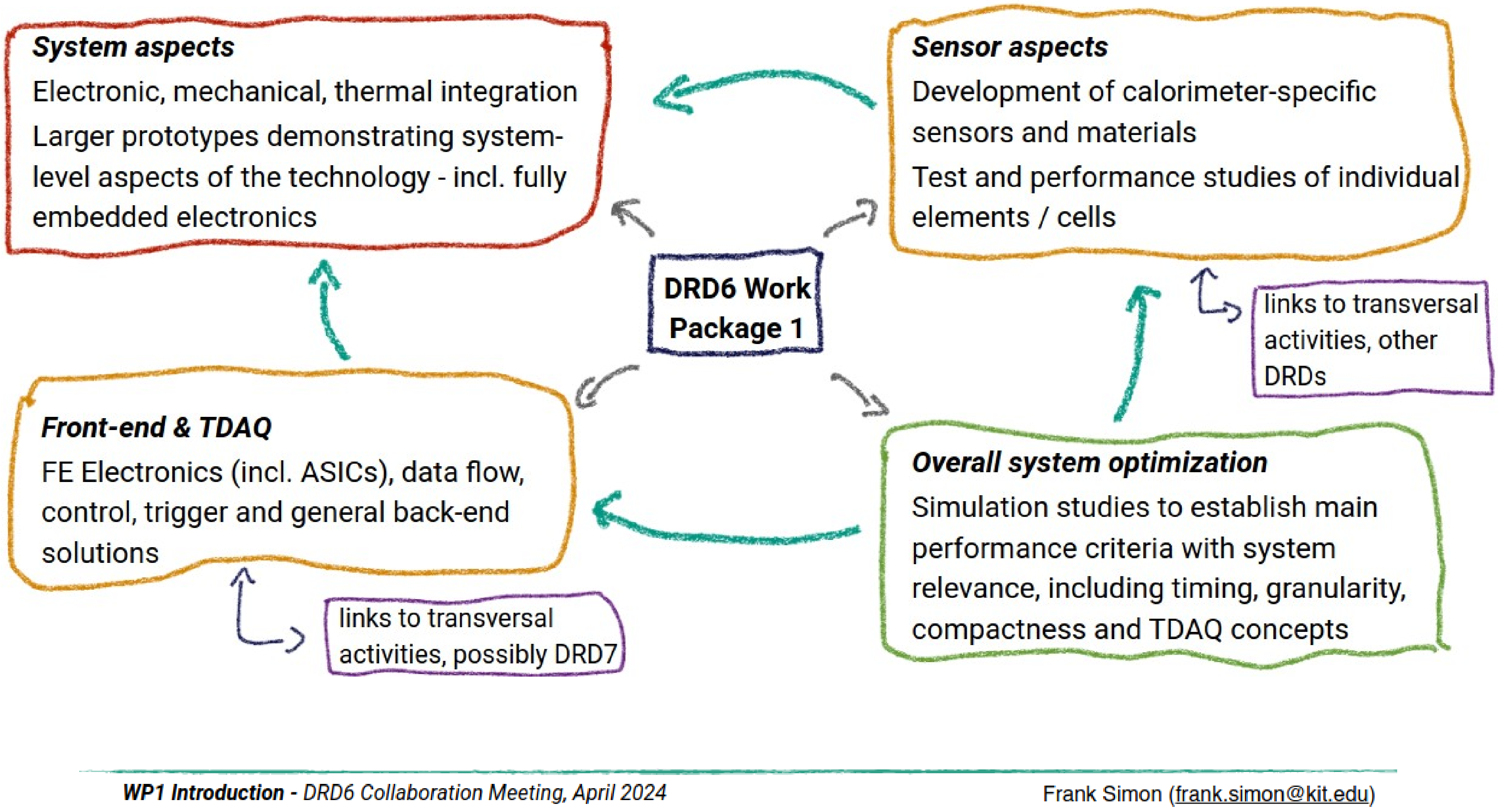
Much more exciting news next week:
DRD6 collaboration meeting

https://indico.cern.ch/event/1449522/

Back-up slides

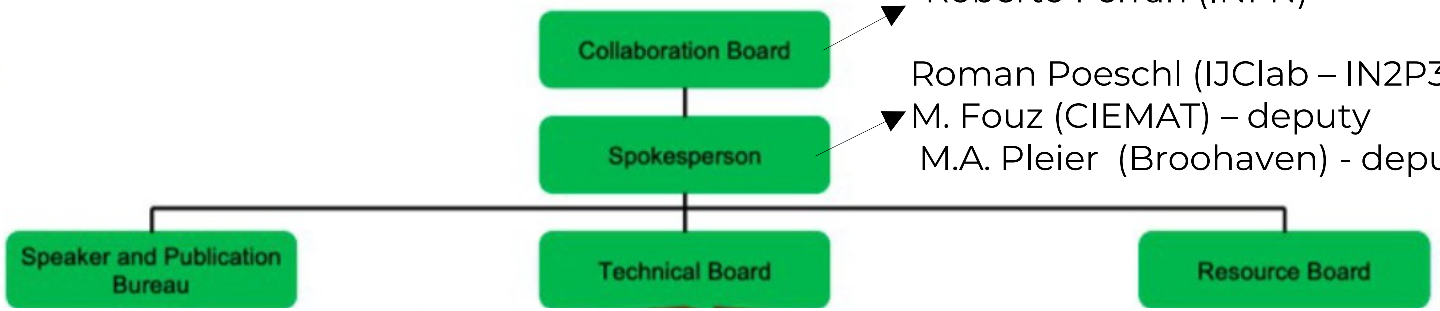
High Granularity Calorimetry in DRD6

IFIC INSTITUT DE FÍSICA CORPUSCULAR



DRD6 Calo

MANAGEMENT:



Roberto Ferrari (INFN)

Roman Poeschl (IJClab – IN2P3/CNRS)
M. Fouz (CIEMAT) – deputy
M.A. Pleier (Broohaven) - deputy

W. Ootani (CIEMAT)

G. Gaudio (INFN)

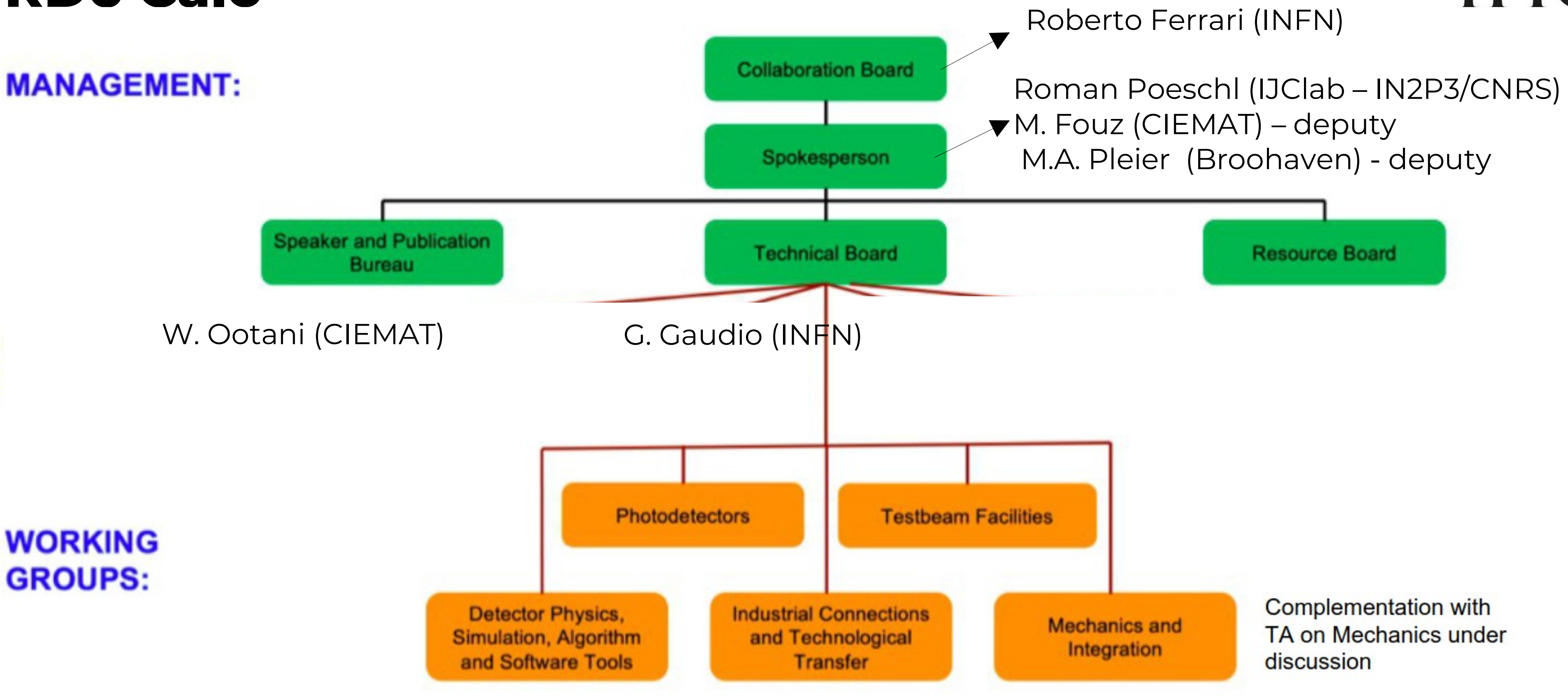
???

Approved by CERN DRC

- First Collaboration Meeting 9^{th} - 11^{th} April

DRD6 Calo

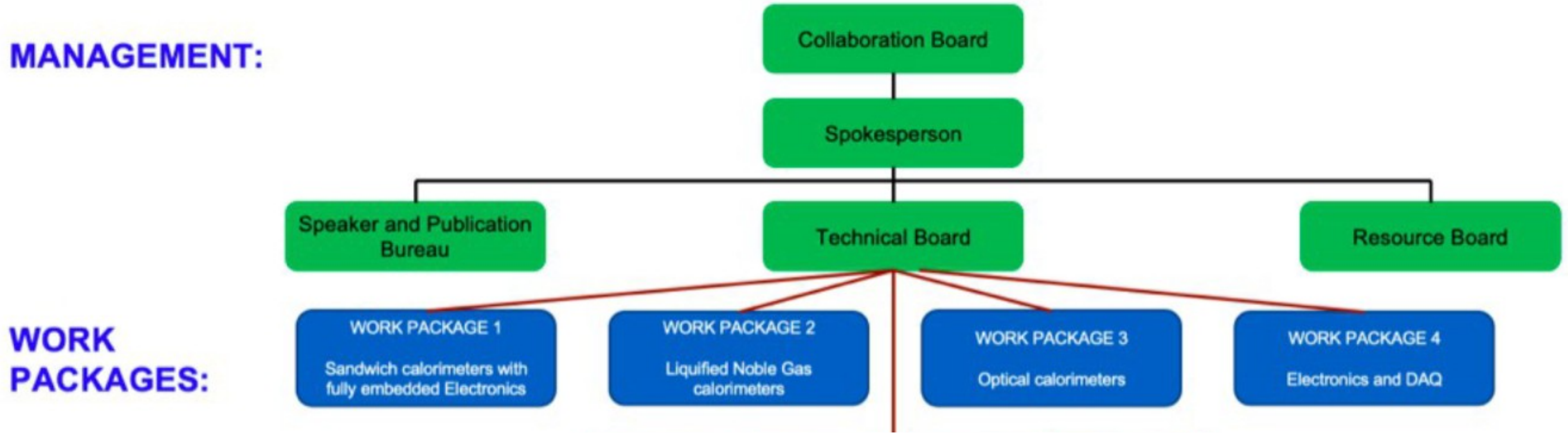
IFIC



Approved by CERN DRC

- First Collaboration Meeting 9th - 11th April

DRD6 Calo



Lucia Masseti (Mainz)
A. Irles (IFIC) - deputy

N. Morange (IJCLab)

M. Mlynáriková (CERN)

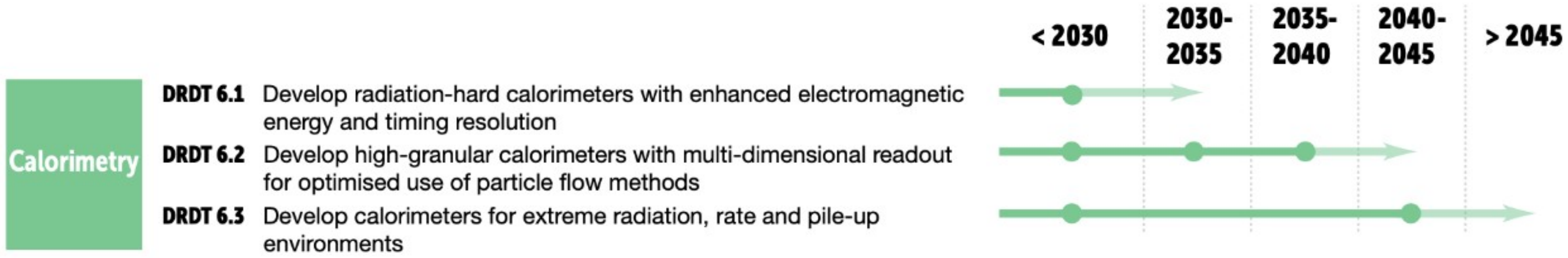
C. de la Taille (Omega)

Approved by CERN DRC

- First Collaboration Meeting 9th - 11th April

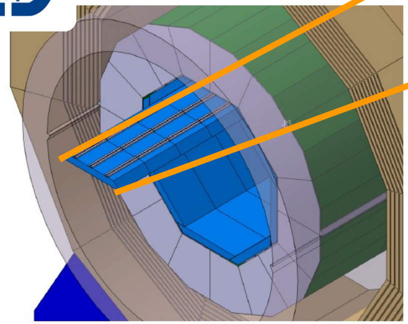
DRD6 Calo

SPS fixed target
Other fixed target, FAIR (hep)
Belle II
ALICE LS3
PIP-II/LBNF/DUNE/Hyper-K
ALICE 3
LHCb (≥ LS4)
EIC
LHeC
ILC
FCC-ee
CLIC
FCC-hh
FCC-eh
Muon Collider
< 2030
2030-2035
2035-2040
2040-2045
> 2045



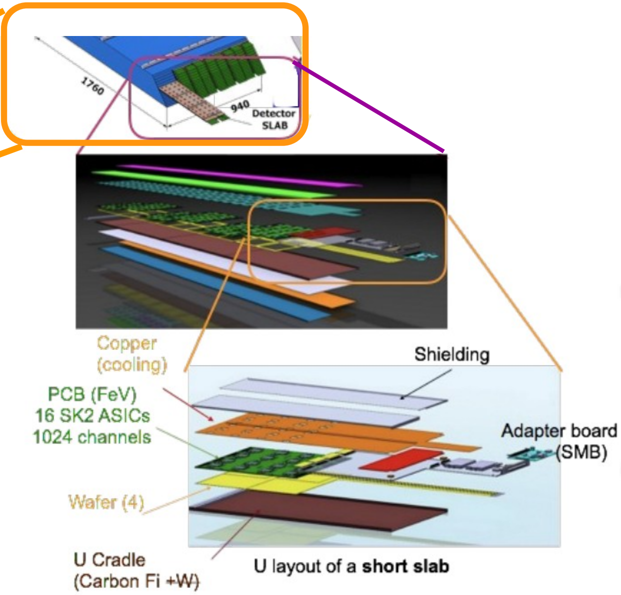
< 2030
2030-2035
2035-2040
2040-2045
> 2045
Calorimetry
DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments

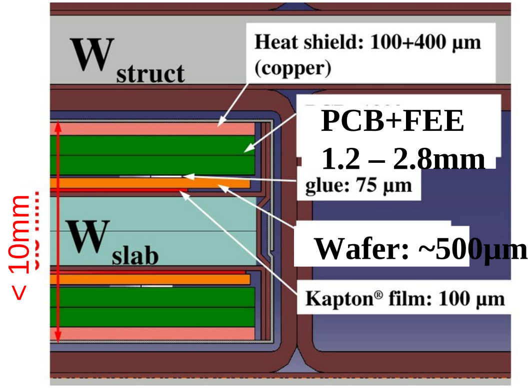
Requirements: highly integrated



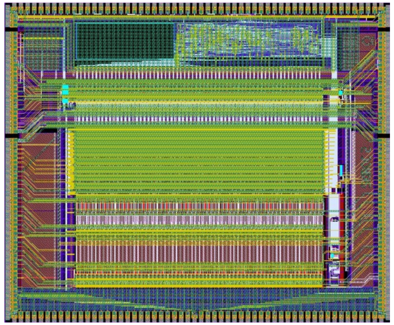
The SiW ECAL in the ILD Detector

SiW Ecal





e.g. SKIROC (for SiW Ecal)



Barrel

- ▷O(10^4) slabs
- ▷O(10^5) ASUs (PCB+wafer+ASIC+DigReadout)
- ▷O(10^{6-7}) ASICS
- ▷O(10^8) cells
  - 2000 m² of Si
- ▷130 T of tungsten

Cell size of 5x5 mm → all cells are self triggered + zero suppression

Size 7.5 mm x 8.7 mm,

64 channels

Dual gain, autotrigger, powerpulsed

(goal of 25uW / chn)

Requirements: highly compact

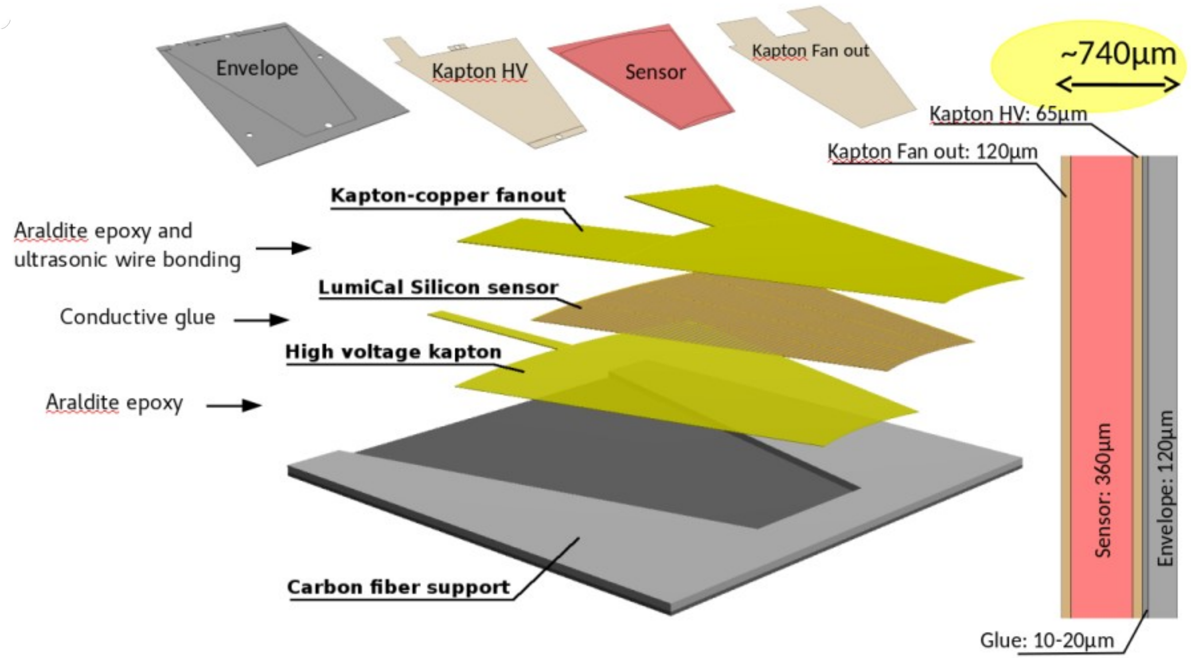


Figure 5.13. Structure of a sensitive layer of the LumiCAL calorimeter.

Forward region (LUMICAL)

- Ultra thin layers <1mm for minimal Moliere Radius
- Not embedded electronics
- Higher radiation levels

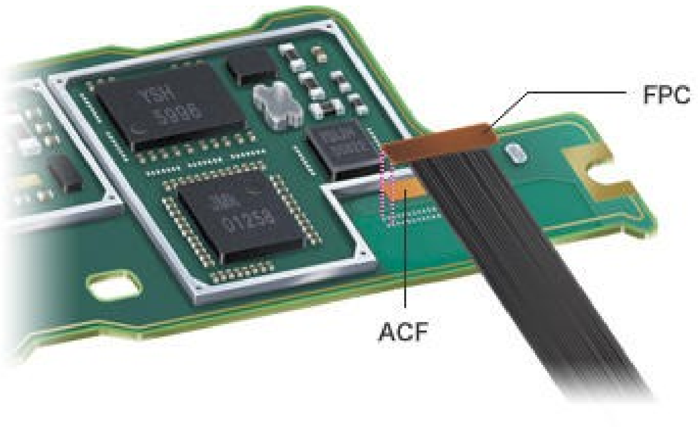
Si ECAL hybridization / integration

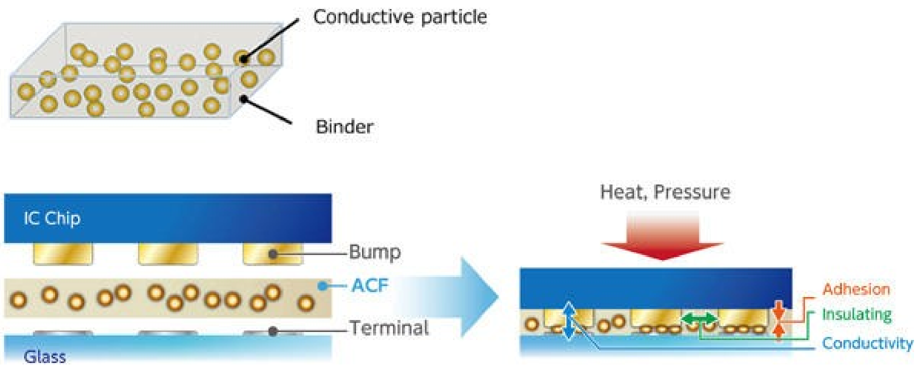
IFIC INSTITUT DE FÍSICA CORPUSCULAR

Common R&D Mid-term

▷ R&D Alternative solutions:

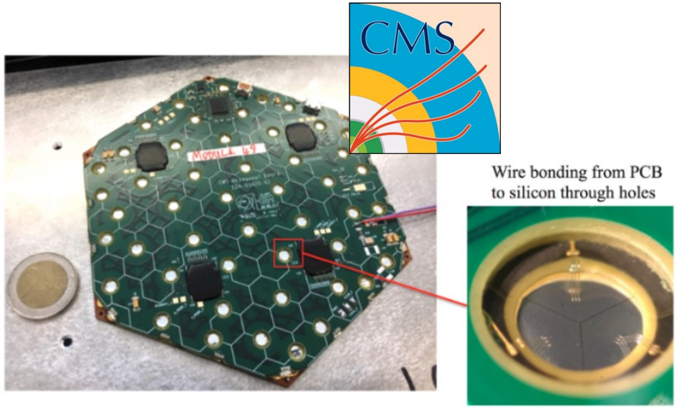
- Check what the industry is doing (smartphones, LCD screens, etc)
- → Anysotropic Conductive Films, Micropearls... (investigated also in the context of AIDAInnova & LUXE)
- Affordable for large surface sensors in rigid PCBs ??





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)

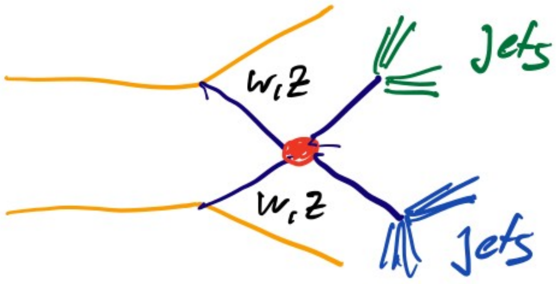
The **most compact solution**… but no space for required components (i.e. for power pulsing)

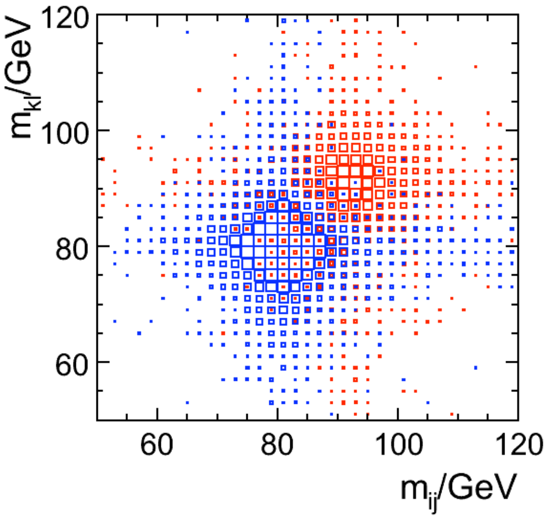
Seeking the lowest JER

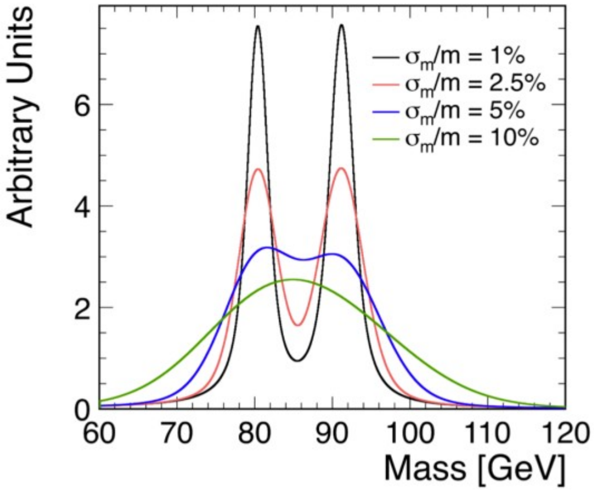
▷ **Separation of hadronic final** states of heavy bosons:

▷ **Requires jet energy resolution of ~ 3.5%** over a wide energy range

- Very high rates that require
- (e.g. 2x better than ALEPH / ATLAS)







want:

JER 3 - 5%

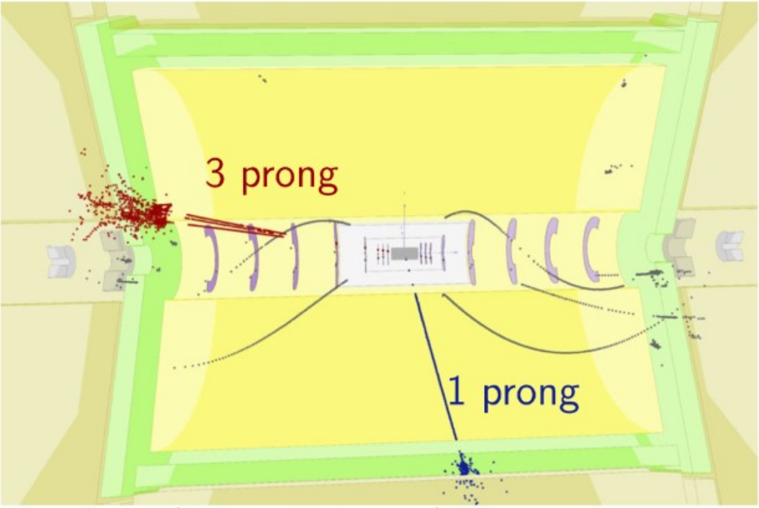
Complicated topologies: τ - reconstruction

▷ Flavour physics (low energy tau's)

▷ Direct pair production by Z, H, top decays, … (high energy taus)

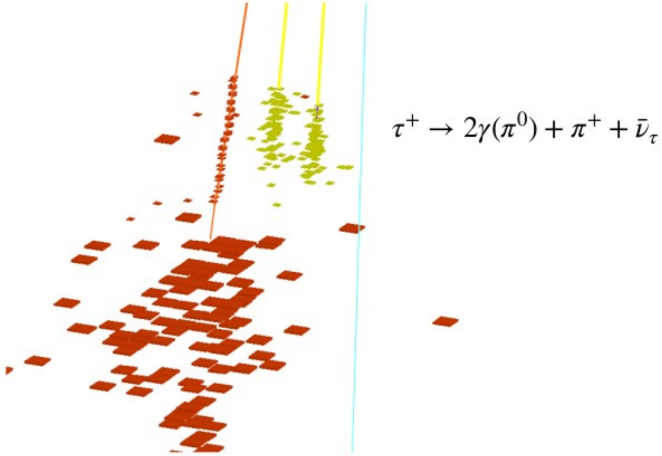
▷ Require excellent tracking, vertexing and PID capabilities and… **good ECAL resolution and high granularity in calorimetry**

A classic example: Tau reconstruction



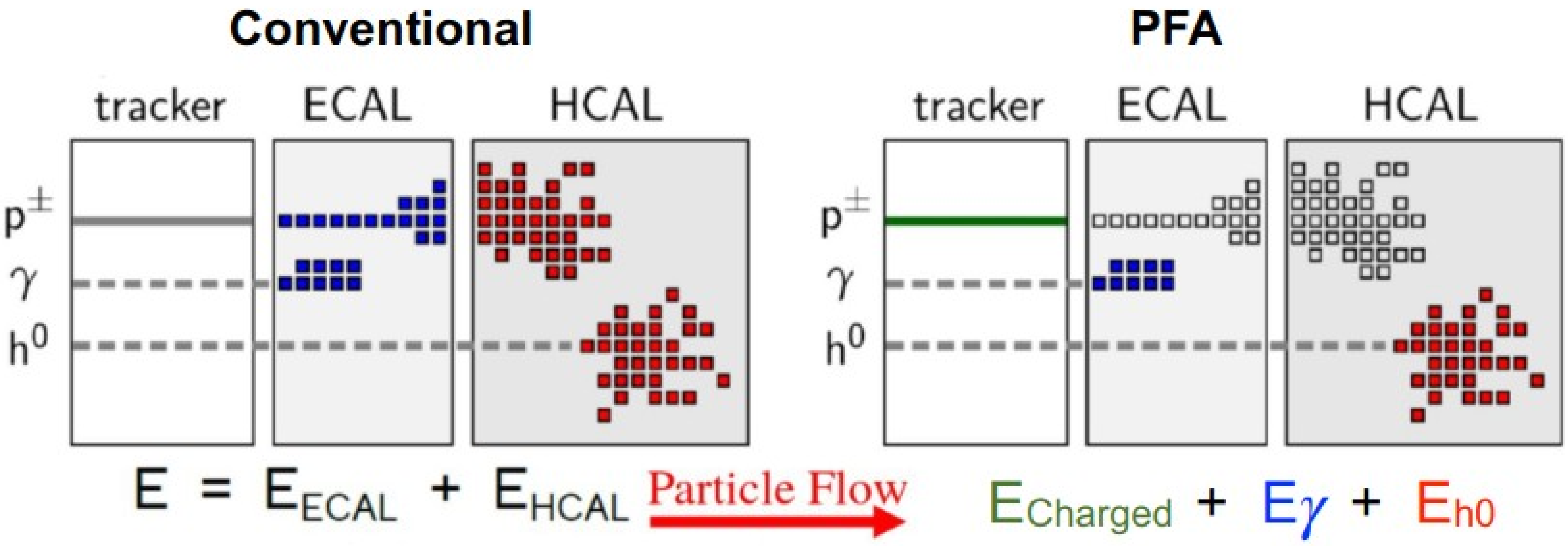
$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow \tau^+\tau^-\nu\bar{\nu}$

@ 1.4 TeV at CLIC



- Results in close-by / overlapping electromagnetic and hadronic showers

Particle Flow Algorithms



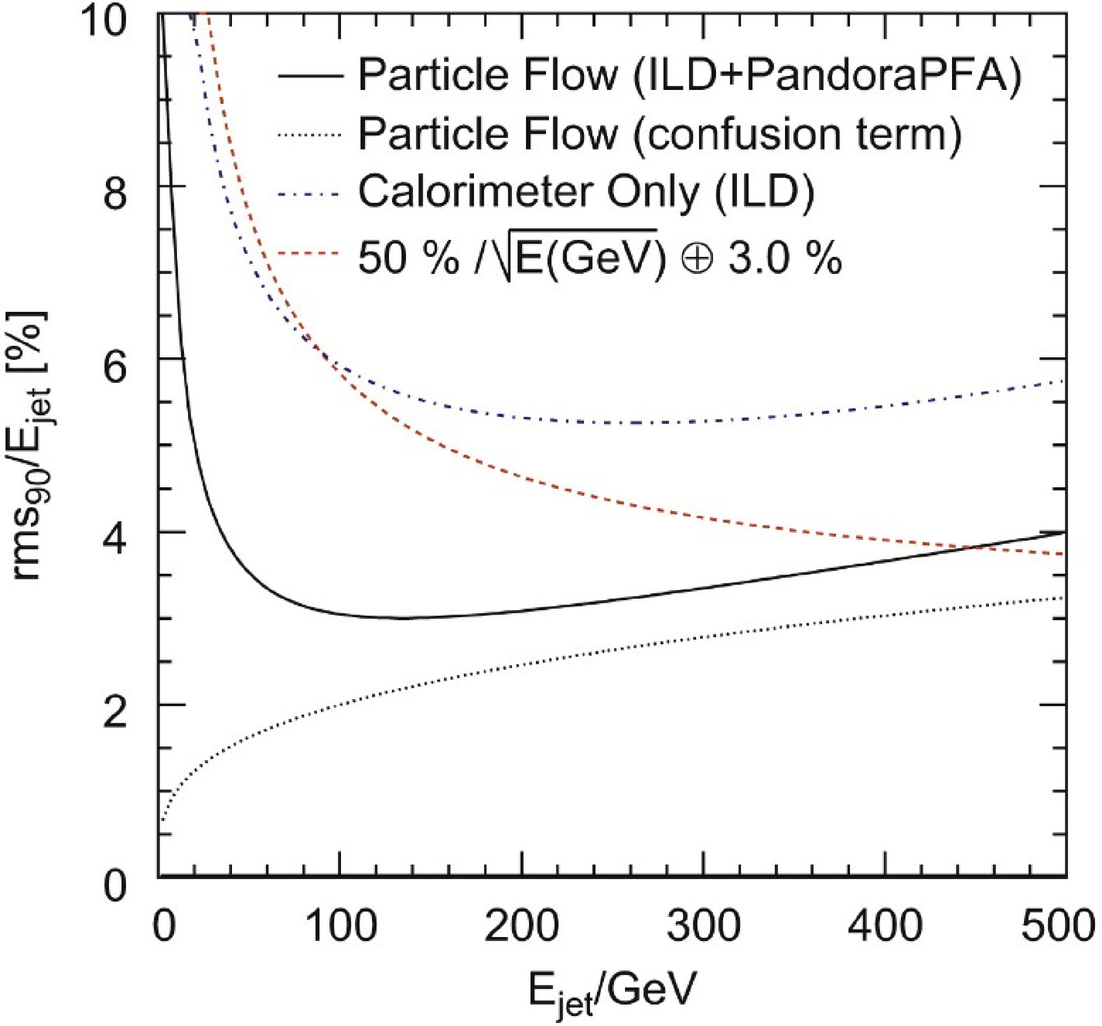
Aim: perform single particle reconstruction and use the best information in our detector estimate the energy

Example: jet created by a proton

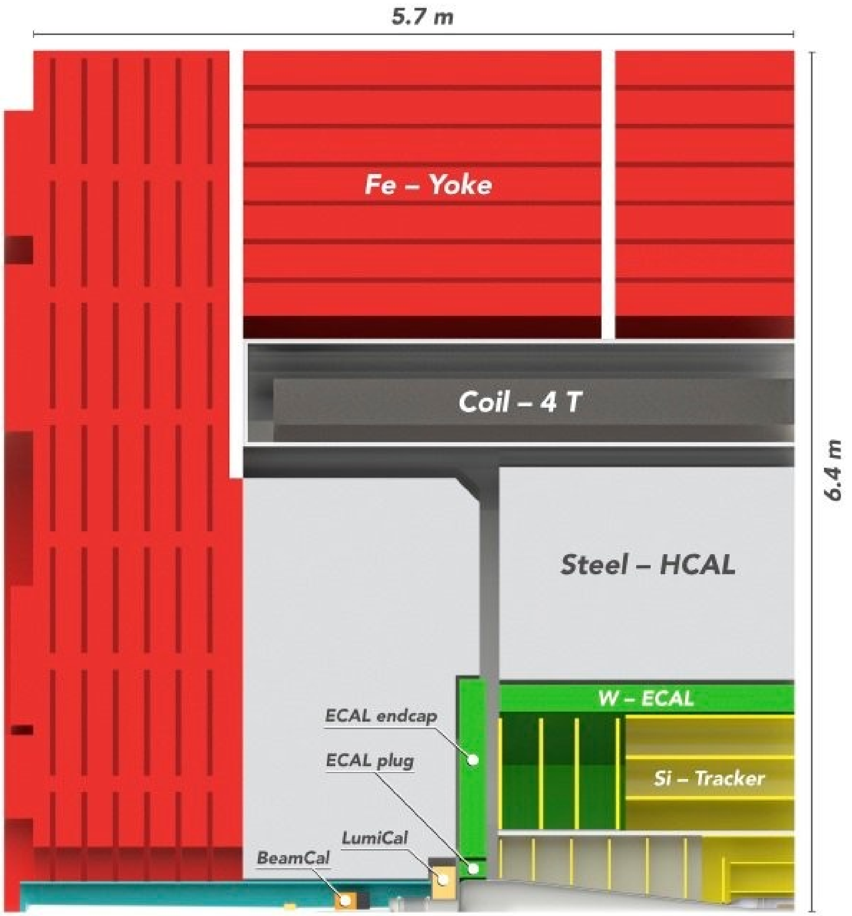
"traditional" detector : $(\Delta E)^2 \sim (\Delta E_{ECAL})^2 + (\Delta E_{HCAL})^2$

Particle Flow detector: $\Delta E \sim \Delta E_{track}$

High granular calorimetry



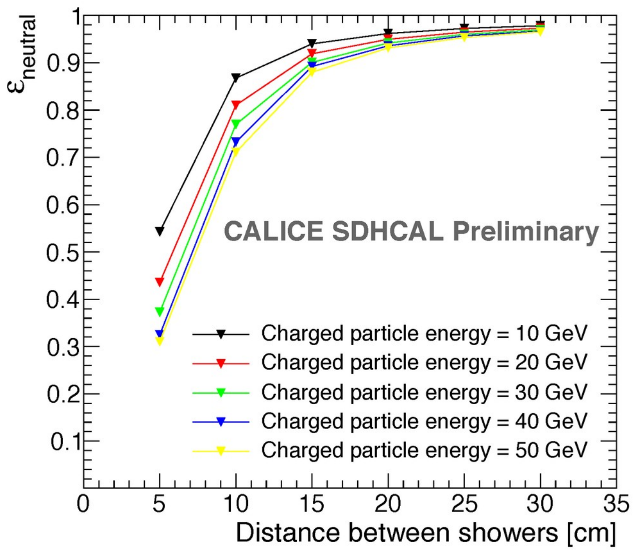
Design of a PF detector

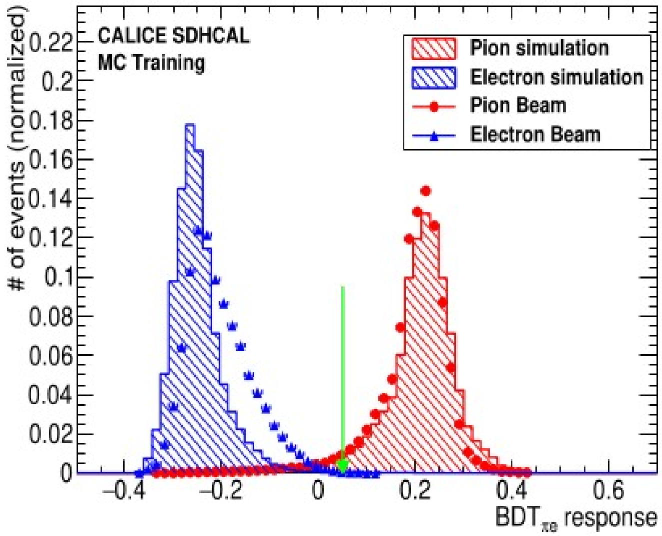


- ▷ **Holistic** approach:
  - Tracking, vertexing, PID detectors, calorimeters, coils, etc.. all systems are at the service of the event reconstruction
- ▷ Maximal **acceptance** minimizing cracks, dead material, endcap-barrel transitions…
  - Forward calos as close as possible to the IP.
- ▷ **Minimum material** in front of the calorimeters,
  - Low material budget tracking systems.
  - Calorimeters **inside a large magnetic field** (no coil between trackers and calos)
- ▷ **Highly compact calorimeters** (cost and physics)
  - **Readout is highly integrated**: data processing done "in" the detector
- ▷ **Highly Granular calorimeters**
  - Between 10^6-10^8 channels (barrel)

High granularity calorimeters: more than “only” PFA

INSTITUT DE FÍSICA CORPUSCULAR





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

High **granularity** offers unprecedented capabilities to perform **PID in the calorimeters**