Calorimetry for Higgs Factory Detectors

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Plan de Recuperación, Transformación y Resiliencia

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LCWS2023 INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

This is an **incomplete overview** of Calorimetry R&D

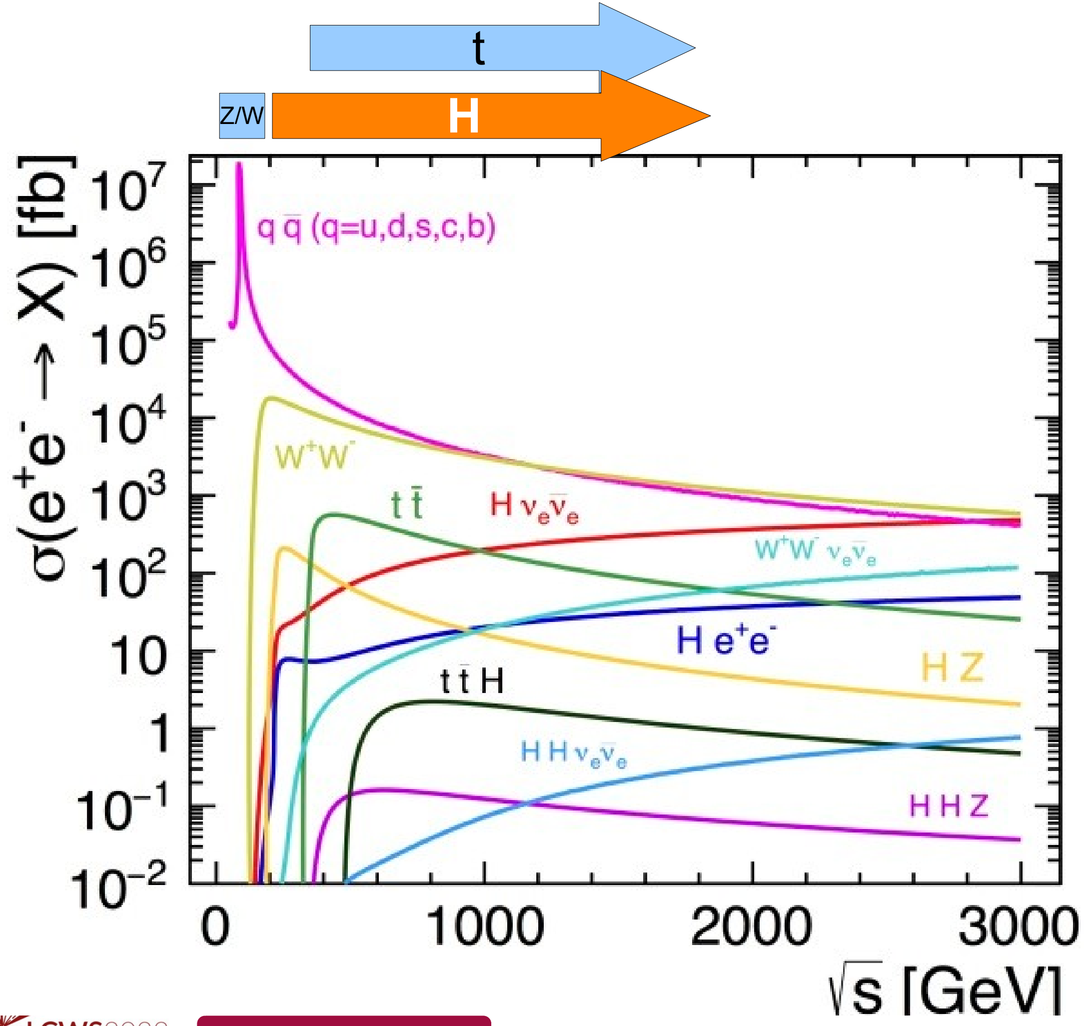
This is **not a review of all the detector proposals** for all Higgs Factories.

Thanks to R. Poeschl, K. Krueger, F. Simon, T. Peitzmann, Y. Benhammou, V. Boudry et many more for material.

1 Calorimetry for Higgs Factories: physics drivers

Higgs Factories

e+e- colliders



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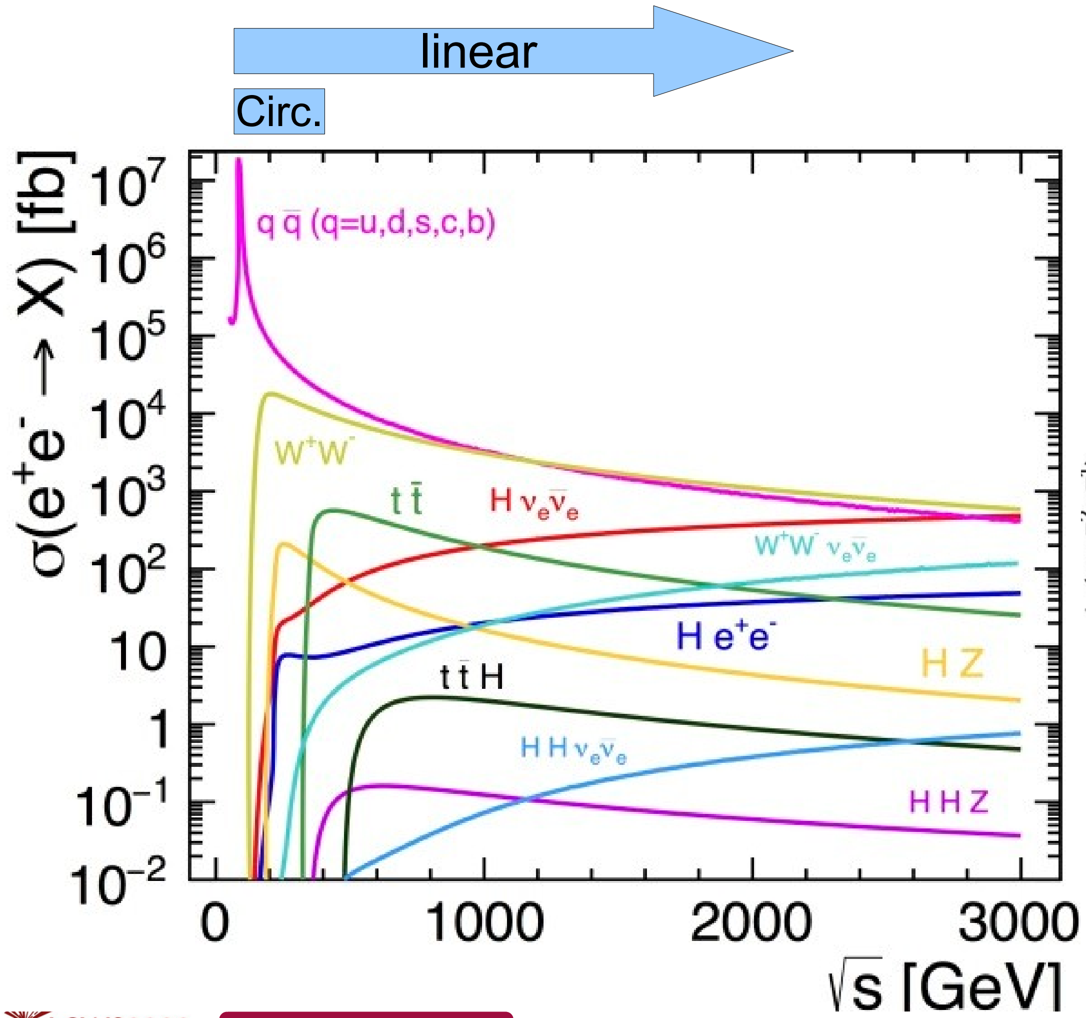
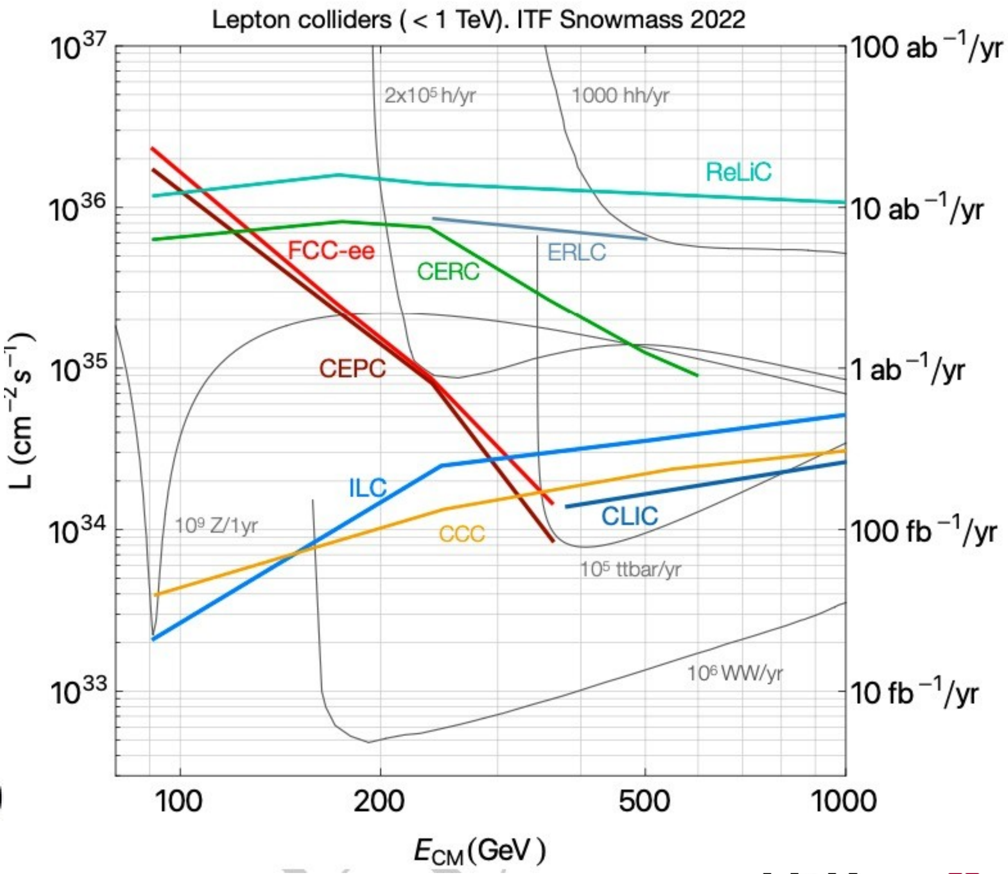
Higgs Factories





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Higgs Factories proposals: Differences and similarities (for calorimetry)

- Higher energy reach implies higher energy for produced particles and jets
  - direct impact on crucial design parameters of calorimeters such as thickness, absorber material, granularity

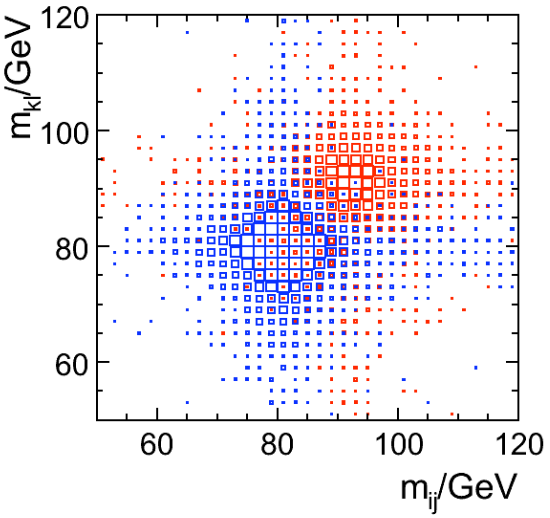
- Linear colliders have bunch trains, circular colliders not.
- Bunched beam structure allows
  - for power pulsed electronics:
  - Highly integrated
  - Reduced of cooling systems
  - Triggerless readout

} compactness

Check R.. Poeschl talk:
Highly Granular Calorimeters - Impact of different Higgs Factory Options

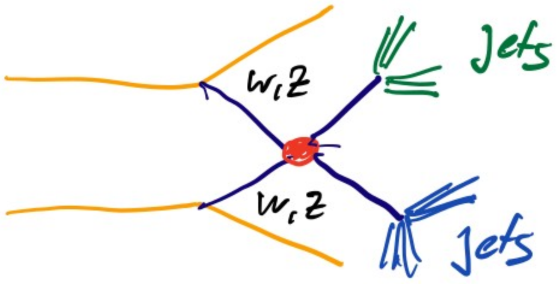
Seeking the lowest JER

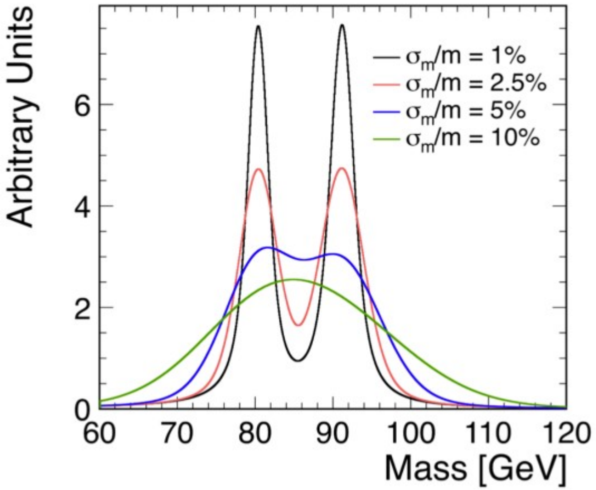
▶ **Separation of hadronic final** states of heavy bosons:



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

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





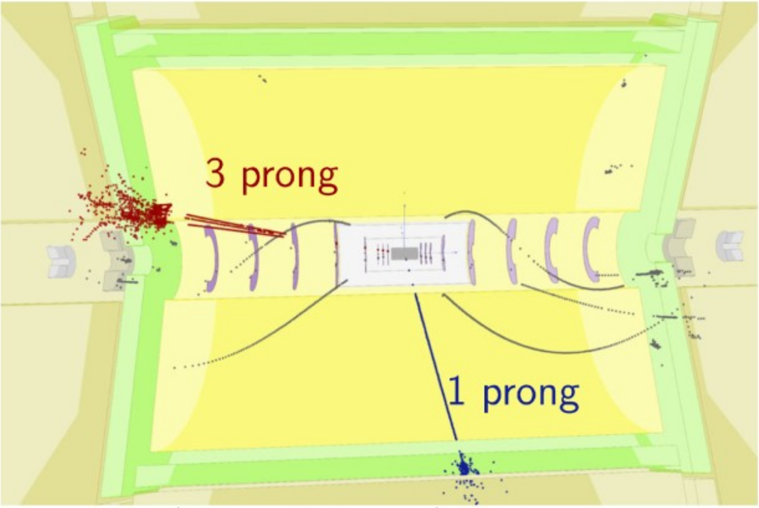
want:

JER 3 - 5%

Complicated topologies: τ - reconstruction

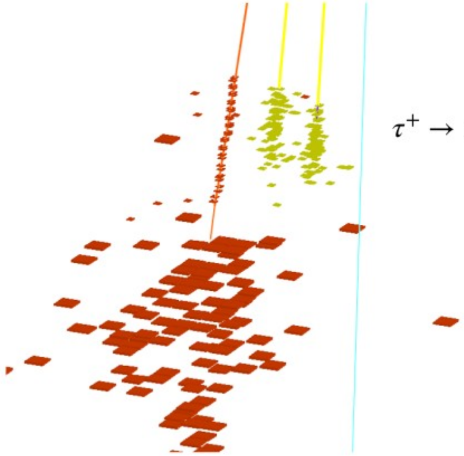
- Flavour physics (low energy tau's)
- Direct pair production by Z, H, top decays, … (high energy taus)
- Require excellent tracking, vertexing and PID capabilities and… **good ECAL resolution and high granularity in calorimetry**

A classic example: Tau reconstruction



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

@ 1.4 TeV at CLIC



$\tau^+ \rightarrow 2\gamma(\pi^0) + \pi^+ + \bar{\nu}_\tau$

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

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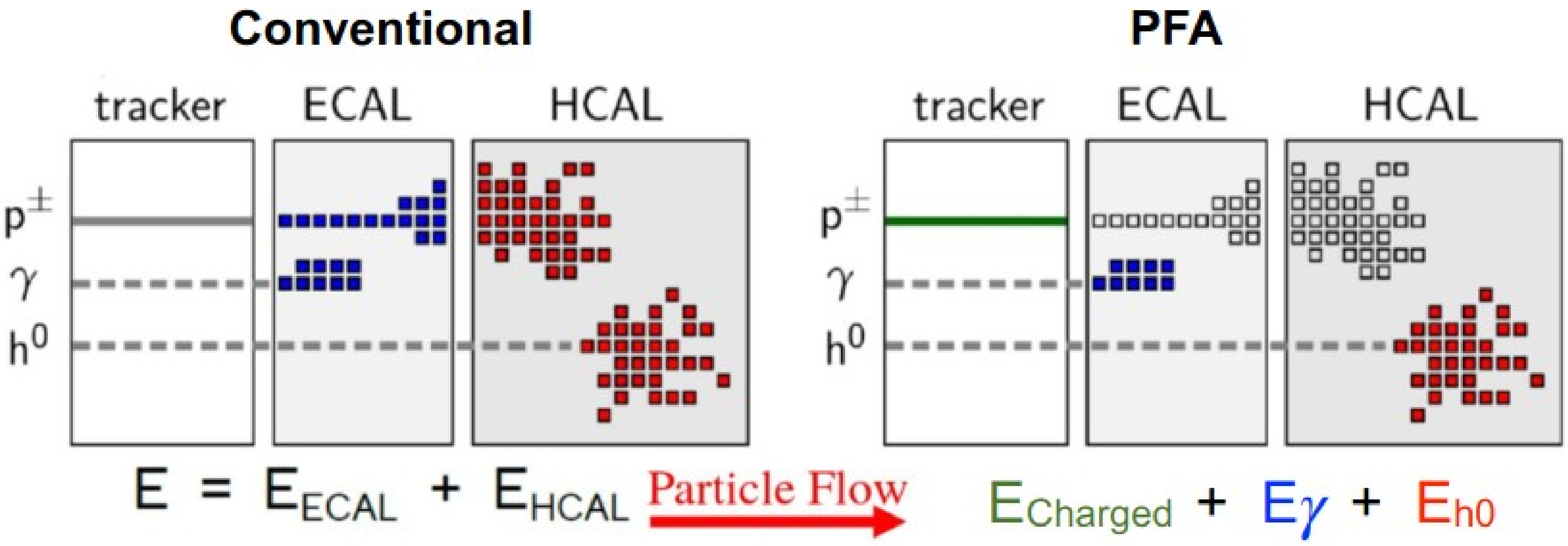
2 Highly Granular calorimetry (Particle Flow)

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: $\Delta E \sim \Delta E_{track}$

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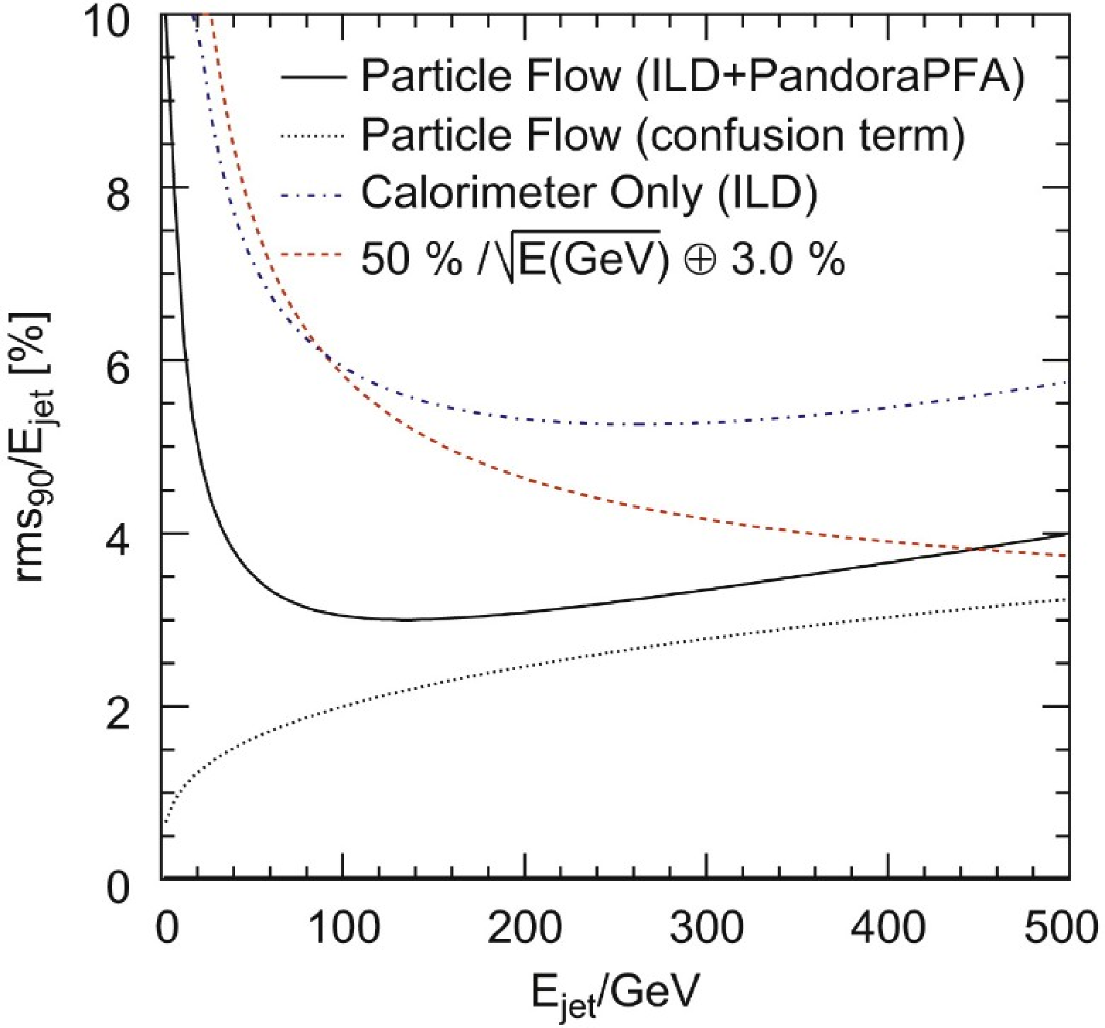
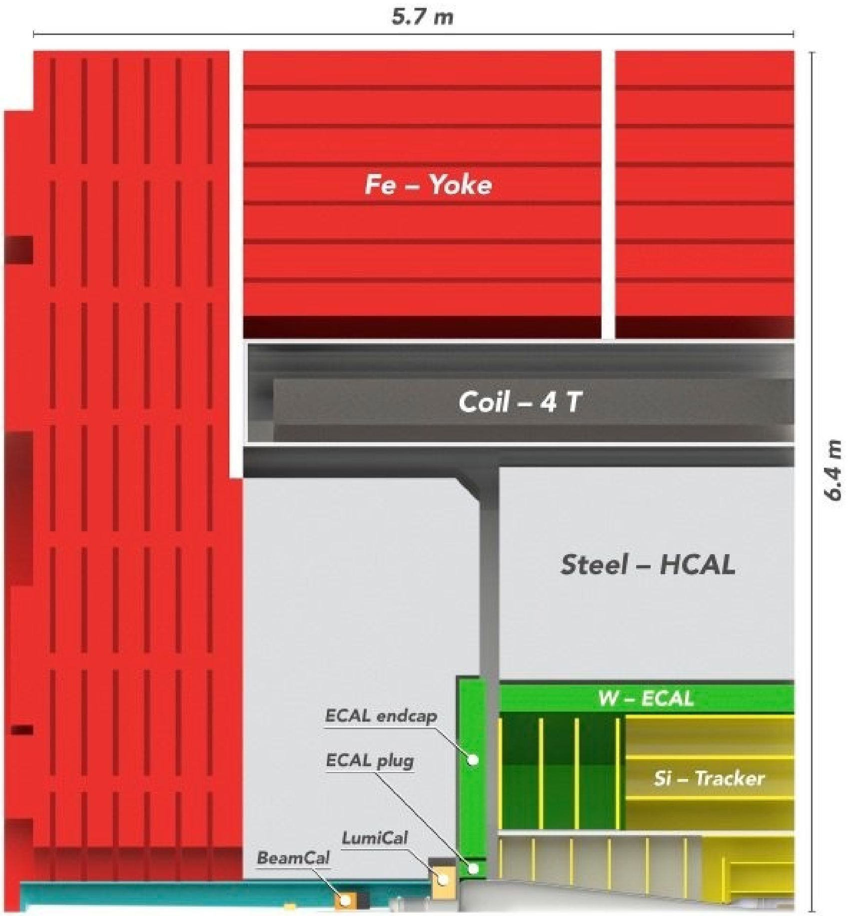
High granular calorimetry



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)

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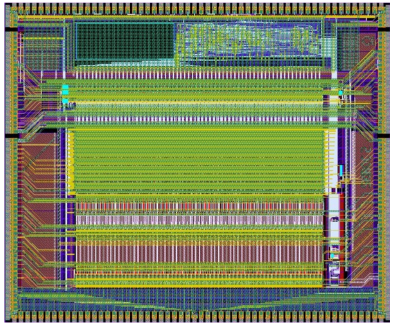
3 Highlights on Calorimetry R&D

PFA: Technological premises à la CALICE

Highly integrated (very) front end electronics

e.g. SKIROC (for SiW Ecal)

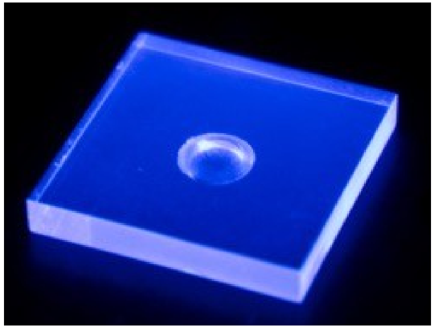


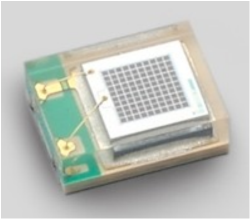
Size 7.5 mm x 8.7 mm, 64 channels

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

- **Common developments on different CALICE projects**

Miniaturisation of r/o devices





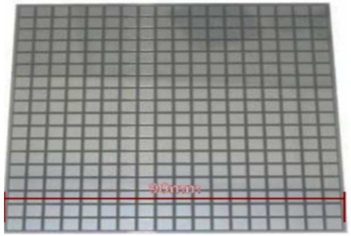
- Small scinitllating tiles
- (Low noise) SiPMs

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

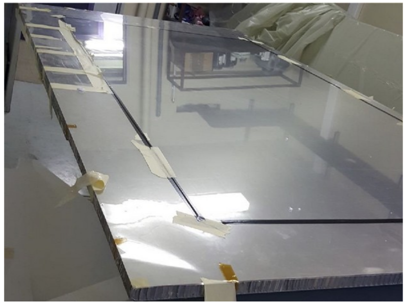
Self trigger of individual cells below MIP level

Large surface detectors

Si Wafer



RPC layers



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

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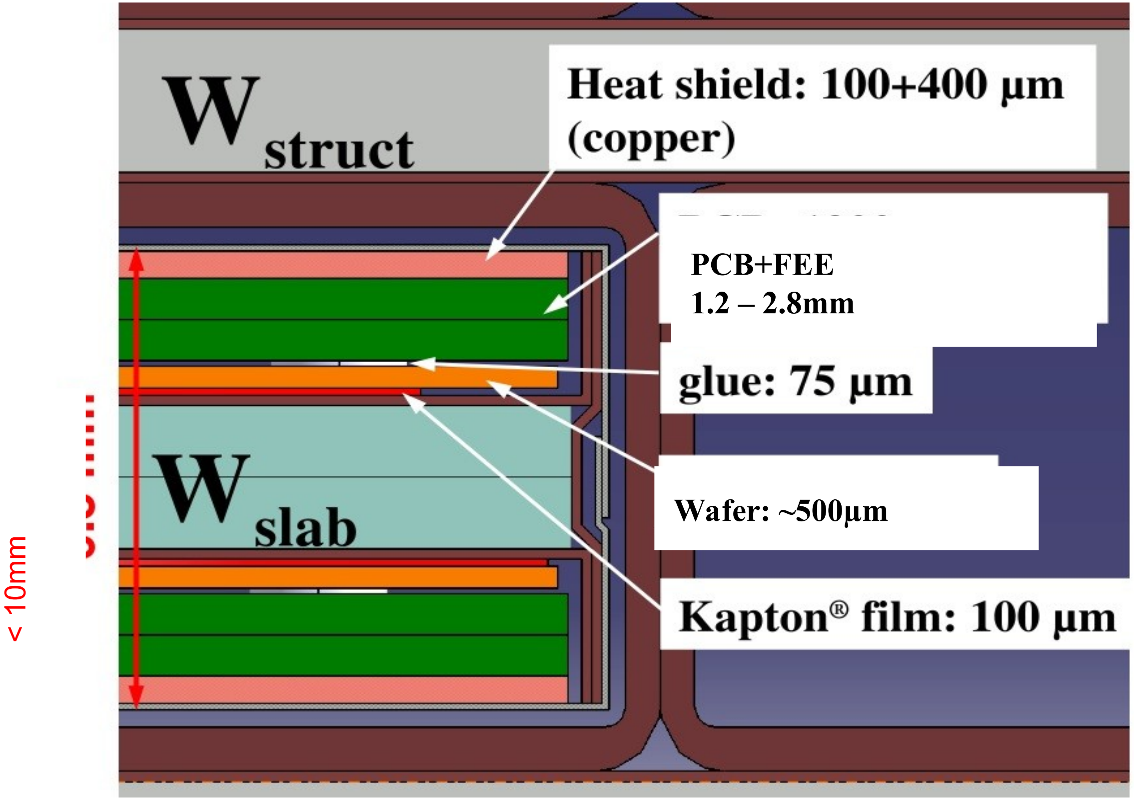
PFA technological premises: sandwich calorimeters



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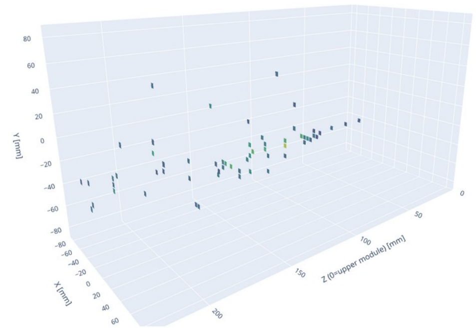
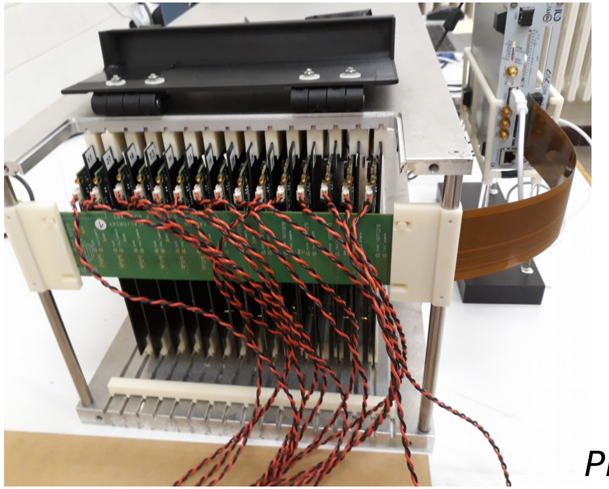
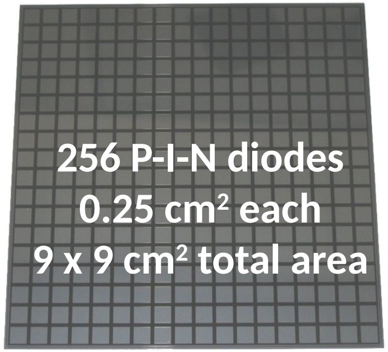
SiW-ECAL

SiW-ECAL

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







EUDET layout
Prototype from Hamamatsu

Production of a large scale prototype (adapted to LUXE)

Proposed for the ECAL of:
ILD,
CLICd
CLD...

Check R. Poeschl and A.I. talks in Track 3 session

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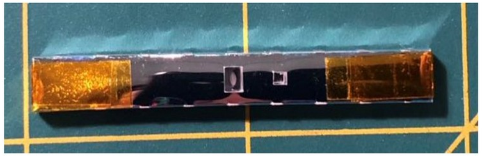
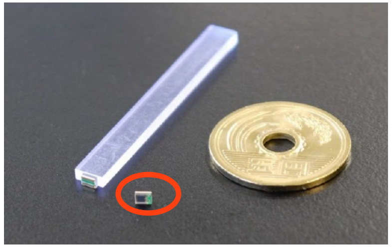
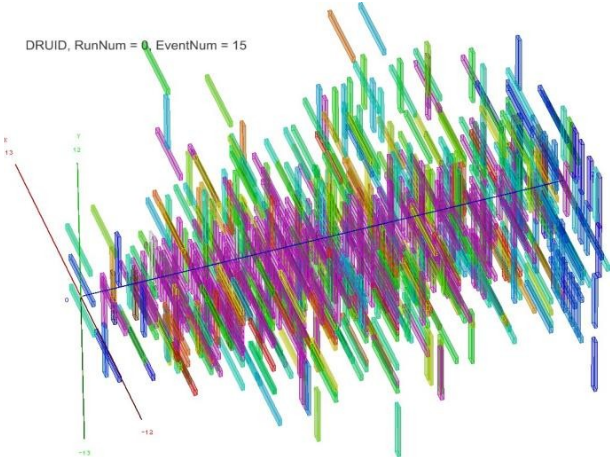
Sc-ECAL





Production of a large scale prototype
Large scale TB campaign ongoing

Proposed for the ECAL of:
ILD,
CEPC detector



- 30 layers, 22cm*22cm, 6300 channels
- 22X0
- 300 kg
- Strips 5 mm x 45 mm x 2 mm^3

Effective granularity of $5x5mm^2$
(but with x10 less channels) → relevant for power consumption control

Digital ECAL based on MAPS

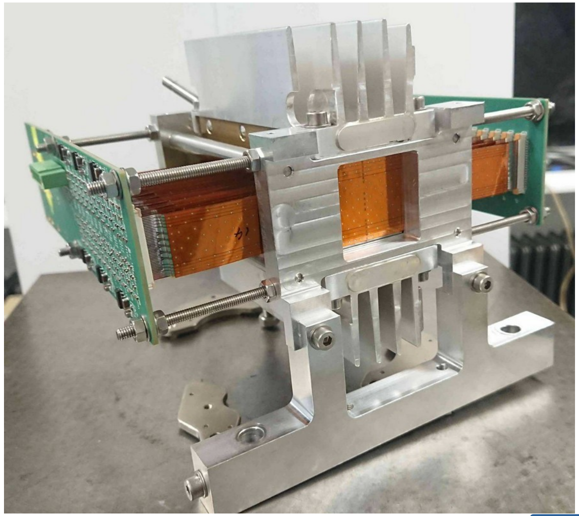
- Primary experimental context: ALICE FOCAL, Higgs Factories
- A MAPS-based digital Silicon-Tungsten ECAL,
  - building on current DECAL and EPICAL projects, partially integrated in CALICE
  - Also relevant activities (and interest) at SLAC, U Oregon with connections to CERN

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

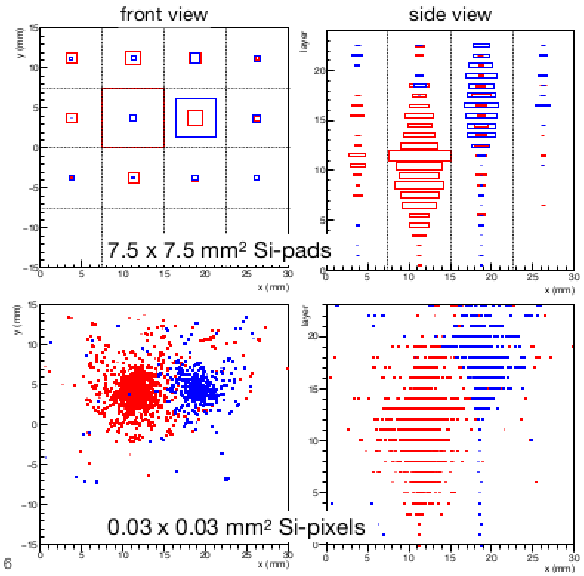
29.24 x 26.88 µm² pixel size

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

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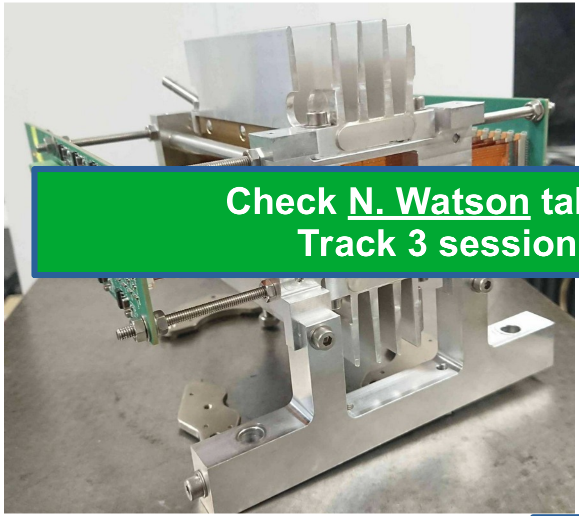
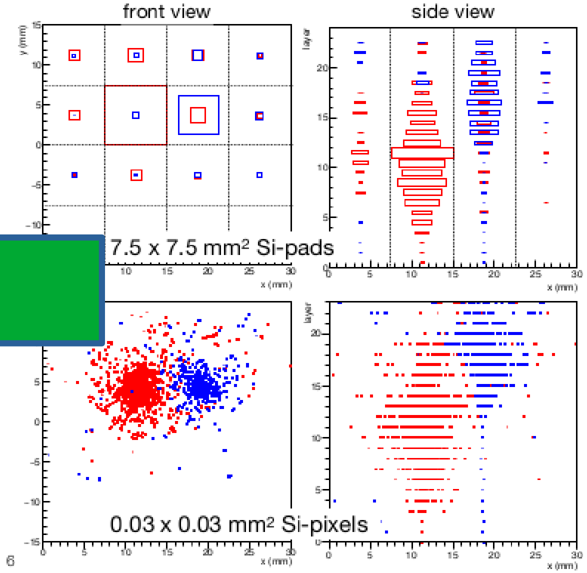


EPICAL-2

Check N. Watson talk in Track 3 session



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

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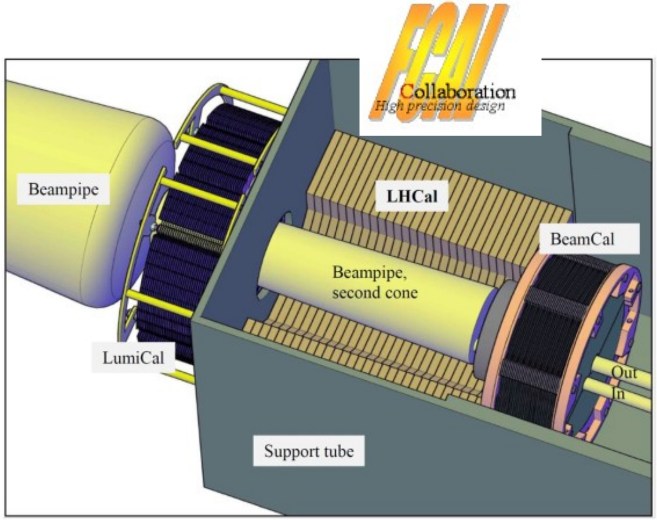
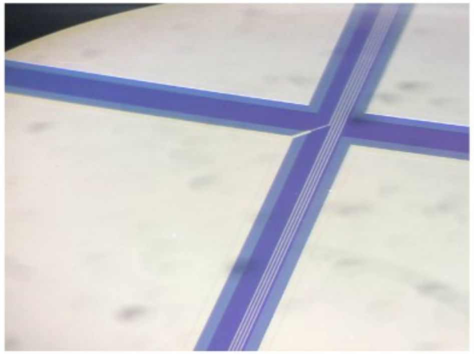
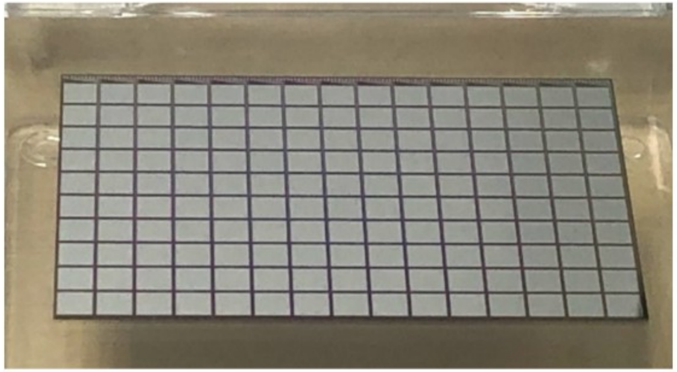
Forward Calorimetry (extreme compactness)

- 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)
- Recent progress:
  - investigation of new GaAs sensors with integrated signal routing → similar signal size to silicon sensor
  - Wireless DAQ?

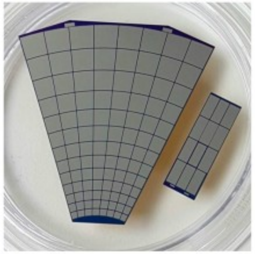






Production of a large scale prototype (adapted to LUXE)

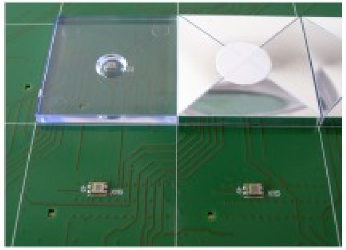
LumiCal:
Silicon sensor

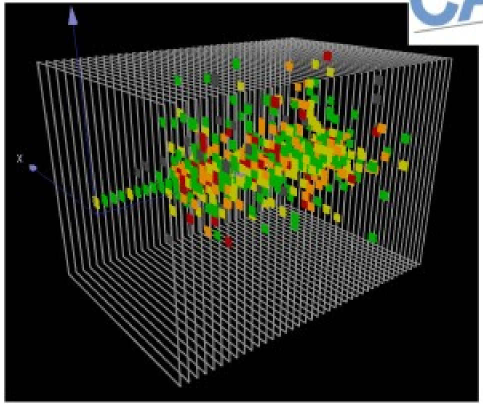


BeamCal:
GaAs sensor

Slide from K. Krueger

Sc Analogue HCAL





CALICE

Same readout

- Granularity optimised for CEPC. (40x40 mm²)
- 38-layer scintillator-steel HCAL prototype assembled,
- Recent beam test with Sc-ECAL at CERN.

38-layer HCAL prototype, 30*30 mm²
Extensive beam test campaigns
(including CMS-HGCAL and common beam tests with SiWECAL)

Large scale Prototypes existing.

Proposed for the HCAL of:
ILD,, SiD
CLICd
CLD, CEPC

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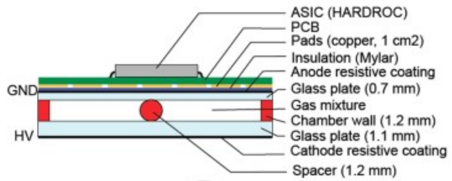
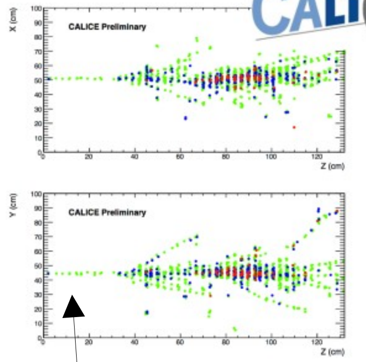
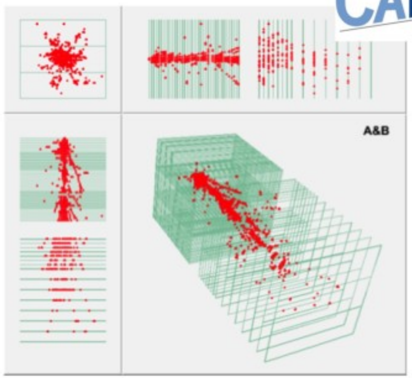
(Semi) digital Hadronic calorimeters

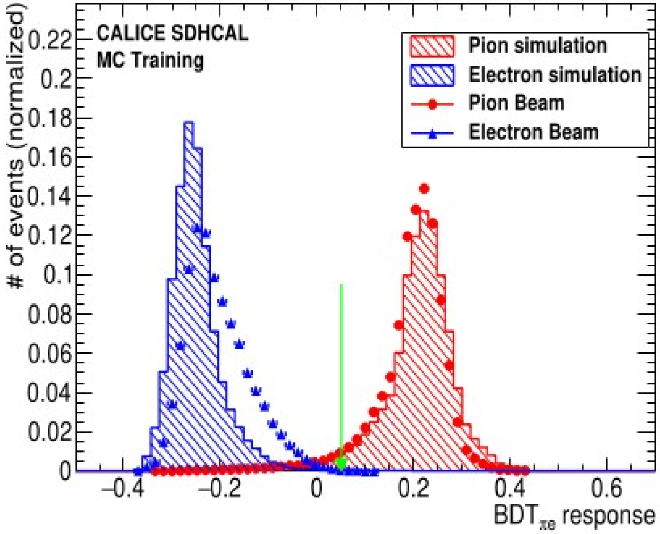
semi-digital	digital
1*1 cm^2	1*1 cm^2
RPCs (or μMegas)	RPCs (or GEMs)







48-layer HCAL prototype,
~440000 readout channels (SemiDigital)



Large scale prototypes existing.
R&D on timing, electronics

Proposed for the HCAL of: ILD,, SiD

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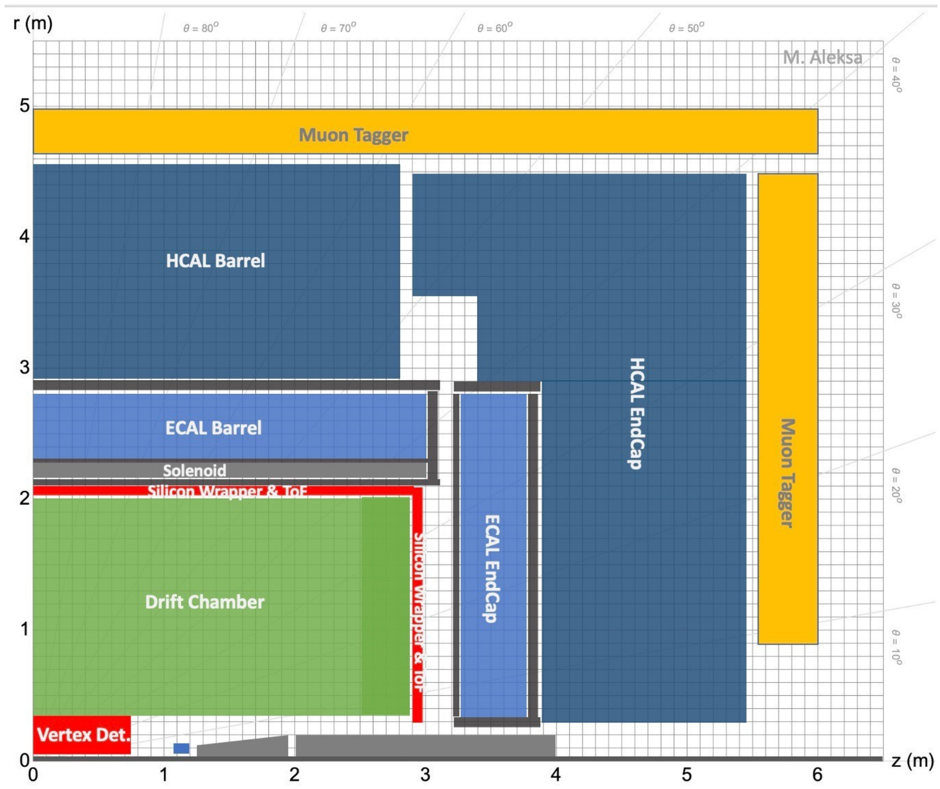
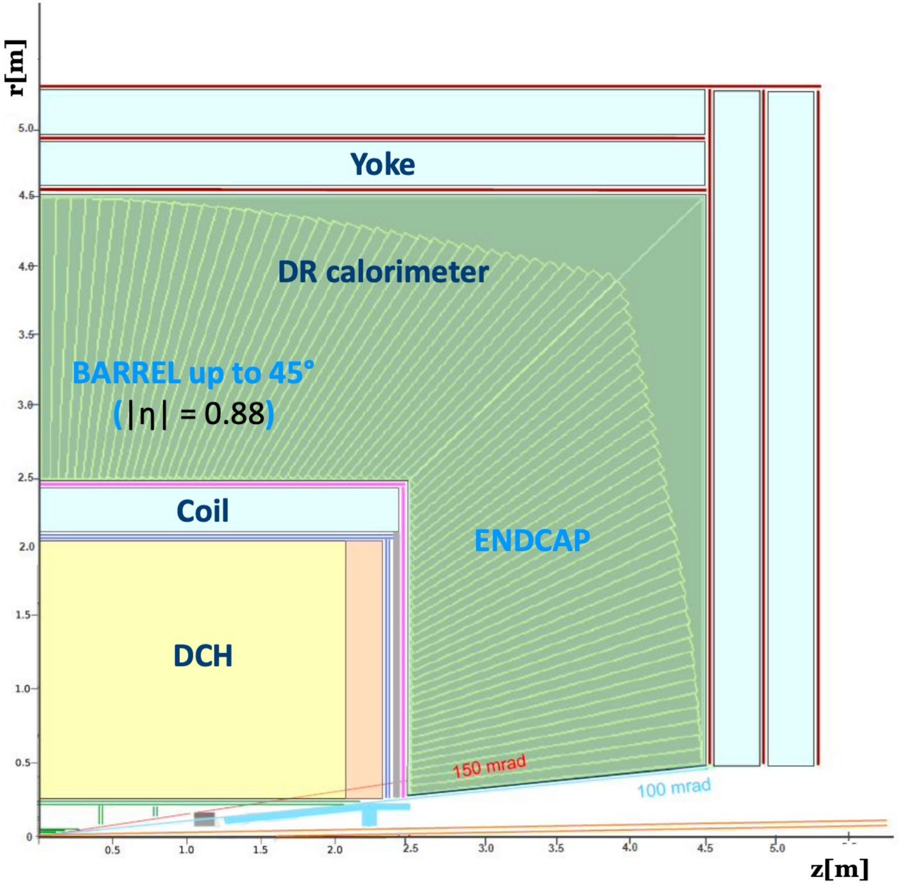
LAr & Dual Readout Calorimetry



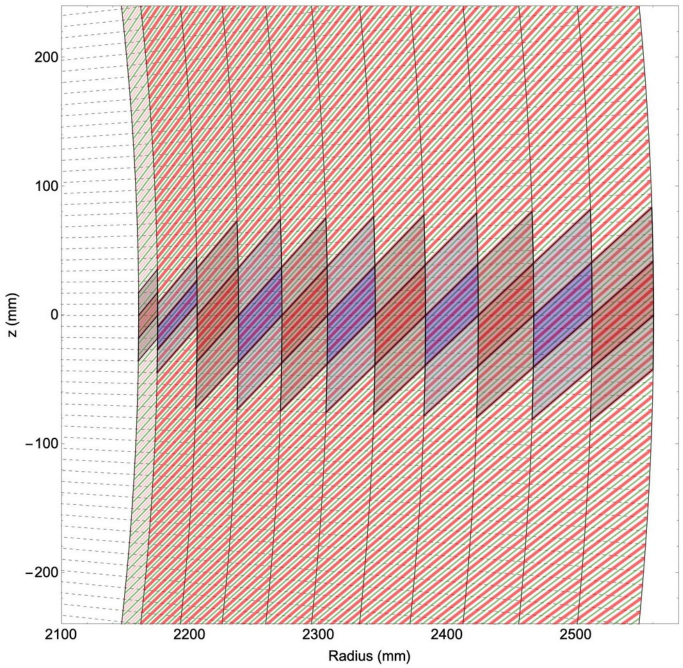
LAr (for FCC)



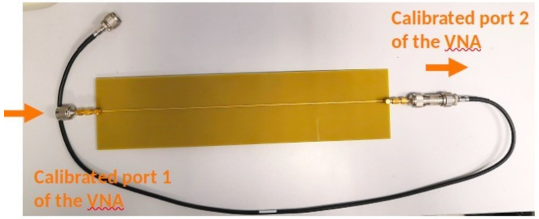
DR (for IDEA-FCC)

LAr

- Noble-liquid calorimetry: High intrinsic stability (demonstrated at **ATLAS**)
  - Pedestal stability < 100 keV (!)
  - Gain stability 2.6x10^{-4}
- Aim for Higgs factory: reach **10 times higher granularity than in ATLAS**
  - longitudinal segmentation: 12 layers in baseline design
- **Optimisation** of the design for FCC-ee ongoing



- Further ongoing investigations
  - Requires electrodes as multi-layer PCBs
  - Thin cryostat
  - High-density feed-through
  - Low-noise readout electronics (warm or cold?)



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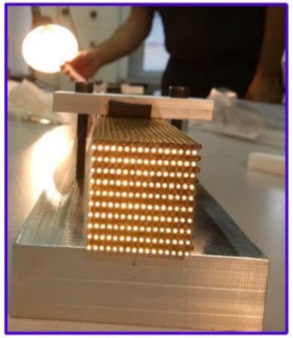
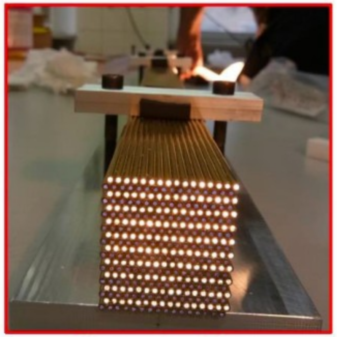
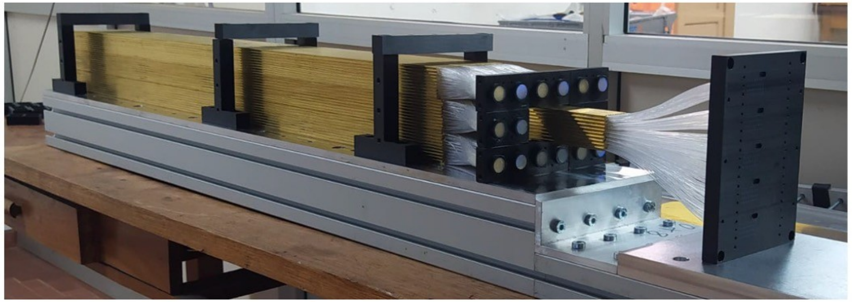
Dual Readout Calorimetry

- ▶ Idea: measure two signals simultaneously to determine electromagnetic fraction of hadron shower
  - Improve energy measurement by correcting with (known) e/h of calo
- ▶ Measure simultaneously
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- ▶ Calibrate both signals with electrons


Scintillation fibers


Cherenkov fibers

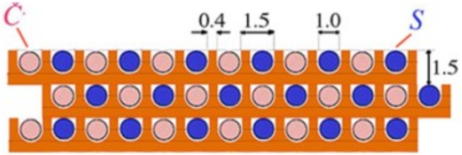


Existing ECAL size prototype

$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$



Novel ideas for DR in Particle Flow -like detectors (see. S. Kunori& T. Takeshita's talks)

what more? precise timing?

The technologies offer good prospects on timing

- Actual prototypes can do up to 1 ns (keeping the power budget)
  - Silicon can go up to the ~30ps
  - Scintillator (small tiles with high lightyield, crystal) ~30ps
  - RPC multi-gap RPC have demonstrated ~60ps
  - (numbers for MIPs)
- **5D Particle Flow?**
  - What time resolution would be needed to improve particle flow reconstruction?
- **Particle Identiication using Time-of-flight**
  - A first ECAL layer for TOF with ~10-50ps can help for pion/kaon/proton PID (with momentums of few GeV)

- Note: Also readout electronics contributes to time resolution, and **better resolution in general needs more power**

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3 Summary

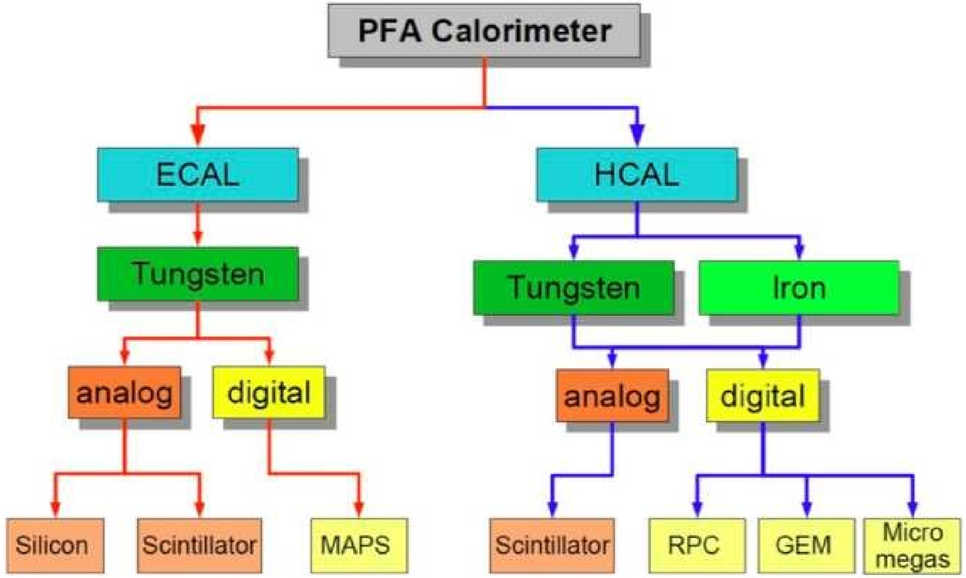
Summary

- **Calorimeters are central** systems for future Higgs Factories
- **Calorimetry** for Future Higgs Factories **is highly granular**
- Detector concepts around **PFA calorimeters** well established**; dual readout; also LAr**
- **The technologies are mature**
  - Concepts being implemented for HL-LHC upgrades
  - But further understand requirements - and the match to possible technological solutions
  - (example: we need to fully establish the benefit (and requirements) for timing - depending on technology)
- Many R&D concepts are tailored to linear colliders.
  - Adaptation to circular colliders requires further R&D

back-up

Particle Flow Calorimetry R&D

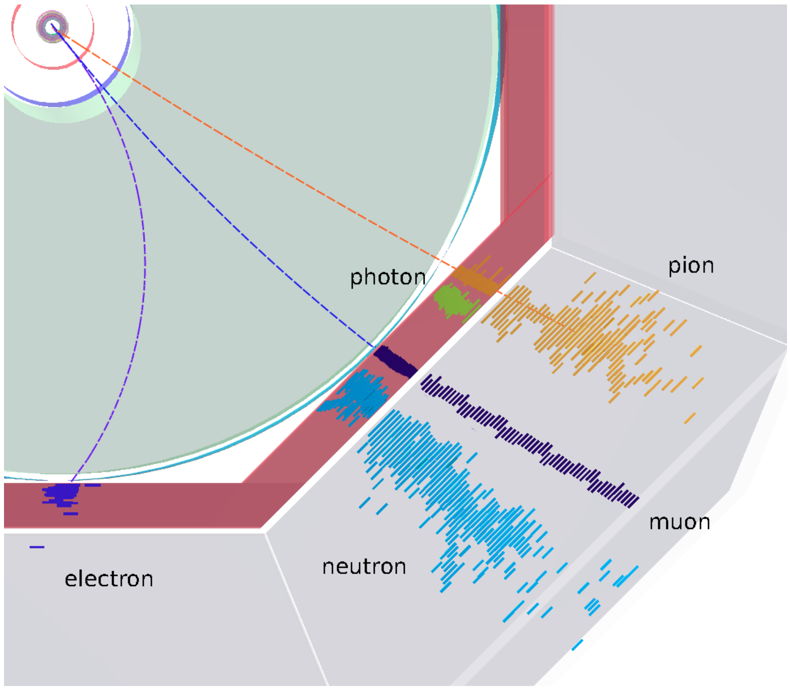
Pioneered by the CALICE Collaboration



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

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

Particle Flow Algorithms



Calorimetry requirements
Ultracompactness: small Molière radius of calorimeters to minimize shower overlap
Extreme high granularity

Calorimetry requirements

- 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

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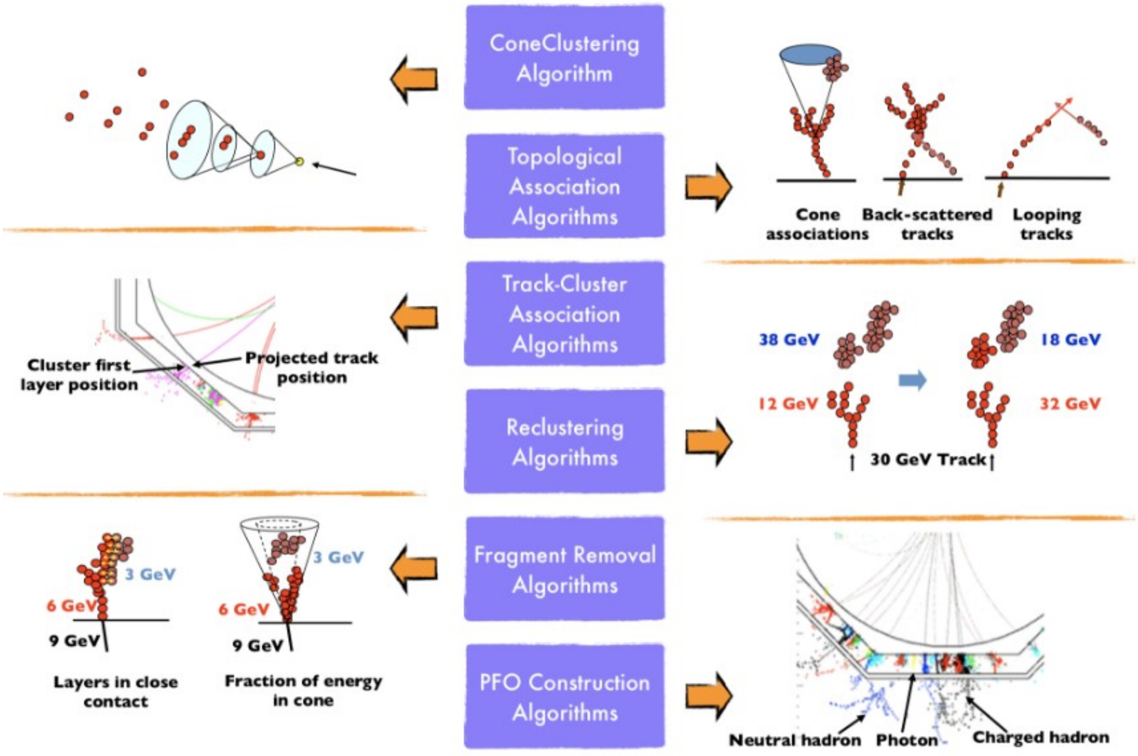
Pandora: a Particle Flow Algorithm

A Multi-Algorithm Pattern Recognition Tool

Illustration of Key Steps of PandoraPFA



J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

- PandoraPFA: Complex multi-algorithm chain using pattern recognition for event reconstruction
  - ➡ Performs calorimeter hit clustering, topological associations, …
  - ➡ Highly recursive: Find most accurate reconstruction scenario
  - ➡ Overall goal: Distinguish energy depositions originating from charged and neutral particles in calorimeters and avoid **confusion** among those

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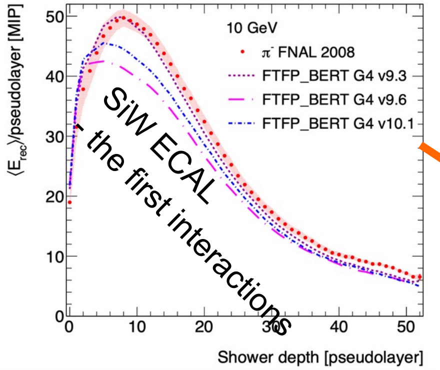
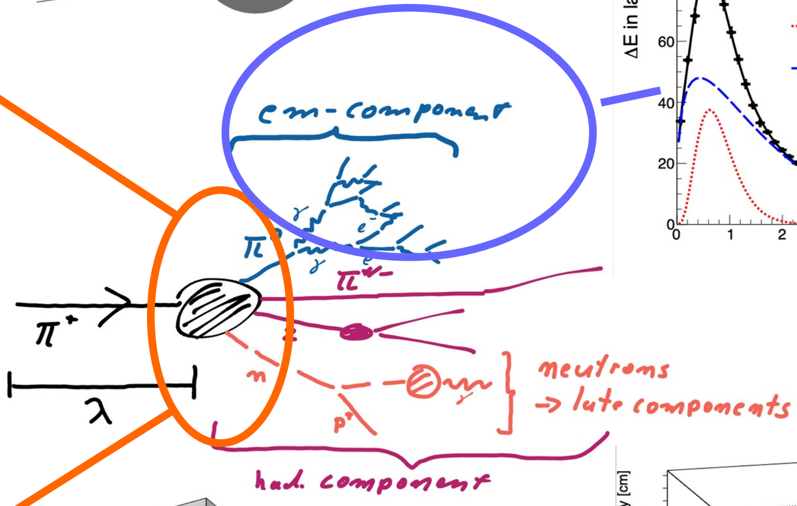
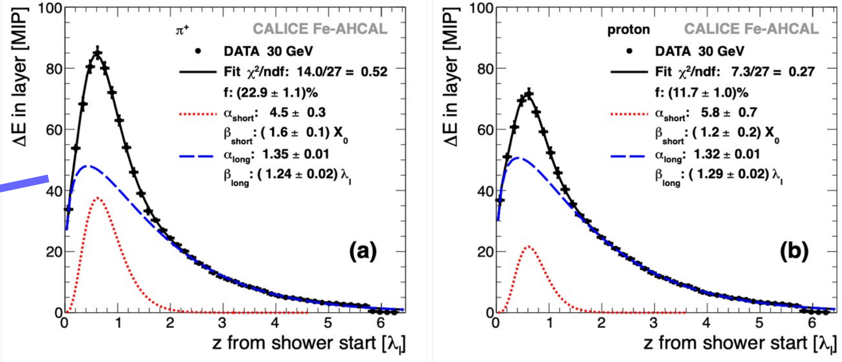
Others

- ARBOR PFA
  - Shower development topology in an imaging calorimeter reminds of a tree structure.
  - Backward approach, from leaf to branches to tree with seeds often in the last layers
- APRIL
  - ≈ Arbor PFA with modified cluster merging for SDHCAL
- Garlic
  - Gamma reconstruction at a Linear Collider
- TICL (The Iterative Clustering)
  - a modular framework integrated and under development in CMS software (CMSSW) –> High Granular CMS
- **Innovative Machine Learning approaches**
  - **Profit from the high granularity (x,y,z,E,t)**
  - **Coming soon(?)**

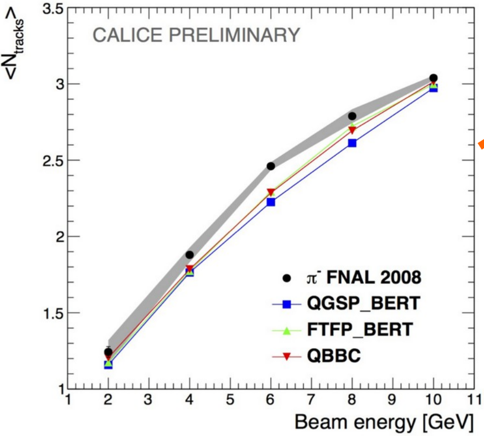
High granularity calorimeters: more than "only" PFA

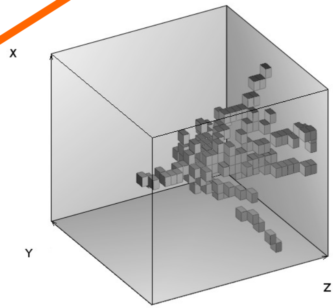


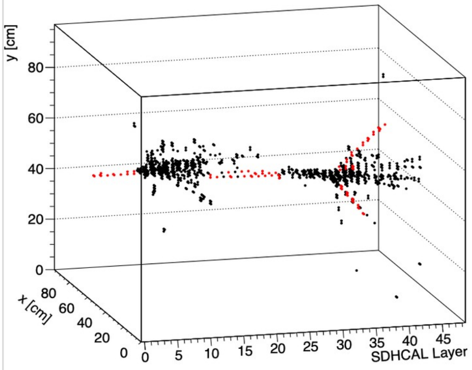


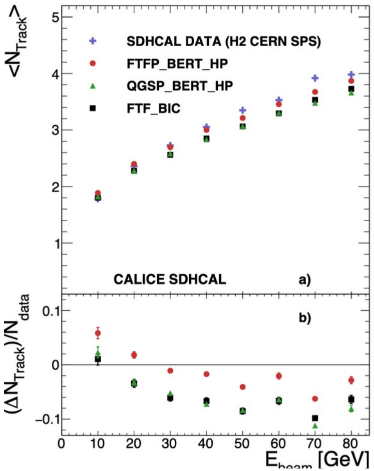


F. Simon, FCCee Meeting, Jan. 2020



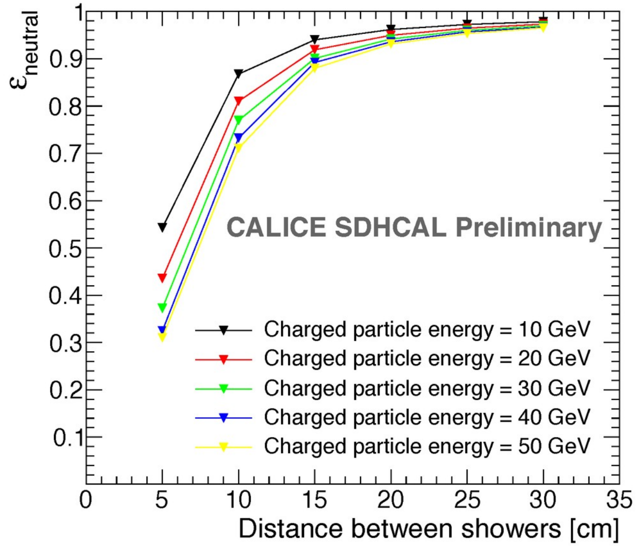


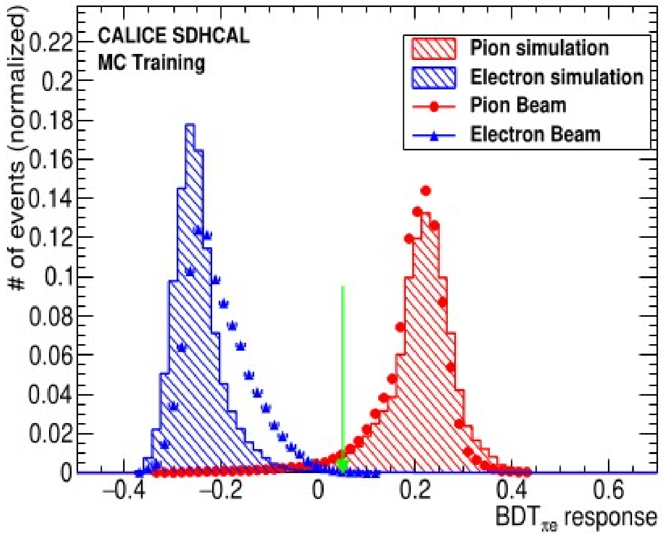




High **granularity** offers unprecedented capabilities to **study** the **development of showers**

High granularity calorimeters: more than "only" PFA



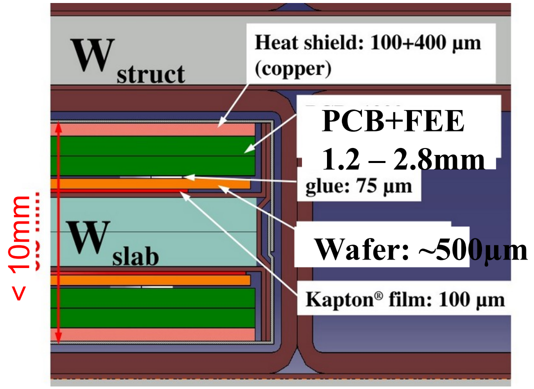


- **SDHCAL**: Separation of 10 GeV between neutral hadron and charged hadron [CALICE-CAN-2015-001]
  - More than 90% efficiency and purity for distances ≥ 15 cm
- **SDHCAL** using 6 variable discriminnating **BDT for Particle Identification** [JINST 15 (2020) P10009]

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

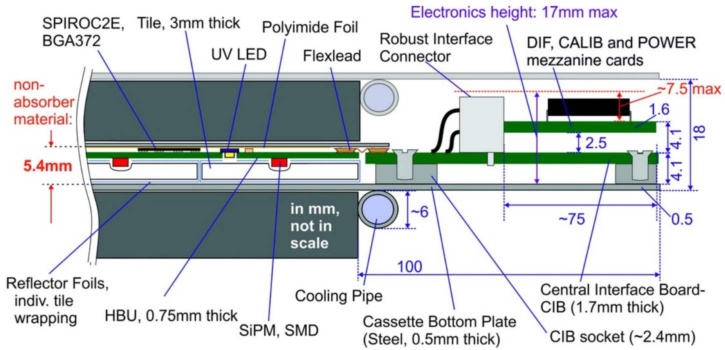
Technological solutions for final detector I

SiW Ecal



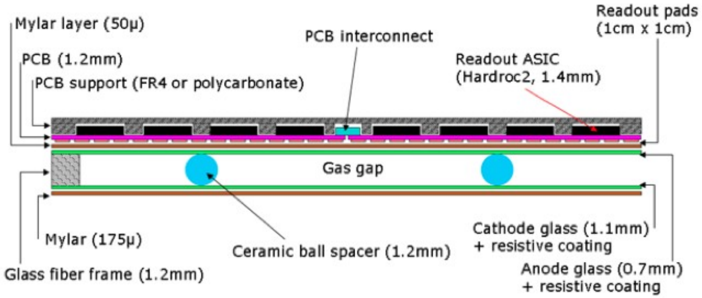
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

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

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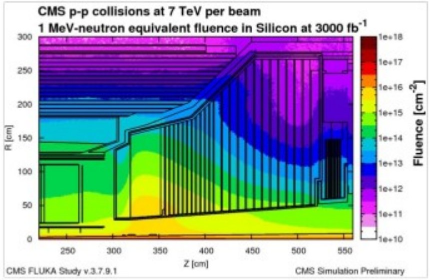
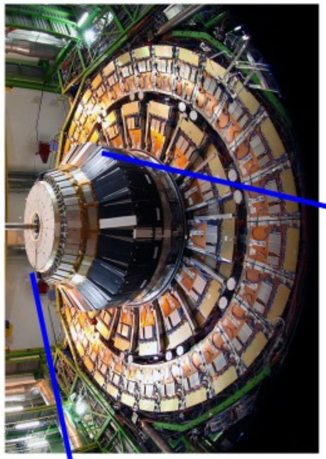
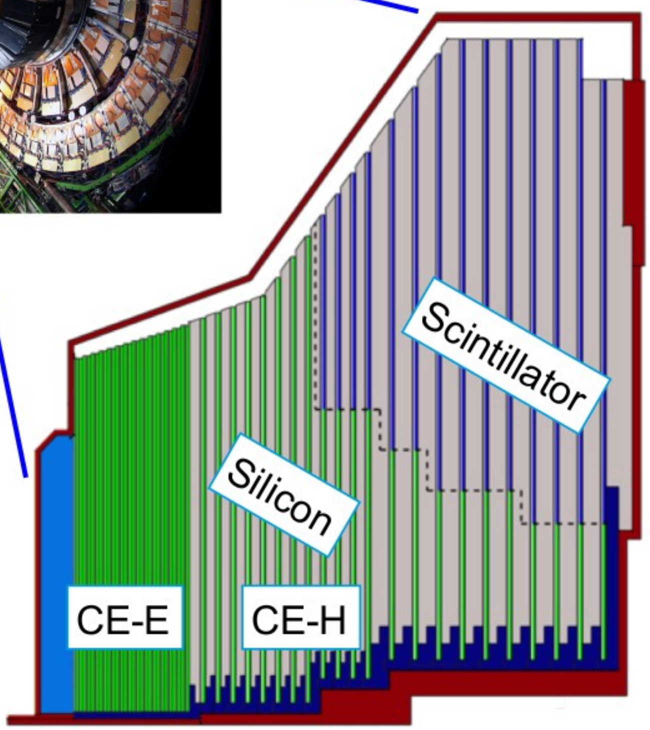
CMS HGCAL

- CMS calorimeter endcap will be replaced for HL-LHC by **H**igh-**G**ranularity **cal**orimeter
  - High granularity for pile-up rejection & particle flow
- synergy with high granularity calorimeter concepts developed for electron-positron colliders
  - silicon in the front and close to the beam pipe
    - ~620m² in ~30000 modules
    - ~6M Si channels, 0.5 or 1cm² cell size
  - scintillator tiles wherever radiation levels allow
    - ~400m² in ~4000 boards
    - ~240k scintillator channels, 4-30cm² cell size
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- New challenges compared to e+e-
  - Radiation levels
  - Operation at -35° C
  - Data rates



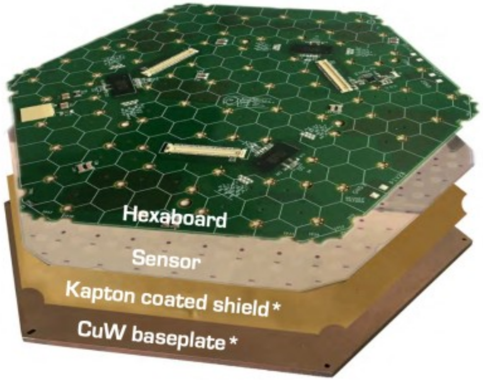


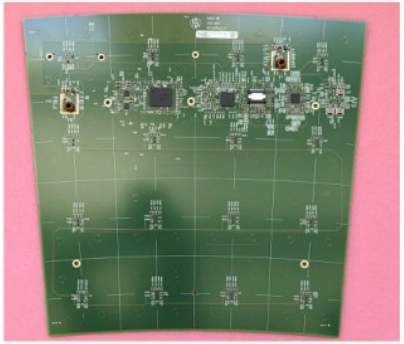


CMS HGCAL Status

- Needs to be ready for installation in 2026/27
- Finalising overall design
- Transition from R&D phase to production ongoing
  - First (close to) final silicon modules assembled
  - First (close to) final scintillator modules will be assembled in 2022
- Setting up full production and assembly infrastructure
  - Module assembly
  - Cassette assembly
  - Endcap assembly
  - QC setups in all steps

- Valuable experience for the construction of a highly granular calorimeter → feedback to Higgs/EW/top factory detectors
- Higgs/EW/top factory calorimeters will have more than an order of magnitude more channels!





Dummy scintillator module