Skimming through FCC-ee Calorimetry

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13/05/2020 on Zoom

Synoptic:

Not included:

- Forward calorimeters → FCAL collaboration, E. Perez talk on $\mathscr{L}$
- Particle flow and SW techniques → G. Grenier
- Particle ID → Guy Wilkinson
- Muons

Central calorimeters: ⊕ systems, ⊖ sensors

- ECAL + HCAL
  - ILD → CLICdp → CLD
  - SiD
- IDEA

My apologies for all those whose work has not been properly attributed

Biased toward Particle Flow (PFA), CALICE and ILD

Requirements from Physics

Basis: sep of H → WW/ZZ → 4j

- $\sigma_Z/M_Z \sim= \sigma_W/M_W \sim= 2.7\% \oplus 2.75\sigma_{sep}$

⇒ σ_E/E (jets) < ~4%

- Sign ~ S/√B ~ (resol)$^{-1/2}$
  60%/√E → 30%/√E ⇔ + ~40% in $\mathscr{L}$

Large acceptance

Large Tracker

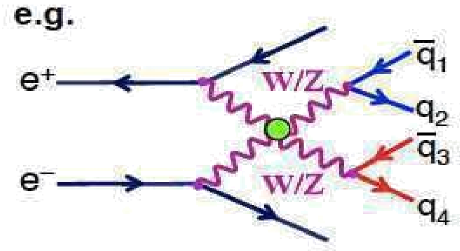
- Precision and low X_0 budget
- Pattern recognition

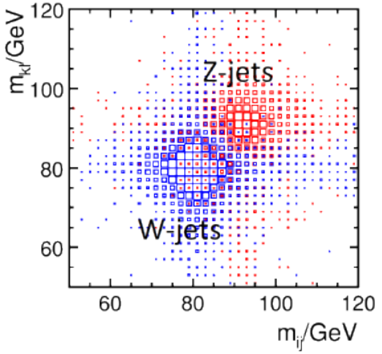
High precision on Si trackers

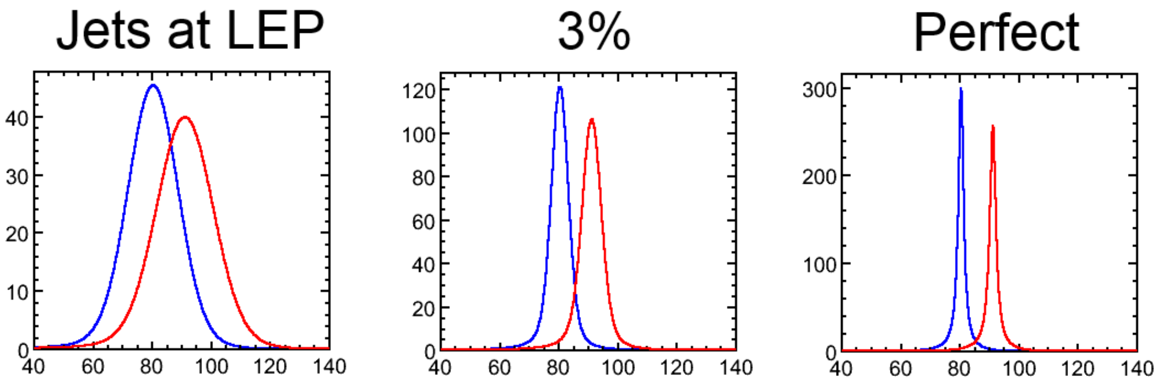
- Tagging of beauty and charm

Fwd Calorimetry:

- lumi, veto, beam monitoring



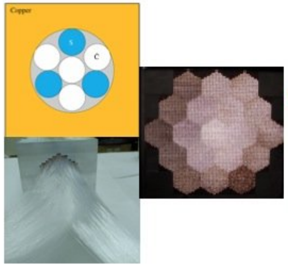




σ_E/E (γ) ≤ 10 %/√E

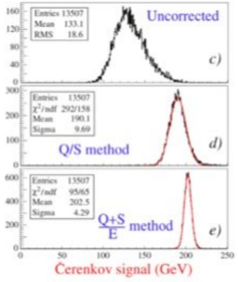
Tau Physics (γ vs π_0) → Photons in jets ?

Dual Readout approach: *improving calorimetry*



$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

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



Concept:

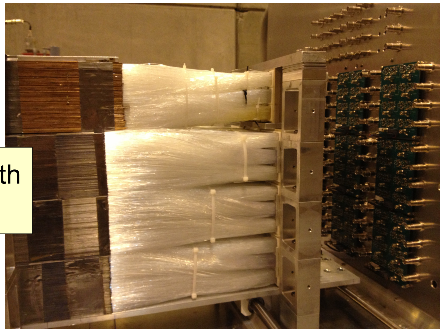
- Improved energetic resolution calorimeter by
  - combining dual readout of showers
  - with different yields to EM (π0's) and hadronic components

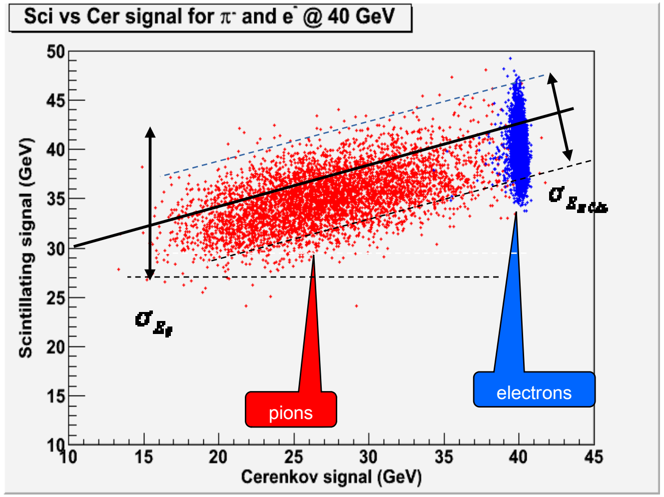
  ⇔ Rotation in S – Č plane →
  - $\sigma_E/E(EM) \sim 10\%/\sqrt{E}$; $\sigma_E/E(\pi) \sim 30\%/\sqrt{E}$; **jets ?**
- Restores Gaussian-ness of fluctuations
- Single Uniform Calorimeter
  - ~~No long. segmentation~~ (if no front readout)

Possible Long segmentation by fibre of ≠ length
Rem by P. Janot

Prototypes:

- RD52/DREAM





Concept of exp.

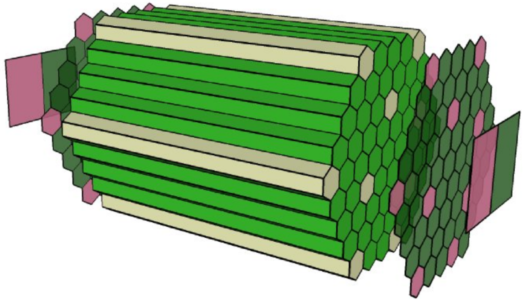
- 4th concept (TESLA), IDEA (+CEPC): design on-going

Future R&D in Dual Readout

- Solid detector design
  - Non pointing fibres, Mechanics

- Add a Neutron component ?
  ⇒ REDTOP/ADRIANO experiment
  - Boron loaded fibres,
  - waveform/delay analysis

Homogeneous
Dual Read-Out Calorimeter



- Improve granularity→ merge PF and DR concepts ?

- “Meta-materials”: AIDA–2020 Crystal Fibres
  with double response

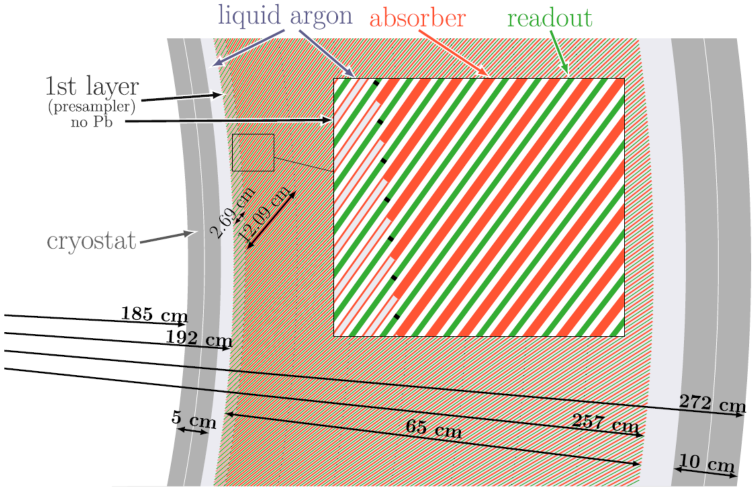
ℓAr ECAL for FCC-ee ?

FCC-hh: "Atlas with straight PCB", Tile HCAL

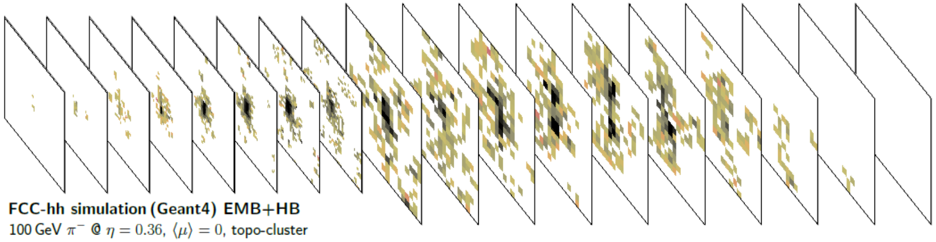
- (lat. granularity ×10) × (8 long. layers)
  - 2.5M channels; ASICs from Omega

Full FCC-hh simulation available; used for studies for FCC-ee ℓAr-ECAL

- 22 X0 / 7λ → 45 cm W
- σ(E)/E (γ) ~ 8%/√E ⊕ ≤1% [Eγ > 300 MeV]
- σ(E)/E (Jets) ≤ 30%/√E
  - Single particle estimations
  - **PFlow in FCCSW: started**
- Timing & Rate vs Resolution
  - Optimal shaping time ?



From C. Neubuser, J. Kieseler



Rem by C. Helsens: linkt to Noble Liquid Cal. for Fut. Accel. Exp. mini-WS (13/05/2020)

Slide adapted from Th. Guillemin

Particle Flow Approach : *an holistic view*

Full Reconstruction of single particles

- Charged mostly from tracker
- Neutrals only from calorimeters

Large Tracker

- Precision and low X_0 budget
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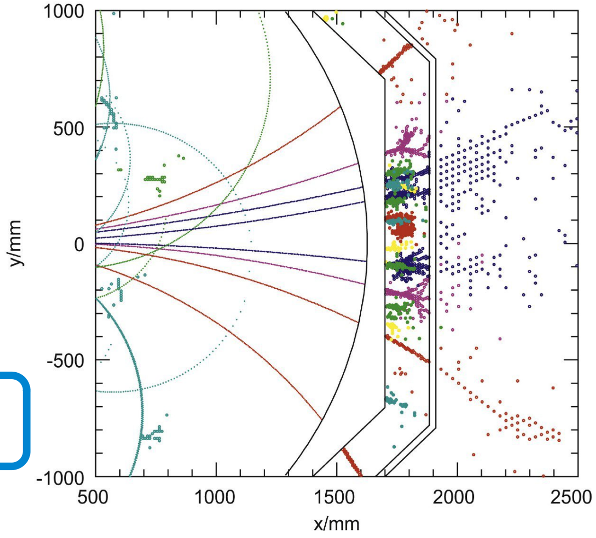
HG Imaging Calorimetry

Particle Flow Algorithms :

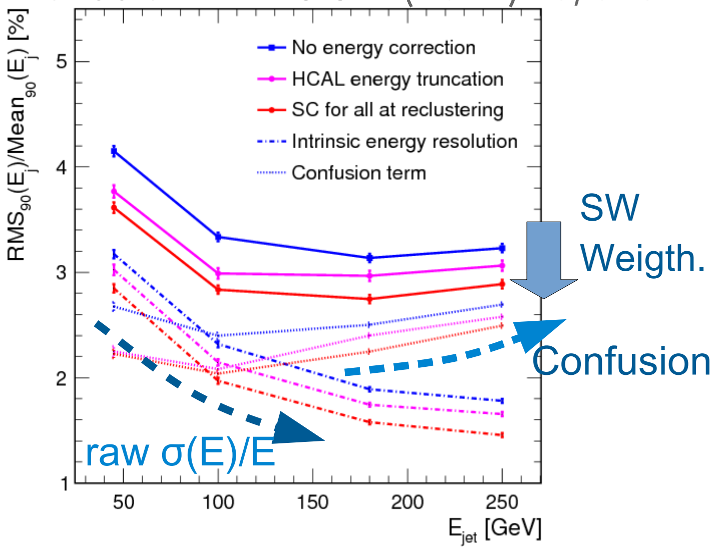
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 E+HCAL
- TPC $\delta p/p \sim 5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 10\ \mu m$

+ timing

H. Videau and J. C. Brient, "Calorimetry optimised for jets," (CALOR 2002)



Pandora PFA: EPJ C77 (2017) 10, 698



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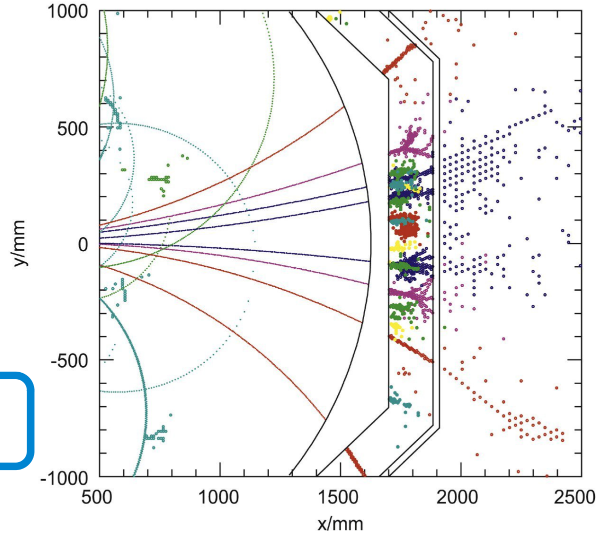

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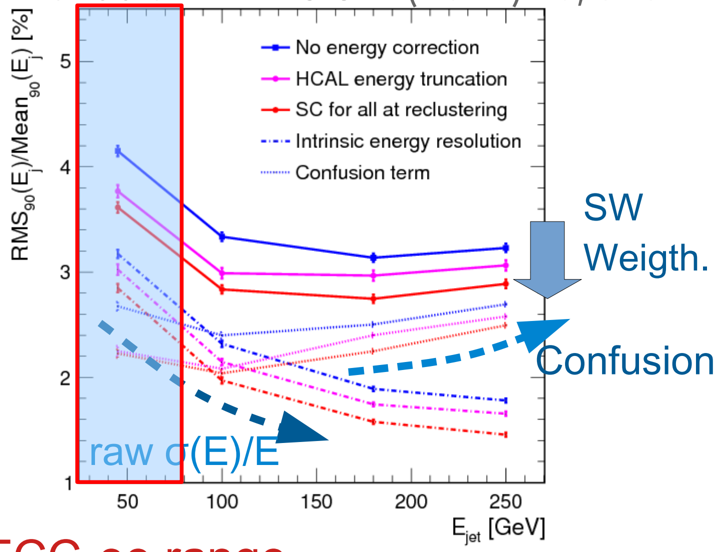


FCC-ee range

High Granularity Calorimetry Ins & Outs

Pluses

- Small constant term
- Particle Tracking (with mip sensitivity)
  - “online” Calibration
- new Particle ID tools
  - Shower shapes, Fractal Dim, Tracks in calo, ...
- SW compensations
  - Global (density) ↔ EM fraction
  - Start of shower → leakage corr.
  - in-calo tracking
    - "Not yet fully exploited"
    - new estim.
    - loss leakage,

Minuses

- Complex Calibration (100M+ channels)
- System: Power & Cooling, Integration

Scaling laws

- cell size = d, N_{layers}
- Sensor & Electronics cost, power ~ $1/d^2 \times N_{layers}$
- Raw timing precision ~ d/2 / (2/3c) (25 ps for 1 cm)
- FE elect. power ~ ...

Detector concepts for PF

Calorimeters ILD, SiD, CLIC-Dp, CEPC-Baseline

- Many similarities
  - Magnet outside
  - Compact design, min dead space,
  - small gap ECAL–HCAL
- Small differences:
  - Inner diameter
  - Granularity: cell-size, number of layers
  - Sensor's technology (next slides)

Differences in level of details in implementations

- Simulation, costs
- Integration of services:
  - power, cooling, readout

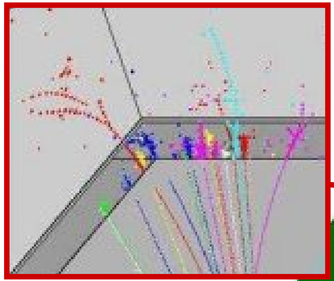
Geometry:

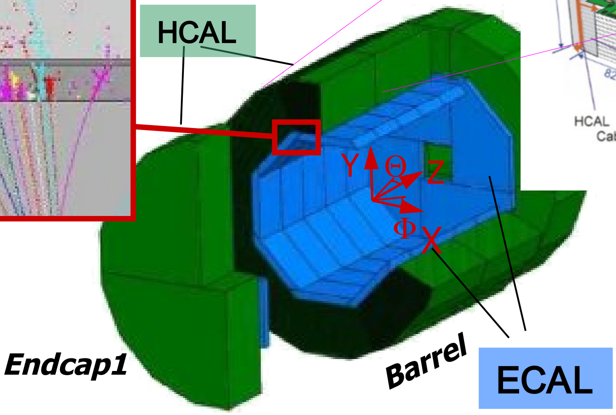
- ECAL hangs to
  HCAL hangs to
  Coils
- for ILD: 2 geometry explored for the HCAL
  - TESLA : barrel made of staves (sectors)
    - electronics between barrel and endcaps
  - «a la Videau» / H1: barrel made of rigid wheels
    - services outside (cooling , power, readout interface)

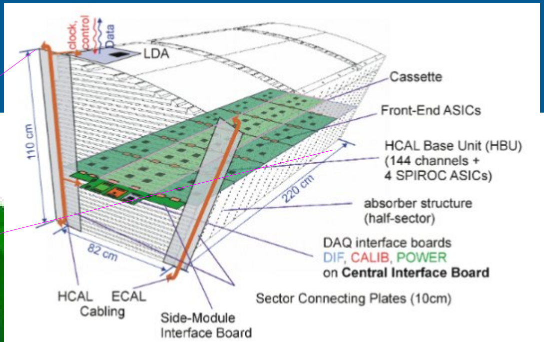
Base elements of HG PFlow calorimeters:

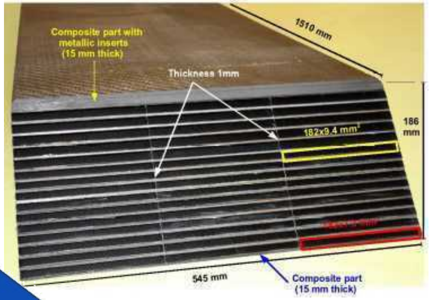
- "Standard" stitchable elements with embedded FE (ASIC's) driven at a single end.
  - gases, power, readout, cooling

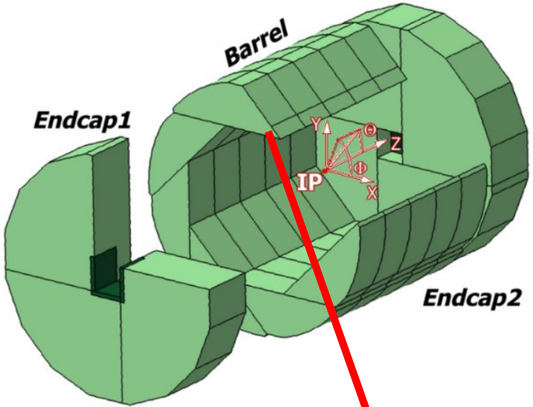
Geometries

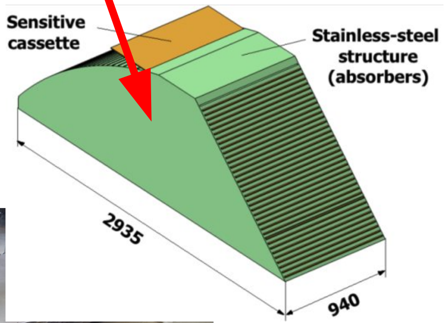


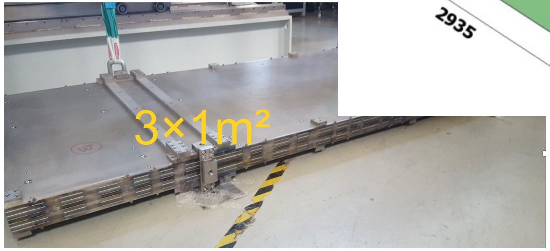

HCAL
Y
Θ
Z
Φ
X
Endcap1
Barrel
ECAL

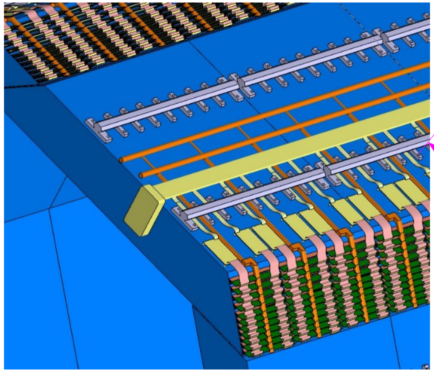

clock, control
Data
LDA
Cassette
Front-End ASICs
HCAL Base Unit (HBU)
(144 channels +
4 SPIROC ASICs)
absorber structure
(half-sector)
DAQ interface boards
DIF, CALIB, POWER
on Central Interface Board
Sector Connecting Plates (10cm)
110 cm
220 cm
82 cm
HCAL
ECAL
Cabling
Side-Module
Interface Board

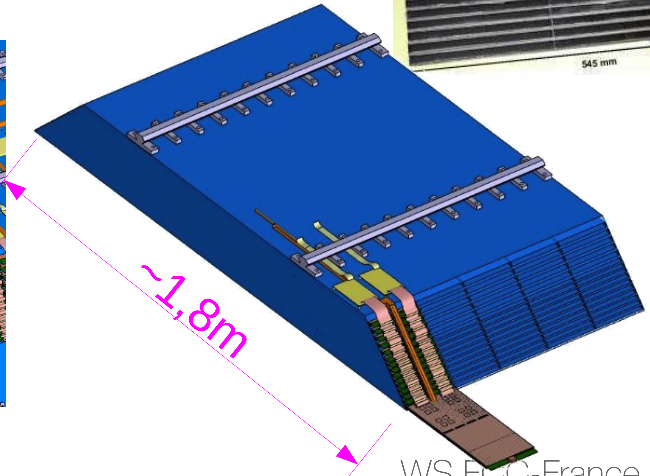

Composite part with
metallic inserts
(15 mm thick)
1510 mm
Thickness 1mm
186
mm
182x9.4 mm²
545 mm
Composite part
(15 mm thick)


Barrel
Endcap1
Y
Θ
Z
IP
Φ
X
Endcap2

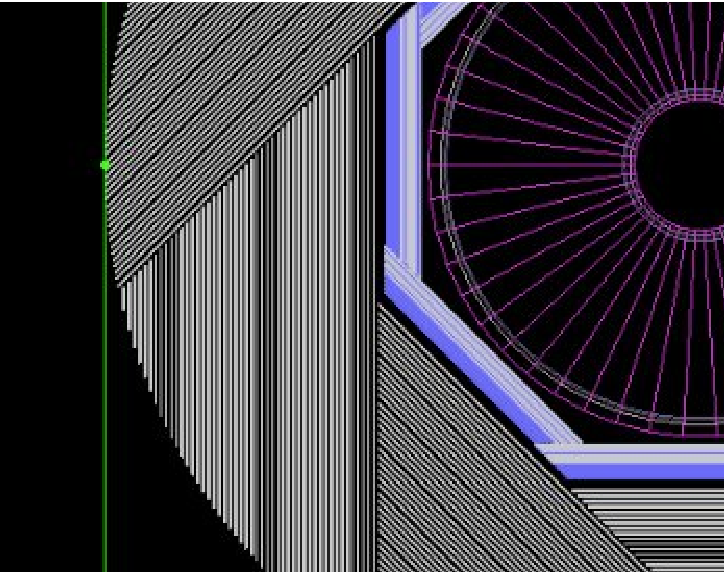

Sensitive
cassette
Stainless-steel
structure
(absorbers)
2935
940

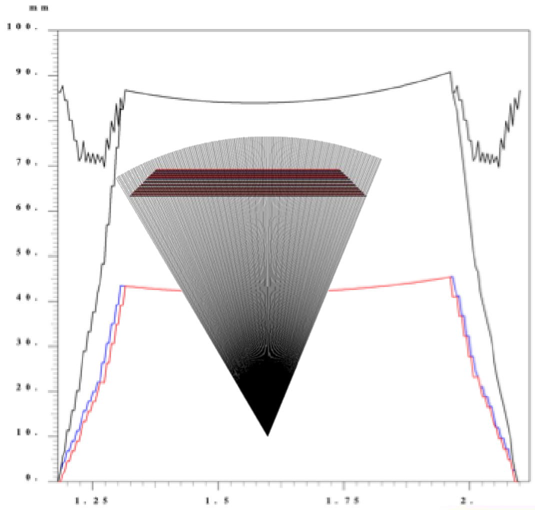

3×1m²

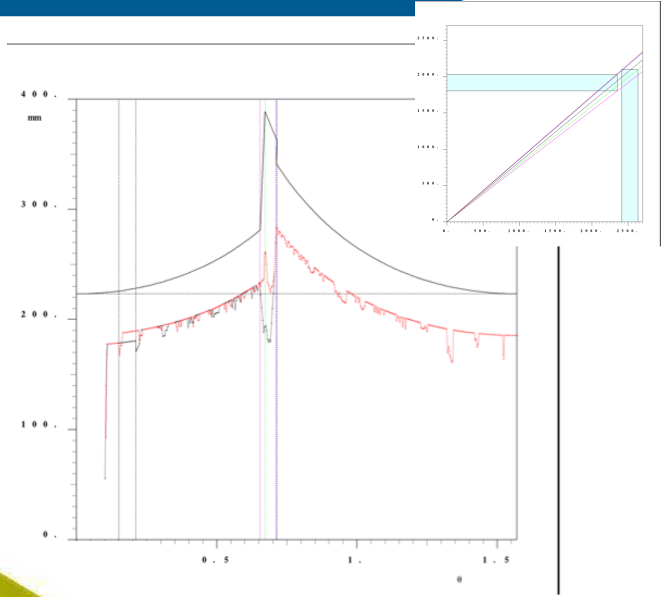


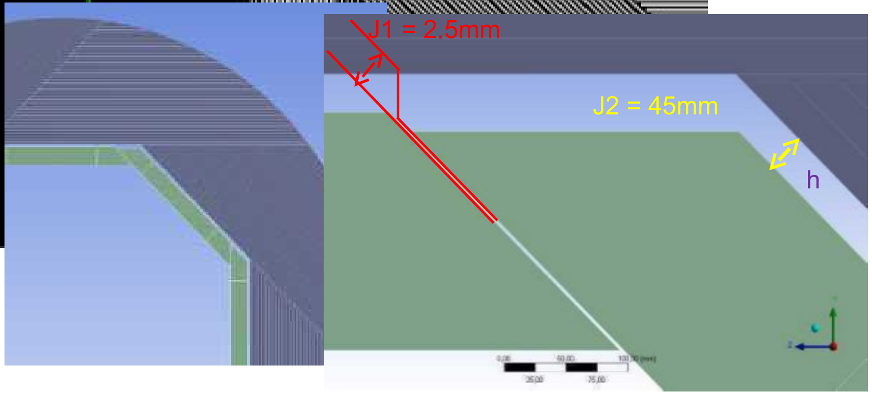

~1,8m

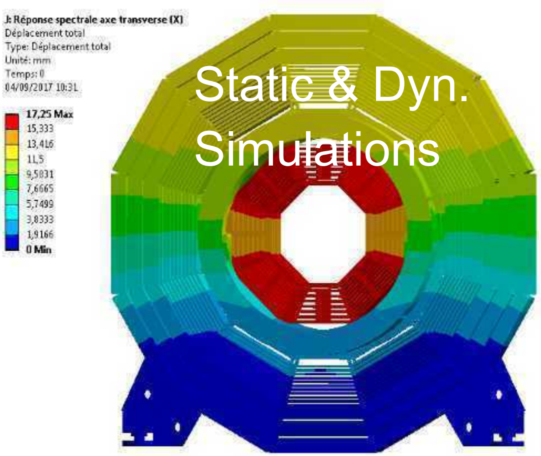
A crack-less ECAL geometry

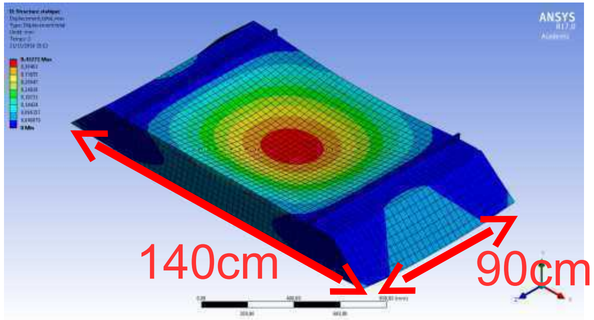










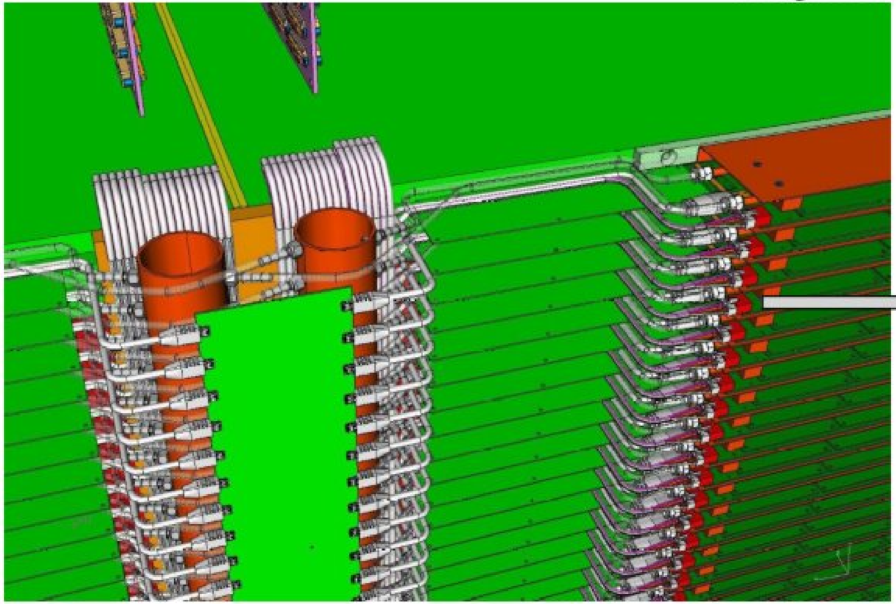


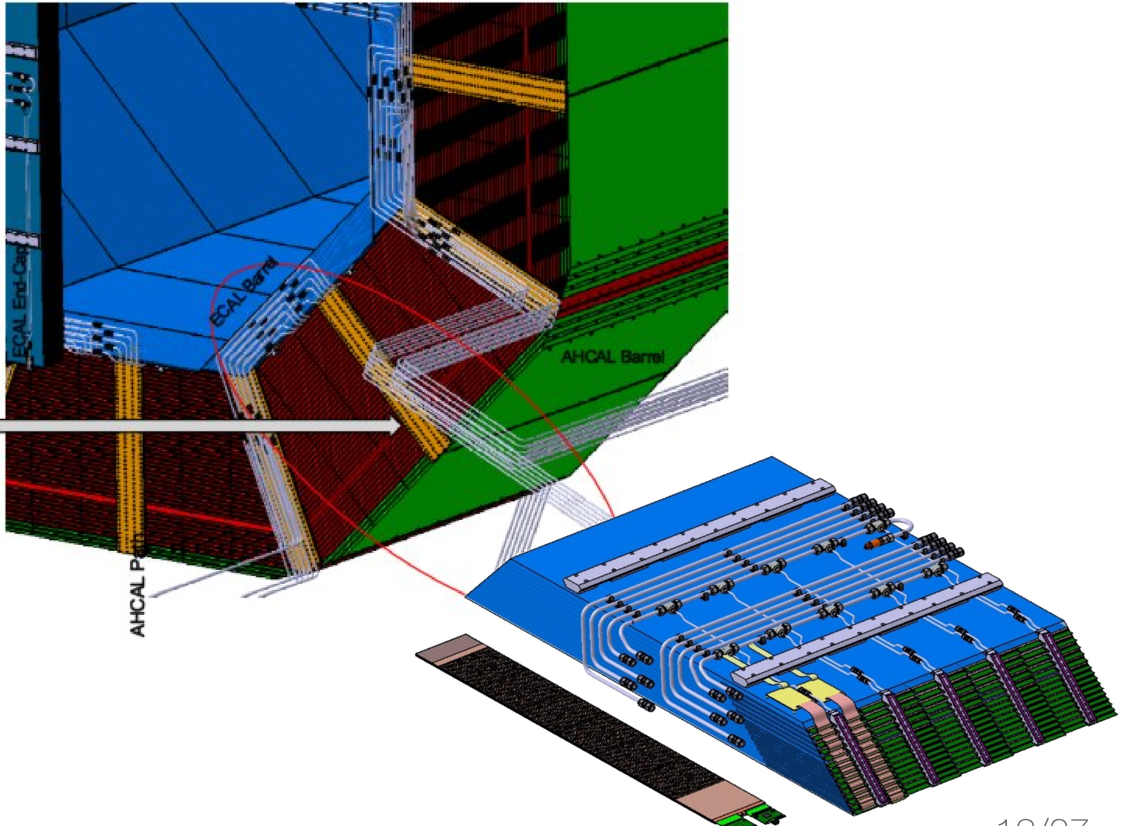
Services: integration & cooling

Task 2-2 AHCAL/ECAL services integration

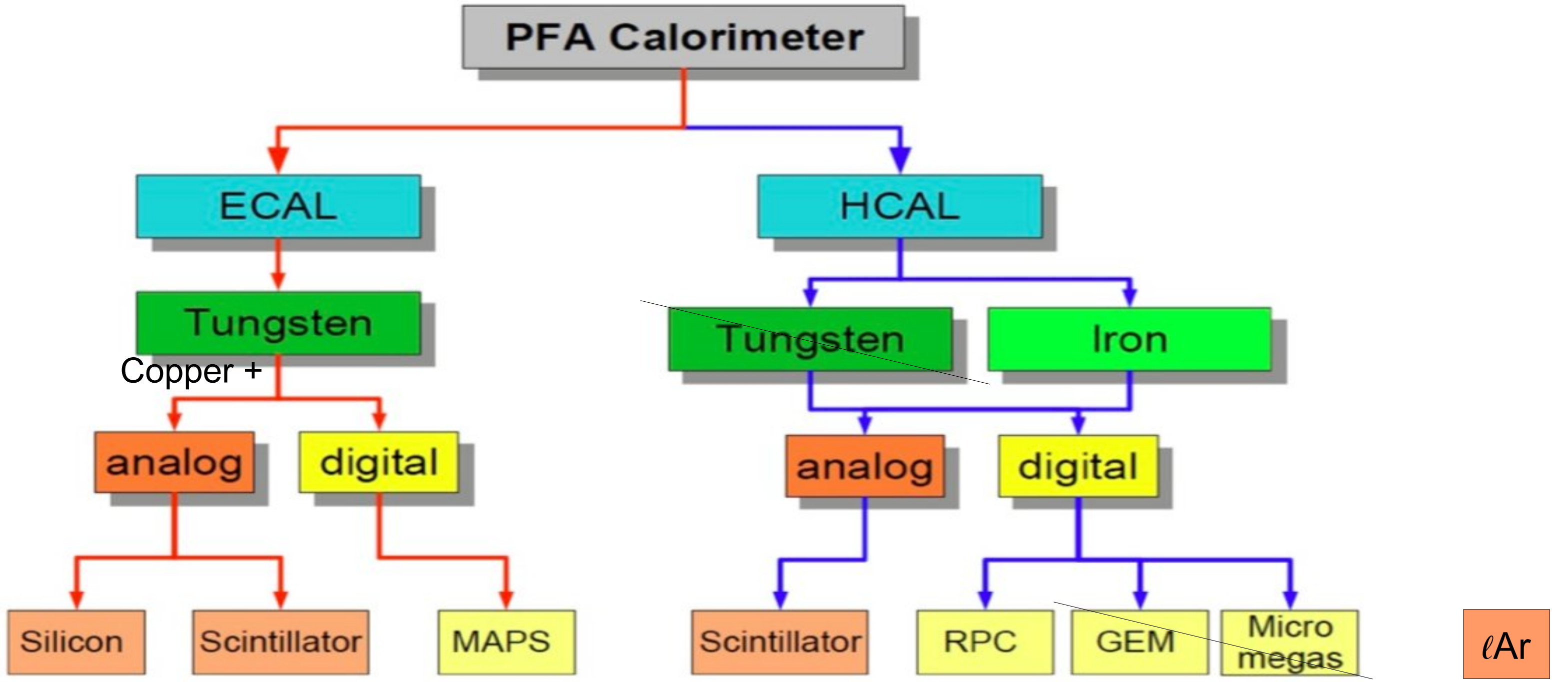
- Detailed design of the AHCAL and ECAL services

Integration





Sensor's Technologies (CALICE++)



Grain
Stability,
Timing
Cost

Cost,
Stability,
Grain

Ultimate Grain
Cost,
Early R&D,
System

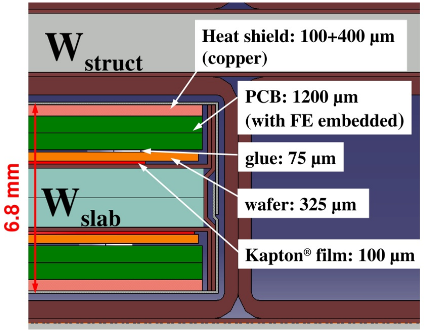
« Easy »,
Cost,
Stability,
Grain

Cost,
Timing (ps),
Stability,
System (gas)

Efficiency,
Grain,
Stability
Timing,
System (cryo)

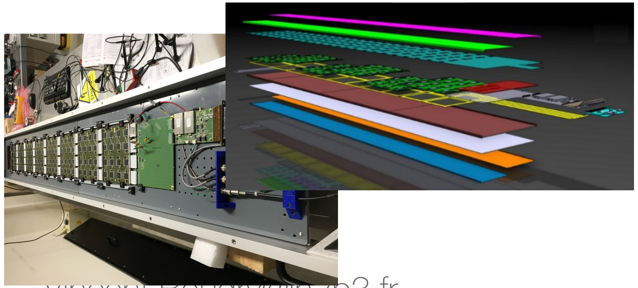
CALICE Thin, long cassettes → all prototyped

Silicon / Scint W-ECAL

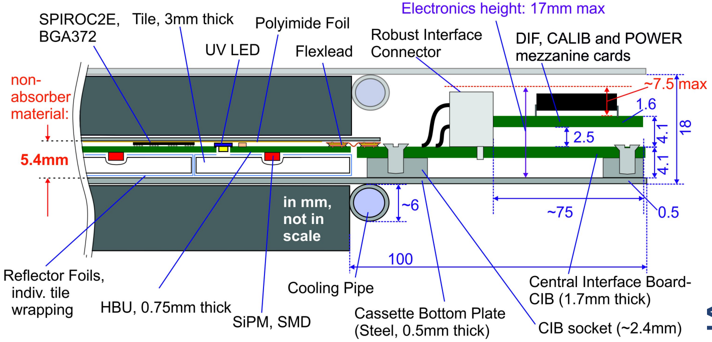


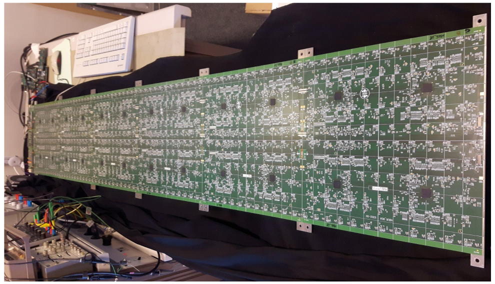
≤1.8m long

- Passive cooling

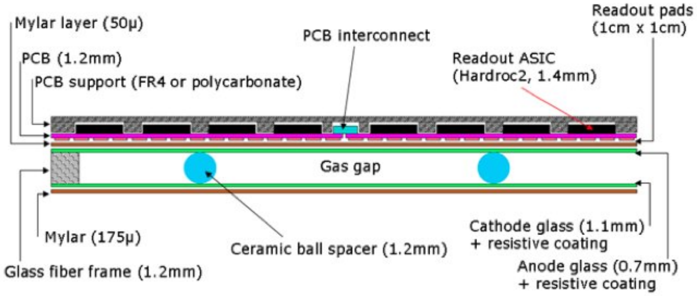


Scint Analog HCAL (also used for HGCAL)



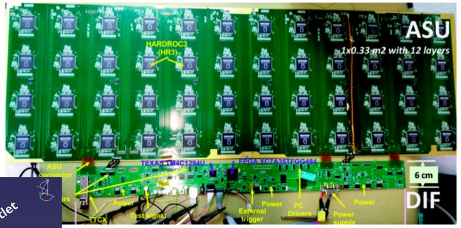


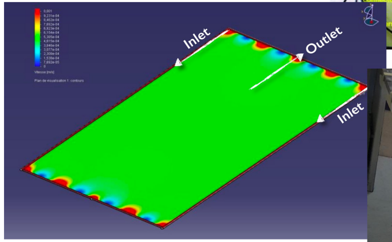
(Semi)Digital Gaseous HCAL

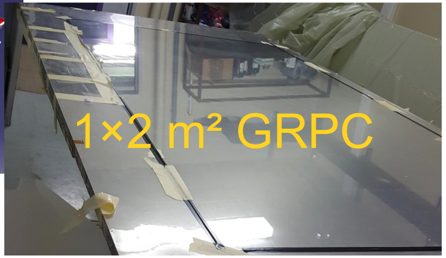


≤ 3m long

No cooling or gas flow



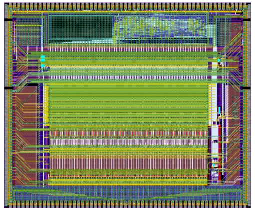




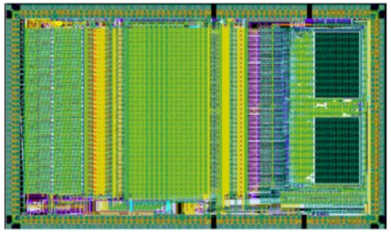
Readout electronics

ASICs readout many channels

- SLAC
  - KPIX ILC chip: 1024 channels
    - SiD ECAL
- Omega ILC (SiGe AMS035)
  - auto-trigger, delayed readout, power-pulsed (≤1%): incremental dev't of many versions
    - moderate timing (1+ ns)
  - SKIROC: 64 channels for Silicon sensors
  - SPIROC: 30 channels for SiPM readout
  - HARDROC: 64 channels for semi-digital readout of GRPC



- Omega LHC (CMOS130)
  - HGROC: new techno. 10 ps capacity
  - Cont. readout ~

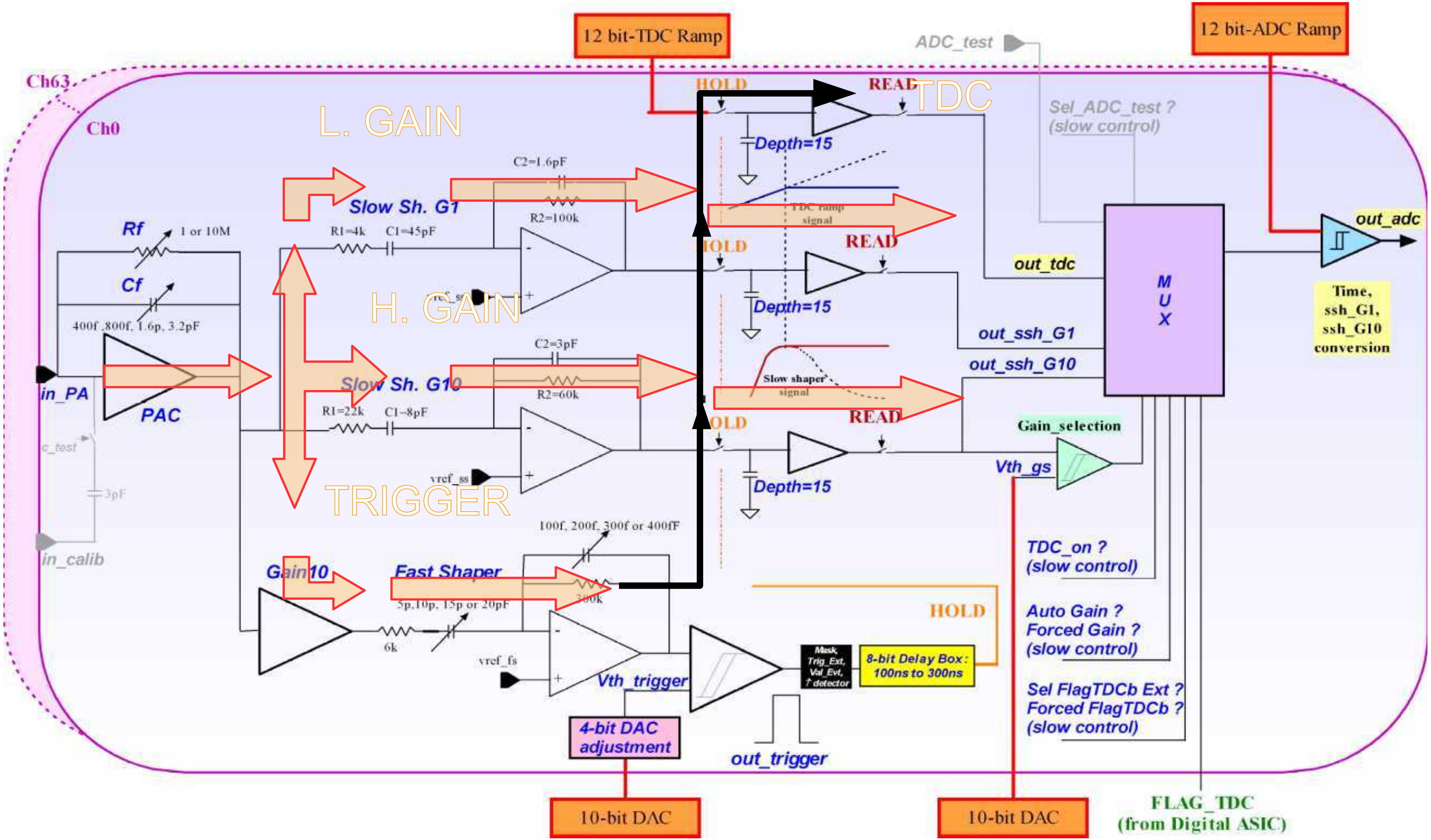


Open questions for FCC-ee operations:

- Bunch spacing: 16ns (Z) ~ 5000ns ($t\bar{t}$)
  ⇒ NO power pulsing
  - ~ 20 mW/ch → Power budget ?
    - Active cooling
    - Coarser granularity
- Continuous or Triggered readout ?
  - Level of noise ≠ in trigger and ADC branches
    - Critical for auto-trigger
    - no so if central trigger (if times allow...)

      Ex: SiW-ECAL: S/N: Trig ~ 12, ADC ~ 20

Ωmega: SKIROC2 / 2A Analogue core

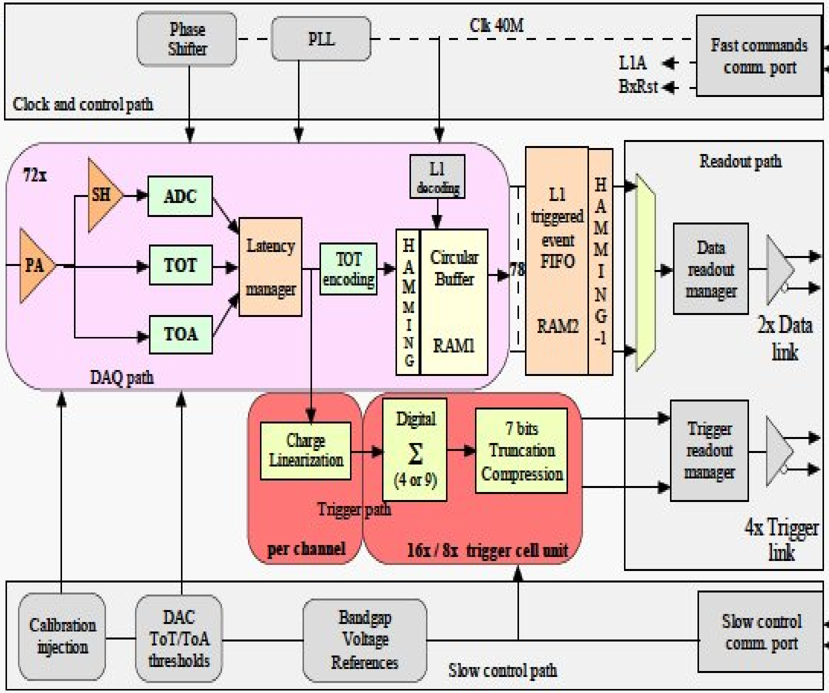


Similar to SiD Kpix

- 64 channels
- Preamp
  + 2 (auto)Gains
  + TDC (~1.4ns)
- Auto-triggered
  - per cell adj.
- 15 (×2) analogue memories
- Low consumption
  - 25 μW/ch with 0.5% ILC-like duty cycle
- Power-pulsed
- OK sf retrigger

HGCROCv2

- **Analog**
  - 72 active channels +2 for calibration +4 for Common Mode
  - Dynamic range ~0.2fC–10pC
  - ENC < 2500e (Cd=65pF)
  - Shaping Time ~20ns
  - Linearity <1%
  - Pos. & neg input charge
- **Energy Measurement**
  - ADC 10b SAR range: 0 > 100fC (150fC)
  - TOT range 100fC > 10pC
  - TOT bin size 2.5fC
- Time Of Arrival (TOA)
  - 10b TDC
  - LSB <25ps, 25ns full range
- **2 HGCROC versions:**
  - Different preamps optimised for Si & SiPM readout



- **Comm port**
  - 320MHz clock
  - Reception of T1 fast commands
  - From lpGBT
- **Data Readout Path**
  - Data packets after LV1A
  - LV1A latency up to 12.5us
  - 2 SLVS outputs @ 1.28Gbps
- **Trigger readout Path**
  - Trigger primitives
  - 4 SLVS outputs @ 1.28Gbps
- **Slow Control**
- Programmable registers
- I2C protocol
- Connected to SCA

Monitoring of DACs and essential bias voltages to GBT-SCA

A. Lobanov

5

CMOS 130 nm
- 15x6 mm²
- **Si and SiPM readout**
- 20mW/ch
- 1st of "new" Tech
  - SiGe → CMOS

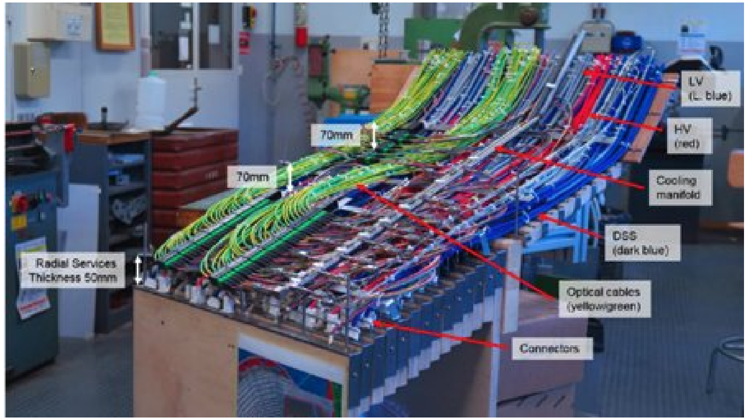
Time-Over-Thres.
- First use for exp.

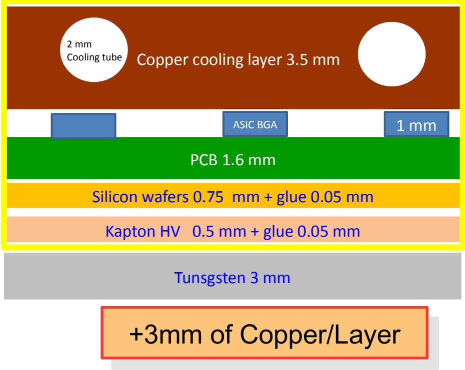
Options:
- FlipChip
- BGA

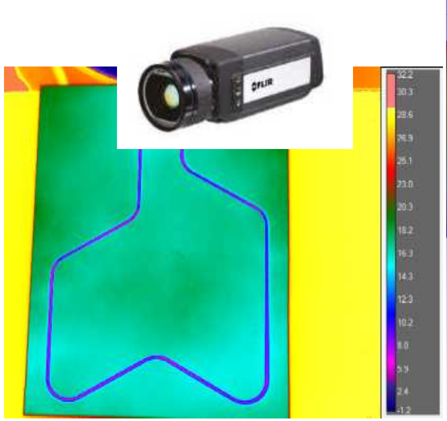
Test Stands:
- @CERN, LLR, IRFU and OMEGA

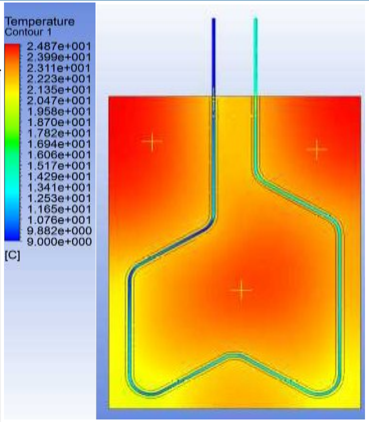
HGCROCv3 submission in 2020

Services: integration & cooling



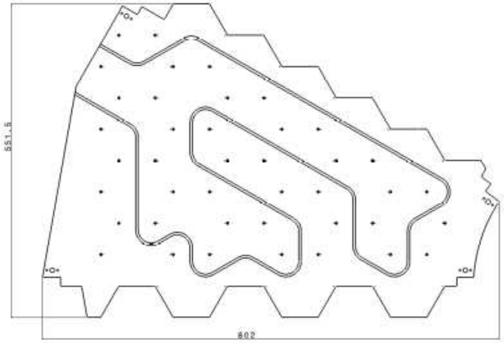


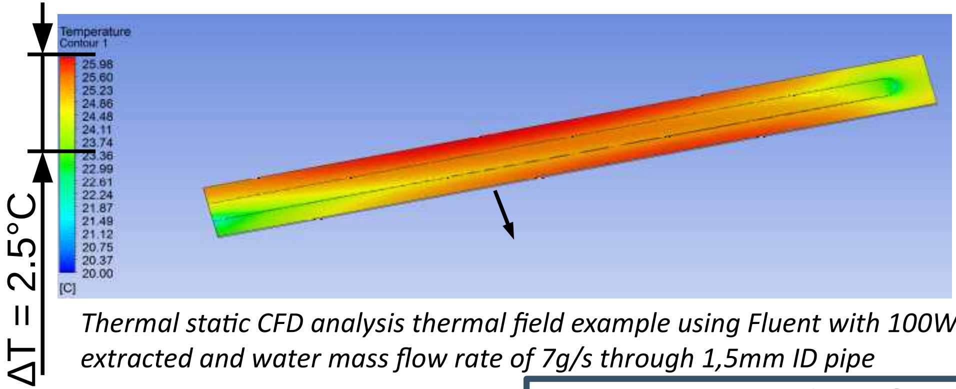




Pipe insertion on a cooling prototype

- Pipe insertion process introduces some efficiency loss due to the thermal contact resistance.
- The benefit remains significant with regard to a passive cooling



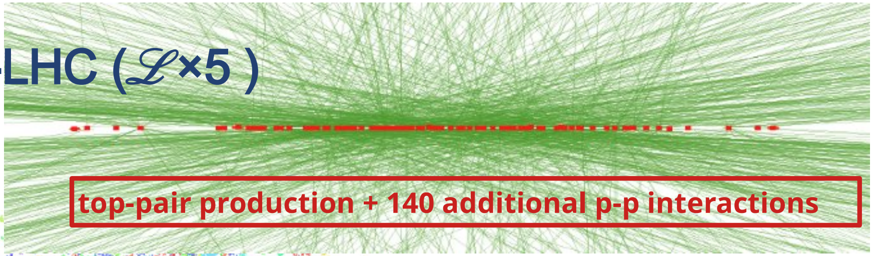


Thermal static CFD analysis thermal field example using Fluent with 100W extracted and water mass flow rate of 7g/s through 1,5mm ID pipe

= 2× cont. operation of a SLAB

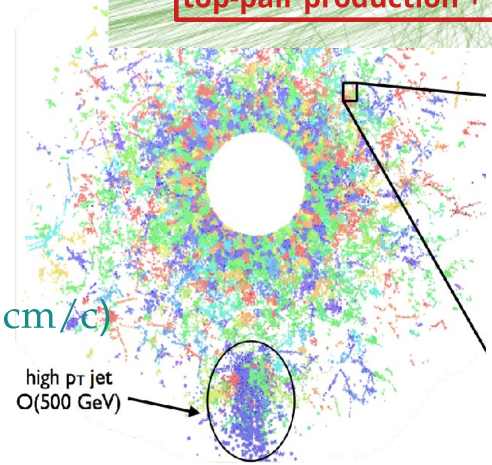
CMS-HGCAL: Going 5D for HL-LHC

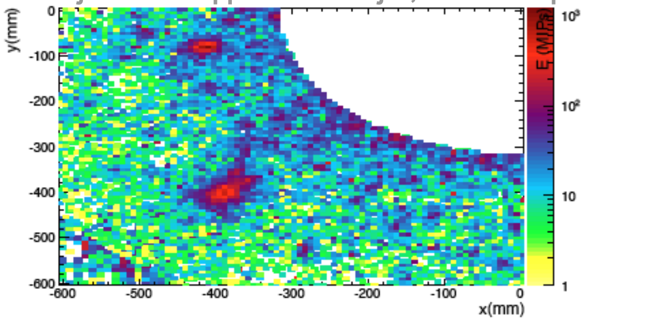
Goal: replace the C2MS Calo endcaps for HL-LHC ($\mathscr{L}$×5)



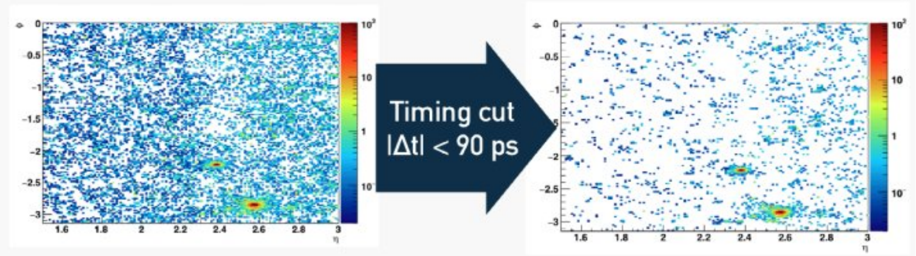
- Reconstruct crowded events with high granularity 3D+E + 1
  - 28 X_0 ECAL + 9 λ HCAL
- Adding timing for vertex separation
  - δz = 50mm ⇒ σ(t) = 30 ps

    Possible because of HG calorimeters (30ps = 1 cm/c)





Endcap coverage: 1.5 < |η| < 3.0		
Total	Silicon sensors	Scintillator
Area	620 m²	410 m²
Number of modules	29 900	3800
Cell size	0.5 — 1.2 cm²	5 — 30 cm²
N of channels	6 260 000	240 000
Power	Total at end of HL-LHC: 2x125 kW @ -30°C	

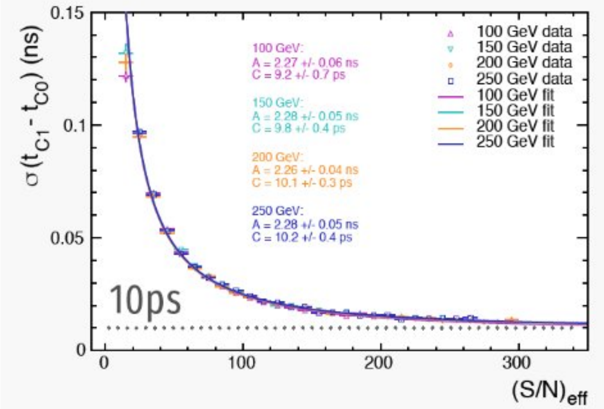


Simulated HGCAL event with and without timing selection

Timing

Timing of Showers

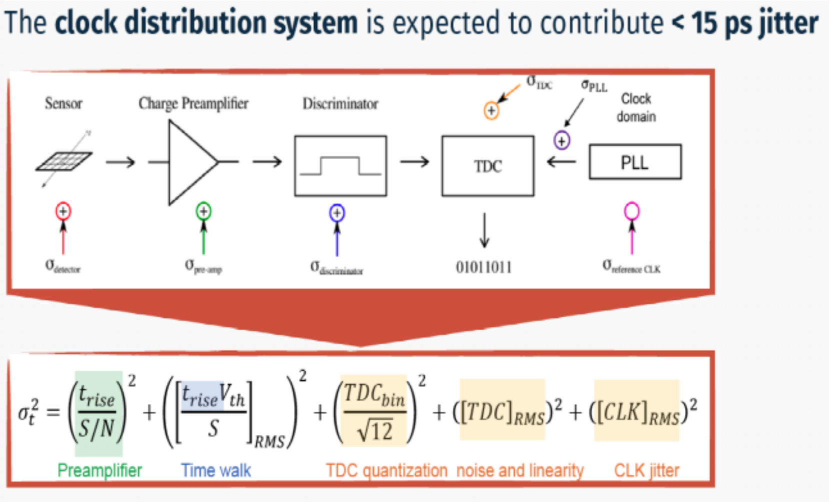
- For events reconstruction
- From Core Hits to avoid contamination

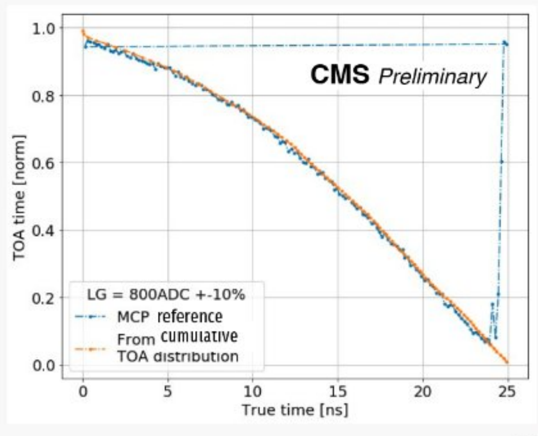


Single HGCAL **sensor timing performance** evaluated in 2016 **beam tests** [JINST 13 (2018) P10023]

R&D

- HGCROC ASIC: 3 stage TDC
- Clock distribution (CEA)





Data vs MCP calibration

- Correction of non-linearity of ToA response

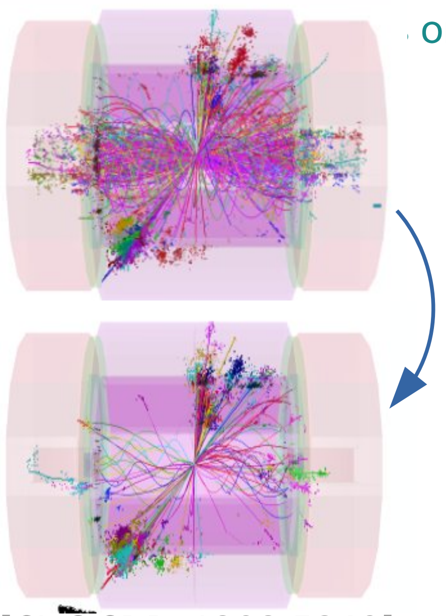
Timing in calorimeters: 0.1–1ns range

Particle ID by Time-of-Flight

Cleaning of Events

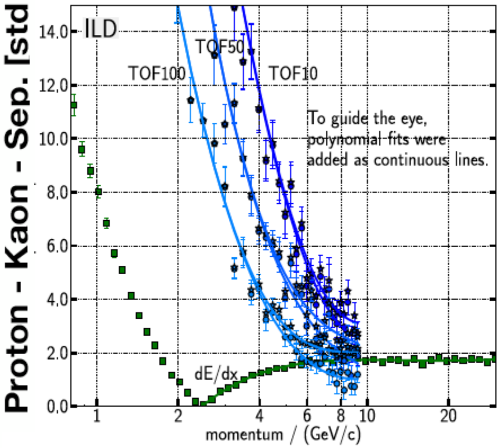
– Complementary to dE/dx

on



time
cut

[CLIC CDR: 1202.5940]
adapted from L. Emberger



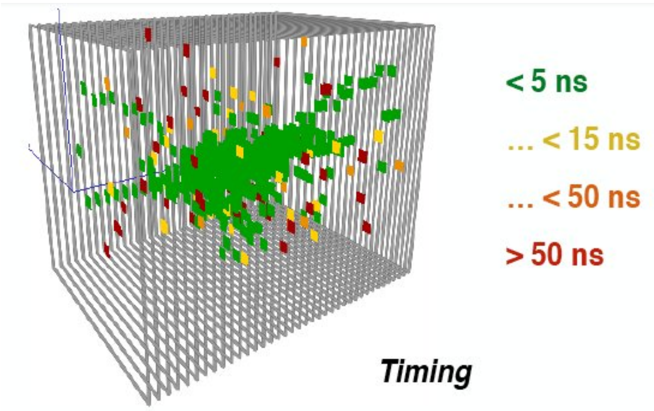
S. Dharani, U. Einhaus, J. List

Ease Particle Flow:

– Identify primers in showers

– Help against confusion

– Cleaning of late neutrons & back scattering.



Ch. Graf

Conclusions

High Performance Calos *is* cost efficient

Much R&D has been done

- CALICE ≥2001 + SiD
- HGCAL ≥ 2016
- DREAM ≥ 2004
- Integration: ILD → CLICdp → CLD
- R&D++: ℓAr (H1, D∅, ATLAS)

FP7/H2020 : EUDET, AIDA, AIDA-2020, AIDA-innova ?

Many technological options (in / out FRANCE)

- Dual Readout
- **High Granularity + PFlow**
  - **Si**, Scint, **Gaseous, ℓAr**
- **Expertise in ASICs, integration and HG calos**

Still much to do:

- Basic sensors & electronics improvement
- Simulations, SW and algorithms improvement
  - ILD new simulations = multiple technologies in 1 go (PCB = the other one)
- Optimal granularities, Precisions on Timing, Positioning
- Granularity in DR or DR in PFA …
- Power & Better timing → Sensors, clock and ASIC dev't
  - What is feasible in cont operations ?
  - Silicon (Plain, LGAD) & Multi-gap GRPC's

Building calorimeters system: 5-6 years

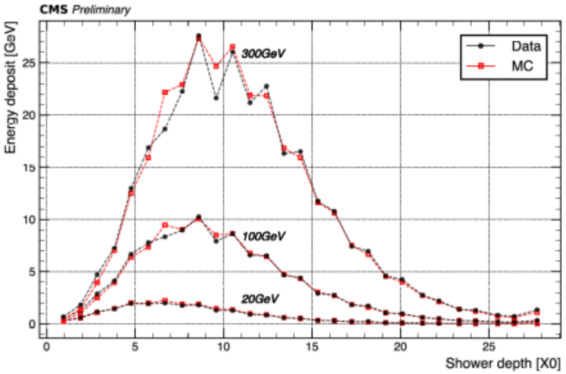
- e.g. Time is Shorter (than for other det.)
- large place for synergy between e+e- machines
  - special place for CALICE … ***open to all !***

Extras

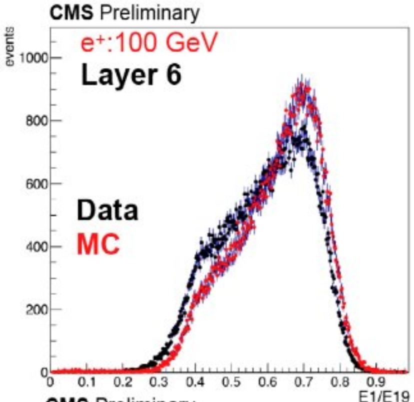
HGCAL: Calorimetric Performances

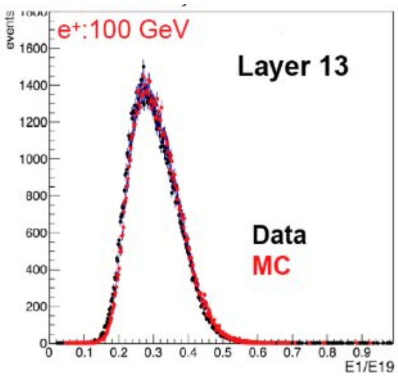
Shower profiles

- Longitudinal

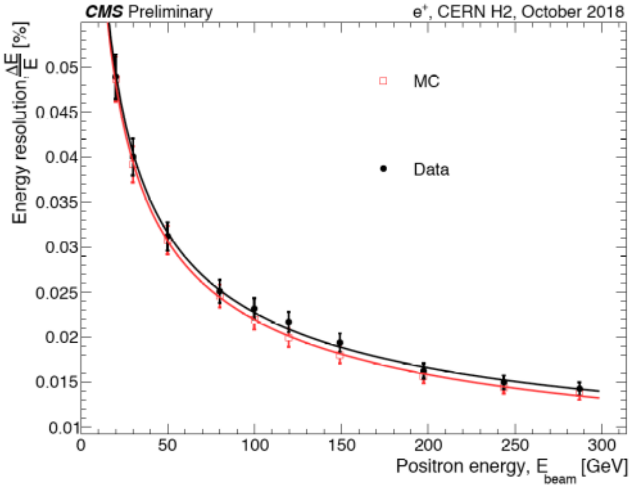


- Lateral fraction of E in center (E1/E19)
  - “Early” ~ “Late” ✓



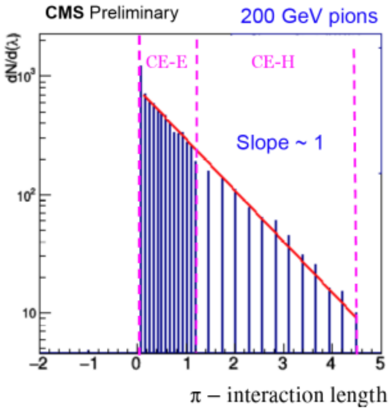


EM Linearity: 0.5%
EM Resolution ✓

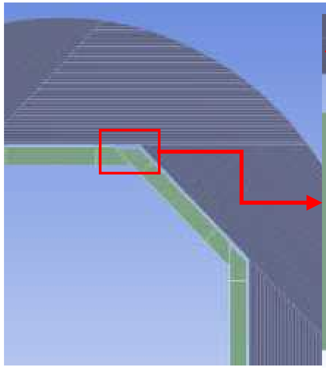


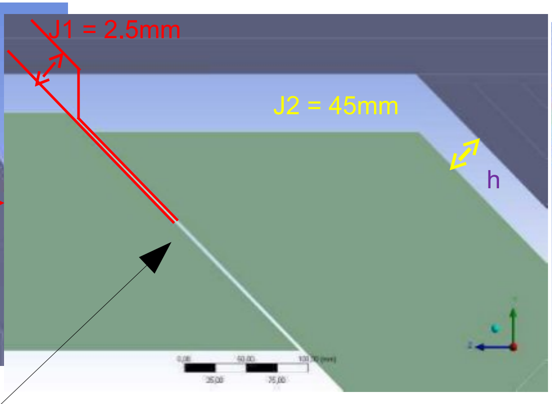
Hadronic interactions

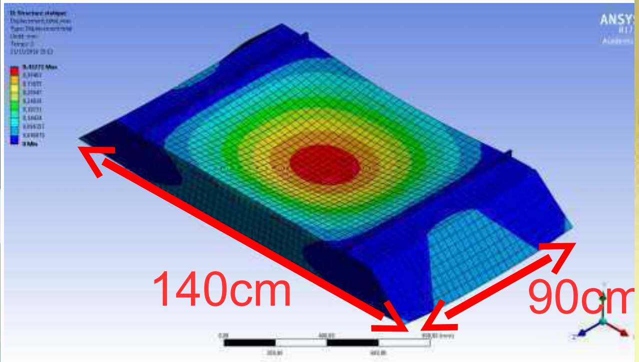
- 1st IA Point
- Comparisons with MC ~ OK.

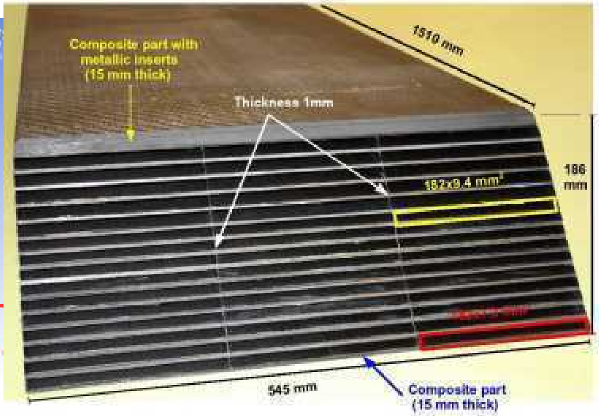


CFRP+W Structures





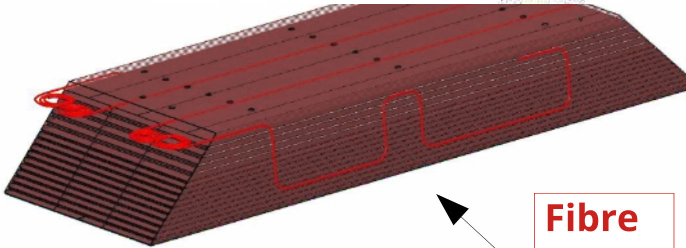


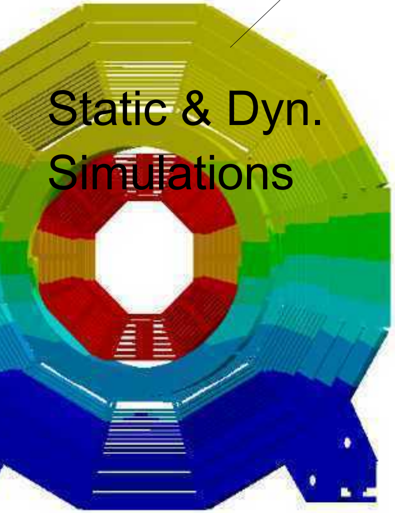


J1 = clearance between modules for the ECAL

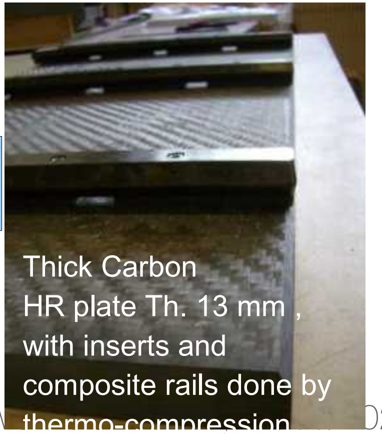
J2 = Clearance at ECAL edges between ECAL and HCAL

h = height of the rails 30mm





Static & Dyn. Simulations



Thick Carbon HR plate Th. 13 mm , with inserts and composite rails done by thermo-compression

Moulding of one layer of 3 alveoli

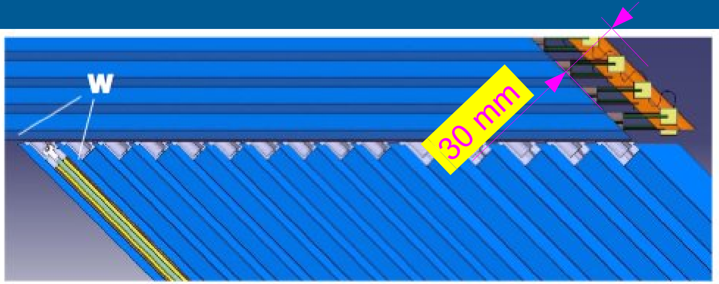
L = 2.490 m wall thick. = 0.5mm

Moulding of one layer of 3 alveoli L = 2.490 m wall thick. = 0.5mm

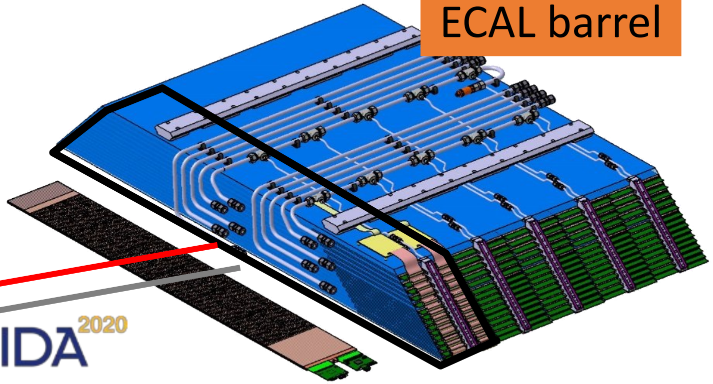
Fibre Bragg-Grated

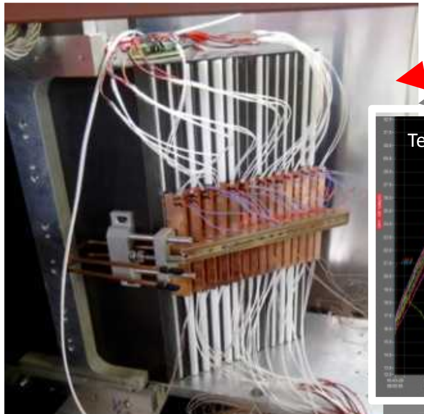
measurements still to be done...

Rails, Cables & Pipes (Services)



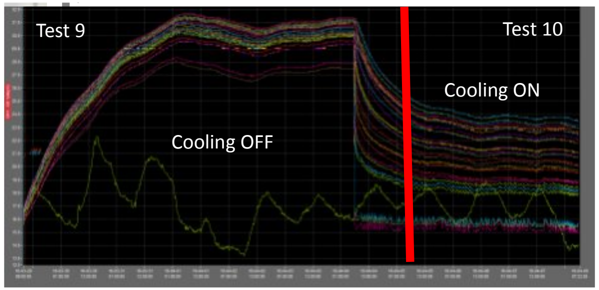
ECAL barrel





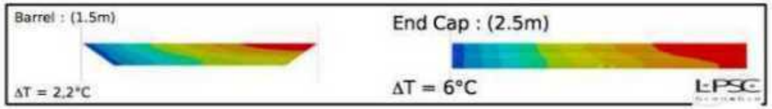
EUDET module (carbon structure) equipped with it's heat exchanger 15 slab in EUDET module

AIDA 2020



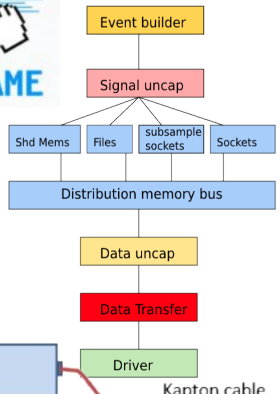
First tests results in line with simulations

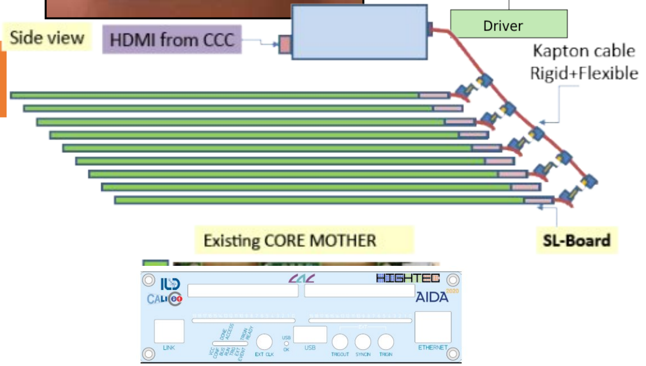
ECAL end cap

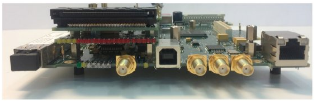


DAQ

PYRAME







P2IO Physique des 2 Infinis et des Origines

HIGHTEC

on going…