CALICE & ILD
SiW-ECAL for CEPC

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for

CEPC WS

25/10/2022

Highly-Granular ECAL at Higgs Factories for Particle Flow Approach based detectors

Full Reconstruction of single particles

- Charged measured mostly from trackers
- Neutrals only measured from calorimeters

➡ **Large Tracker**

- Precision and low X_0 budget
- Pattern recognition

➡ **High precision on Si trackers**

- Tagging of beauty and charm

Large acceptance

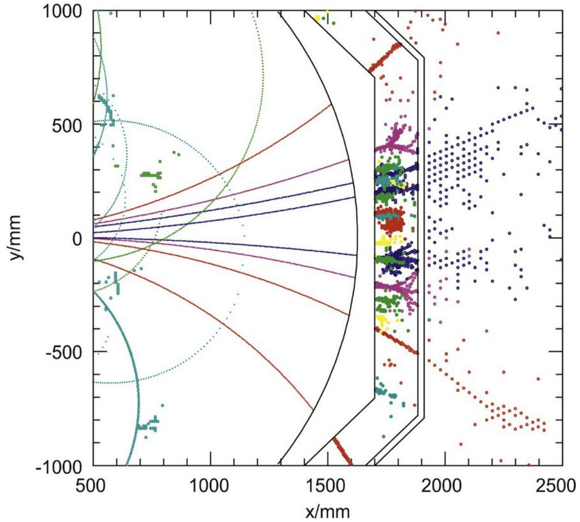
➡ **Highly Granular Imaging Calorimetry**

Particle Flow Algorithms : **ECAL**

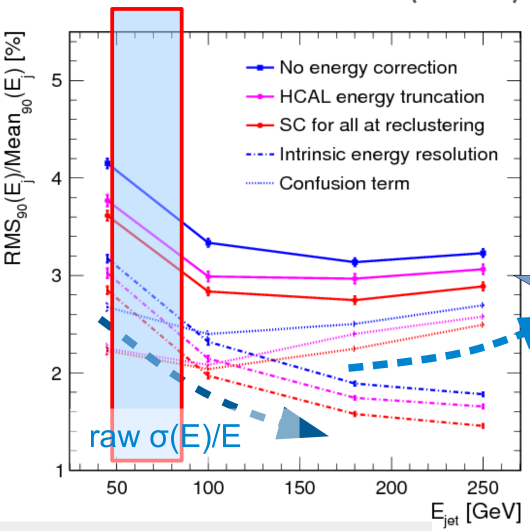
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 E+HCAL
- TPC $\delta p/p \sim 5{\cdot}10^{-5}$; VTX $\sigma_{x,y,z} \sim 10$ μm

τ tagging + timing

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



Pandora PFA: EPJ C77 (2017) 10, 698

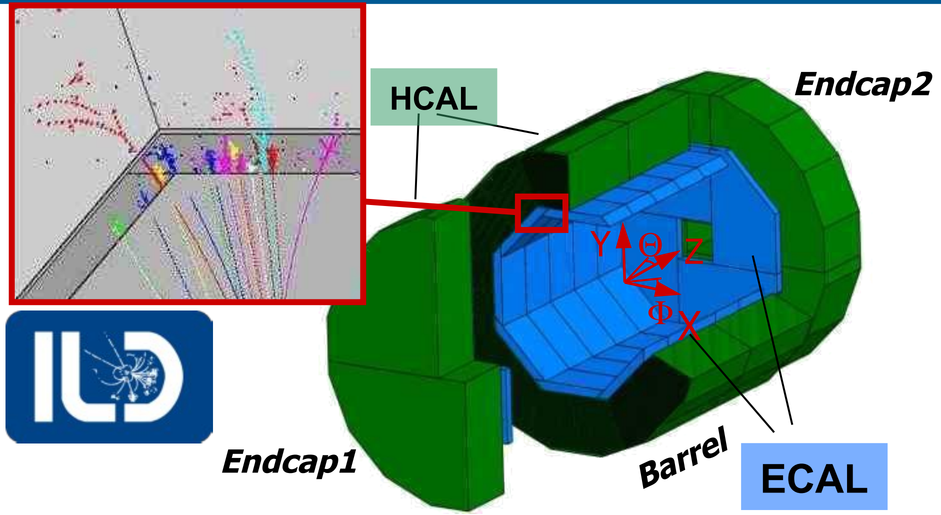


Software Weigthing

Confusion (cluster misattrib, merging)

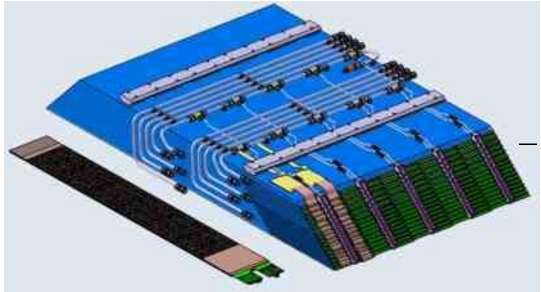
Low E jets ⇒ where PFA brings most

An Ultra-Granular SiW-ECAL for experiments



Particle Flow optimised calorimetry

- Standard requirements
  - Hermeticity, Resolution, Uniformity & Stability (*E*, *(θ,φ)*, *t*)
- PFlow requirements:
  - Extremely high granularity
  - Compacity (density)



SiW+CFRC baseline choice for future Lepton Colliders:

- Tungsten as absorber material

  X_0 = 3.5 mm, R_M = 9 mm, λ_I = 96 mm

  Narrow showers

  Assures compact design

- Silicon as active material

  Support compact design: Sensor+RO≤2mm

  Allows for ~any pixelisation

  Robust technology

  Excellent signal/noise ratio: ≥10

  Intrinsic stability (vs environment, aging)

  Albeit expensive…

- Tungsten–Carbon alveolar structure

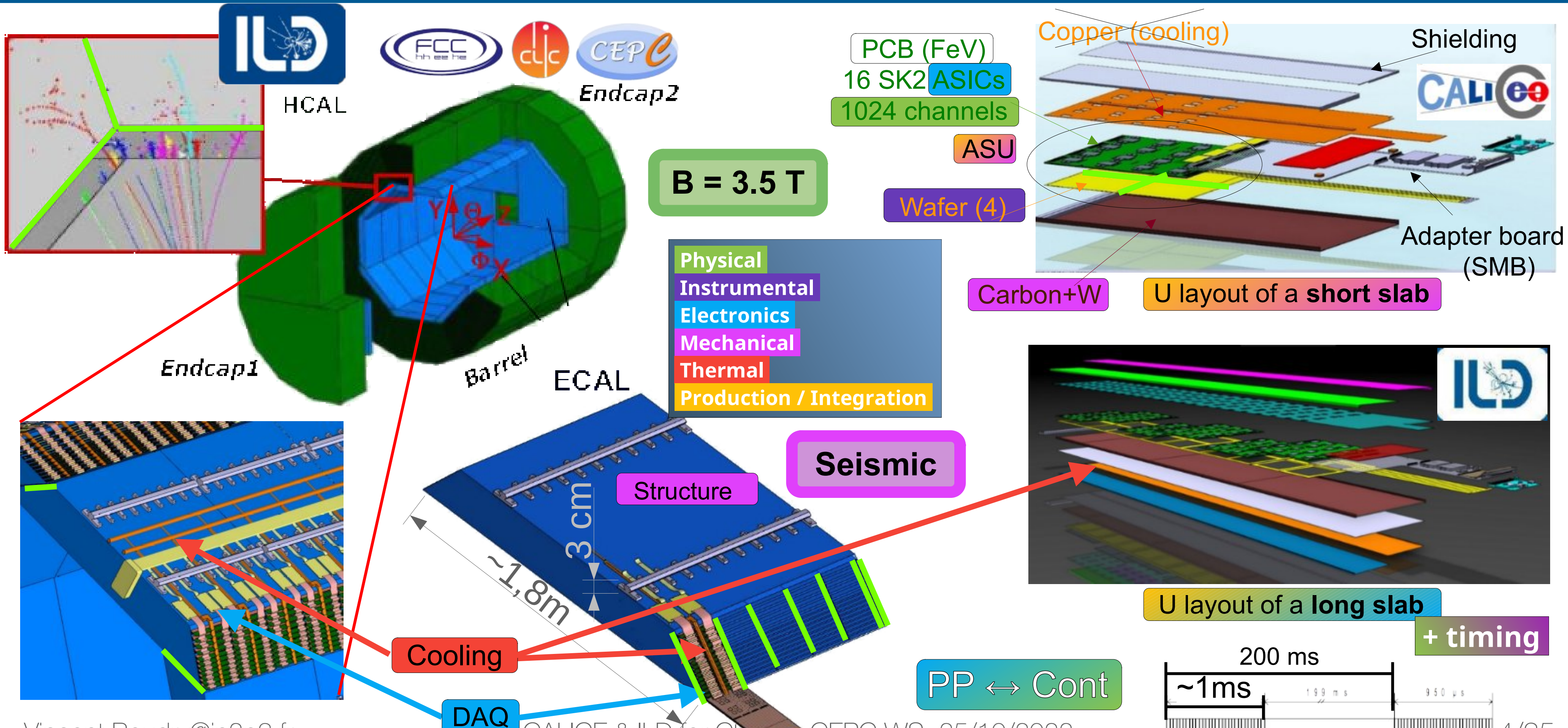
  Minimal structural dead-spaces

  Scalability

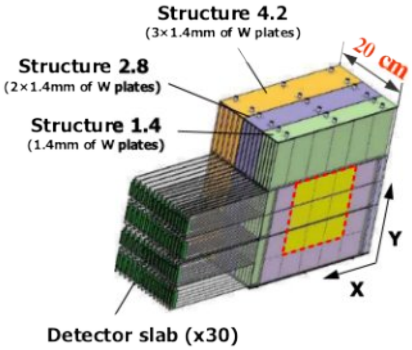
To be assessed by prototypes

Not included: general services

Modular & Transverse Constraints

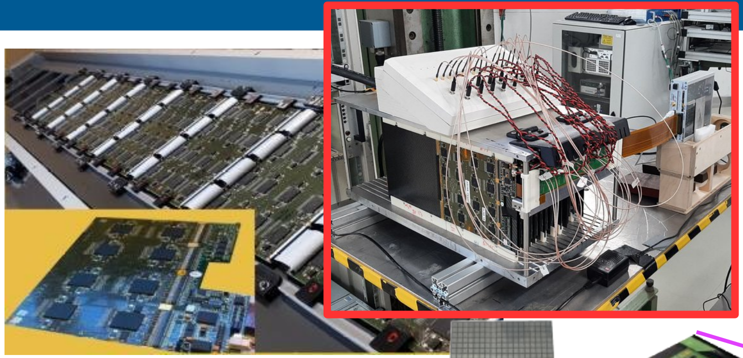


Timeline of SiW-ECAL Prototypes



Physical (2005-11)

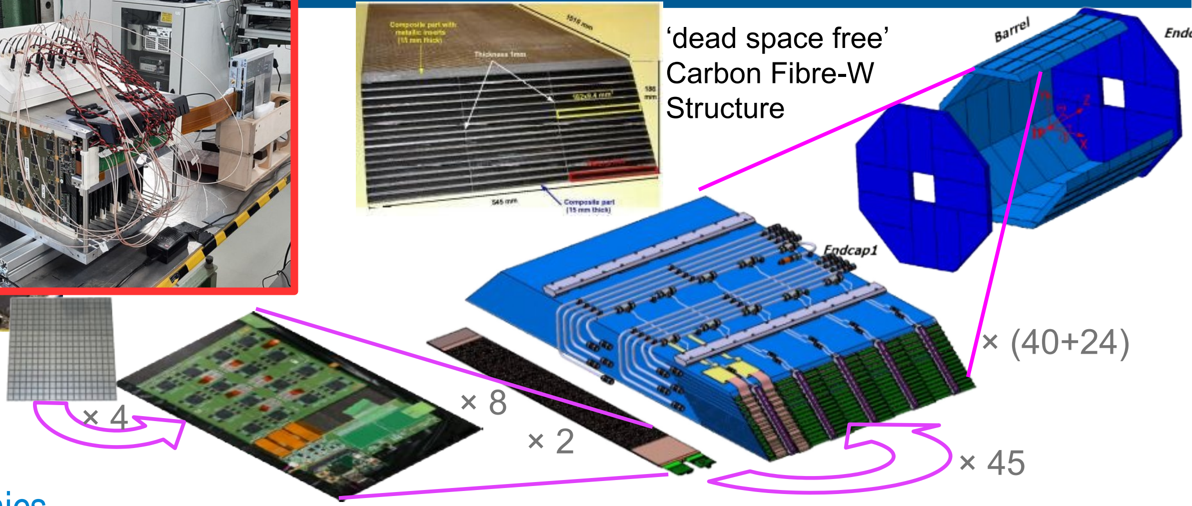
- 1×1 cm² on 500µm 6×6 cm²
  Pad glued on PCB
  Floating GR
- × 30 layers (10k chan).
- External readout
- Proof of principe



Technological (now)

- Embedded electronics
  - Power-Pulsed, Auto-Trig, delayed RO
  - S/N = (MPV/σ_{Noise}) ≥ ~12 (trig)
- Compatible w/ 8+ modules-slab
- 5×5 mm² on 320–650µm 9×9 cm² × 26–30 layers
  - 8k (slab) ~ 30k (calo) channels

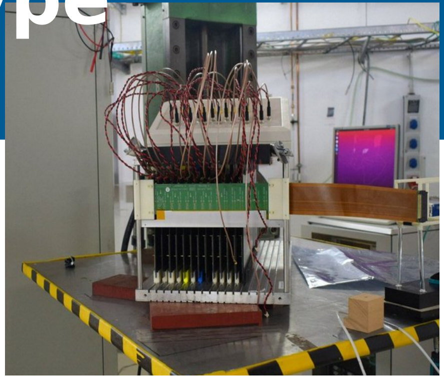
We are here



Pilote ➡ Full Detector

- 1M ➡ 70M channels
- on 750µm 12×12 cm² 8'' Wafers ?
- Pre-industrial building
- Full integration (⊃ cooling)
- Final ASIC

CALICE SiW-ECAL Technological Prototype Beam tests (… at last!)



Nov. 2021 + March 2022 : electrons of 1–6 GeV (4th attemp…)

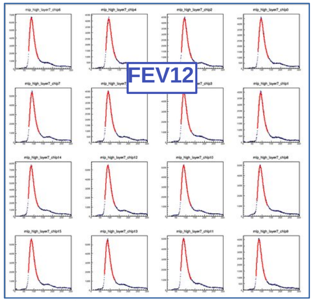
- 15 layers of 1024 cells + Compact "ILD-like" DAQ
  - 5 types de VFE boards (FEV10, 11, 12, 13, COB) ⊗ 3 Wafer thicknesses (320, 500, 650 μm)
  - 2 Tungsten absorbers configurations.

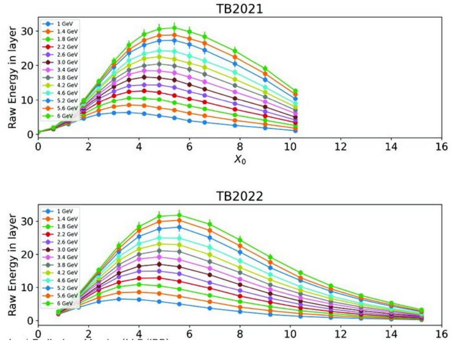
~3 weeks of commissioning and training

- Mechanical structure (adding or removing the tungsten plates)
- Hold values, Gain optimization, Threshold optimization, single cell calibration, etc
  - ~500k fits (15 boards × 16 ASICs × 64 ch × 15 SCAs × 2 gains)
- Test of combined DAQ : ECAL + AHCAL
- Full simulations (⊃ cell masking)

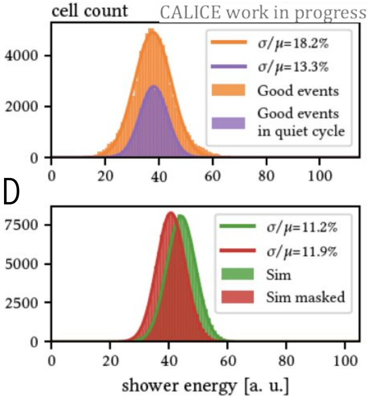
1st full shower profiles & resolutions

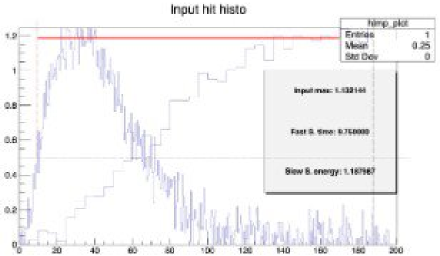
- Filtering needed (retriggers, events splitting, …)

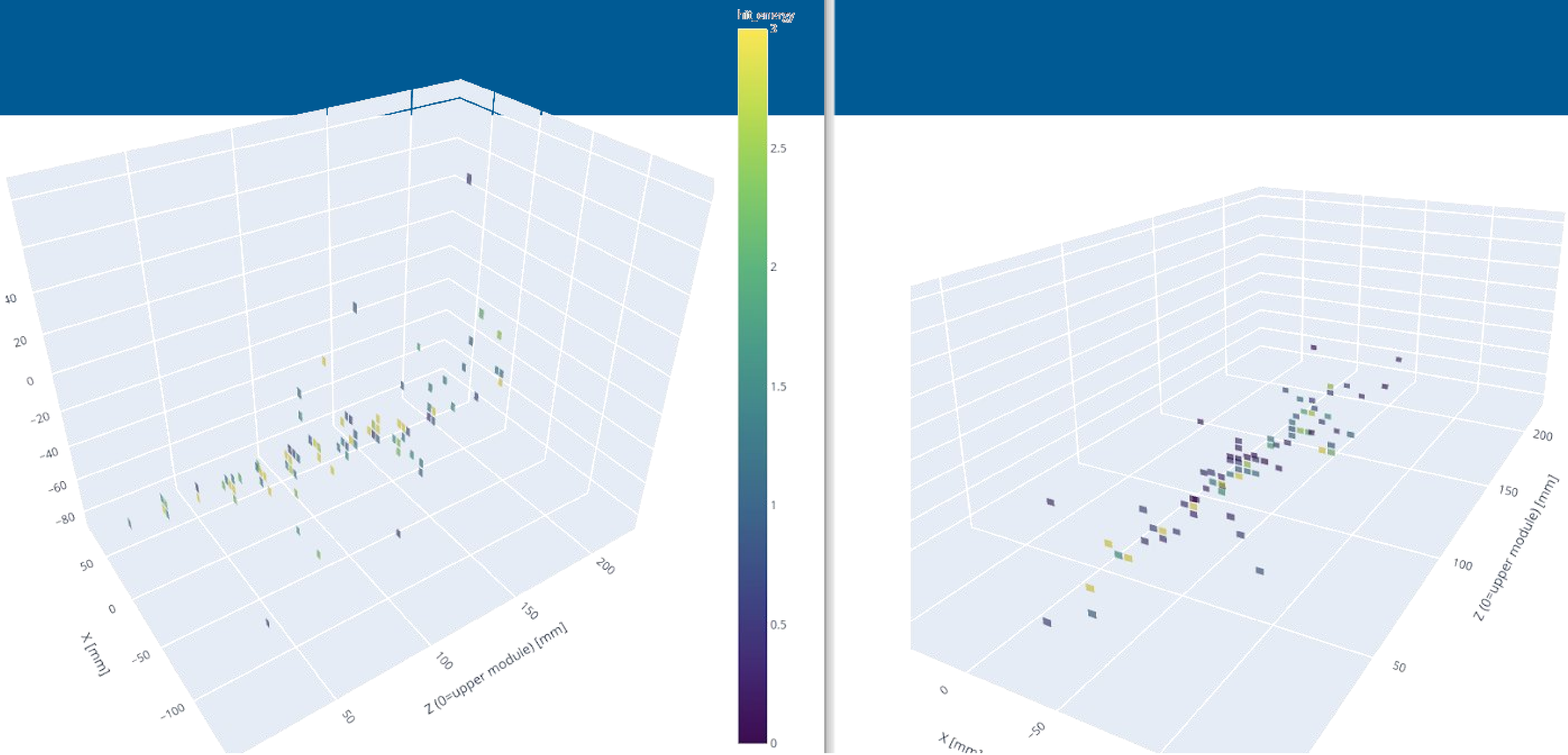




J. Kunath, PhD






hit_energy
3
2.5
2
1.5
1
0.5
0
X [mm]
Z (0=upper module) [mm]
40
20
0
-20
-40
-60
-80
50
0
-50
-100
50
100
150
200

Beam test: CERN

2 weeks in June @ SPS-H2

– SiW-ECAL + AHCAL

  15 layers, 1 configuration W

– Running : 75% of time :

- e : 10, 20, 40, 60, 80, 100, 150 GeV
- μ : 50, 150 GeV
- π : 10, 20, 70, 100, 150, 200 GeV

Two issues:

– Increased delaminations of wafers on the edges

  under investigation; main suspects:

    Too much handling; Small batch production; Glue aging

– Collective wafer trigger at high energy (≥20 GeV)

- linked to HV distribution

Electron

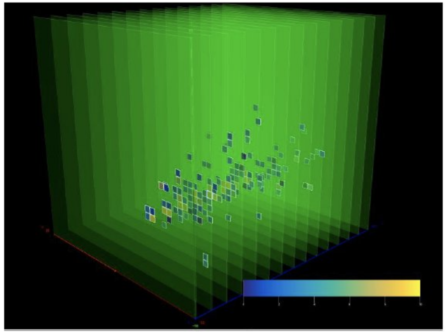


Fig. Simulation e- 10 GeV

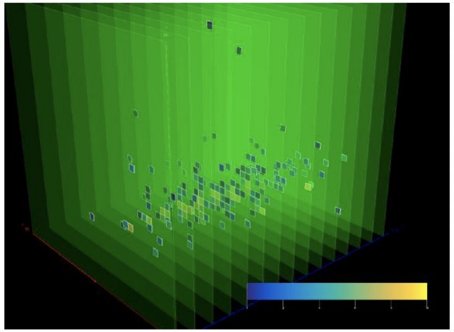


Fig. Reconstructed e- 10 GeV

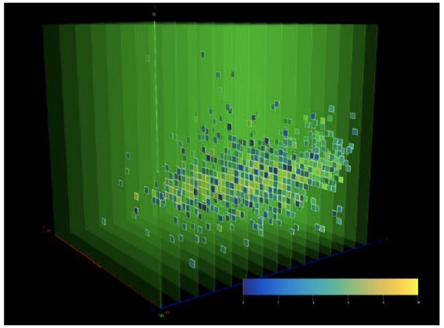


Fig. Simulation e- 100 GeV

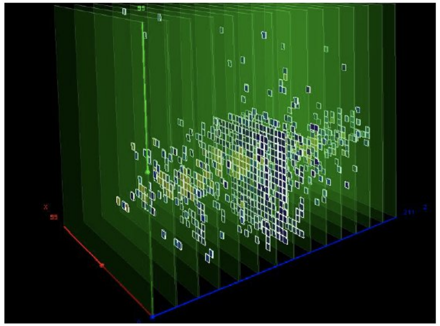
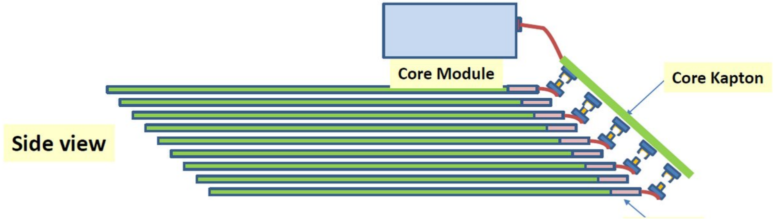


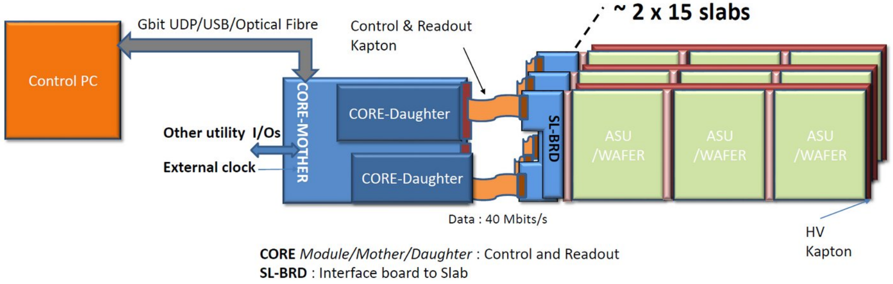
Fig. Reconstructed e- 100 GeV

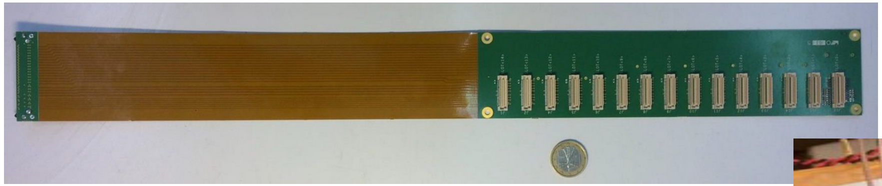
New DAQ system (2020)

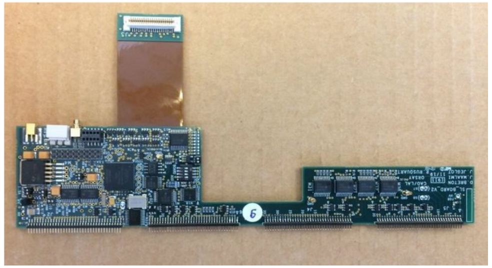
Since 2018, IJClab develop new DAQ

- New interface board: SL Board
- New concentrator board: Core mother
- Add backplane board for stack
- Software based on LabWindows









Acquisition software

Written in C under Labwindows CVI

- Handle whole detector
- Two sides with 15 SLABs
- 5 ASU per SLAB

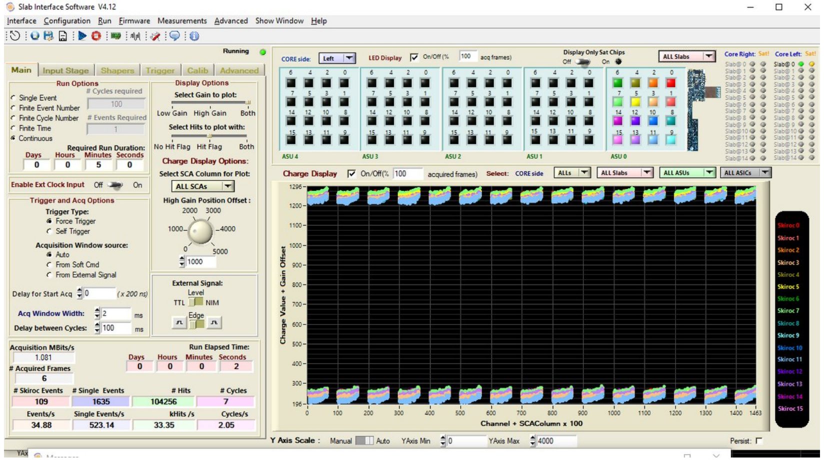
Make advanced measurements

Hardware automatically detected

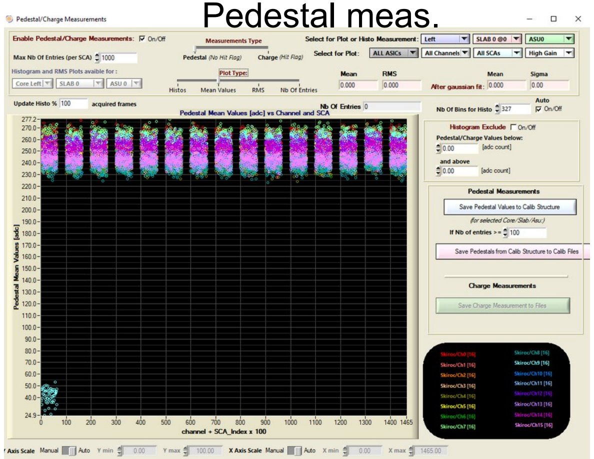
- Number of SLAB
- FEV type + number of ASU

Slowcontrol:

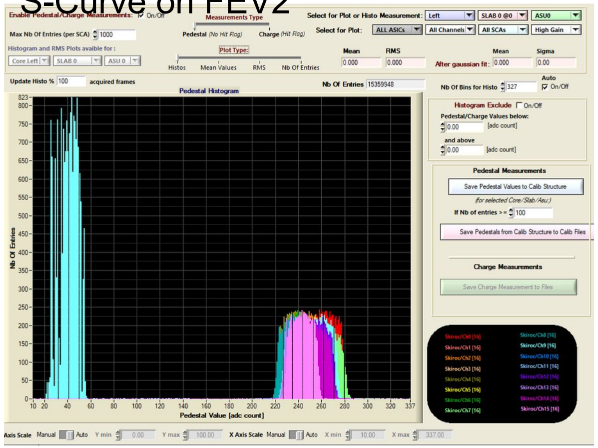
- All parameters programmable
- Integrated analysis



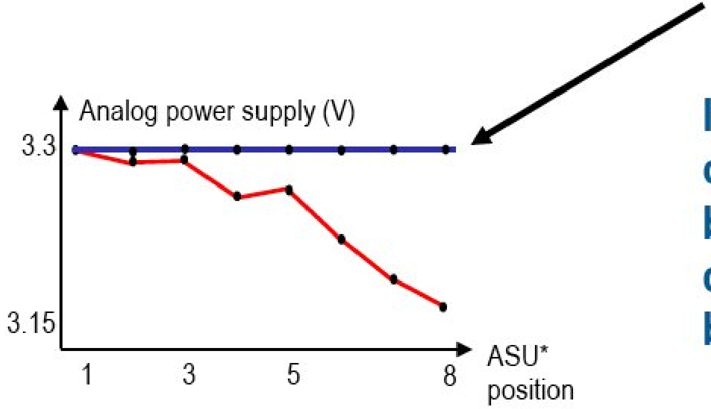
Pedestal meas.



S-Curve on FEV2



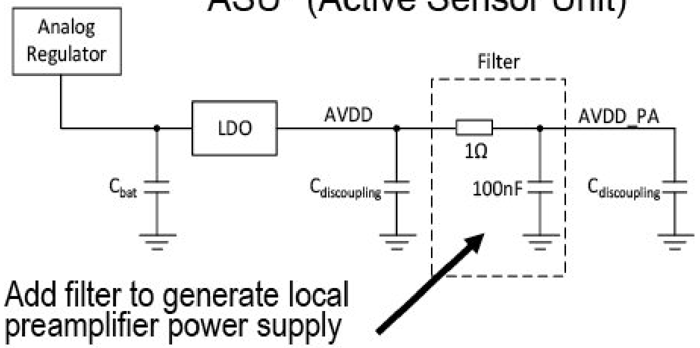
Power distribution dedicated for LONG SLAB



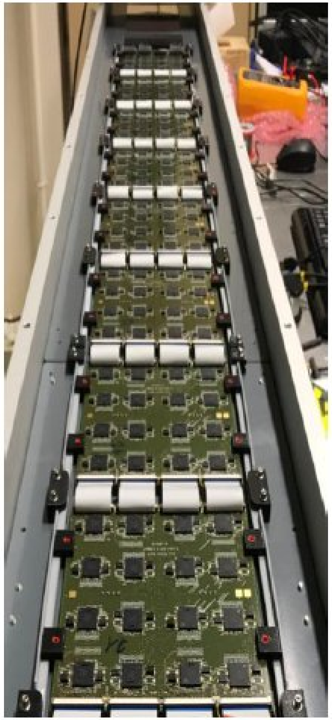
Expected results

In the electrical long SLAB, 8 boards are chained and due to resistivity of layer per board on analog 3.3V, we measure voltage drop along the long SLAB coupled with bandgap distribution.

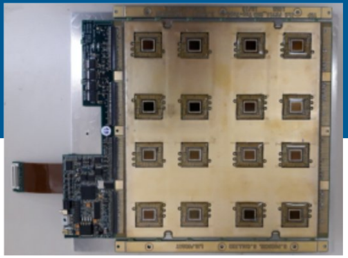
ASU* (Active Sensor Unit)



→ We decide to generate local power supply with LDO (Low Drop Out) to cancel voltage drop and reduce common noise.

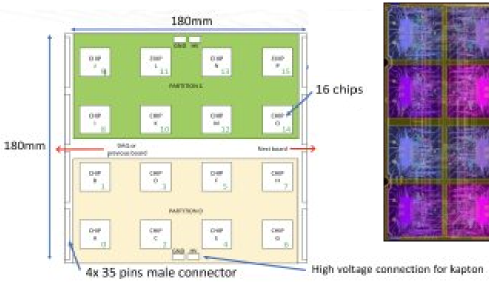


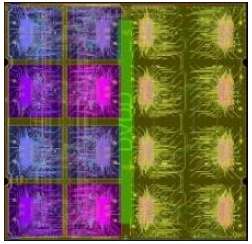
New front end board FEV2.0 (2021)

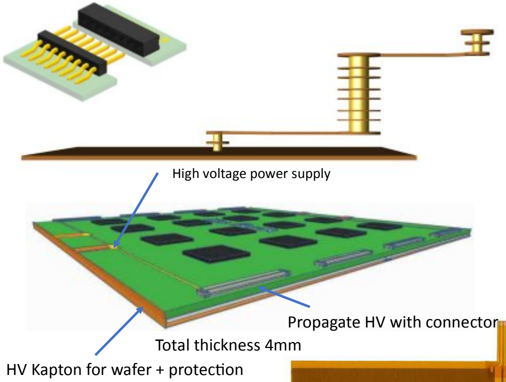


Observation from previous test beam @ DESY 2018 with electrical long SLAB:

- Voltage drop
- Clock configuration integrity
- Power pulsing



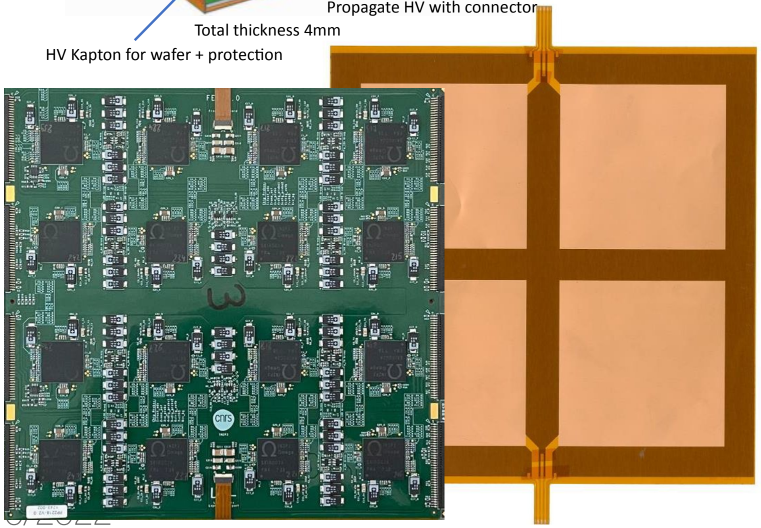




New feature of FEV 2.0:

- 1 LDO (low drop out) per SK2A on analog power supply
- 1 LDO per 4 SK2A on digital power supply
- Add buffer on configuration clock (every 8 SK2A)
- Driving HV (up to 350V) + add filter for each wafer
- Improve shielding for analog signal and power supply

6 months delayed due to cabling problem components supply



SiW-ECAL for circular EW/Higgs Factories

Running conditions

Linear e+e- (ILC, HL-ILC, …)

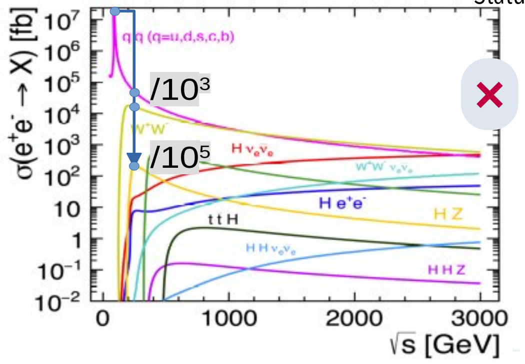
- 250 GeV (ZH), 365 GeV (tt), 500 GeV (ZHH) + [1000 GeV], $\mathscr{L}$ ~ cst.
- Power pulsing : 5 [10–15]Hz × 1 [2] ms

Circular e+e- (CEPC, FCC-ee) :

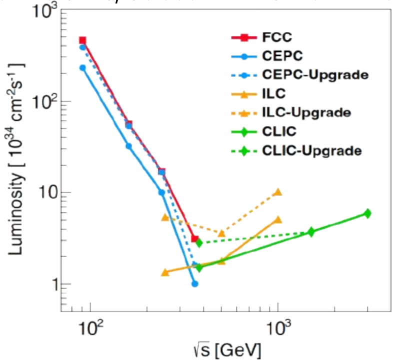
- 90GeV × 10^7 fb × $5{\cdot}10^{36}$ cm^{-2} s^{-1} (qq × 20,000 ILC @ 250GeV)
- 150 GeV (WW) + 250 GeV (ZH)+ 365 GeV (tt)
  ~10^4 fb × $5{\cdot}10^{35}$ cm^{-2} s^{-1} (qq × 5–10 ILC @ 250)

Paradigme Change: *Continuum hypothesis*

– ASIC, Power/Cooling, DAQ, *Granularity, Precisions (E, t),* New ideas…



Status of the CEPC, October 2022 J. Guimarães da Costa



HL-ILC:

– $\mathscr{L}$ × 4 (6)
– $N_{bunches}$ × 2 : τ_{Train} : 1 → 2 ms
– f_{rep} ×2 (3): 5 → 15 Hz

Dominated by ACQ time:
P(~25µW/ch) × 6

HL-CLIC:

– $\mathscr{L}$ × 2
– $N_{bunches}$ → : τ_{Train} : 176 ns
– f_{rep} ×2 : 50 → 100 Hz

Dominated by Set-up & Conversion time: P (~82µW/ch) ×2

FCC-ee parameters		Z	W+W-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	230	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	92,000	8.4	1	0.1
"Pile up" parameter [µ]	10^{-6}	1,800	1	1	1

https://indico.cern.ch/event/1064327/contributions/4893208/
Mogens Dam @ FCC Week, 10/06/2022

	Higgs	W	Z	ttbar
Bunch number	249	1297	11951	35
Bunch spacing [ns]	636	257	23 (10% gap)	4524
Bunch population [10^{10}]	14	13.5	14	20
Bunch number	415	2162	19918	58
Bunch spacing [ns]	385	154	15 (10% gap)	2640
Bunch population [10^{10}]	14	13.5	14	20

Snowmass2021 White Paper AF3-CEPC, arXiv:2203.09451

Detector Parameters: scaling rules

- Cell lateral size
  - Shower separation (EM~2×cell size)
  - Cell time resolution (1 cm/c ~ 30 ps)
    - Time performance for showers
      - » ParticleID, easier reconstruction
- Longitudinal segmentation
  - sampling fraction
    - E resolution (ECAL ~15%/√E)
  - shower separation/start
- ECAL inner radius; Barrel Z_{Start}
- ECAL–HCAL distance
- Barrel–Endcap distance
- Dead-zones sizes (from Mechanics, Cooling)

Number of cells ↗ ⇒ Cost ↗ (1/size²)
Cell density ↗ ⇒ Power consumption ↗

Time resolution ↘ ⇒ Power ↗

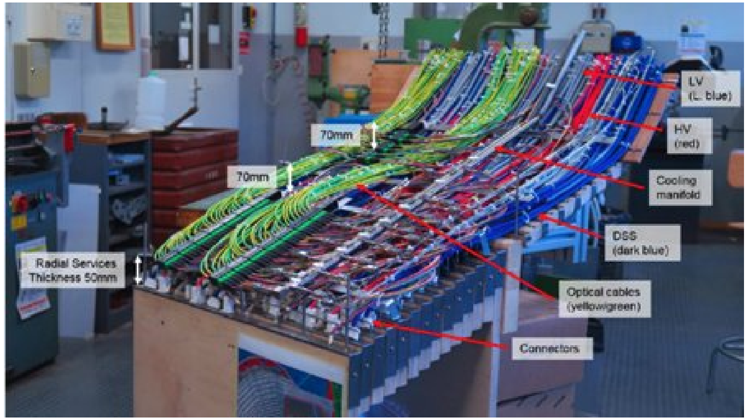
threshold, passive vs active cooling
dead-zones ↗

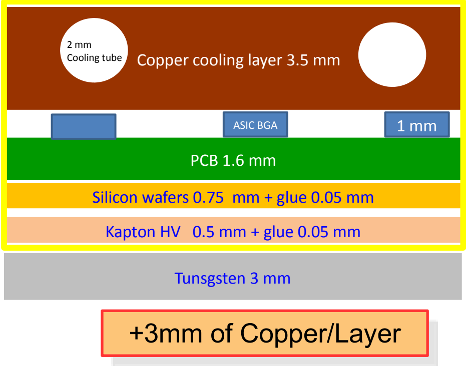
NEED TO BE FULLY RE-EVALUATED for EW region

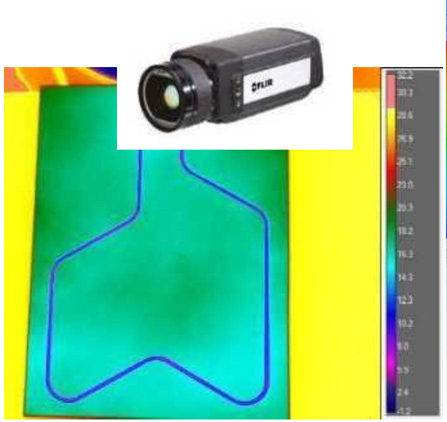
Inner Radius ↗ ⇒ Tracking performance ↗
Cost ↗² (⊃ Magnet, Iron)
Gaps ↗ ⇒ PFlow performances ↘
⤷ ⊃ *Active cooling*

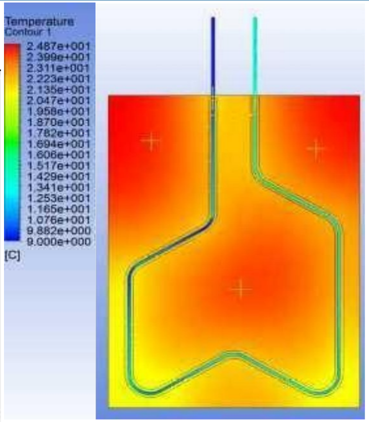
Review of physical implication (from TeV): see Linear collider detector requirements and CLD, F. Simon @ FCC-Now (nov 2020)
Physics Requirement studies @ 250 GeV: see Higgs measurements and others, M. Ruan @ CEPC WS, (nov 2018)

Services: integration & cooling



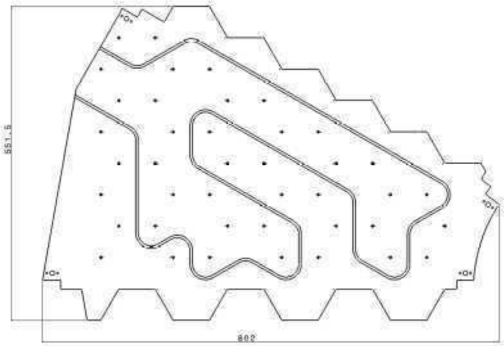


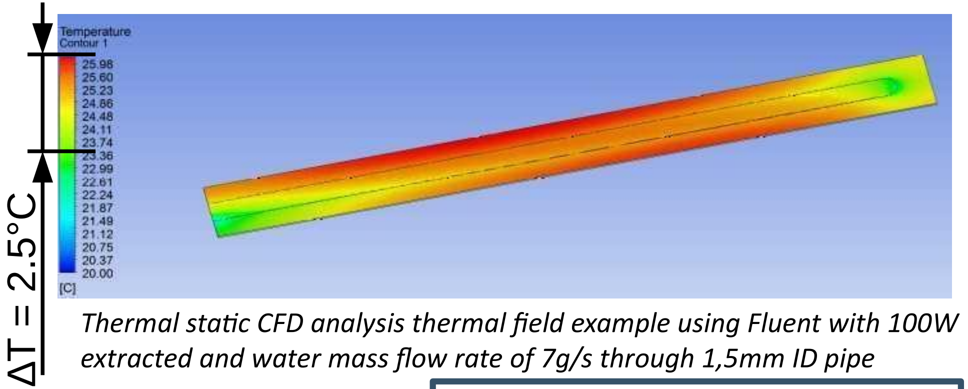




- Pipe insertion process introduces some efficiency loss due to the thermal contact resistance.
- The benefit remains significant with regard to a passive cooling

Pipe insertion on a cooling prototype



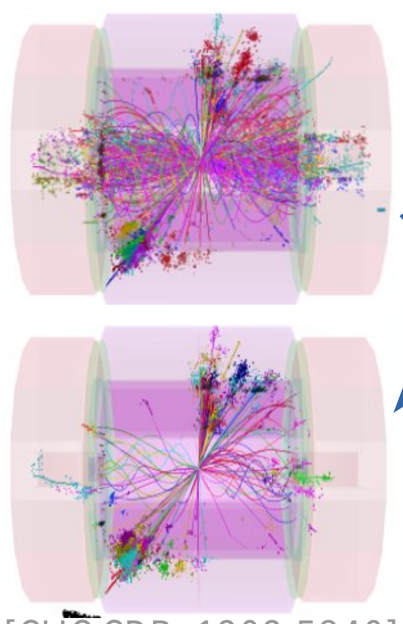


Thermal static CFD analysis thermal field example using Fluent with 100W extracted and water mass flow rate of 7g/s through 1,5mm ID pipe

= 2× cont. operation of a SLAB

Timing in calorimeters: 0.1–1 ns range

Cleaning of Events



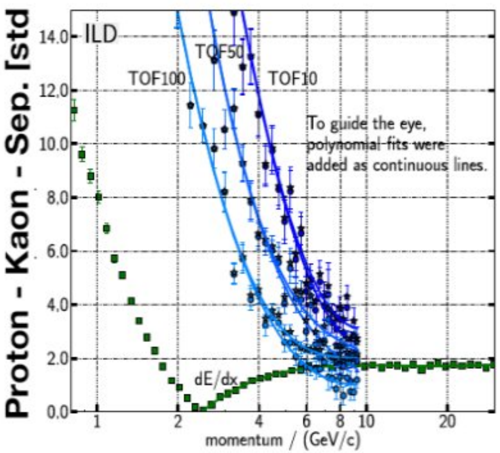
time cut

[CLIC CDR: 1202.5940]

adapted from L. Emberger

Particle ID by Time-of-Flight

– Complementary to dE/dx
  • here with 100ps on 10 ECAL hits

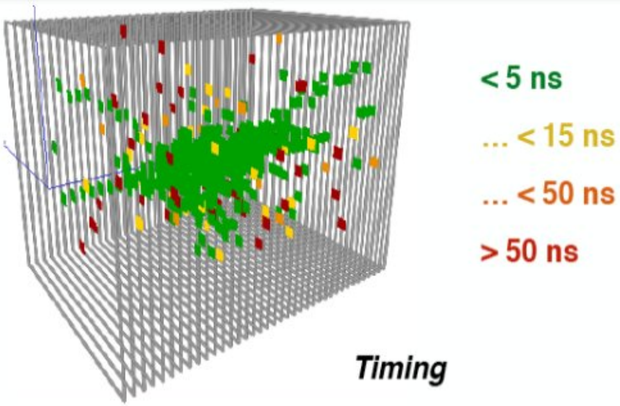


S. Dharani, U. Einhaus, J. List

See Cluster timing and leakage in time at the CEPC baseline Calorimeter (Yuzhi Che)

Ease Particle Flow:

– Identify primers in showers
– Help against confusion
  better separation of showers
– Cleaning of late neutrons & back scattering.
– Requires 4D clustering

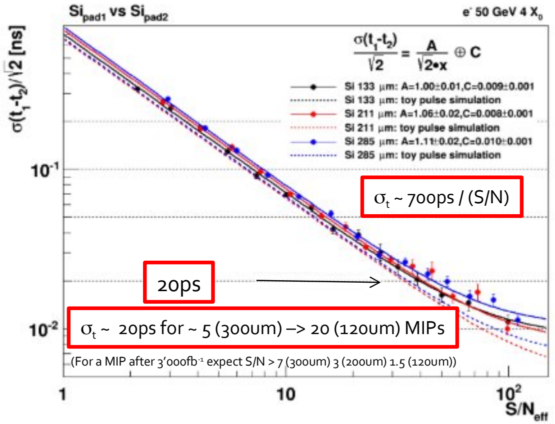


Ch. Graf

Timing Studies

2015 CMS HGCAL CERN timing test beam

– Time resolution vs S/N ratio

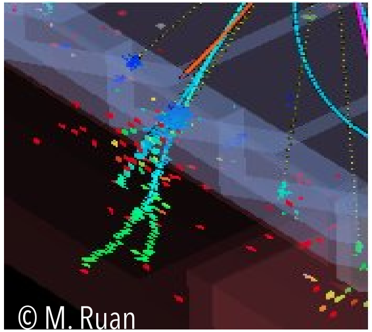


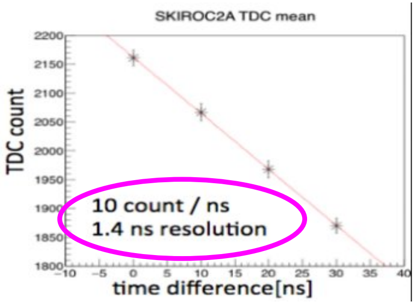
Transparent cells => no timing

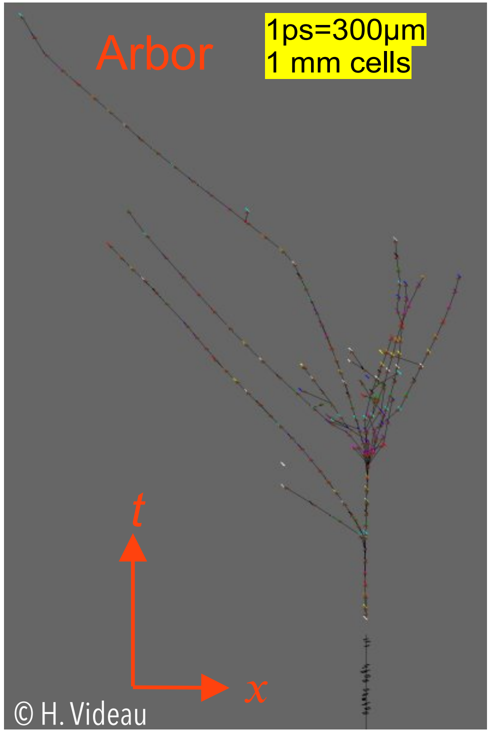
Solid cells = > timing information ~50ps

CALICE / ILD

– Bulk Timing







See Cluster timing and leakage in time at the CEPC baseline Calorimeter (Yuzhi Che)

SiW-ECAL optimisation

Rationale/Questions

PFA combines : particles to get the best possible Jet Energy Resolution (JER):

- Charged Particle ~65% of E
- Long Lived Neutral Hadrons ~ 10%, measured by ECAL+HCAL
- Photons: 27 % E, solely measured by ECAL ← **how well are those measured ?**
- Separation of close photons, photon/charges (τ and π^0's tagging)

How can we improve the resolution... ?

- Lower E–gamma threshold
- "Best" E-resolution ← that depends on the average energy of the photons

… while keeping the cost and reasonnable and technical feasibility

- Contants: number of layers, amount of tunsgten

Parameters space

Main parameters of the ILD SiW-ECAL

- 24 X_0 of W
- 15 layers (CALICE proto) / 30 layers (ILD)
- 2 sections of 1 and 2 thickness of W
- Cell size of $(5.5\ mm)^2 \times 500\ \mu m$

Boundaries: What needs to be fixed ?

- Cost ?
- Min. Performances

Each needs introspection

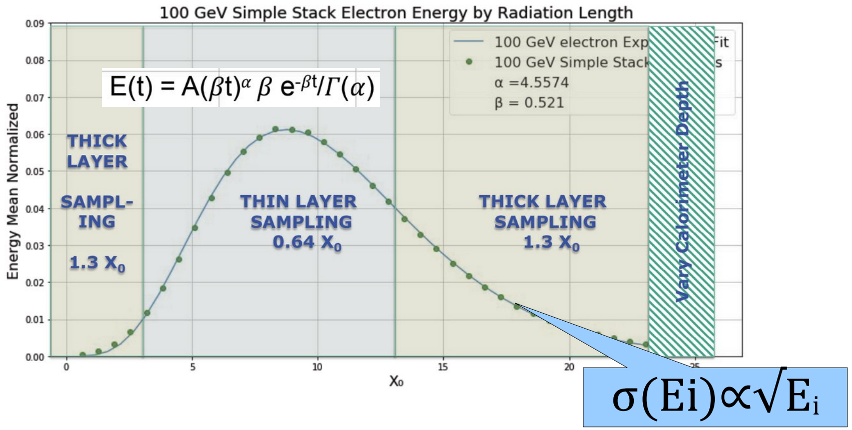
- Optional W thickness ?
  - Photon (and Electron) containment
    - Highly dependant on E tails and angles
- Optimal number of layers ?
  - More is better…
  - Upper limits from cost and heat
  - Lower limit from performances
- Absorber repartition: ~ started
  - Unhomogenous might bring longitudinal dependance of E
- Cell size: studied (PFA, CALICE prototypes)
  - To be reassesed for circular colliders

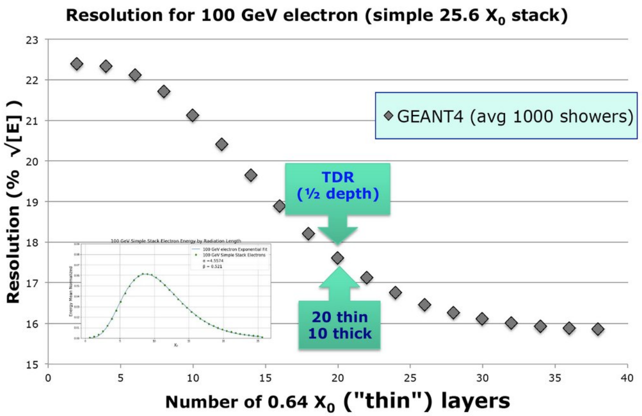
Previous studies

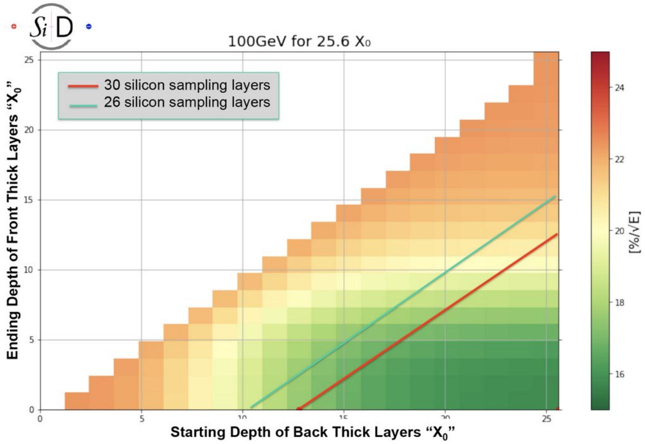
SiD SiW ECAL Fast Sim Studies

- Thin W : 20× 0.64 X_0
- Thick W: 10× 1.3 X_0
- 13 mm² Hex pads

J. Brau, LCWS 2018





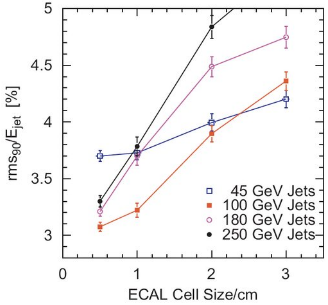


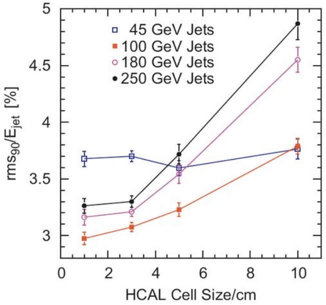
Previous studies: PFA

PandoraPFA Studies

NIM A611 25–40 (2009)

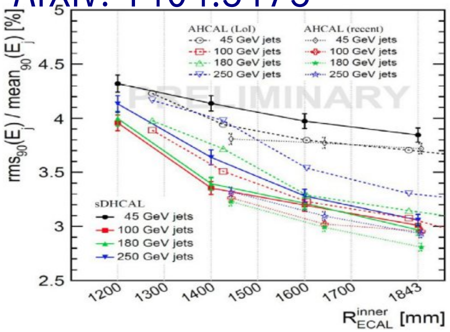
- JER Optimisation vs
  - Radius, cell size, B
  - Scint HCAL





- Radius with SDHCAL
  - vs Radius, B

ArXiv: 1404.3173



ARBOR:

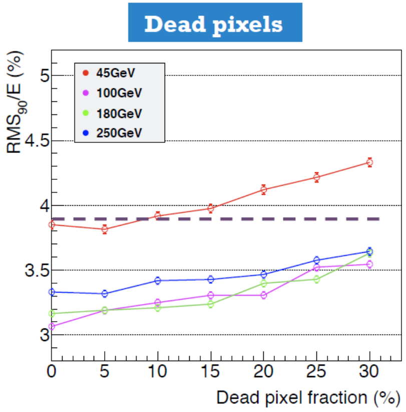
- CEPC Baseline ➡ CDR

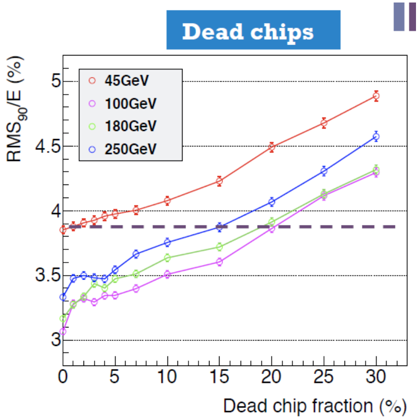
ILD: Robustness of a SiECAL used in Particle Flow Reconstruction

- Jet Energy Resolution vs
  - dead channels, noise, mis-calibration and cross-talk
  - using PandoraPFA

JER

ArXiv:1404.0124

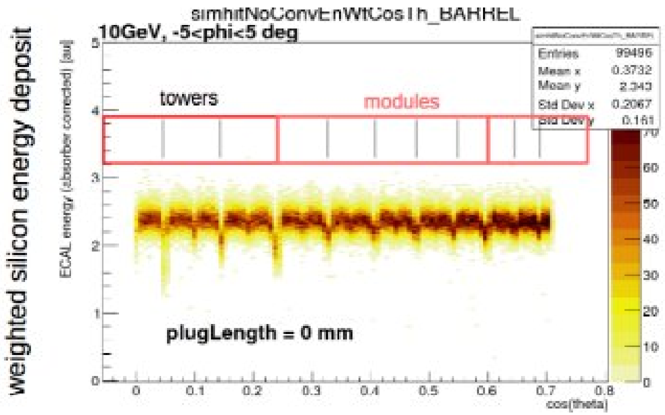


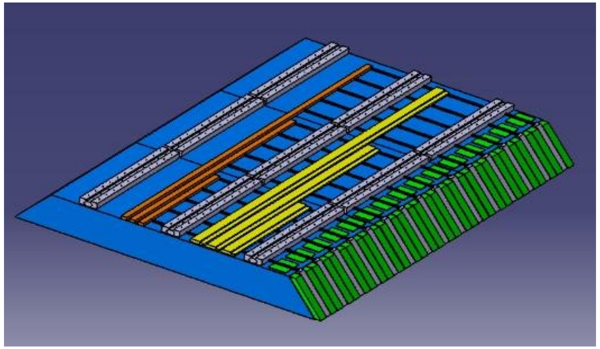


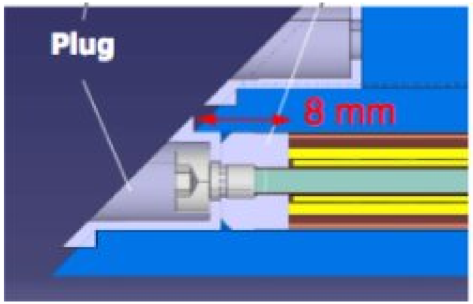
Specific studies

Dead materials

– ILD: . Jeans



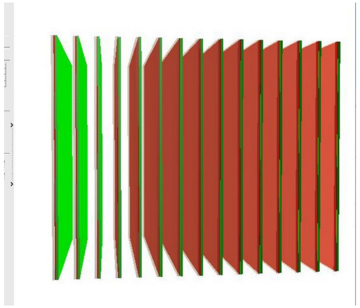


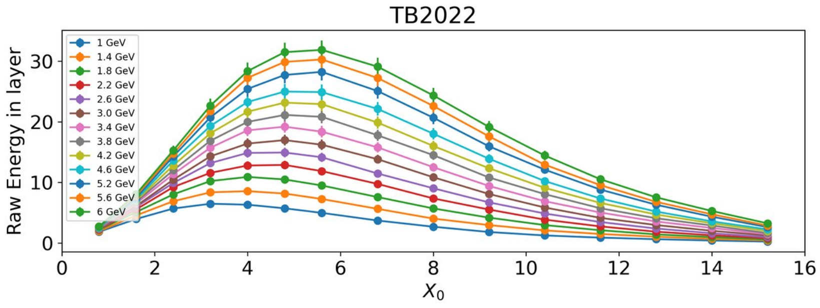


EM shower in Highly-Granular ECAL

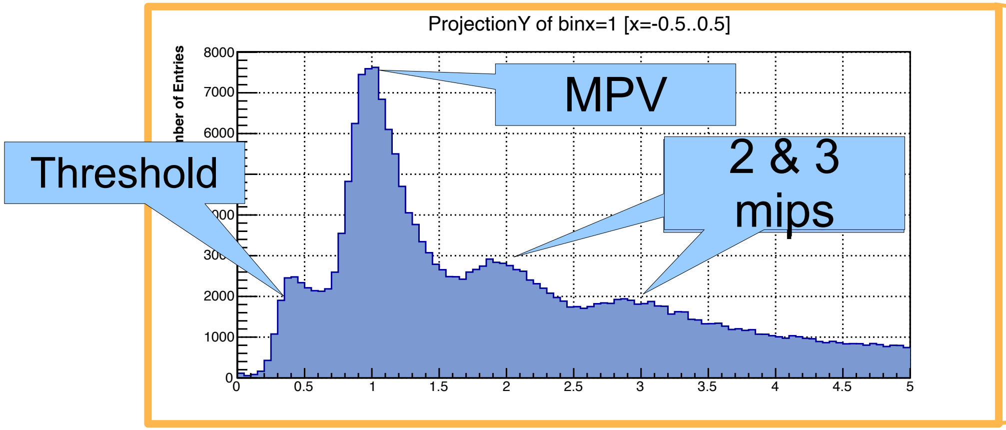
As illustration:
Full Simulation of
SiW-ECAL prototype
(DD4Sim)

- 15 layers × (5.5 mm)²
  - Silicon Sensors 500 µm + 650µm
  - W of 7× 4.2 mm (1.2X_0) and 8× 5.6 mm (1.6X_0)
    - ≠ ILD but easy modifications
- Calibration on muons

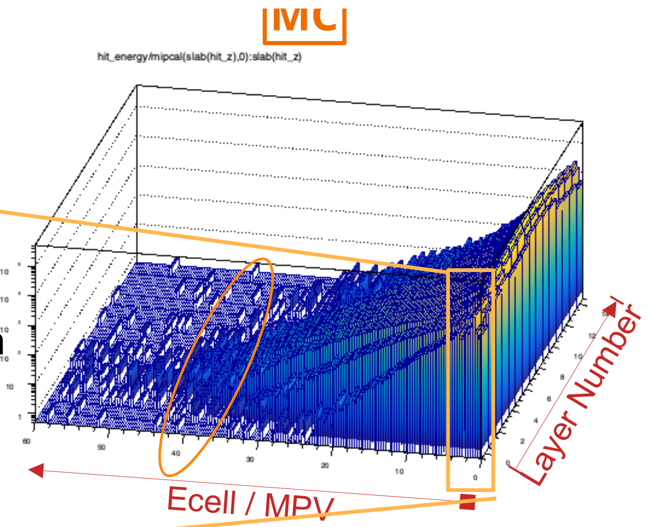




F. Jimenez



3 GeV electrons energy deposited in (5.5 mm)² cells



Escale → ≤ ~40 mips / cells

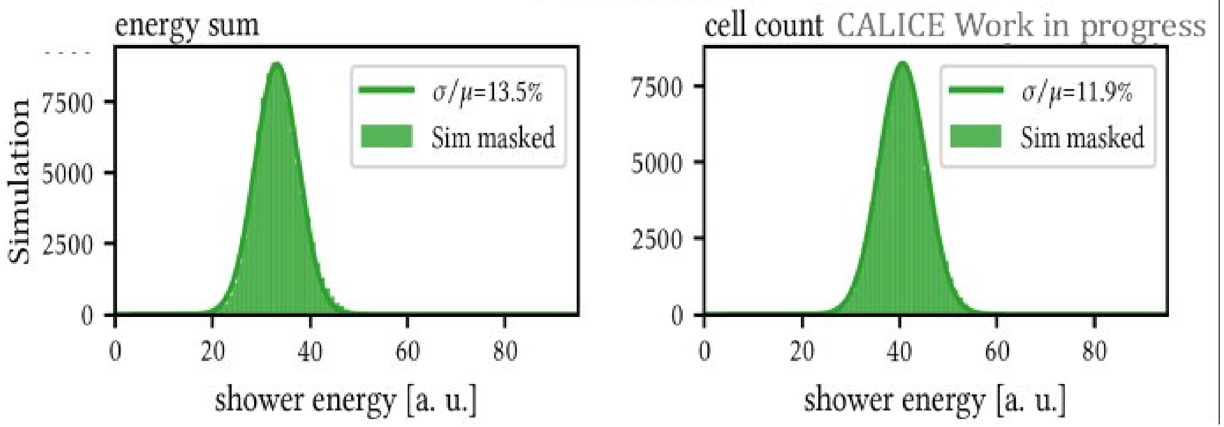
Energy measurements

Energy reconstruction

Energies

- $E_\Sigma = \sum E_i$
- $E_f = \sum \omega_i E_i$; $\omega_i = 1/(1+f_i)$;
  f = mip sampling fraction
- $E_h = \sum (E_i > 0{,}5 \text{ mips})$
- $E_{fh} = \sum \omega_i \times (E_i > 0.5 \text{ mips})$

3 GeV electron

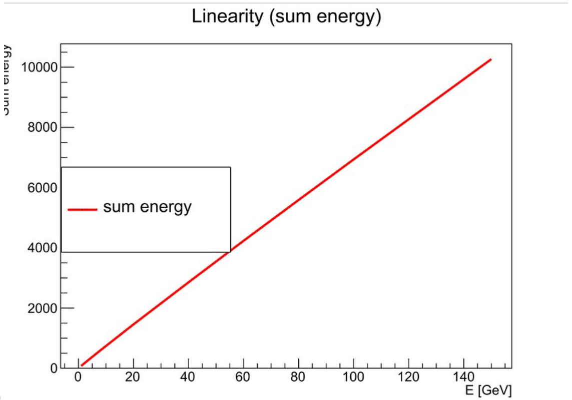


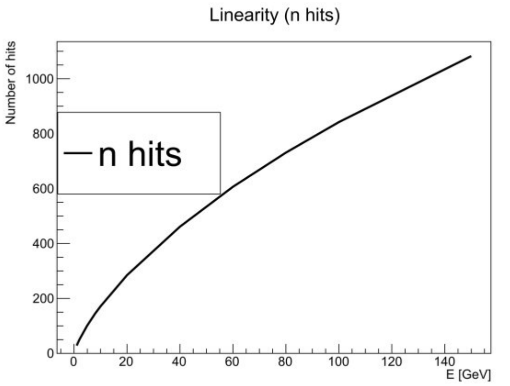
J. Kunath, F Jimenez

Nhits E_h

At least as regular as energy…

… but saturates at high energy.





Energies Resolutions

Preliminary resolutions

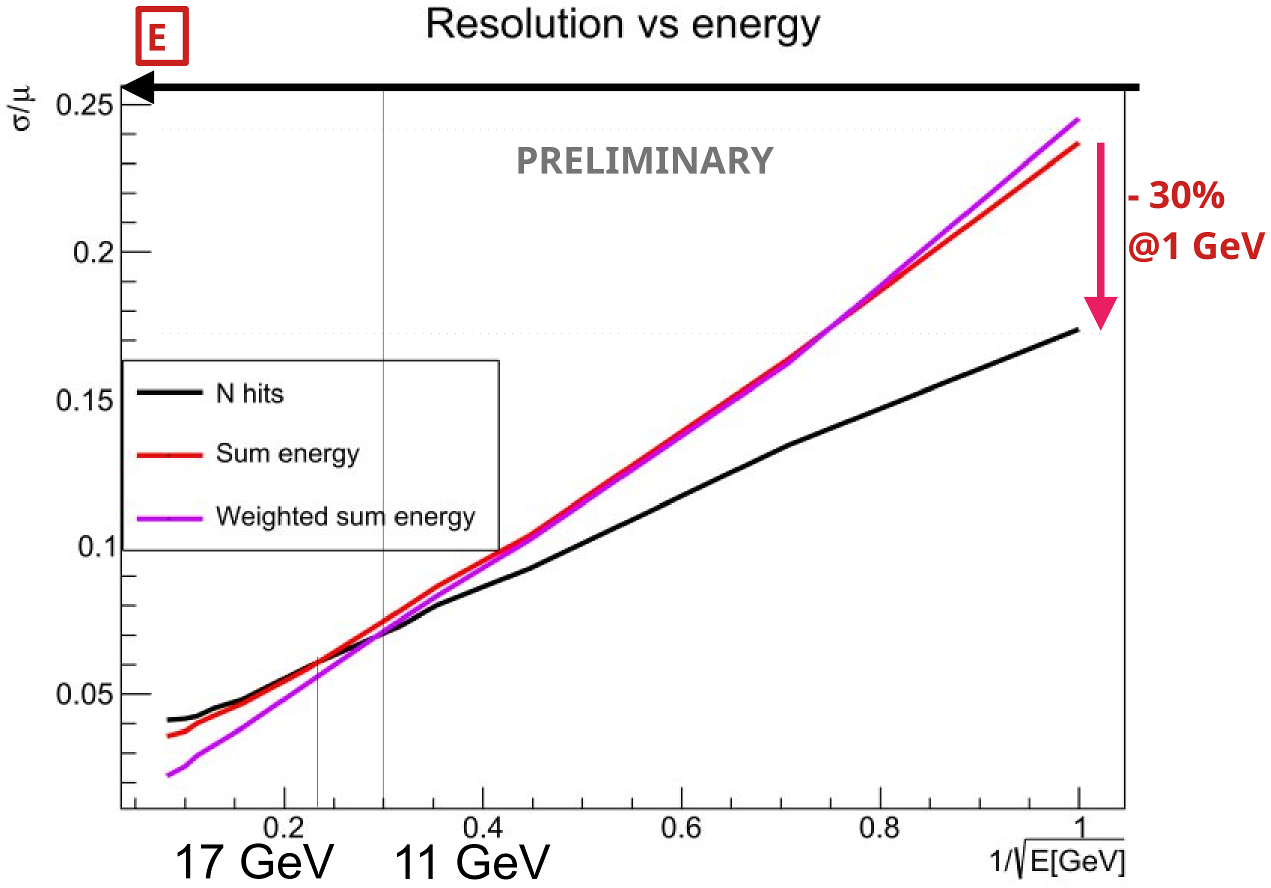
- Linearity corrected
- Errors bars within the lines
- No digitization, No clustering, No noise
  - But cut at 0.5 mips
  - Small incidences expected

E_Σ and E_f :

- Nearly identical
  - little difference between sections

E_h :

- (Significant) Improvement ≤ 11 GeV
- Possible explanation:
  cutting out Landau fluctuations

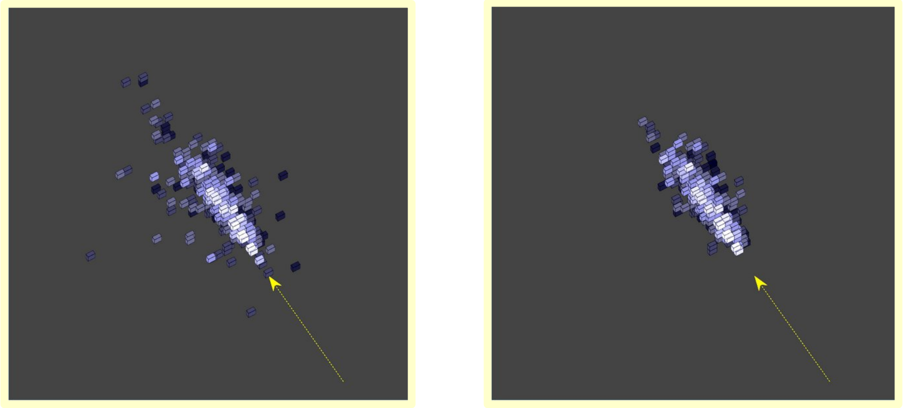


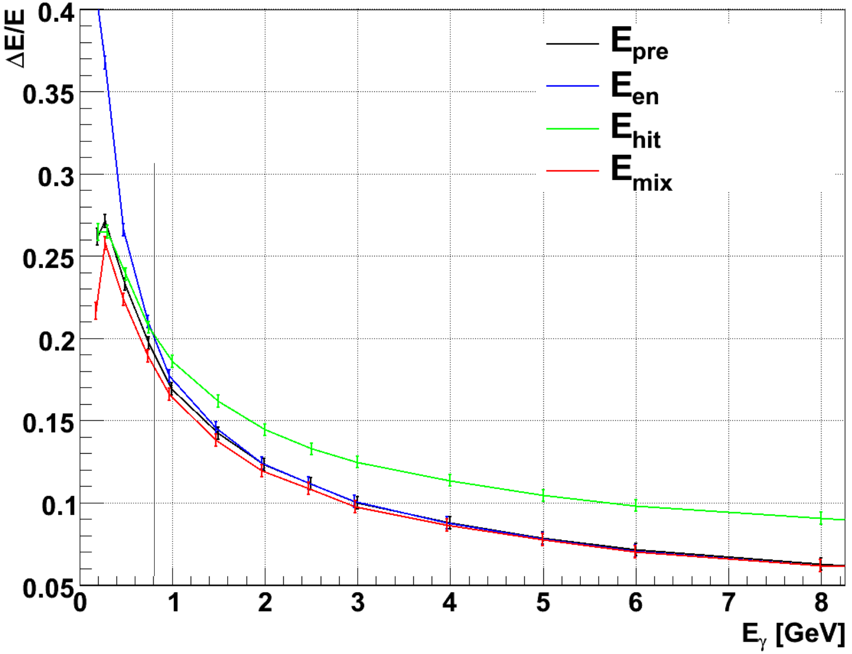
Previous work

M. Reinhard PhD (2009, adv: J-C Brient)

$$E^{en}_{meas} = \alpha(f_1 E_1^{even} + (1-f_1)E_1^{odd}) + \beta(f_2 E_2^{even} + (1-f_2)E_2^{odd})$$
$$E^{hit}_{meas} = \gamma N_1 + \delta N_2$$

- On ILD SiW-ECAL
  - $(5mm)^2$ cells, 2 sections
- GARLIC clustering (cleaning of outlier hits)

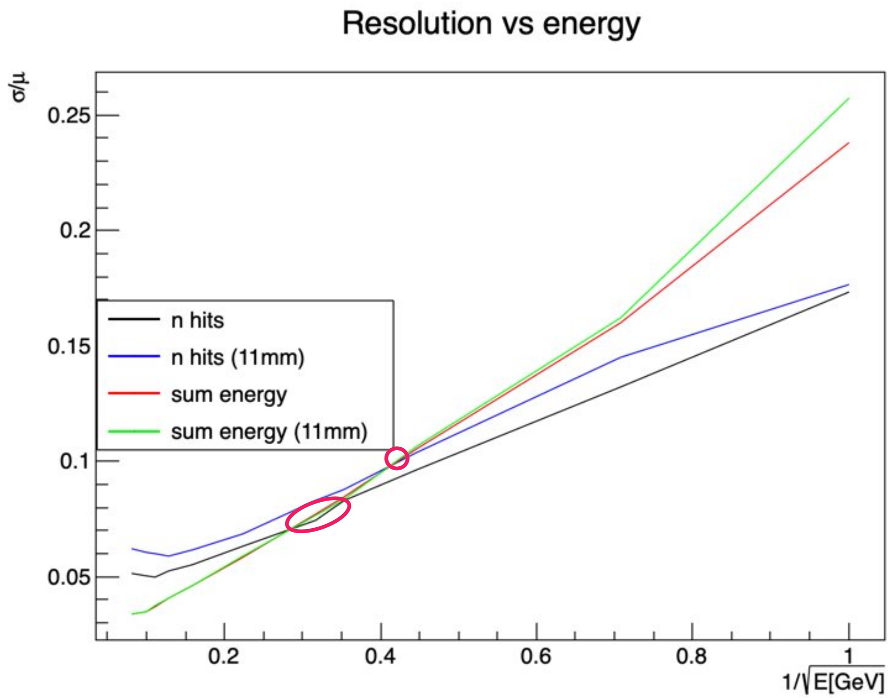




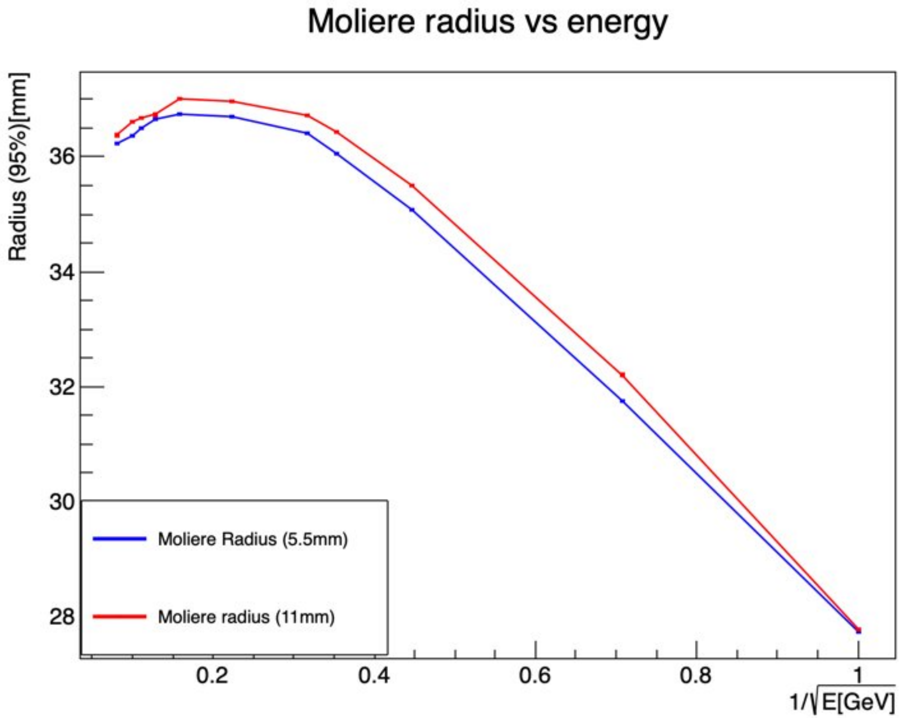
- Not obvious in all regions
  - overlaps, gaps, …

Molière Radius & Cell size

Resolution for 11 and 5.5 mm



Molière Radius for 5.5 and 11 mm

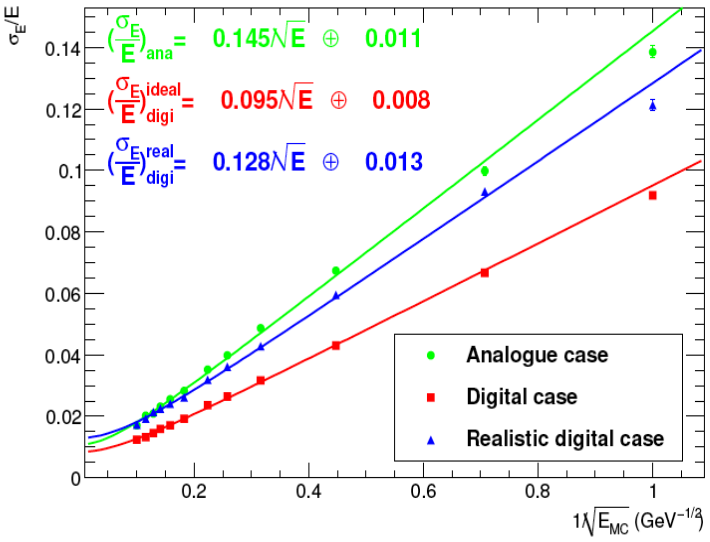


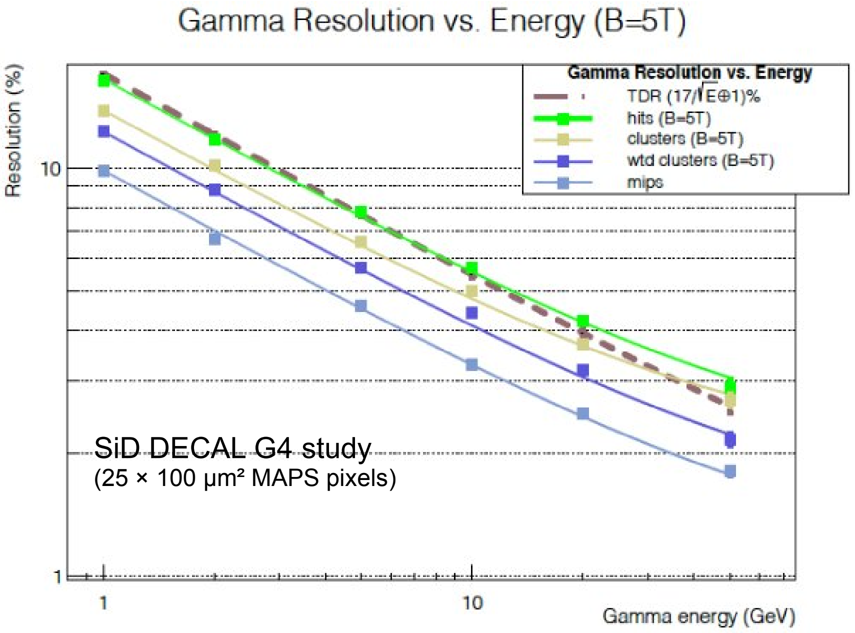
Ultimate Granularity ?

Studies by SID ECAL group (2021)

arXiv:0901.4457

- Large area MAPS
- Pixels of 50×50 µm² or 25×100 µm²

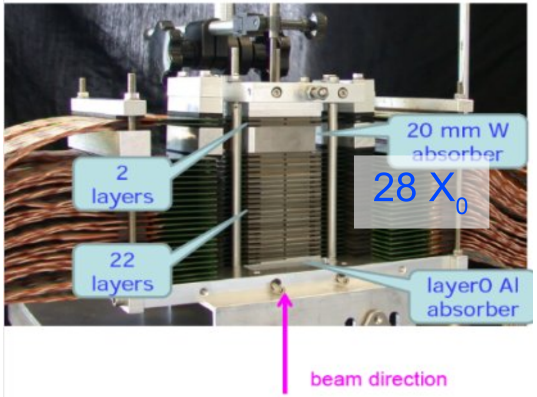


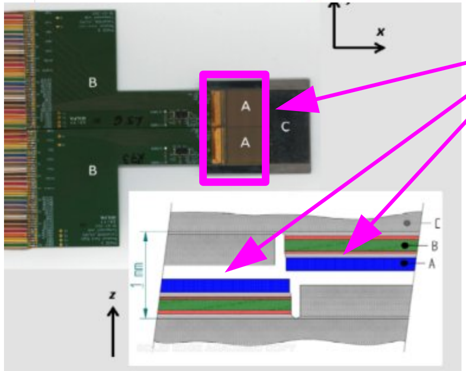


Updating the SiD Detector concept arXiv:2110.09965

MAPS & DECAL

FOCAL DECAL prototype





4 MIMOSA-26 / Layer
CMOS sensors (IPHC)

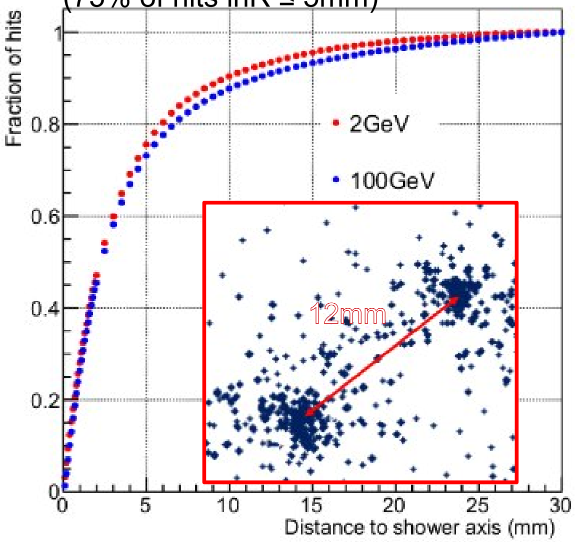
- 6×6 cm²
- 30×30 μm² pixels
- 39 M pixels
  = full readout

FOCAL = 2 layers of MAPS

but How to build a full detector ?

- Services: Power + Cooling ?
  - Gains by going fully digital ?
- For what physical gain ?
  - Improved separation ✔
  - Improved resolution ?

R_M = 10.5mm
(75% of hits in $R \leq$ 5mm)



Technical feasibility

Detector optimisation for Higgs Factories

Continuous running ≠ Pulsed runnning

– Power × 100 !

Low energy (90 GeV)

– Lower energy – less focused jets
  - Lower granularity needed (1–2 cm OK ?)
  - Lower dynamic range
– Other criterions ? Tagging

… but not so for the rest (≥ ~250 GeV)

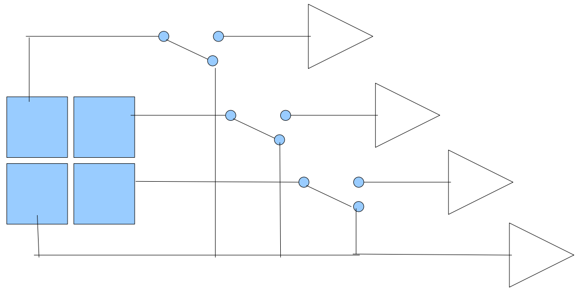
Reduce the number of layers + thicker sensors

– See “Small ILD” model

– 6’’×500μm wafers ➡ 8’’ × 725 μm (resolution $1/\sqrt[5]{d}$)

One size fit all ?

– Have a dynamic granularity ?



– Have a semi-digital readout ?
  - Hit counting for low energy
  - E measurement for high energies

Use full simulations to estimate fluxes :
- Occupancy, Power, Data …
- … for various hypothesis (ℒ, Granularity, ASIC technology, DAQ scheme, ...)

Conclusions

SiW-ECAL technological prototype

- does calorimetry with 15 (heterogeneous) layers
  - first showers, with filtering
- Numerous emerging issues
  - gluing, HV filtering at high energy
- ➡ New VFE boards
  - Cleaner PS & Clock distributions; more uniform

DD4Sim model for CALICE prototype(s) ready

- Flexible Geometry
- Cell masking, Digitization (↔ Data) ➡ ILD

Parameters can probably be optimized

- ECAL composition :
  - For single photons, for photons in Jets (with clustering)
  - For Tau decays
  - For Particle ID (with timing)
  - For pointing (Long Lived Particles)
- Energy reconstruction with high-granularity started on single electrons
  - Hit counting seems reliable for low (≤15 GeV) electrons on 15 layer prototype.
  - Needs combination of different E's measurements

Fluxes to be estimated for continuous operations

- On full simulation (ILD) ➡ Power, Granularity, …