Fundamental of Silicon Calorimeters

Vincent Boudry

Laboratoire Leprince-Ringuet,
Institut Polytechnique de Paris

Workshop on Advanced Radiation Detectors and Instrumentation in Nuclear and Particle Physics

RAPID2021

25-19 October 2021

University of Jammu (online)

ÉCOLE POLYTECHNIQUE

INSTITUT POLYTECHNIQUE DE PARIS

IN2P3 Les deux infinis

Classical calorimetry

Measure the energy of a particle by stopping it (⊥ tracker philosophy)

- "Calorimeter ≅ Instrumented bloc of matter"

Measure of neutrals :

- Electromagnetic : γ
- Hadronic : n, K^0_L

Performances (position, energy, time resolutions, linearity, scale) fully depends on applications

Measure electrons & positrons energy and position & angle, time: $e^{\pm}$

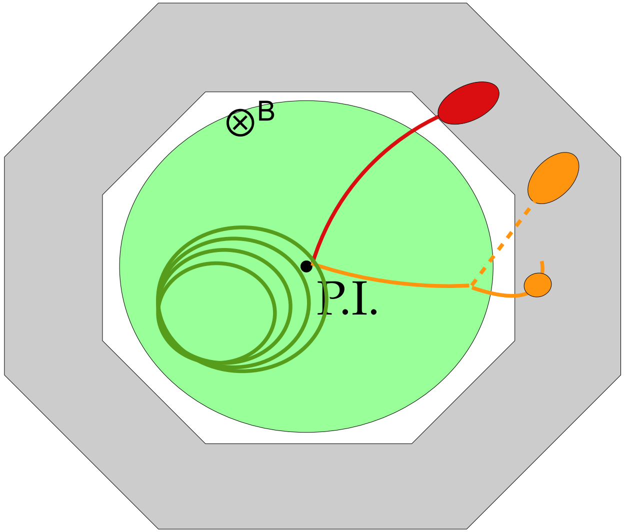
Measure charged hadrons energy and position (& angle), time: $h^{\pm}$

Identify leptons : $e, \mu, \tau, \pi^{\pm}, K^{\pm}, \ldots$

- Muons ≃ tracks in the detector (esp in calorimeter, iron)
- τ ~ jets with small population

Measure jets (~quarks) → «Energy Flow» «Particle Flow»

- $\gamma c \tau$ = mean path length > size of tracking
  - $K^0_L, \pi^{\pm}$
  - $\mu, p, n \gg 100$ m



Typical lengths

$e^\pm$ et γ ⟶ shower in "EM calorimeter" (ECAL)

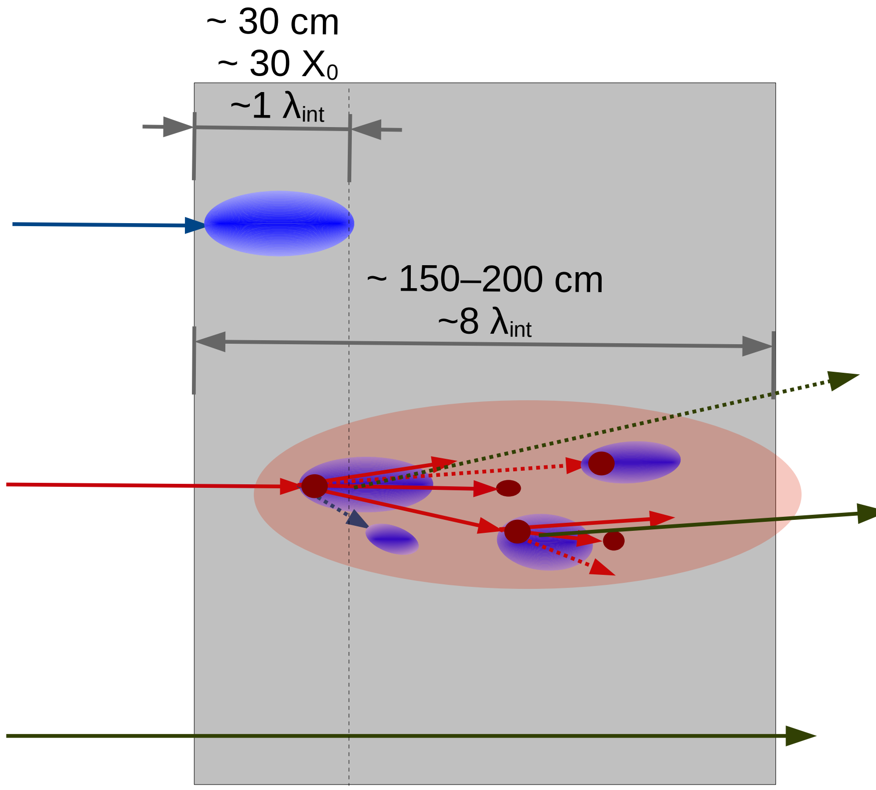
- ~30 X_0 ~ 20-30 cm of dense material
- r ~ 2 R_M ~ qq cm ; (R_M = $R_{90\%}$)

Hadrons ⟶ showers in ECAL *and* HCAL

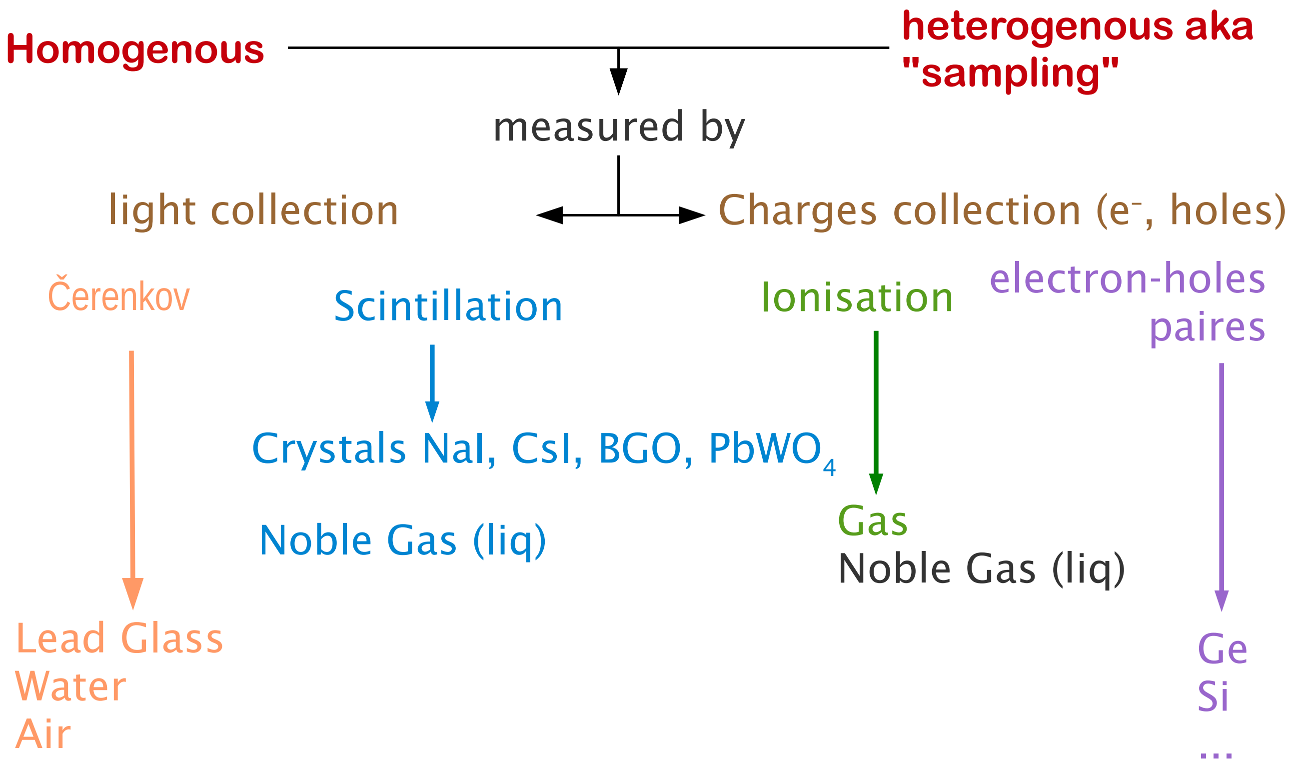
- 1 λ_{int} ~ 30 X_0
- Shower : $L_{95\%}$ ~ 8 λ ~ 1.5–2 m, $R_{95\%}$ ~ 1,5 λ ~ 30 cm
- Large fluctuations (EM fraction, shape, …)

Muons

- … passing through ...
  - Granular calorimeters + Magnetic field = tracker



Sensor's technology



Silicon (highly resistive) as sensor:

- ⊕ Robust technology (processing, rad. resist.)
- ⚠ fragile handling
- ⊕ Support compact design: Sensor+RO≤2mm with minimal dead spaces
- ⊕ Allows for ~any pixelisation, very precise
- ⊕ Fast & Excellent signal/noise ratio: ≥20
- ⊕ Intrinsic stability (vs environment, aging)
- ⊖ Albeit expensive ! (~ 2\$/cm² for simple diodes)

Some numbers

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

$$R_M = X_0 E_s / E_c$$

(sol. & liq.)

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24}$$

Material	Z	A	ρ / g cm^{-3}	X_0 / cm	R_M / cm	E_c / MeV
Si	14	28	2,33	9,4	4,9	40,0
liq Argon	18	40	1,4	14,0	7,9	37,0
Iron	26	56	7,9	1,8	1,7	22,0
Copper	29	64	8,9	1,4	1,5	20,2
Lead	82	207	11,35	0,56	1,6	7,4
Uranium	92	238	18,9	0,32	1,1	6,2
Tungsten	74	184	19,3	0,32	0,8	8,1
NaI			3,67	2,59		
Air			0,001	30420		

Combinaison of meterials:

$$1/X_0 = \sum w_j / X_j$$

$$\frac{1}{R_M} = \frac{1}{E_s} \sum \frac{w_j E_{cj}}{X_j}$$

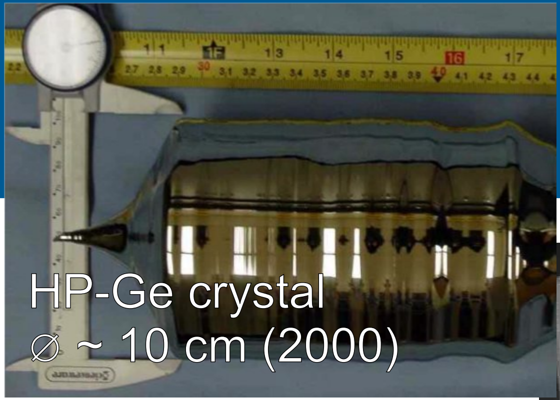
ω_j = relatives weigths

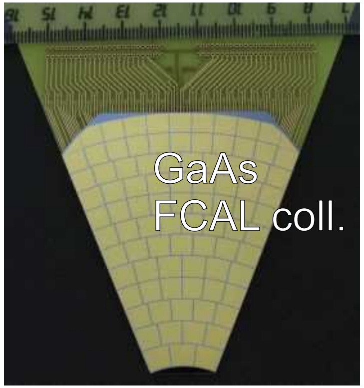
Some candidates

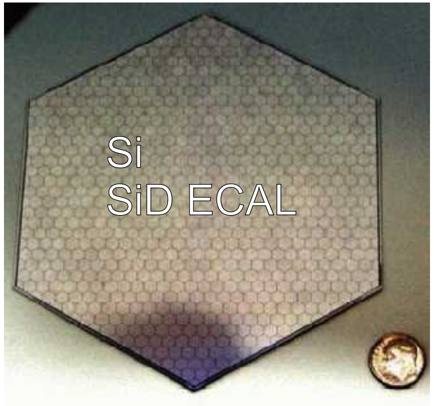
Material	Z	Bandgap [eV]	Mobility [cm^2/Vs] electrons	Mobility [cm^2/Vs] holes	Density g/cm^3
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe_2	74-34	1.4	100	80	
BiI_3	83-53	1.7	680	20	
Bi_2S_3	83-16	1.3	1100	200	6.7
Cs_3Sb	55-51	1.6	500	10	
PbI_2	82-53	2.6	8	2	6.2
HgI_2	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

For layers

– Small dead Space







Pros & Cons of Semi-Cond in calorimeters

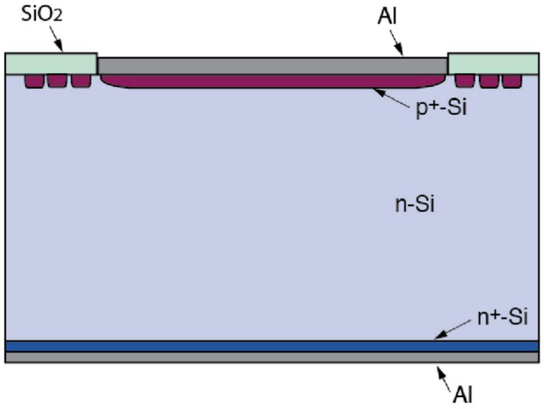
- High Signal (~×10 wrt gaseous det for same deposit)
- High Charge collection (HV)
  - Insensitive to magnetic field
- Intrinsic Stability
- Fast O(10's ps)
- Granularity O(1–100 μm)
  - High Precision
- Low resistivity fine for Calo's (less expensive)
- Large support from industry for Silicon
  - Processes, R&D

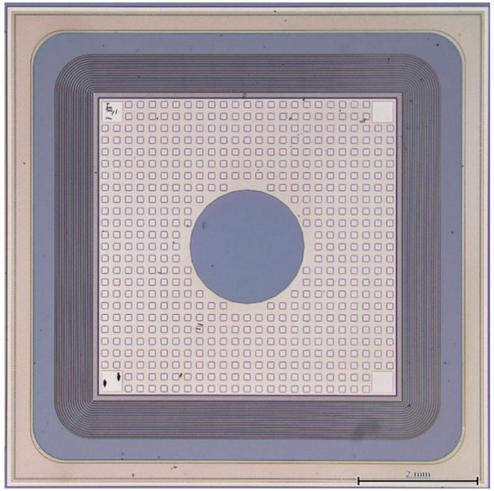
- Cost → **~ limited to ECAL's**
  - with high variations
- Fragility
- Radiation damages
  - In some cases
- No intrinsic amplification
  - Low noise readout electronics needed

Sensor type

Pad Detector

The most simple detector is a large surface diode with guard ring(s).





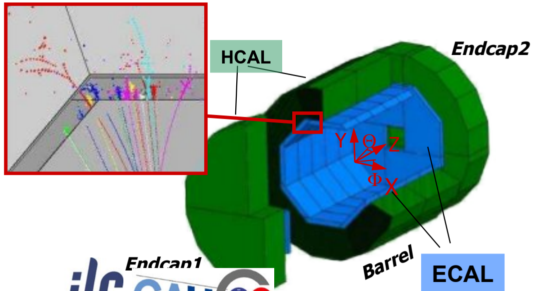
Manfred Krammer RAPID2021 Silicon Detectors 29

As of today, *almost* the only calorimetric sensor

it will change…

See "Basics Principles of the Silicon Detector"
Manfred Krammer

Highly-Granular Compact Si-ECAL for experiments



Particle Flow '5D' calorimetry

Standard requirements:

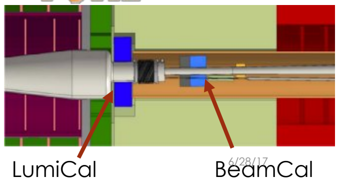
- Hermeticity, Resolution, Uniformity & Stability (*E, (θ,φ), t*)

Particle Flow requirements:

- Very High Granularity
- Compactness (density)
- Lower E resolution ?

'Forward' calorimetry

- High precision
- High data fluxes
- Radiation Hardness



Tungsten as absorber material

X_0 = 3.5 mm, R_M = 9 mm, λ_I = 96 mm

⊕ Narrow showers → good separation in jets

⊕ Ensures compact design → cost red. (ext. layers)

⊕ Good rigidity ⊖ difficult machining, cost

Second choice : Pb+Cu, W-Cu

Silicon (highly resistive) as active material

⊕ Robust technology (processing, rad. resist.)

⚠ fragile handling

⊕ Support compact design: Sensor+RO≤2mm with minimal dead spaces

⊕ Allows for ~any pixelisation, very precise

⊕ Fast & Excellent signal/noise ratio: ≥20

⊕ Intrinsic stability (vs environment, aging)

⊖ Albeit expensive ! (~ 1-2$/cm² for simple diodes)

Silicon based ECAL’s : Where do we stand ?

CALICE (2005–...)

SSC † (1989)

First concepts :
SICAPO LEP-Lumi (1986)
SLD–Lumi (1991)

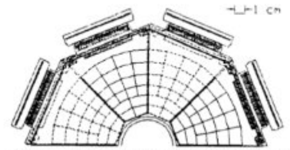
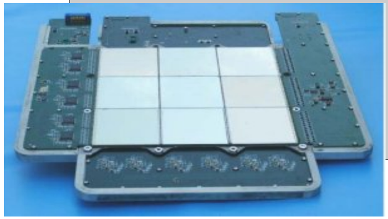


Figure 2. Front face of one LMSAT module as seen from the IP. Detectors shown with dashed lines have their ground planes facing away from the IP.

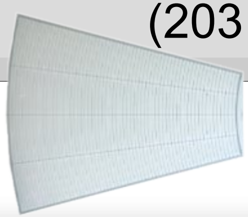
1st Medium
[Fermi (2008)]
PAMELA (2006)



First Large Scale:
HGCAL
(2026+)

Full Large Scale :
Higgs Factories
(2031+)

Small scale implementations :
FOCAL (2026+), LUXE
FCAL (2031+)
/ FCC-ee Lumi (2035+)



Year:	1986	1991	1997	2008	2007+2008	2026+	2026+	2031++	2031++
Experiment:	SICAPO PICASSO LEP-Lumi	SLD-Lumi	[NINA]	PAMELA sat	[AGILE+ FERMI]	FOCAL	HGCAL	FCAL	HF Dets
Number of ch.:		2×7k		12.7k		39M ??	6.3M	n×(30+40)	70–100M
Size of pixels:		▱ ~1 cm	▯ 8×0.24 cm²	□ 1 cm	µSTrips + W	□ 30 µm	⬡ 1 cm	⌒0.18×[ ]cm²	0.5 cm □
Surface :		2×0.7 m²		2,5 m²		1 m²	630 m²	2600 m²	2600 m²

Silicon based ECAL's : Where do we stand ?

CALICE (2005–...)

SSC † (1989)

First concepts :
SICAPO LEP-Lumi (1986)
SLD–Lumi (1991)

1st Medium
[Fermi (2008)]
PAMELA (2006)

First Large Scale:
HGCAL
(2026+)

Full Large Scale :
Higgs Factories
(2031+)

Small scale implementations :
FOCAL (2026+), FCAL / FCC-ee Lumi
LUXE (2031+) (2035+)

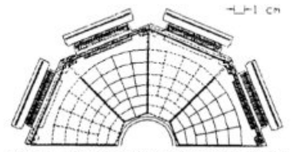
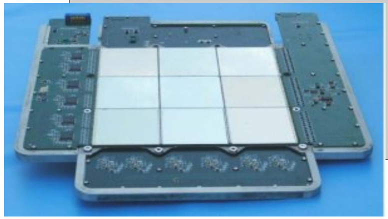
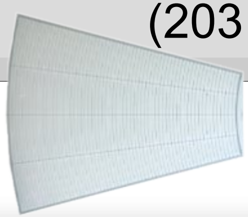


Figure 2. Front face of one LMSAT module as seen from the IP. Detectors shown with dashed lines have their ground planes facing away from the IP.





Year:	1986	1991	1997	2008	2007+2008	2026+	2026+	2031++	2031++
Experiment:	SIC[illegible] PIC[illegible] LEP[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]CAL	HF Dets
Number of ch.:		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]×(30+40)	70–100M
Size of pixels:		~1 cm	8×0.24 cm²	□ 1 cm	µSTrips + W	□ 30 µm	⬡ 1 cm	0.18×[ ]cm²	0.5 cm □
Surface :		2×0.7 m²		2,5 m²		1 m²	630 m²	2600 m²	2600 m²

… in a transition from Small to Large detectors
➡ R&D on costs, integration and production
➡ R&D on improved performances

CALICE / ILD and Higgs Factories

Requirements from ILC Physics & Particle Flow

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) < 3.8%

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

Large Tracker

– Precision and low X_0 budget

– Pattern recognition

High precision on Si trackers

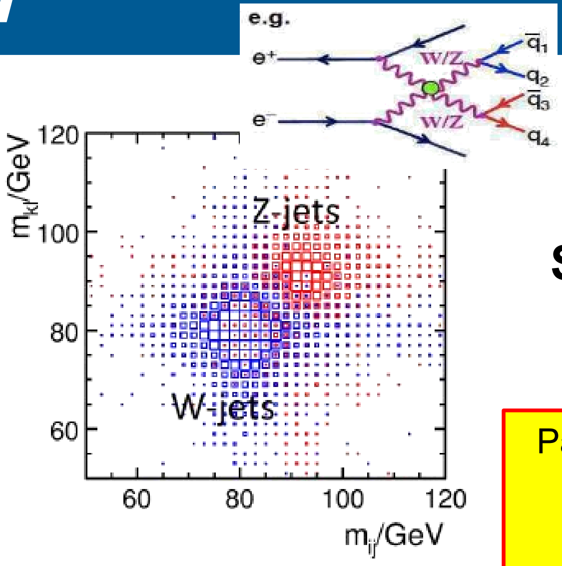
– Tagging of beauty and charm

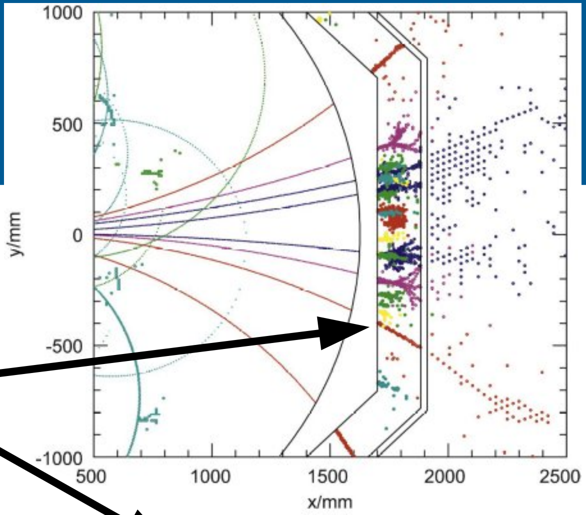
Large acceptance

Fwd Calorimetry:

– lumi, veto, beam monitoring

HG Imaging Calorimetry





SiW-ECAL

Particle Flow Algorithms :

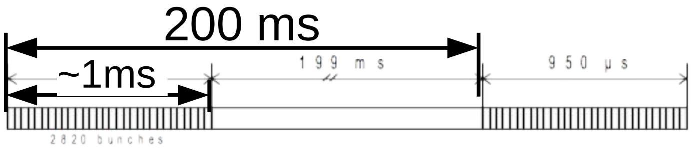
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 CALO's
- TPC $\delta p/p \sim 5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 10$ µm **+ timing ?**

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

Photons in jets (vs punch-true, h^0)

Tau physics (γ vs π_0)

2/3 of Hadr IA in **ECAL**



⇒ **FCAL**

⇒ **CALICE / ILD + SiD**

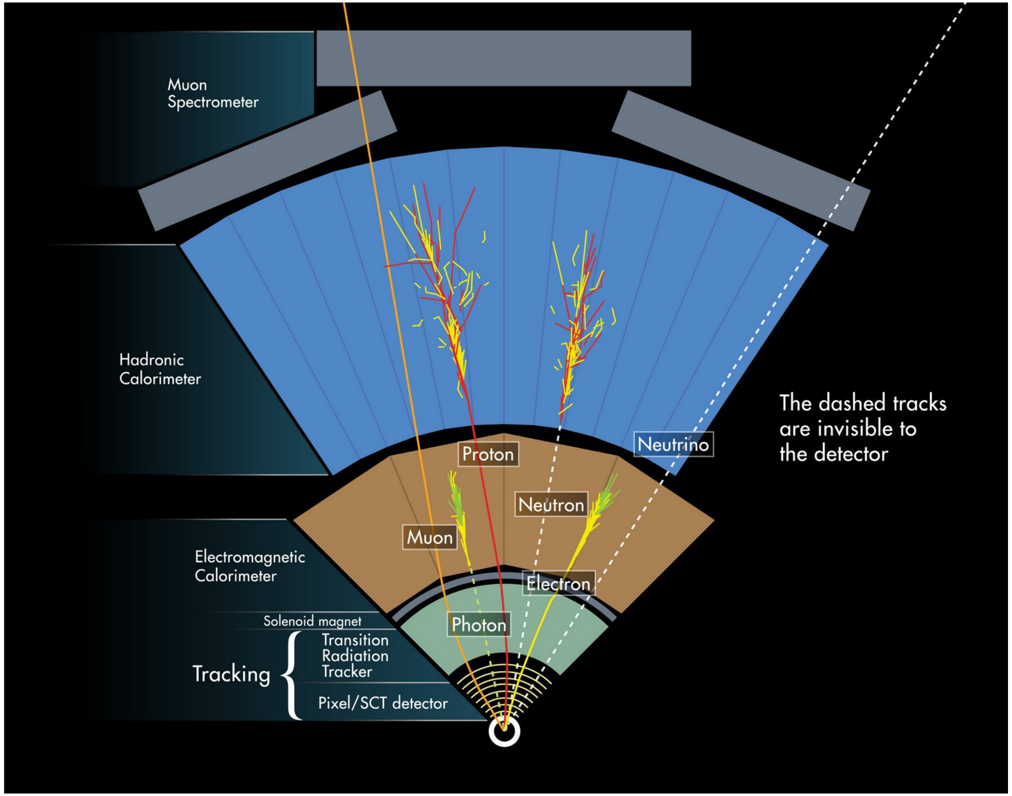
- Time between collisions : 350–700 ns
- Trains of 1300–2700 Bunches
- Low detector occupancy
- Low bgd : $e^+e^- \to qq \sim 0.1$ / BC
  $\to \gamma\gamma \to X \sim 200$ / BX

- High B field
- Trigger-less
- Power Pulsing (≤1%)
- Differed readout

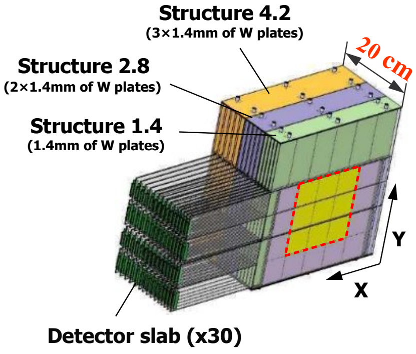
ECAL *raison d'être*

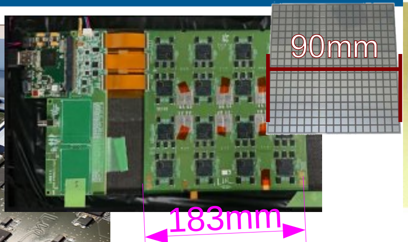
Probability of such an event ?

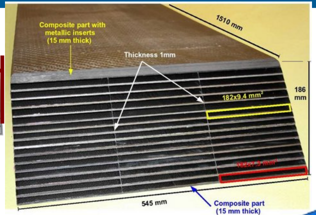
- 2 hadronics showers starting after $1\lambda_{int}$
- $= (1/e)^2 \sim 1/10$



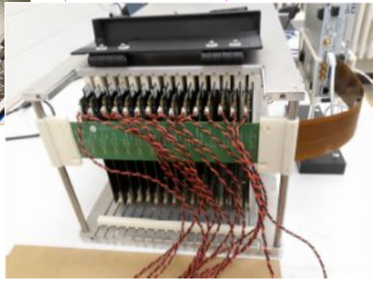
CALICE prototypes for ILC

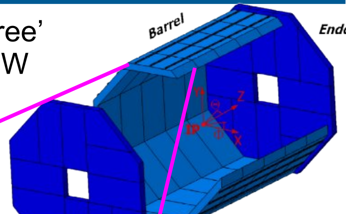


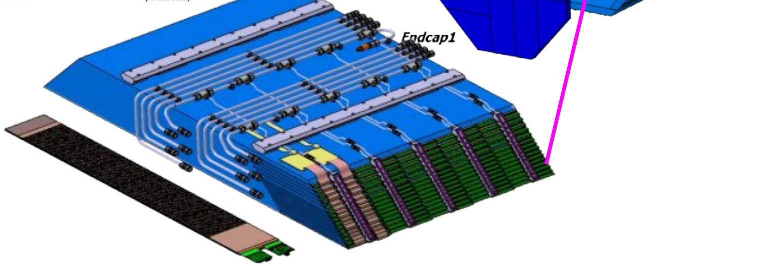




'dead space free'
Carbon Fibre-W
Structure







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

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 feasibility

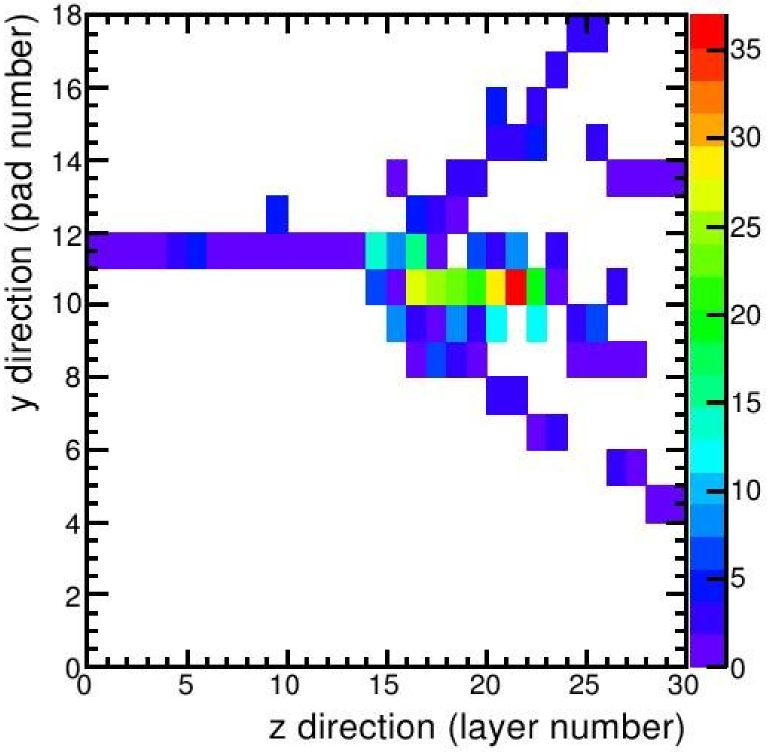
Pilote (2025+) ➡ Full Det (2033)

- 1M ➡ 70M channels
- on 750µm 12×12 cm² 8'' Wafers ?
- Pre-industrial building
- Full integration (⊃ cooling)
- Final ASIC (Ωmega SK3 ?)

30 years

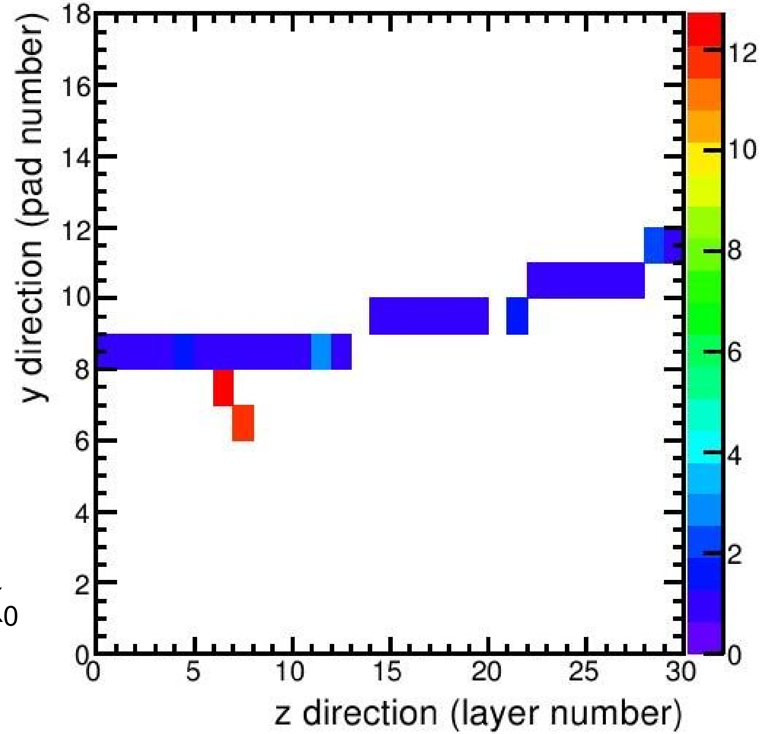
CALICE SiW-ECAL Physics Prototype

Complex and Impressive (Start of) Hadronic Showers in the SiW Ecal



Inelastic Reaction in SiW Ecal

Cell size :
1 cm
× 30 layers
~ 1 λ_I / 24 X_0



Nucleon Ejection in SiW Ecal

SiW-ECAL Building blocks: SLAB's & Detectors Units

R&D for mass production and Quality Insurance

- Modularity → Building blocks: Units & SLABs
- Choice of square wafers ≡ Quantum Unit of length
  - (≠ from hex: SiD, CMS HGCAL)
- Glued wafers
- **Optimal size of base elements for large production ?**

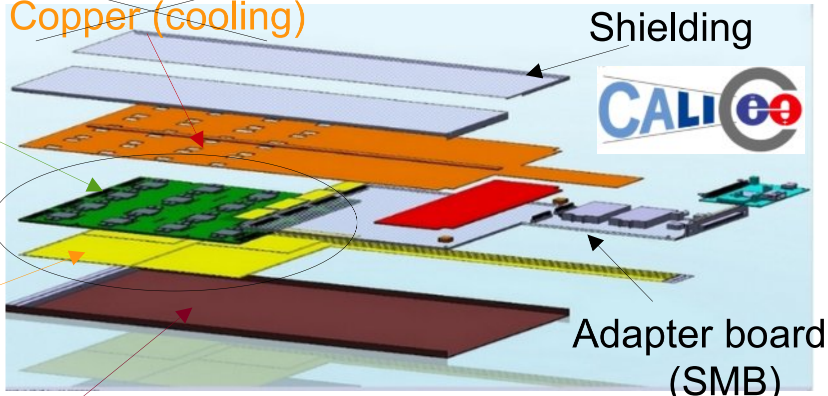
Large quantities

- Modules: 40 (barrel) + 24 (endcaps, 3 types)
- Detector Elements = ~75,000
  - Wafers ~ 300,000 (**2500 m²**)
  - VFE chips ~ 1,200,000
  - Channels: ~ 77 Mch
- Slabs = ~ 9600
  - ≠ lengths and ending

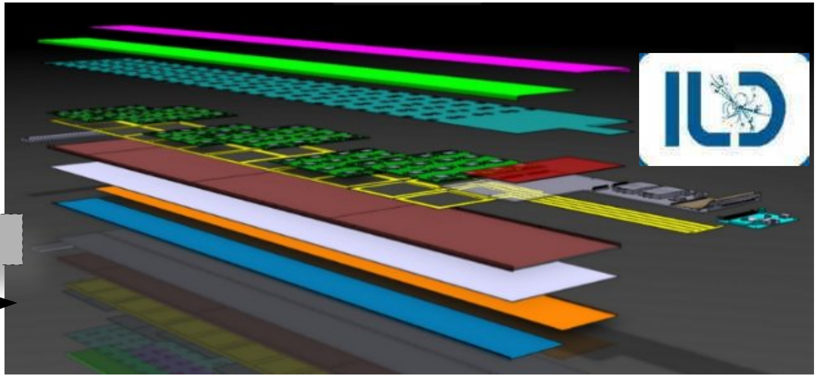
Tests of producibility

Implication of industry is mandatory

Tests of feasability

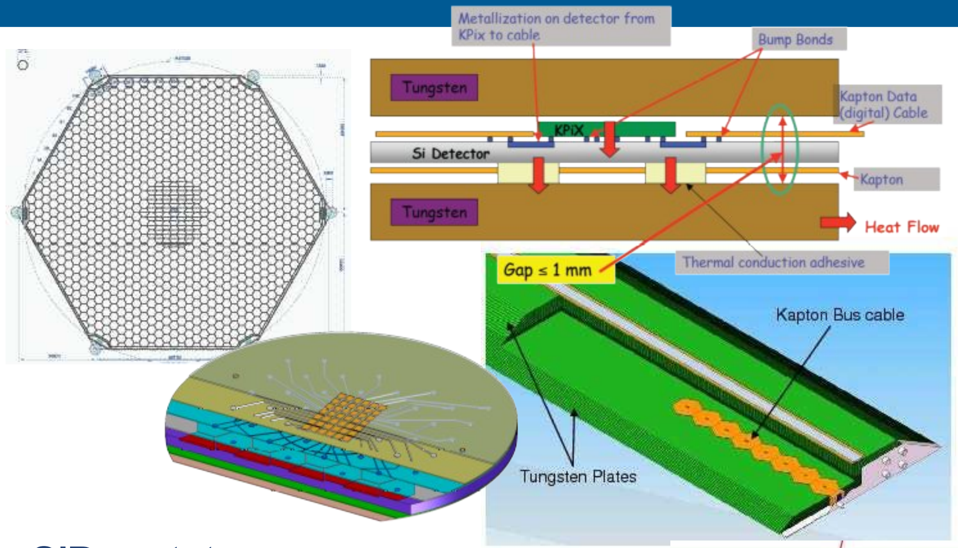


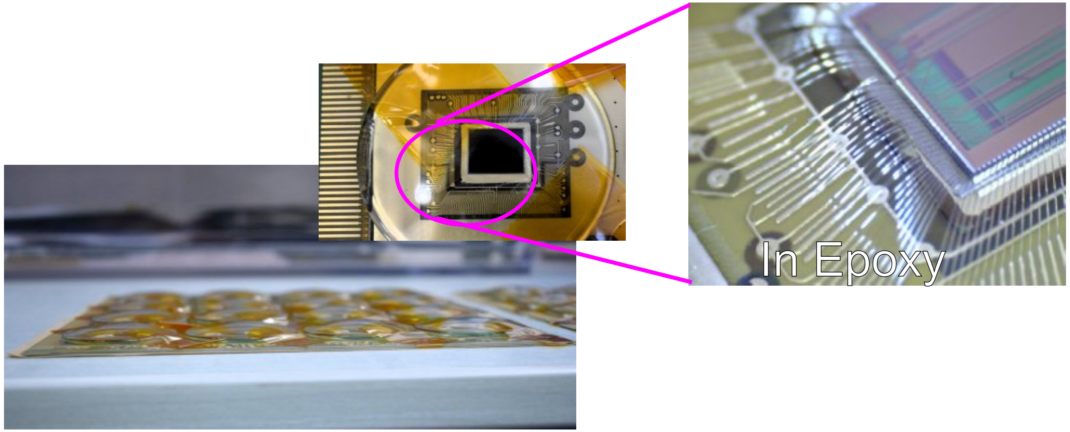
U layout of a **short slab**



U layout of a **long slab**

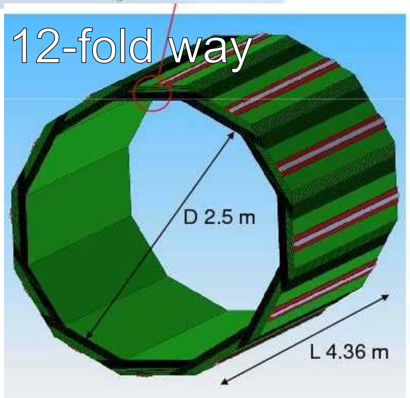
Very Compact Designs: W absorber + …





SiD prototype

- Hexagonal geometry (Cost)
- Chips on Wafers : KPix, 1024 ch
- 30 layers prototype BT (2020)
- R&D:
  - X-talk, System



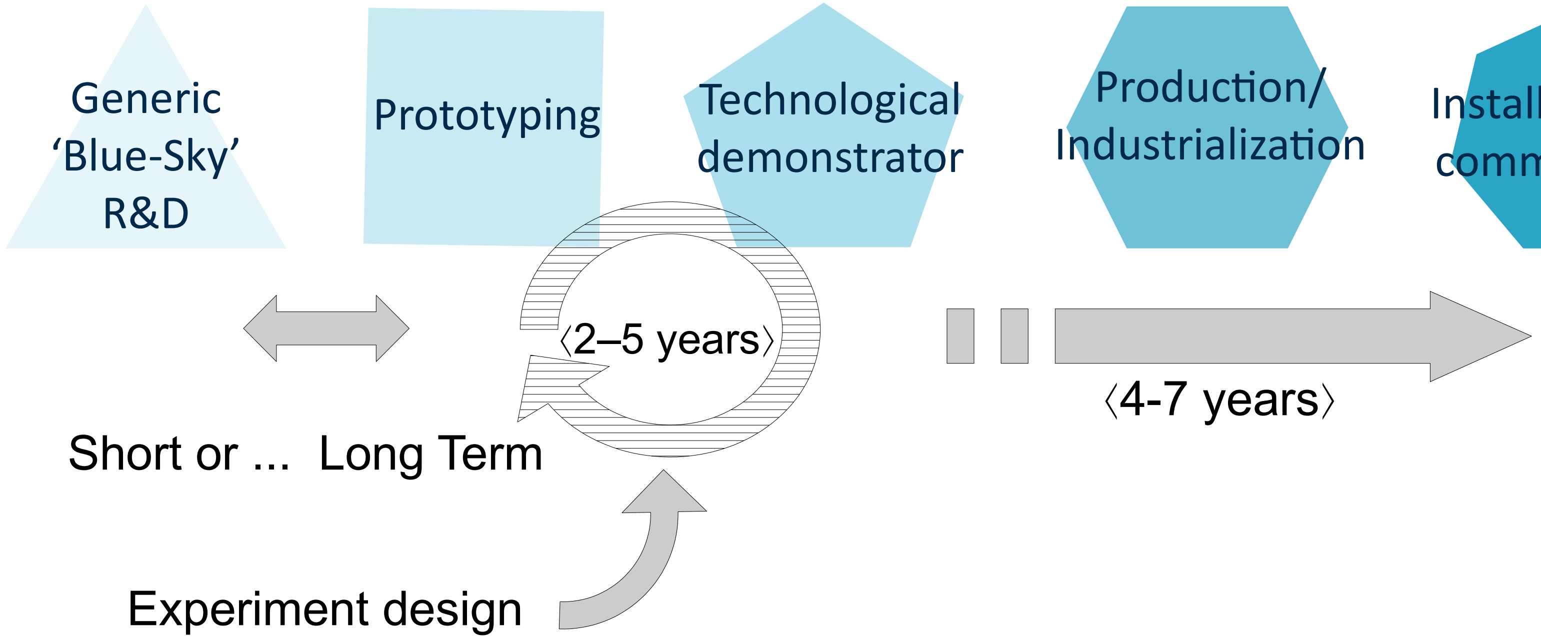
CALICE SiW-ECAL Chip-on-Board (COB)

- PCBs with embedded ASIC's **≤ 1.2mm thickness**

  (vs 2.9 mm for Baseline BGA + Components)
- 2 layers in BT (2019)
- R&D:
  - Power distribution (Pulsing + Decoupling)
  - Connections, System

Development cycle(s)

Adapted from IN2P3 2021 prospectives
Giulia Hull (CNRS/IJCLab)
Mariangela Settimo (CNRS/SUBATECH)




Tau « jet » dans ILD
Physics Optimisation of performance:
- Z-jets, Tau's
- ILC, CEPC
90 GeV π shower in SDHCAL in beam test at CERN
PFA tools Pandora, ARBOR, GARLIC
Simulation & Reconstruction of a hadronic shower in ILD
ECAL Model in ILD
Systems
- Mechanics
- Integration
- Cost
ILD
Mechanics R&D
Large Carbon Fiber & Tungsten Structure (Instrumented)
Structure
Tungstène-Fibre de Carbone
45 alvéoles, 700kg + SLABs
CALICE
Calorimeter for ILC
Simulation:
Mokka / DD4HEP
W struct
Heat shield: 100+400 μm (copper)
PCB: 1200 μm (with FE embedded)
glue: 75 μm
wafer: 325 μm
Kapton® film: 100 μm
W slab
6.8 mm
wafers studies
R&D Instrum.:
Design, Test & industrialisation Silicon Wafers
Embedded R/O ASICs
Building & Test of prototypes (processes)
R&D DAQ
generic
HW, FW et SW
PYRAME
Giga-DCC
Event builder
Signal uncap
Shd Mems
Files
subsample sockets
Sockets
Distribution memory bus
Data uncap
Data Transfer
Driver

CMS–HGCAL

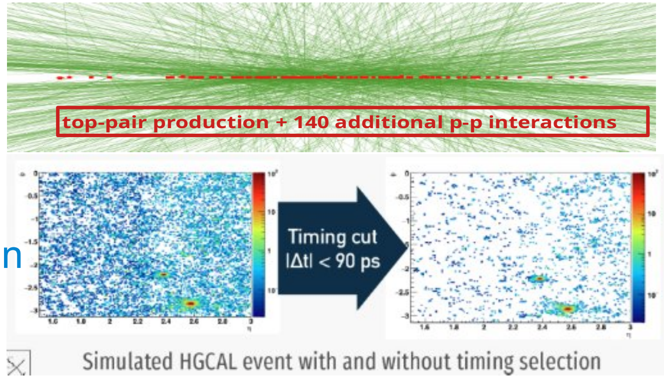
CMS-HGCAL: Going 5D for HL-LHC

See Lessons learned
David Barney

Goal: replace the CMS Calo end-caps for HL-LHC ($\mathscr{L}$×5)

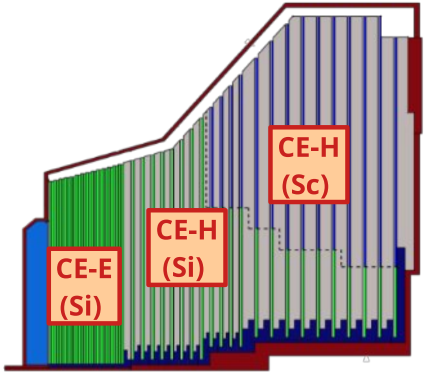
- Reconstruct crowded events with high granularity 3D+E+T
  - 28 X_0 ECAL + 9 λ HCAL
- Adding timing for vertex separation
  - δz = 50mm ⇒ σ(t) = 30 ps

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



Simulated HGCAL event with and without timing selection

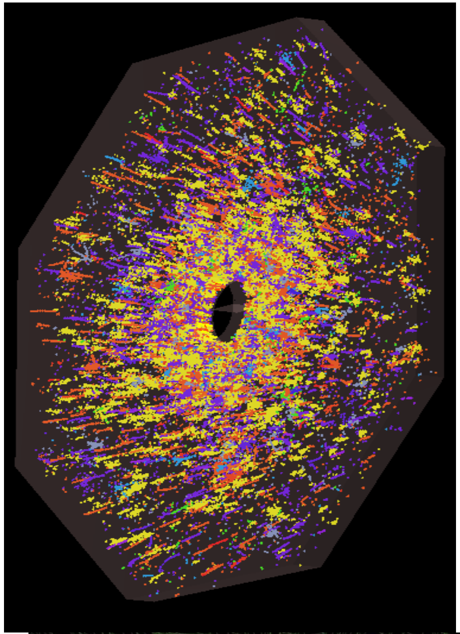
Endcap coverage: 1.5 < |η| < 3.0		
Total	Silicon sensors	Scintillator
Area	620 m²	410 m²
Number of modules	29 900	3800
Cell size	0.5 — 1.2 cm²	5 — 30 cm²
N of channels	6 260 000	240 000
Power	Total at end of HL-LHC: 2x125 kW @ -30ºC	



Constrains :

- Physical:
  - Very high doses (≤ 10^{16} n_{eq}/cm²)
    - Run at -35°C (~ semi-Lazarus)
    - Limited effective thicknesses
  - Very high occupation & very high rates
    - small cells (cm²) ⇒ high number of channels
      ⇒ power consumption ⇒ active cooling
      ⇒ PCB/ Si Stress
    - High throughput ⇒ Fast trigger system
      ⇒ Less demanding S/N ratio
- Mechanical:
  - Circular geometry, very little space
- Timeline:
  - Build and install for LS3 (≤2026)

« 5D » calorimetry



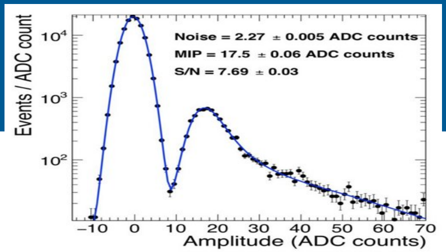
SW sepration of components

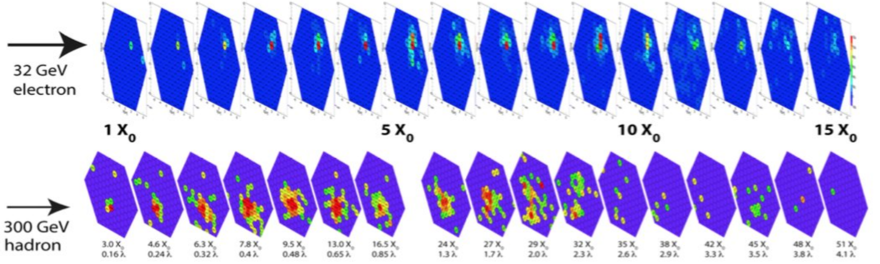
Real reconstruction « 5D »

– 4D x,y,z,E + Time

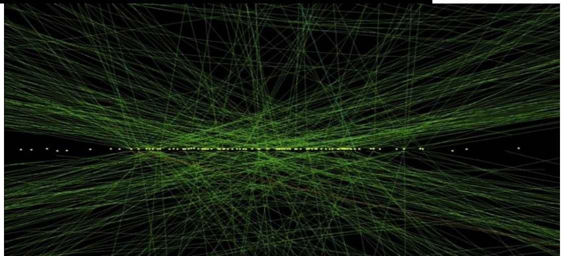
Time measurement Time-over-Threshold (TOT)

– but : 100ps / plan, ~30 ps / gerbe

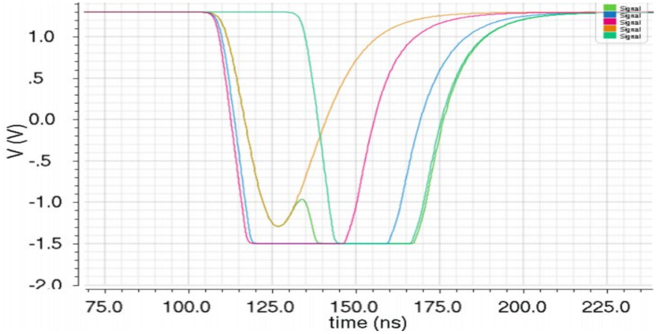


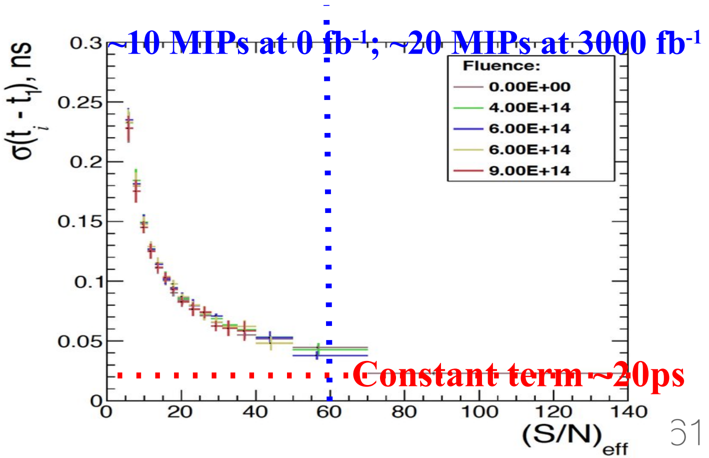


From HGCAL 2015 Beam Test



140–200 pile-up evt



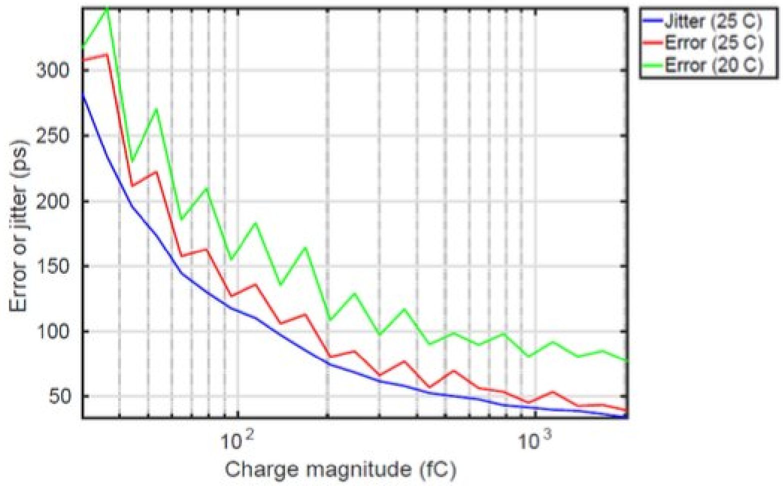


Timing

Timing of Showers ≠ Cell Timing

- For events reconstruction: **ideally cell-size/c for mips**
- Showers: needs care (slew time, propagation, contamination)

Time Jitter



C. de La Taille Front-End elecectronics CHEF 2017

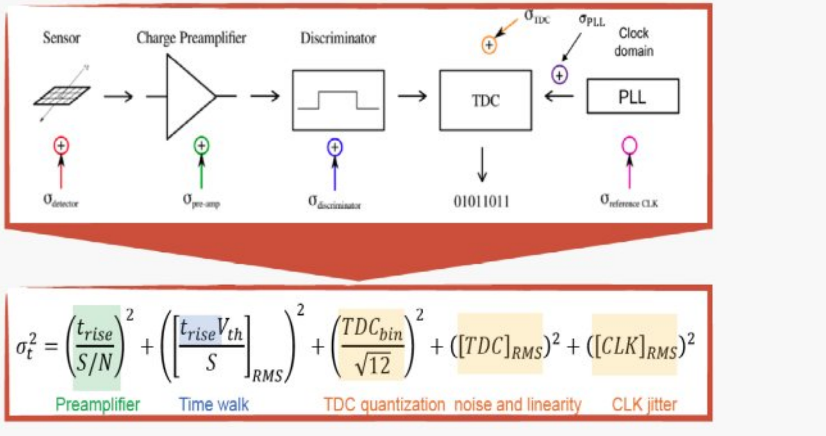
R&D

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

See Timing in Calorimeters
Nural Akchurin

⚠ Time precision costs power

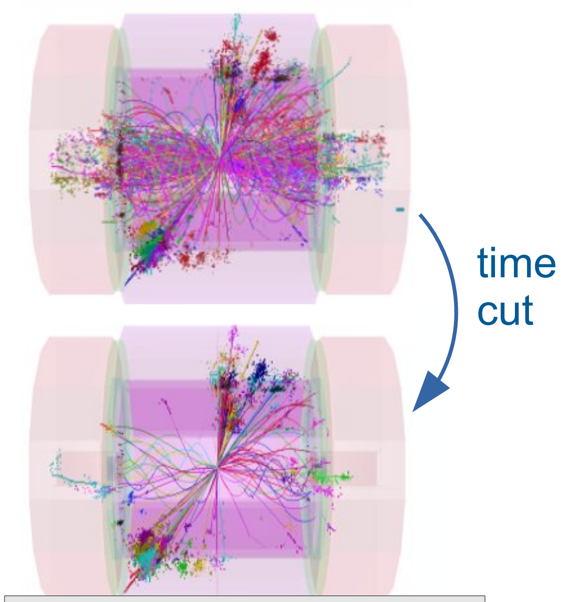
The **clock distribution system** is expected to contribute **< 15 ps jitter**



$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + ([TDC]_{RMS})^2 + ([CLK]_{RMS})^2$$

Timing in calorimeters: 0.1–1ns range

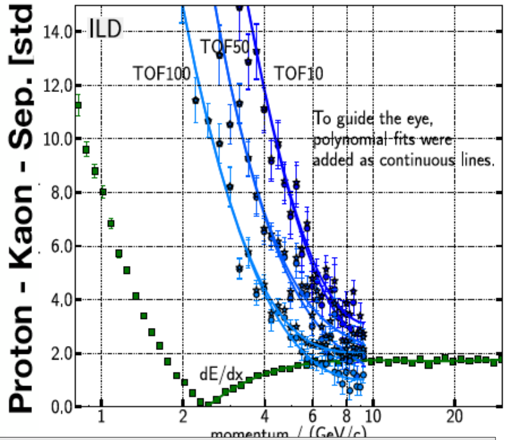
Cleaning of Events



[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

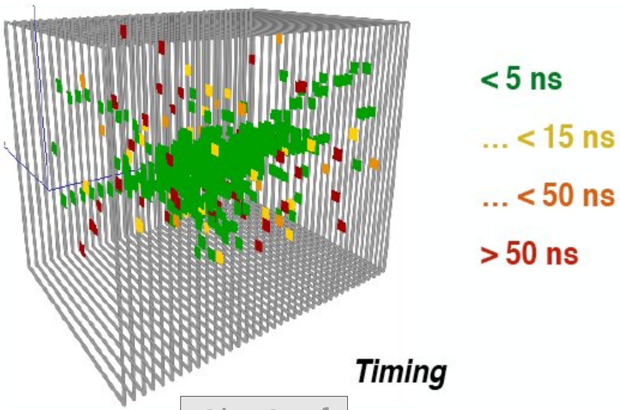
- Complementary to dE/dx
  - here with 100ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

Ease Particle Flow:

- Identify primers in showers
- Help against confusion
- Cleaning of late neutrons & back scattering.

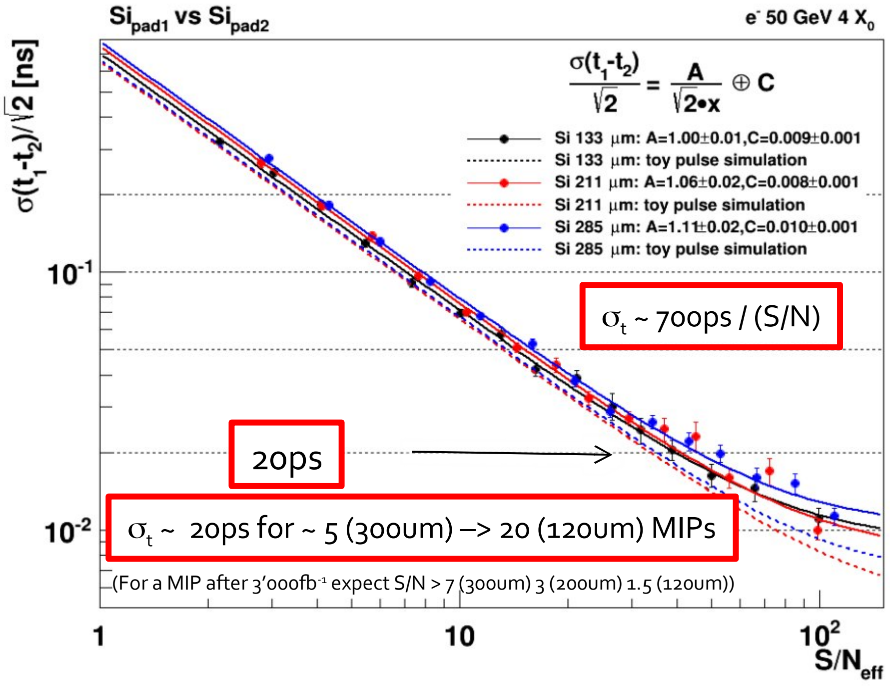


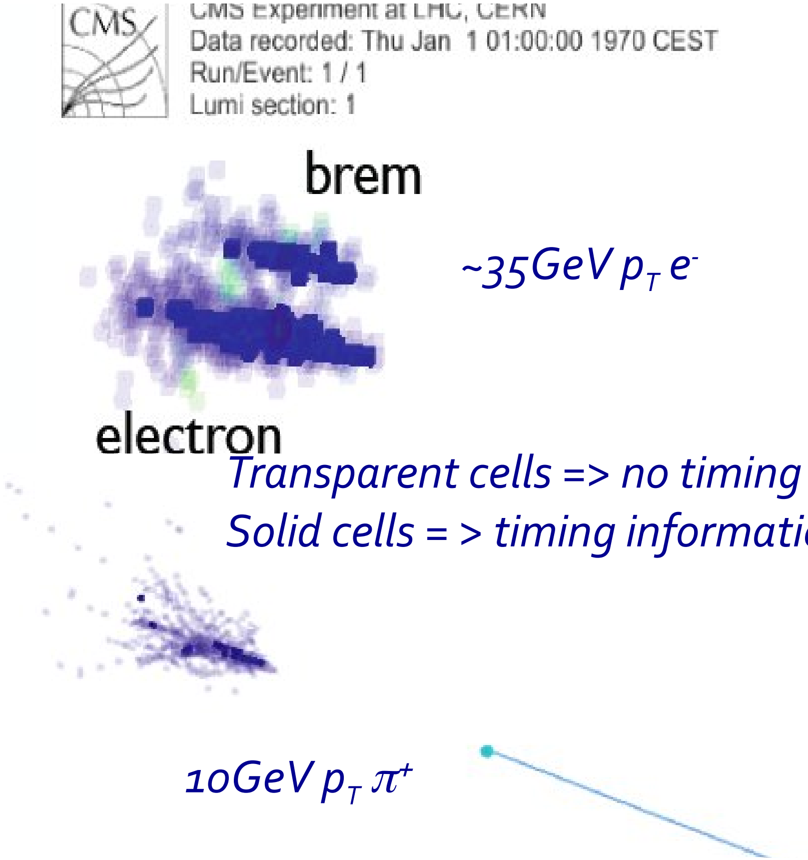
Ch. Graf

CMS HGC Timing Studies

2015 CERN timing test beam

– Plot shows time resolution vs S/N ratio





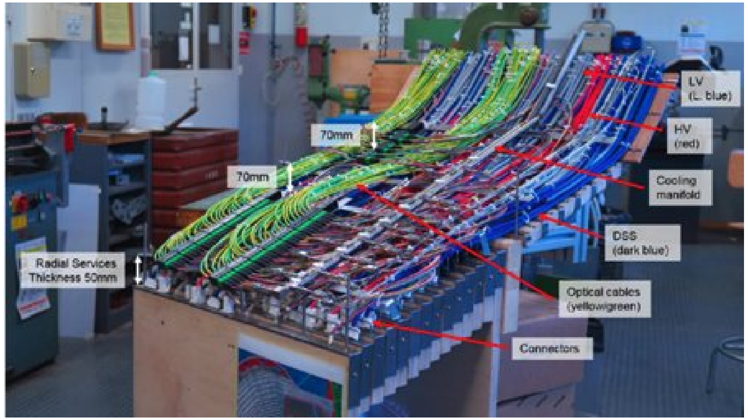
~35GeV p_T e^-

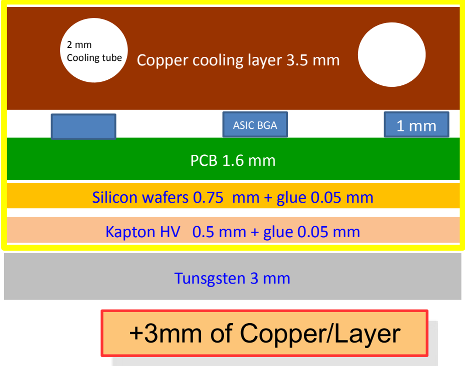
Transparent cells => no timing

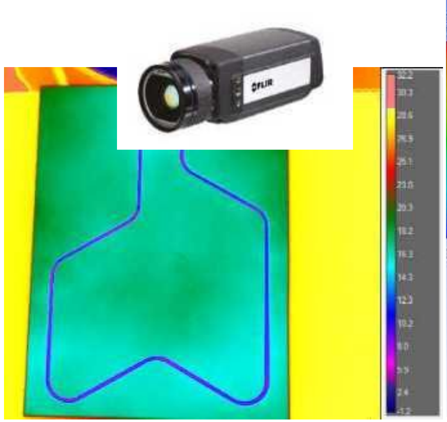
Solid cells = > timing information ~50ps

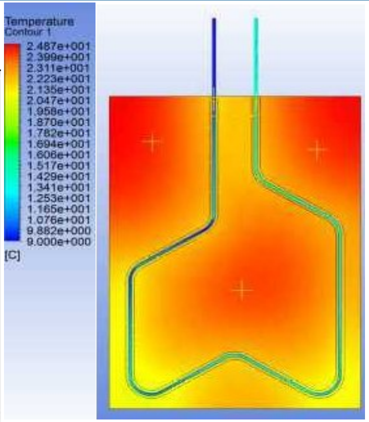
10GeV p_T π^+

Services: integration & cooling



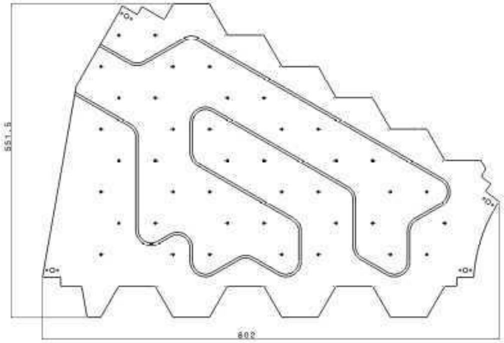


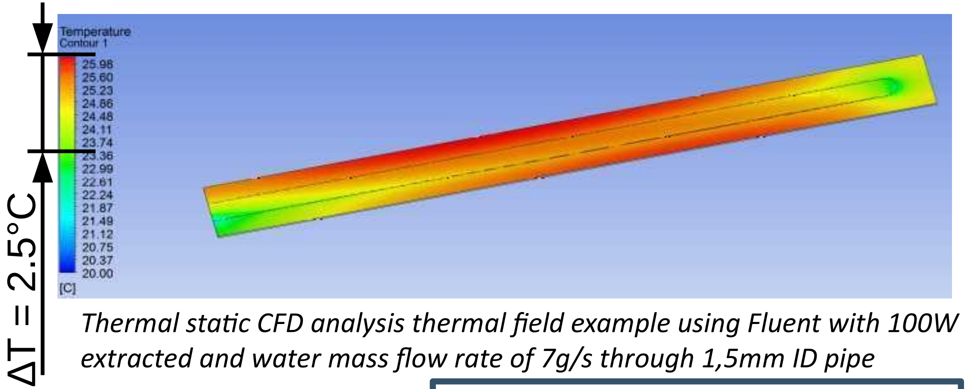




Pipe insertion on a cooling prototype

- 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

Common Challenges of Large HG calorimeters

Design

- Embedded electronics
  - Low noise (small cells, large dynamics: ½ –3000 mips)
    - ‘trigger-less & local’ noise < triggered systems
- Design combines:
  - Mechanics, Electronics, Cooling
    - **To be thought-of from the start**
- Lack of experienced persons in highly-integrated systems (≡ system engineers)
  - 1 experiment every 20~30 years ?
  - ⇒ Huge steps in industry (smartphone)
  - Make «Building Blocs» for all experiments ?
    - As for SW tools: Higgs Factories → EIC, LHCb, FCC–hh
    - Optimisation procedures ?

Building:

- Scalable design: 30k (HGCAL) ~ 100k (ILD) elements
  - Industrial production: quality chain, 6σ
    - Homogenisation of elements ⇒ reduced cst term
    - Database → Simulation of defects
  - (Semi-)automated assembly

Running: Calibration & Monitoring

- 6M–70M chan
  - × 10+ params for calibration per channel
    - ⇒ handling of 70–700M params for reconstruction
  - Monitoring → corrections, uniform samples (‘runs’)
    - 1% failure / ch / year = ~80 per hour for 70M channels
  - Redundancy

Forward Calorimetry

FCAL Collaboration: LumiCal & BeamCAL with extreme precision for Lin. Colliders

LumiCal :

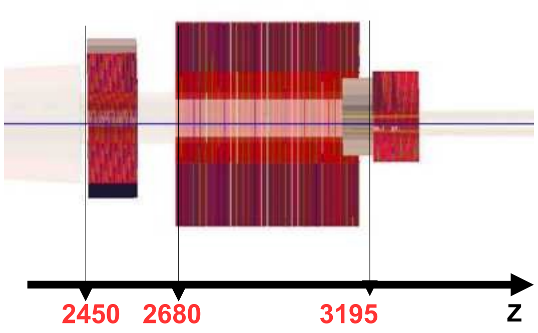
- Symmetrically on both sides at ~2.5m from IP.
- Integrated luminosity measurements (Bhabha events) $\mathcal{O}(10^{-4})$
  - $\Delta\mathscr{L} / \mathscr{L} \simeq 2\Delta\theta/\theta_{min} \Rightarrow \sigma(x,y) \sim 250$ µm on Shower positions
  - Accept. err $\mathcal{O}(10^{-5}) \Rightarrow$ 10s of µm, hermeticity (nocracks!)
- Extend calorimetric coverage to small polar angles.

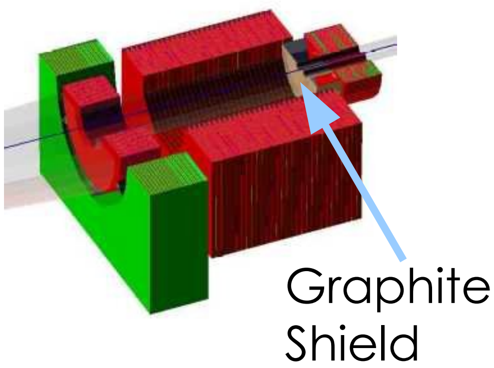
LHCal :

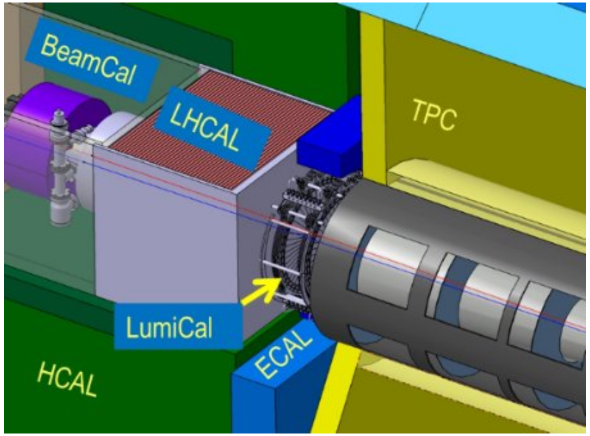
- Extend the hadronic calorimeter coverage
- 29 layers of 16mm thickness. Absorber : tungsten or iron

BeamCal :

- Measure instant Luminosity. Feedback for beam-tuning
  - + tagging of high energy electrons to suppress backgrounds to potential BSM process
- Sampling calorimeter based on tungsten plates
  - 30 layers for ILC, 40 layers for CLIC
- Due to large dose, rad hard sensors (GaAs, Diamond, Sapphire)







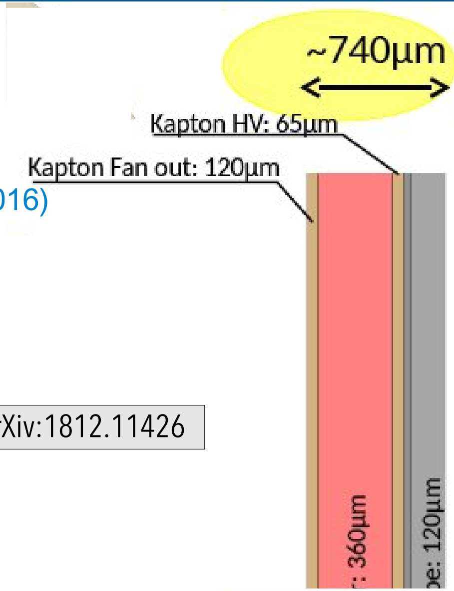
× 2

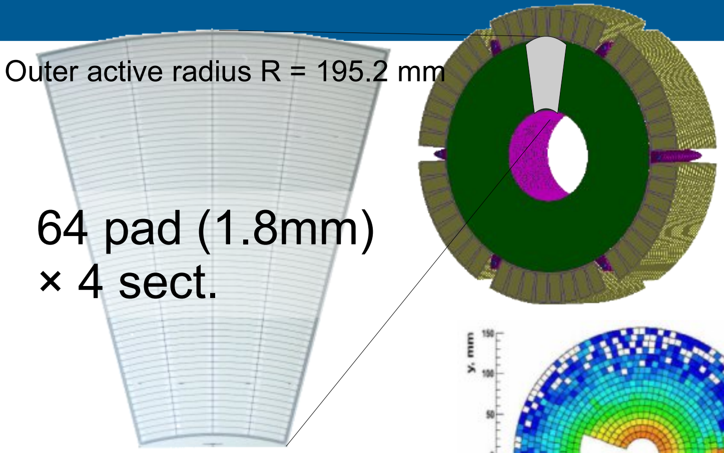
FCAL collaboration: LumiCal

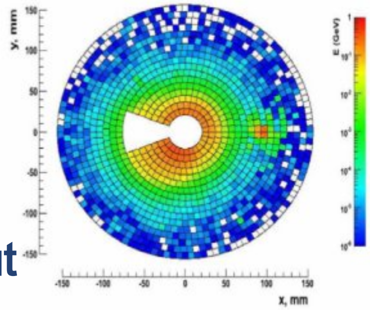
SiW-ECAL

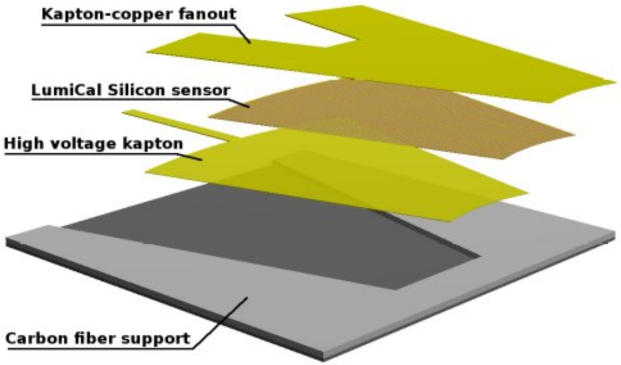
- 30 layers of 3.5 mm thick tungsten plates ($1X_0$)
- Si (p+ implants in n-type bulk) :320 µm and 750 µm (2016)
  - DC coupling to readout
  - through Kapton foils glued on wafer
- R_M=12mm expected;
  - $R_M^{eff} = 8.1 \pm 0.1_{stat} \pm 0.3_{syst}$ mm meas on 8 layers (2016) ~16 mm extrapolated to 30 layers
- σ(x,y) ~ 440 µm @ 5 GeV ⇒ OK at 250 GeV ?
- **Positioning $\mathcal{O}$(50µm) ?**

arXiv:1812.11426





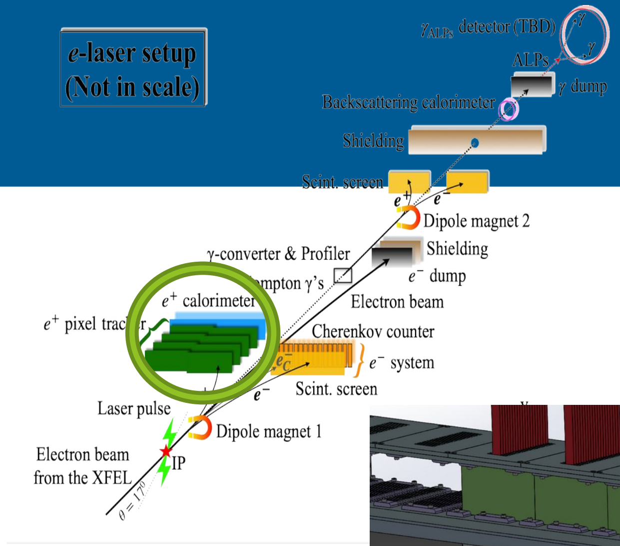


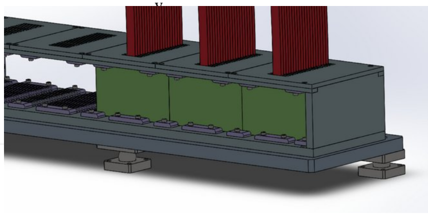


External Readout

- S/N ~ 19; Xtalk ≤1%
- Occupancy ~ 100%
- Limited space → Consumption
  - FLAME ADC
- PP possible @ Lin Coll.

Very Compact "Small Scale" Prototypes





FCC-ee LumiCal

- ~ Same requirement as FCAL
  - higher precision in positioning $\mathcal{O}$(1 µm)
  - Rad-Hardness
- Higher rates; continuous mode
  - 100kHz physics rates
  - readout @ 50 MHz BC rate ?
- Cooling
- Even Crowdier environment

LUXE @ XFEL

- Aim: Extreme QED Probe
  → Schwinger limit
  BSM searches
- Interaction between :
  - Electron beam (16.5 GeV, 10 Hz)
  - Powerful laser (40TW/1.2J → 350TW/10J, 1 Hz)
- SiW-ECAL 55×5 cm² × 20 layers of 1 X_0
  5×5 mm² Pixels
  - Very reduced R_M
  - Spin-off / Extension of FCAL
    - same Bunch structure
  - Use of novel connection technique: µ-Pearls–Glue + Masking Grid
    Connects Sensors ↔ Pad with uniform deposits

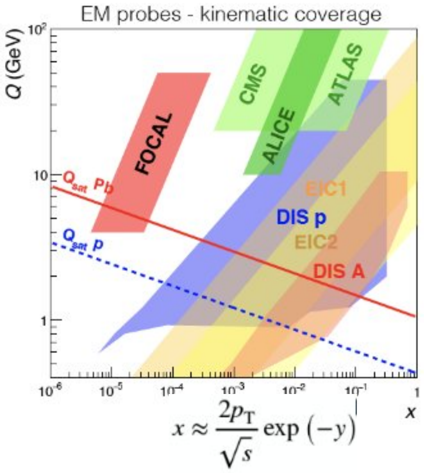
Ultimate(?) Granular Calorimetry : FoCal-E @ ALICE

FOCAL-E @ ALICE

Goal: measure of the (n)PDFs at low x_{Bj}

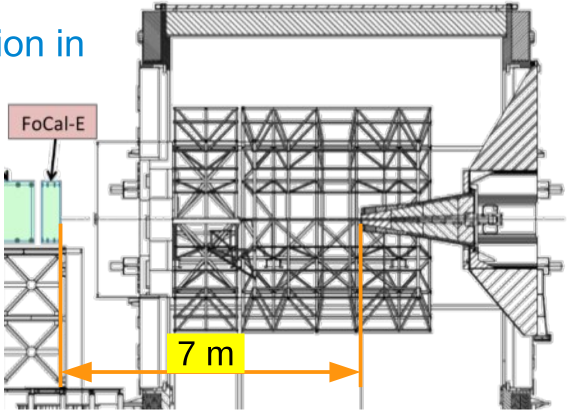
- FoCal-E : Tagging of very forward γ and π^0's
  - z = 7m; $3.2 < \eta < 5.8$
  - π^0 decay @ $P_T = 10\ \mathrm{GeV/c}$, y=4.5, α = 0.5 ⇒ **d = 2mm**

    ⇒ Requires <u>≤ 1×1mm² granularity</u>



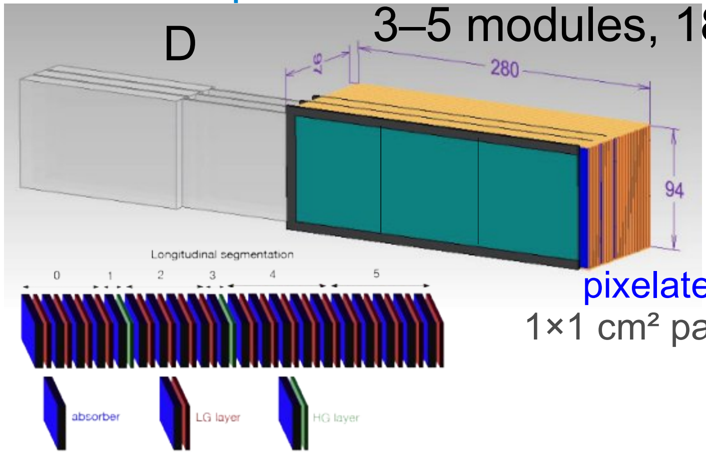
Status:

- Under disc. for possible installation in LS3 (2024–26)
- Proof a feasibility with prototypes
  - HG pads of 1×1 mm² from **DECAL (30×30 μm²)**



Design

- to be optimized...



pixelated layers

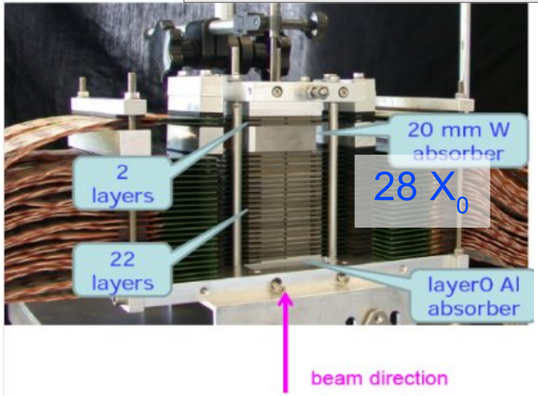
1×1 cm² pad layers

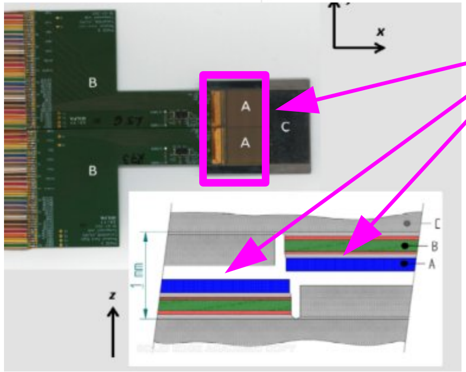
- W (3.5mm ≈ 1 X_0)
- Si-sensors:
  - Si-pads 1×1 cm² ⇒ energy measurement, timing(?)
  - 3 HG layers

FOCAL @ ALICE : MAPS aka Digital-ECAL

DECAL prototype

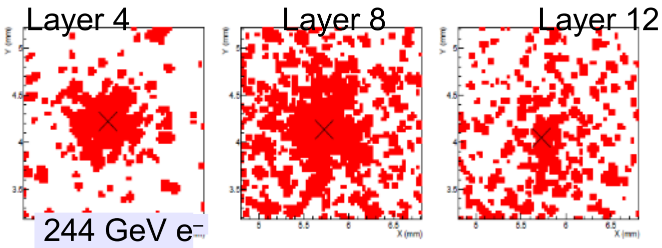
JINST 13 (2018) P01014



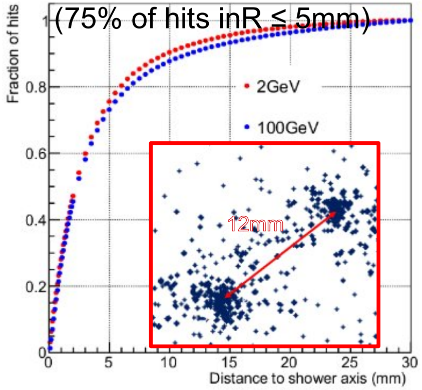


– 4 MIMOSA-26 / Layer CMOS sensors (IPHC)
  - 6×6 cm²
  - 30×30 μm² pixels
  - 39 M pixels = full readout

Ultra-compact Digital Calorimeter



R_M = 10.5mm



Follow-up

– ALPIDE in mTower (2018-08)
  - 29×27 μm² × (1024×512)
    – SW grouped in 1×1 mm² cells
  - 0-suppr.; consumption ↘ speed ↗;
  - rad-hardness

Digital calorimetry challenges

– Dead hits ?
⇒ Symmetries in r + profile

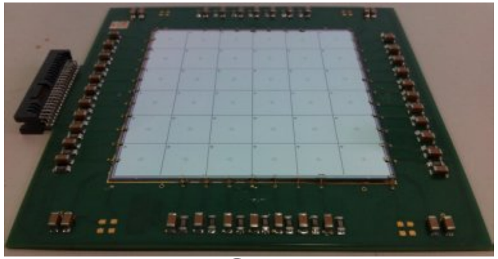
– E ∝ cluster size
→ Number of hits
  - Saturation & Overlap in core

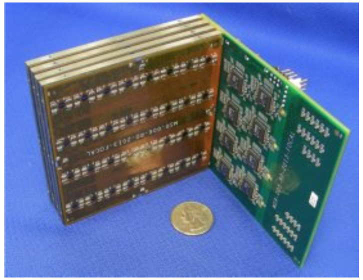
Promising!
➡ Maturity for 'fixed target' set-up
R&D needed for full det @ VHE (Power, Price)

FoCal-E: Si-Pad Prototypes

Si-Pad: NIM A764 (2014) 24

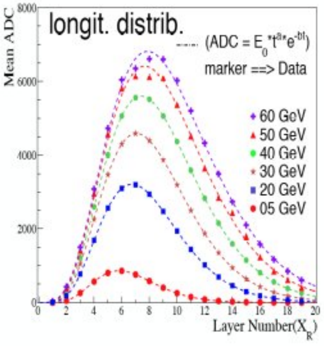
- Japan (Tsukuba) + India (VECC, BARC)
- Design close to final

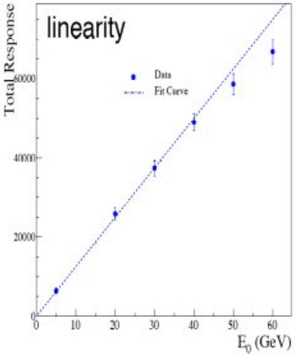


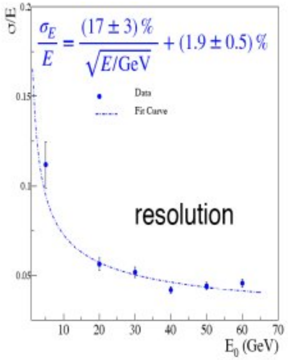


Pad Sensors
APV readout hybrids

- Agreement of simulations
  - 17±3%/√E/GeV + (1.9±0.5)%
  - Incl. electronics saturation
- **Final readout chip: Ωmega HGCROC**

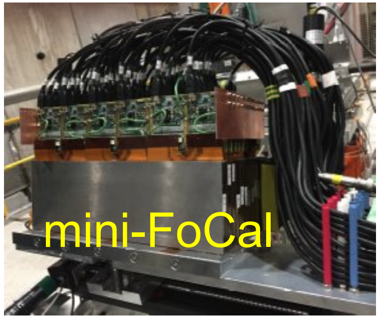


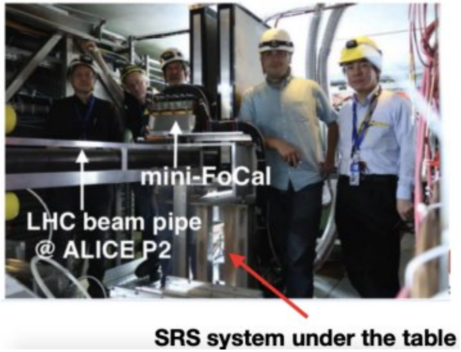


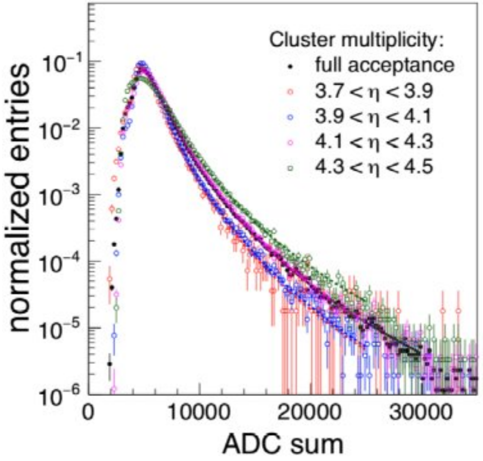


Mini-FoCal (2018-08)

- In-situ with 13 TeV collision



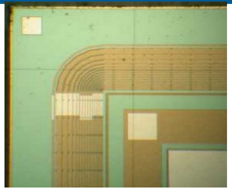


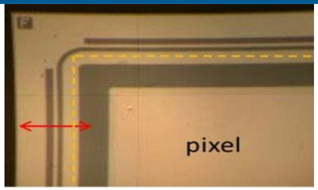


Sensors R&D

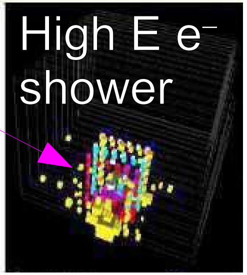
Sensor R&D

Improved uniformity





– Less dead spaces ?
  - Min inter wafer gap ~ 100µm (on same board)
    ➡ Go for larger sensors.
  - + Guard Rings ~ wafer thickness
    – Floating = extra signal by X-talk
    – Grounded = lost signal



– Larger Silicon Matrices:

2'' (51 mm)	275 µm	1969
3'' (76 mm)	375 µm	1972
4'' (100 mm)	525 µm	1976
4.9'' (125 mm)	625 µm	1981
150 mm (5.9'', ~6'')	675 µm	1983
200 mm (7.9'', ~8'')	725 µm.	1992
300 mm (11.8'', ~12'')	775 µm	2002
450 mm (17.7'') [proposed]	925 µm	future
675 mm (26.6'') [Theoretical	Unknown.	future

We are here

Source: Wikipedia & F450C

More signal ➡ Improved S/N, E resolution and Time Measurement

– Higher Intrinsic Signal ➡ thicker sensors:

e/h# ∝ th, noise ∝ C ∝ 1/th ⇒ S/N ∝ th²
EM resolution: $\sigma(E)/E \propto 1/\sqrt[5]{(1+th/100\mu m)}$

  – Need R&D on Improving the edge quality: electron beam cutting ? Edge treatment ? … ?

– Physical Gain: LGAD (Limited Gain in Avalanche Diode)

See Timing in Calorimeters
Nural Akchurin

  – Gain ➡ S/N ↗, σ(t) ↘ + instabilities ?
  – Wait experience from ATLAS HGTD, CALICE

PSD = Position Sensitive Detector

– Reduces the number of channels, power (& costs ?)

Sensor R&D

More Intelligence with CMOS

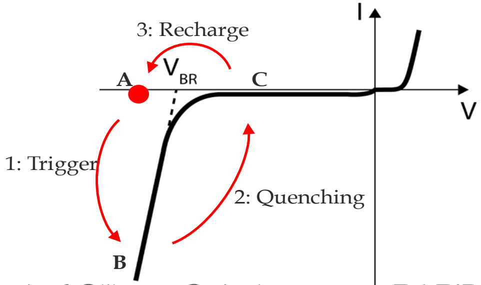
- Industry (2017): 10 nm (/10 every 15 years)
  Detectors = Ind– 20 y (130 nm ~ 65 nm)
  - ⇒ Smaller, lower-power electronics

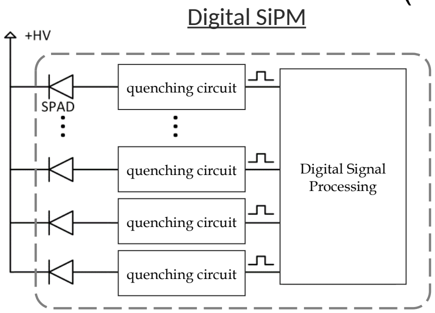
seeDevelopment of the Silicon Pixel Technology and Challenges, Walter Snoeys (CERN)

- Merging of Sensors and Amplifications and Readout ?
  - ⚠ ASIC price / mm² ⚠
  - Ex: FE-I4 ATLAS & CMS Tracker: linear FE chips integration of Analogue section in sensors → smaller in-print
  - **Calo: size is not really a problem (1000 µm² = 1‰ of a 1mm² pixel)** … or go 3D (€€€)
- Digital Pixels with counting: 3D dSiPM (with larger pads ?)
  - Consumption ∝ Occupancy (~1 mW/cm²)
  - Excellent time resolution
  - Sherbrook U. (CA) + Fraunhofer

See Timing in Calorimeters
Nural Akchurin

SPAD = Single Photon Avalanche Diode → SMAD (Single Mip) ?

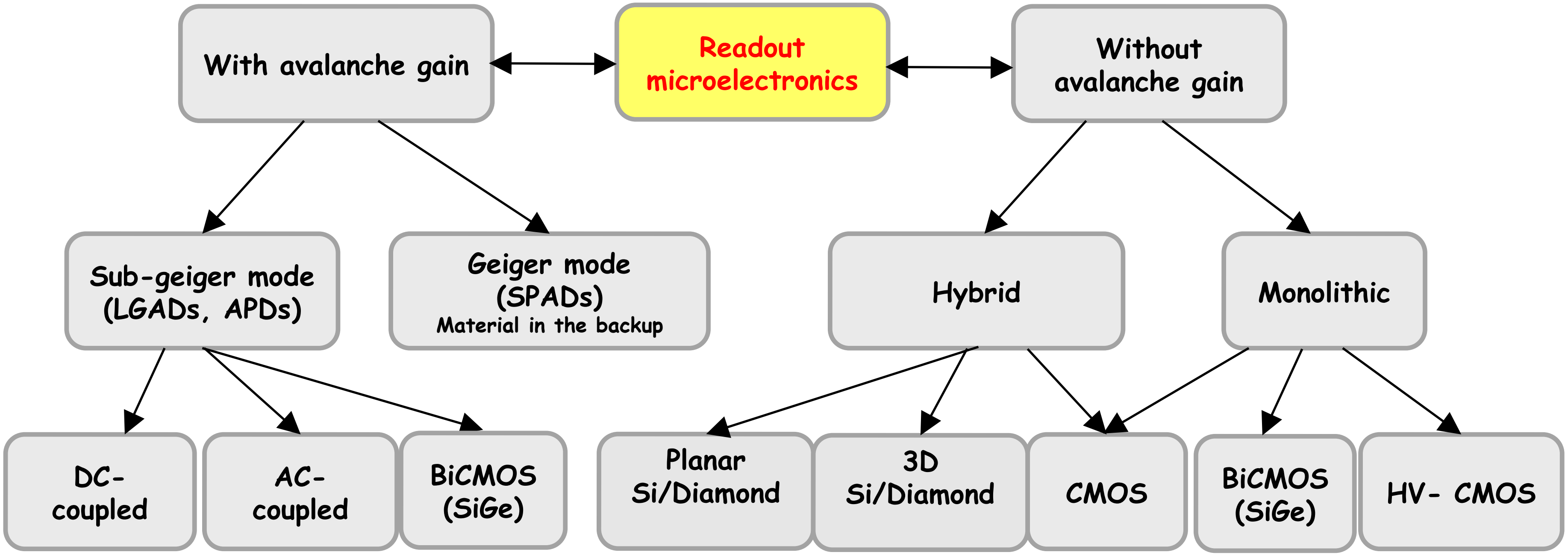




SS Detector for the future (4D) trackers
from Valerio Re (TF3 SSD)

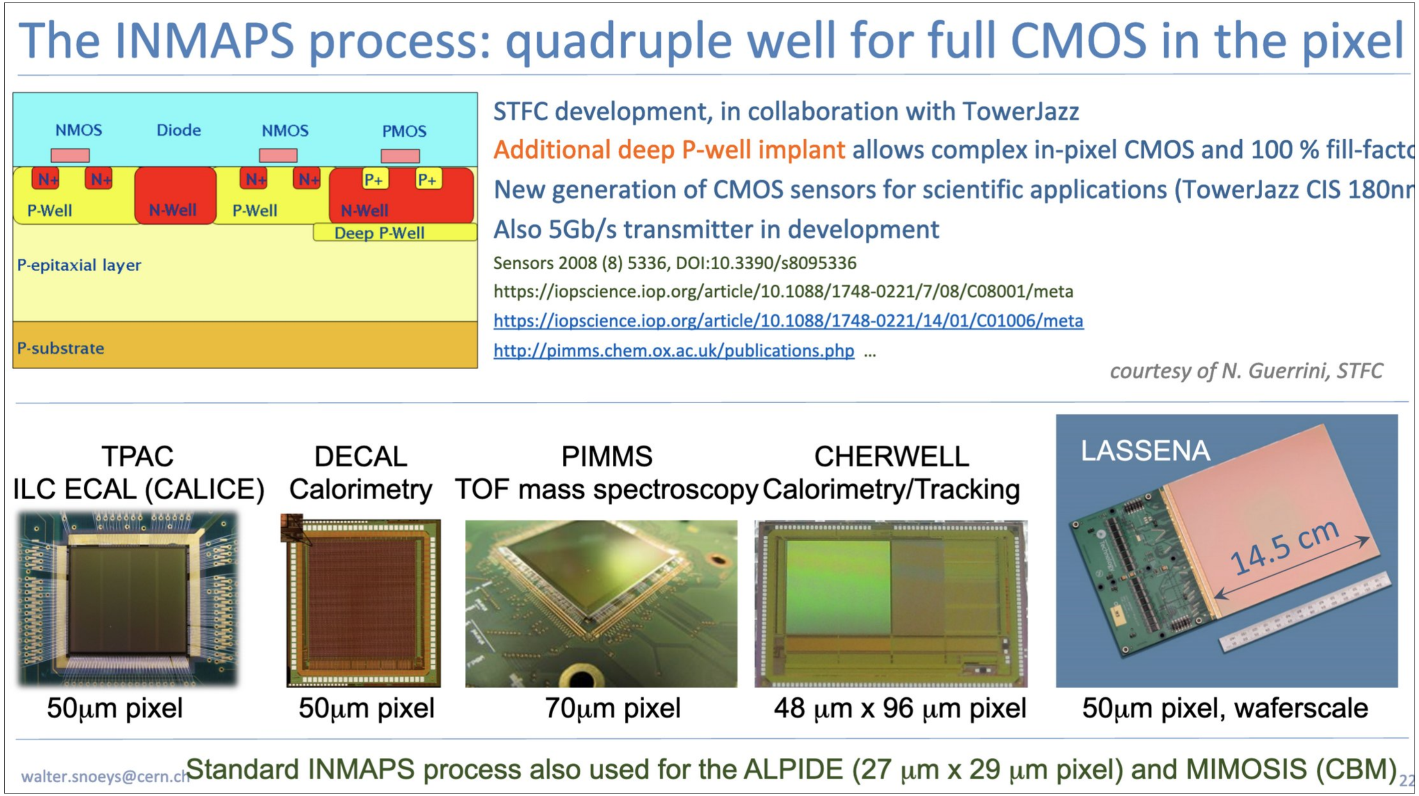
SS Detector for the future (4D) trackers
from Valerio Re (TF3 SSD)

Tracker devices → “Imaging Calorimeters”



What can be adapted to Calorimeters ?
- ➡ Thin Design (Material Budget) ↔ Large Signals (Resolution)
- ➡ Optimal Spatial Resolution (in Analogue, in Digital modes)
- ➡ Budget (× ~40 more surface in calorimeters)

CMOS ECAL ? → FoCAL follow-up



FOCAL = 2 layers of MAPS

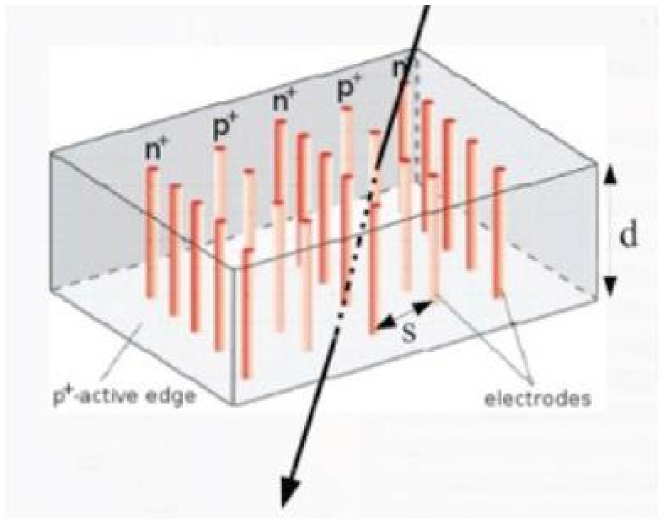
- 1 prototype with 30 layers of maps

but How to build a full detector ?

- Services: Power + Cooling ?
- For what physical gain ?

See "Development of the Silicon Pixel Technology and Challenges",
Walter Snoeys (CERN)

3D sensors



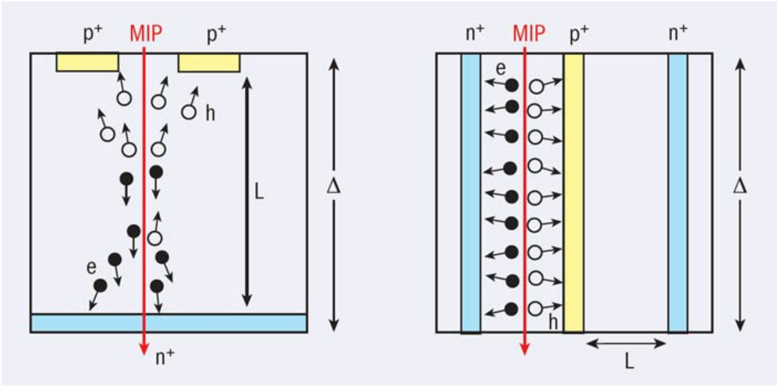
Grid of alternated n and p wells

- For LHC experiments

Lateral drift of charges

- Smaller drift distances
  - ind’t from thickness ⇒ thicker det’s
- Faster collection
- Reduced depletion voltage
- Reduced X-talk

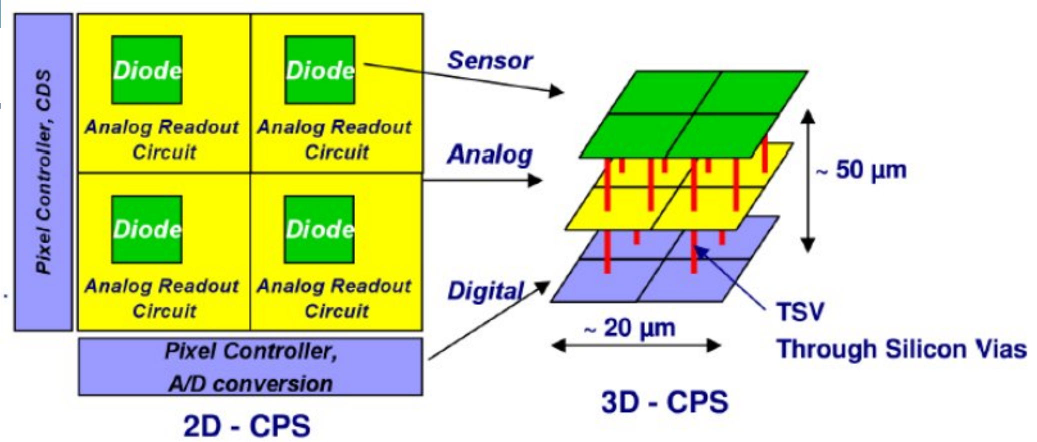
Potentially more RadHard



Non standard technology, (very active) R&D

http://cerncourier.com/cws/article/cern/49691

3D integration

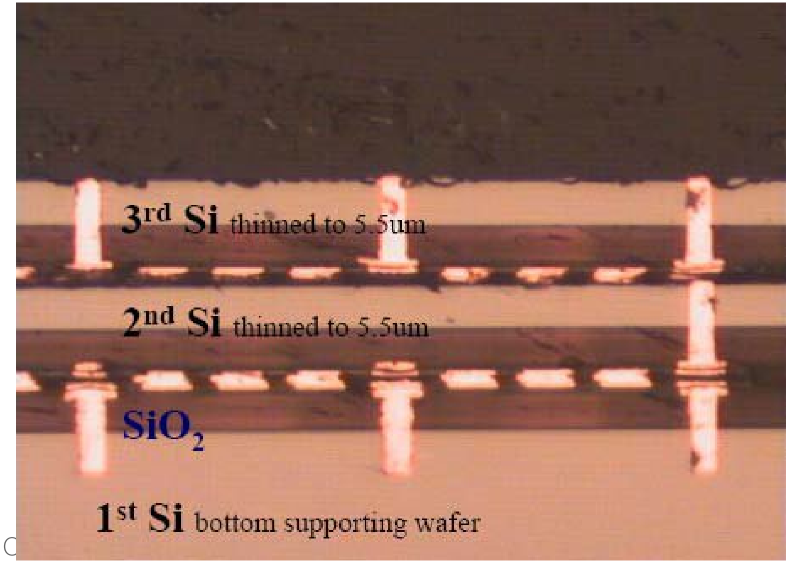


Move ancillary services above and below sensor

- Independent technology for
  - Sensor
  - Analog readout
  - Digital treatment
  - Data transfer
- Removal of dead zones
- Better integration

Many R&D

- Conection
- Budget
- Power comsuption



Other Semi-Conductors ? Photon Science & Medicine (PET)

Material	Z	Bandgap [eV]	Mobility [cm²/Vs]		Density g/cm³
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe_2	74-34	1.4	100	80	
BiI_3	83-53	1.7	680	20	
Bi_2S_3	83-16	1.3	1100	200	6.7
Cs_3Sb	55-51	1.6	500	10	
PbI_2	82-53	2.6	8	2	6.2
HgI_2	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

CdZnTeSe, Perovskites (MHP, $MAPbI_3$, $FAPbBr_3$, …)

Ideal SC for calorimeters

- High density
  - Reduced R_M, Higher signal
- BandGap ~ eV
  - sub-eV required cooling
  - supra-eV loss of signal (ionisation ~ 3-4 BG).
- Good $\mu\tau$ for signal collection
- Good μ_e for fast collection
- Large Crystals ⇒ Growth techniques
- Low processing price

Ref: IEEE NSS/MIC/RTSD (Room-Temperature Semiconductor Detectors) conference, paid access, closed proceedings

Conclusions

Transition phase for Highly Granular Silicon Calorimeter

- 1st large implementation (HGCAL) being built (a bit in haste), **with 5D !!** [spin-offs: LHCb, CMS-HFnose]
- Synergy with long term projects for ILC (now Higgs Factories) : 2030–35 … and beyond (EIC, FCC-hh, μ-coll)
- Need for R&D and investment in basic sensor : lower cost, **diversify production if possible in EU**

‘Small projects’ push R&D and basic science:

- Thinner and compacter designs: FCAL, FCC-FCALs
- Ultimate granularity (DECAL)
- Implementations for physics: ALICE FOCAL, LUXE

Long Term R&D from:

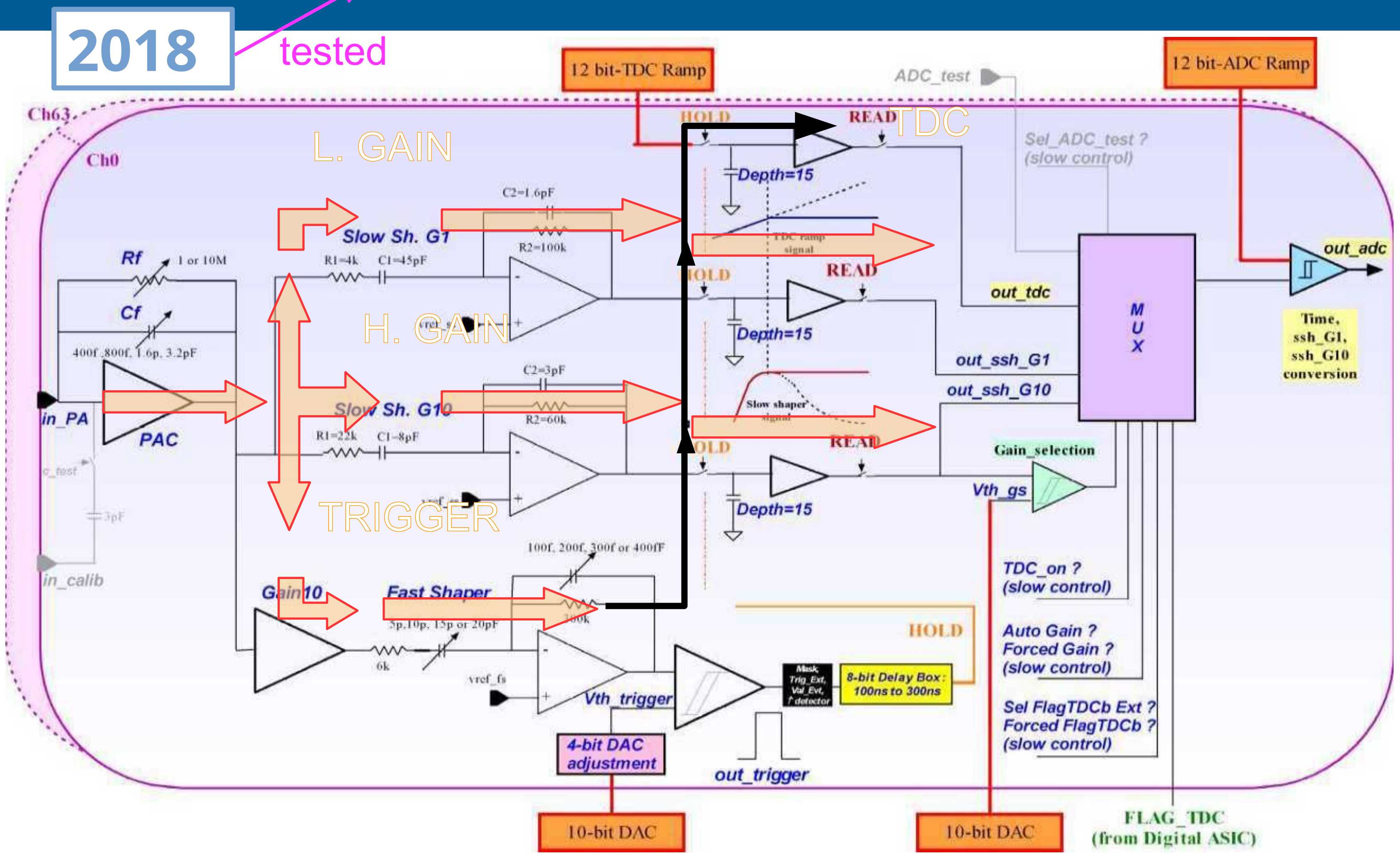
- Extension of advanced design from tracker to calo (€€€)
- New Semi-Conductors from X-ray and Medicine needs ?

Tribute

Credits: HGCAL teams (mostly mat from CHEF2019), D Thienpont & Ch. de la Taille (OMEGA),
A. Lobanov (LLR & DESY), Th. Peitzmann (Utrecht U./Nikhef), Y. Benhammou (TAU),
W. Riegler (CERN), V. Re (U. Bergamo), CALICE and ILD teams esp. SiW-ECAL @ LAL/IJClab & LLR from last 10 years...

BACK-UP

Ωmega: SKIROC2 / 2A Analogue core



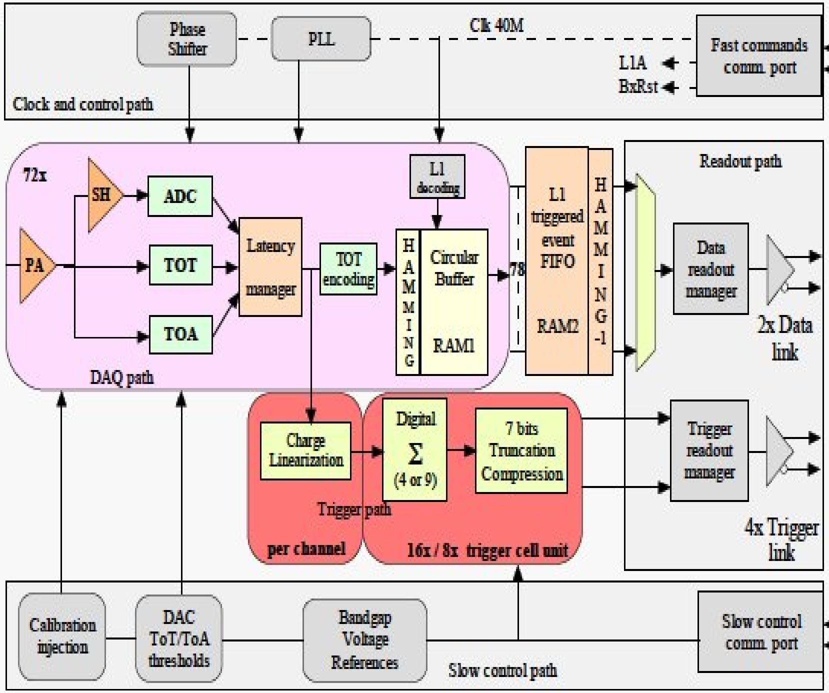
Similar to SiD Kpix

- 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

SKIROC3 needed
(full 0-suppr.)

Ωmega 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

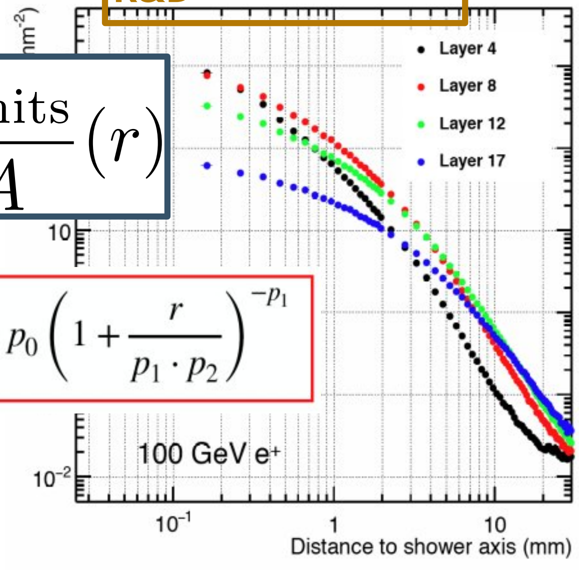
HGCROCv3 submission in 2020

DECAL: Shower profiles

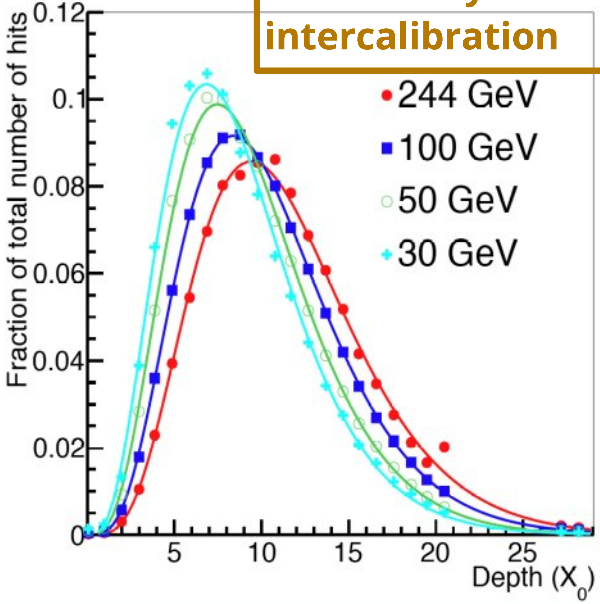
R&D

$$\frac{dN_{\text{hits}}}{dA}(r)$$

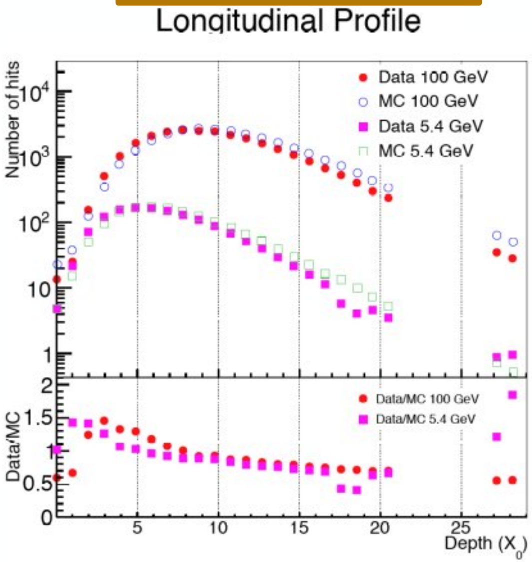
$$f_4(r) = p_0\left(1 + \frac{r}{p_1 \cdot p_2}\right)^{-p_1}$$



Used for layer intercalibration



MC Tuning



Unprecedented spatial lateral accuracy

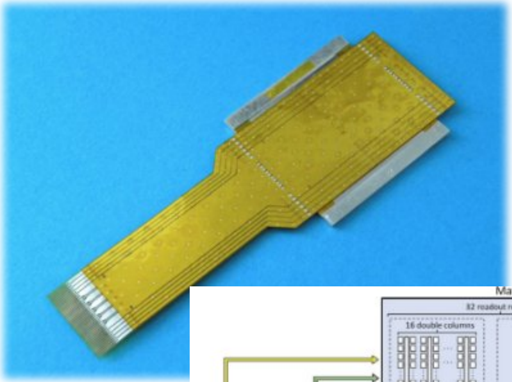
⇒ New EM Shower lateral profiles parametrisation

Longitudinal profiles:

≠ MC / data, as seen by CALICE AHCAL & HGCAL

- Earlier showers

FoCal: Conclusions and todos

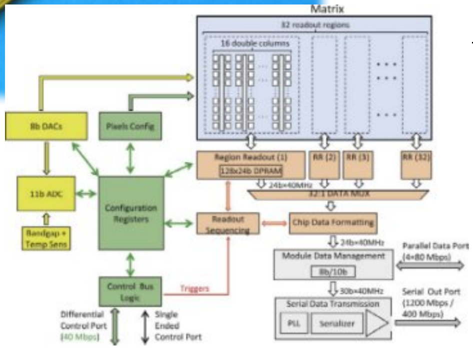


Successful running of Si-pad calorimeter at High Energy

- VHE to be analysed

Proof of principle of small very compact digital calorimeters

- proof of principle with extreme granularity
- Basic Science on shower profiles
- Full Understanding of calibration & saturation to be completed
  - tuning of MC models



New prototypes: mTower with ALPIDE CMOS MAPS sensors (CERN)

- Small digital calorimeter (3x3 cm²) with 24 layers of 2 ALPIDE sensors
  - 2 layers of 2 ALPIDE in PS+SPS in 2018
- ALPIDE (for ALICE ITS upgrade)
  - 30×15mm² / 1024×512 pixels
    - 30×14μm²
  - Hit Driven (zero-suppr).
  - Rad. Hardness: 1Mrad / $n_{eq} \sim 10^{13}$
  - Power consumption ∝ occupancy
  - High speed readout (0.4–1.2Gb/s)

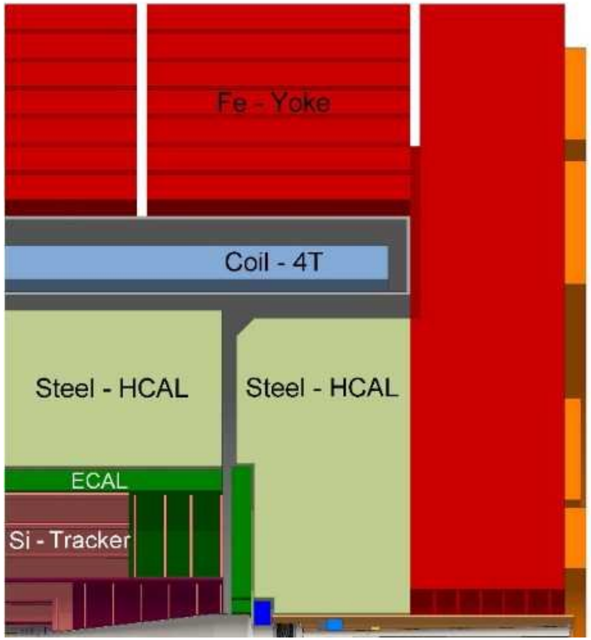
    Sufficient for high occupancy ?

Construction: 2022–2026

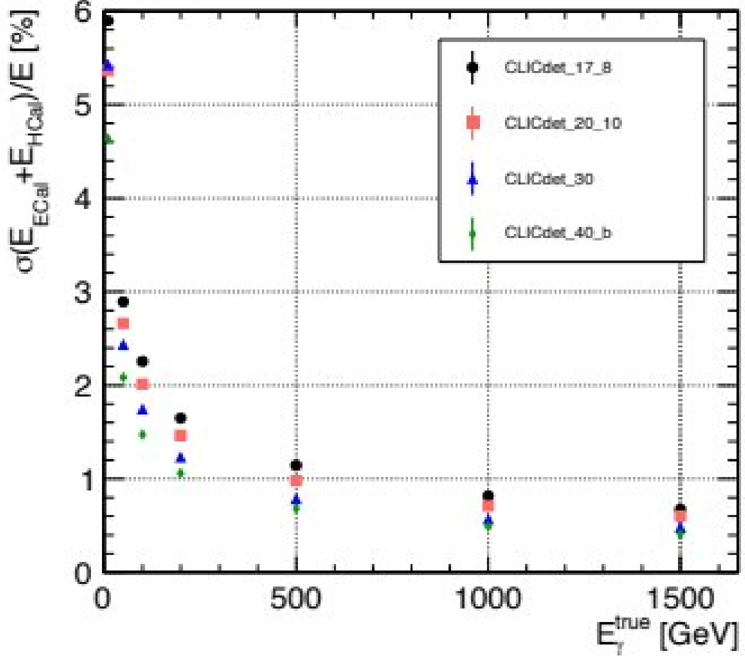
- LoI → LHCC in prep.

Further contrib to RUN-5 (LPSC, Subatech ?)

CLIC calorimeters



Energy Resolution for central high energy photons



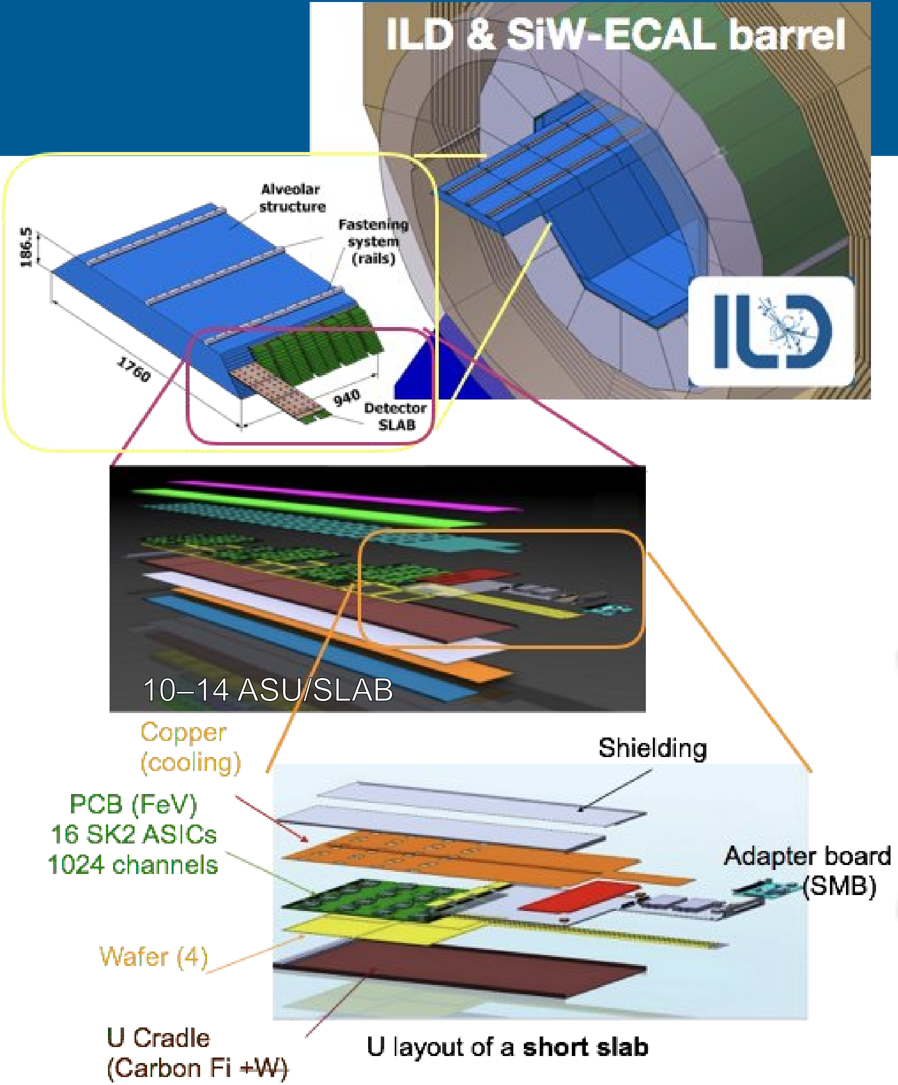
ECAL Optimization:

40 layers uniform fine sampling silicon-tungsten plates

(1.9 mm W, 5x5 mm^2 silicon cells)

22 X_0 (1 λ_i) total thickness

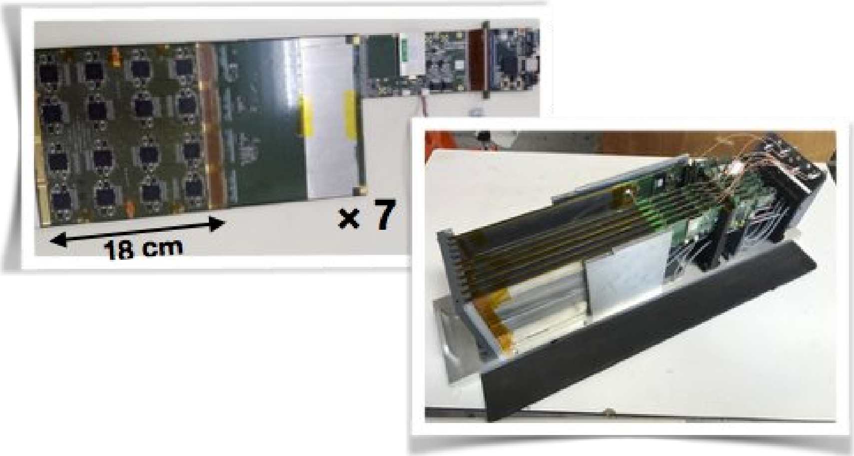
Large Scale Building



ILD SiW-ECAL	Prototyped*
~10,000 SLAB's	~0.1
100,000 ASU's	~20
400,000 Wafers	~350
1,600,000 ASIC's	~1000
100,000,000 channels	~20000

* incl. Physical Prototype

+ Mechanics , Cooling, Integration, ...



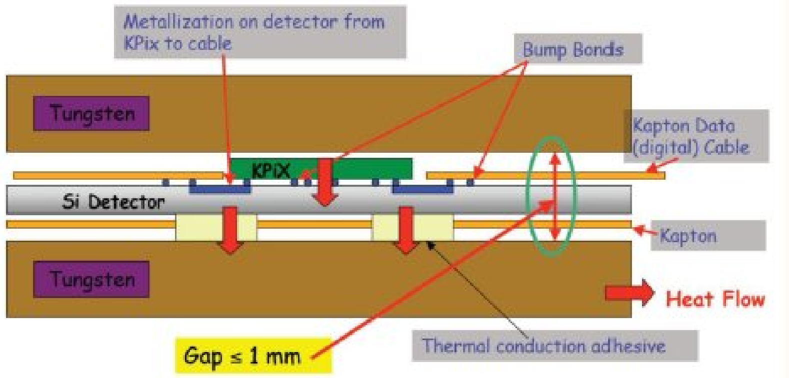
SiD SiW-ECAL

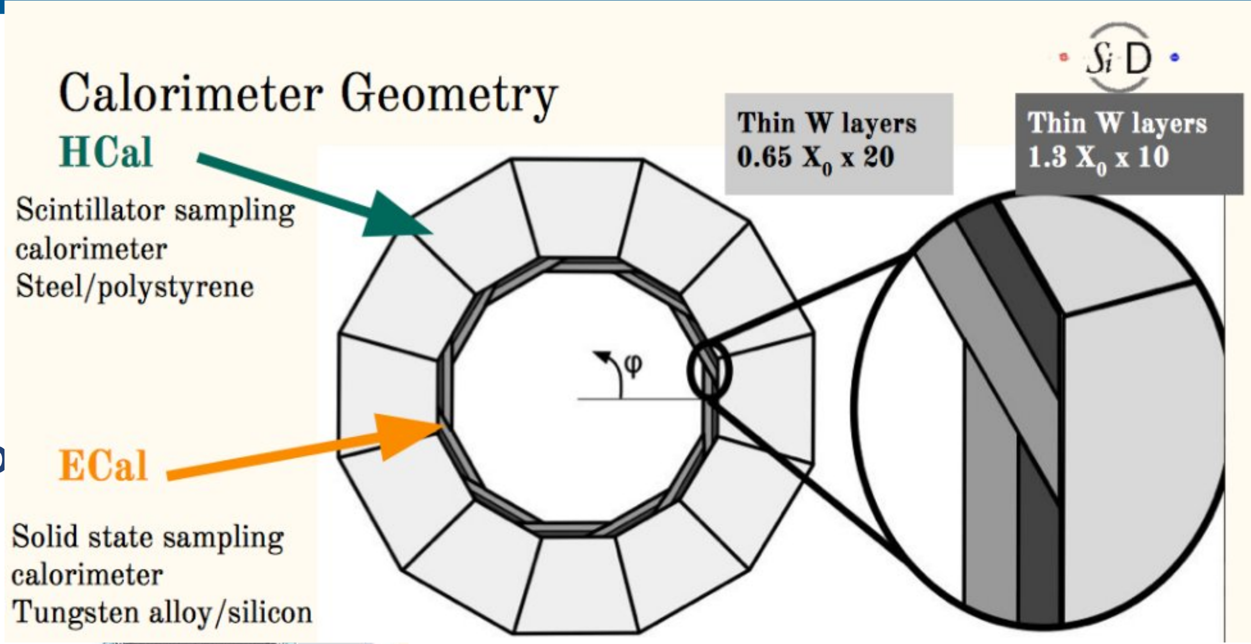
20 + 10 layers

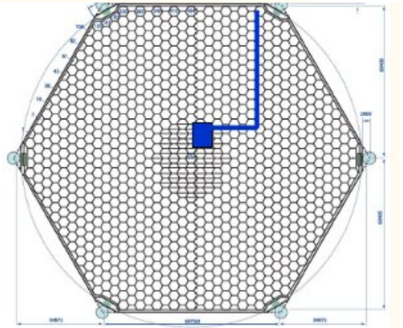
1.25 mm gap between W layers

- Minimize R_M (~ 13 mm effective)
- Keep calorimeter compact

Tungsten plates ⇒ thermal bridge to co







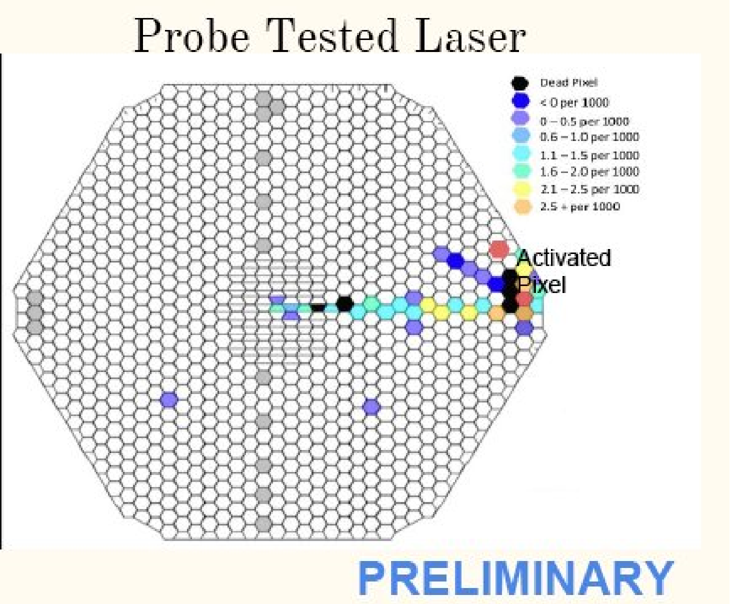
Hexagonal Wafers (optim material)

1 Kpix Chips (1024 ch) per Wafer

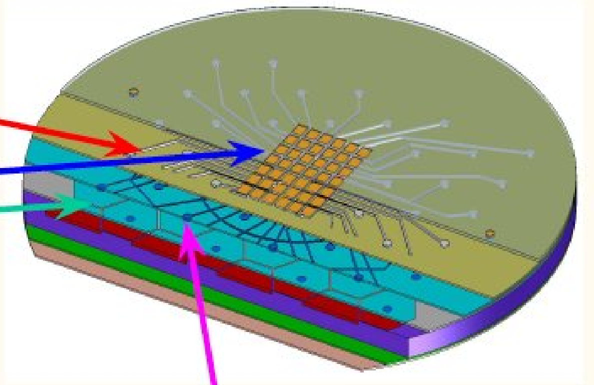
- Bump Bounder on Sensor.

Prototype testing

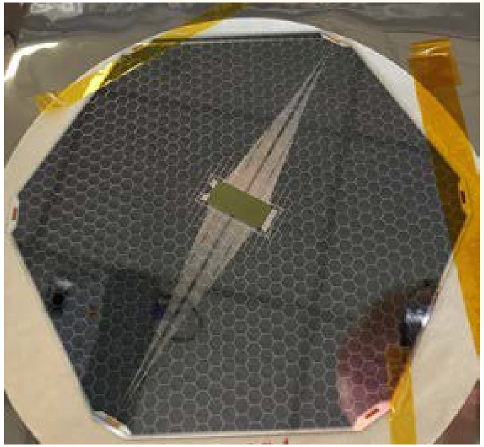
Laser injection in single pad



In present design, **metal 2 traces** from **pixels** to **pad array** run over other pixels: parasitic capacitances cause crosstalk.



New scheme has "same" metal 2 traces, but a fixed potential metal 1 trace shields the signal traces from the pixels.

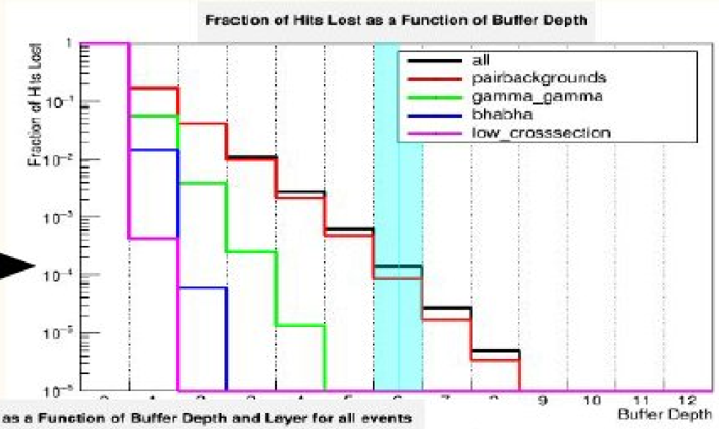


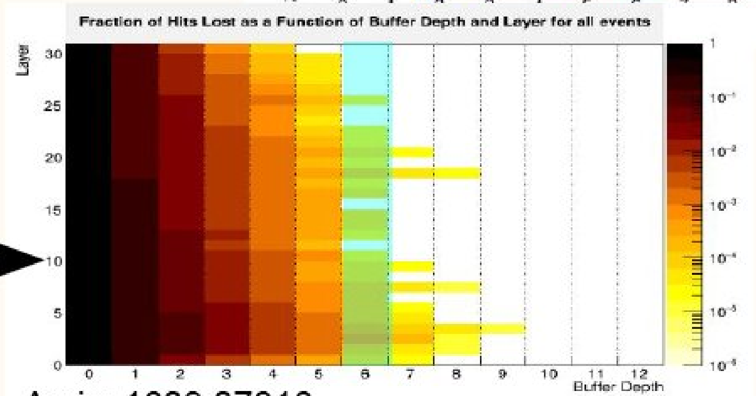
Occupancy

A. Steinhebel @ ALCW2017

KPiX Studies - Buffer Multiplicity

- Forward multiplicity might be more than 4 buffer KPiX (current design) could handle
  - Recent optimization studies indicate that 6 buffers will be adequate, taking into account all known processes.
- 6 buffers also improve fractional hit loss within detector at shower max and radially
- Must study KPiX to see if more buffers might be added while preserving architecture (preconceptional ideas only)

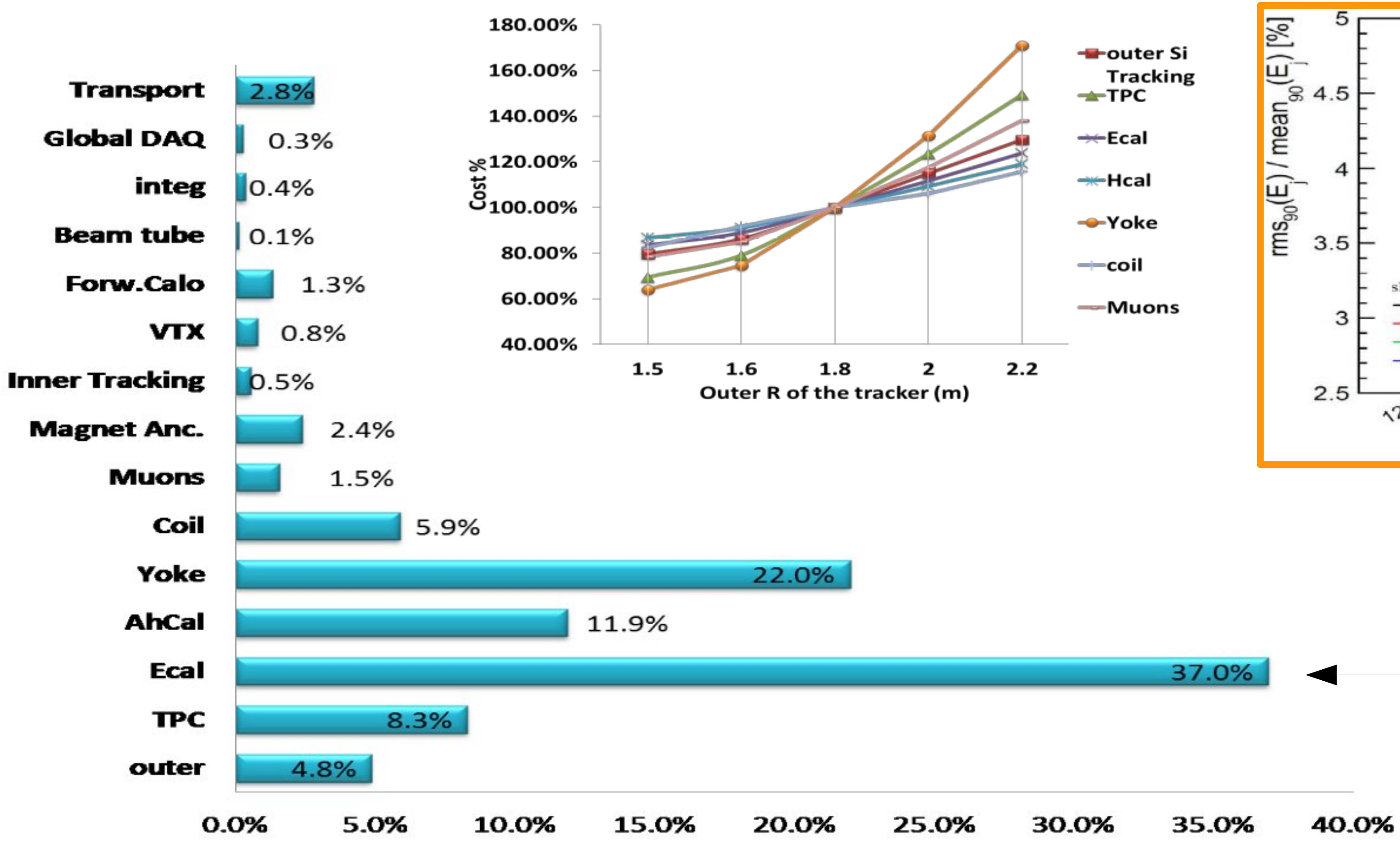


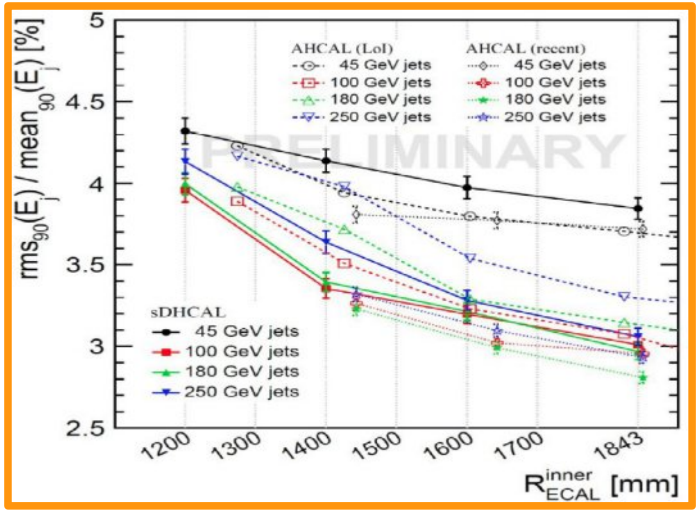


Arxiv: 1609.07816

6

Cost Structure of ILD





← Full Silicon option

Reduced number of Layers

Going from 30 to 22 layers

- Reduction of cost; (small) reduction of R_M ; increase of Energy resolution
  - "better separation at the expanse of the intrinsic resolution"

Increasing the Si thickness to 725µm, if really feasible (next slide)

Energy resolution σ(E)/E:

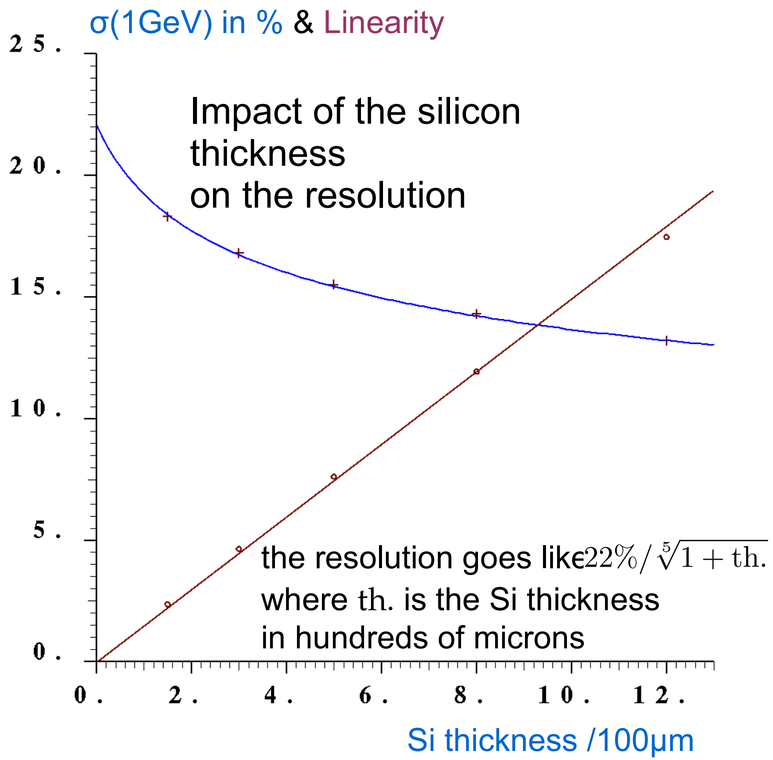
- for 22 layers w.r.t. 30: +16.8%
- with 725µm w.r.t 500µm : –6.1%

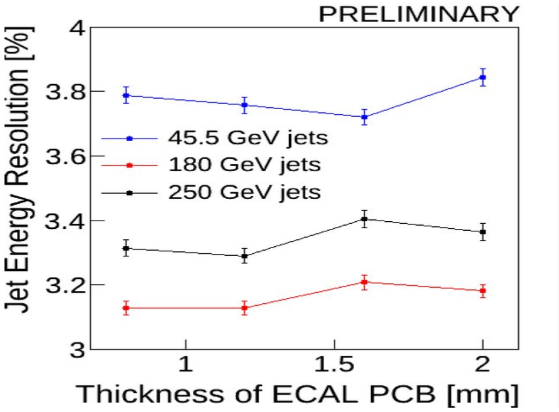
ECal thickness = 190.1 mm (close to 185 mm of DBD).

- 22 layers = 14 layers with 2.8mm thickness
  + 8 layers with 5.6mm shared between structure and slabs.

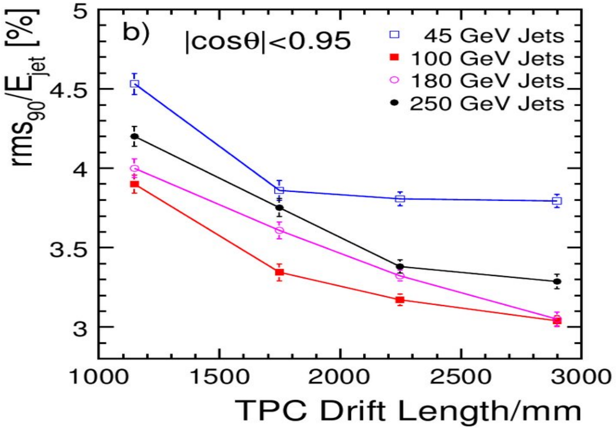
Study needed on separation, resolution and efficiency performances at low energy.

- JER : $\sigma(E_J)/E_J$ +10% for 20 layers (500 µm).

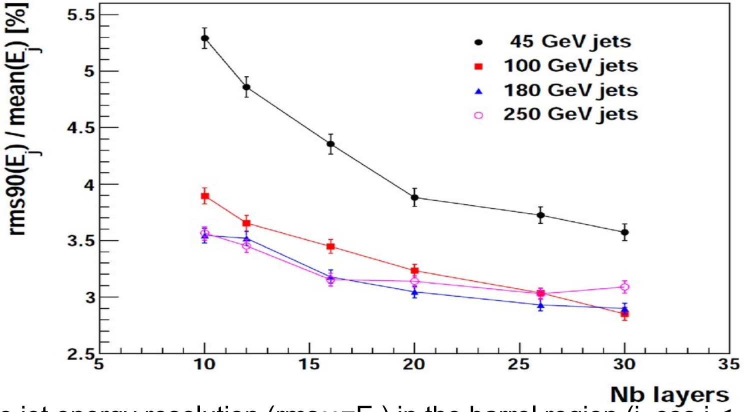




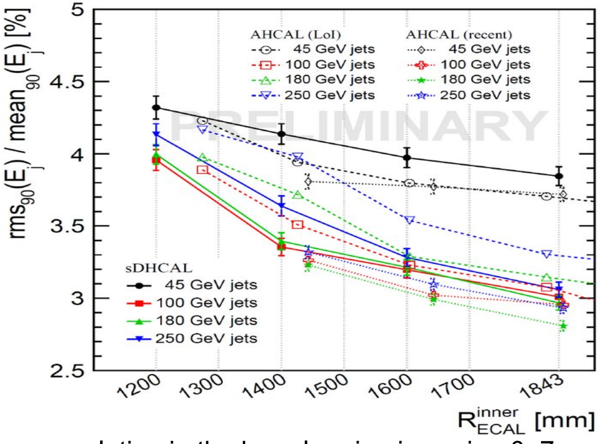
Single jet energy resolution as a function of the thickness of PCB with embedded electronics.



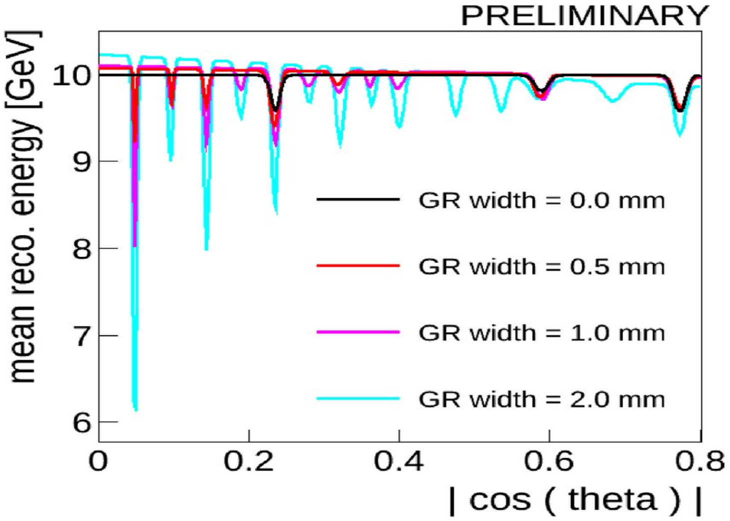
Single photon energy resolution as a function of the number of silicon layers for four photon energies.



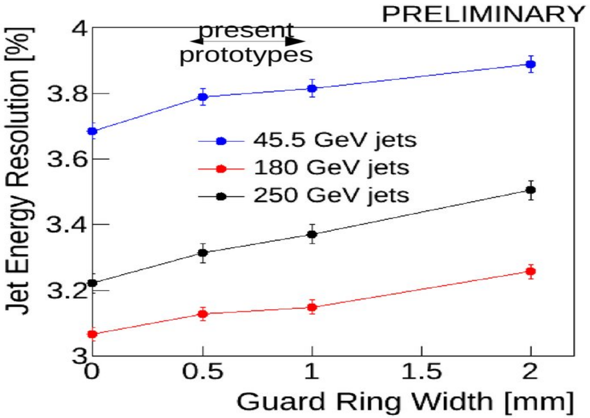
Single jet energy resolution (rms90=E) in the barrel region (j cos j < 0: 7) as a function of the number of ECAL silicon layers in events e+e- → ZX → usd



ILD jet energy resolution in the barrel region j cos j < 0: 7 as a function of its radius.

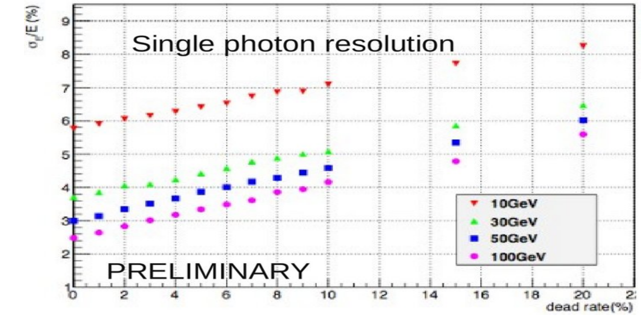


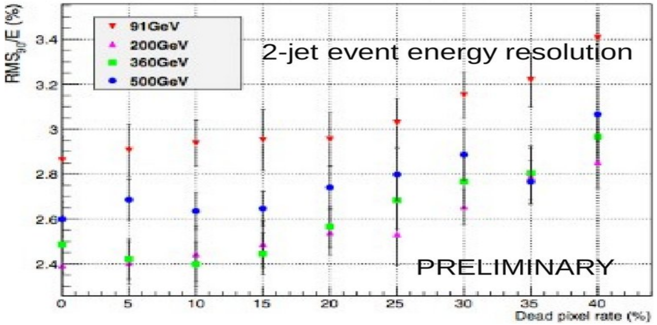
An ECAL average signal versus azimuthal angle. The loss in inter-sensor dead areas is visible (between barrel modules, barrel and endcap
and between the sensors, the latter depends on the guard ring).

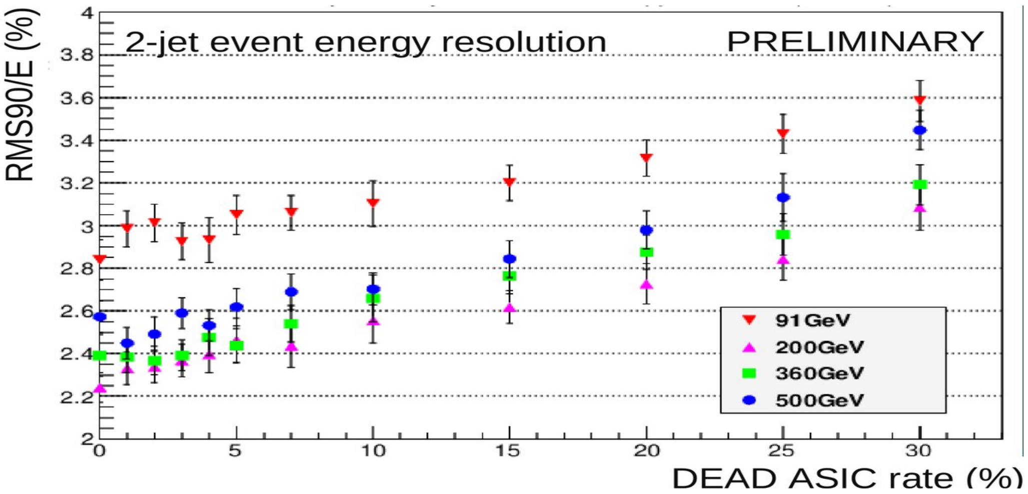


the single jet energy resolution after a simple dependent correction as a function of the guard ring thickness.

Resilience


Single photon resolution
σ_E/E (%)
10GeV
30GeV
50GeV
100GeV
PRELIMINARY
dead rate(%)


RMS_{90}/E (%)
91GeV
200GeV
360GeV
500GeV
2-jet event energy resolution
PRELIMINARY
Dead pixel rate (%)


RMS90/E (%)
2-jet event energy resolution
PRELIMINARY
91GeV
200GeV
360GeV
500GeV
DEAD ASIC rate (%)