Silicon-Based Highly Granular Calorimeters

Vincent Boudry

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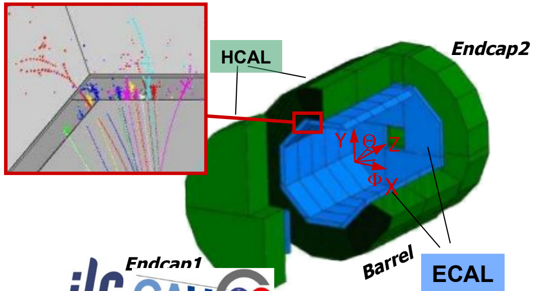
Credits: HGCAL teams (mostly mat from CHEF2019), D Thienpont & Ch. de la Taille (OMEGA),
A. Lobanov (LLR & DESY), Th. Peitzmann (Utrecht U./Nikhef), Y. Benhammou (TAU),
V. Re (U. Bergamo), CALICE and ILD teams esp. SiW-ECAL @ LAL/IJClab & LLR from last 10 years…

ECFA R&D Symposium TF6

Highly-Granular Compact Si-ECAL for experiments



Particle Flow '5D' calorimetry

Standard requirements:

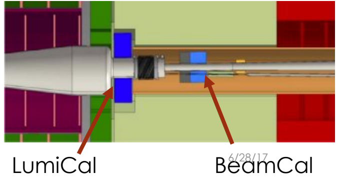
- Hermeticity, Resolution, Uniformity & Stability (*E*, *(θ,φ)*, *t*)

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 ?

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

SSC †
(1989)

CALICE (2005–...)

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+)

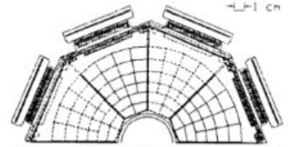
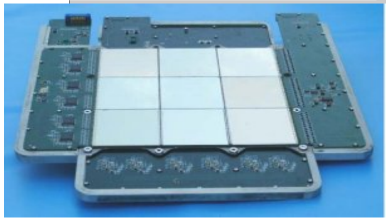
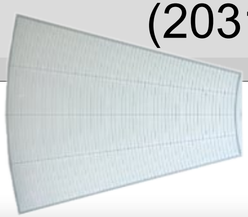


Figure 2. Front face of one LMSAT module as seen from the IP. Detectors shown with dashed lines have their ground planes facing away from the IP.





Year:	1986	1991	1997	2008	2007+2008	2026+	2026+	2031++	2031++
Experiment:	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

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(1989)

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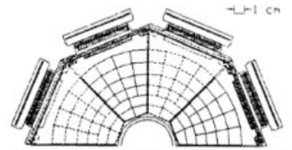

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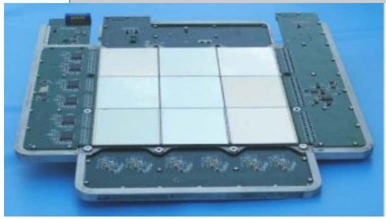

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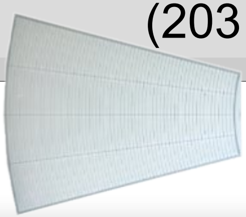

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… in a transition from Small to Large detectors
➡ R&D on costs, integration and production
➡ R&D on improved performances

CALICE / ILD
and Higgs Factories

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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 ~ $(\text{resol})^{-1/2}$
  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

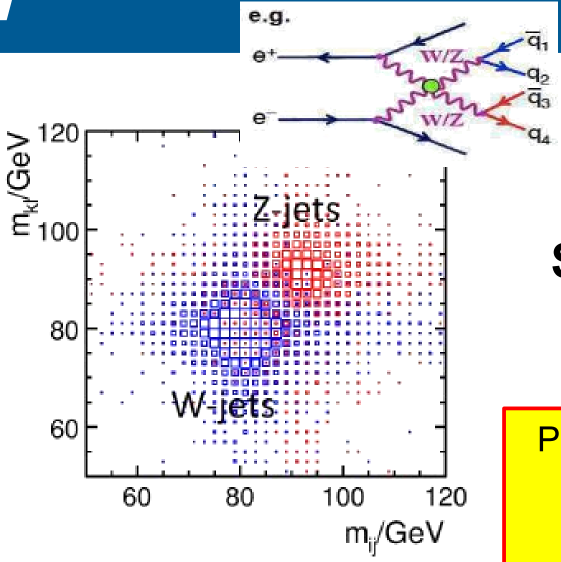
Fwd Calorimetry:

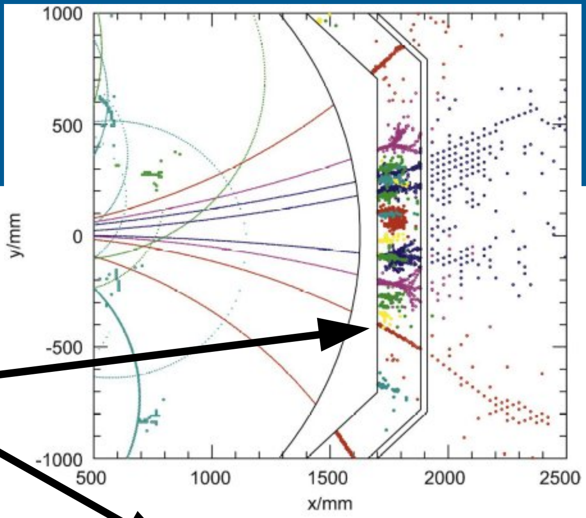
- lumi, veto, beam monitoring

HG Imaging Calorimetry

⇒ **FCAL**

⇒ **CALICE / ILD + SiD**





SiW-ECAL

Particle Flow Algorithms :

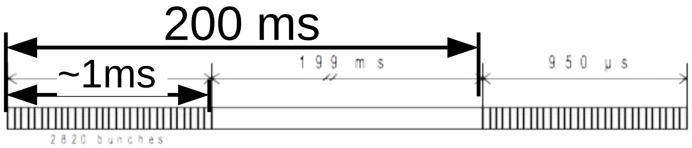
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 CALO's
- TPC $\delta p/p \sim 5{\cdot}10^{-5}$; VTX $\sigma_{x,y,z} \sim 10\ \mu m$ **+ timing ?**

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)

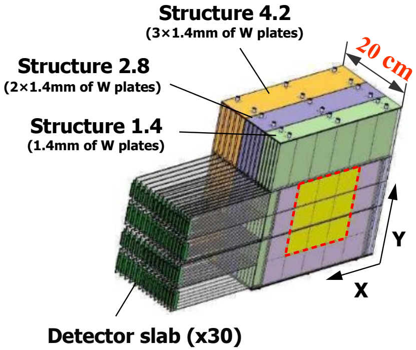
2/3 of Hadr IA in **ECAL**



- 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

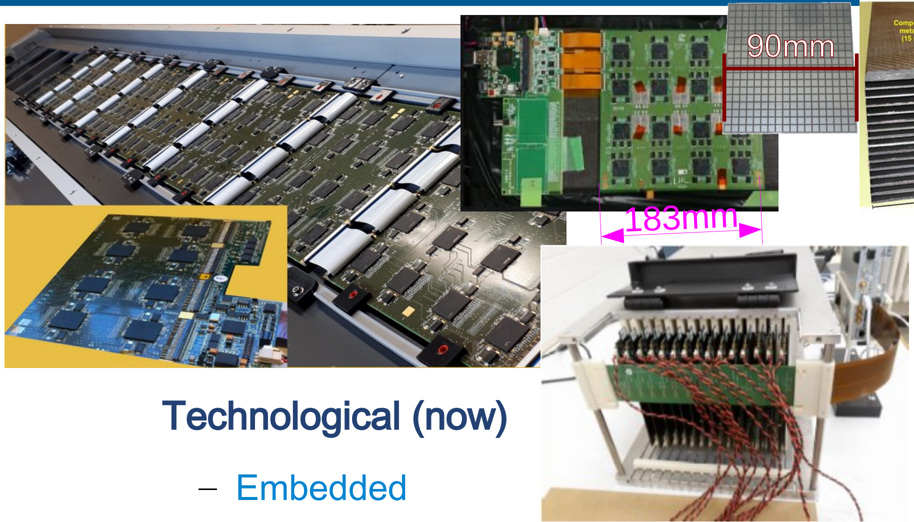
- High B field
- Trigger-less
- Power Pulsing (≤1%)
- Differed readout

CALICE prototypes for ILC



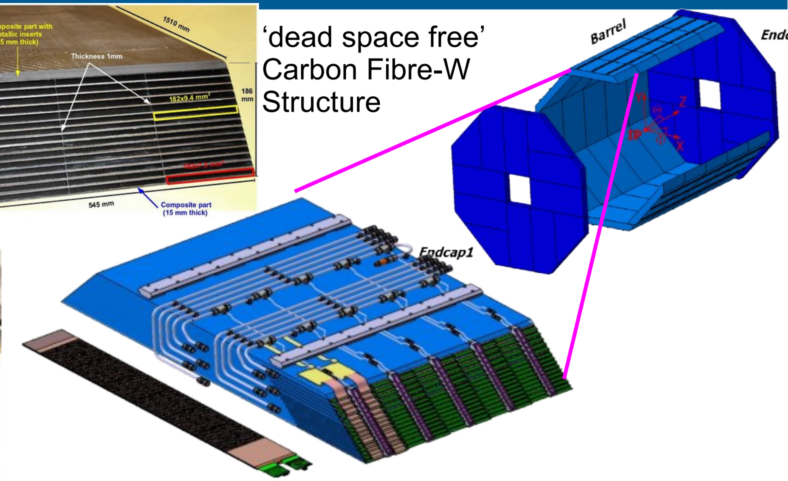
Physical (2005-11)

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



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



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

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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 ?**

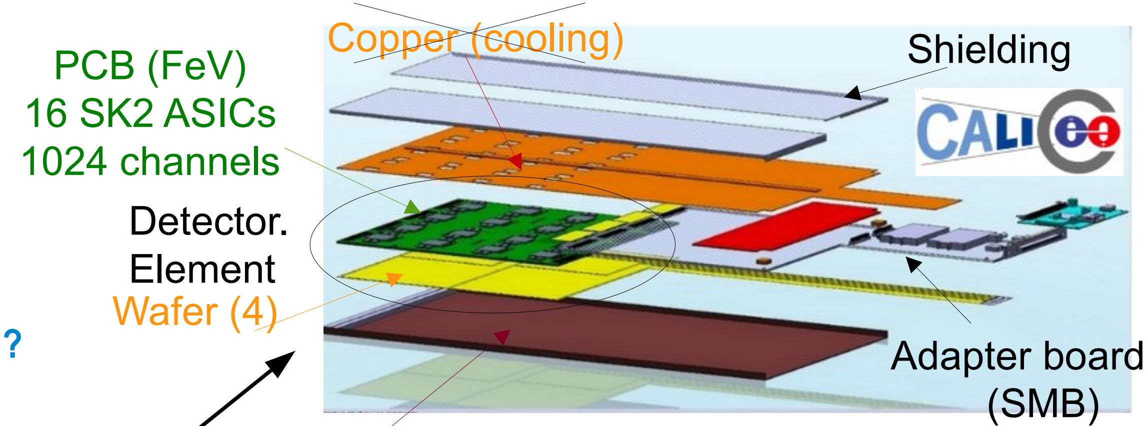
Large quantities

- 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

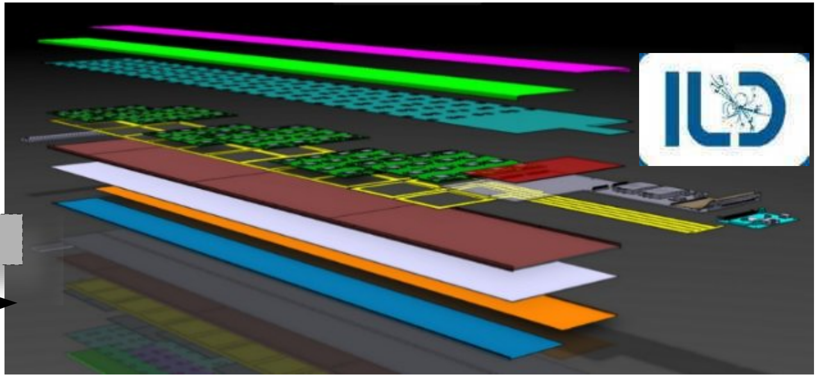
Tests of producibility

Implication of industry is mandatory

Tests of feasability

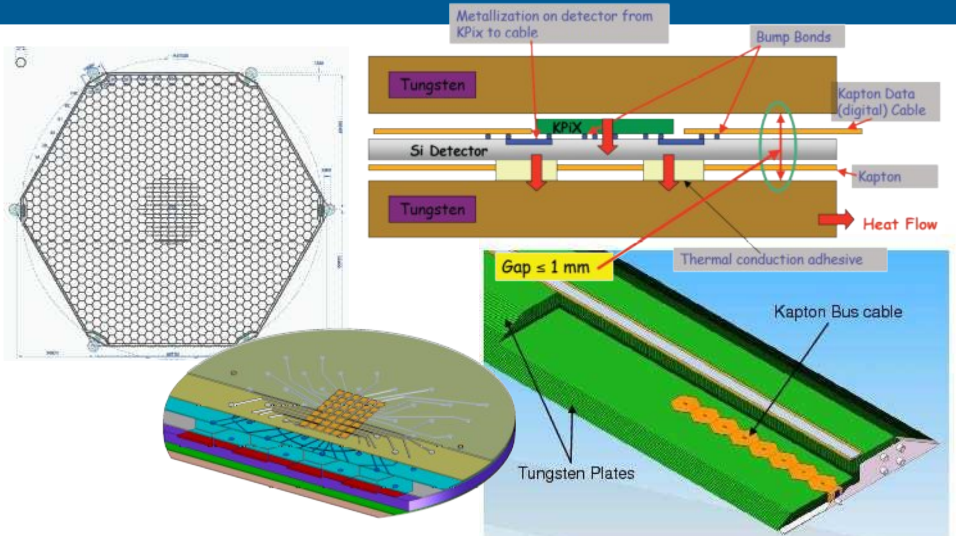


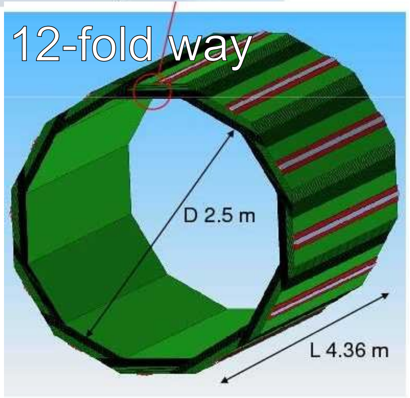
U layout of a **short slab**



U layout of a **long slab**

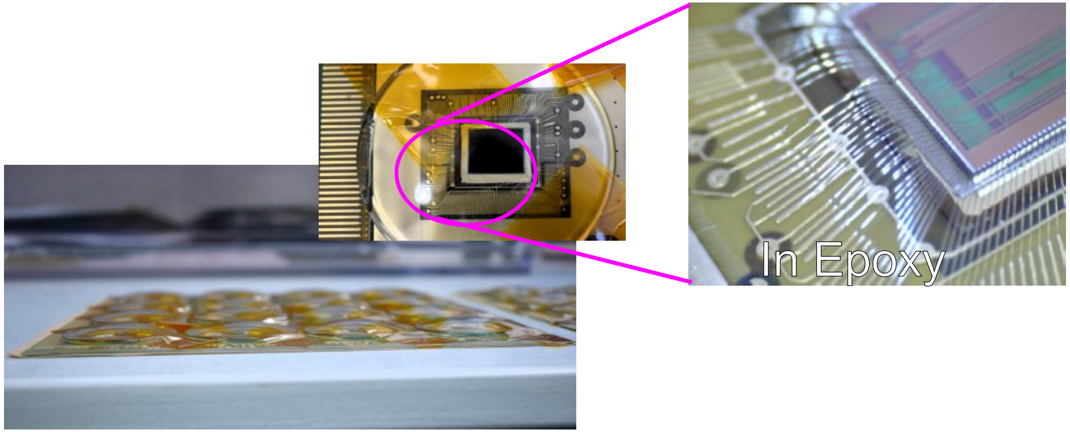
Very Compact Designs: W absorber + …





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

CMS–HGCAL

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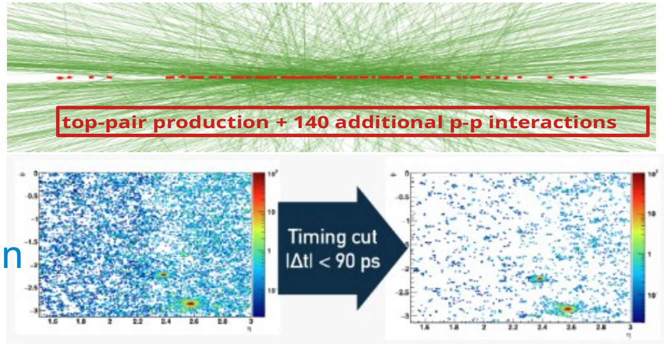
CMS-HGCAL: Going 5D for HL-LHC

See Lessons learned
David Barney

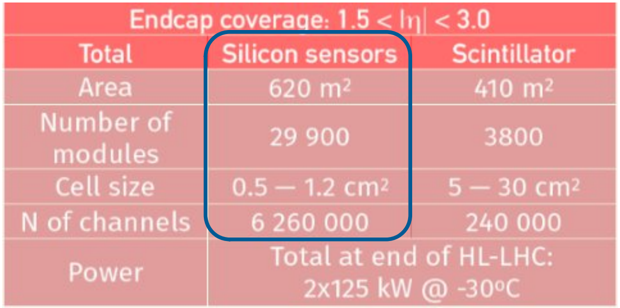
Goal: replace the CMS Calo endcaps for HL-LHC ($\mathscr{L}$×5)

- 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

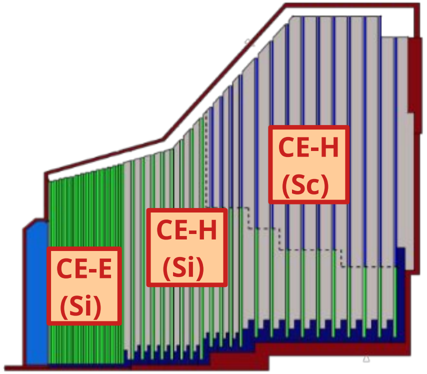
Possible because of HG calorimeters
(30ps = 1 cm/c)



Simulated HGCAL event with and without timing selection



Endcap coverage: $1.5 < \|\eta\| < 3.0$		
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	



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)

Timing

Timing of Showers ≠ Cell Timing

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

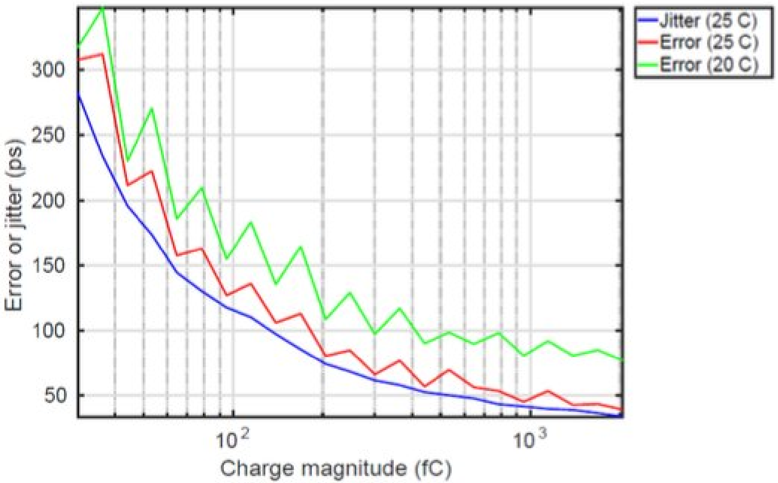
R&D

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

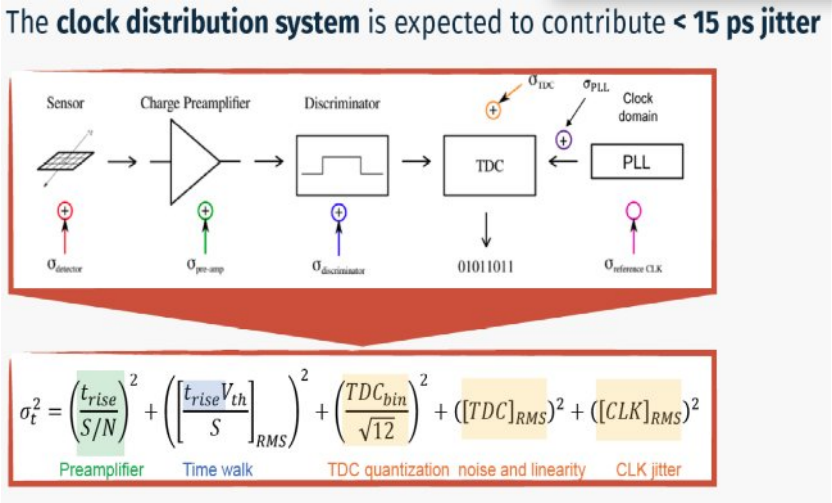
See Timing in Calorimeters
Nural Akchurin

⚠ Time precision costs power

Time
Jitter



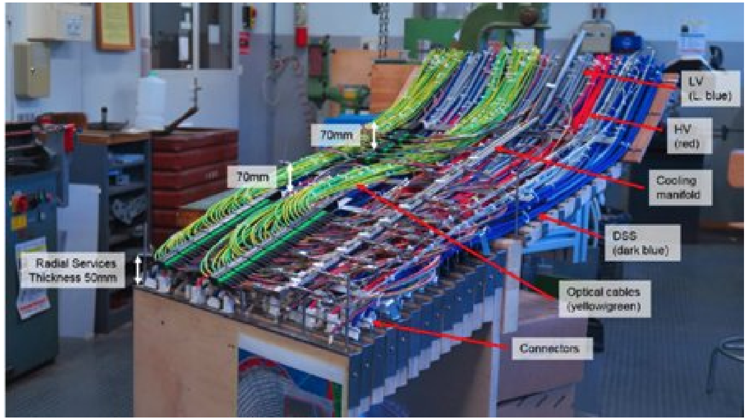
C. de La Taille Front-End elecectronics CHEF 2017

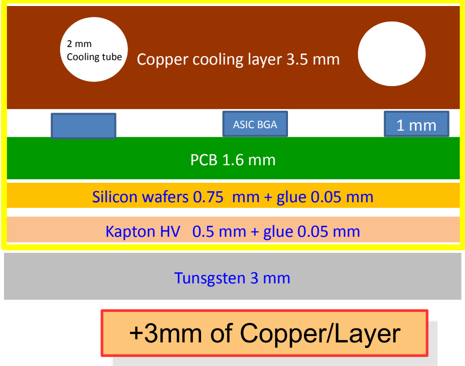


The **clock distribution system** is expected to contribute **< 15 ps jitter**

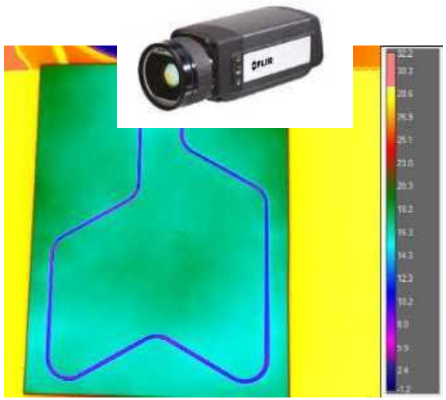
$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + ([TDC]_{RMS})^2 + ([CLK]_{RMS})^2$$

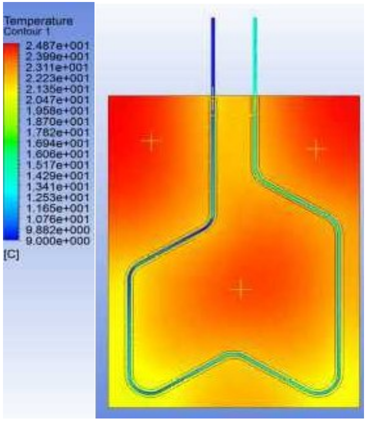
Services: integration & cooling





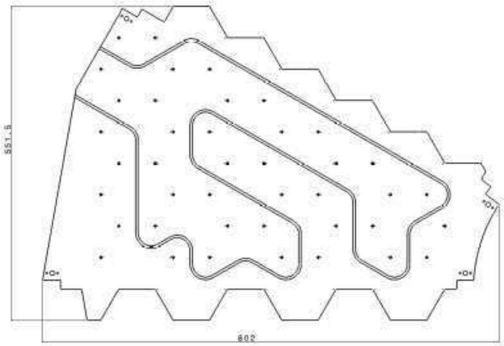
+3mm of Copper/Layer

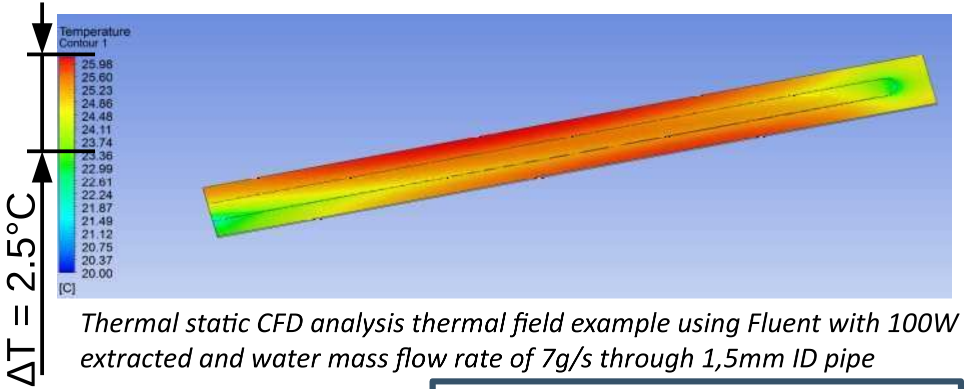




- Pipe insertion process introduces some efficiency loss due to the thermal contact resistance.
- The benefit remains significant with regard to a passive cooling

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

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

Open R&D Collaborations, a way to be promoted ?

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Forward Calorimetry

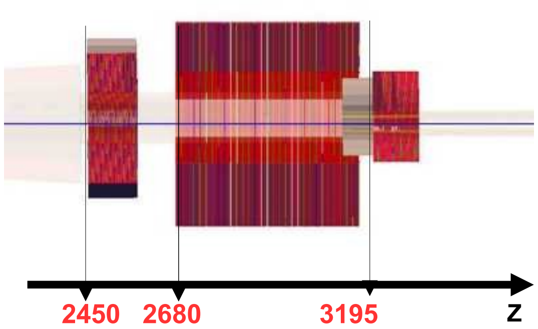
FCAL Collaboration: LumiCal & BeamCAL with extreme precision for Lin. Colliders

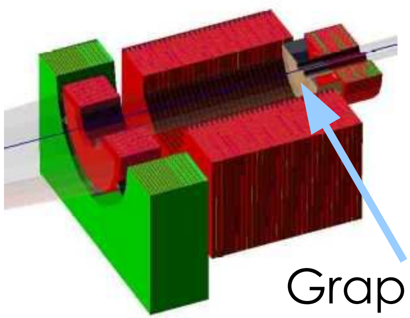
LumiCal :

- Symmetrically on both sides at ~2.5m from IP.
- Integrated luminosity measurements (Bhabha events) $\mathscr{O}(10^{-4})$
  - $\Delta\mathscr{L} / \mathscr{L} \simeq 2\Delta\theta/\theta_{min} \Rightarrow \sigma(x,y) \sim 250\ \mu m$ on Shower positions
  - Accept. err $\mathscr{O}(10^{-5}) \Rightarrow$ 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

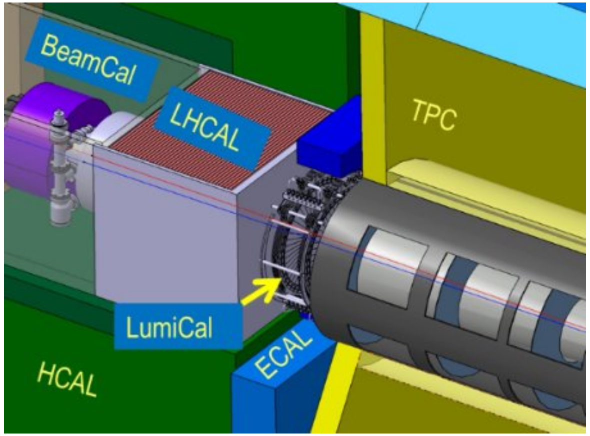




Graphite Shield

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)



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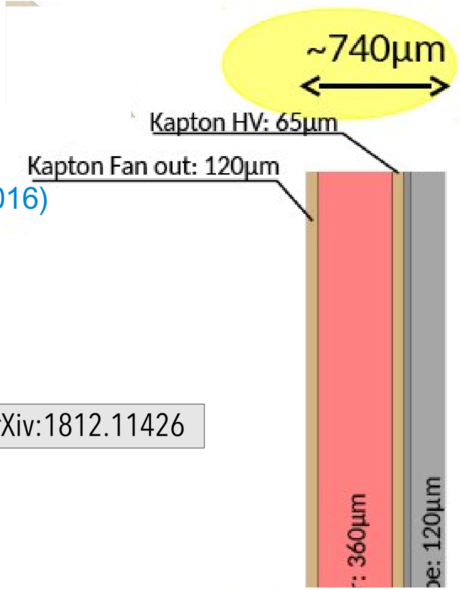
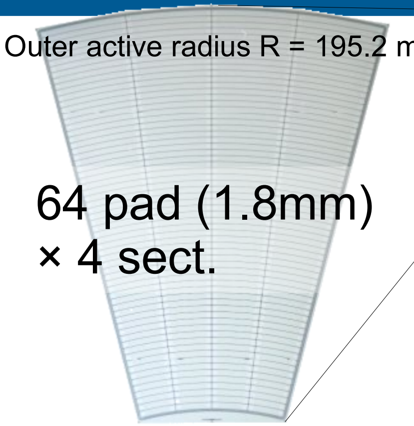
FCAL collaboration: LumiCal

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
- $\sigma(x,y)$ ~ 440 µm @ 5 GeV ⇒ OK at 250 GeV ?
- **Positioning $\mathcal{O}$(50µm) ?**

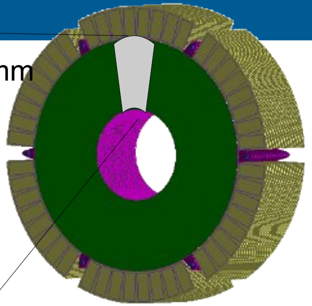
arXiv:1812.11426

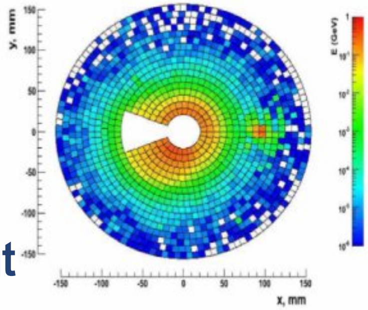


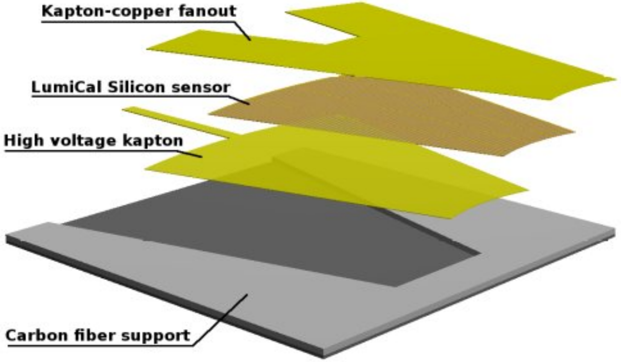


Outer active radius R = 195.2 mm

64 pad (1.8mm) × 4 sect.



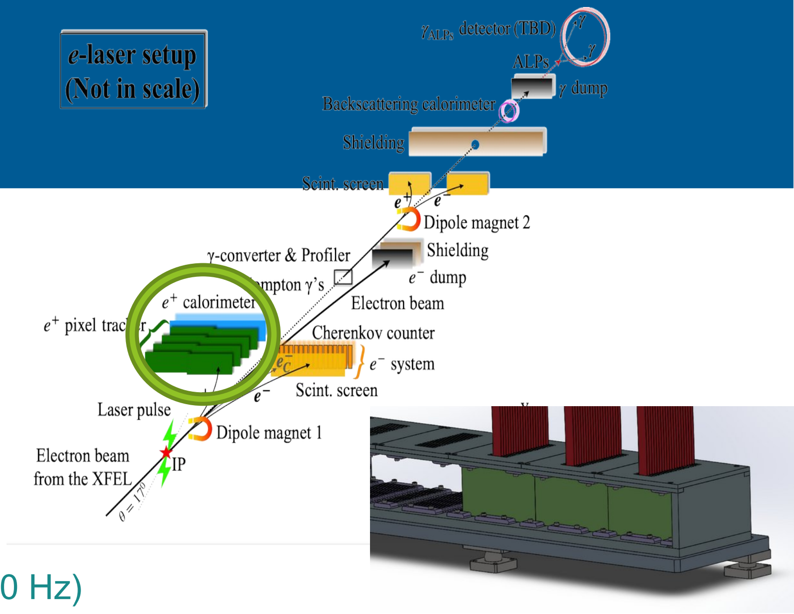




External Readout

- 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 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

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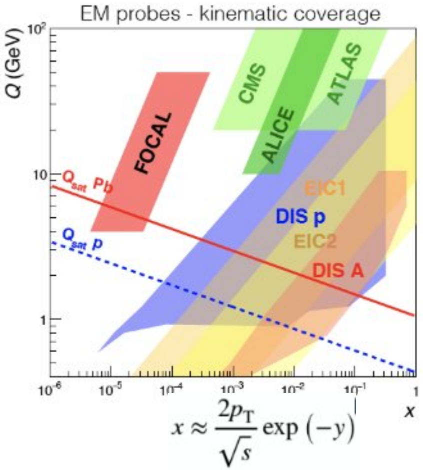
Ultimate Granular Calorimetry :
FoCal-E @ ALICE

FOCAL-E @ ALICE

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

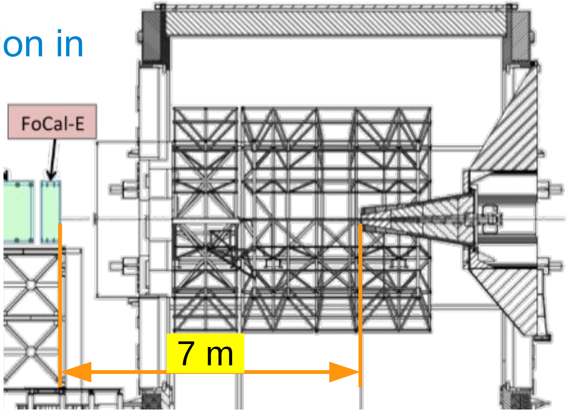
- FoCal-E : Tagging of very forward γ and π^0's
  - z = 7m; $3.2 < \eta < 5.8$
  - π^0 decay @ $P_T = 10\ \mathrm{GeV/c}$, y=4.5, $\alpha = 0.5 \Rightarrow \mathbf{d = 2mm}$

    ⇒ Requires ≤ 1×1mm² granularity



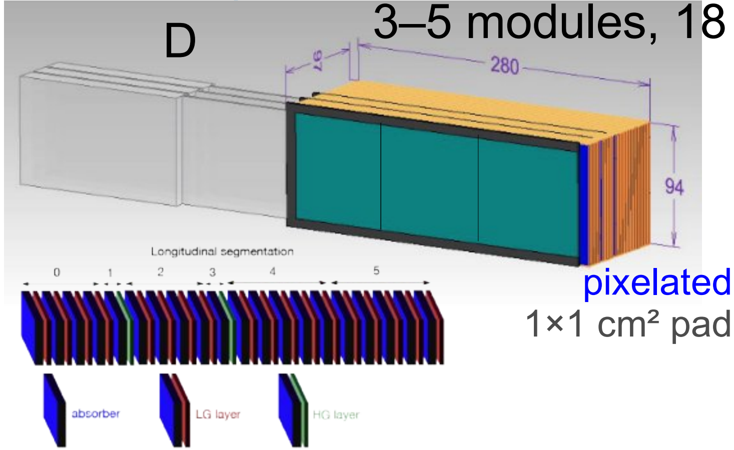
Status:

- 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...



D

3–5 modules, 18 layers

pixelated layers

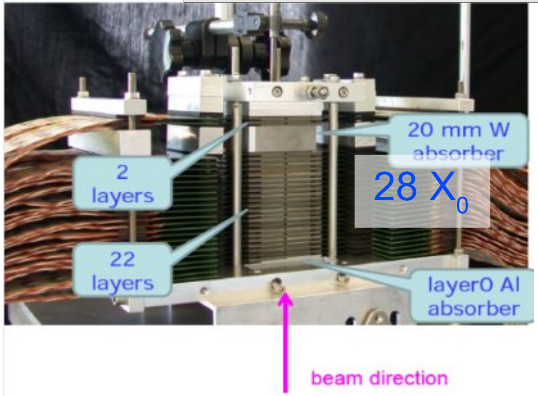
1×1 cm² pad layers

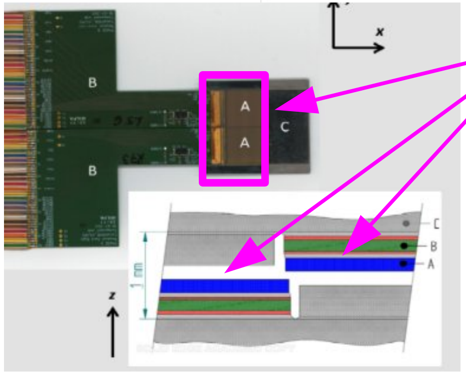
- W (3.5mm ≈ 1 X_0)
- Si-sensors:
  - Si-pads 1×1 cm² ⇒ energy measurement, timing(?)
  - 3 HG layers

FOCAL @ ALICE : MAPS aka Digital-ECAL

DECAL prototype

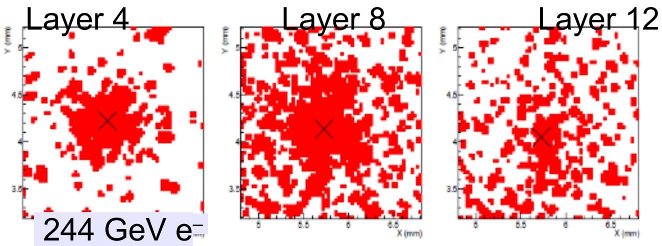
JINST 13 (2018) P01014





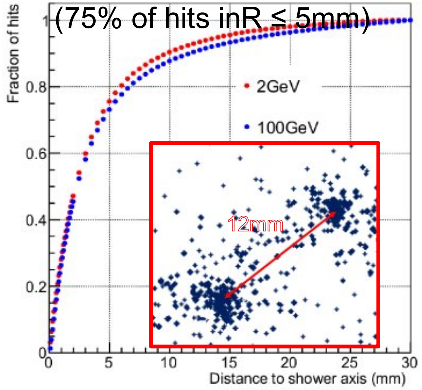
- 4 MIMOSA-26 / Layer CMOS sensors (IPHC)
  - 6×6 cm²
  - 30×30 μm² pixels
  - 39 M pixels = full readout

Ultra-compact Digital Calorimeter



R_M = 10.5mm

(75% of hits in R ≤ 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

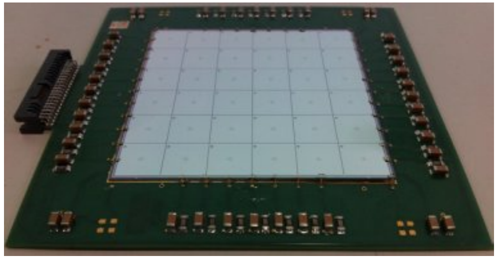
Promising!
➡ Maturity for 'fixed target' set-up
R&D needed for full det @ VHE (Power, Price)

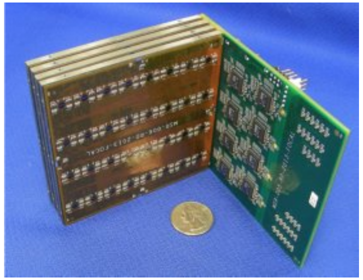
FoCal-E: Si-Pad Prototypes

Si-Pad:

NIM A764 (2014) 24

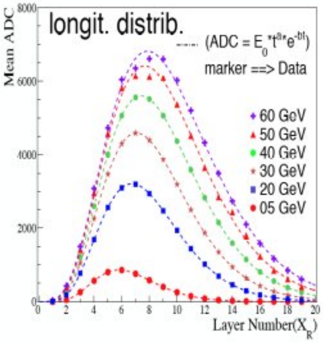
- Japan (Tsukuba) + India (VECC, BARC)
- Design close to final

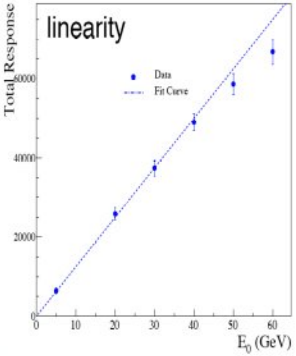


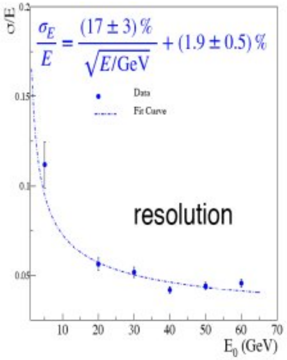


Pad Sensors
APV readout hybrids

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

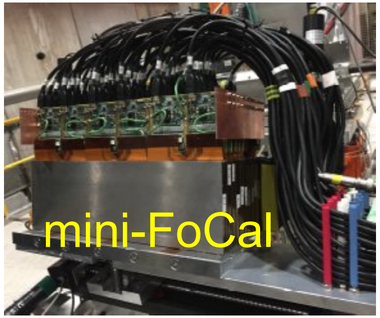


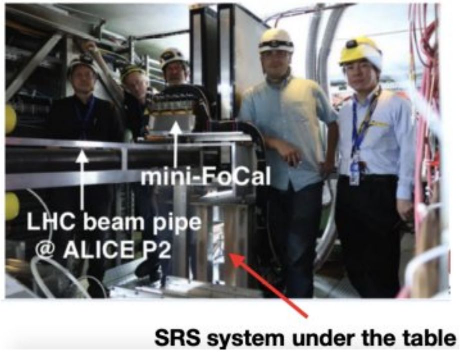


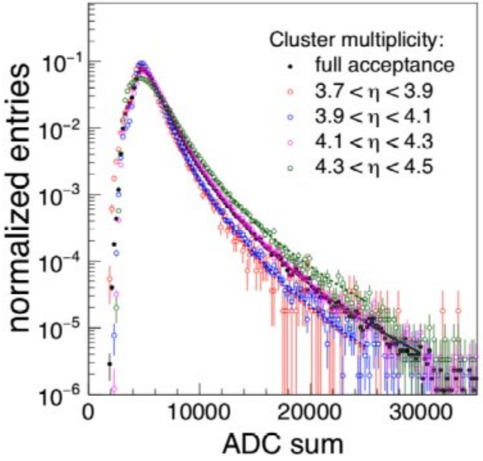


Mini-FoCal (2018-08)

- In-situ with 13 TeV collision



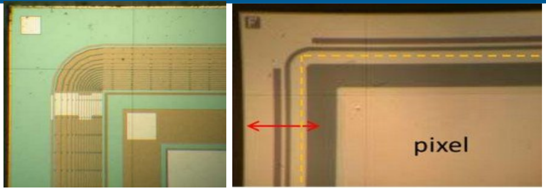




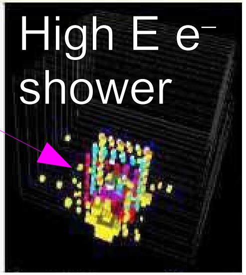
Sensors R&D

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:

  $e/h\# \propto th$, noise $\propto C \propto 1/th \Rightarrow S/N \propto th^2$
  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)
  - Gain ➡ S/N ➚, σ(t) ➘ + instabilities ?
  - Wait experience from ATLAS HGTD, CALICE

See Timing in Calorimeters
Nural Akchurin

PSD = Position Sensitive Detector

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

Caveat: almost single producer game (HPK)
➡ risk of ‘single point failure’ for large projects
➡ some EU candidates inventoried by M. Moll
but in need for investment for HEP

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Sensor R&D

More Intelligence with CMOS

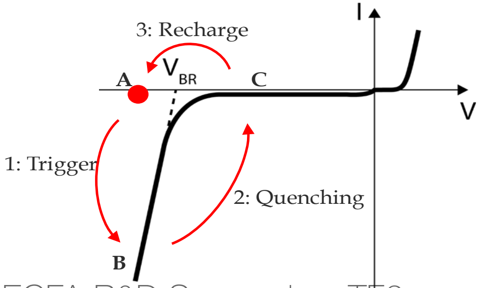
- Industry (2017): 10 nm (/10 every 15 years)
  Detectors = Ind– 20 y (130 nm ~ 65 nm)
  - ⇒ Smaller, lower-power electronics

see all of TF3 Solid State Detector presentations

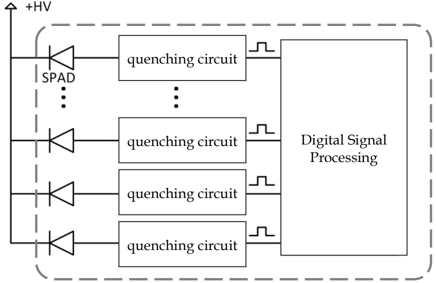
- Merging of Sensors and Amplifications and Readout ?
  - ⚠ ASIC price / mm^2 ⚠
  - Ex: FE-I4 ATLAS & CMS Tracker: linear FE chips integration of Analogue section in sensors → smaller in-print
  - **Calo: size is not really a problem (1000 µm^2 = 1‰ of a 1mm^2 pixel)** … or go 3D (€€€)
- Digital Pixels with counting: 3D dSiPM (with larger pads ?)
  - Consumption ∝ Occupancy (~1 mW/cm^2)
  - Excellent time resolution
  - Sherbrook U. (CA) + Fraunhofer

See Timing in Calorimeters
Nural Akchurin

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



Digital SiPM

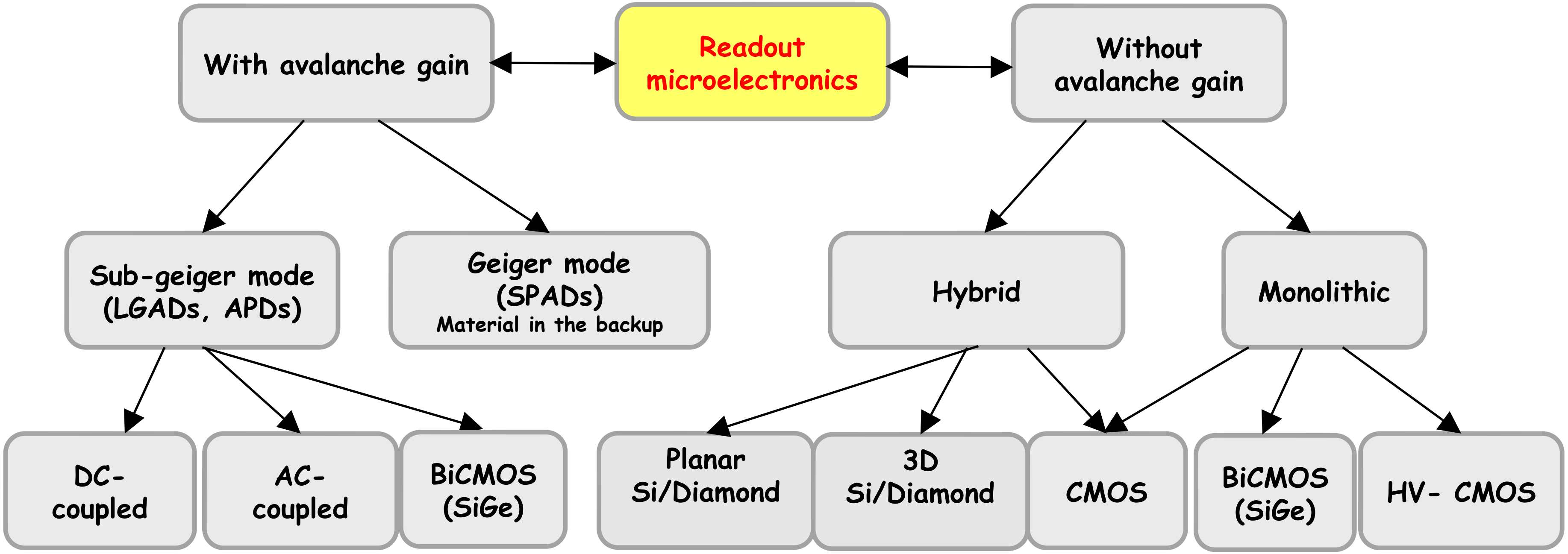


SS Detector for the future (4D) trackers

from Valerio Re (TF3 SSD)

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

Tracker devices → “Imaging Calorimeters”



With avalanche gain

Readout microelectronics

Without avalanche gain

Sub-geiger mode (LGADs, APDs)

Geiger mode (SPADs)
Material in the backup

Hybrid

Monolithic

DC-coupled

AC-coupled

BiCMOS (SiGe)

Planar Si/Diamond

3D Si/Diamond

CMOS

BiCMOS (SiGe)

HV- CMOS

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)

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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

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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 ?

Best organisation of R&D and implementation ?

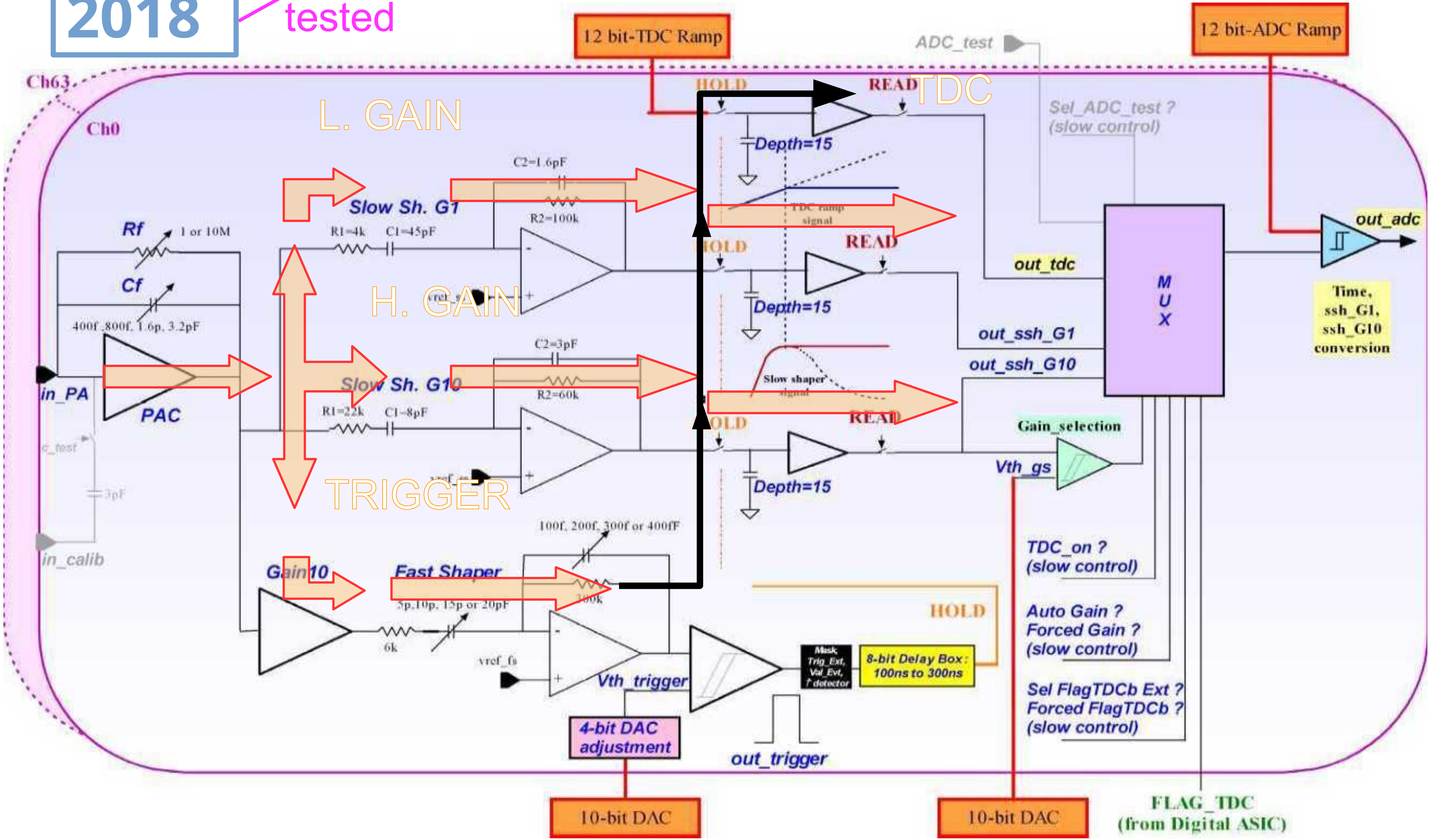
- ‘Generic’ R&D Collaborations
  - For sensors {CERN RD-like}
  - For detector integration: CALICE, FCAL
  - For experiments: ILD↔CLICdp↔CECP det, {FCC-ee, –hh}, IDEA
- European programs: AIDA-like

BACK-UP

Ωmega: SKIROC2 / 2A Analogue core

2018

tested



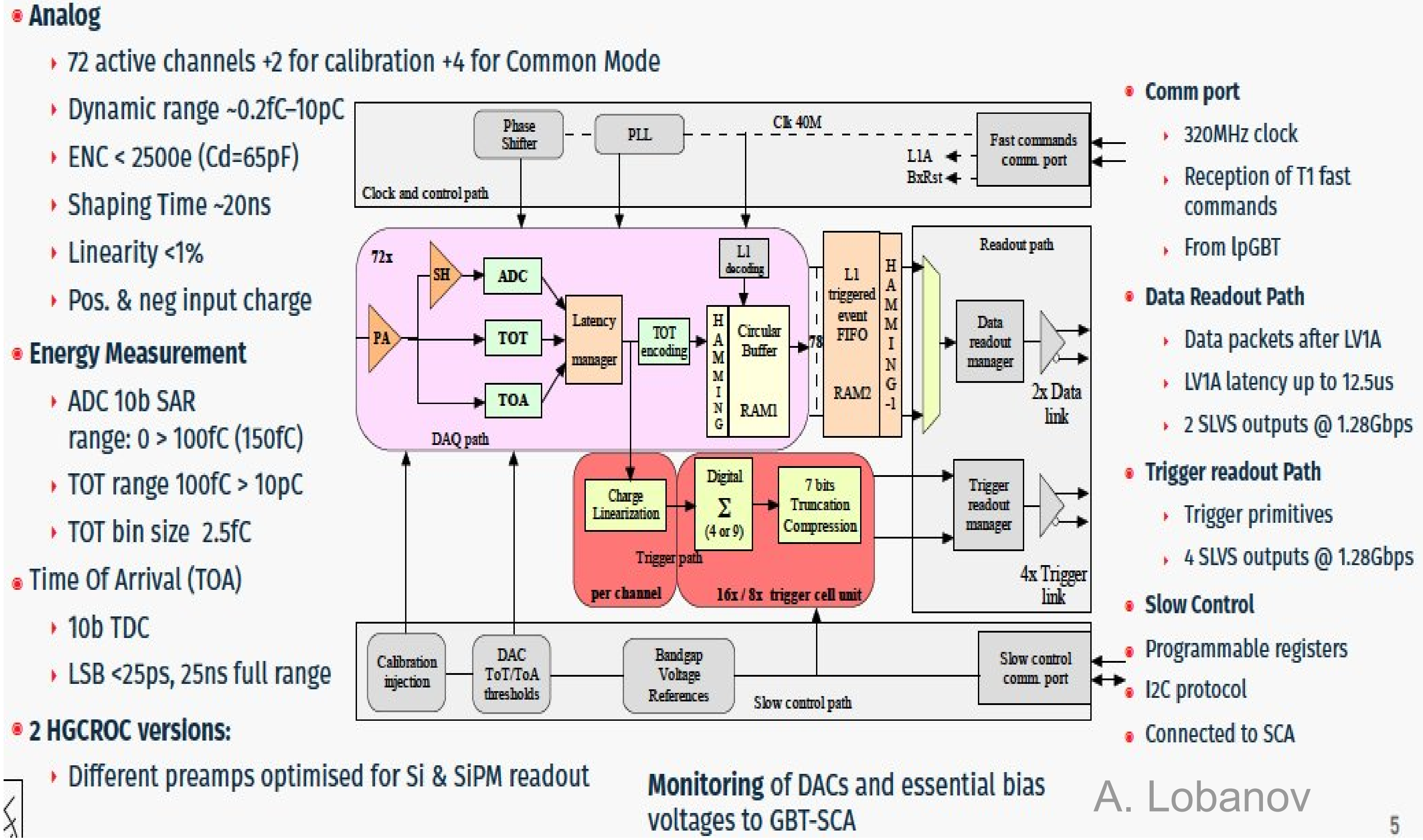
Similar to SiD Kpix

- 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 mm^2
- 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

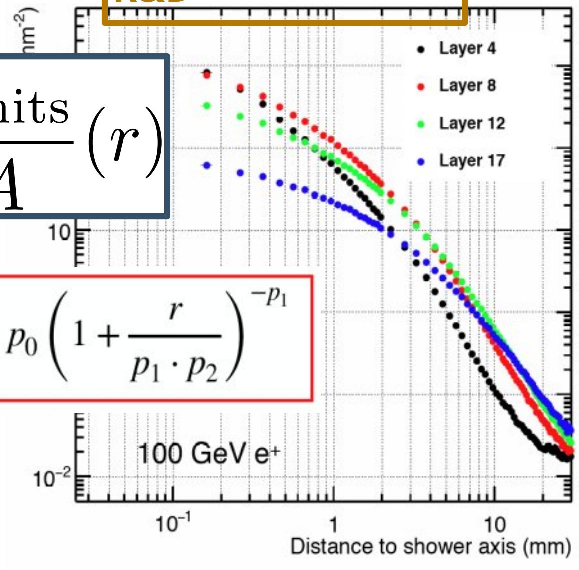
HGCROCv3 submission in 2020

DECAL: Shower profiles

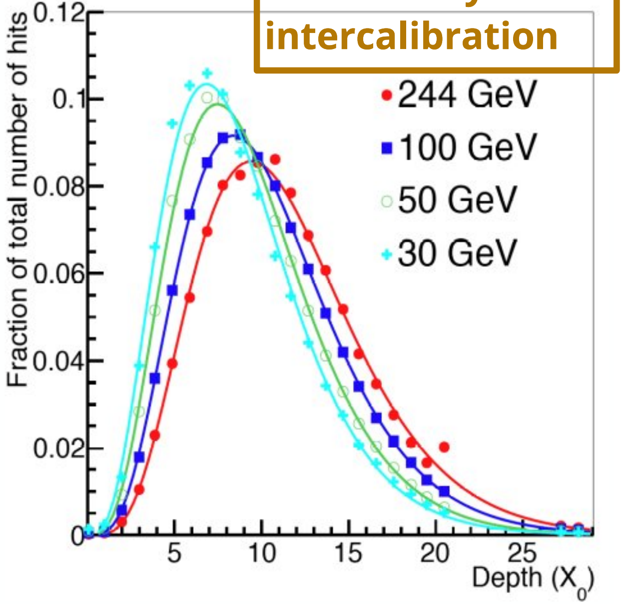
R&D

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

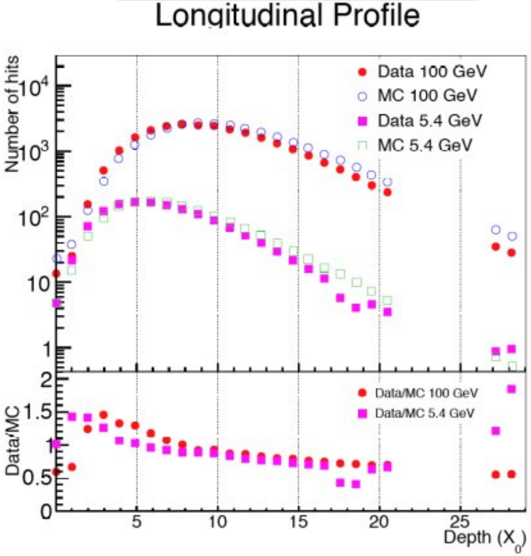
$$f_4(r) = p_0 \left(1 + \frac{r}{p_1 \cdot p_2}\right)^{-p_1}$$



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

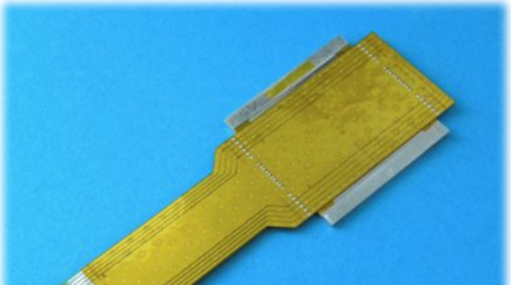
FoCal: Conclusions and todos

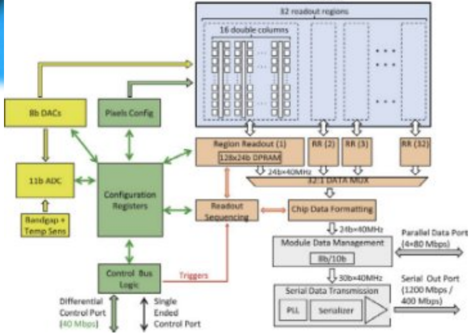
Successful running of Si-pad calorimeter at High Energy

- 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)

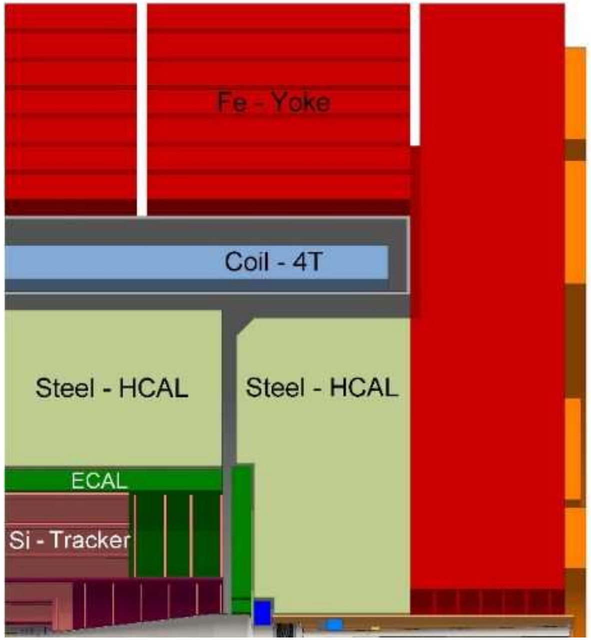
Sufficient for high occupancy ?

Construction: 2022–2026

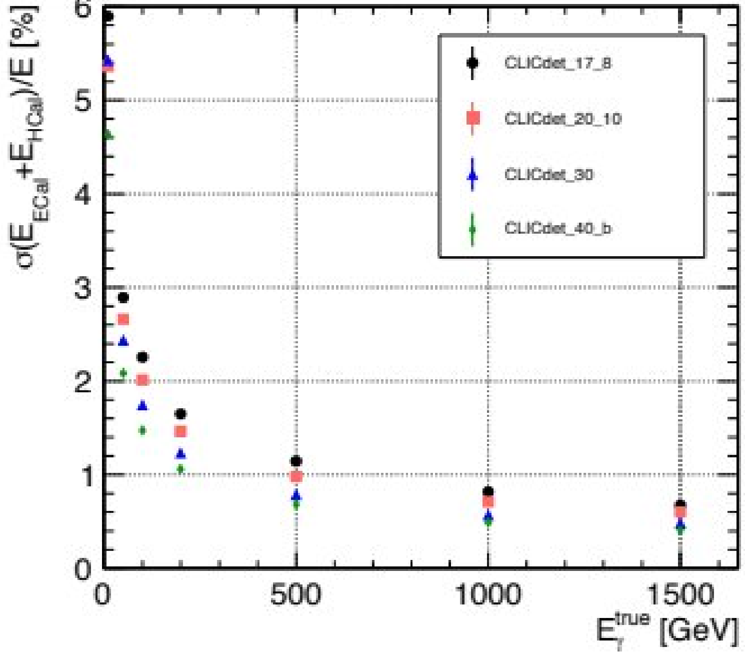
- LoI → LHCC in prep.

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

CLIC calorimeters



Energy Resolution for central high energy photons



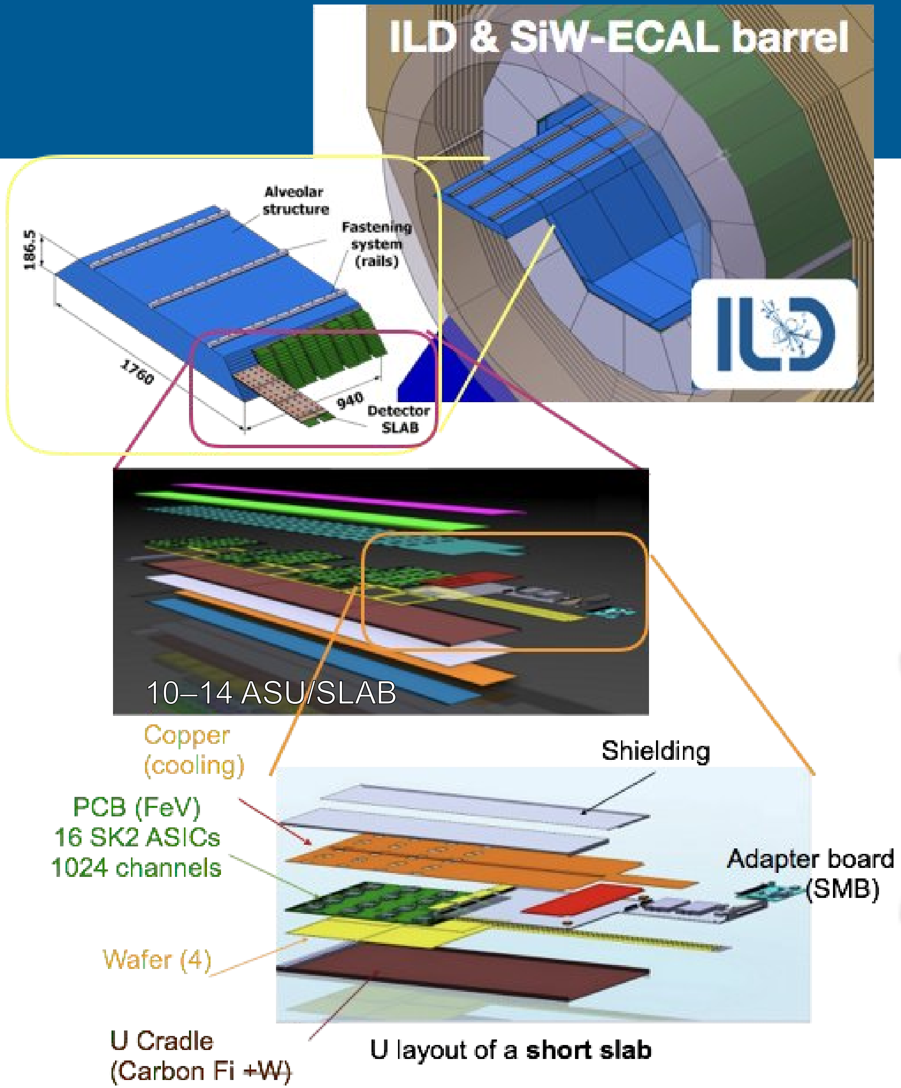
ECAL Optimization:

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

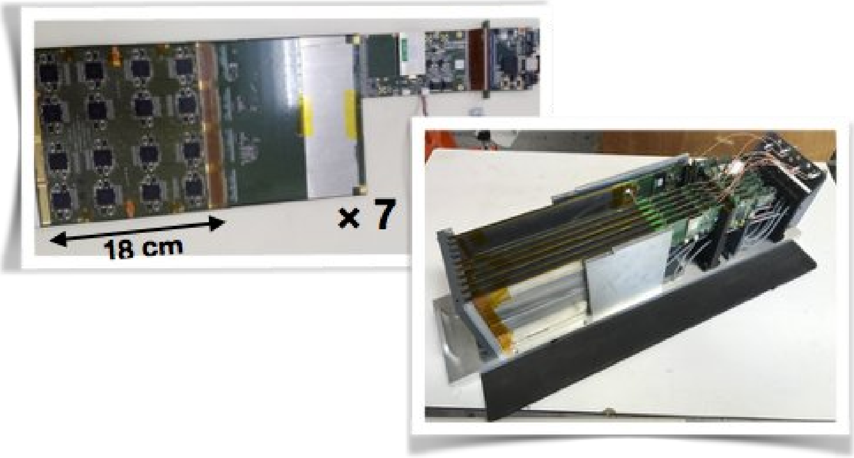
Large Scale Building



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, ...



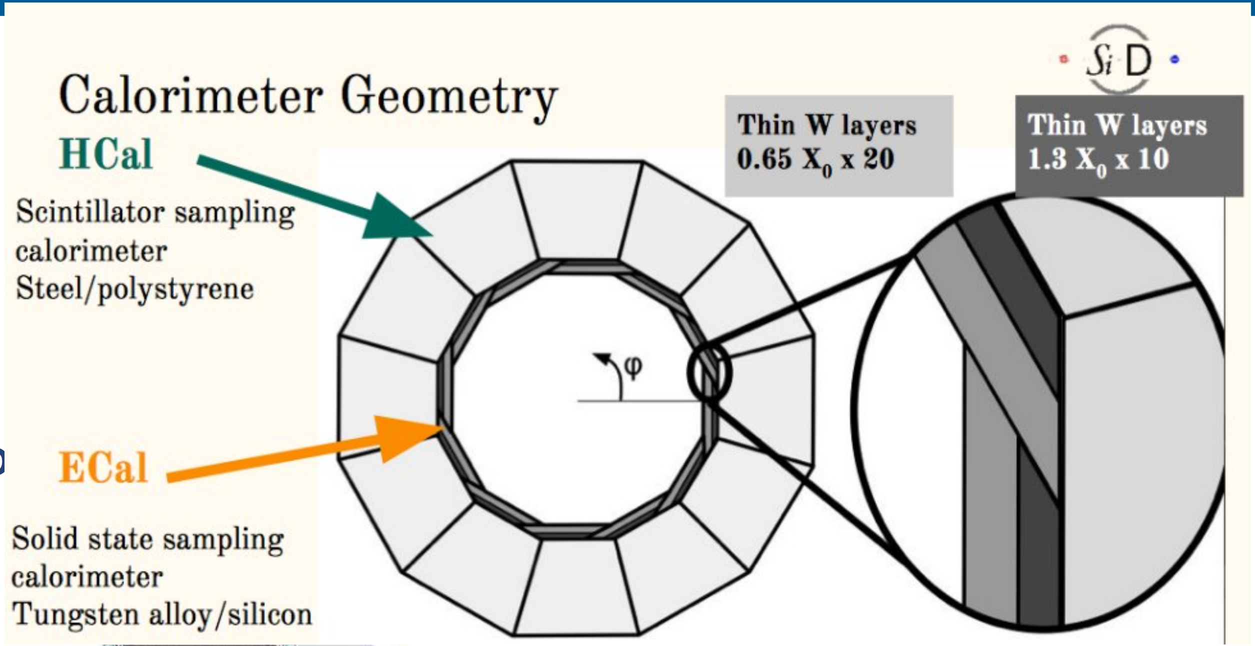
SiD SiW-ECAL

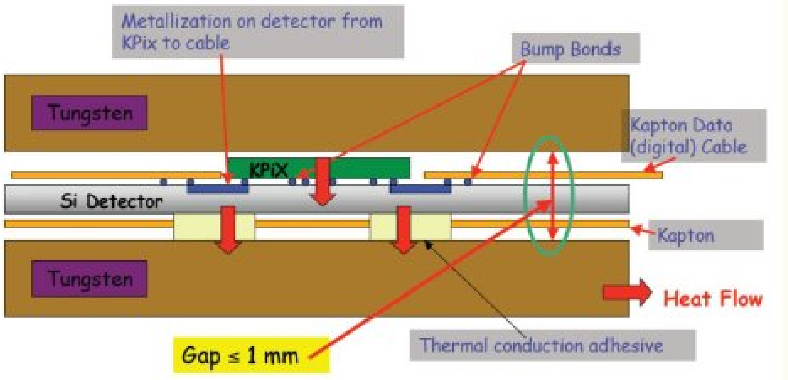
20 + 10 layers

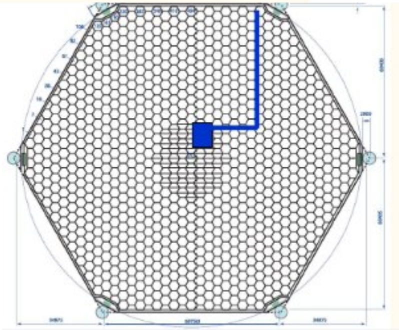
1.25 mm gap between W layers

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

Tungsten plates ⇒ thermal bridge to co







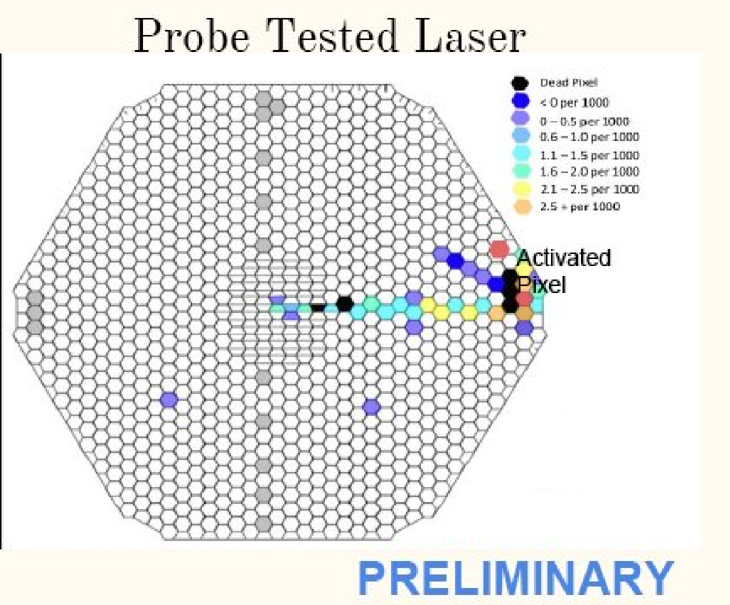
Hexagonal Wafers (optim material)

1 Kpix Chips (1024 ch) per Wafer

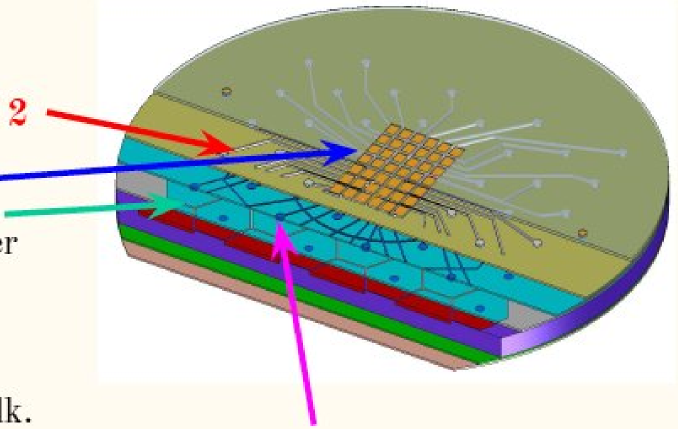
- Bump Bounder on Sensor.

Prototype testing

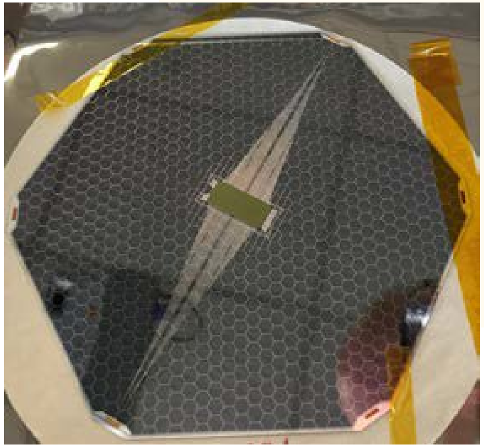
Laser injection in single pad



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

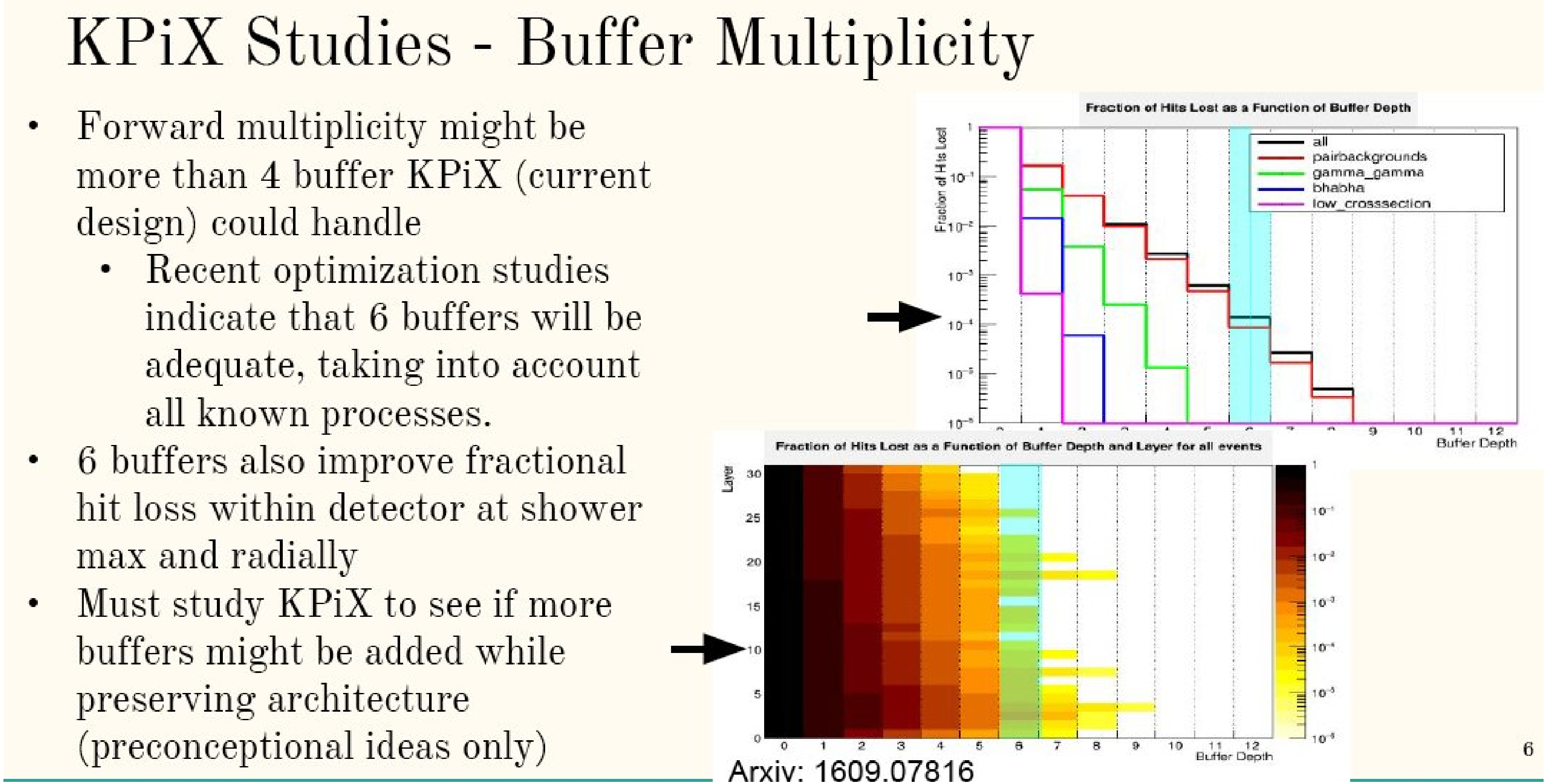


New scheme has “same” metal 2 traces, but a fixed potential metal 1 trace shields the signal traces from the pixels.



Occupancy

A. Steinhebel @ ALCW2017

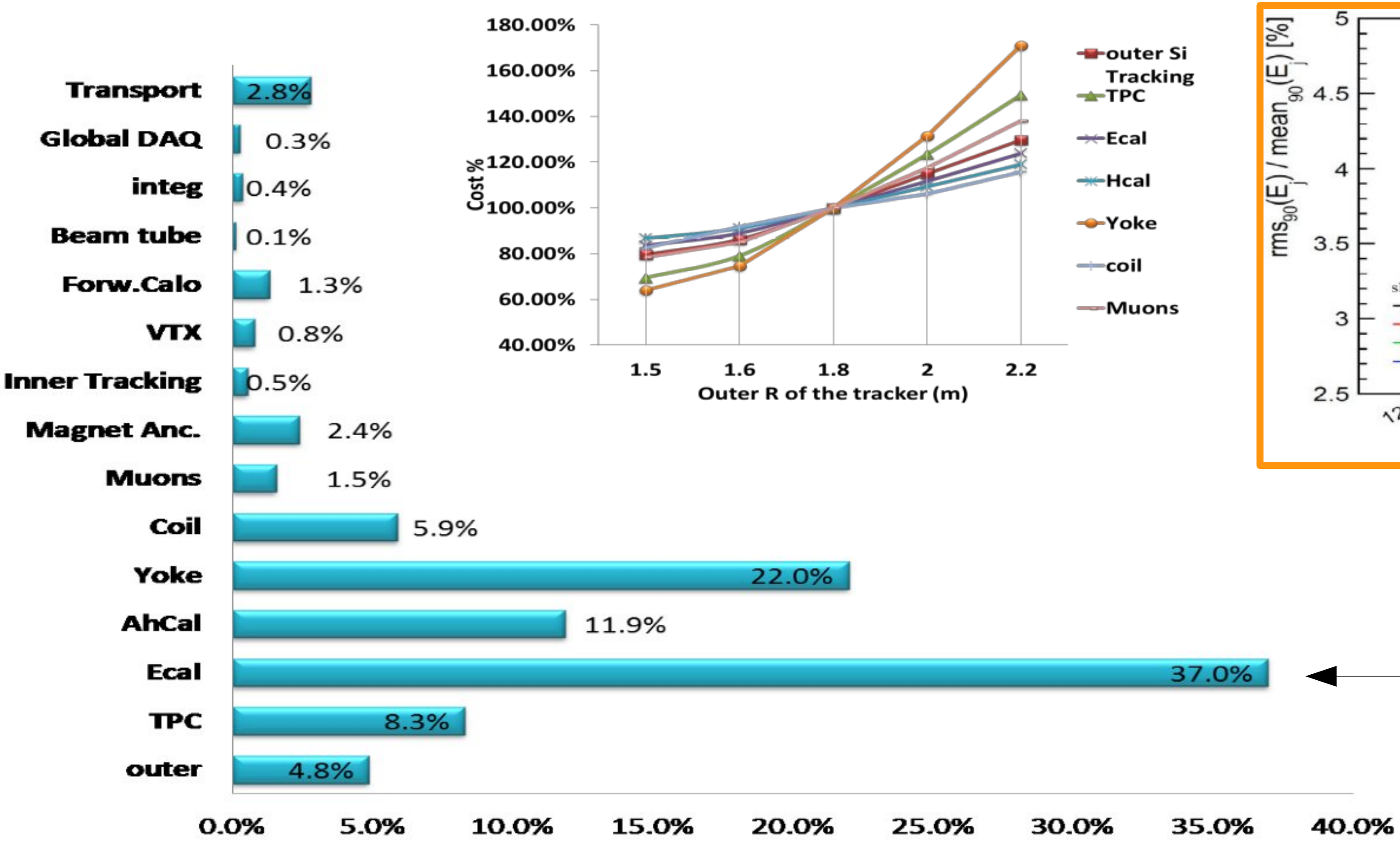


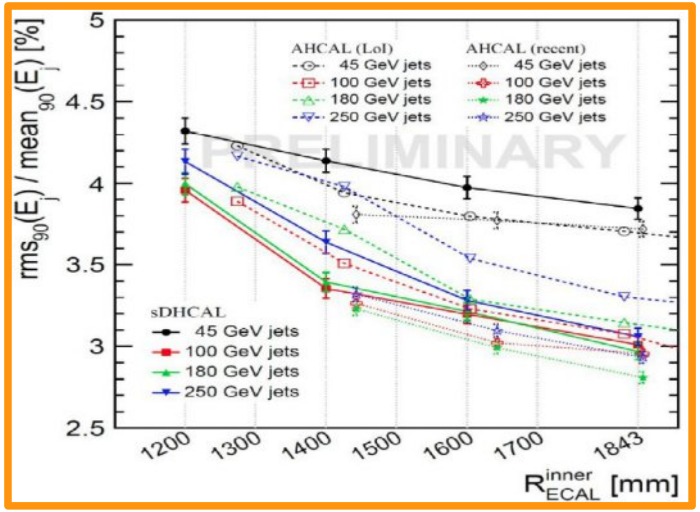
KPiX Studies - Buffer Multiplicity

- 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

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:

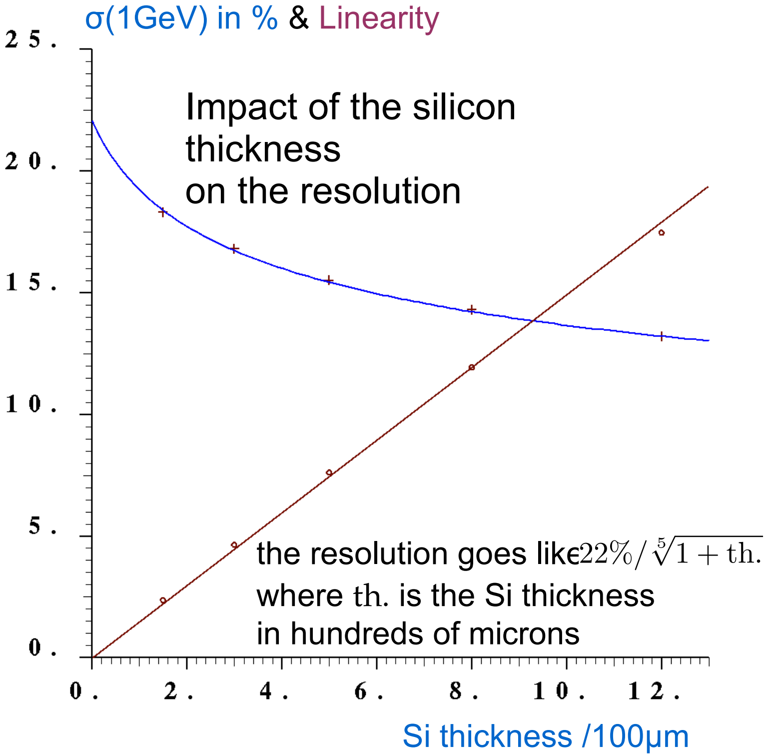
- for 22 layers w.r.t. 30: +16.8%
- with 725µm w.r.t 500µm : –6.1%

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.

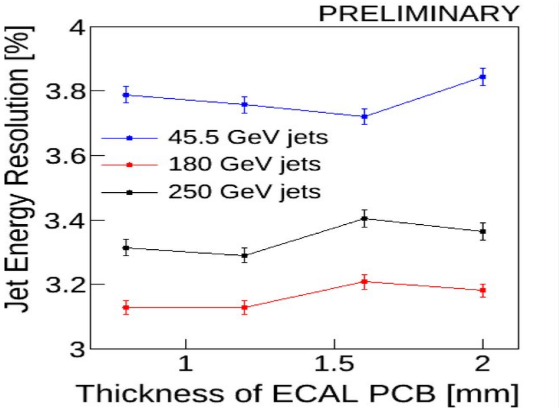
Study needed on separation, resolution and efficiency performances at low energy.

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

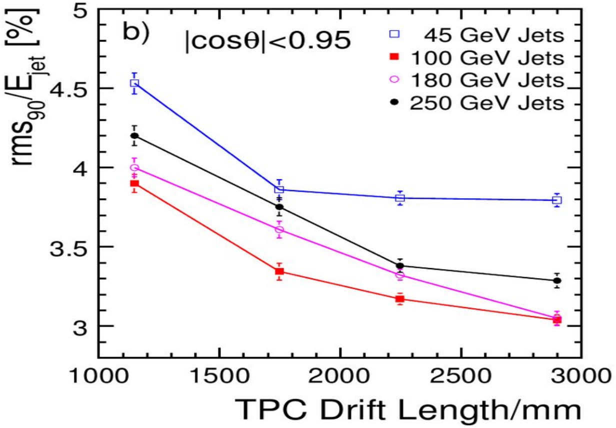


Impact of the silicon thickness on the resolution

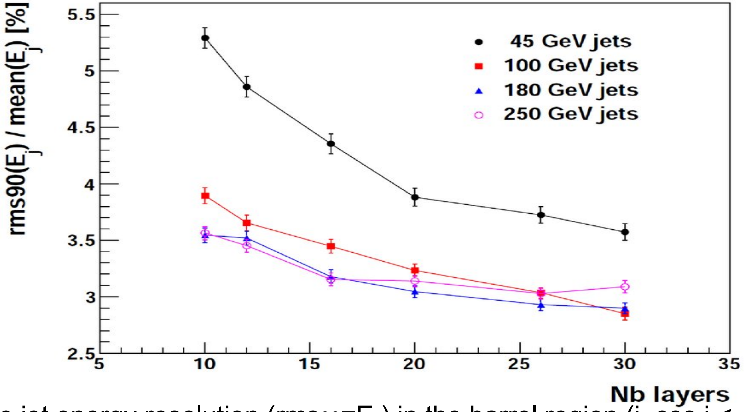
the resolution goes like $22\%/\sqrt[5]{1+\mathrm{th.}}$
where $\mathrm{th.}$ is the Si thickness
in hundreds of microns



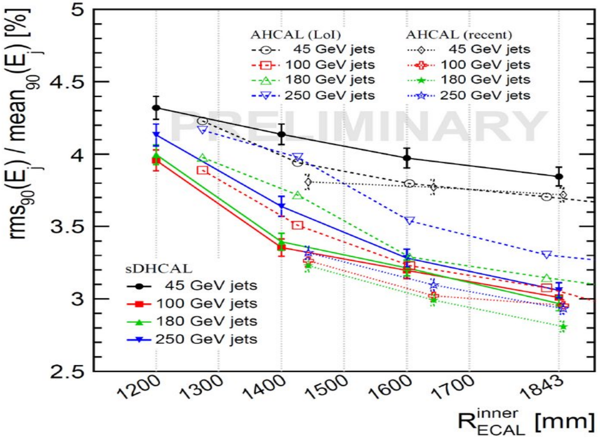
Single jet energy resolution as a function of the thickness of PCB with embedded electronics.



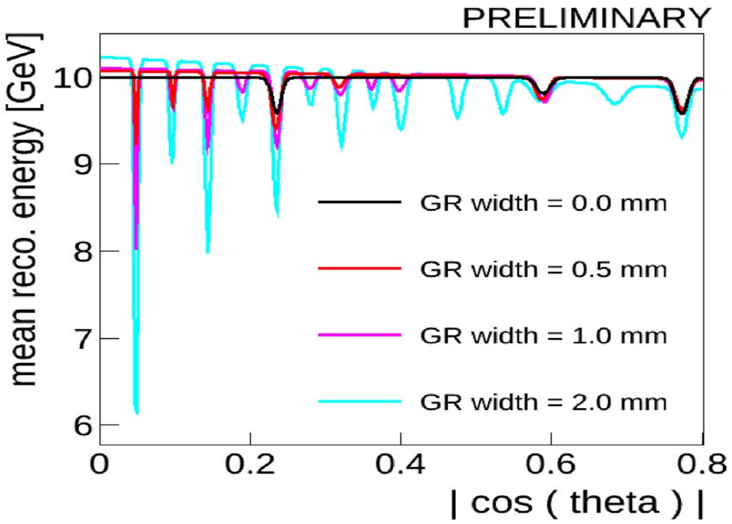
Single photon energy resolution as a function of the number of silicon layers for four photon energies.

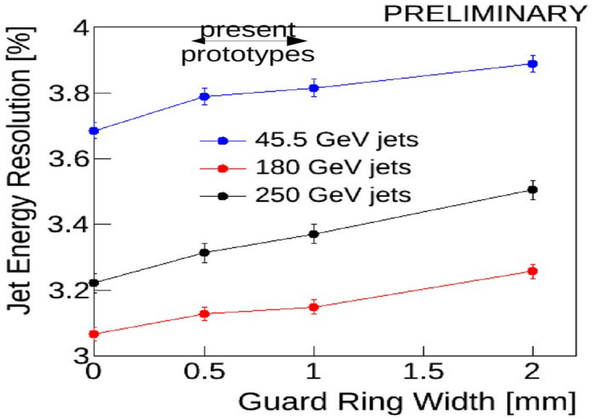


Single jet energy resolution (rms90=E) in the barrel region (j cos j < 0: 7) as a function of the number of ECAL silicon layers in events e+e-→ ZX → usd



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

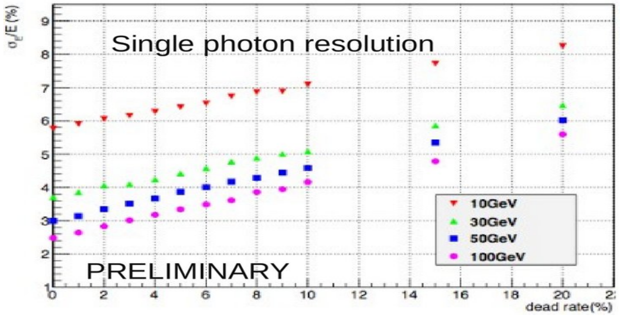


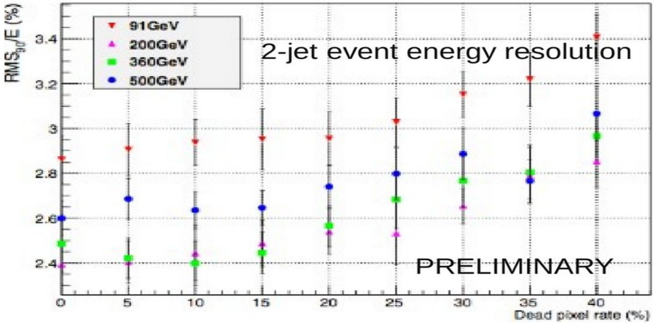


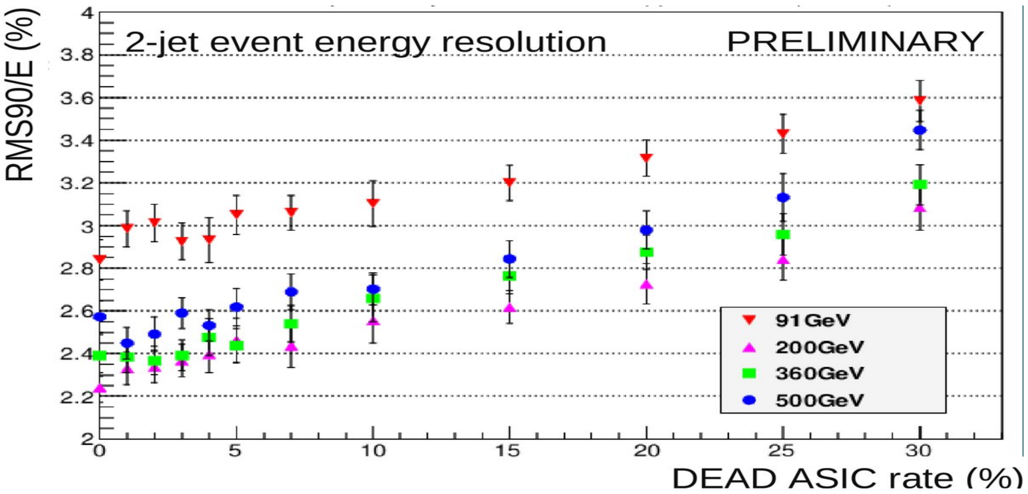
the single jet energy resolution after a simple dependent correction as a function of the guard ring thickness.

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).

Resilience


Single photon resolution
σ_E/E (%)
9
8
7
6
5
4
3
2
1
PRELIMINARY
10GeV
30GeV
50GeV
100GeV
0
2
4
6
8
10
12
14
16
18
20
dead rate(%)


RMS_{90}/E (%)
91GeV
200GeV
360GeV
500GeV
2-jet event energy resolution
3.4
3.2
3
2.8
2.6
2.4
PRELIMINARY
0
5
10
15
20
25
30
35
40
Dead pixel rate (%)


RMS90/E (%)
2-jet event energy resolution
PRELIMINARY
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
91GeV
200GeV
360GeV
500GeV
0
5
10
15
20
25
30
DEAD ASIC rate (%)