



ALICE

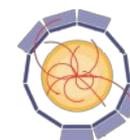
Calorimètres Silicium Compacts Ultra-Granulaires

Vincent Boudry

École polytechnique, Palaiseau

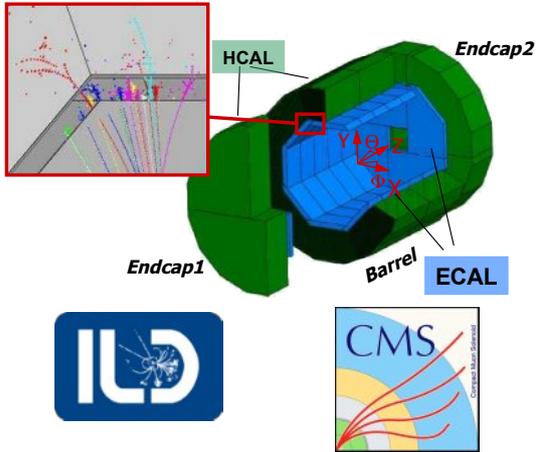
LMR

**Prospectives IN2P3 GT8
23 jan 2020 @ IJCL**



AIDA 2020

Ultra-Granular Compact Si-ECAL for experiments



Particle Flow calorimetry

Standard requirements:

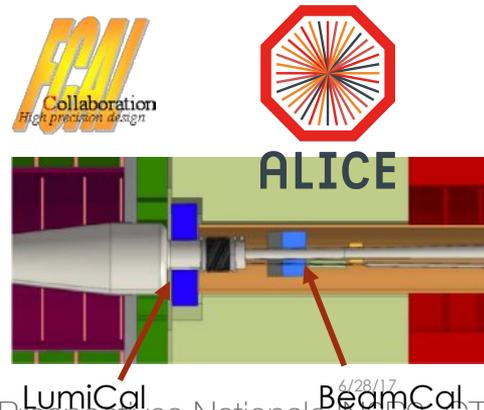
- Hermeticity, Resolution, Uniformity & Stability ($E, (\theta, \varphi), t$)

PFlow requirements:

- Extremely high granularity
- Compactness (density)

Forward calorimetry

- High precision
- High data fluxes
- Radiation Hardness



Tungsten as absorber material

$$X_0 = 3.5 \text{ mm}, R_M = 9 \text{ mm}, \lambda_I = 96 \text{ mm}$$

- ⊕ **Narrow showers** → good separation in jets
- ⊕ **Ensures compact design** → cost red. (ext. layers)
- ⊕ **Good rigidity** ⊖ **difficult machining, cost**

Second choice (HGCal): Lead + Copper

Silicon (highly resistive) as active material

- ⊕ **Support compact design: Sensor+RO ≤ 2mm** with minimal dead spaces
- ⊕ **Allows for ~any pixelisation**
- ⊕ **Robust technology (processing, rad. resist.)**
- ⚠ **fragile handling**
- ⊕ **Fast & Excellent signal/noise ratio: ≥ 20**
- ⊕ **Intrinsic stability (vs environment, aging)**
- ⊖ **Albeit expensive ! (~ 1-2\$/cm² for simple diodes)**

SiW-ECAL's: a brief historical perspective

Beam and Luminosity Monitors

- Small EM calorimeter: precision positioning, fast return
- in view of LEP (1986)
- SLD (1991)

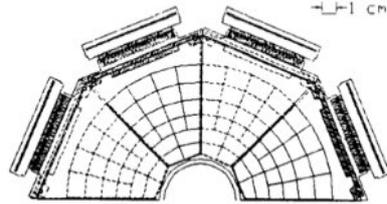


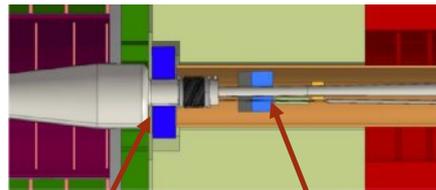
Figure 2. Front face of one LMSAT module as seen from the IP. Detectors shown with dashed lines have their ground planes facing away from the IP.

Forward Calorimeters

- Compact, small.
- FCAL collaboration for Future ee Colliders
 - LumiCal, LHCAL, BeamCal

FOCAL @ ALICE

Ultra-High Granularity

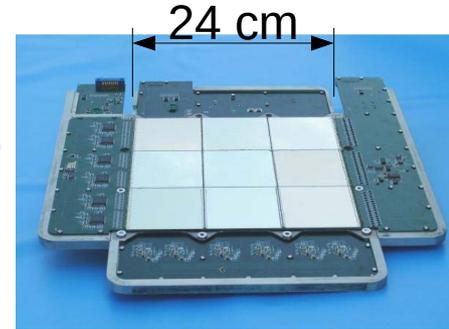


LumiCal

BeamCal

Full size calorimeters

- Ballon & Space experiments
 - FERMI (2008), PAMELA (2006)
- Large experiments
 - SSC proposal (1984) †
 - e+e- collider proposals:
 - SiD SiW-ECAL (US ILC): design & prototype



CALICE/ILD SiW-ECAL

ILC, CEPC, CLIC, FCC-ee

- LHC upgrades (2026)
 - HGTD → Tracking with HP timing

CMS-HGCAL

- large numbers of ch.
- integration
- cooling
- uniformity
- Very precise timing

Common Challenges

Integration

- Embedded electronics
 - Low noise (small cells, large dynamics: $\frac{1}{2}$ –3000 mips)
- Design combining:
 - Mechanics, Electronics, Cooling

Large number of channels

- Scalable design
 - Quality chain
 - Semi-automated assembly
- Calibration & monitoring

CALICE / ILD

Requirements from Physics

Basis: sep of $H \rightarrow WW/ZZ \rightarrow 4j$

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

$\Rightarrow \sigma_E/E \text{ (jets)} < 3.8\%$

– Sign $\sim S/\sqrt{B} \sim (\text{resol})^{-1/2}$
 $60\%/\sqrt{E} \rightarrow 30\%/\sqrt{E} \Leftrightarrow +\sim 40\% L$

Large Tracker

- Precision and low X_0 budget
- Pattern recognition

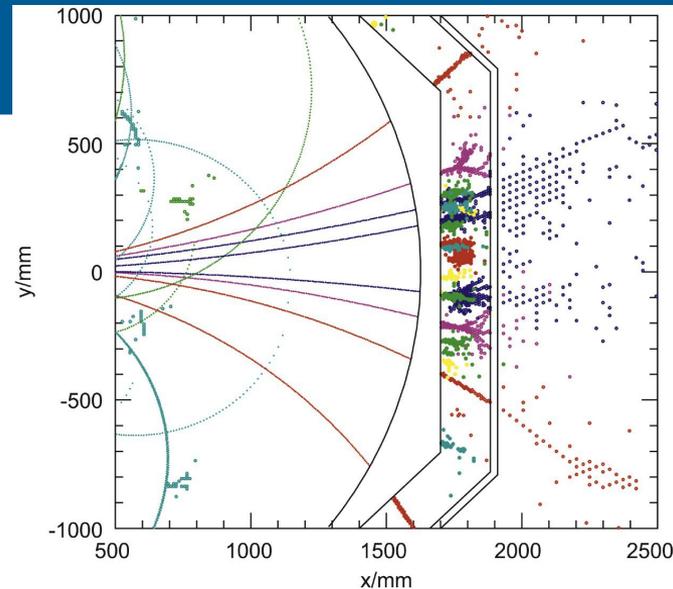
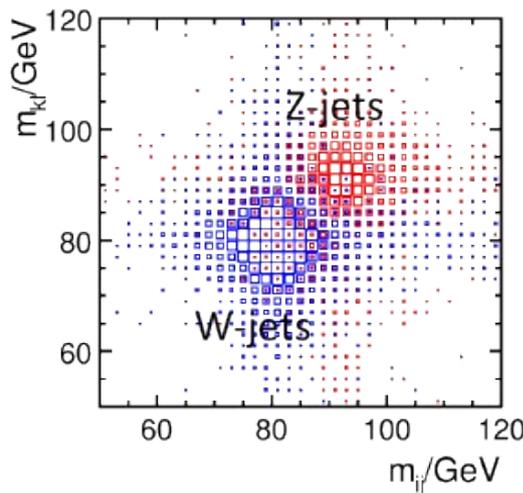
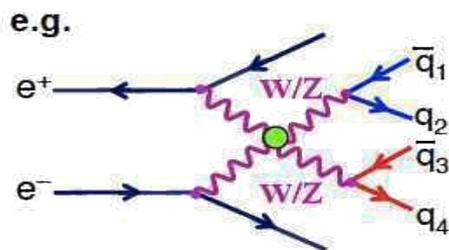
High precision on Si trackers

- Tagging of beauty and charm

Large acceptance

Fwd Calorimetry:

- lumi, veto, beam monitoring



Photons in jets
Tau physics (γ vs π_0)
2/3 of Hadr IA in ECAL

Particle Flow Algorithms :

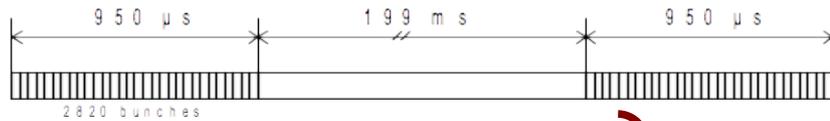
- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 CALO's
- TPC $\delta p/p \sim 5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 10 \mu\text{m}$ + timing ?

HG Imaging Calorimetry

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

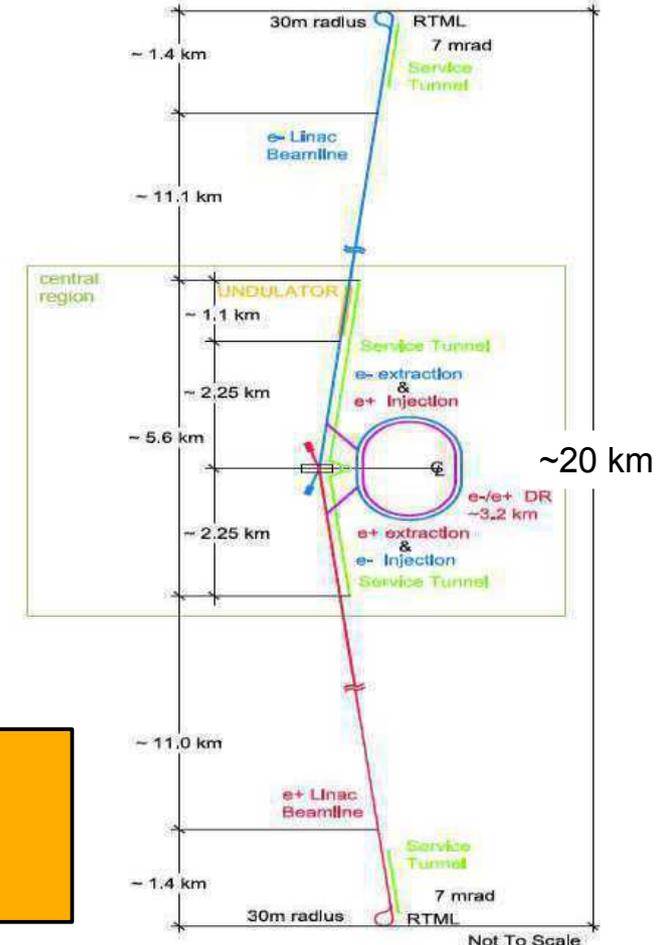
ILC parameters

Max. Center-of-mass energy	250–500 (90)	GeV
Peak Luminosity	$0,8–3 \times 10^{34}$	$1/\text{cm}^2\text{s}$
Beam Current	5.8	mA
Repetition rate	5 (10)	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	120-300	MW



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

- High B field
- Trigger-less
- Power Pulsing ($\leq 1\%$)
- Differed readout



CALICE SiW ECAL: Physics & Technological prototypes

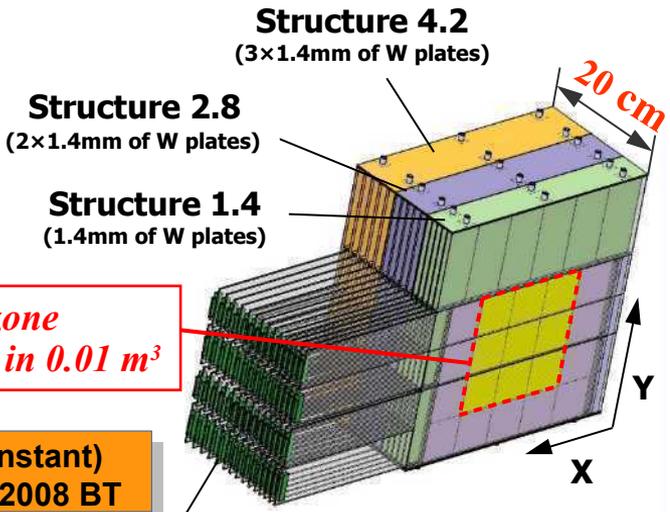


Physics prototype: 2005–2011

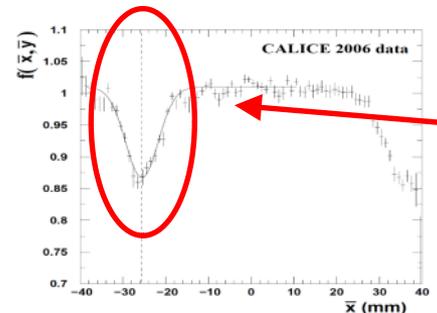
PFA proof of concept with comparison to MC Electronics outside

- $1 \times 1 \text{ cm}^2$ pixels

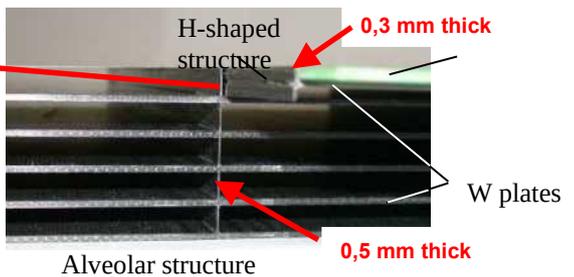
Active zone
~10000 pixels in 0.01 m^3



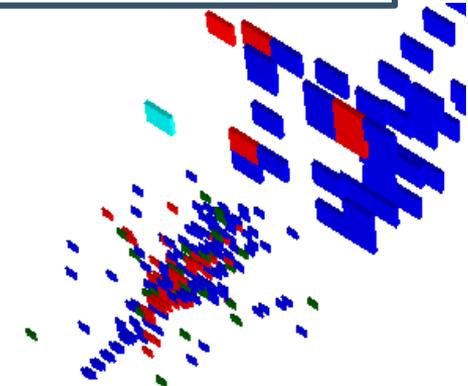
16.5% (stochastic) 1–2% (constant) with 1–45 GeV e^-/e^+ at 2006/2008 BT



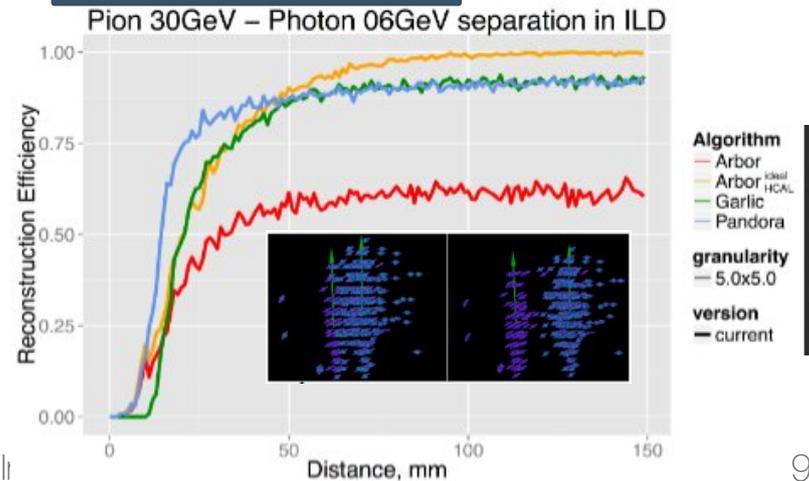
Detector slab (x30)



GEANT4



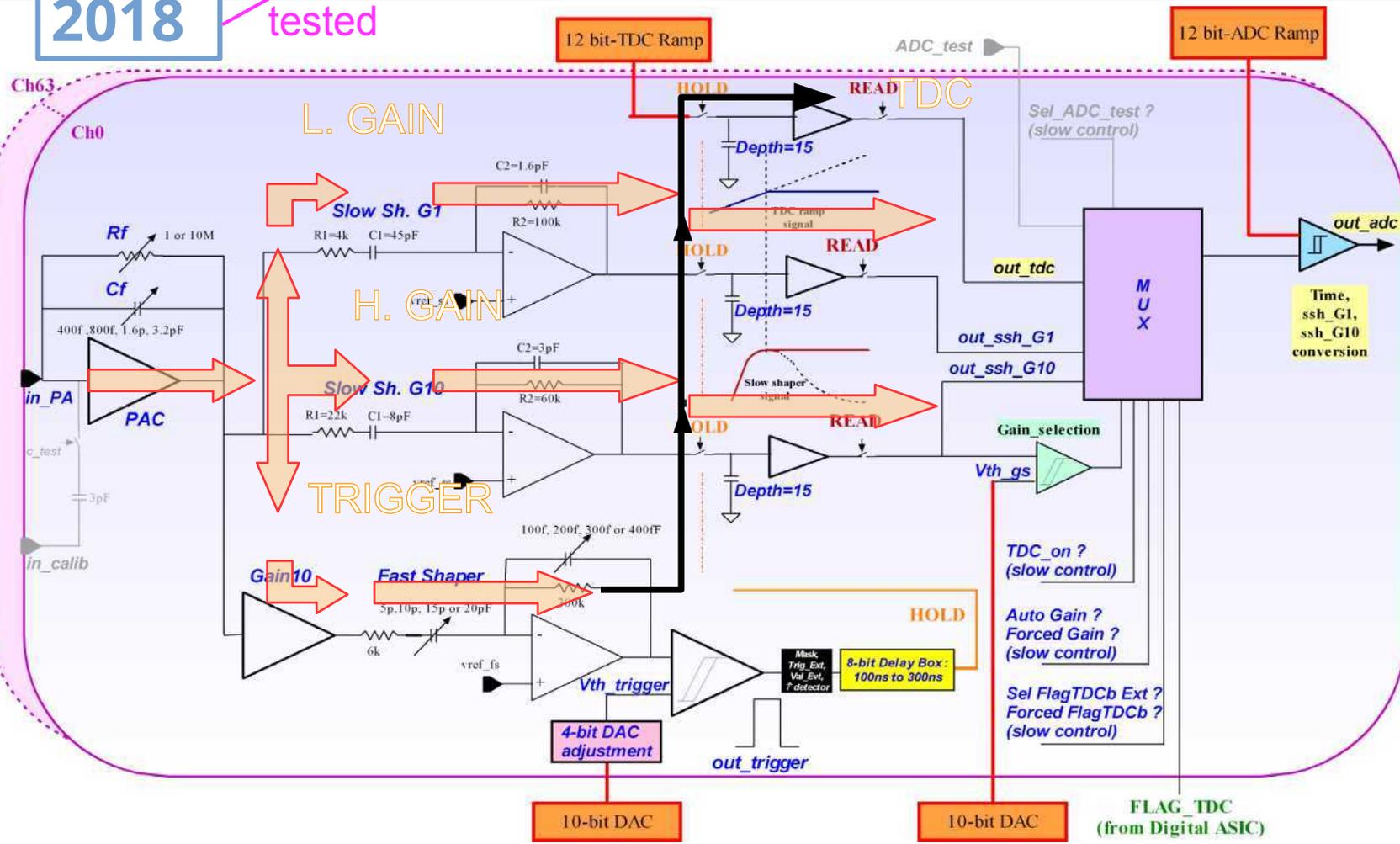
PFA reconstruction



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 (x2) analogue memories
- Low consumption
 - 25 μ W/ch with 0.5% ILC-like duty cycle
- Power-pulsed
- OK sf retrigger

SKIROC3 needed (full 0-suppr.)

SiW-ECAL Building blocks: SLAB's & ASU's

R&D for "mass production" and QA

- Modularity → Building blocks: ASU & SLABs
- Choice of square wafers
 - (≠ from hex: SiD, CMS HGCal)
- Glued wafers

Large quantities

- Modules: 40 (barrel) + 24 (endcaps, 3 types)
- ASUs = ~75,000
 - Wafers ~ 300,000 (2500 m²)
 - VFE chips ~ 1,200,000
 - Channels: 77 Mch
- Slabs = 6000 (B) + 3600 (EC) = 9600
 - ≠ lengths and ending

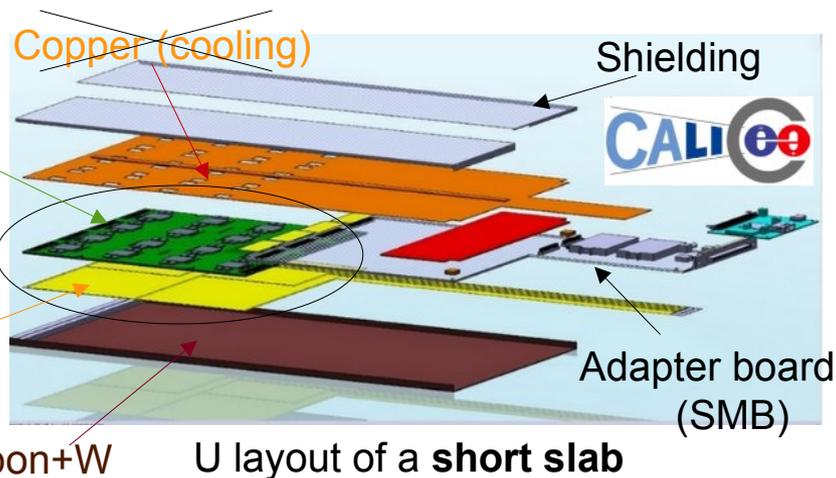
Tests of
producibility

PCB (FeV)
16 SK2 ASICs
1024 channels

ASU

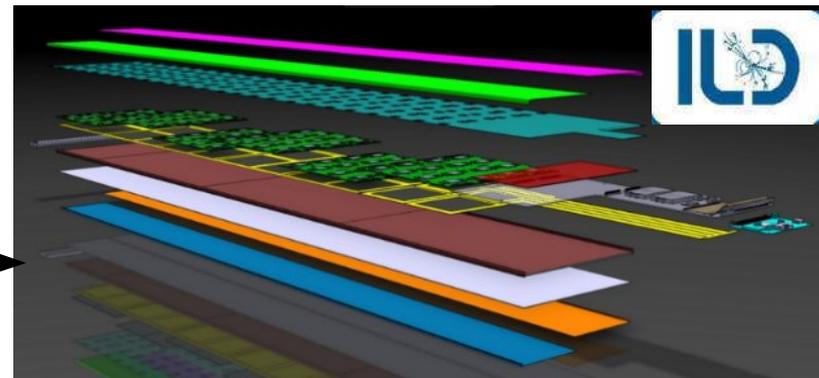
Wafer (4)

Carbon+W

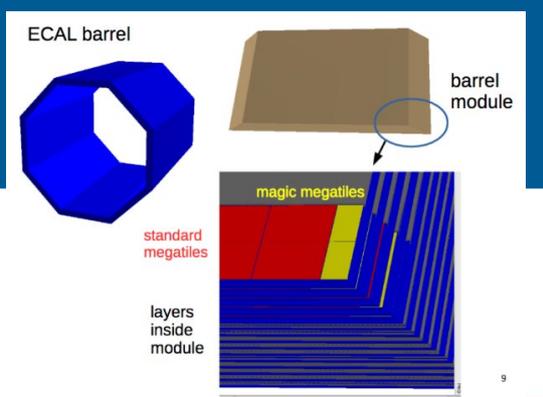
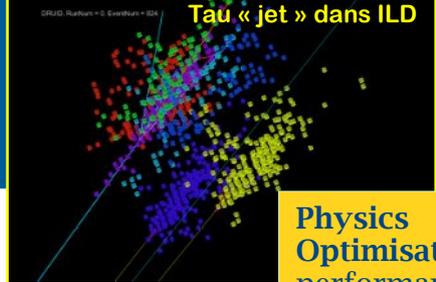
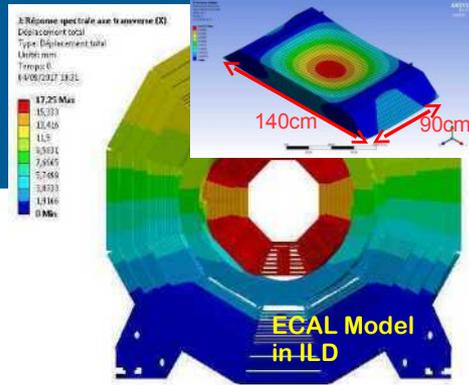


U layout of a **short slab**

Tests of feasibility



U layout of a **long slab**



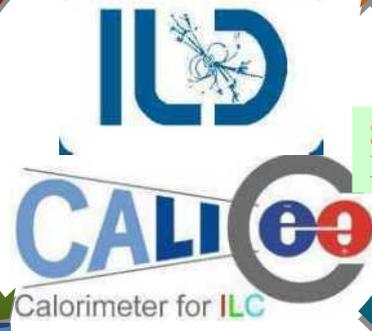
Physics Optimisation of performance:
 - Z-jets, Tau's
 - ILC, CEPC

PFA tools Pandora, ARBOR, GARLIC

Systems
 - Mechanics
 - Integration
 - Cost

Simulation:
 Mokka / DD4HEP

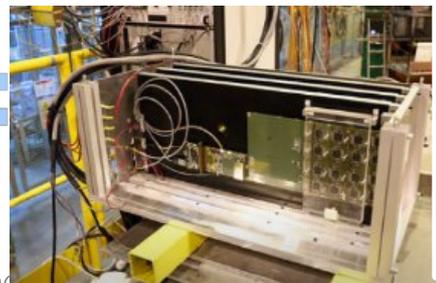
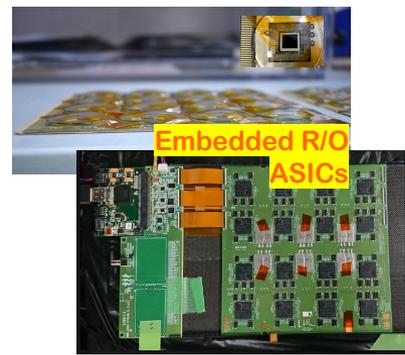
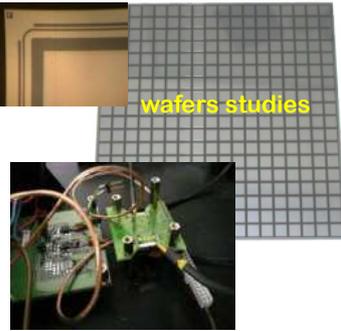
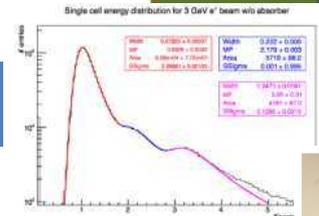
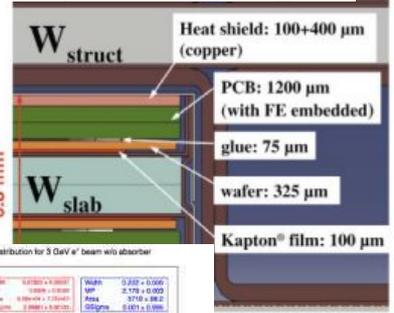
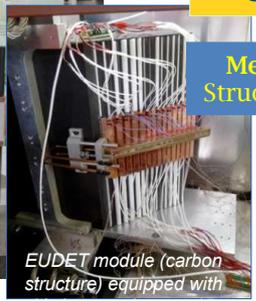
Mechanics R&D
 Structure & Services



R&D Instrum.:

Prototypes
 Building & testing

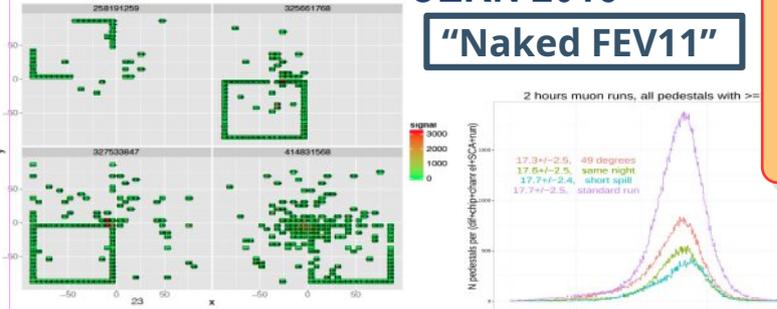
R&D DAQ



Beam-test 2015-2018

CERN 2015

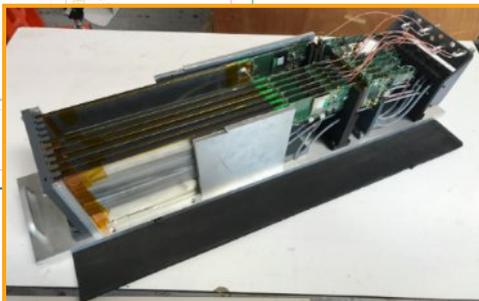
"Naked FEV11"



$$S/N_{ADC} = 16-17$$

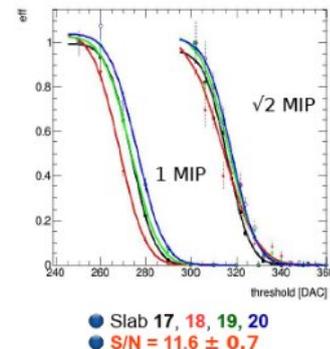
$$(MIP - ped) / \sigma_{ped}$$

- Defaults cataract :
- Negative signals
 - re-triggers
 - ~ high thr.
 - sq events / 10



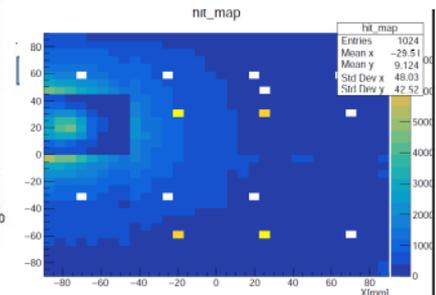
DESY 2018

7 FEV11 + 1 FEV13(650μm)



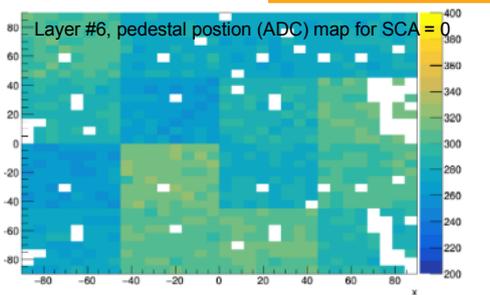
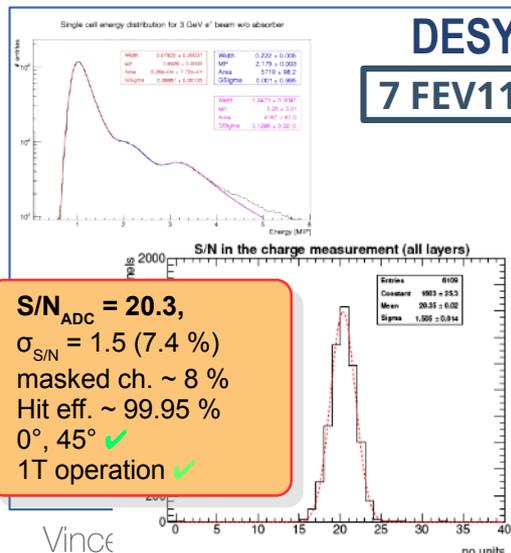
$$S/N_{Trig} \sim 11.6 \pm 0.7$$

Trigger → ~1/3 mip (est.)
First comm. of FEV13



DESY 2017

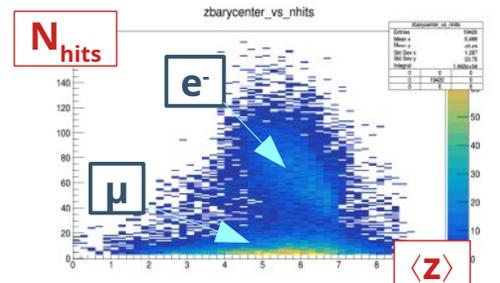
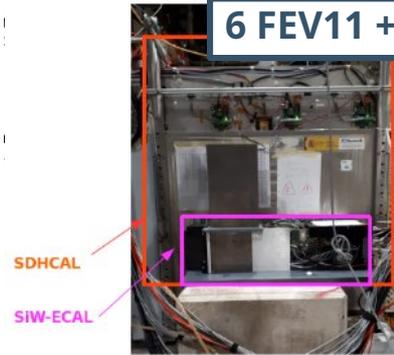
7 FEV11



CERN 2018

6 FEV11 + 4 FEV13(320 & 650μm) + 24X₀ W

Masked ch (FEV11) ~ 4 %



Summary & ToDo's

Basic Detector Building blocks ✓

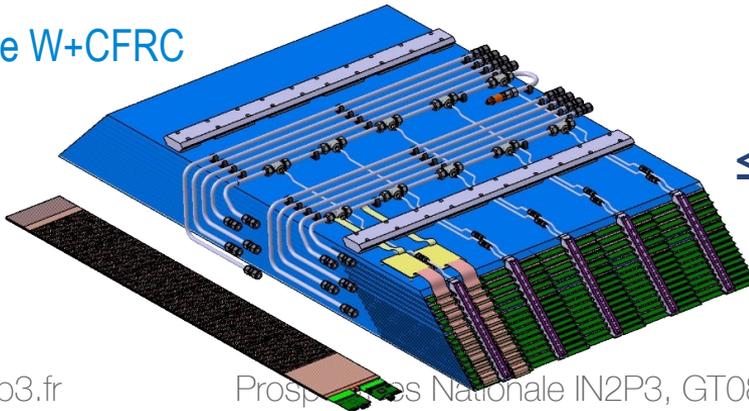
- Electronics + PCB + Wafers : S/N ~20 (≥ 10 in trigger)
- Reliance and Options being tested

Integration in large cassette: ✓

- Design with larger & thicker wafers
- Compact DAQ

Integration in detector: ✓ but “on-hold”

- Large Structure W+CFRC
- Cooling
- Powering



2020: Complete the building and testing of a stack of ASU

- 16–18 layers ($18 \times 18 \text{ cm}^3$)
- Pros/cons of different designs

Prepare the design of long slabs with all constrains

- Thicker & larger wafers ? ($8'' \times 700 \mu\text{m}$ wafers)
- 1.5 m long, 8–12k channels
 - connections, noise & power issues...
 - prototype for industry contact
- \Rightarrow Design of a final ASIC (full-zero suppr.)

$\leq 2024-5?$ Build a stack of long slabs

- Testing & Tuning of an assembly chain
- Prepare the construction ~5–6 years

CMS-HGCAL

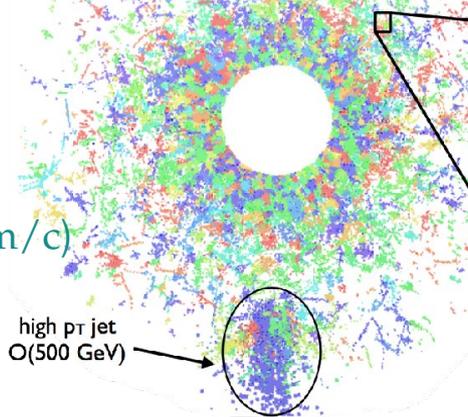
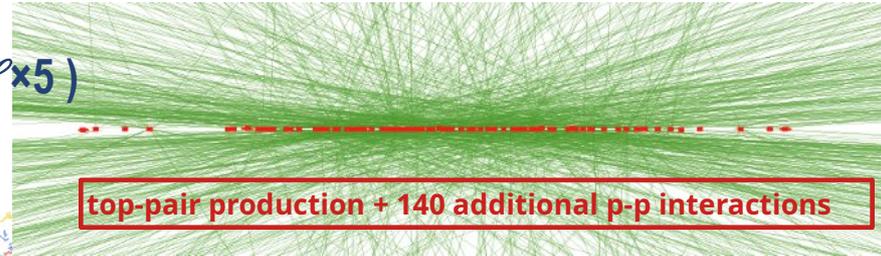
CMS-HGCAL: Going 5D for HL-LHC

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

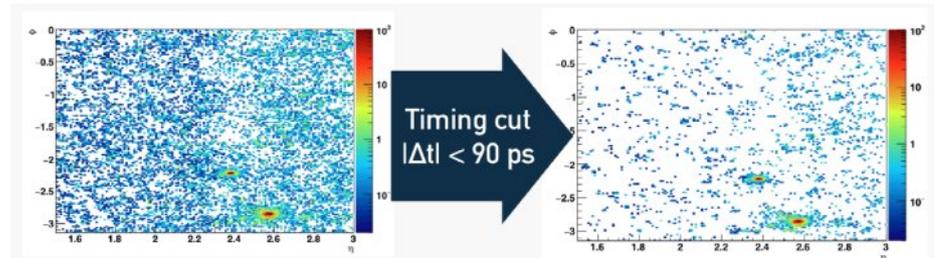
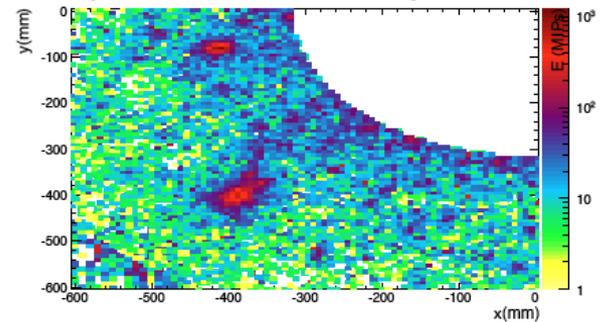
- Reconstruct crowded events with high granularity 3D+E + 1
 - 28 X_0 ECAL + 9 λ HCAL
- Adding timing for vertex separation
 - $\delta z = 50\text{mm} \Rightarrow \sigma(t) = 30\text{ps}$

Possible because of HG calorimeters ($30\text{ps} = 1\text{cm}/c$)

Endcap coverage: $1.5 < \eta < 3.0$		
Total	Silicon sensors	Scintillator
Area	620 m ²	410 m ²
Number of modules	29 900	3800
Cell size	0.5 – 1.2 cm ²	5 – 30 cm ²
N of channels	6 260 000	240 000
Power	Total at end of HL-LHC: 2x125 kW @ -30°C	



VBF jets + H $\rightarrow \gamma\gamma$: 720 GeV jet, 175 GeV photon



Simulated HGCAL event with and without timing selection

Constraints

Physical:

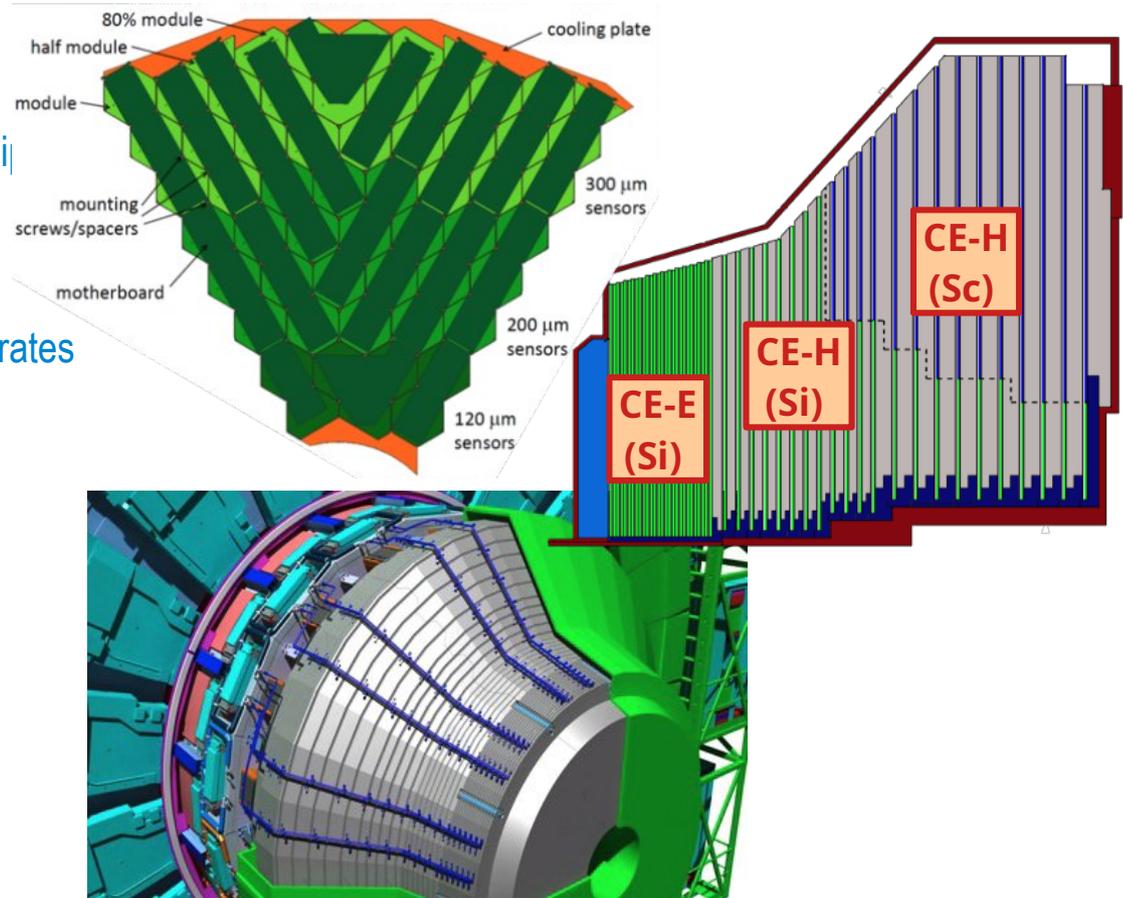
- Very high radiation doses (10^{16} n_{eq}/cm^2 near beam pi)
 - Limited effective thicknesses
 - Run at $-35^{\circ}C$
- Very high occupation (140–200 pile-up) & very high rates
 - requires small cells (cm^2) \Rightarrow high number of channels
 \Rightarrow **power consumption** \Rightarrow **cooling**
 - High throughput \Rightarrow Fast trigger system

Mechanical:

- Circular geometry, very little space

Time

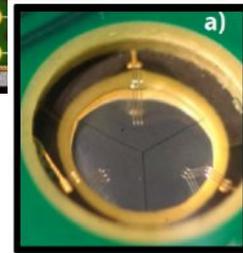
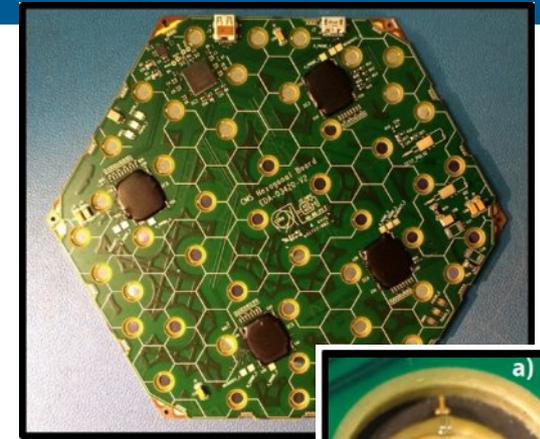
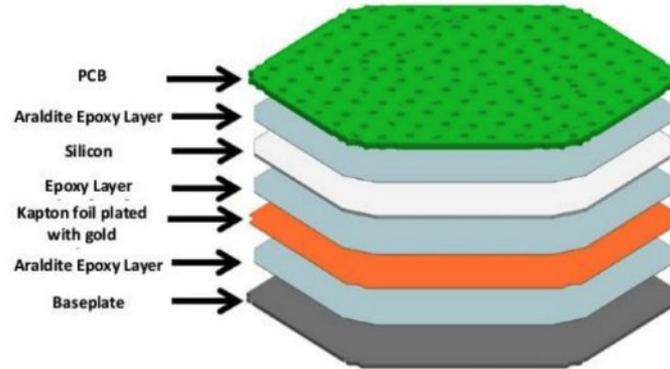
- Build and install for LS3 (≤ 2026)
 - HGCAL will see 90% of LHC luminosity



R&D: Sensors & hexaboards

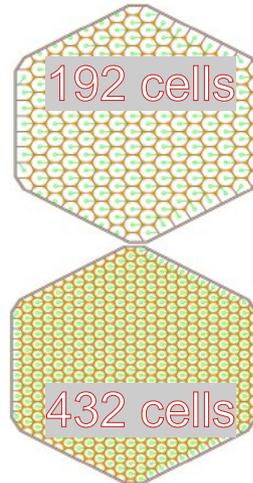
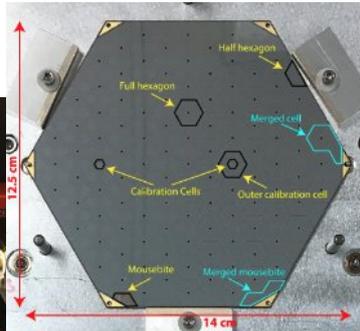
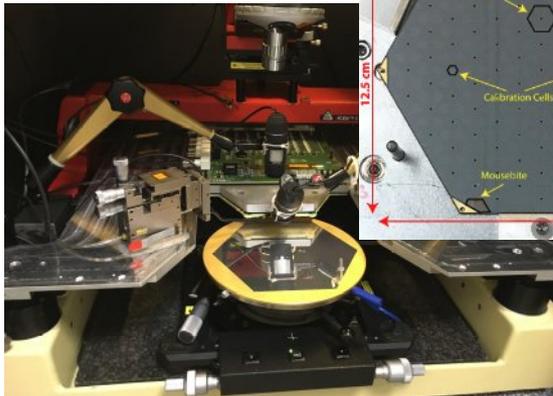
600 m² of sensors

- 8" Hexagonal for cost (Hamamatsu)
- 3 depletion thicknesses: 120, 200, 300 μm
- 2 granularities: 0.5, 1 cm²
- Complex structure



R&D test station to read all channels

- Sampling



Hexaboards:

- 1 per wafer, bonded through holes
- 3–6 HGCROC per board
- Absorber in Cu/CuW
- Fixation with screws on absorber plates with cooling
- 8" board with HGCROC-V2 in production
 - 6 Lead Module Assembly Centre (MAC) world-wide
 - 30,000 modules to be produced

Omega HGCR0Cv2

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

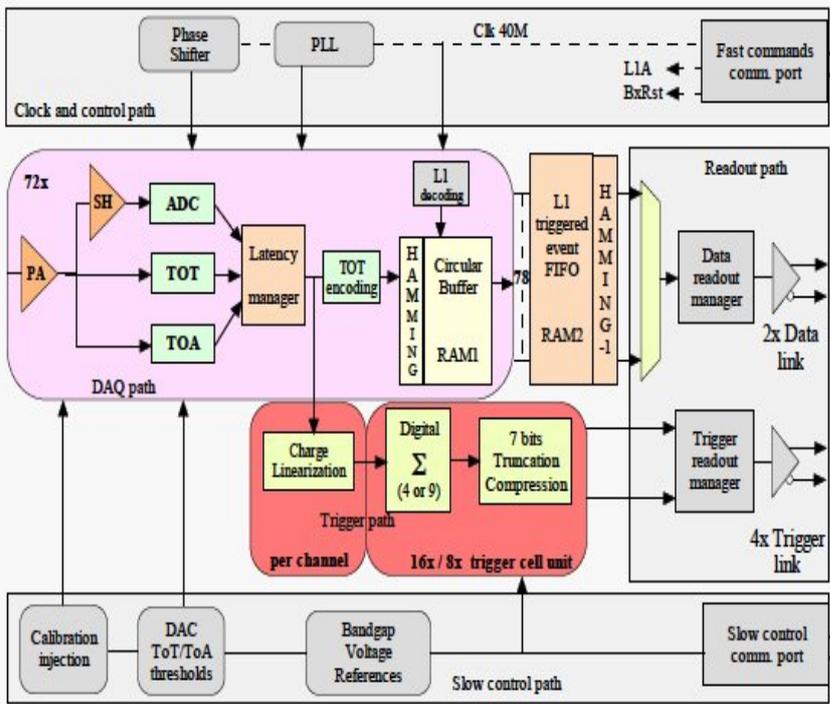
- ADC 10b SAR range: 0 > 100fC (150fC)
- TOT range 100fC > 10pC
- TOT bin size 2.5fC

Time Of Arrival (TOA)

- 10b TDC
- LSB <25ps, 25ns full range

2 HGCR0C versions:

- Different preamps optimised for Si & SiPM readout



Comm port

- 320MHz clock
- Reception of T1 fast commands
- From IpGBT

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

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

HGCR0Cv3

submission in 2020

Monitoring of DACs and essential bias voltages to GBT-SCA

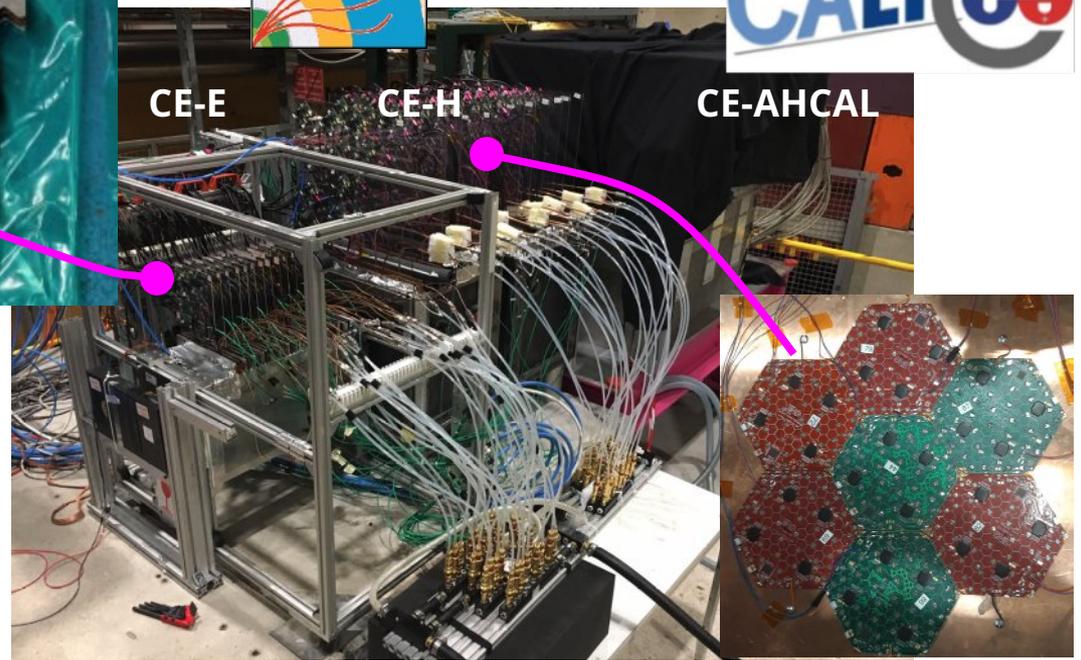
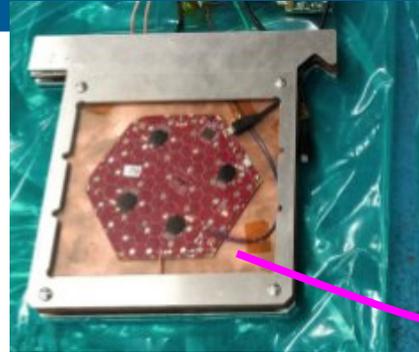
A. Lobanov

Beam Test Results



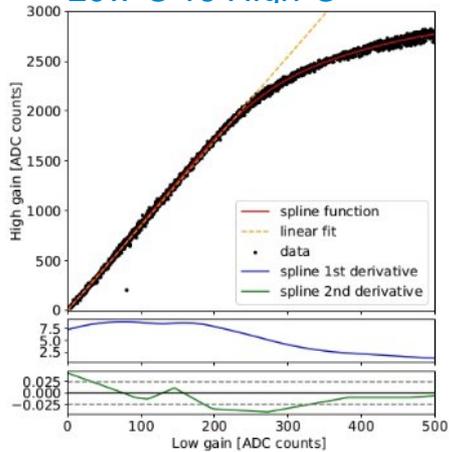
Si-ECAL+HCAL + AHCAL

- 90 CE modules with 6" sensors
- Oct 2018 @ CERN

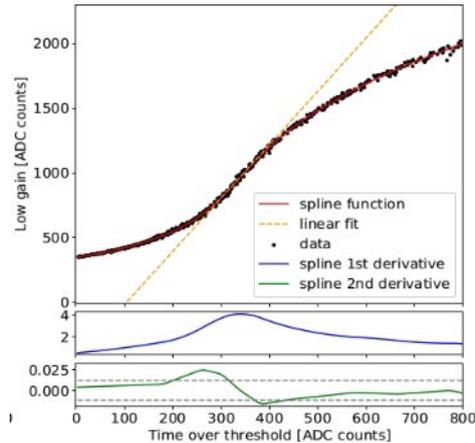


Calibration

- Overlaps
Low G vs High G



Low G vs TOT



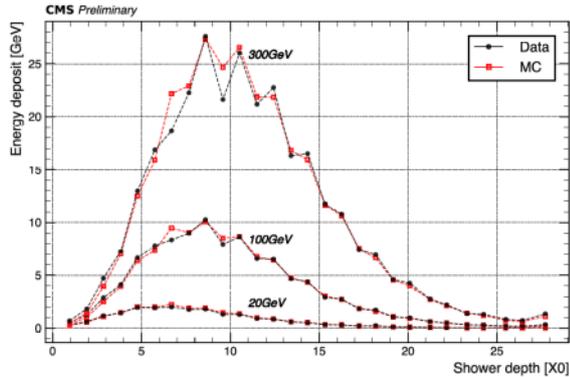
300 GeV pion starting showering in CE-H-Si



Calorimetric Performances

Shower profiles

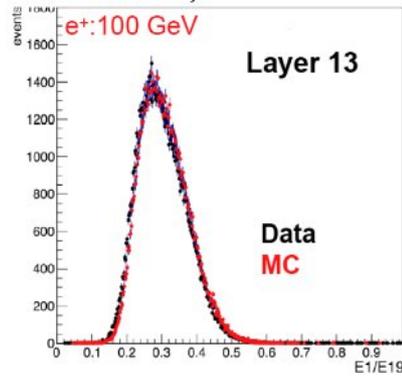
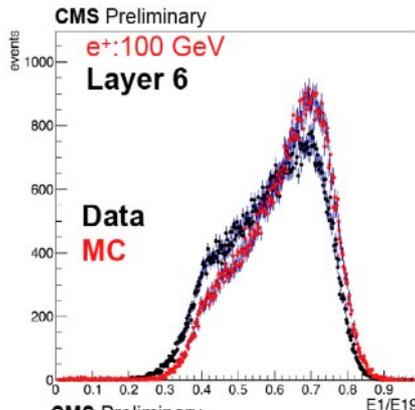
— Longitudinal



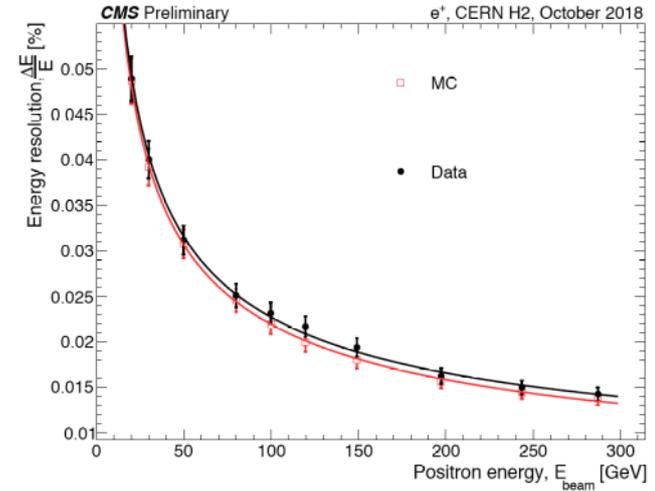
— Lateral fraction of L_{EM} in $CE-E$ (L_{EM}/L_{EM+H})

• “Early” ~

“Late” ✓

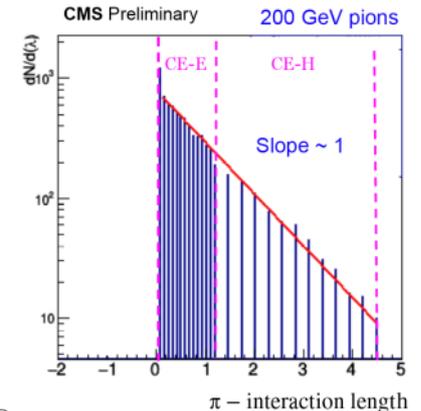


EM Linearity: 0.5%
EM Resolution ✓



Hadronic interactions

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



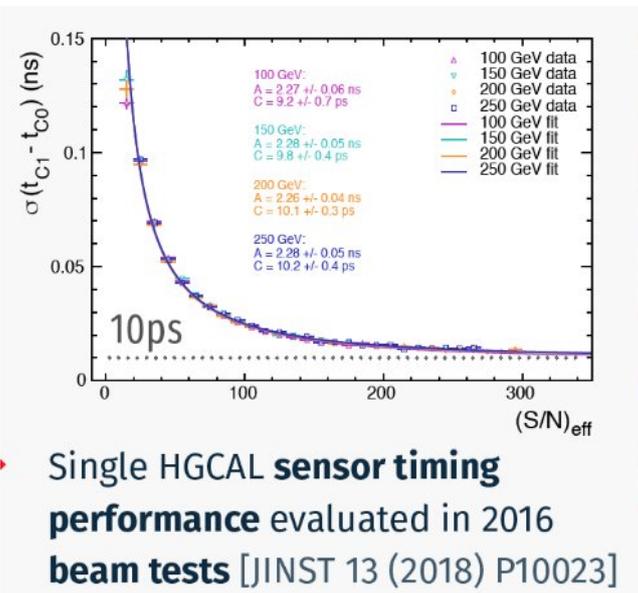
Timing

Timing of Showers

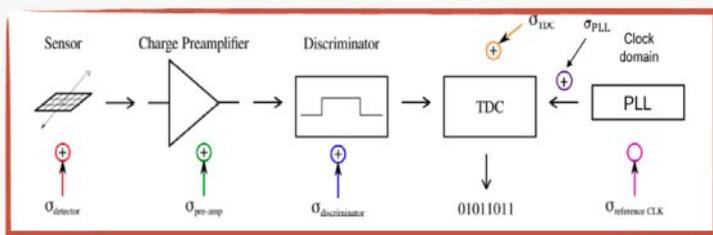
- For events reconstruction
- From Core Hits to avoid contamination

R&D

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

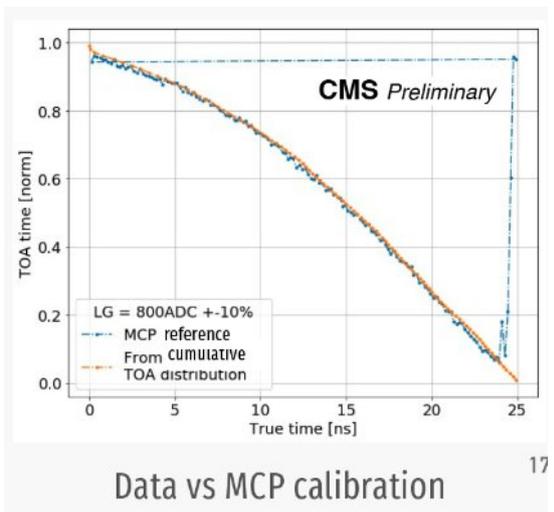


The **clock distribution system** is expected to contribute < 15 ps jitter



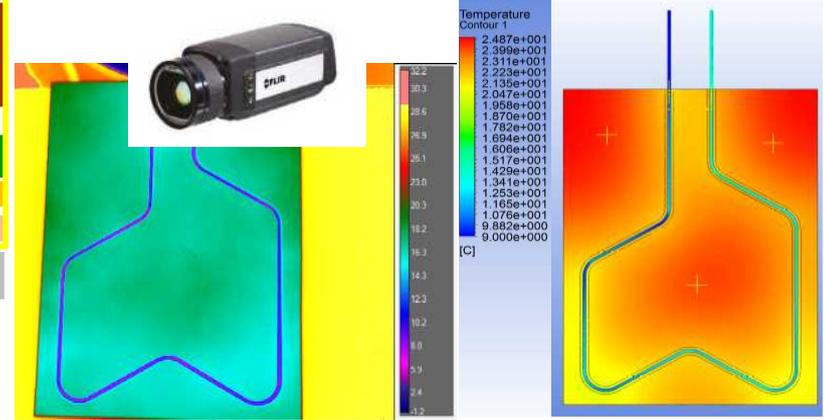
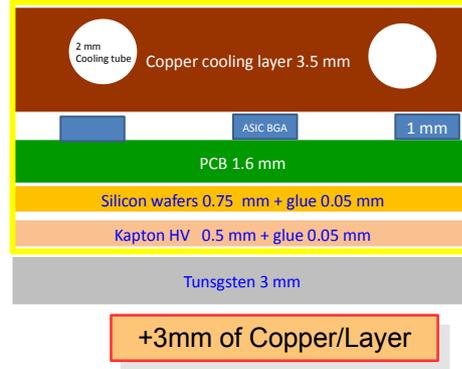
$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\frac{t_{rise} V_{th}}{S}\right)_{RMS}^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + ([TDC]_{RMS})^2 + ([CLK]_{RMS})^2$$

Legend for the equation terms: Preamplifier, Time walk, TDC quantization, noise and linearity, CLK jitter.

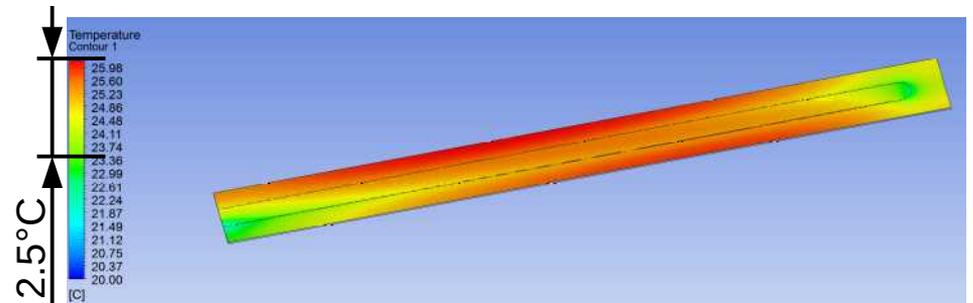
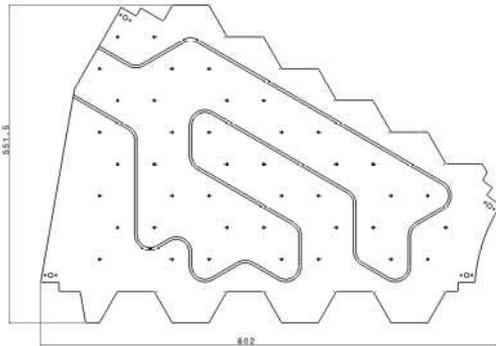


- Correction of non-linearity of ToA response

Services: integration & cooling



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



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 = 2x cont. operation of a SLAB

Pipe insertion on a cooling prototype

HGCAL summary

Huge progress made in couple of years

- Innovative ideas made real
 - ToT
 - cm/c timing precision
- Effects to be assimilated for physics
- Challenge for simulation

Status:

- Sensors
 - “Good deal” with Hamamatsu
 - Any other producers ?
- FE Electronics
 - small Kick-start from CALICE
 - HGCROCV3 ~ready
 - All performances at reach
- Module production
 - Design finalized → Prod to be started in 6 places
- Integration:
 - on tracks

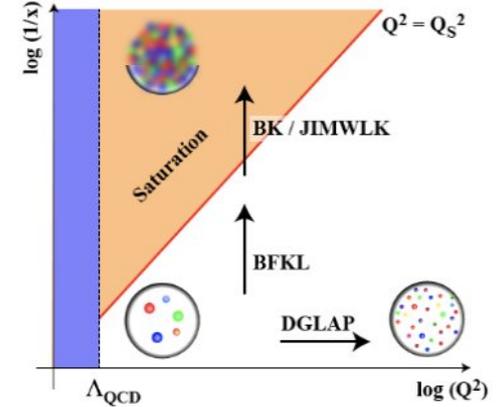
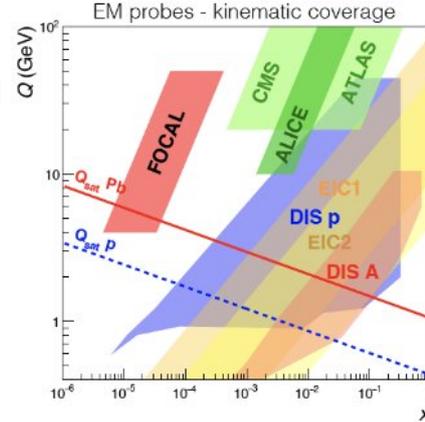
FoCal-E @ ALICE

FOCAL @ ALICE : Towards truly ultra-granularity

Goal: mesure of the (n)PDFs at low x

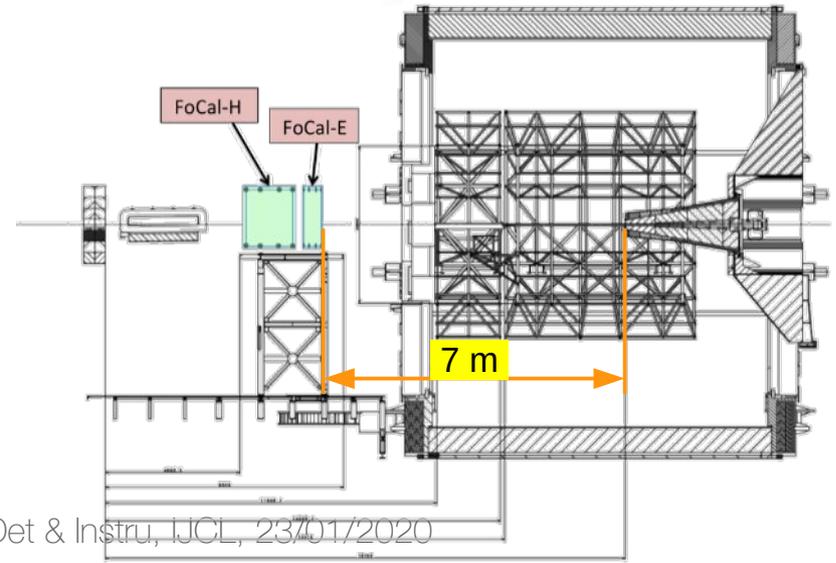
- “unobstructed forward view” in ALICE
- FoCal-E : Tagging of **very forward γ and π^0 's**
 - $z = 7\text{m}; 3.2 < \eta < 5.8$
 - π^0 decay @ $P_T = 10 \text{ GeV}/c, y=4.5, \alpha = 0.5 \Rightarrow d = 2\text{mm}!$
 $\Rightarrow 1 \times 1\text{mm}^2$ granularit
- FoCal-H: classical HCAL for isolation & jets

$$x \approx \frac{2p_T}{\sqrt{s}} \exp(-y)$$



Status:

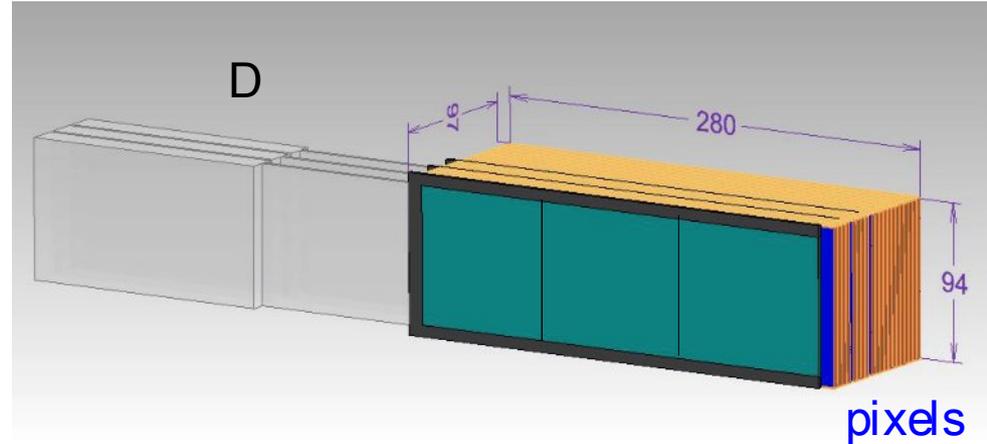
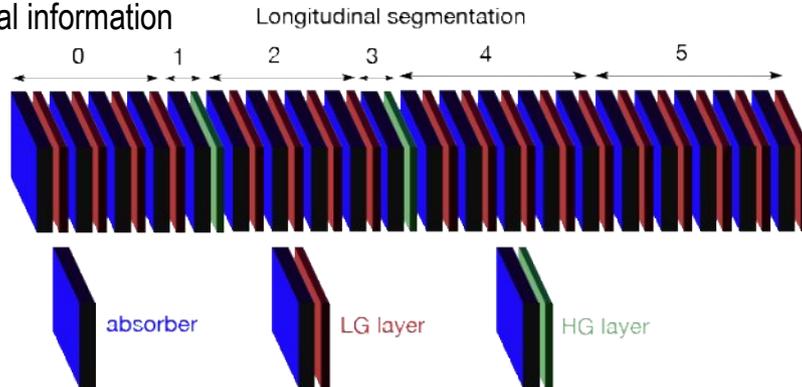
- Under disc. for possible installation in LS3 (2024–26)
- Proof a feasibility with prototypes



FoCal-E: Design

24-18 layers in 3-5 towers

- W (3.5mm $\approx 1 X_0$)
- Si-sensors:
 - Si-pads ($\approx 1 \text{ cm}^2$):
 - energy measurement, timing(?)
 - CMOS pixels ($\approx 30 \times 30 \mu\text{m}^2$):
 - two-shower separation, position resolution
 - Digital information



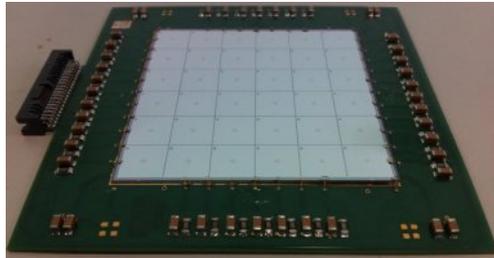
Mains optimizations to be done:

- number of pixels per layers
- number of pad layers
- sep between layers

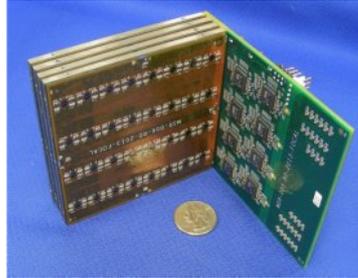
FoCal-E: Si-Pad Prototypes

Si-Pad: NIM A764 (2014) 24

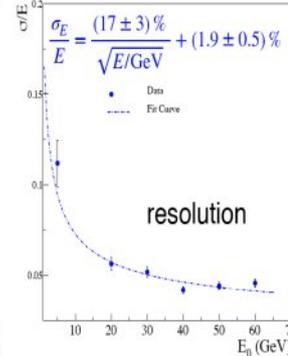
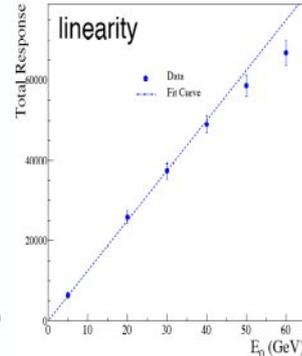
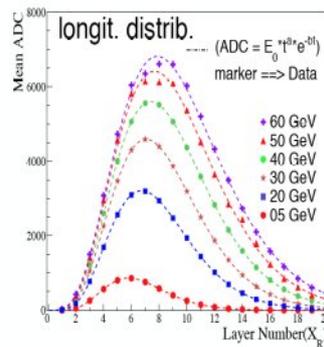
- Japan (Tsukuba) + India (VECC, BARC)
- Design close to final



Pad Sensors
APV readout hybrids

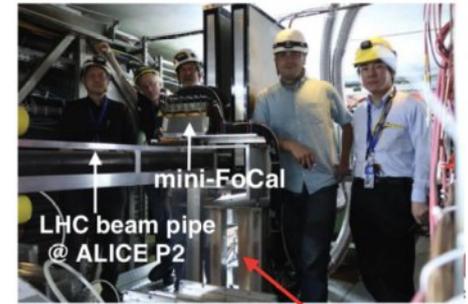


- Agreement of simulations
 - $17 \pm 3\% / \sqrt{E/\text{GeV}} + (1.9 \pm 0.5)\%$
 - Incl. electronics saturation
- Final readout chip:
Omega HGCROC

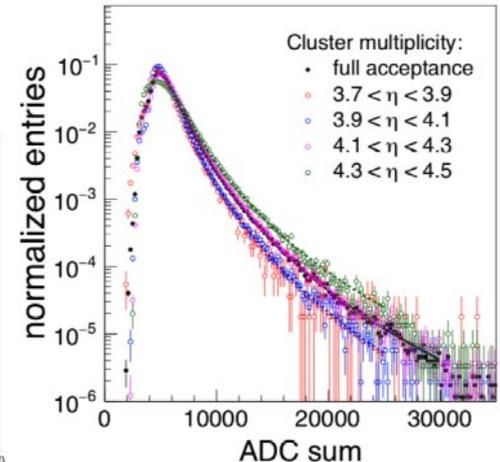


Mini-FoCal (on-going)

- In-situ with 13 TeV collision



SRS system under the table



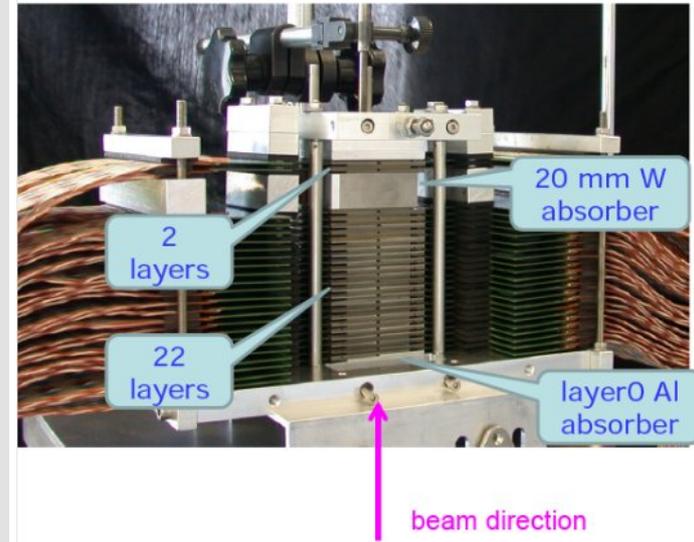
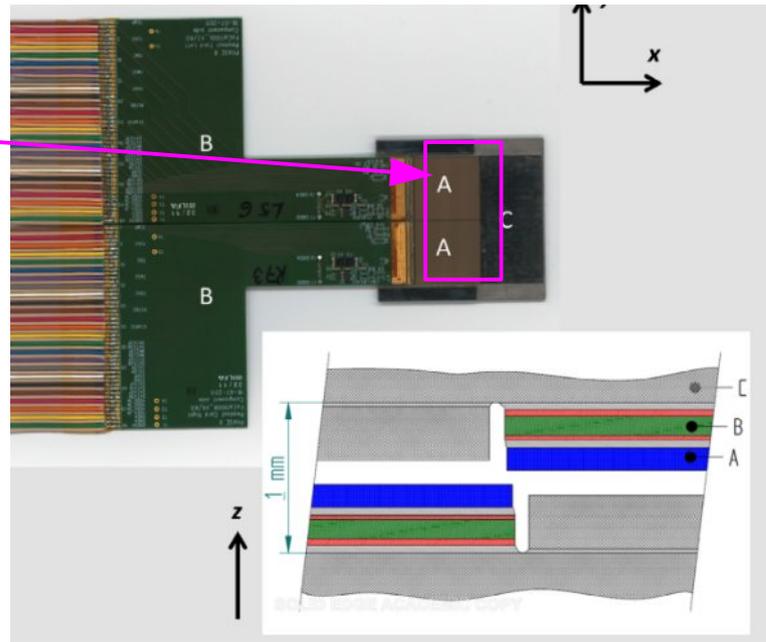
FoCal-E: Digital-ECAL prototypes

Digital calorimetry

- $E \propto$ cluster size & number

Prototype:

- 24 layers \times 4 MIMOSA-26 CMOS sensors (IPHC)
 - 6×6 cm²
 - 30×30 μm^2 pixels
 - 39 M pixels = full readout
- W layers
- $28 X_0$
- Very compact calorimeter



Beam tests:

- DESY (e^- , 2–5.4 GeV) + SPS (mixed, 30–244 GeV)

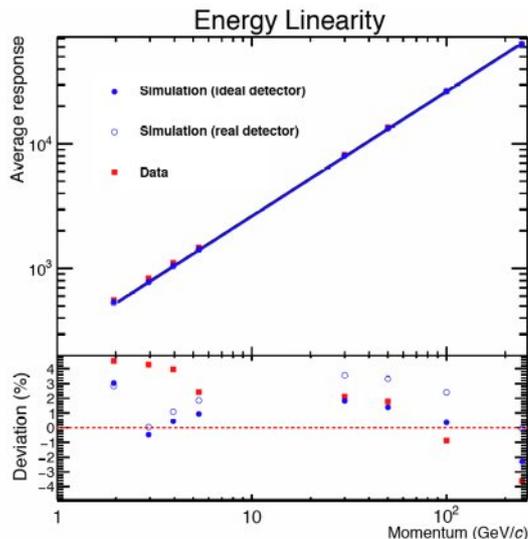
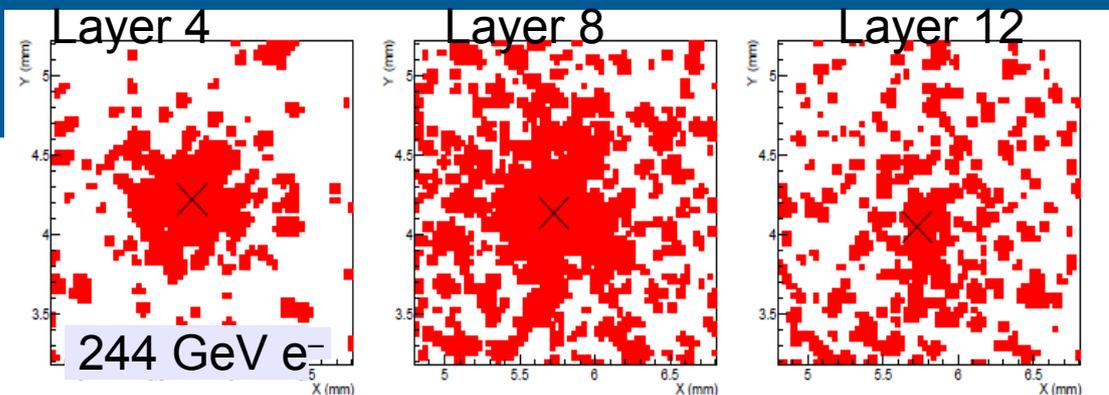
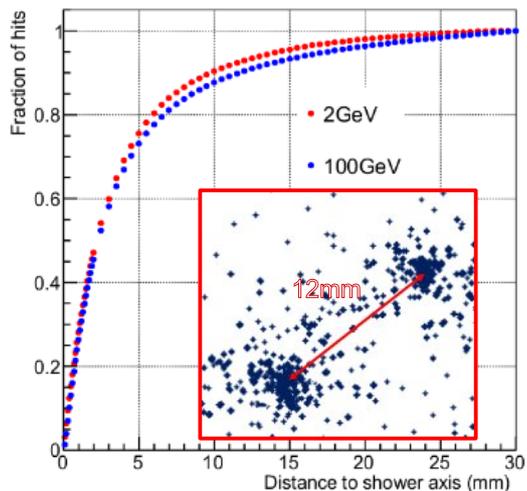
Netherlands (Utrecht/Nikhef) and Norway (Bergen)

DECAL: Results

Digital calorimetry *JINST 13 (2018) P01014*

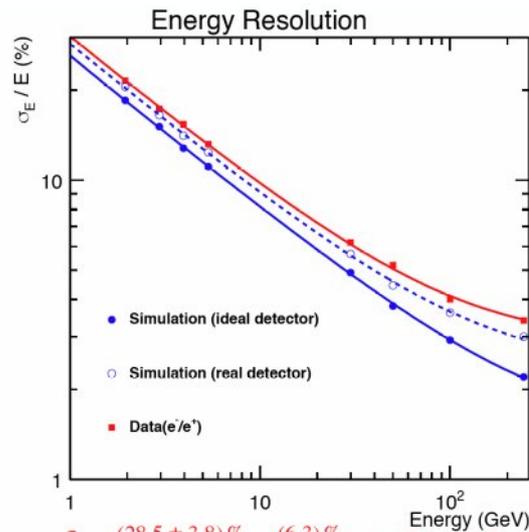
- Dead hits † \Rightarrow Symmetries in r + profile
- $E \propto$ cluster size \rightarrow Number of hits
- Saturation & overlap effects at core

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



Good linearity & resolution

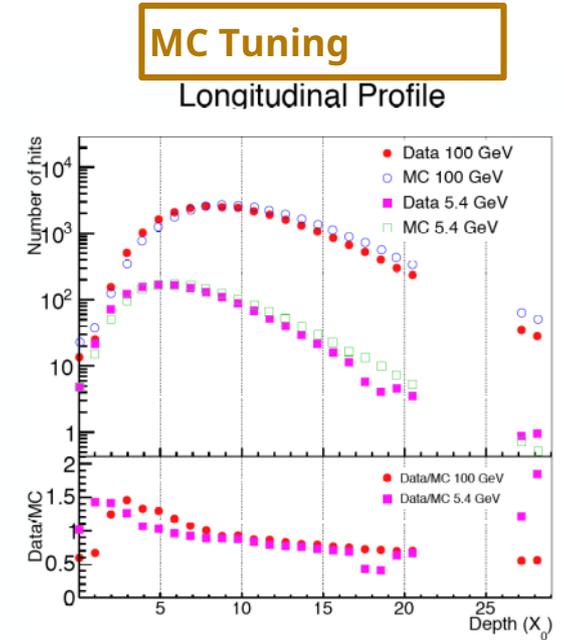
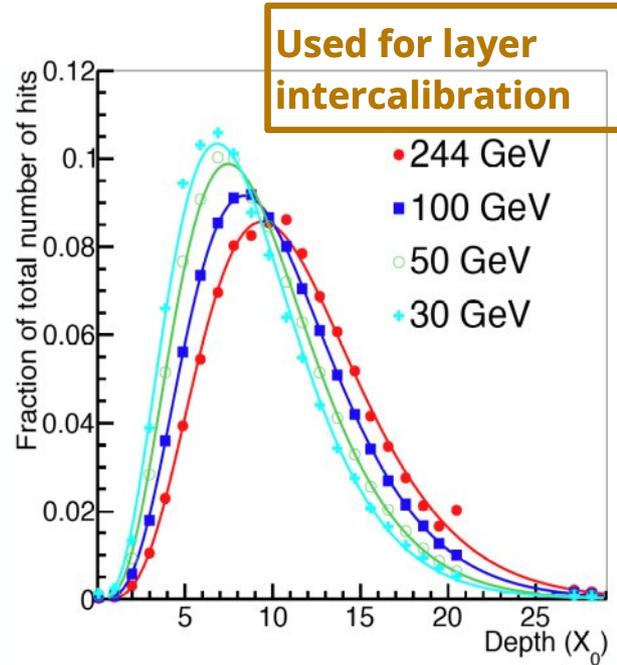
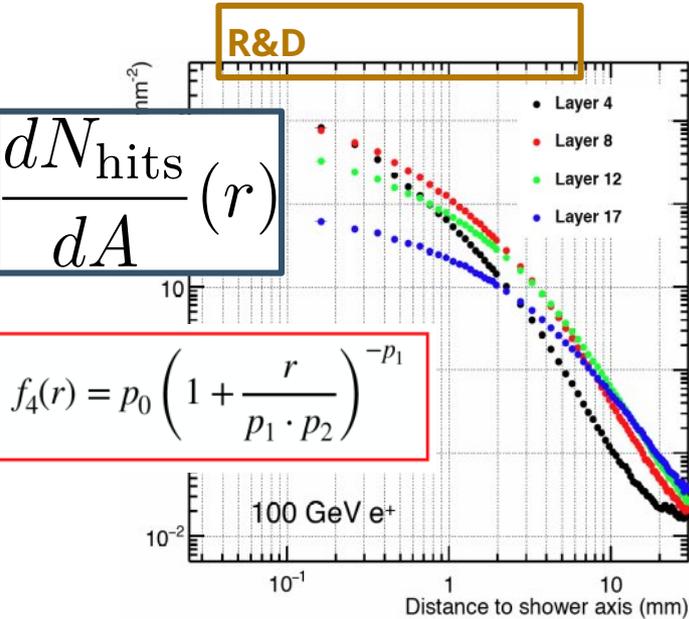
- \neq calib @ low and high E ;



$$\frac{\sigma_E}{E} = \frac{(28.5 \pm 3.8)\%}{\sqrt{E/\text{GeV}}} + \frac{(6.3)\%}{E/\text{GeV}} + (2.95 \pm 1.65)\%$$

- Saturation @ 244 GeV

DECAL: Shower profiles



Unprecedented spatial lateral accuracy

⇒ New EM Shower lateral profiles parametrisation

Longitudinal profiles:

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

- Earlier showers

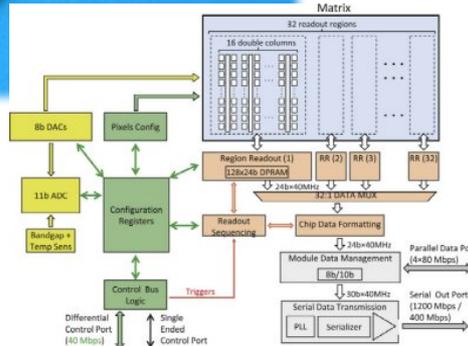
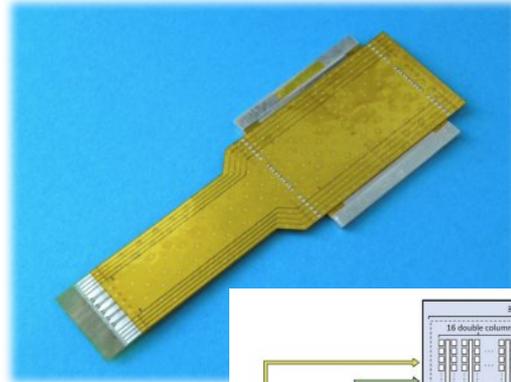
FoCal: Conclusions and todos

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} ~ 10¹³
 - Power consumption ∝ occupancy
 - High speed readout (0.4–1.2Gb/s)
Sufficient for high occupancy ?

Construction: 2022–2026

- Lol → LHCC in prep.

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

Silicon ECAL: summary

“Historical” turn-out for large Silicon calorimetry

- Small Devices (Beam, Sat) → Full Scale detectors
 - 10^4 × number of channels
- Digital Ultra-granular Calorimetry
 - 10^6 × number of channels

Revolution due to embedded electronics.

- Strong know-how in France: Omega, IPHC

Long path:

CALICE (~2002)

→ First implementations:

CMS-HGCAL (2026),

FoCal (2026)

→ Future e⁺e⁻ collider (203?)

- Forte expertise dans l’IdF (LLR, IJCL, LPNHE, Omega)
 - Projet emblem du labex P2IO HiGTEC

New measurements:

- Precision timing → 5D calorimetry
- Digital calorimetry: B&W images (4D) enough ?
- Improved performances via PF Algorithms
 - Better particle separation
 - Better use of information (shower profiles)
 - MC will have to be improved

New challenges

- More complex integration
 - Electronics, Thermo-Mechanical, Physics
- Change of scale (100,000 pieces)
 - → link to industry for building ?

Extras

Tributes

HGCAL teams (mostly mat from CHEF2019)

- F. Sefkow (DESY)
- M. Damien Thienpont (OMEGA)
- A. Lobanov (LLR) × 3

Th. Peitzmann (Utrecht University/Nikhef)

- ALICE FoCAL : CALICE collab meeting and CERN Det. presentation

CALICE and ILD teams

- esp. SiW-ECAL @ LAL & LLR : from last 10 years...