CALICE, a legacy

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ÉCOLE POLYTECHNIQUE

INSTITUT POLYTECHNIQUE DE PARIS

NUCLÉAIRE & PARTICULES

* with many slides adapted from R. Pöschl, F. Simon, O. Wataru, I. Laktineh,, K. Krüger and others.

Introduction : Calorimetry and Particle Flow

Classical Calorimetry in HEP :

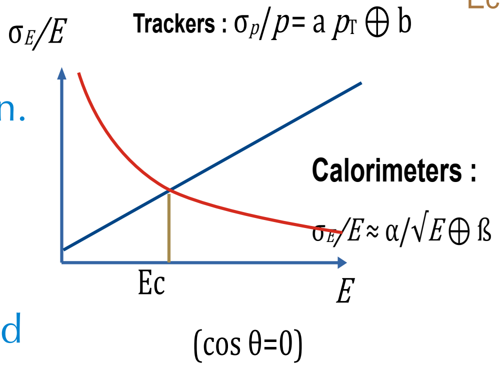
– Precise measurement of particle energies and identification.

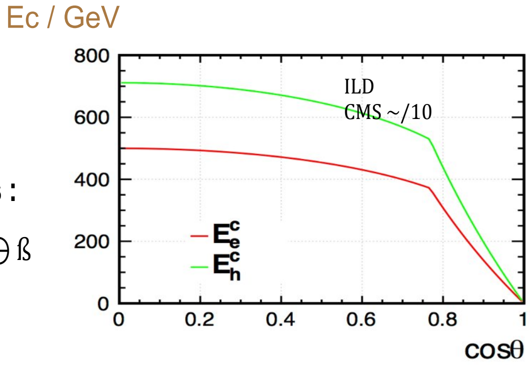
Particle Flow Approach for Jets :

– Calorimeter as a part of a detector system

– Charged particles are most of the time way better measured in tracking than in calorimeters

– Combine tracks and calorimeters clusters *topologically,* to avoid “bad” calorimetric resolutions





CALICE :

– Calorimeter for the Linear Collider Experiment, founded in 2004 with a specific focus on developing **highly-granular calorimeters** suitable for particle flow reconstruction techniques.

- Deemed impossible to design calorimeters system with 10–100’s of Millions of channel, although electronics allows
- **CALICE as a challenge**

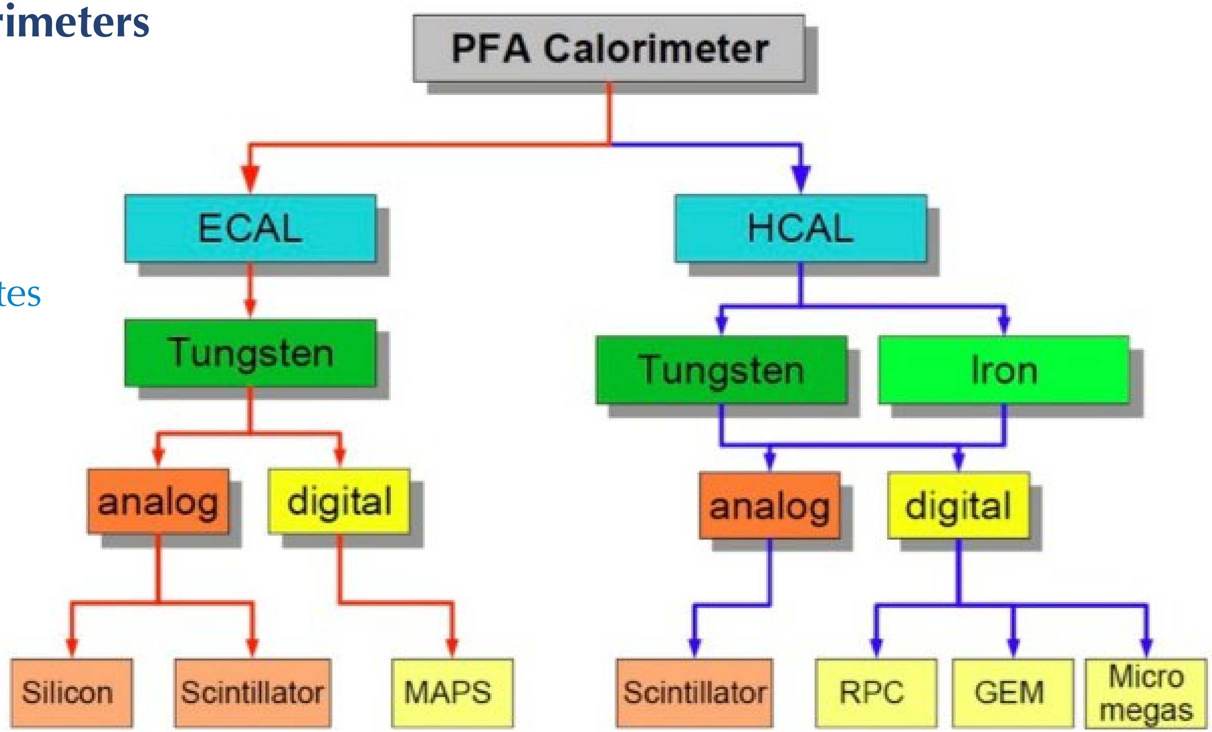
The CALICE Collaboration

Calorimeter R&D for large imaging calorimeters

- MOU 2005

  first Spokesperson: Jean-Claude Brient

  current (& last?) : Roman Poeschl
- ~270 physicists/engineers from 62 institutes and 18 countries from 4 continents
- Integrated R&D effort
- Acceleration of detector development due to coordinated approach



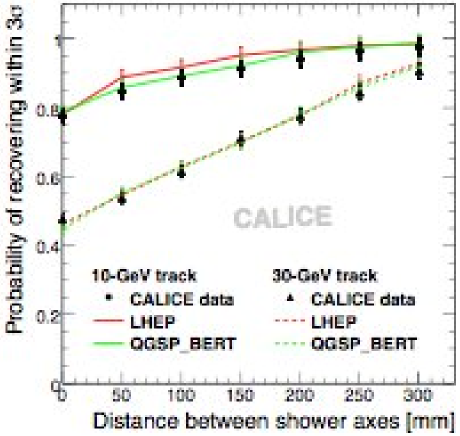
Here,
we explore CALICE's journey in advancing calorimetry for future collider experiments.

Steps of R&D

Physics Prototypes

2003 - 2012

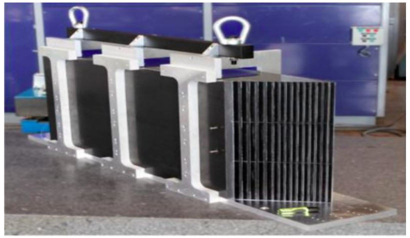
JINST 6, P07005 (2011)

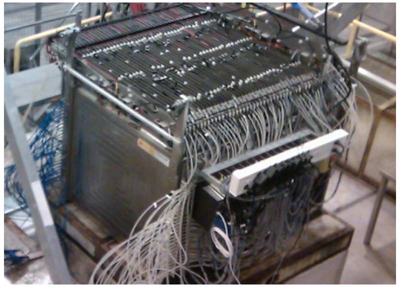


- Proof of principle of granular calorimeters
- Large scale combined beam tests
- Inspiration for CMS HGCAL

Technological Prototypes

2010 - ...

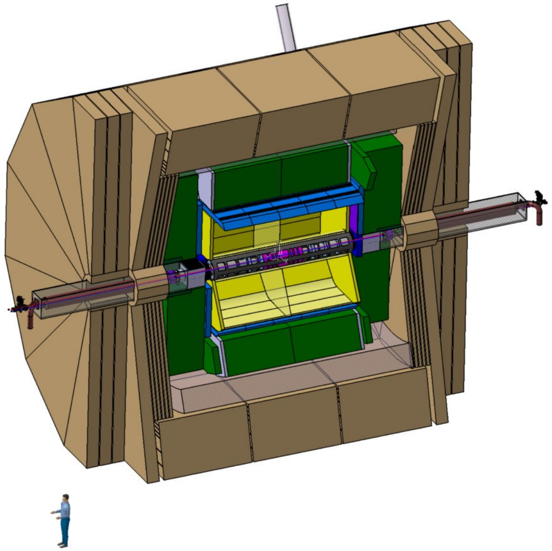




- Engineering challenges
- Higher granularity
- Better sensitivity (lower noise)
- $\mathcal{O}(10^4–10^6)$ cells

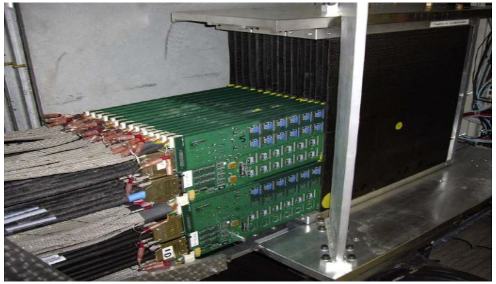
Current period

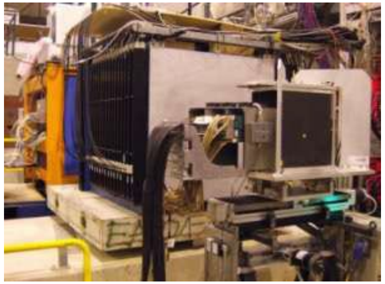
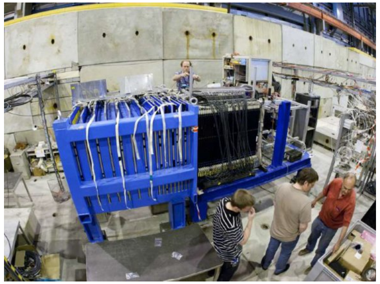
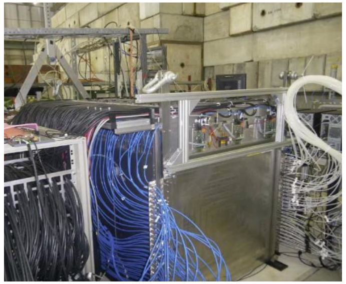
Higgs Factory Detector



- The goal
  - Typically 10^8 calorimeter cells
- Compare:
  - ATLAS ℓAr ~10^5 cells
  - CMS HGCAL ~10^7 cells

Physical Prototypes (2005–2012^{++})



SiW-ECAL
- Silicon-sensor
- 10,000 cells of **1×1**cm²
- Analogue readout
- **Tungsten** absorber
- 30 layers ($24X_0$, 1λ)

ScW-ECAL
- Scintillator strips 2160 cells of **1×4.5** cm² each
- Analogue readout
- **Tungsten** absorber
- 30 layers ($24X_0$, 1λ)

AHCAL
- Scintillator tiles :
- 7608 cells of **3×3** (cent), 6×6, 12×12 cm²
- Analogue readout
- **Steel** or **Tungsten** absorber
- 38 layers (5.3λ)

DHCAL* **SDHCAL***
- GRPC
- up to 500,000 cells, **1×1**cm² each
- Readout : Digital (1 bit) semi-digital (2 bits, 3 thr.)
- **Steel** or **Tungsten** absorber
- Up to 48 layers (~6λ) different readout ASICs

Full-layer test beam prototypes for proof-of-principle of high-granularity calorimeter concept

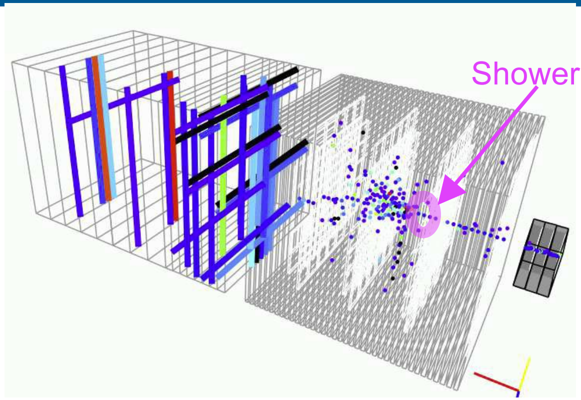
Some / Many technological criteria set aside : uniformity, embbeded electronics, pulsed mode, mechanics…

* Except for (S)DHCALs

Hadronic Shower Studies : pion vs proton, shower start

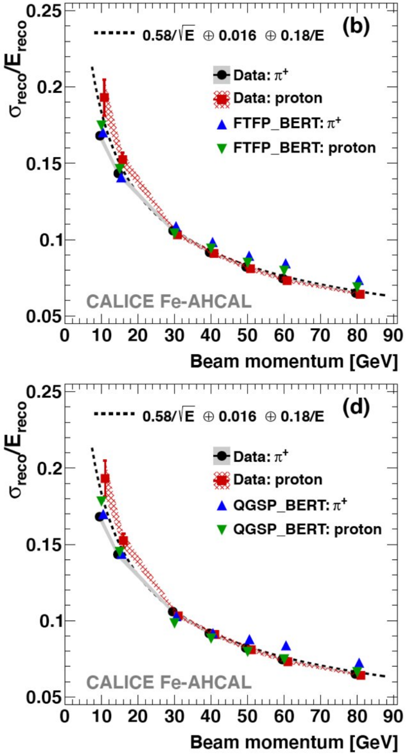
Hadronic shower studies by AHCAL

- Test beam data: π+, p 10–80GeV@CERN and FNAL
- Simulation
  - GEANT4 ver9.6
  - Physics lists: FTP_BERT, QGP_BERT



JINST 10 (2015) P04014

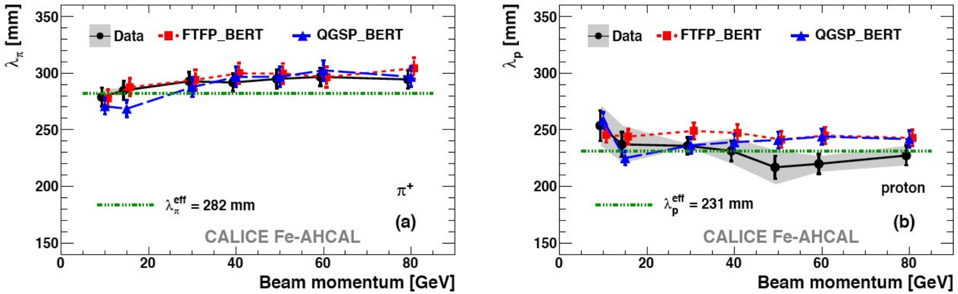
Energy resolution (data vs. MC)



Pion vs Proton-induced hadronic showers

- Longitudinal segmentation allows to measure shower start on event-by-event basis
- Interaction length extracted from distribution of shower starts
- Good agreement as calculated from detector compounds

Nuclear interaction lengths for π+ and p



Hadronic Shower Studies : Profiles

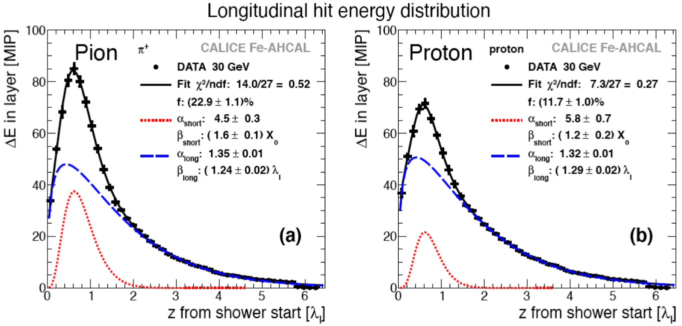
Longitudinal shower profile measured by the AHCAL

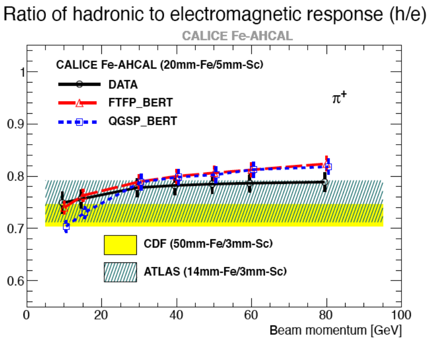
- Test beam data: π^+, p 10–80GeV@CERN and FNAL
- Decompose shower components
  - Short component: electromagnetic component
  - Long component: hadronic component
- Extract ratio of hadronic to electromagnetic response (h/e)

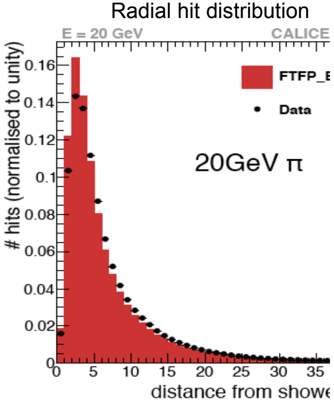
Radial profile study measure in SDHCAL

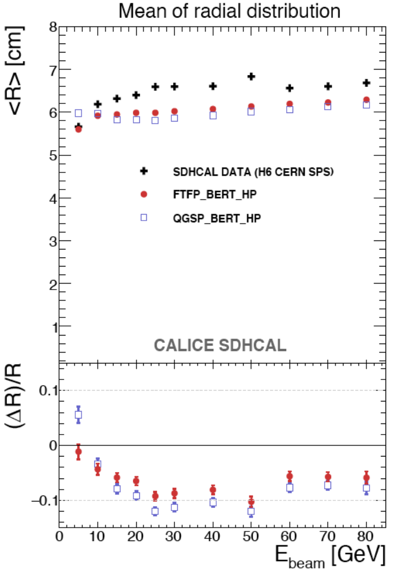
- Large tranverse segmentation (1 cm)
- Test beam: 5-80GeV pions @CERN SPS
- Simulation: GEANT4 ver9.6 with High Precision (HP) package

Radial profile is narrower in simulation









JINST 11(2016)P06013

JINST 11(2016)P06014

Hadronic Shower Studies : low energy in ECAL

Shower studies with low energy hadrons using SiW-ECAL

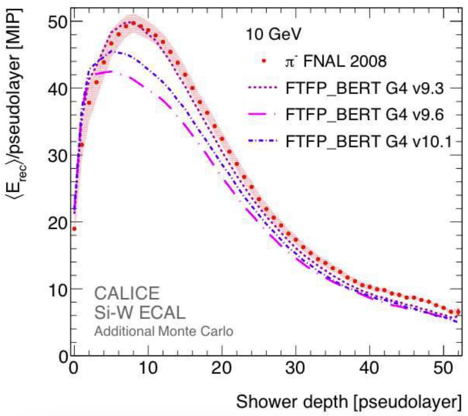
- Test beam: π^- 2-10GeV @FNAL

Comparison with simulation

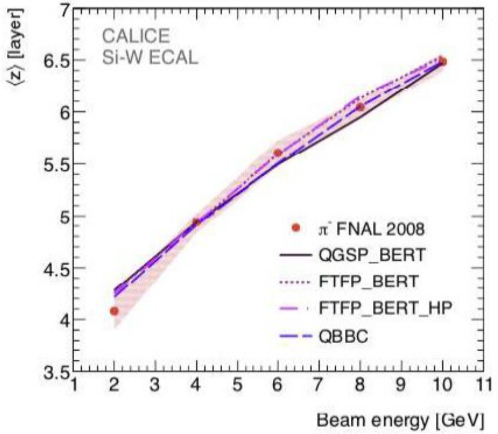
- Agreement to within 20% (much closer for most observables)
- Longitudinal hit distributions well described
- Largest discrepancies in longitudinal and radial profile of reconstructed energy

NIM A794 (2015) 240-254

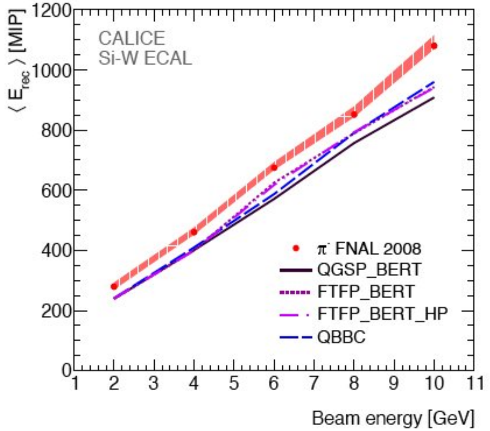
Longitudinal energy distribution (10 GeV π^-)

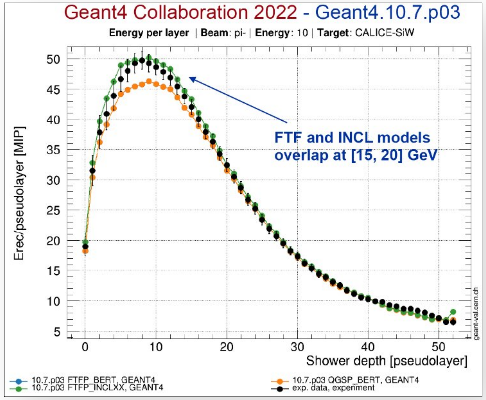


Mean of longitudinal hit distribution



Mean of longitudinal energy distribution





GEANT4 Validation samples

L. Pezzotti, A. Ribon and D. Konstantinov, CALICE Meeting, Valencia, 2022

SiW-ECAL

- 2008 $\pi-$ data
  - 2, 4, 6, 8, 10 GeV

NIM A794 (2015) 240-254

AHCAL

- Planned

params.conf

```
!PHYSLIST=FTFP_BERT, QGSP_BERT
!CONST:ENERGY_UNIT=GeV
PARTICLE | ENERGY | PHYSLIST | NEVENTS
pi- | 20. | PHYSLIST | 50000
pi- | 30. | PHYSLIST | 50000
pi- | 40. | PHYSLIST | 50000
pi- | 50. | PHYSLIST | 50000
pi- | 60. | PHYSLIST | 50000
pi- | 80. | PHYSLIST | 50000
pi- | 100. | PHYSLIST | 50000
pi- | 120. | PHYSLIST | 50000
pi- | 150. | PHYSLIST | 50000
pi- | 180. | PHYSLIST | 50000
pi- | 200. | PHYSLIST | 50000
e- | 20. | PHYSLIST | 50000
e- | 40. | PHYSLIST | 50000
e- | 50. | PHYSLIST | 50000
e- | 80. | PHYSLIST | 50000
e- | 100. | PHYSLIST | 50000
e- | 119.1 | PHYSLIST | 50000
e- | 147.8 | PHYSLIST | 50000
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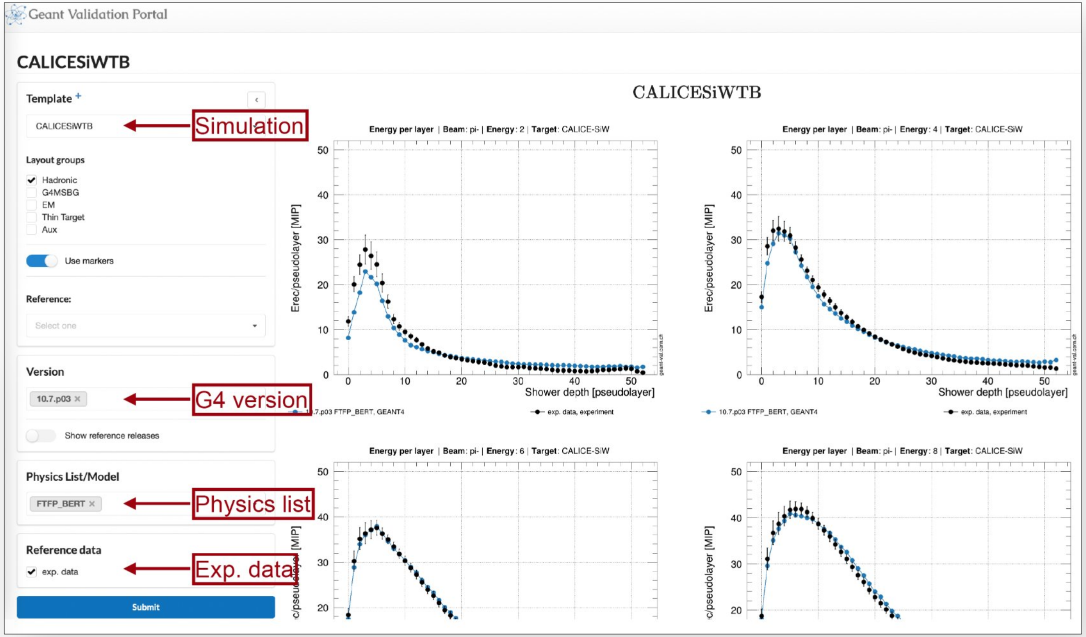
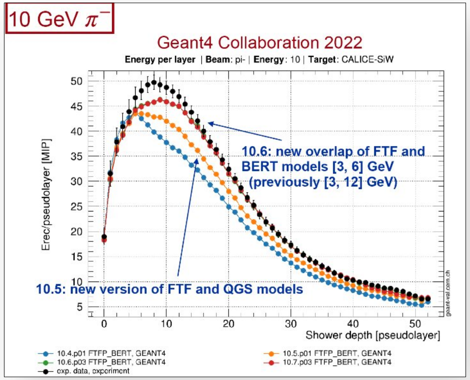
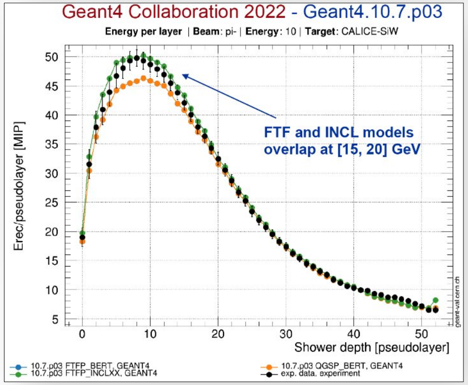






Nice improvements wrt to 2015

- Energy & #hits distributions

Hadronic Shower Studies : sub-structures : track segments

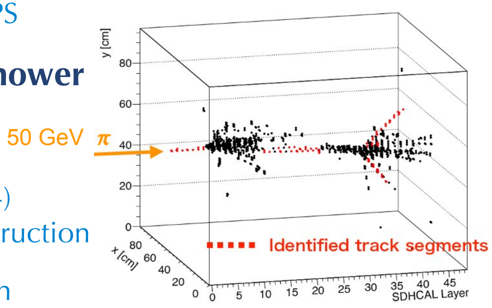
JINST 8(2013)P09001

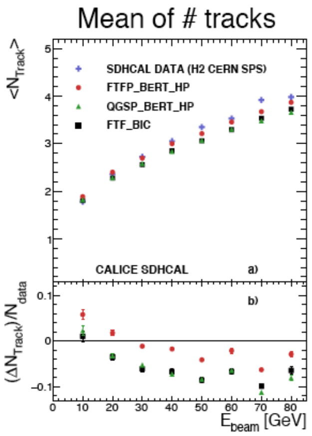
Track segments in SDHCAL

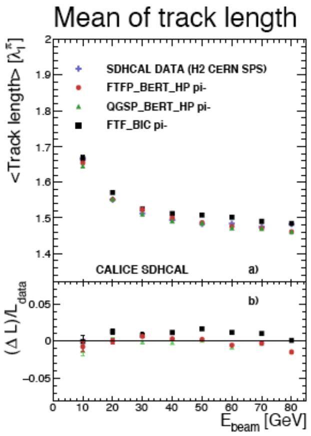
- Test beam data: pions 10-80GeV@CERN SPS

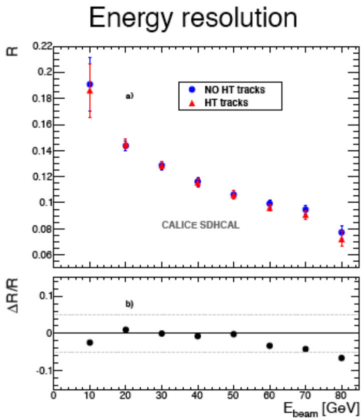
Track segments found in dense hadronic shower

- Track finding using Hough Transform
- Useful for detailed shower study (→ Geant4)
  in-situ calibration and better energy reconstruction
- Slight improvement of energy reconstruction
  by weighting hits in tracks [reduce Landau fluctuations]



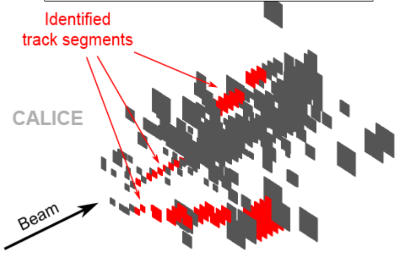






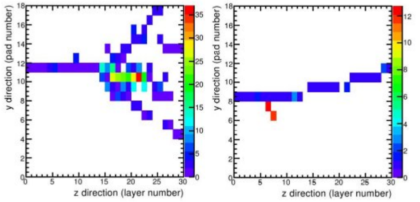
AHCAL

- Test beam data:
  10–80 GeV π^-@CERN-SPS



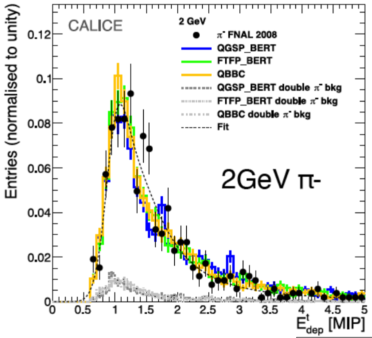
SiW-ECAL

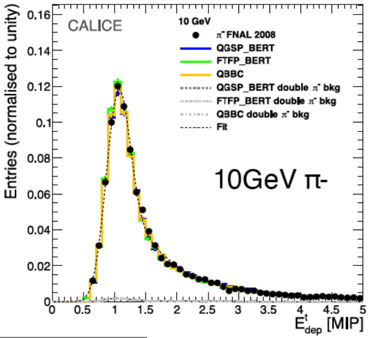
- Test beam data:
  2–10 GeV π^- @FNAL



Inelastic Reaction in SiW Ecal   Nucleon Ejection in SiW Ecal

Energy deposition of secondary tracks @SiW-ECAL



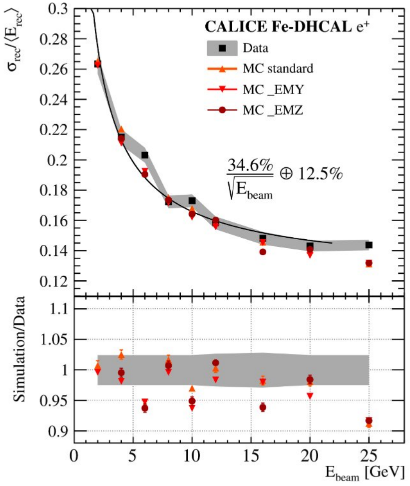


JINST 12 (2017) P05009

NIMA937(2019)41

Hadronic Shower Reconstruction in Digital HCALs

NIM A 939 (2019) 89–105



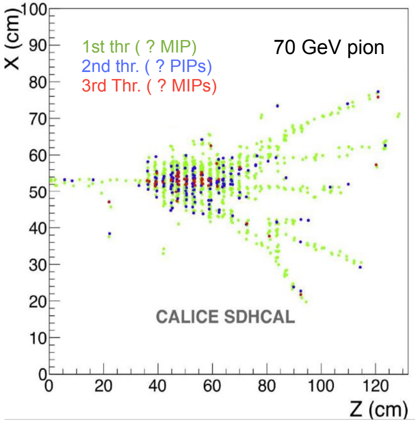
← Single threshold DHCAL

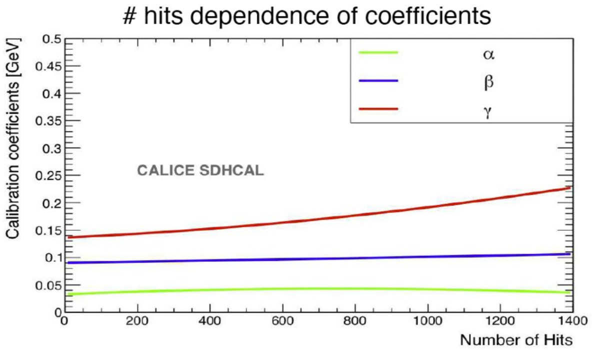
- Hit counting

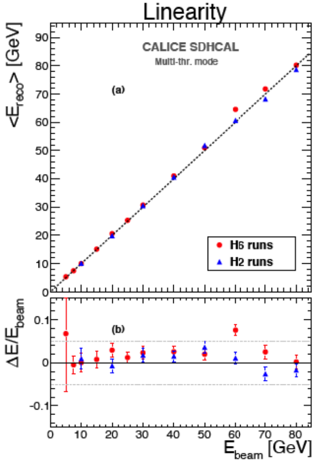
Multi-thresholds readout of SDHCAL →

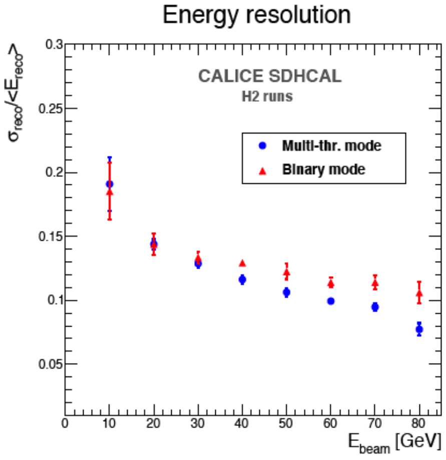
- SDHCAL version of "software compensation"
- Different weights depending on three thresholds
  - N_1, N_2, N_3: exclusive number of hits associated to 1st, 2nd, 3rd thresholds
  - α, β, γ: quadratic functions of total number values of hits
- Paremeter fit using testbeam data @CERN SPS 5, 10, 30, 60, 80 GeV π^-)
- Mitigate saturation of energy resolution at high energy

JINST 11(2016)P04001









Energy Reconstruction: SW Compensation

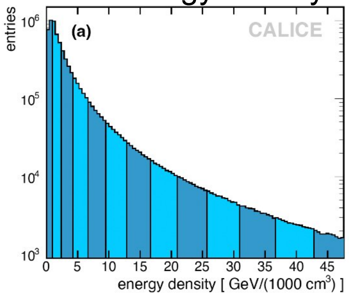
JINST 7 (2012) P09017

JINST 13 (2018) P12022

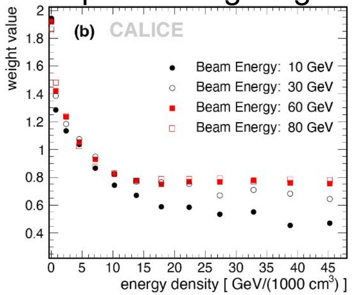
CALICE calorimeters are non-compensating

- Some compensation can be restored by density weighting
- Beam Test : **AHCAL**
  - SPS H6 2007: 10–80 GeV $\pi^{\pm}$
- Weightings :
  - Local Cell energy density (E/V) weigthing
  - Global $C(f(e_{lim}=5\text{ MIPs}))$
- Improvement by ~ 20%

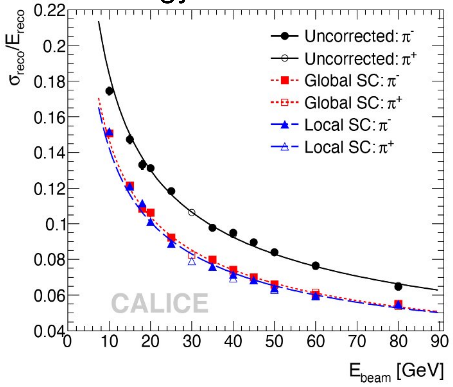
Cell energy density



Optimal weigthing

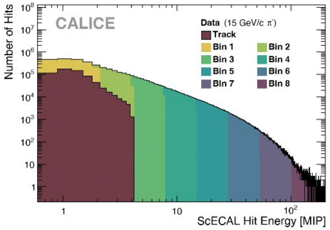


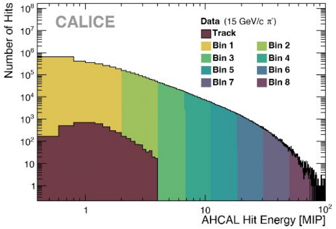
Energy resolution

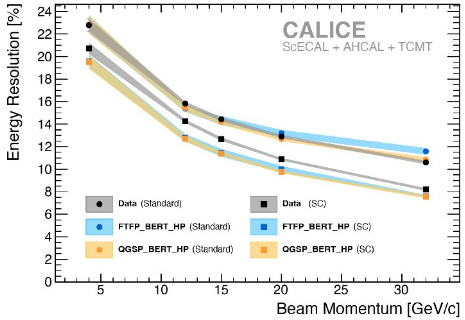


AHCAL and ScW-ECAL

- Combined Beam Test : ScW-ECAL + AHCAL + TCMT
  - FNAL 2009 4,12, 15, 20, 32 GeV $\pi-$
- Optimisation σ(E)/E on 51 parameters
  - Improvement by 10 to 20% (overestimated by simulation)





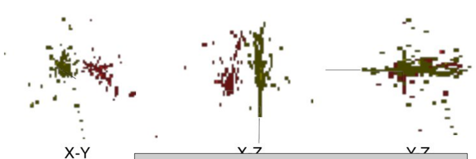


Particle Flow Studies: particle separation & identification

Separation of neutral hadron shower from nearby charged hadron shower in SDHCAL

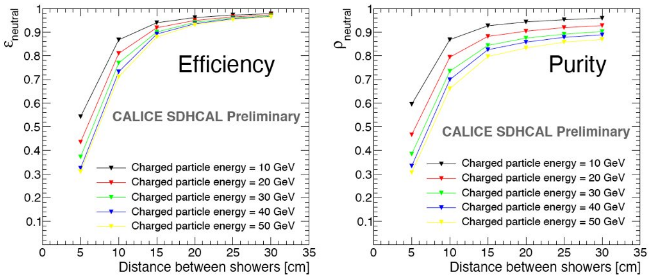
- Test beam data: 10-80GeV pions @CERN SPS
- 10GeV “fake” neutral hadron shower is generated by removing initial track segment and overlaid on charged hadron showers
- >90% efficiency and purity for nearby showers for distance>15cm

10GeV neutral hadron overlaid with 30GeV charged hadron



CALICE-CAN-2015-001

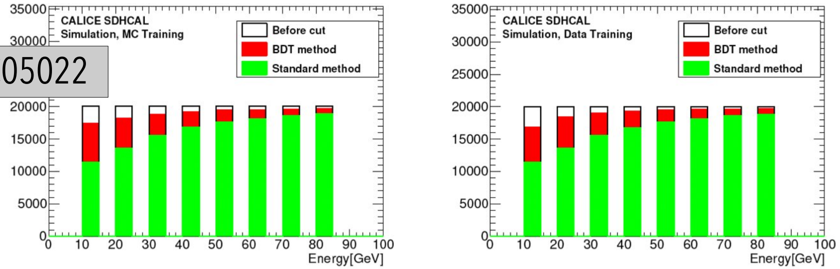
Separation of 10GeV neutral hadron from charged hadron



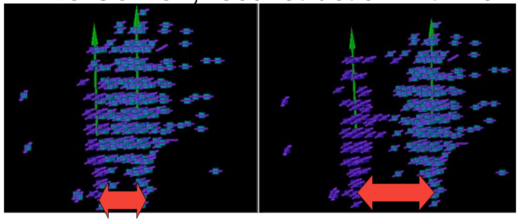
Particle identification with multi-variate analysis

- Test beam data: 10-80GeV pions @CERN SPS
- BDT improves pion selection efficiency at low energies

JINST 15 (2020) C05022



4 + 25 GeV e+, reconstruction with Pandora



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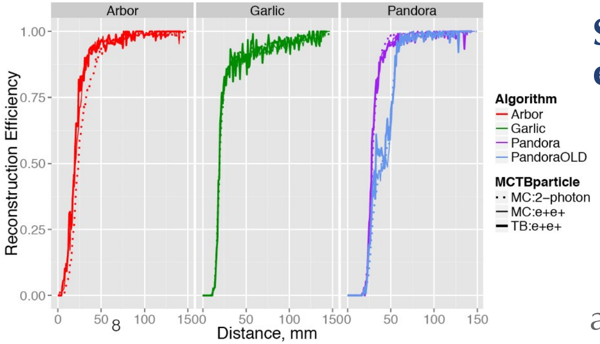


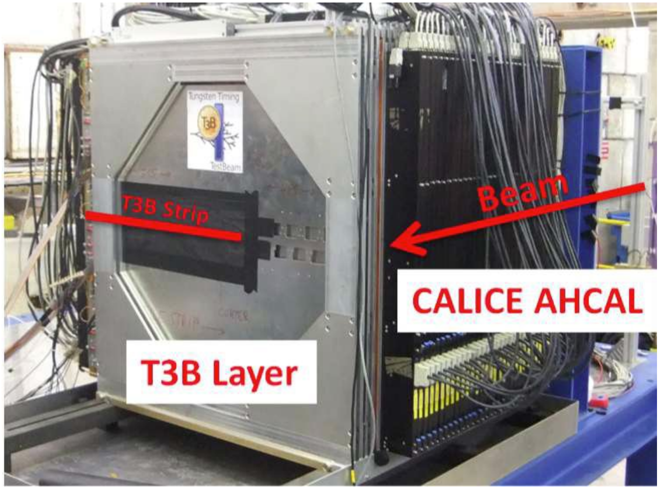
Separation of EM showers (e+e+, $\gamma\gamma$, γ-π) on mixed events SiW-ECAL + (AHCAL || SDHCAL MC)

- Beam test from FNAL 2011 / CERN’07,
- Using Pandora, Garlic and Arbor
- Separation > 90% at 20mm
  - Algorithm tuning mandatory

Time structure of Hadronic Showers

JINST 9(2014)P07022

CALICE T3B Setup



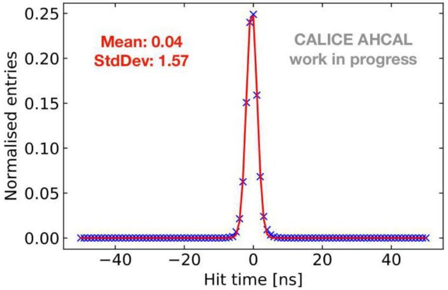
CALICE T3B Experiment

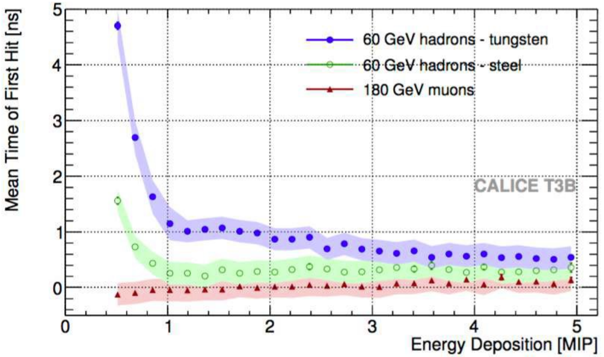
- Small dedicated setup of 15 scintillator tiles (30×30 mm²) with SiPMs placed behind
  CALICE hadron calorimeters (W-AHCAL, Fe-SDHCAL)
- Radial sampling of structure of hadronic showers with sub-ns time resolution over 2.4 μs time window
- More late component in tungsten than in steel

Hit time measurement capability at AHCAL technological prototype

- Hit time resolution of 1.6ns for muons @AHCAL technological prototype
  - Currently limited by front-end electronics
- Analysis for hadrons also in progress

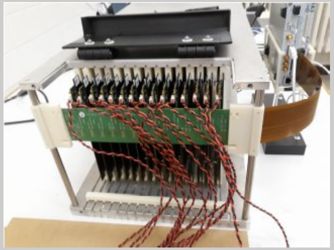
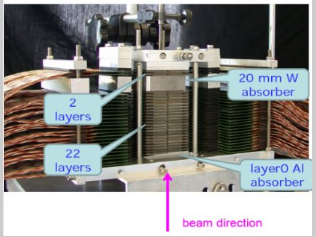
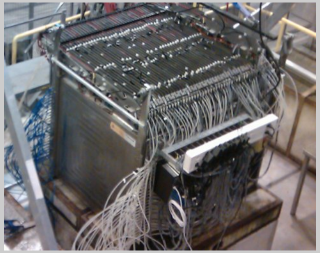
Hit time resolution with AHCAL technological prototype





Technological & new Physics Prototypes

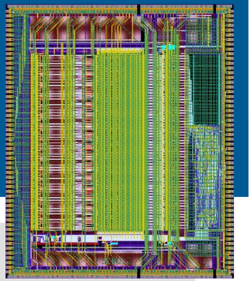
4.5 prototypes, 15⁺ years of R&D, all tested

Si-W ECAL	(ALICE FoCAL)	Scint-W ECAL	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

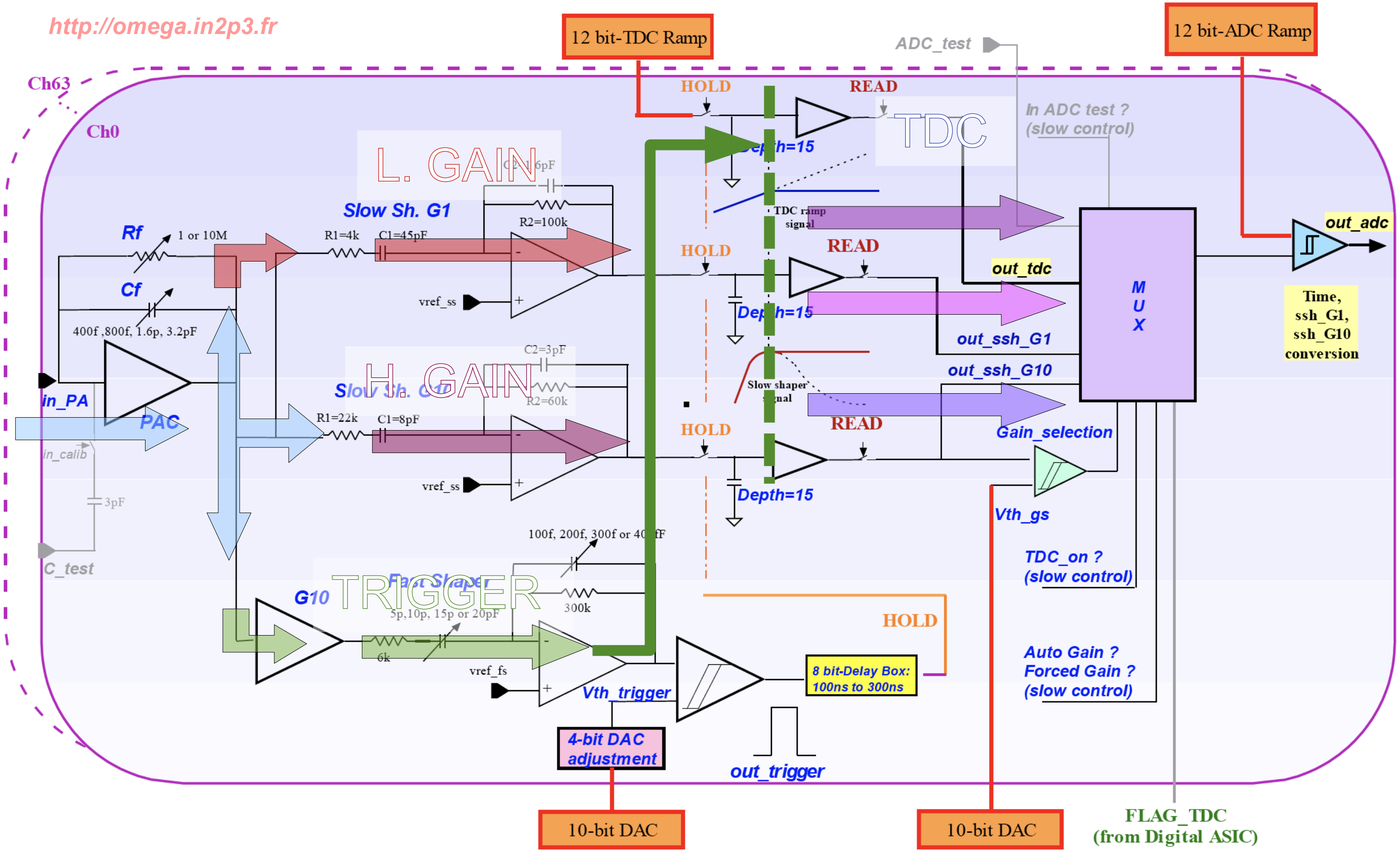
Purposes:

- Prove technological feasibility: electronics inside, thermal capacity, mechanical, DAQ, calibration, …
- Extend physical prototypes : uniformity, “large” production, methods, …

{SKI,SPI,HARD}ROC ASICs



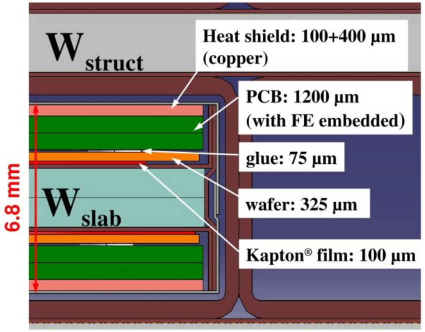
http://omega.in2p3.fr



- **36–64 channels**
- **Auto-triggered**
  - **Partial 0-suppr. : 1 cell triggers all**
- Preamp adapted to SiPMs, Silicons, RPCs
  + **2 Gains** (Auto-select)
  + **TDC** (~ ns)
- 15 (×2) analogue memories (128 digital)
- Dyn range 0.1 ~ 2500 mips
  - 12 bits ADC's
  - 2 bits ADC's
- ~600 *configuation bits*
- Low consumption
  - 25 μW/ch with 0.5% ILC-like duty cycle
- Power-Pulsed

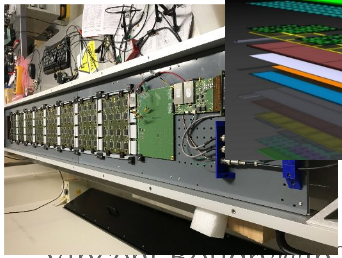
CALICE Thin, long cassettes → all prototyped

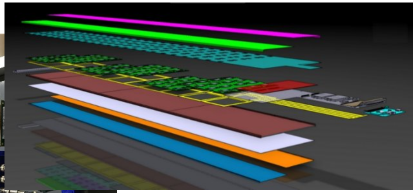
Silicon / Scint W-ECAL



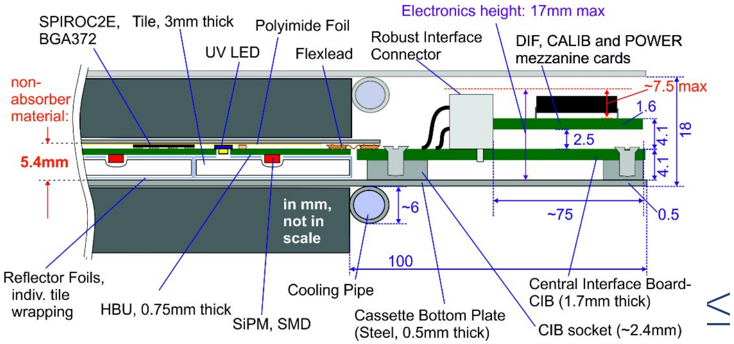
≤1.8m long

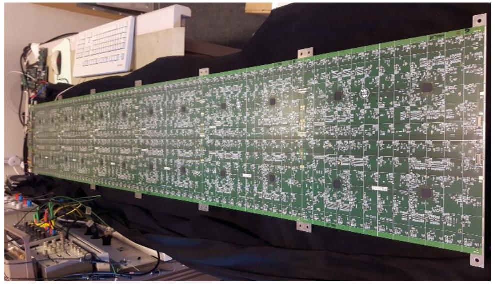
– Passive cooling



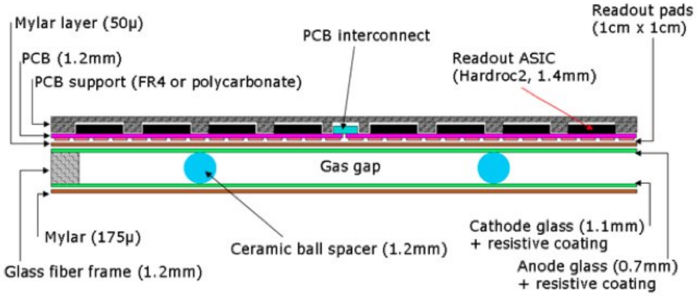


Scint Analog HCAL (also used for HGCAL)



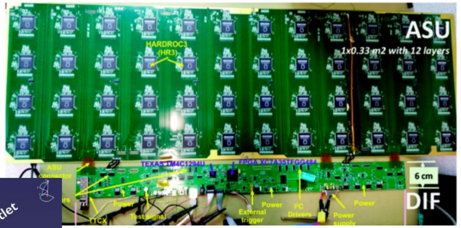


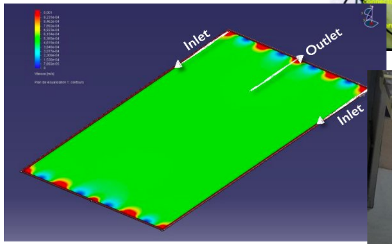
(Semi)Digital Gaseous HCAL

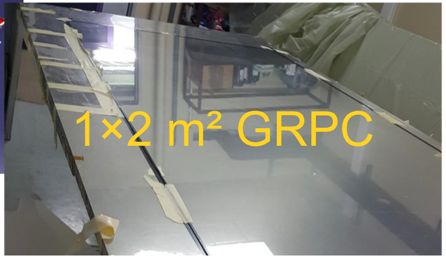


≤ 3m long

No cooling or gas flow







SiW-ECAL

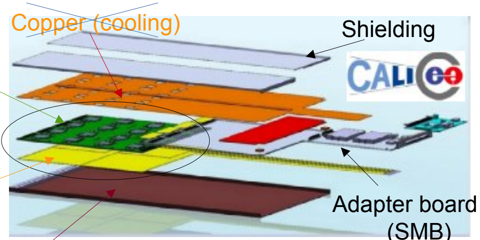
Silicon-Tungsten ECAL

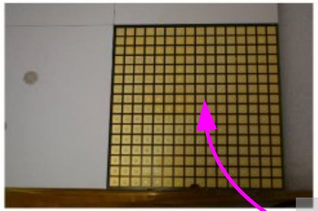
Prototypes for the ILD/ILC

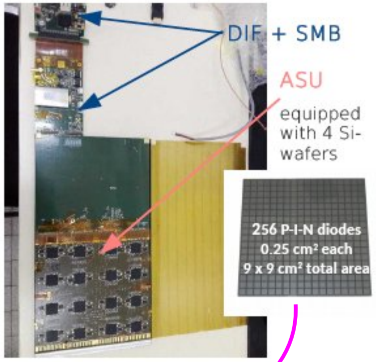
- cells of ~5×5 mm², density = 2.6k–3k cell/dm³
- Ωmega's Skiroc2/2a, 64 ch ASICs
- 25 μW/ch with 1% Power Cycle (0.3W for proto)

Technological prototype

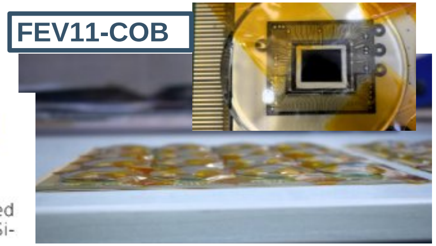
- "Physical prototype" (2005–11): 10k cells, ρ =1.5k cell/dm³
- $S/N = MPV_{mip} / \sigma_{Noise} \geq 10$
- Stacks with **15+7** layers of 1024 ch (15360 cells in a single readout)
  - mix of PCB versions (v10, 11, 12, 13), ⊗ packaged and on-board ASIC's ⊗ 320, 500, 650 μm Silicon wafers
  - New Integrated DAQ, 1st prototype toward ILD-like (≤3cm)

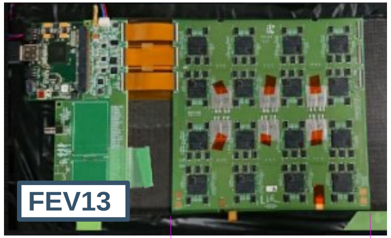




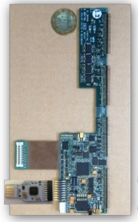


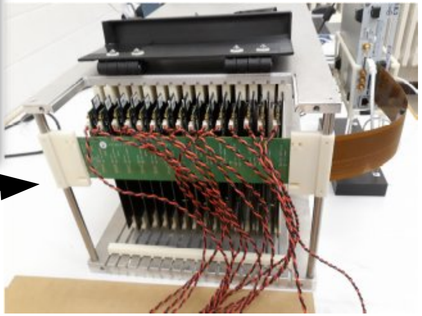
Glued, w floating GR

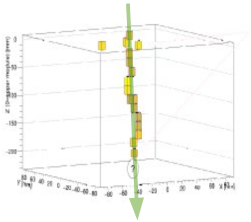


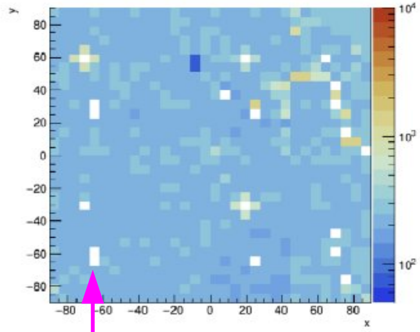


183mm









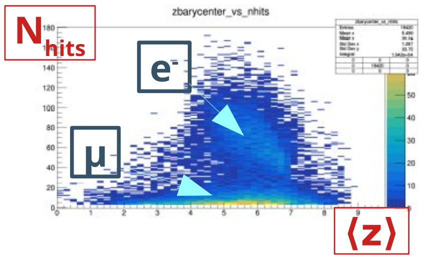
Noisy cells removed ~ 1–3 %

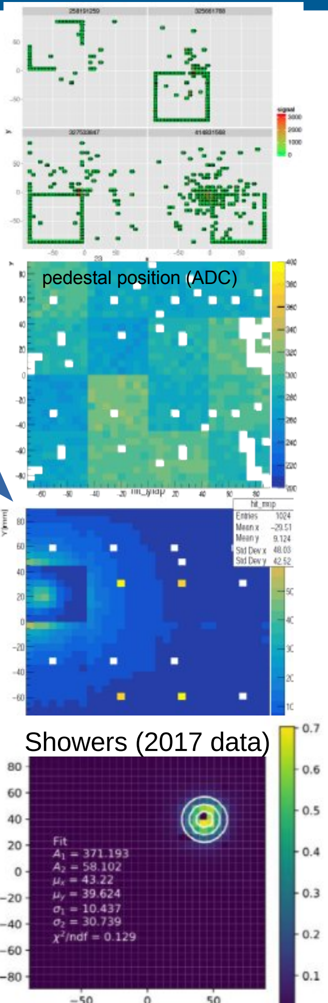
Silicon-Tungsten ECAL: Developments

See Roman's presentation for recent dev't

Improvement in design

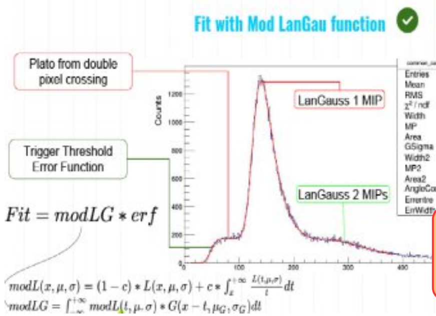
- CERN 2015 "naked FEV11" (320 µm)
  - S/N_{ADC} ~ 16–17
  - Ring X-talk / 10 wrt Phys. Proto.
- CERN 2017: 7 FEV11 (320 µm)
  - S/N_{ADC} ~ 20.3 ± 1.5
  - 8% masking, 1T operation
- DESY 2018: 7 FEV11 + 1 FEV13 (650µm)
  - S/N_{ADC} ~ 30.3 – 40;
  - S/N_{TRIG} ~ 11.6±0.7 ⇒ Cut ~ 1/3 mip @ 4 σ
- CERN 2018: 6 FEV11 + 4 FEV13 + 24 X_0 W

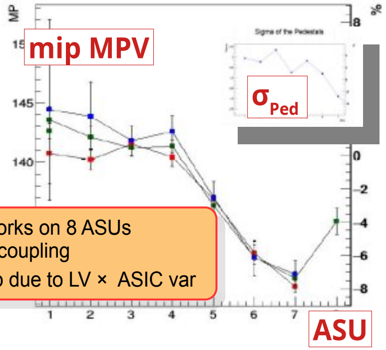




Long Slab

- 8 ASU's with baby wafers (2×2cm²)
  - → **New FEV2.1**





- Readout works on 8 ASUs with HV decoupling
- ~10 % drop due to LV × ASIC var

R&D Highly Resistive Silicon Diodes:

- Ref = Hamamatsu "Guard-Ring-less" design
- 6" Towards 8" (à la CMS-HGCAL) × 725µm ?
  - ⇒ cost, design, perf.

Sc-ECAL

Scintillator-Tungsten ECAL

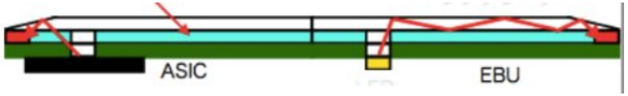
Prototypes for the ILD/ILC & CEPC

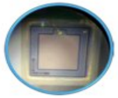
- Ωmega's Spiroc2e, 36 ch ASICs
- 25 µW/ch with 1% Power Cycle
- cells of ~5×45 mm², ρ = 450 cell/dm³

Technological prototype

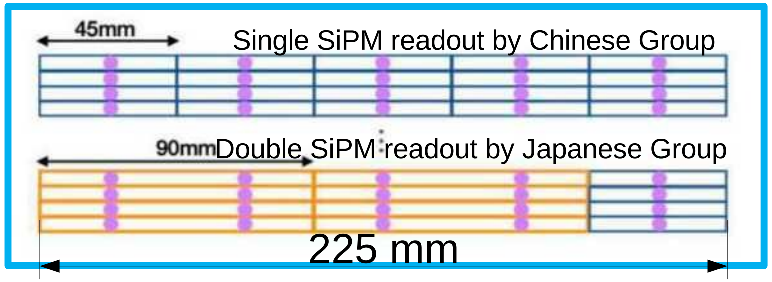
"Physical prototypes" (2005–11, 2013–15)

- Stack with 32 layers
  - aging test made (48h @ 50°C)
  - being assembled





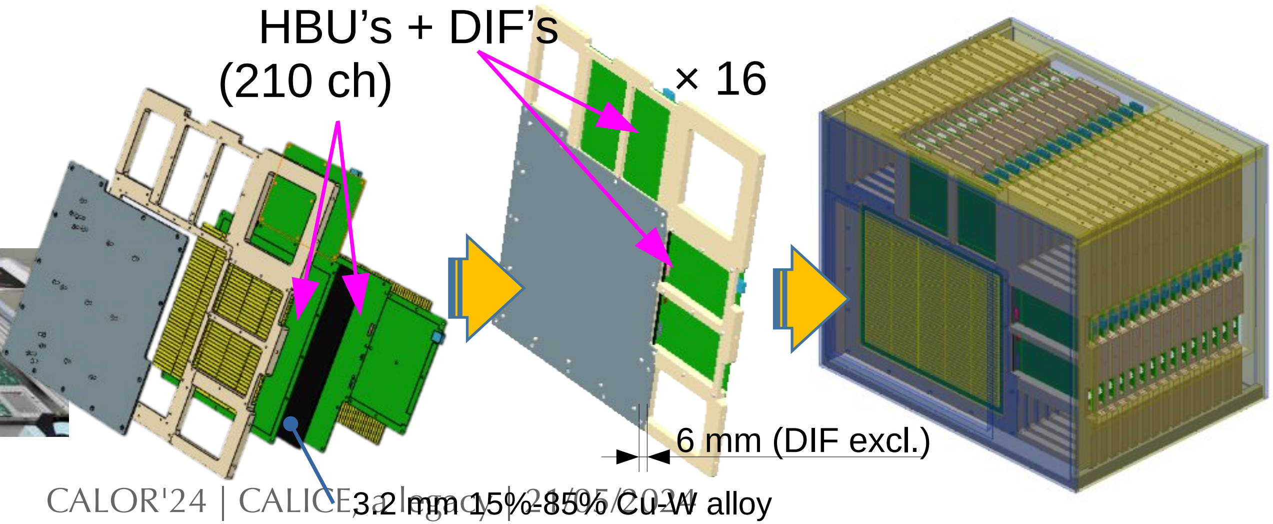
Baseline SiPM
Hamamatsu S12571-010P
- size: $1mm \times 1mm$
- pitch: $10\mu m$
- number of pixels: 10K



× 30

10µm & 15 µm SiPM

× 2

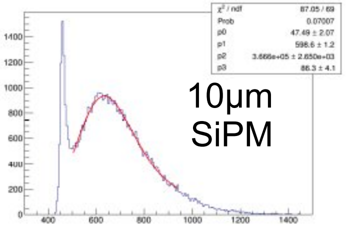


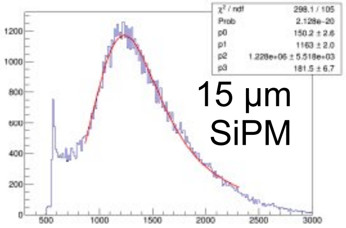
ScECAL: commissioning

See Tatsuki Murata's and Xin Xia's presentations

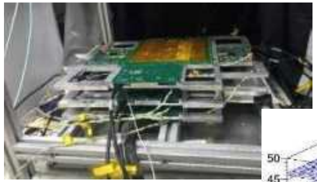
Sr90 Source

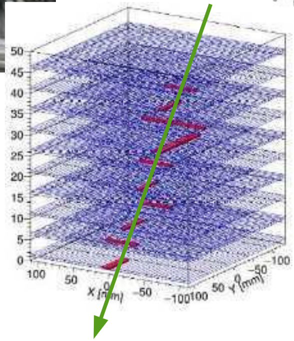
– 25 ns shaping
auto-trig
Landau ⊗ Gauss

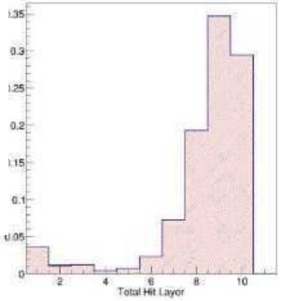




Cosmics test







Beam tests

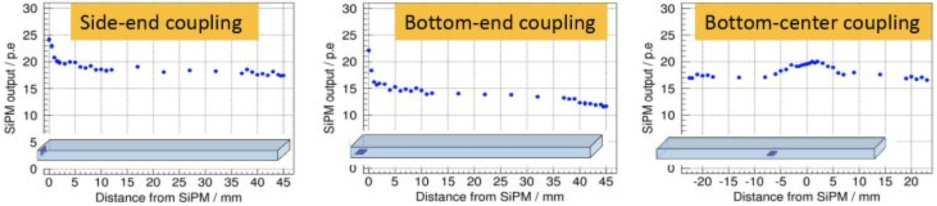
– DESY, CERN.

R&D:

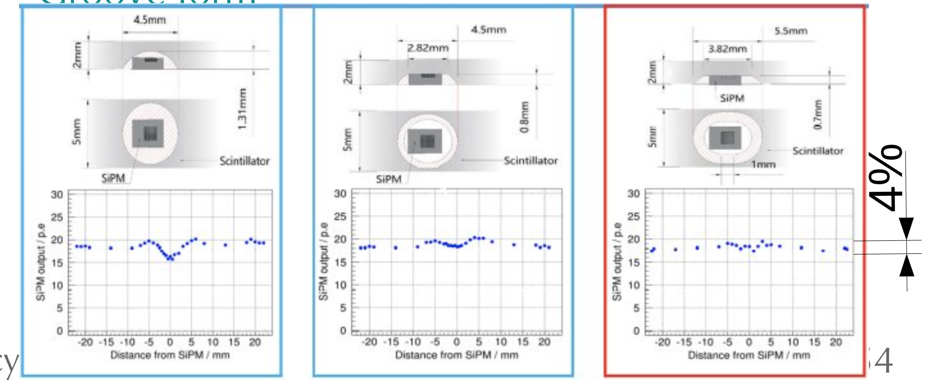
– Scintillator – SiPM coupling

– non-uniformity ⇒ σ (E) ↗

- SiPM position



- Groove form



AHCAL

Scintillator AHCAL

For ILC and CMS

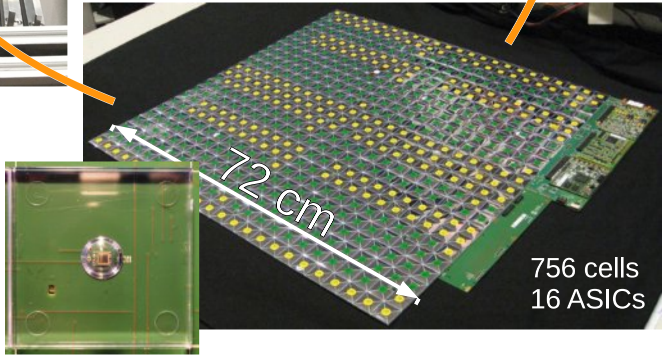
- ILC with Ωmega SPIROC2e
  - HL-LHC will be Ωmega HGROCv3
- 3×3 cm², density ~ 55 cells / dm³

Technological prototype ≥ 2017

Physics prototype ~ 2006-11 (3×3 + 6×6 + 12×12 tiles)

- Uniform 3×3 cm² tiles (moulded) read by SiPM mounted on PCB
- 38 layers of 0,7×0,7 m², 22k cells
  - + additional layers of 6×6 cm²
- 2018: Stand alone tests and with CMS HGCAL
  - 4λ of stainless steel (1.7 cm ×38)
  - $\mathcal{O}$(100M) events accumulated

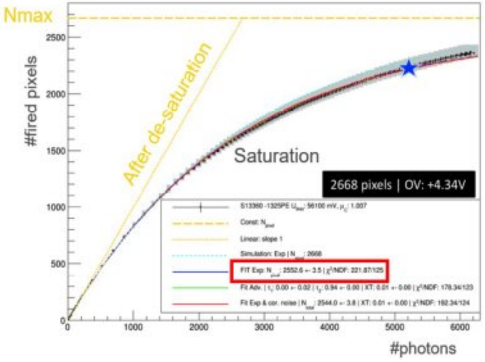
→ Combined beam test with ECALs
→ Stand-alone with full W structure



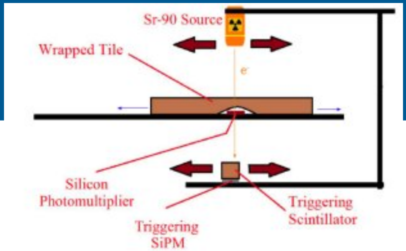
Online corrections: on SiPM's:

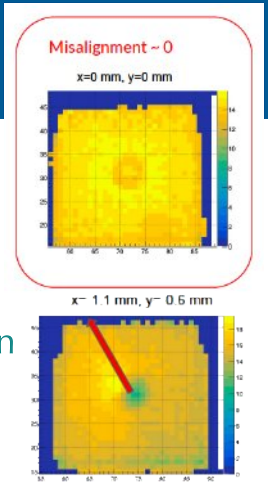
⇒ EM Lin & Resol.

- Gain (Temperature, HV)
- Statistical saturation for $E_{hit} \geq 100$ mips ($N_\gamma \sim N_{pix}$)
  - Corrected for E≲350 mips

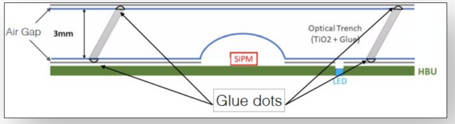


AHCAL developments

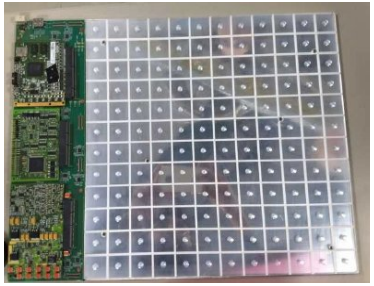


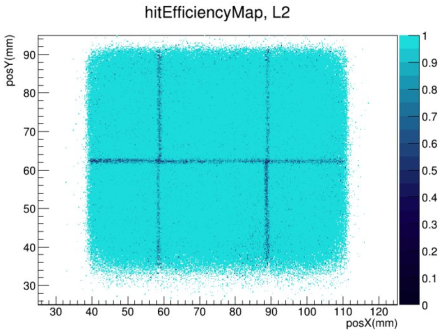


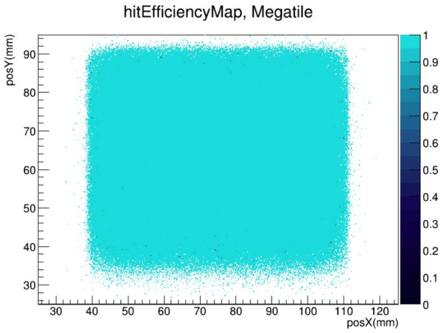
"MegaTiles" R&D:



- Single Scintillator tile with trenches of 3×3 cm²
- 2019 Beam test:
  - Light Yield, Mip resp, Optical Cross-talk
  - Larger Cross-Talk than in cosmics (mechanics)



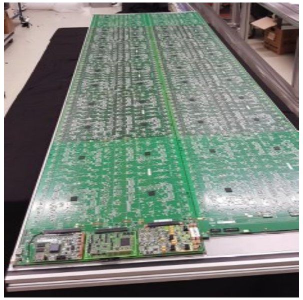




R&D

- Scintillators optimisation
  - Measurements ⇒ Realistic Simulation
- SiPM/MPPC evaluations
- ADC consumption (KLAUS Chip)
  - ➞ Next Gen

Long Layer



- 2×6 HBU's OK in lab…
  - Goals:
    - 3×6 HBU's (ILD)
      … in a test structure (absorbers)

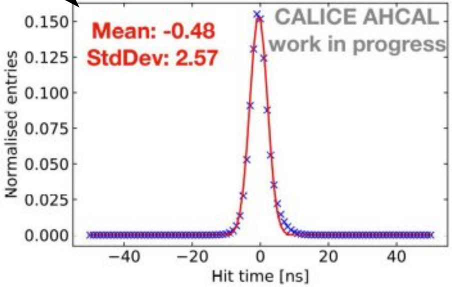
CMS HGCAL:

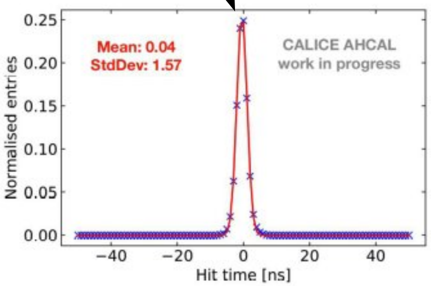
- Production on-going

AHCAL analysis

New: Hit time correlation

- Time profile from muons
  - SPIROC : double analog ramp → ADC
  - with clocks
    - at 250kHz (beam test mode) : σ ~ 2.6 ns
    - 5 MHz (ILC mode): σ ~ 1.6 ns

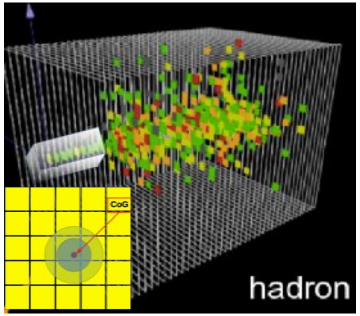


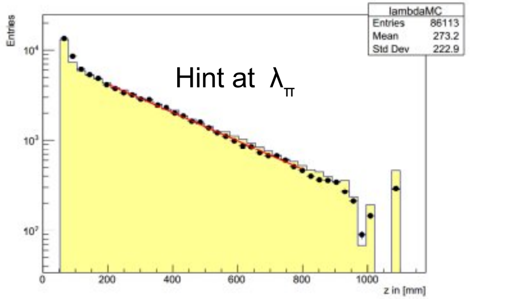


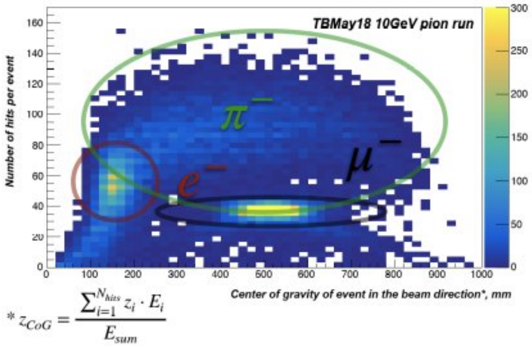
- Goal: 1 ns in ILC mode

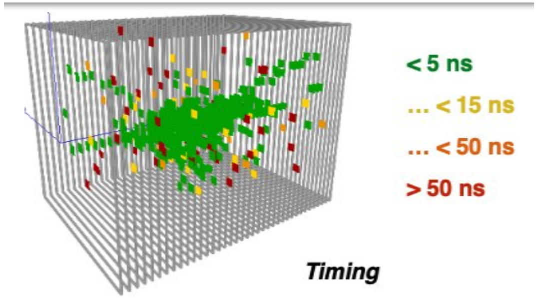
High Level Analyses:

- Shower profiles & PFA tests (≥2011)
- Shower start, PID, f_{neutrons} (time)









(T)-SDHCAL

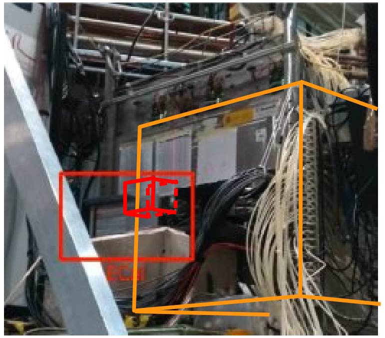
SDHCAL: Semi-Digital Gaseous HCAL

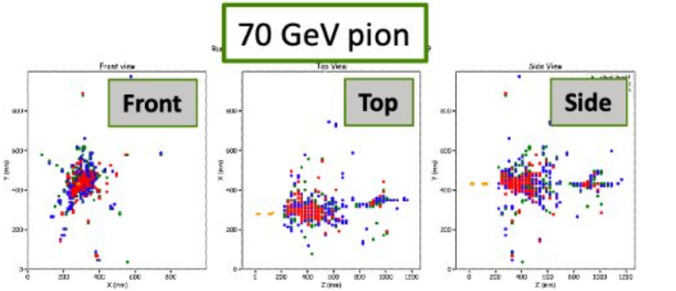
Technological prototype ≥ 2011

- Single and multi-gap thin GRPC's
- Cells of 1×1 cm², ρ = 380 cells/dm³
- Ωmega HARDROC2
- 48 layers of 1×1 m², 460k cells, $6\lambda_I$ (2 cm Stainless steel)

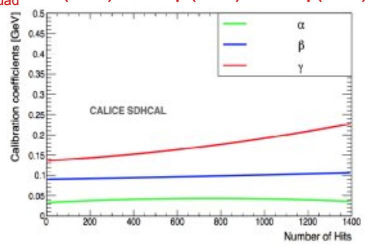
Semi-Digital calorimetry: 3 thresholds

- Uniformity: efficiency & multiplicity
- Threshold optimisations (typ. 1/2 mips, ~5, ~15 mips)
  - and calibration by scans
- Energy measurement:
  - Linearity & Resolution to single e, π, p
  - Simulation: **complex digitization**
    - Large number of overlapping effects in avalanches / readout / time
    - Now, reasonable ≤ 40 GeV e, π

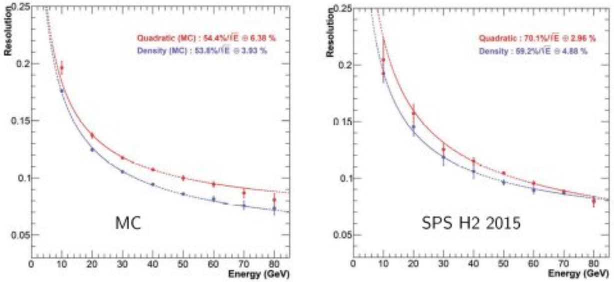


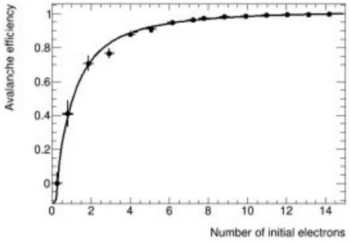


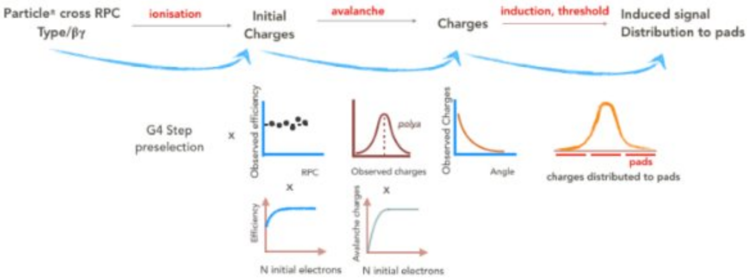
$E_{Quad} = \alpha$ (Ntot) N1 + β(Ntot) N2 + γ(Ntot) N3



$E_{Dens} = \alpha$ B1 + β B2 + γ B3 ; B_i = Neighbours ≥ thr. i







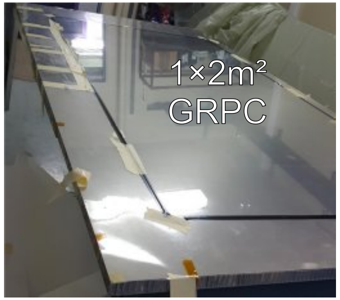
SDHCAL developments

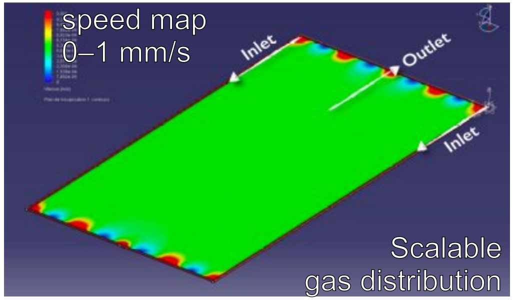
Large cassettes: 1×1 m² → 3×1 m²:

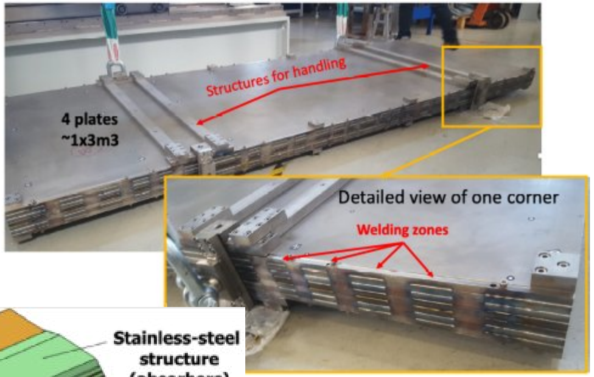
- 432 ASICs HardRoc3:
  I2C, full zero-suppression,
  dynamic range ×3 (15 → 50pC)

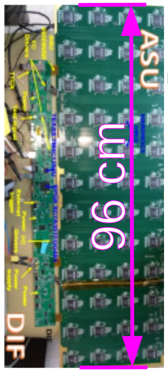
Main goals:

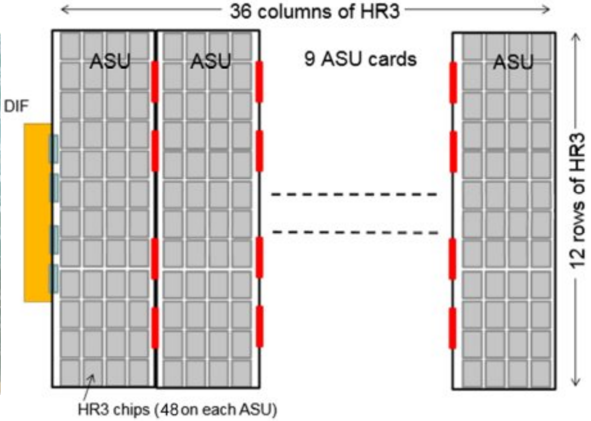
- Sensors: Large uniform GRPC's
- Large & flat PCBs: 32×96 cm²
  - glued on single GRPC chamber
  - interconnections (in 3T field)
- Mechanical assembly
  - Electron
    Beam
    Welding

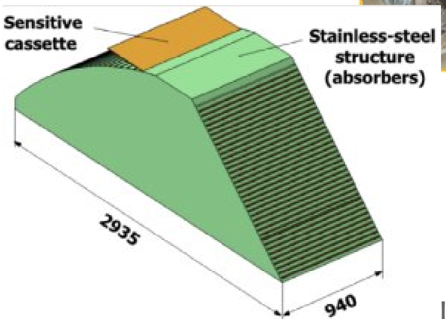












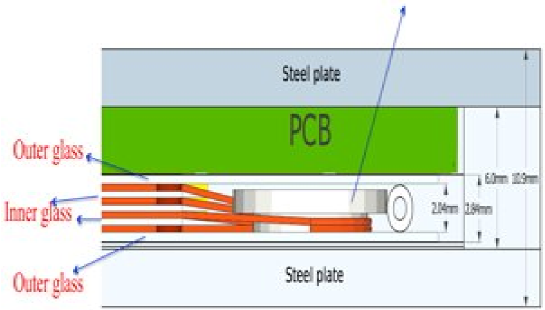
SDHCAL → T-SDHCAL (for Circular colliders)

Power issues ?

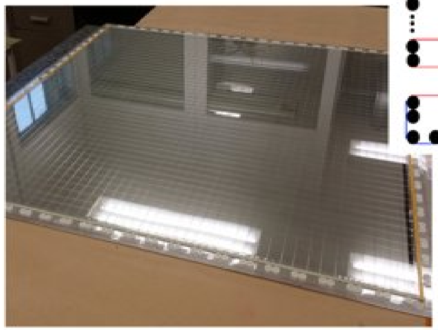
- RPC :
  - Rates OK for RPC ? → MGRPC
  - Cooling possible with gas
    - (flow to be determined from uniformity of response :
    - heat/laminar flow)
  - With Eco-Friendly gas

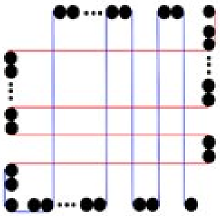
Timing

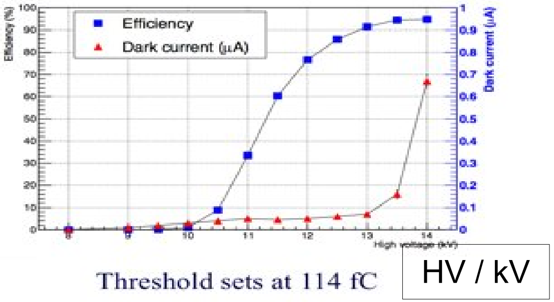
- Prelim. studies show time information could improve significantly hadronic showers separation at lower distances
- ASICs:
  - Ωmega PETIROC ASIC (20 ps) jitter ⊕ Multi-gap GRPC (60 ps)
    - Liroc+internal TDC ?



4-gap MRPC of 1 m²





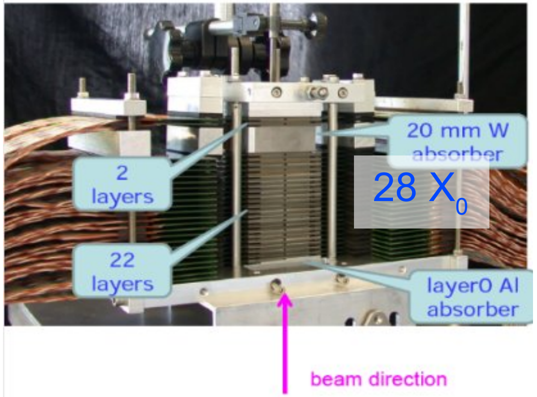


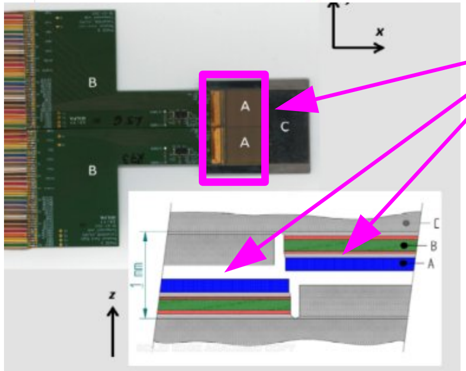
Others : DECAL, Adriano

MAPS & DECAL / EPICAL-2

See Thomas Peitzmann's presentation

FOCAL DECAL prototype



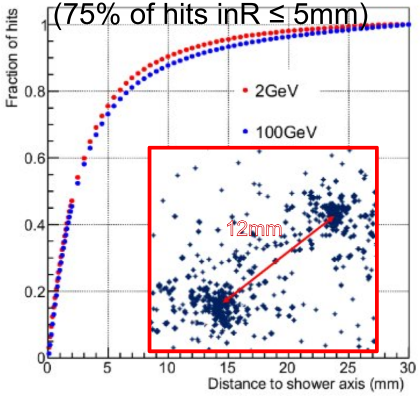


FOCAL = 2 layers of MAPS

but How to build a full detector ?

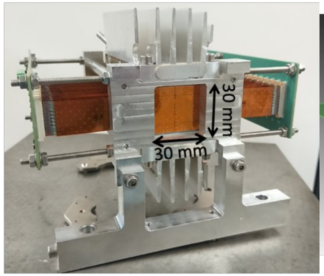
- Services: Power + Cooling ?
  - Gains by going fully digital ?
- For what physical gain ?
  - Improved separation ✔
  - Improved resolution ?

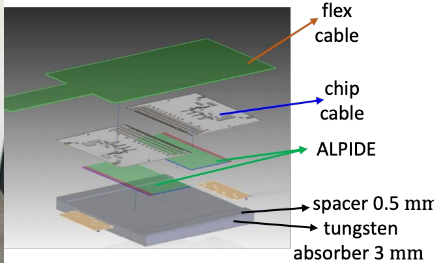
R_M = 10.5mm
(75% of hits inR ≤ 5mm)



4 MIMOSA-26 / Layer
CMOS sensors (IPHC)

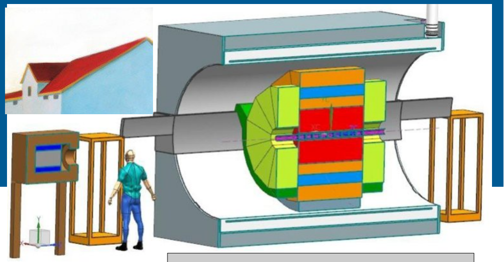
- 6×6 cm²
- 30×30 μm² pixels
- 39 M pixels
  = full readout





- 24 layers with 3 mm tungsten and two ALPIDE chips each
  - chip size 30 mm x 15 mm
- 512 x 1024 pixels per chip:
  - 25 M pixels in total
  - pixel size:
    26.88 μm x 29.24 μm

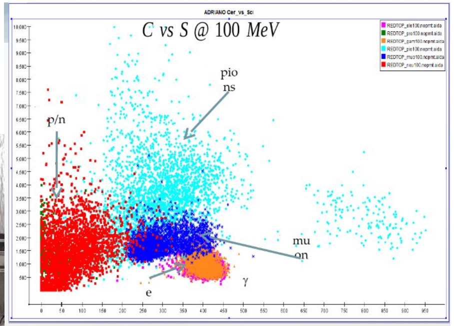
ADRIANO2/3 - Dual/Triple Readout Calorimeter

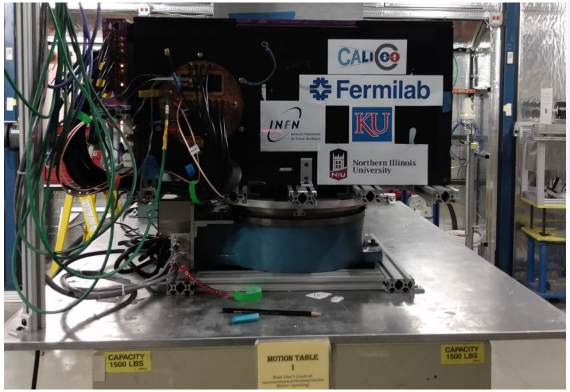


C. Gatto @ CALOR'22

Primary experimental context: REDTOP / T1604 Collaboration

- ADRIANO2: PFA (Granularity) + Dual Readout (Č/Scint)
  - 5D shower measurement, disentangling the neutron component of the shower.
- ADRIANO3: ps timing





Sensors:

- High-density glass as Cherenkov Medium (and absorber)
- Plastic scintillator tiles
- RPCs with cm² pad readout for fast timing

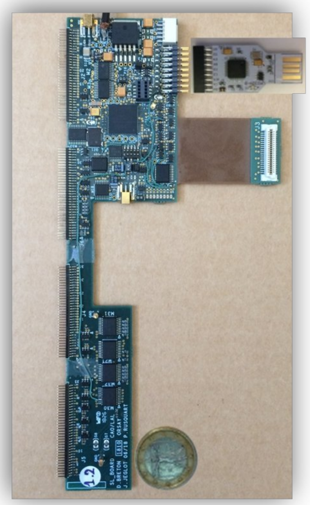
Key R&D goals

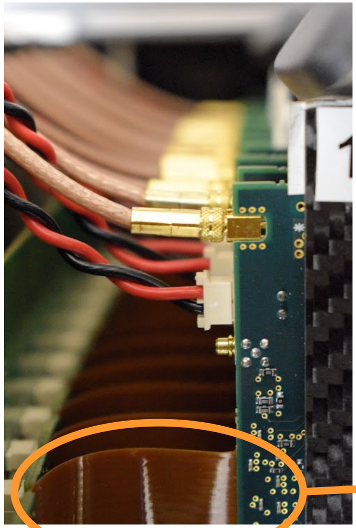
- optimization of the construction technique in terms of:
  - light yield, RPC efficiency, timing resolution, and cost
  - Test layers in 2024, small-scale prototype 2025

Testing many configurations → larger prototype 2026–27

Reminder on compact readout

Current detector interface card (SL Board) and zoom into interface region

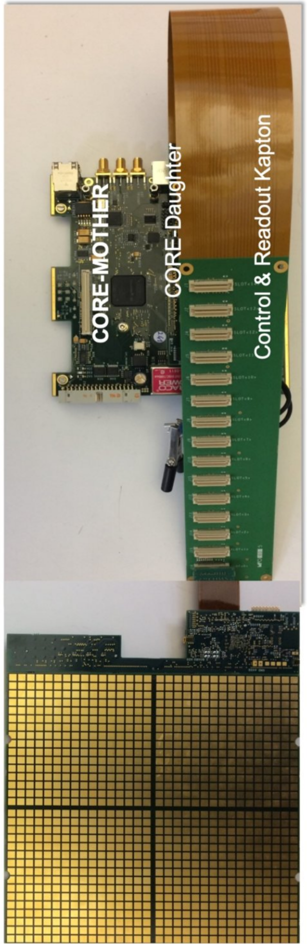




Complete readout system

More compactness
⇒ Less flexibility
~ in CRK

margin ~ ±2×2 cm ?



- "Dead space free" granular calorimeters put tight demands on compactness
- Current developments in CALICE meet these requirements
- Can be applied/adapted wherever compactness is mandatory
- Components already tested in beam tests

Future Directions and Challenges

Immediate Applications:

- Use in real cases :
  - AHCAL for the CMS-HGCAL : on-going, full speed
  - SiW-ECAL for QED & Dark Photons experiments :LUXE@XFEL, EBES@KEK, Lohengrin@ELSA
  - DECAL for the ATLAS-FOCAL

Further developments:

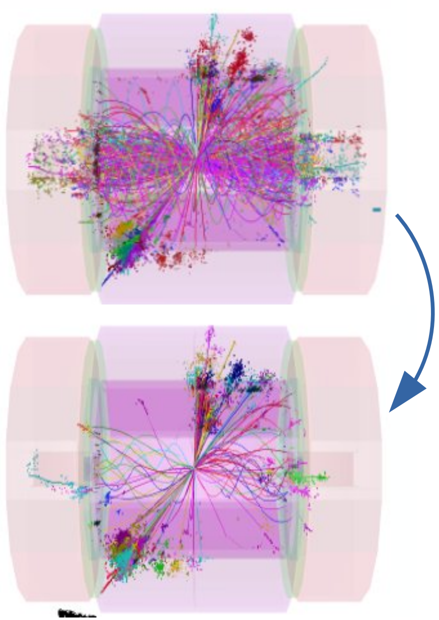
- Timing in calorimeters
- Adaptation to circular colliders

Timing in Calorimeters: 0.1–1 ns range

Technically feasible but adding thermal constrainst

1 cm/c = 30 ps

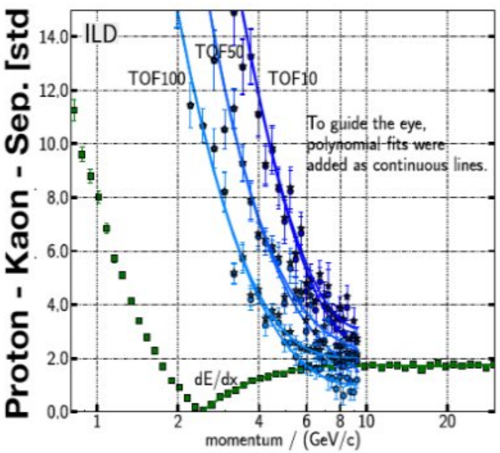
Cleaning of Events



[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

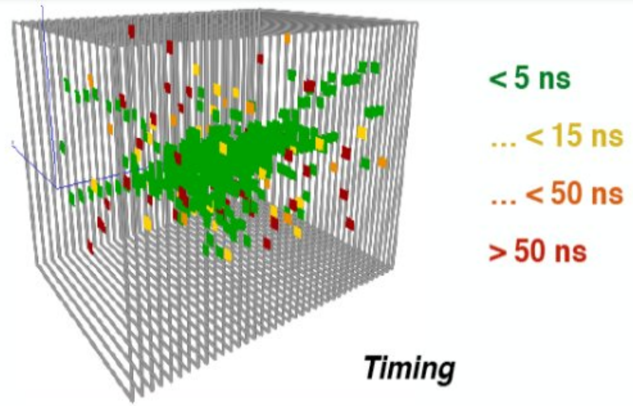
- Complementary to dE/dx
  - here with 100 ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

Ease Particle Flow:

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



Ch. Graf

How to adapt calorimeters to circular collider conditions

CALICE calorimeters:

- Embbeded readout:
  compact design & DAQ
  - Minimal consumption by power pulsing
    - 1–2ms readout , 198–199 ms off.
    - Passive cooling ➞ no dead materials

1) Rates and cross-sections

- Z-peak out-of-scale wrt all the other configurations
  - One detector fits all ? “optimal” granularity ?
- DAQ Scheme ? Continuous readout ?

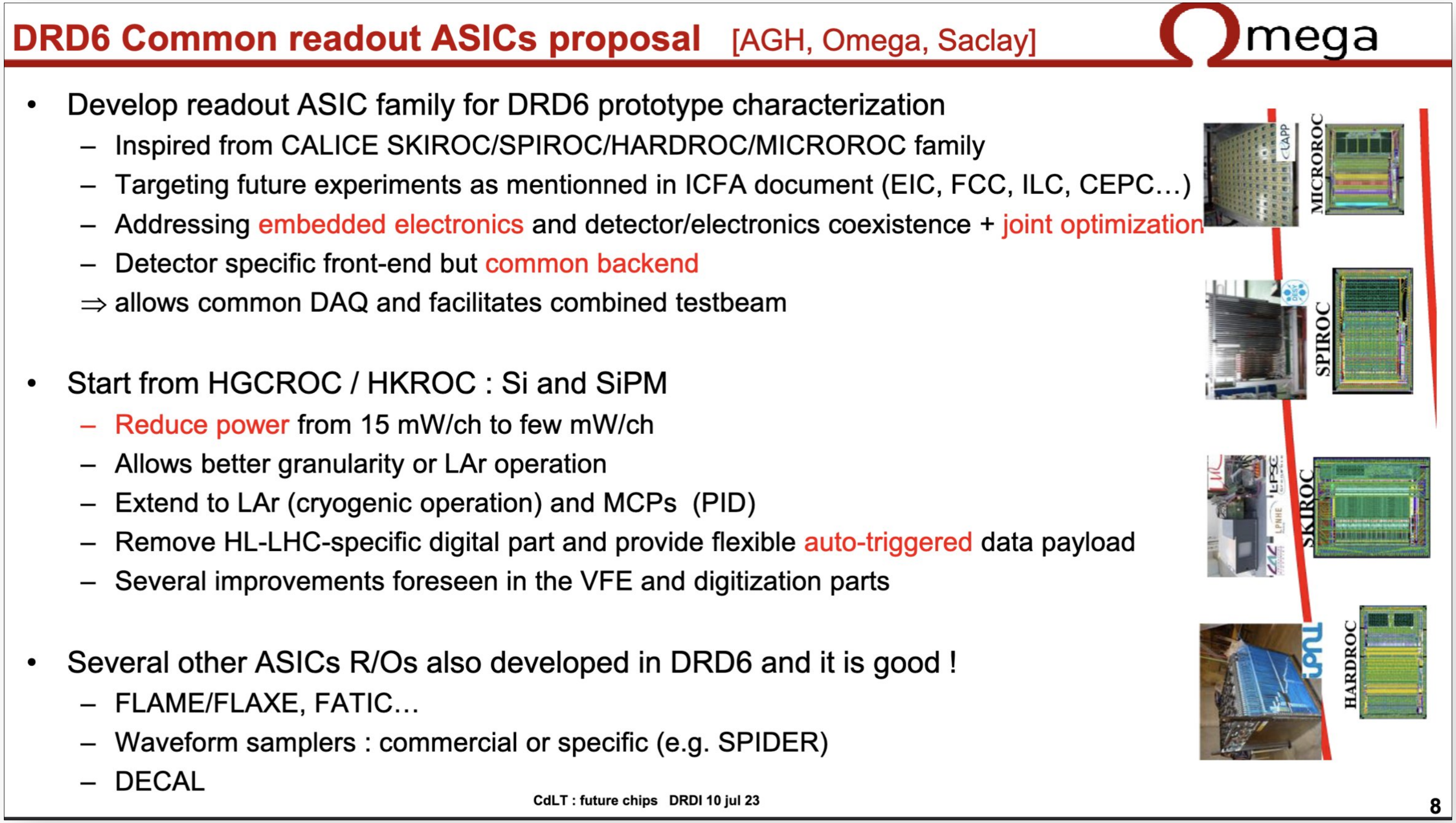
2) Continuous running

- Electronics base comsumption × 100–200 wrt ILC

3) New opportunities: timing in calorimeters

- Adds comsumption
- Large potential but at what cost ? What precision ?

New ASIC:



Low Power

- Timing ?

Low occupancy

- Self-trigger
- Less memory
  - if continuous readout

Optimized dynamic range

Conclusion:

Development of calorimeters with unprecedented granularity

- Exploratory prototype for physics
- Validation of technologies for future experiments

Opening on hadronics showers imaging :

- Precise 3D profiles → GEANT4 validation/adjustment
- In-shower sub-components:
  - Track identification → in-physics calibration, improved energy resolution
  - EM subshowers → SW compensation
- Validation of particle flow algorithms approach

So ? Mission accomplished ?

Yes, … but please go-on

… in DRD6

- Completion of some prototypes
- Explore the potential of timing calorimetry
- Lots of data still to be (re)exploited (with Machine Learning)
  - See M. Borysova on Wednesday

An R&D Collaboration Model ?

- Sharing of tools and experience between otherwise competitive teams
  - ASICs, DAQ, Beam test, Reconstuction techniques, Simulations,
  - Building of expertise & Visibility
- Very flexible framework:
  - Openness … but no financial support
    - Common tasks on Goodwill

Backups

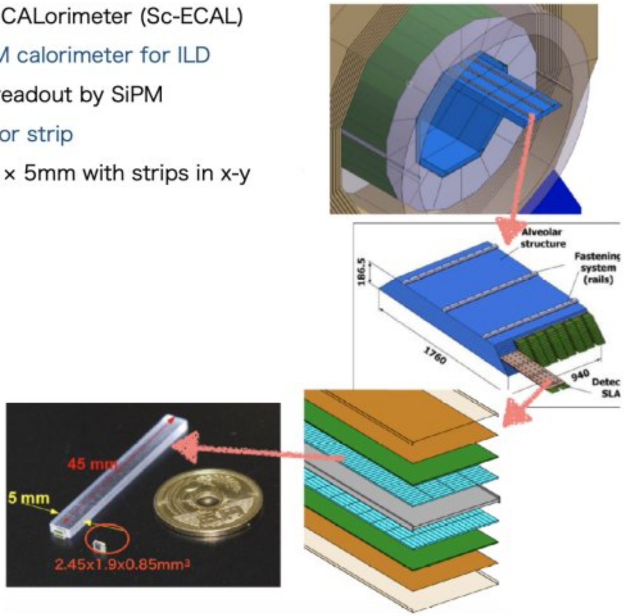
Scint-ECAL tile wrapping

Reflector wrapping (90mm strip)

- Wrapping by hand with a help of jig

Sc-ECAL (reminder)

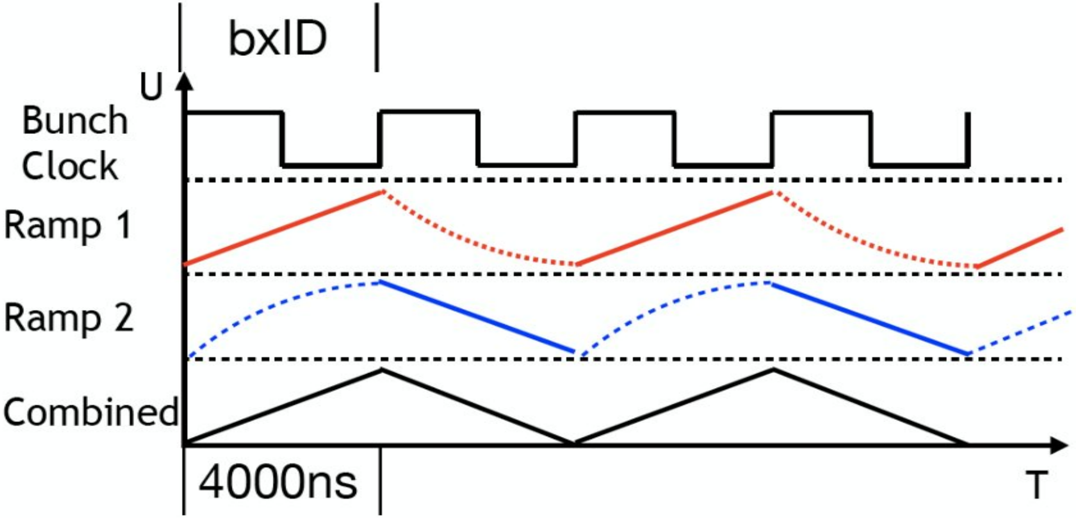
- Scintillator Electromagnetic CALorimeter (Sc-ECAL)
  - Technology option of EM calorimeter for ILD
- Based on scintillator strips readout by SiPM
  - 5 × 45 × 2 mm scintillator strip
- Virtual segmentation : 5mm × 5mm with strips in x-y configuration
- Timing resolution < 1 ns
- Low cost



Time calibration (HW)

Time measurement with Spiroc2E: TDC (time to digital converter)

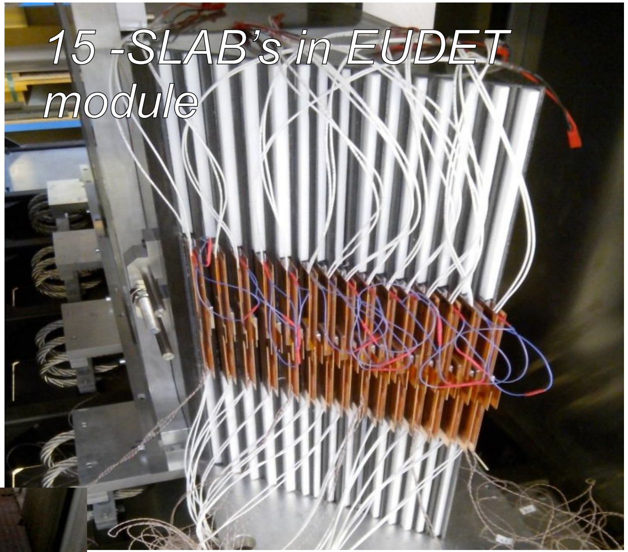
1. Common external clock with ~1ns bins
2. Ramp up voltage during one bunch crossing ID

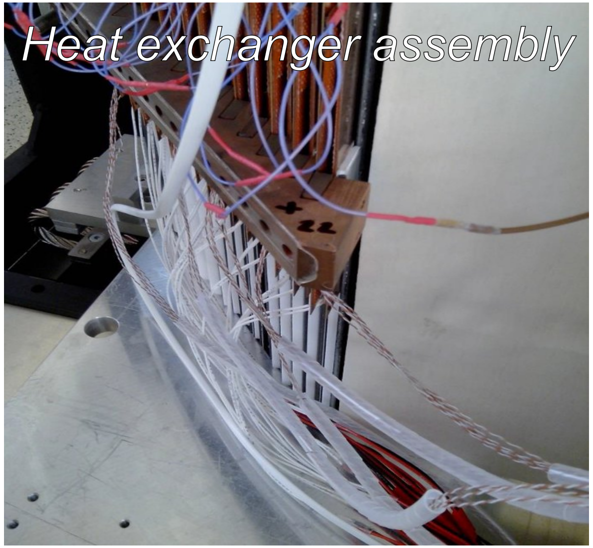


Lorenz Emberger (MPI. Munich)

Integration in ILD: thermal studies

by Denis GRONDIN / Julien GIRAUD (LPSC)



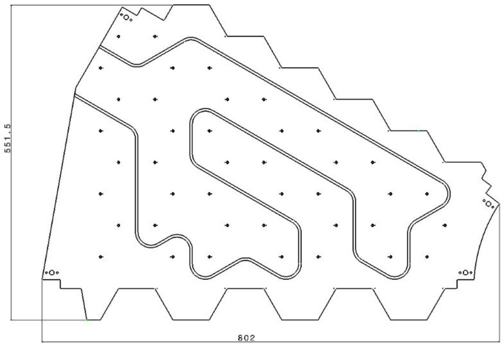


Puissances ASU / SLAB (W)	1	2	1	2
Puissances Front / SLAB (W)	1	1	2	2
Total ASU SLAB (W)	15	30	15	30
Total FRONT SLAB (W)	15	15	30	30
Total (W)	30	45	45	60

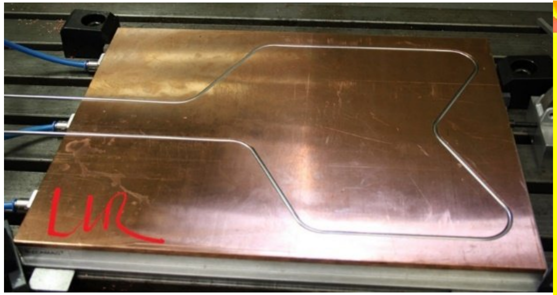
Important thermal inertia => 4 days minimum of stabilization

Active cooling

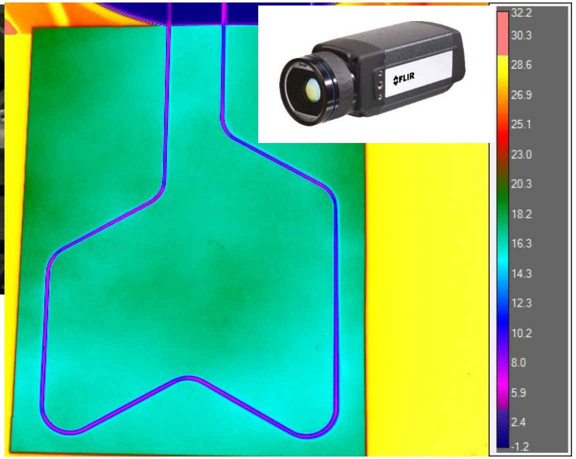
R&D using CMS studies (Thanks to Th. Pierre-Emile from CMS-LLR group)

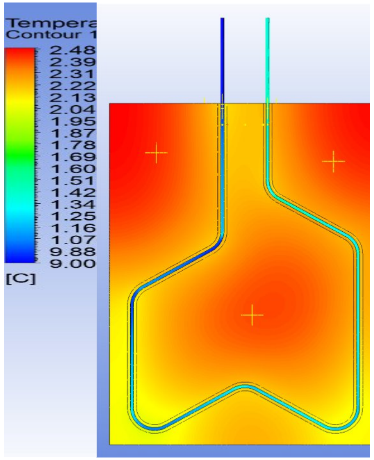


Copper plate prototype dimensions information



Pipe insertion on a cooling prototype for FEA correlation

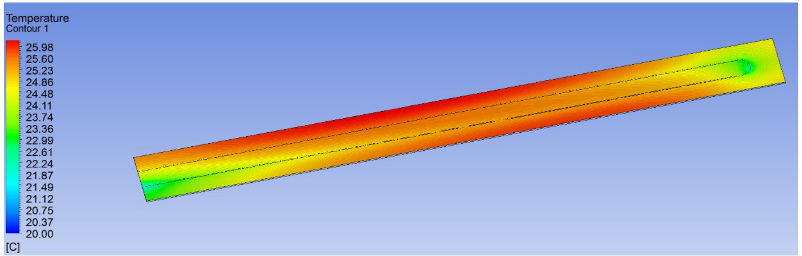




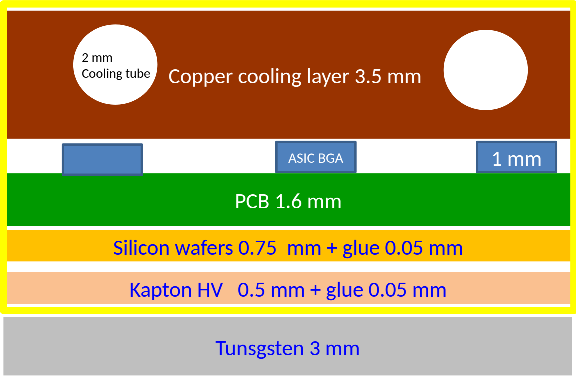
Pipe insertion on a cooling prototype

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

$\Delta T = 2.5°C$

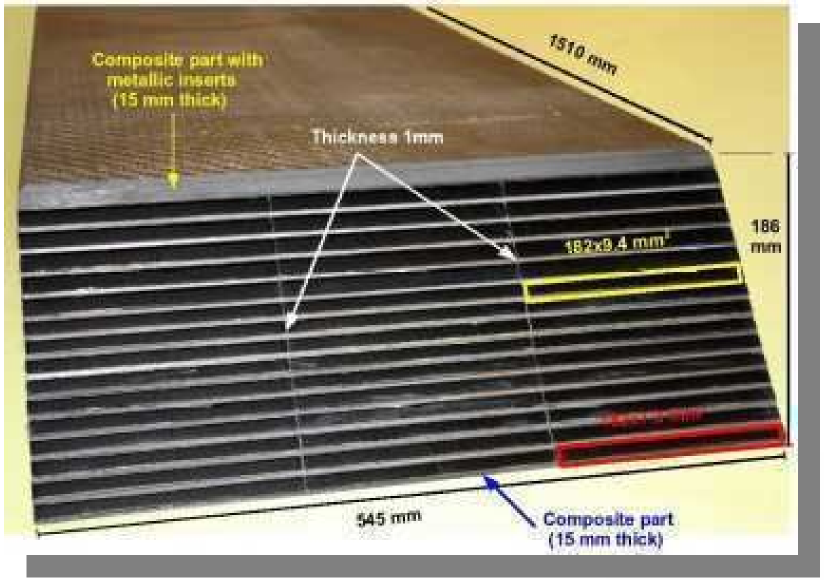


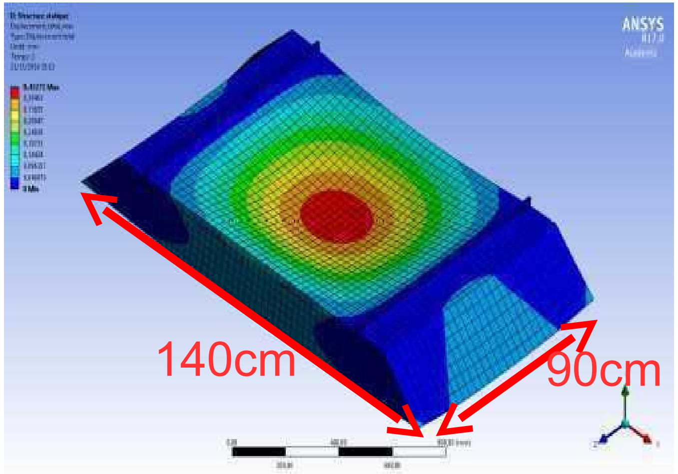
Thermal static CFD analysis thermal field example using Fluent with 100W extracted and water mass flow rate of 7g/s through 1,5mm ID pipe



⇒ 9 mm / layer

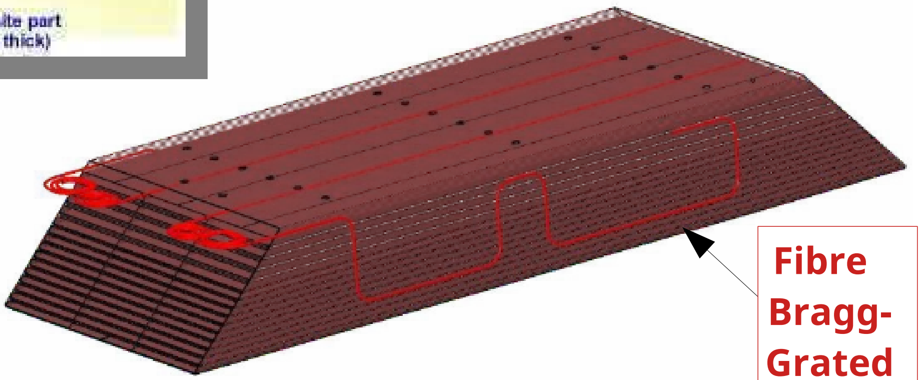
CFRC+W Structures
ILD Design





Study by M. Anduze

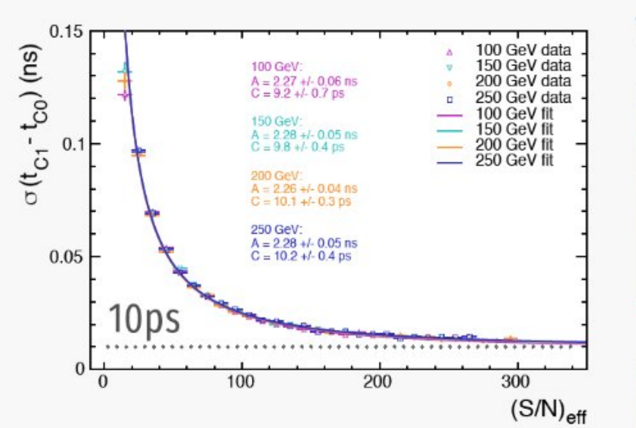
Measurements
with FBG
still to be done...



Timing

Timing of Showers

- For events reconstruction
- From Core Hits to avoid contamination

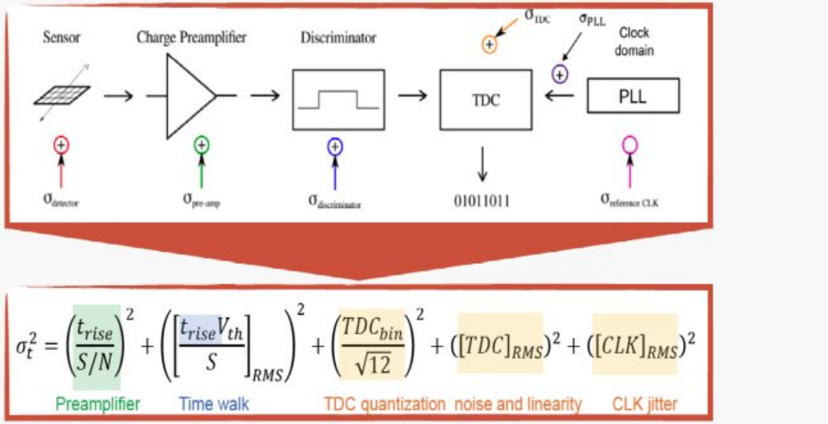


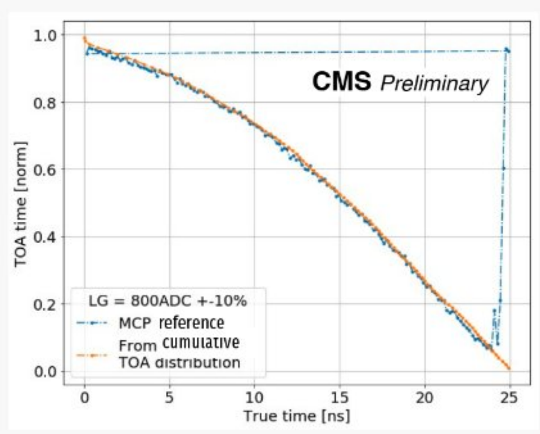
Single HGCAL **sensor timing performance** evaluated in 2016 **beam tests** [JINST 13 (2018) P10023]

R&D

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

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





Data vs MCP calibration

- Correction of non-linearity of ToA response

Requirements from Physics

Basis: sep of H → WW/ZZ → 4j

- $\sigma_Z/M_Z \sim= \sigma_W/M_W \sim= 2.7\% \oplus 2.75\sigma_{sep}$
- ⇒ σ_E/E (jets) < ~4%
- Sign ~ S/√B ~ (resol)$^{-1/2}$
  60%/√E → 30%/√E ⇔ + ~40% in ℒ

Large acceptance

Large Tracker

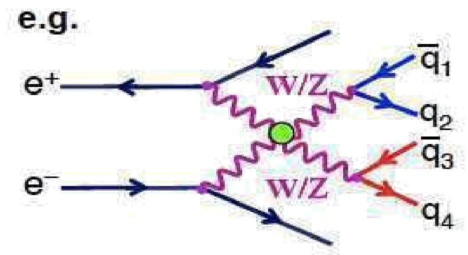
- Precision and low X_0 budget
- Pattern recognition

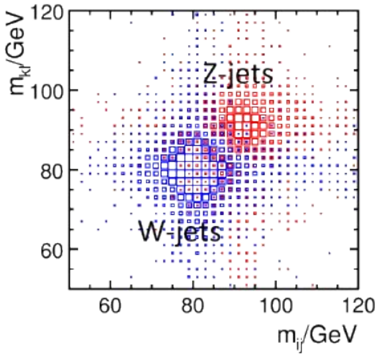
High precision on Si trackers

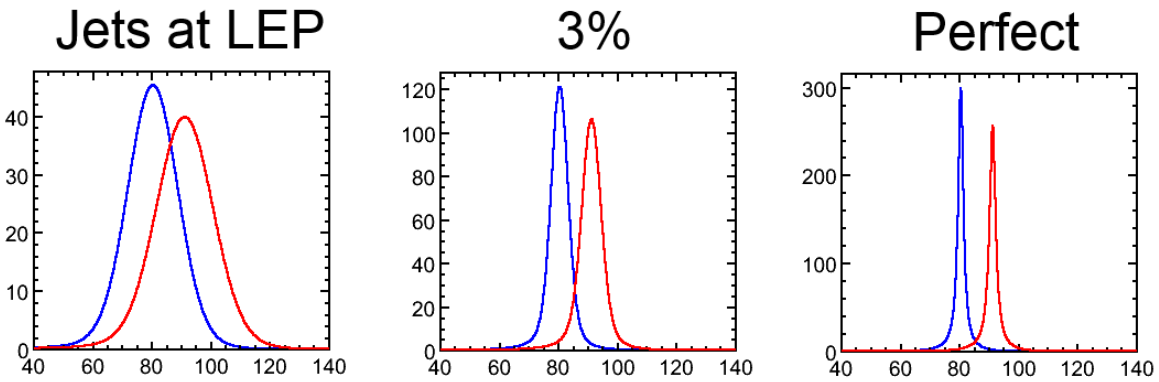
- Tagging of beauty and charm

Fwd Calorimetry:

- lumi, veto, beam monitoring



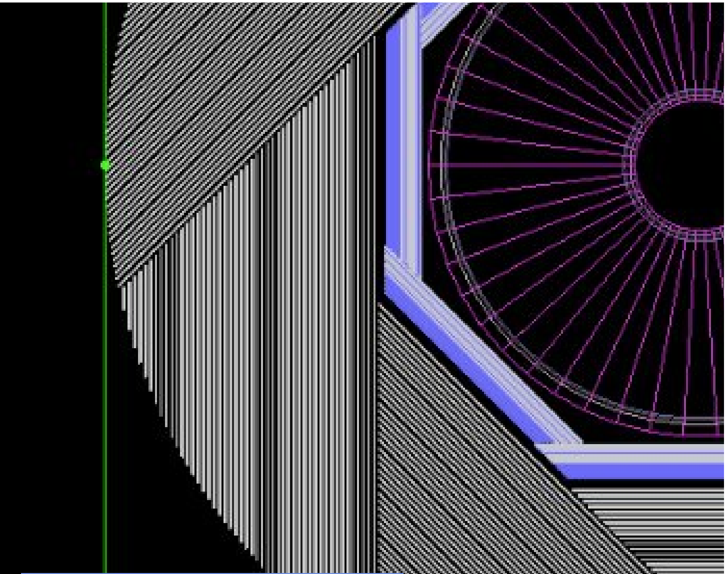


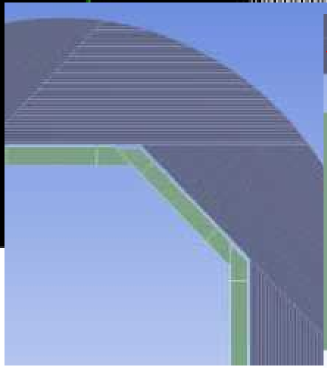


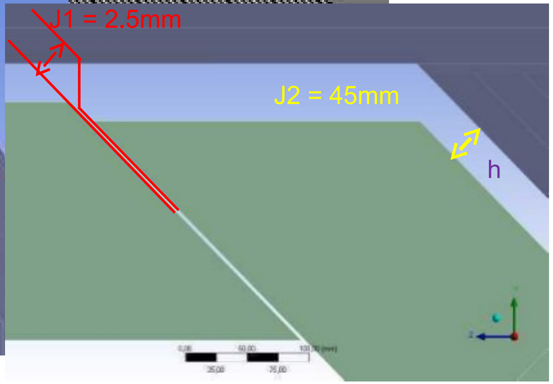
σ_E/E (γ) ≤ 10 %/√E

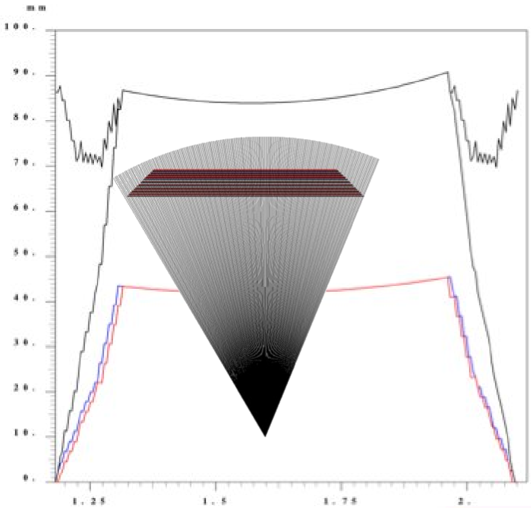
Tau Physics (γ vs π_0) → Photons in jets ?

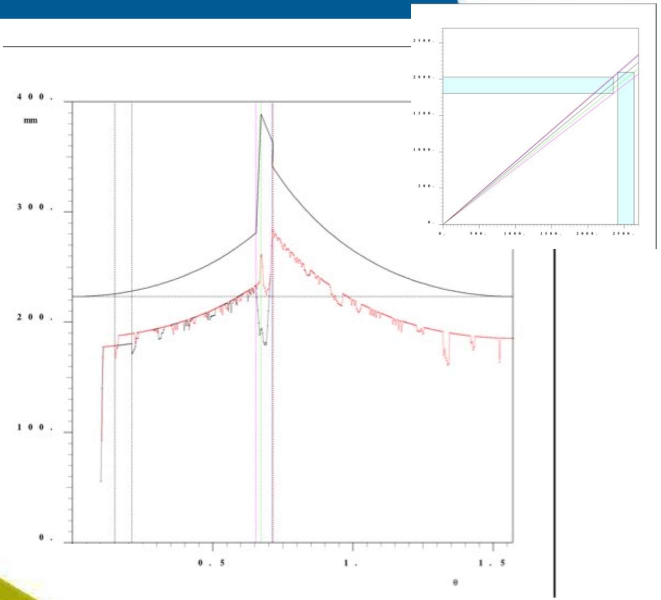
A crack-less ECAL geometry

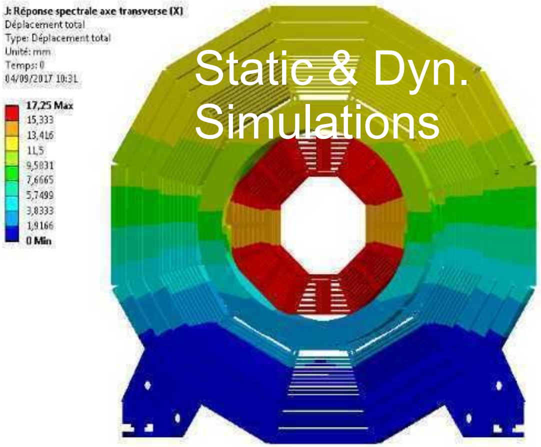


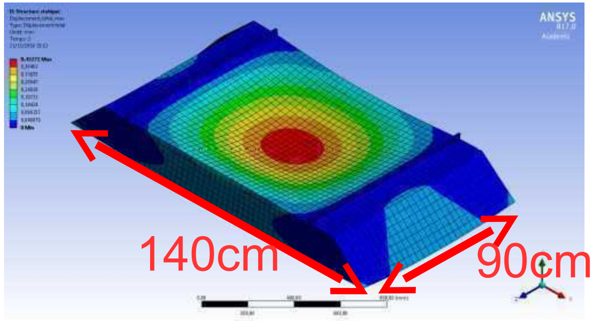




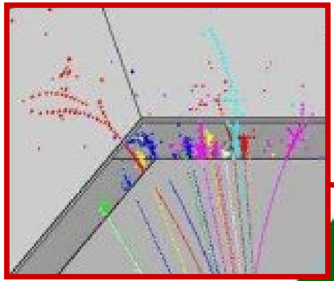


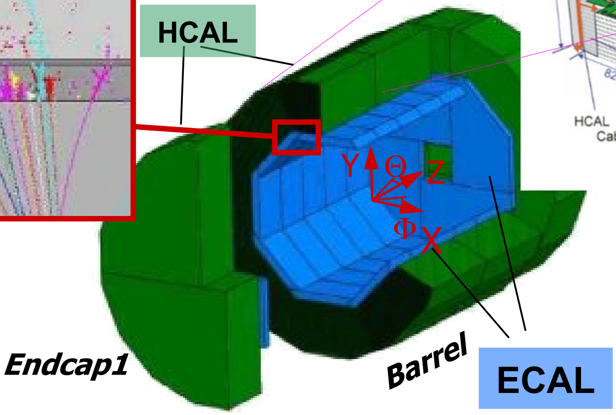


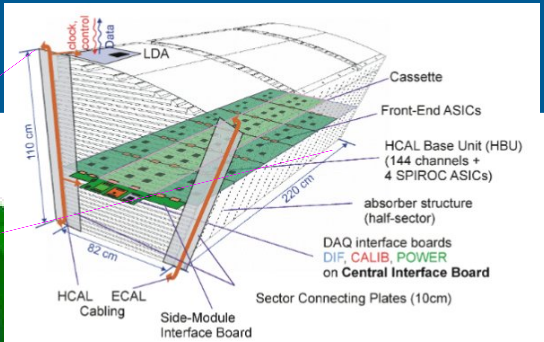


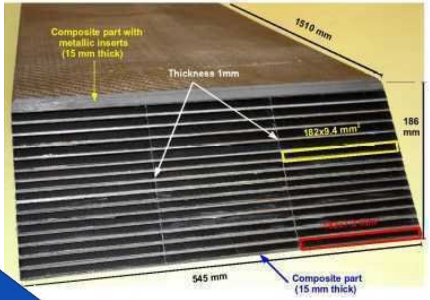


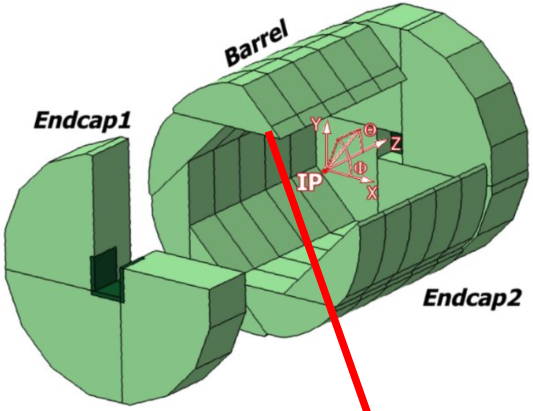
Geometries

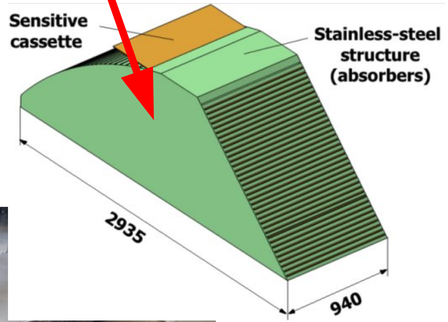


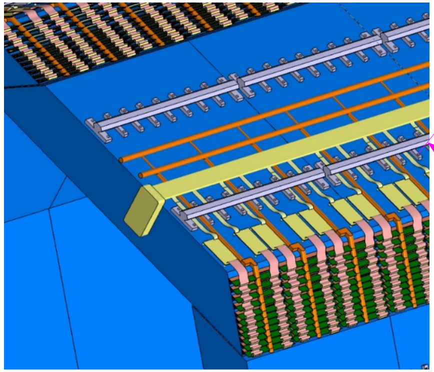

HCAL
Y
Θ
Z
Φ
X
Endcap1
Barrel
ECAL

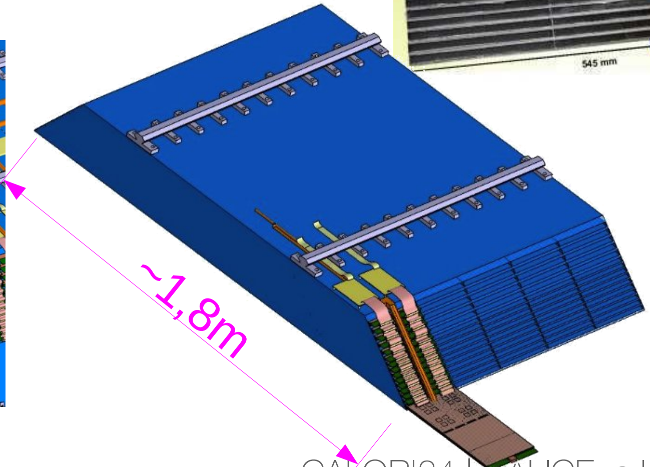

clock, control
Data
LDA
Cassette
Front-End ASICs
HCAL Base Unit (HBU)
(144 channels +
4 SPIROC ASICs)
110 cm
220 cm
absorber structure
(half-sector)
82 cm
DAQ interface boards
DIF, CALIB, POWER
on Central Interface Board
HCAL ECAL
Cabling
Sector Connecting Plates (10cm)
Side-Module
Interface Board

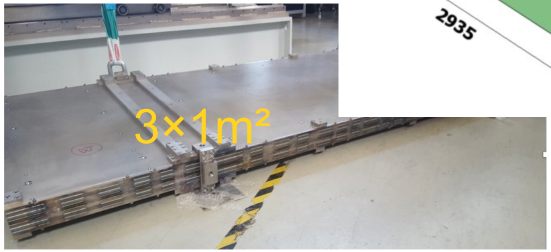

Composite part with
metallic inserts
(15 mm thick)
1510 mm
Thickness 1mm
186
mm
182x9.4 mm²
545 mm
Composite part
(15 mm thick)


Barrel
Endcap1
Y
Θ
Z
IP
Φ
X
Endcap2

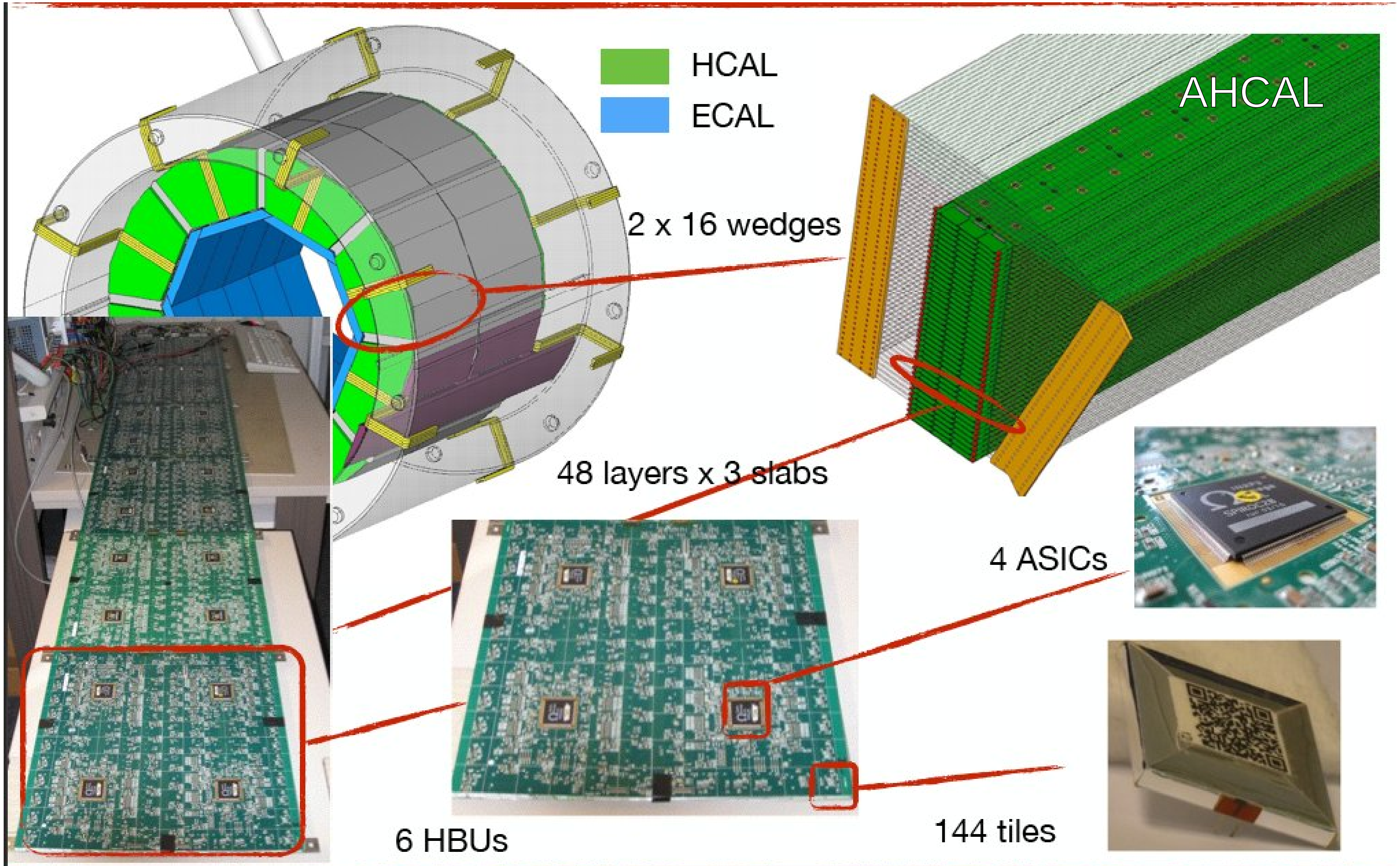

Sensitive
cassette
Stainless-steel
structure
(absorbers)
2935
940



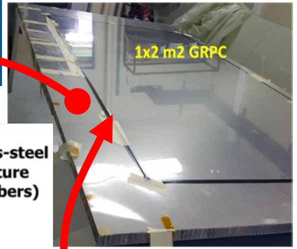

~1,8m

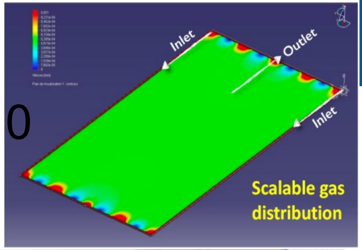

3×1m²

Large Scale Building : CALICE HCALs



Reste à faire



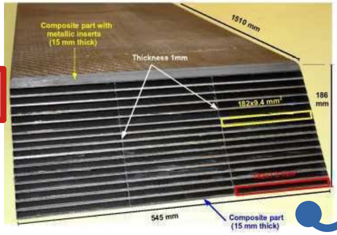


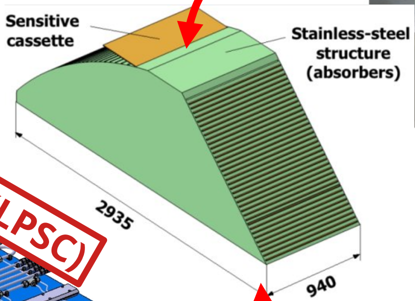
LLR + IJCLab

IP2I

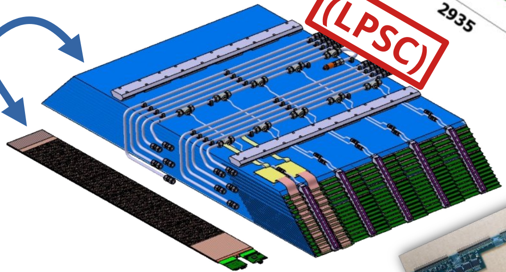
Prototypes technologique de grandes dimensions

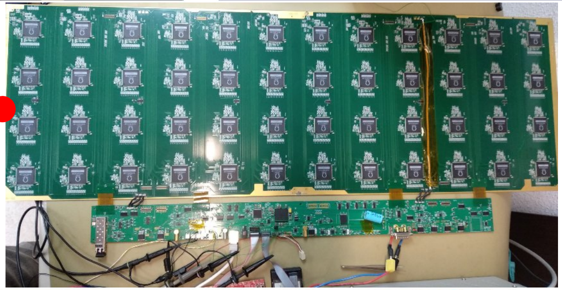
LLR



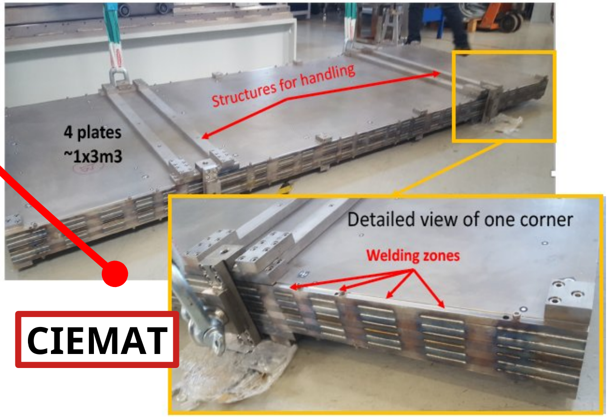


(LPSC)





IJCLab



CIEMAT

Electron beam welding

Pilotes (« modules-0 »)

- 3×1m² HCAL's
- 1.5×0.2m² × 3–5 ECAL

Intégration du «timing centimetrique» : 1 cm = 30 ps.

- Partout ?
- Couche(s) dédiées ?

} **Besoin d'études approfondies**

Ωmega

Electronique « v3 »

- full 0-suppr, power, timing,
  nv techno (AMS → TSMC)

AHCAL Plans: Hardware Developments

Common Readout

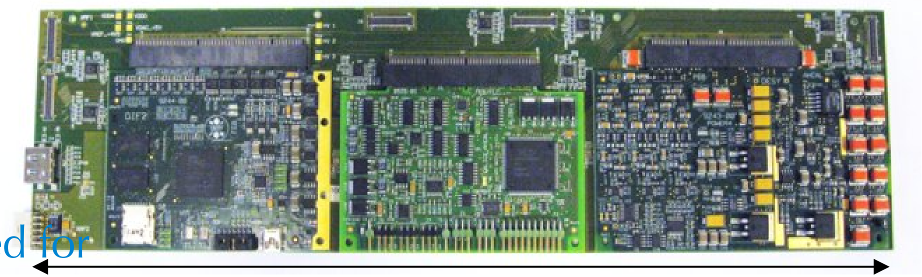
- Harmonise readout between CALICE SiW ECAL and AHCAL

Reduce size of AHCAL interface boards

- Current design is from 2007
- Focus was on modularity
- New SiW ECAL interface board (SL board) optimized for compactness
- Plan to follow SiW design as much as possible
  - Some differences in powering concept
  - Additional LED calibration system in AHCAL

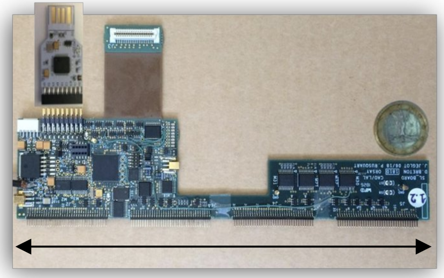
Status: just started

AHCAL interface boards



36 cm

SiW ECAL SL board

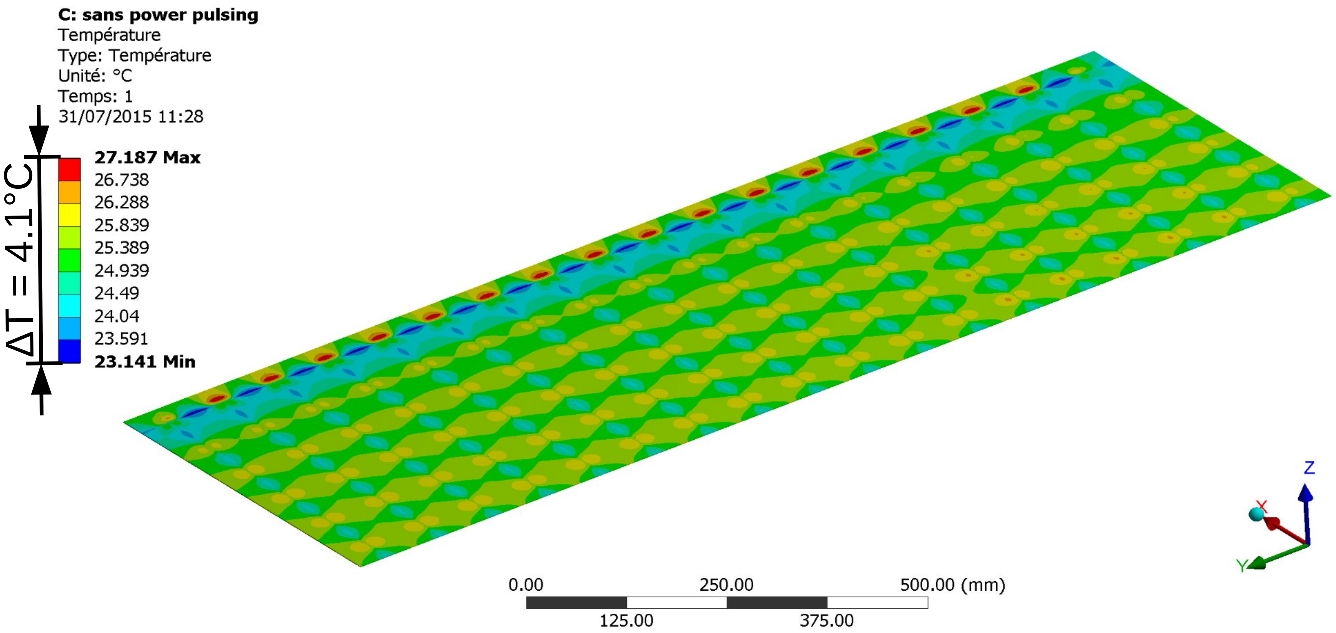


18 cm

T-SDHCAL: cooling & rates

Cooling:
Previous studies were performed on Hardroc (full regime)

We have to do the studies with the new ASICs and the mechanical structure in mind



High-rate capability
Low resistivity materials
Low-resistive PEEK ($10^9\,\Omega\cdot$cm)