Hadrons in the CALICE SiW Ecal
and
Towards a technological prototype

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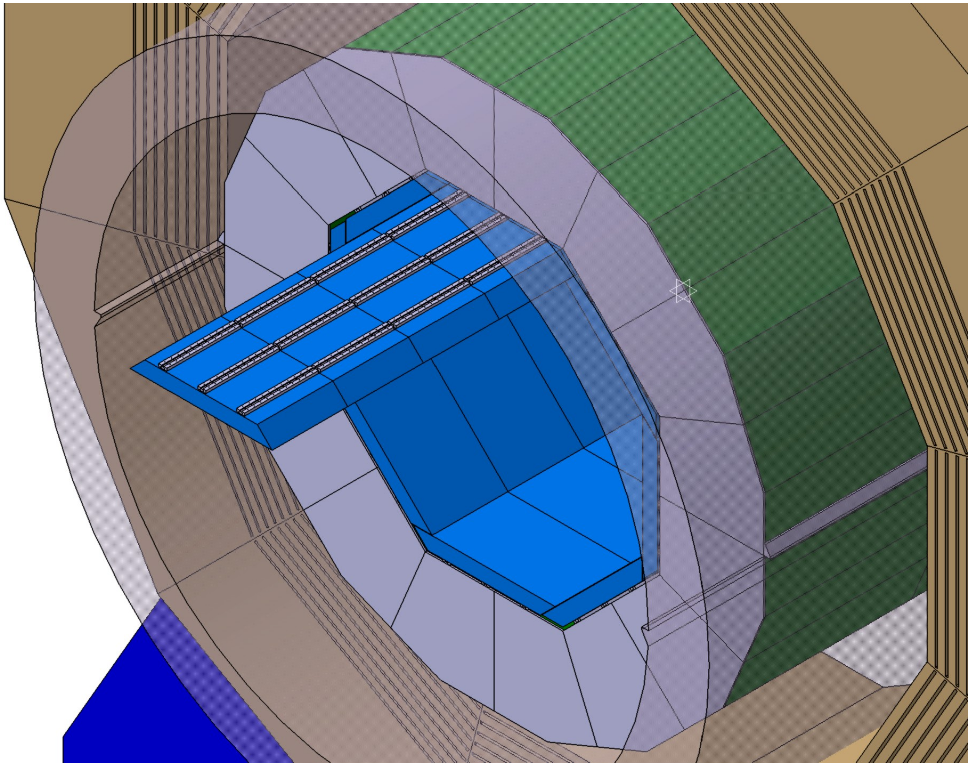
LCWS11 Granada/Spain September 2011

SiW Ecal - Basics

The SiW Ecal in the ILD Detector



Basic requirements

- Extreme high granularity
- Compact and hermetic

Basic choices

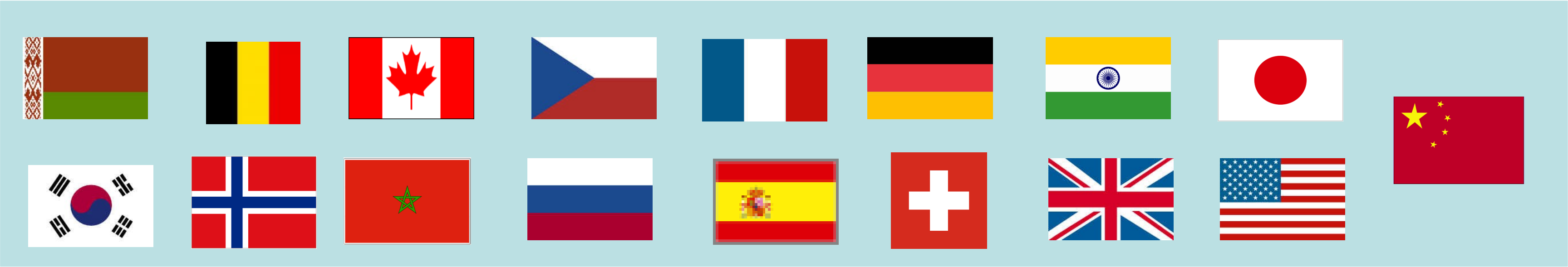
- Tungsten as absorber material
  - X_0=3.5mm, R_M=9mm, λ_I=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisation
  - Large signal/noise ratio

SiW Ecal designed as particle flow calorimeter

The CALICE Collaboration

Calorimeter for ILC

Calorimeter R&D for a future linear collider



~330 physicists/engineers from 57 institutes
and 17 countries from 4 continents

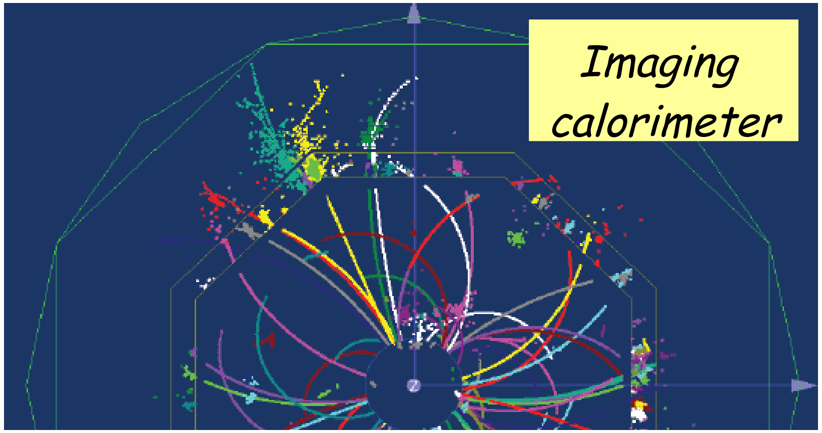
- Integrated R&D effort

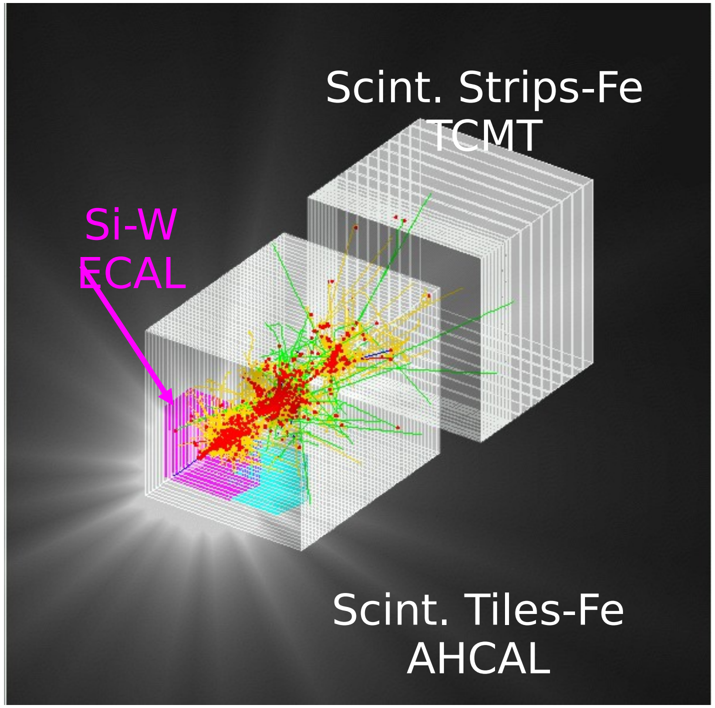
- Benefit/Accelerate detector development due to *common* approach

The Calice Mission

Final goal:

A highly granular calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider

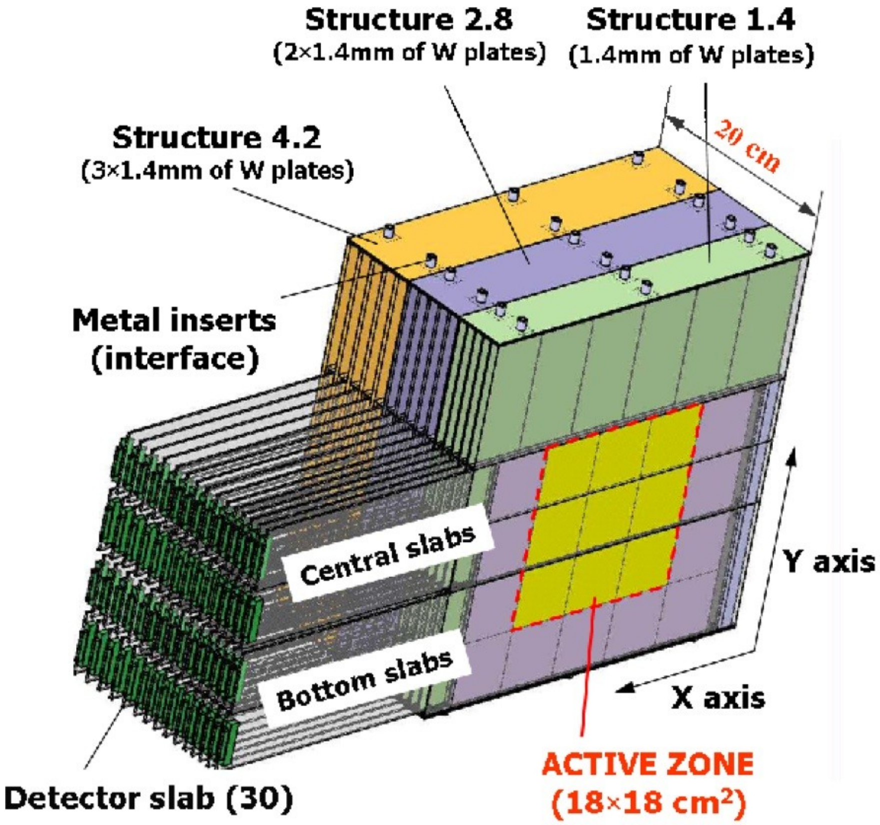


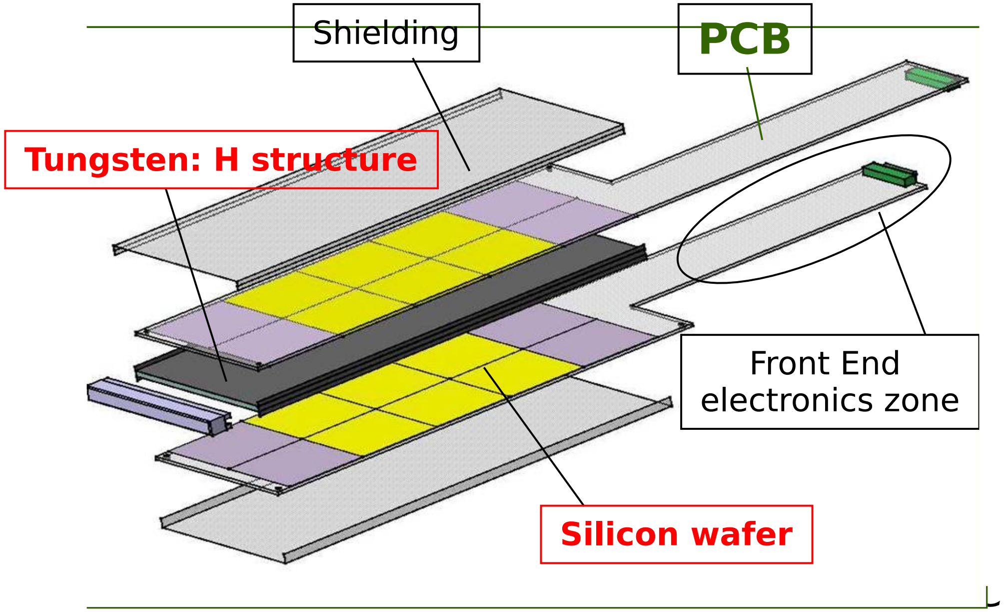


Intermediate task:

Build prototype calorimeters to
- Establish the technology
- Collect hadronic showers data with unprecedented granularity to
  - tune clustering algorithms
  - validate existing MC models

SiW Ecal Physics Prototype





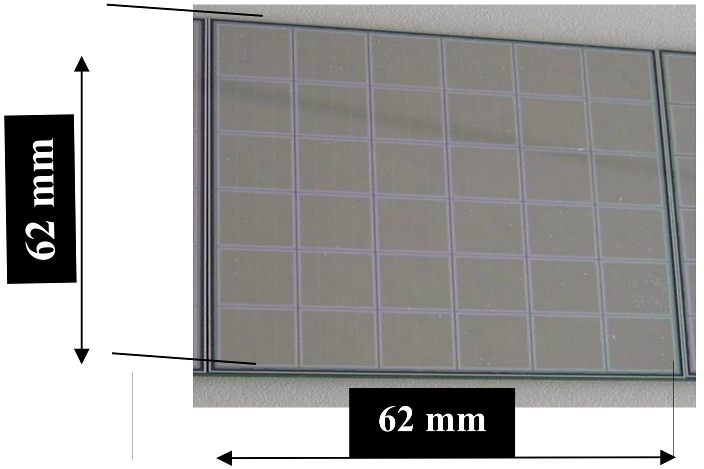
30 layers of tungsten:

- 10 x 1.4 mm (0.4 X_0)
- 10 x 2.8 mm (0.8 X_0)
- 10 x 4.2 mm (1.2 X_0)
- 24 X_0 total, 1 λ_I

½ integrated in detector housing
⇒ Compact and self-supporting detector design

6x6 PIN diode matrix

Resistivity: 5kΩcm - 80 (e/hole pairs)/µm



Thickness:
525µm

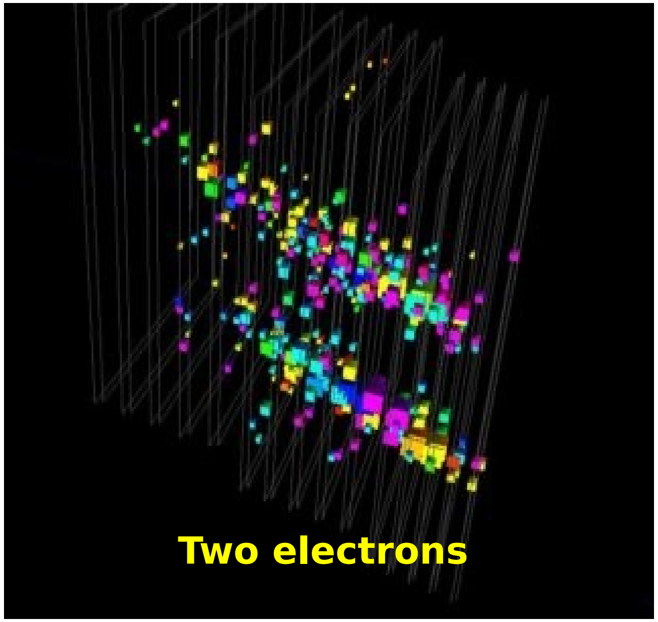
Total: 9720 Pixels/Channels

Large scale beam tests

Experimental setup

Zoom into Ecal

Particle distance~ 5 cm
→ No confusion !!!



Two electrons

- 2006, Ecal 2 / 3 equipped
  Low energy electrons (1-6 GeV at DESY), high energy electrons (6-50 GeV at CERN)

- 2007, Ecal nearly completely equipped
  High energy pions (6-120 GeV CERN), Tests of embedded electronics

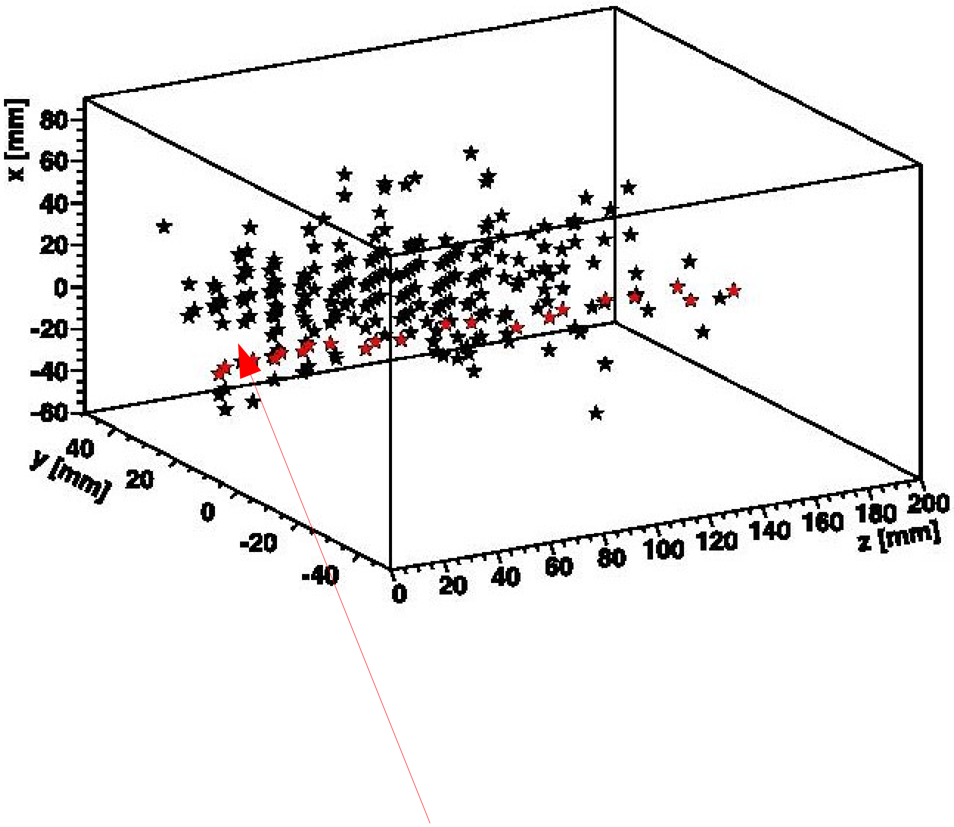
- > 2008 FNAL, Ecal completely equipped
  Pions at small energy,

Exploiting the high granularity – Particle separation

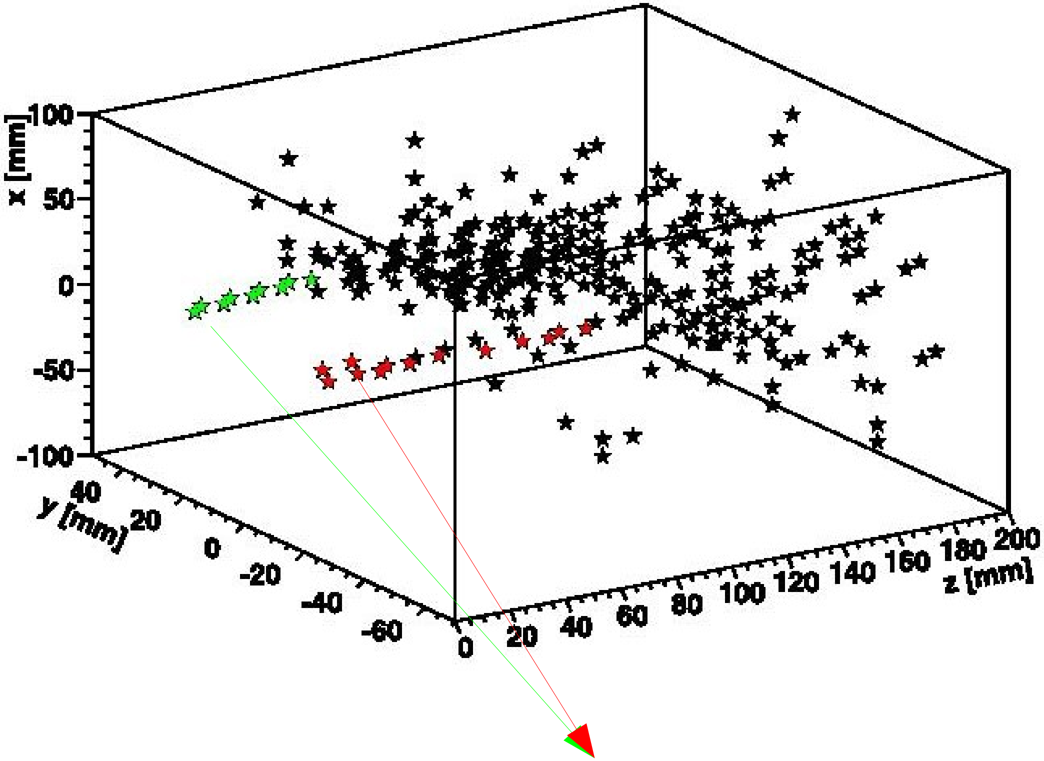
High granularity allows for application of advanced imaging processing techniques

E.g. Hough transformation

Events recorded in test beam



Secondary muon within electron shower

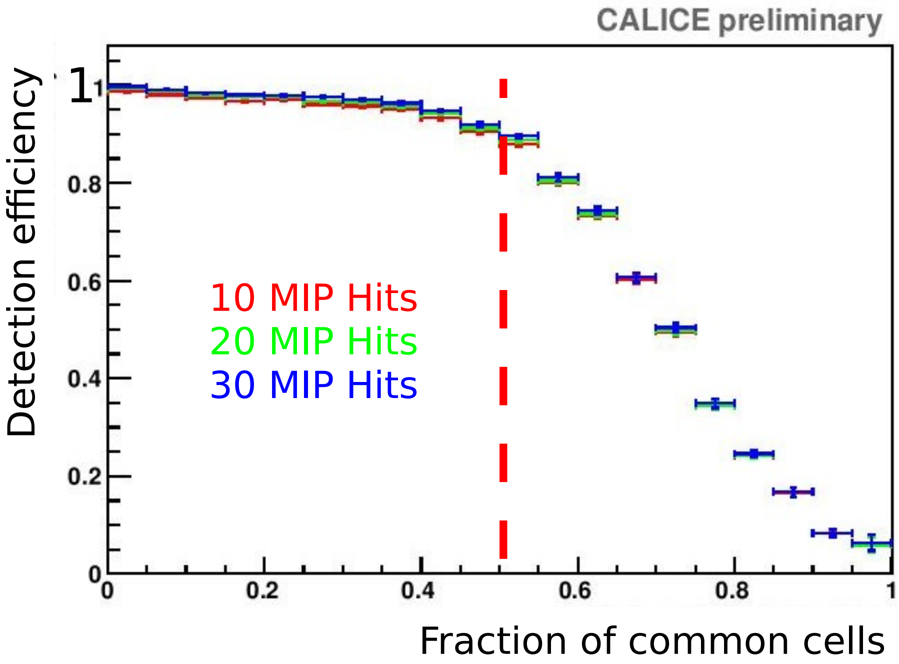


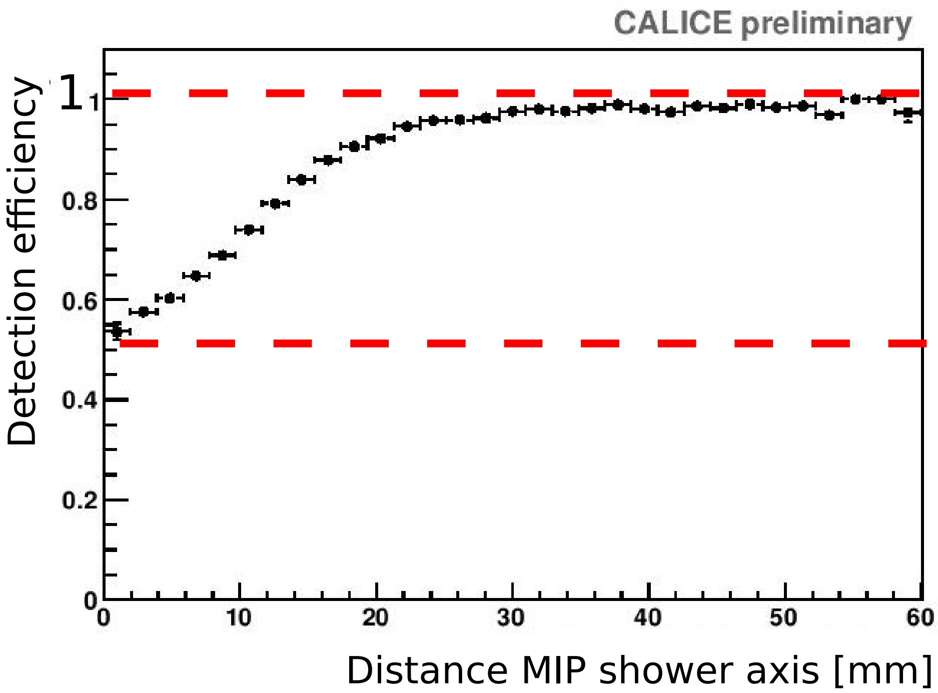
Two pions entering the SiW Ecal

Particle separation – cont'd

Efficiency of particle separation

Separation MIP <-> Electron





E -> 100% for up to 50% shared hits

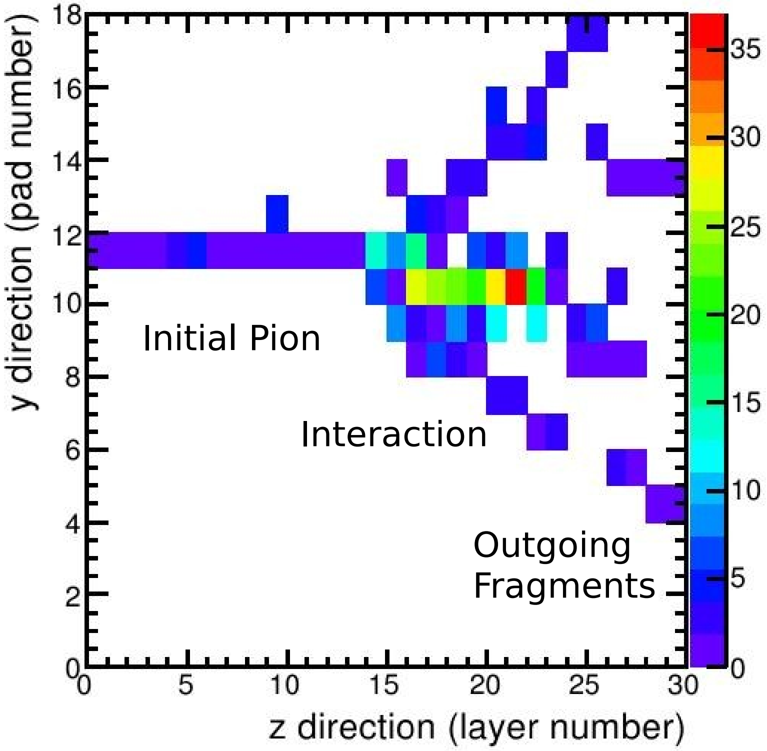
Independent of hits generated by MIP

Full separation for distances > 2.5 cm

Granularity and hadronic cascades

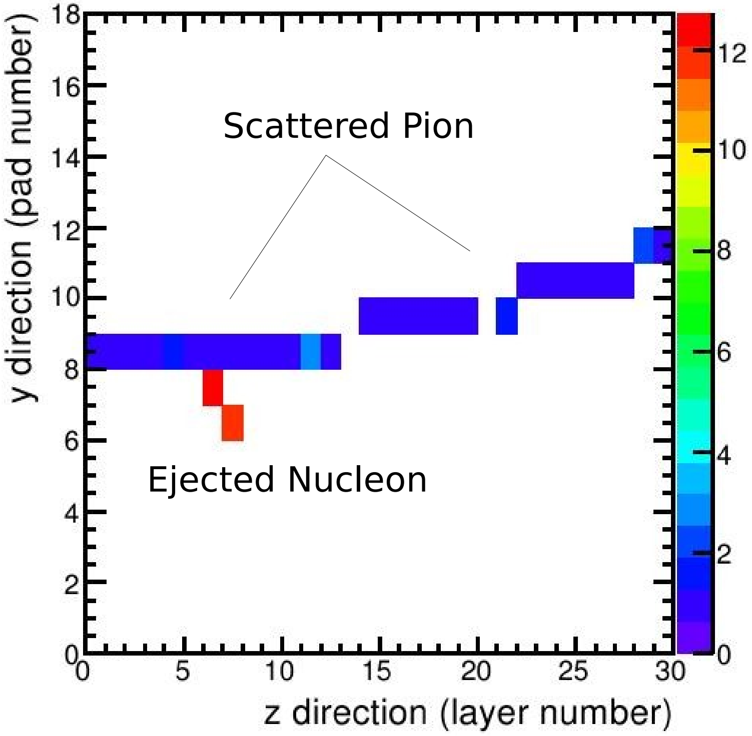
(Start of) Hadronic showers in the SiW Ecal

Complex and impressive



Inelastic reaction in SiW Ecal
Also dubbed FireBall hereafter

Simple but nice

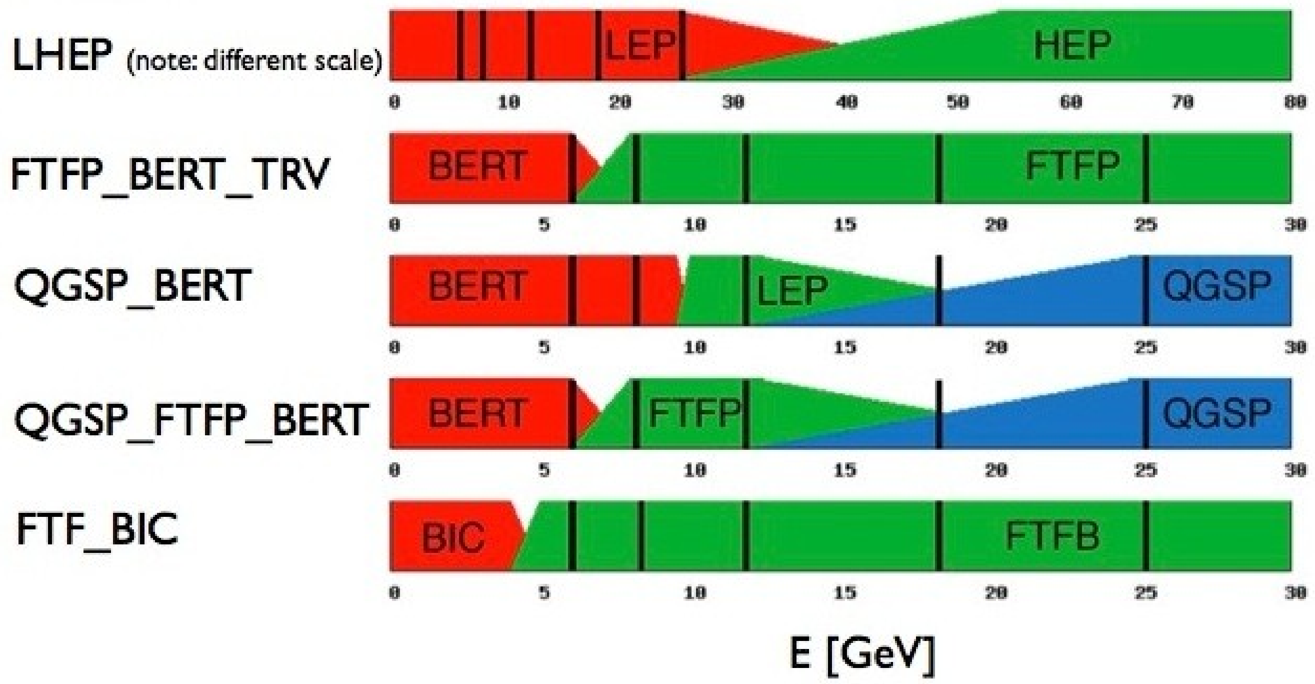


Short truncated showers
Dubbed pointlike hereafter

High granularity permits detailed view into hadronic shower

Hadronic models in GEANT4

Variety of models available to describe hadronic showers

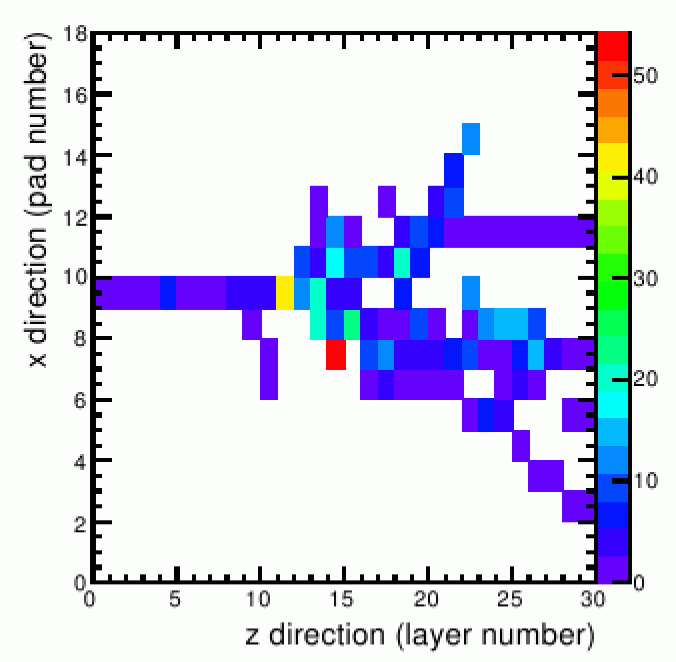


Discriminative power by high granularity !?

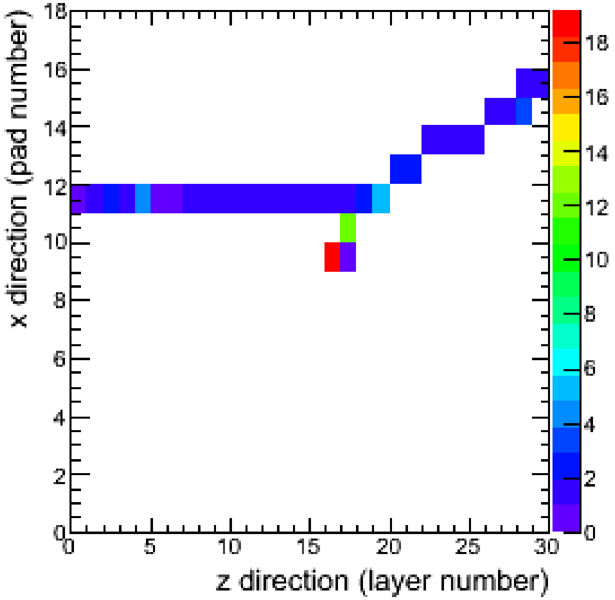
A. Dotti (G4 Collaboration): “Rough granularity of LHC calorimeters limits possibilities”
“CALICE is the perfect tool”

Finding the interaction in the SiW Ecal

Easy at high energies



Difficult at small energies



Check for absolute increase
of energy in consecutive layers

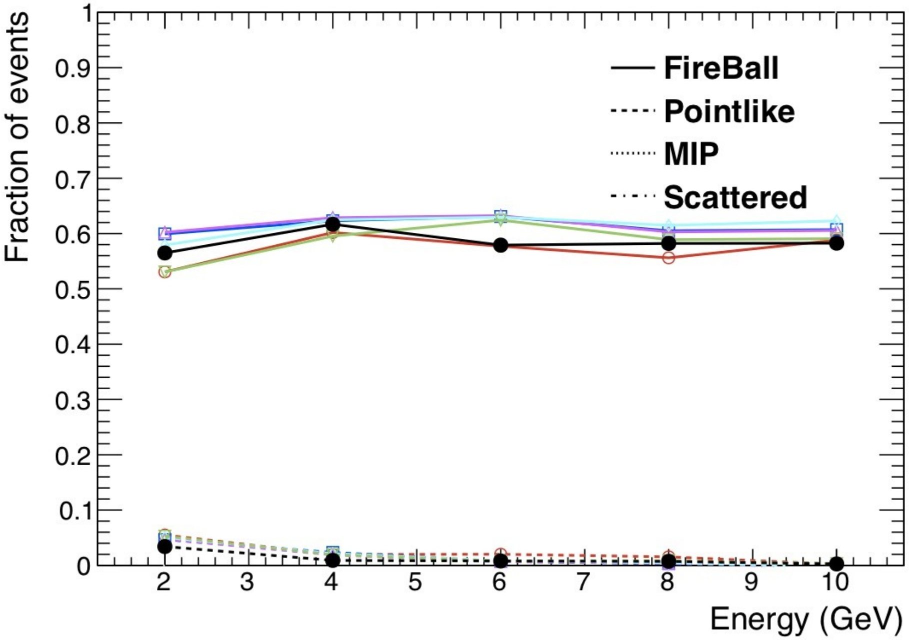
Check for relative increase
of energy in consecutive layers

Efficiency: 10 GeV 84%
Efficieny: 2 GeV 63% (compare with 25% with naive method!!!)

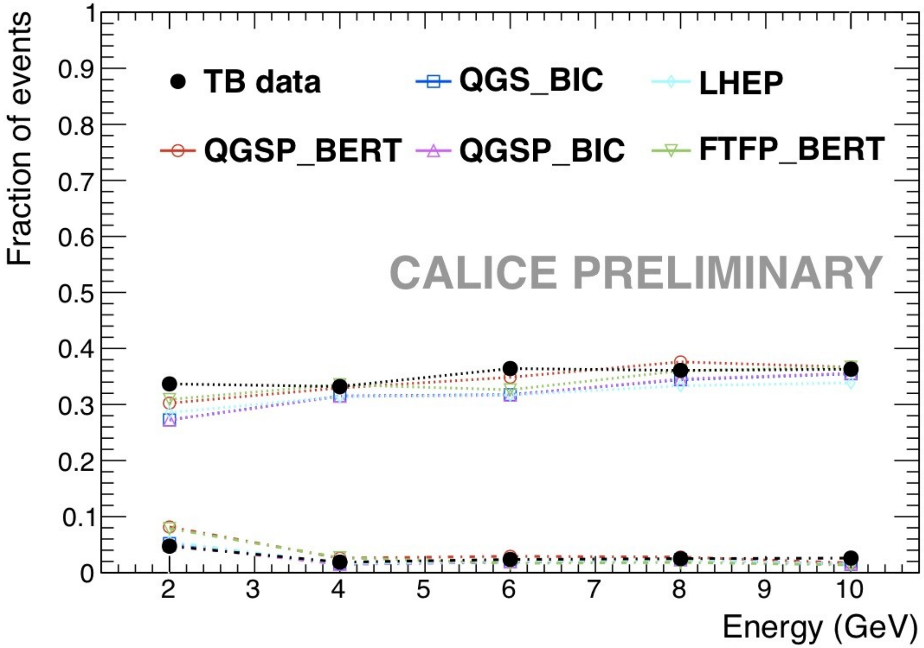
Event types and ratees

Aim: Explore and understand of what we can “see” with the SiW Ecal

Events with found hadronic interaction



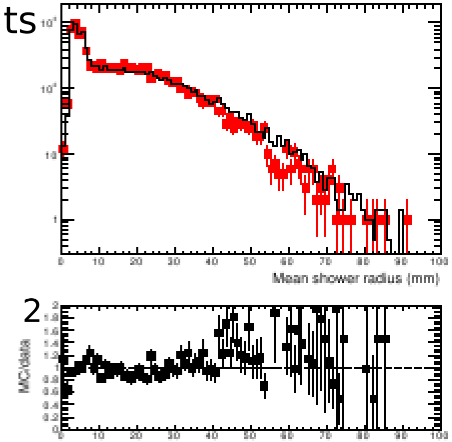
Events w/o found hadronic interaction



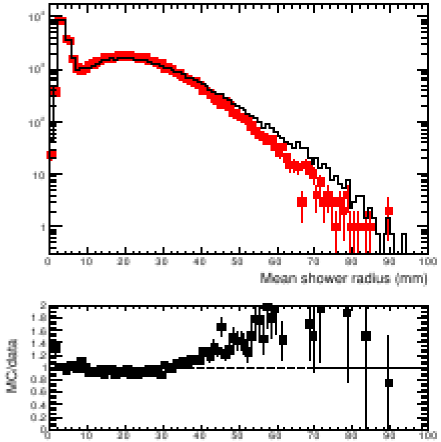
Cross sections of underlying scattering processes well modelled by GEANT4
Decomposition of interactions demonstrate sensitivity to details of interactions

Transverse profiles – Small energies, 2-10 GeV

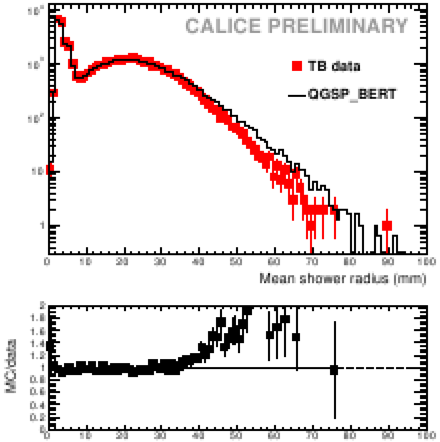
Affects overlap of showers <-> Importance for PFA



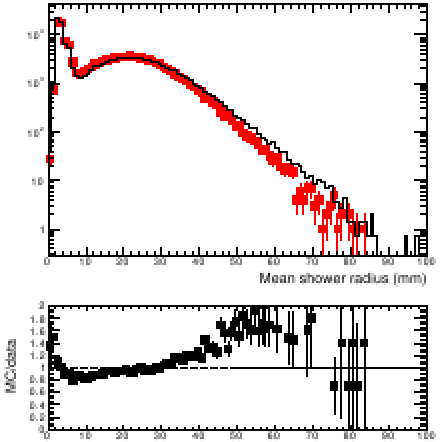
(a) 2 GeV



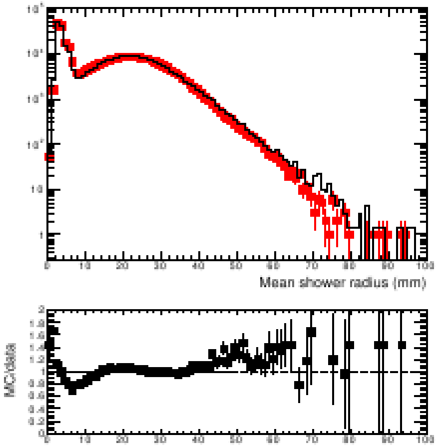
(b) 4 GeV



(c) 6 GeV



(d) 8 GeV



(e) 10 GeV

MC overshoots data for large radii

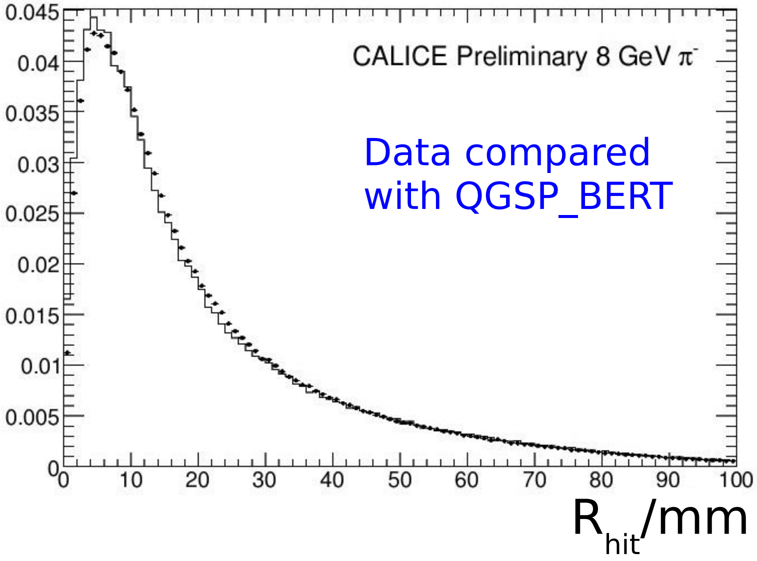
General trend here: Better description at higher energies

(However, MC tends to undershoot data at even higher energies

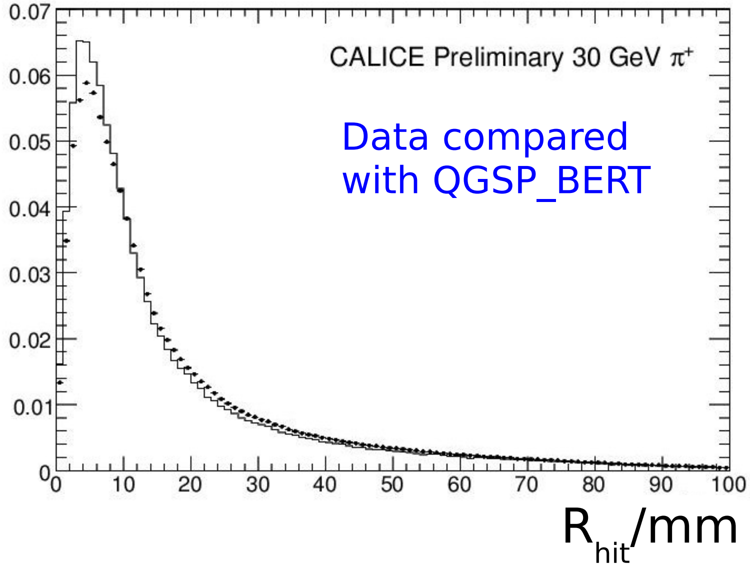
Transverse shower profiles and shower radius – Higher energies, 8-80 GeV

JINST 5 2010 P05007

Transverse profiles

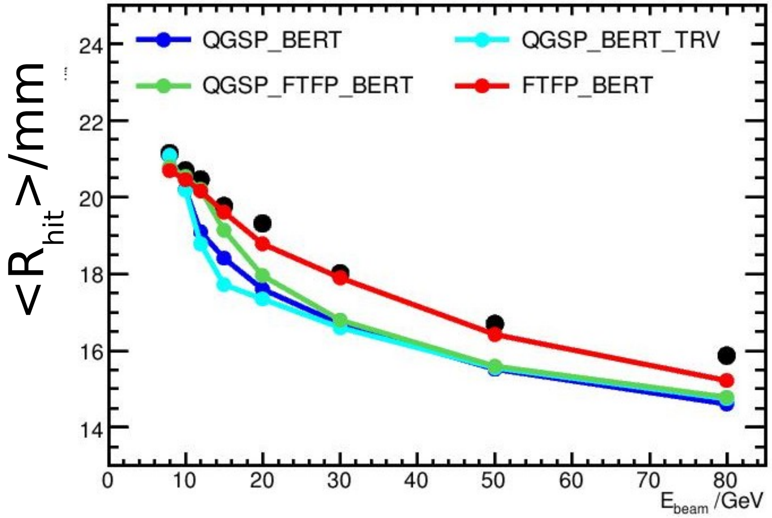


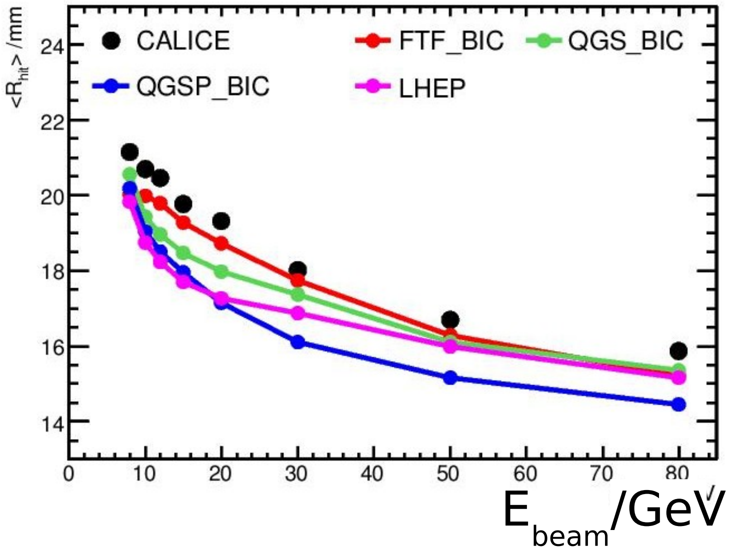
Data compared with QGSP_BERT



Data compared with QGSP_BERT

Shower radius



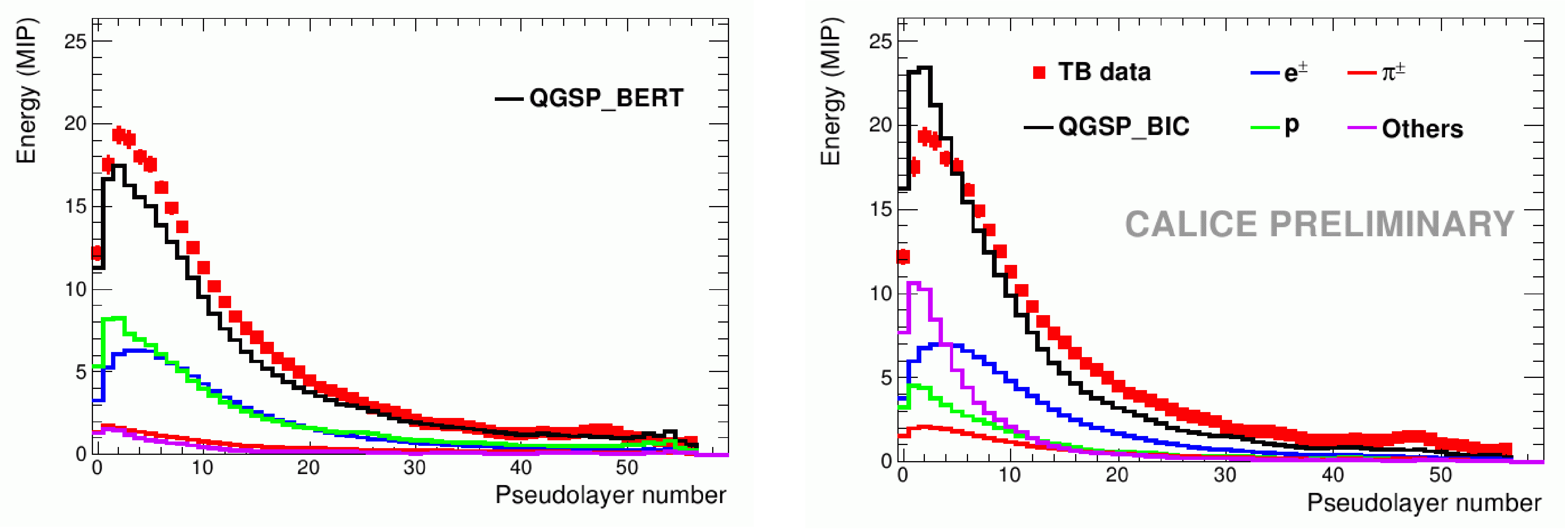


Small energy ok for 'BERT' models
Towards high energy: Underestimation of content in SiW Ecal
Relatively small difference between models (~15%)

Longitudinal energy profiles

Sampling with 30 layers over 1 interaction length
Sensitivity to different phases of shower development

Pi @ 2GeV Inelastic reactions



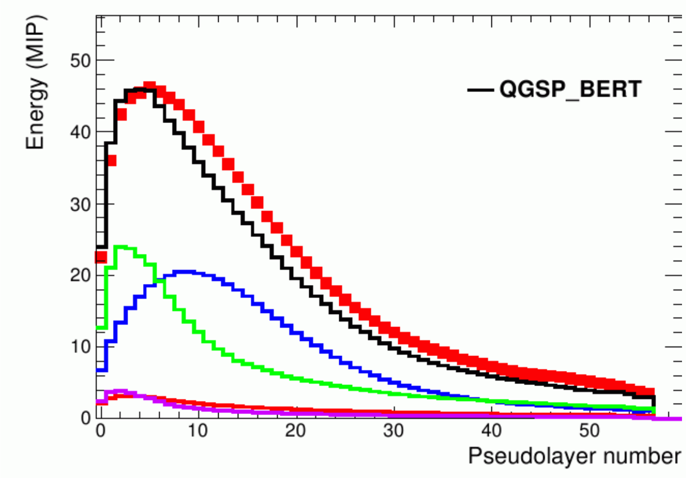
No satisfactory description of longitudinal shower profile

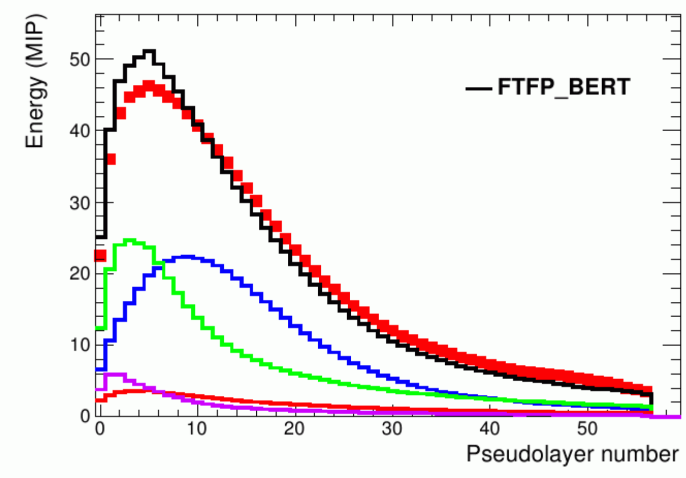
BERT gets tails about right
Models have different approaches for shower composition
Difference most striking in zone after interaction

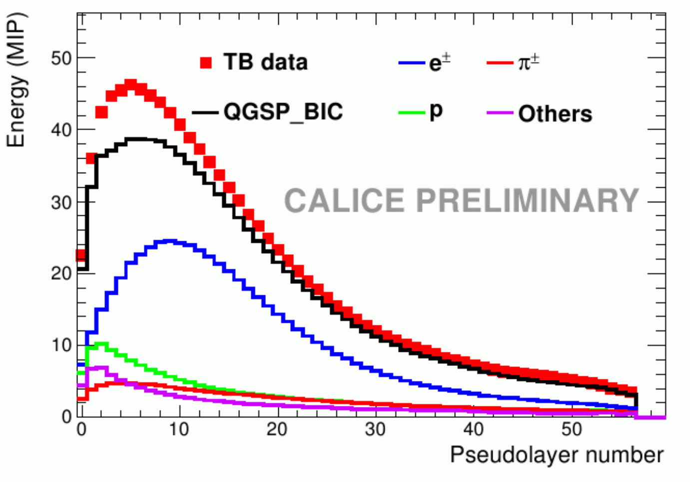
Longitudinal energy profiles

Sensitivity to different shower components

Pi @ 8GeV Inelastic reactions







No satisfactory description of longitudinal shower profile

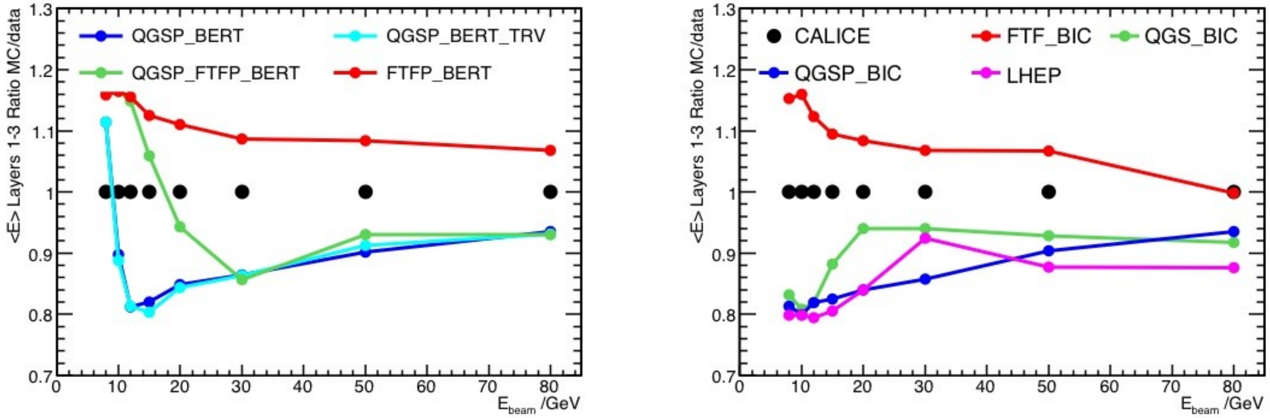
Again tails about right
Large sensitivity to model differences close to interaction region
-> Results compatible with results published earlier by CALICE for higher energies

Energy depositions in different calorimeter depths

Energies 8 – 80 GeV

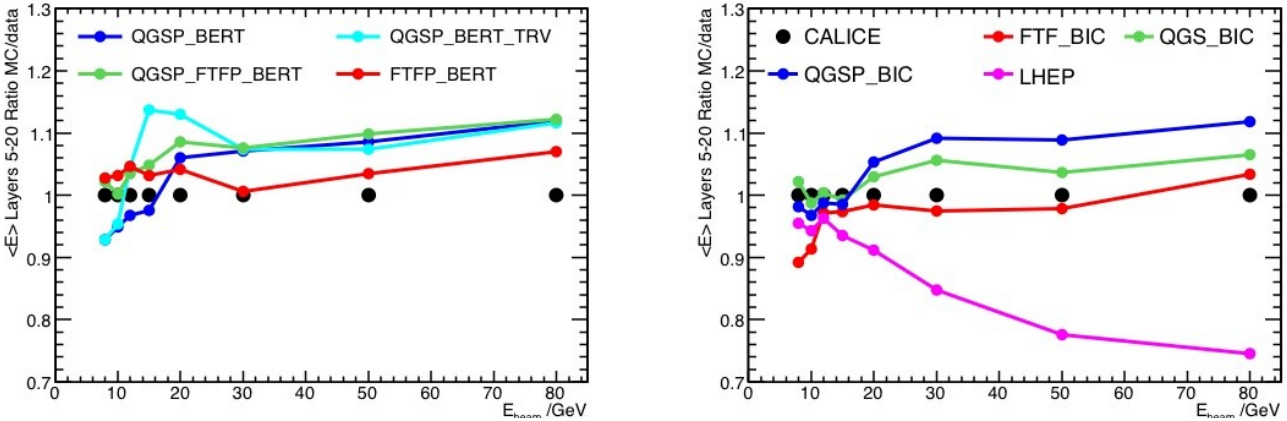
Layer 1-3:

Nuclear breakup



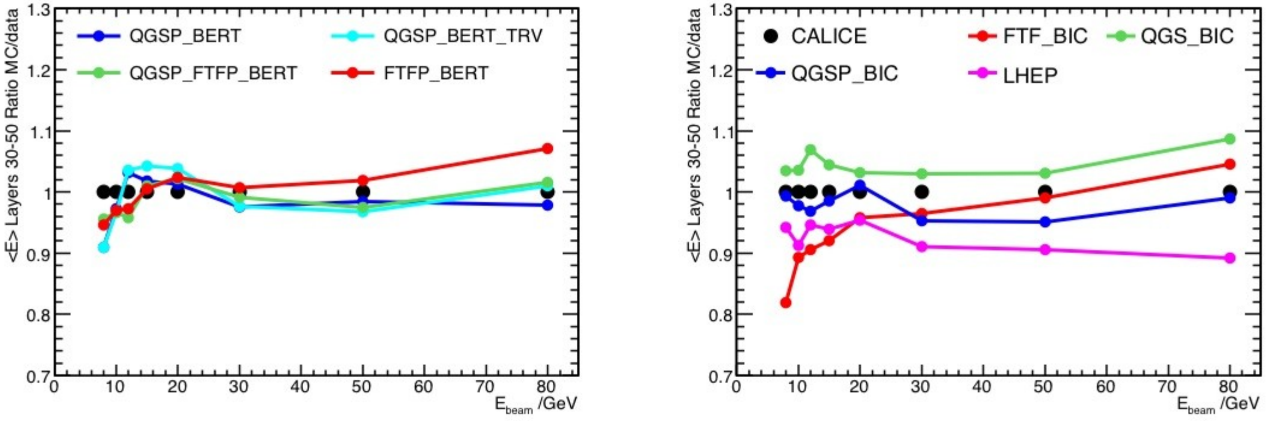
Layer 5-20:

elm. component



Layer 30-50:

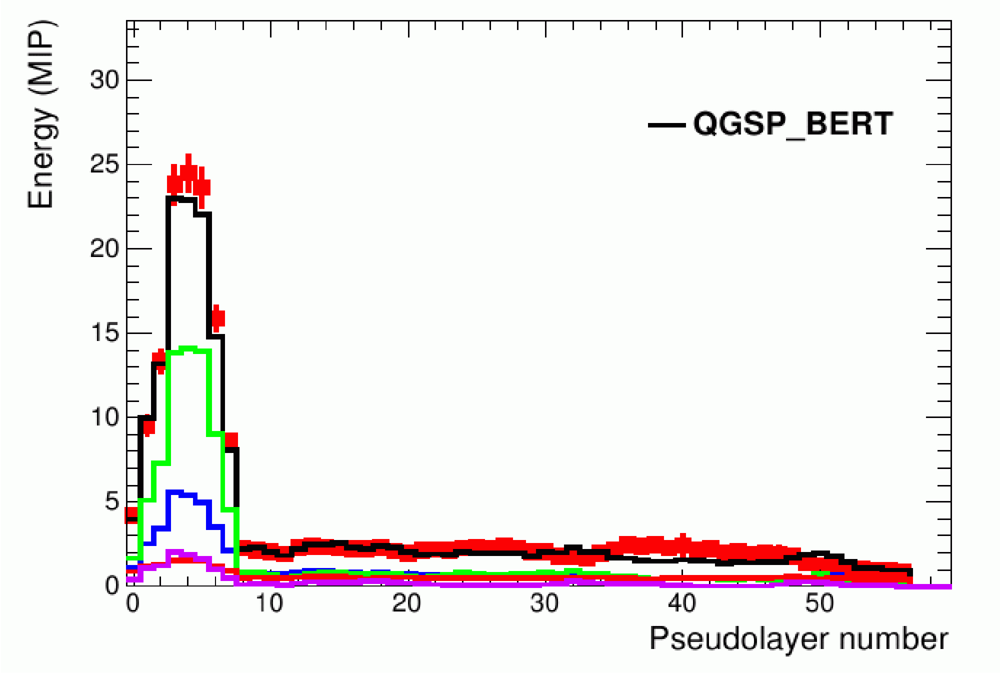
Shower hadrons

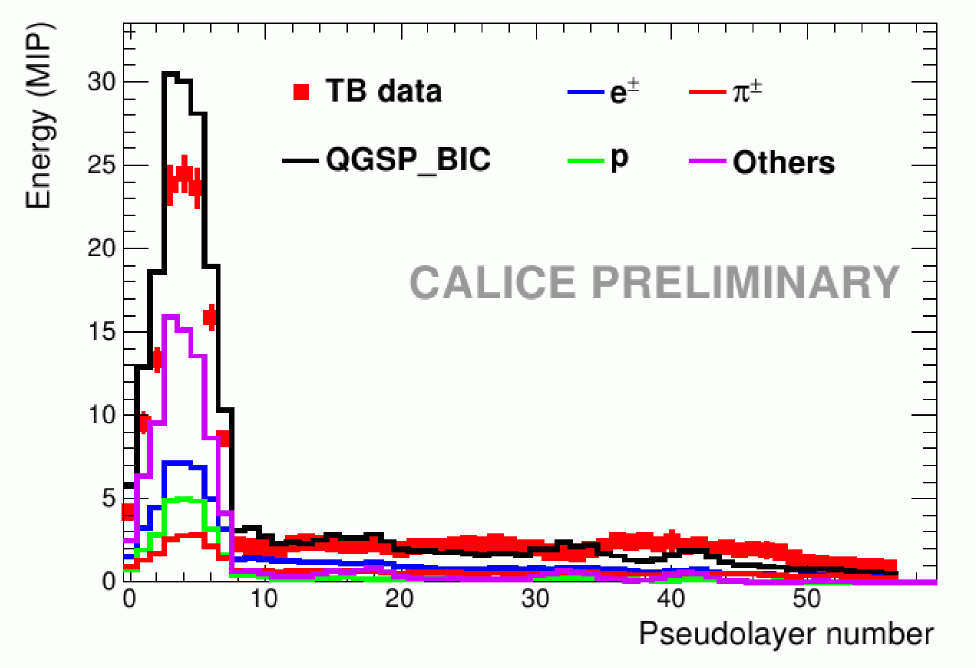


Getting the details right - Pointlike events

Recognition of these events is result of large granularity

Pi @ 2GeV

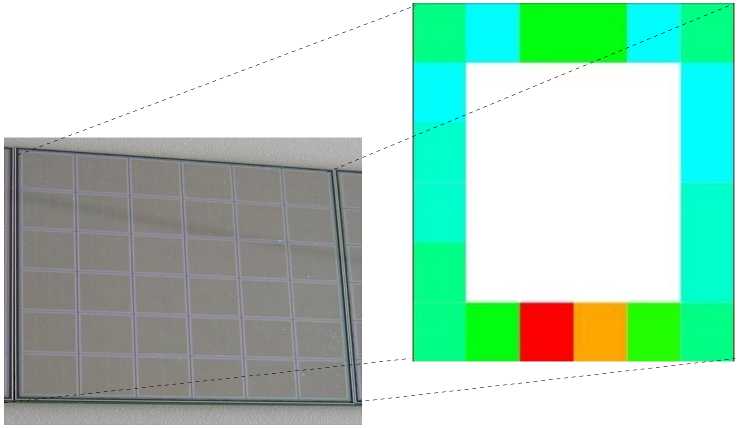




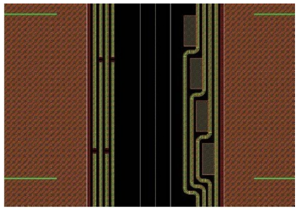
'Focus' on short range component of shower
(Comparitively simple topology)

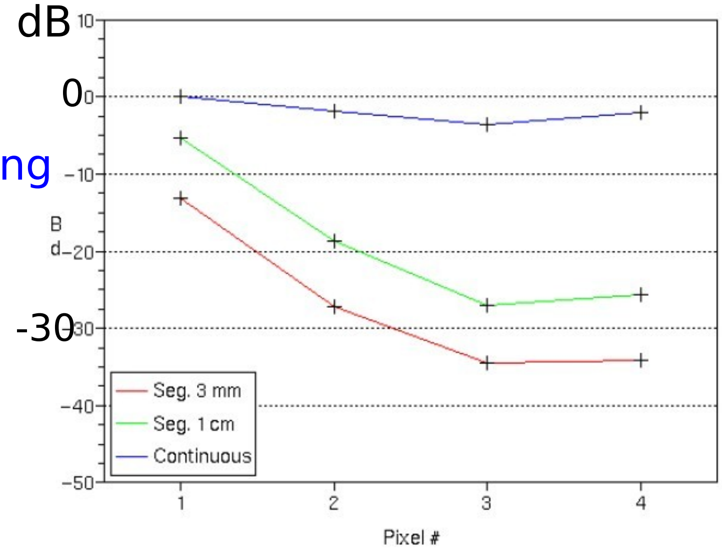
R&D for silicon wafers

Square pattern in wafer response



Segmented guardring



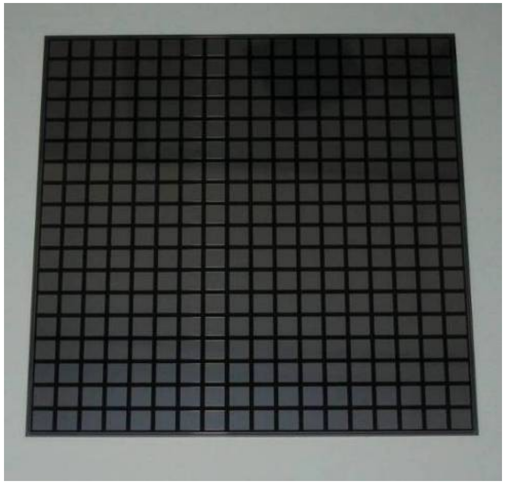


Xtalk continous guardring <-> Pixel

Attenuation of Xtalk

Beyond the physics prototype

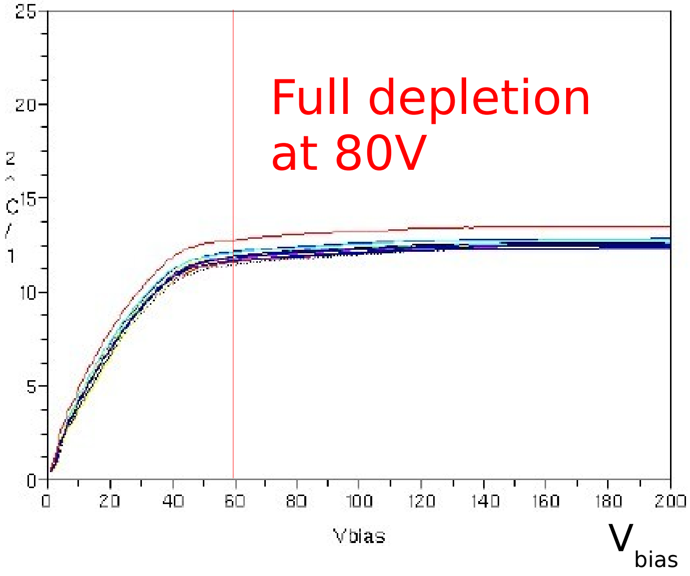
Wafers with smaller pixels



5x5 mm² pixels
~optimal "ILD width"

Thickness: 325 µm

Characterisation

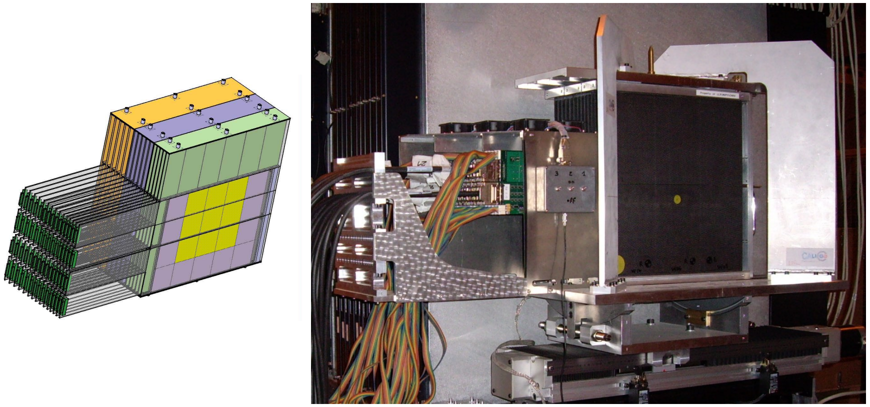


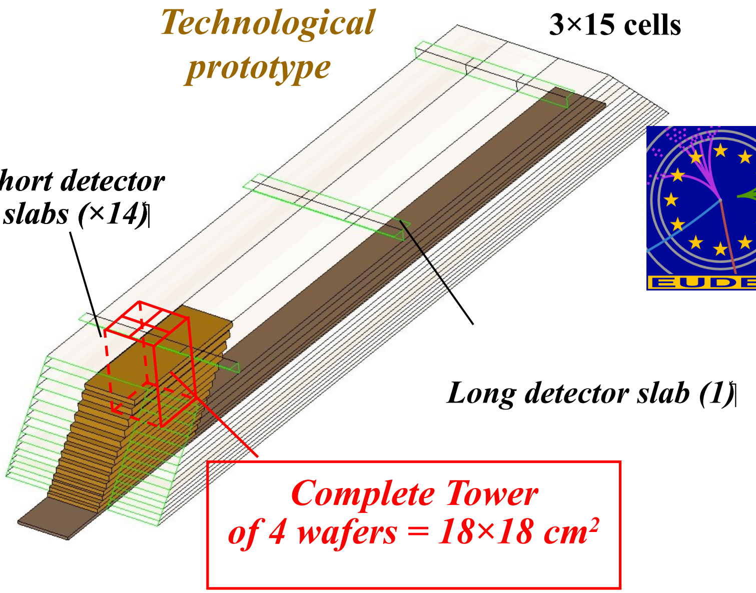
Full depletion
at 80V

Breakdown
at ~500 V

Technological Prototype

Technical solutions for the/a final detector





- Realistic dimensions

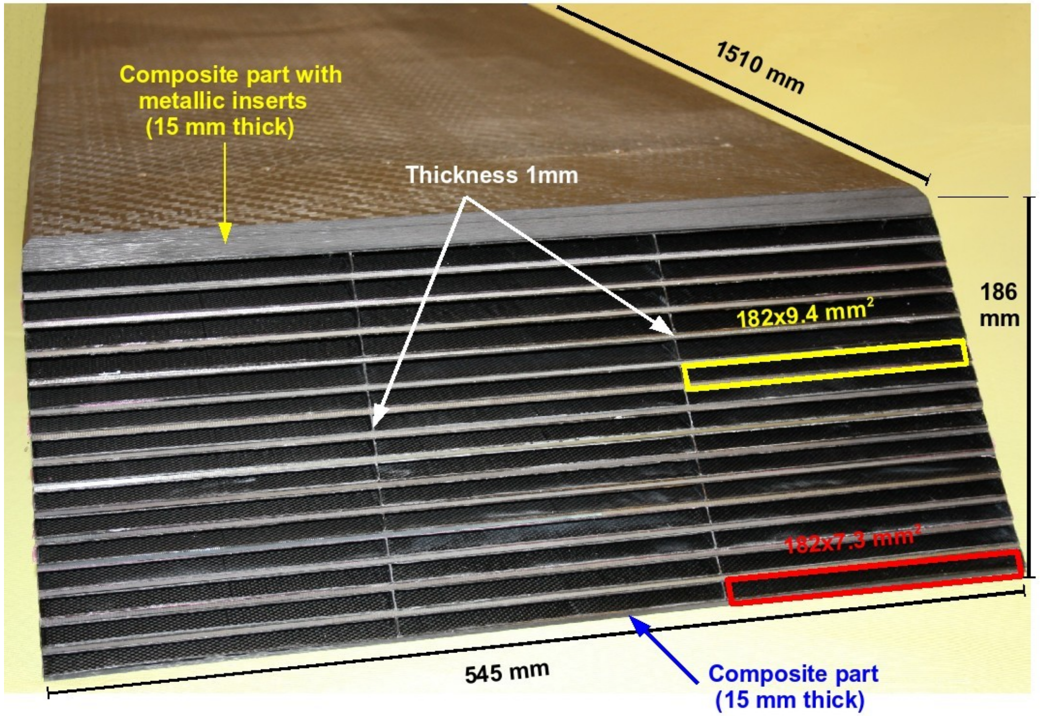
- Integrated front end electronics

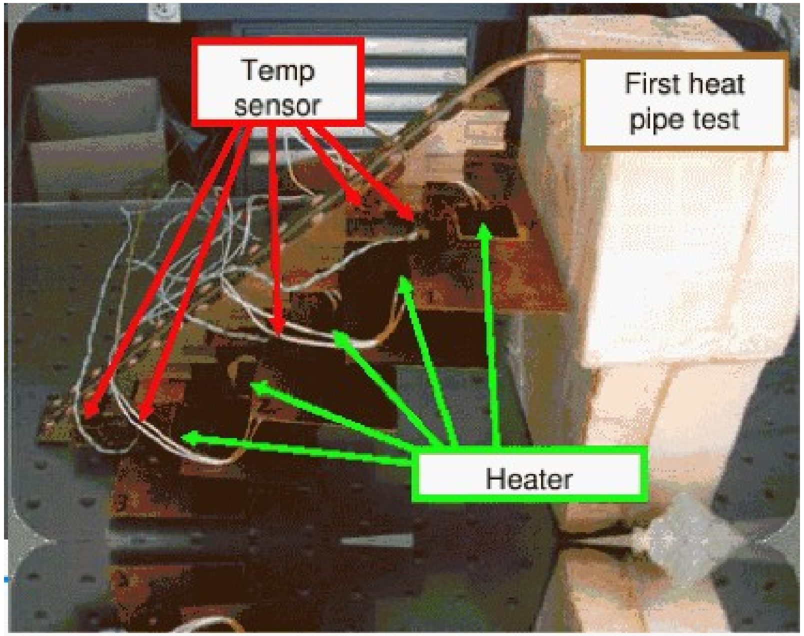
- Small power consumption

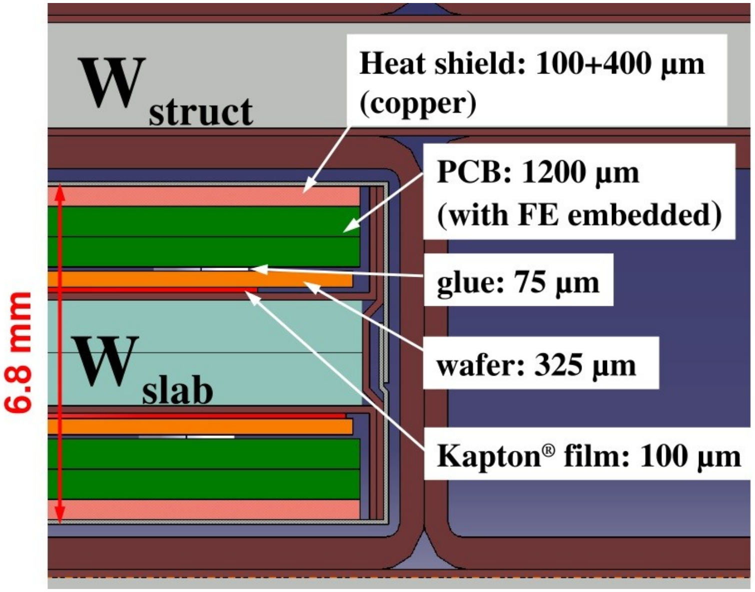
  Power pulsed electronics

- Construction 2010 – 2012, Testbeams 2012-2013

Technological Prototype – Design





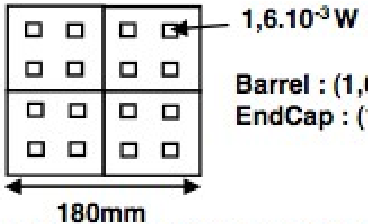


- ⇨ Gaps (slab integration) : 500 µm
- ⇨ Heat Shield: 500 µm
- ⇨ PCB : **~1200 µm**
- ⇨ Thickness of Glue : 100 µm
- ⇨ Thickness of SiWafer : 325 µm
- ⇨ Kapton® film HV : 100 µm
- ⇨ Thickness of W : 2100/4200 µm (± 80 µm)

Thermal studies

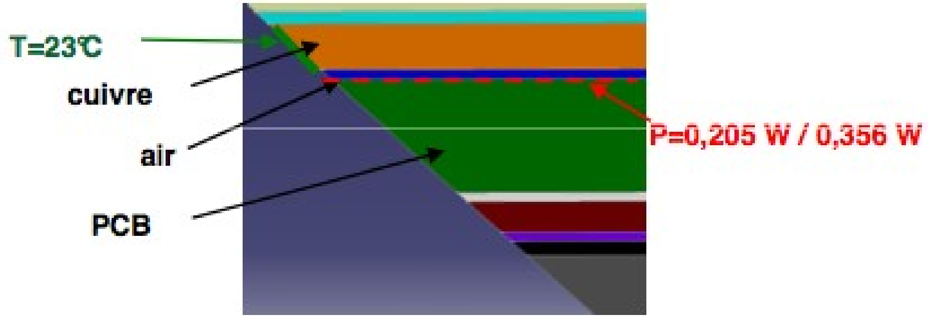
Inlet

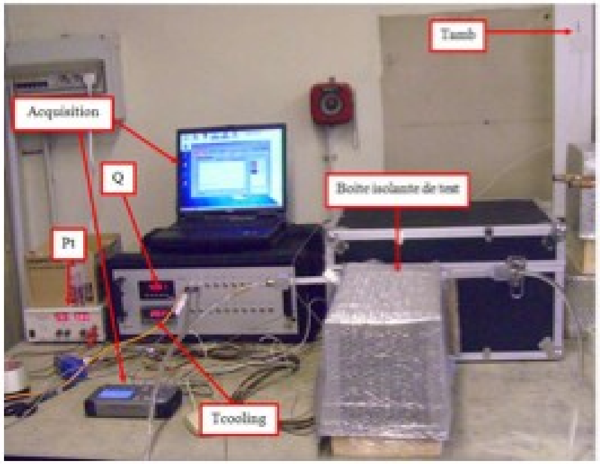
Power on PCB = 0,205 W / 0,356 W



Barrel : (1,6.10-3*16)/180*1445=0,205 W
EndCap : (1,6.10-3*16)/180*2500=0,356W

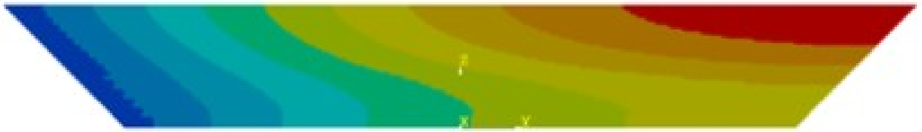
Boundary condition T = 23 °C beginning of the copper plate
Air between copper plate and pcb is in the model





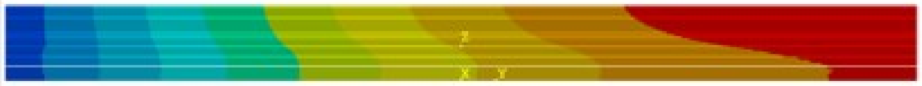
Results

Barrel : (1.5m)



ΔT = 2,2°C

End Cap : (2.5m)

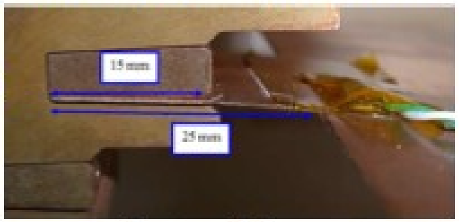


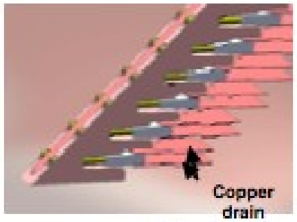
ΔT = 6°C

Conclusion

Low T° gradient -> cooling system suitable
Cooling front –end (front of slab sufficient)

Confirmation: **25 mm** free opening in
DIF for extraction of cooling system



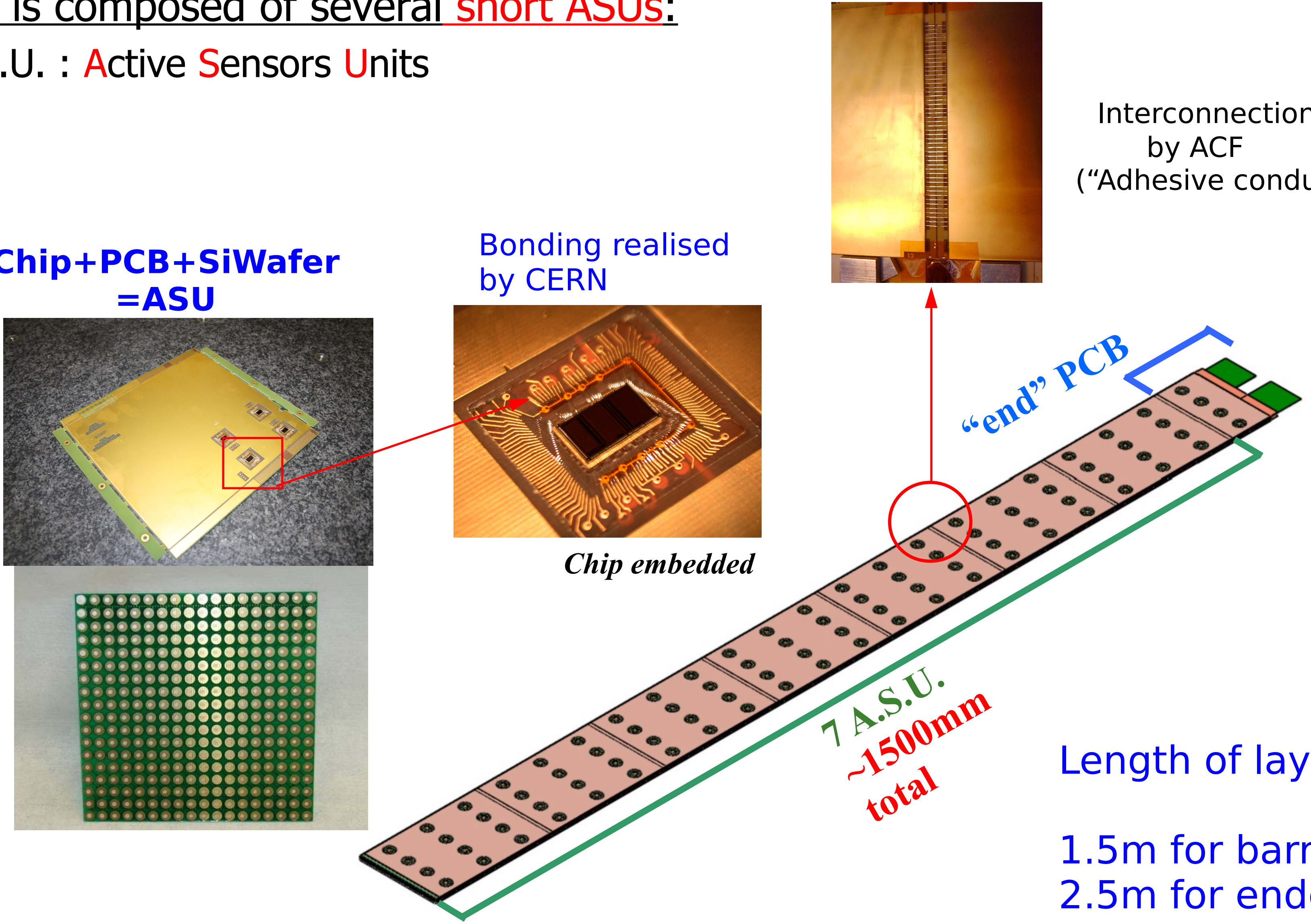


Copper plate / heat exchanger link

Ecal detector layer - Principle

A layer is composed of several short ASUs:

- A.S.U. : Active Sensors Units



Chip+PCB+SiWafer =ASU

PCB is glued onto SiWafers

Bonding realised by CERN

Chip embedded

Interconnection by ACF ("Adhesive conductive film")

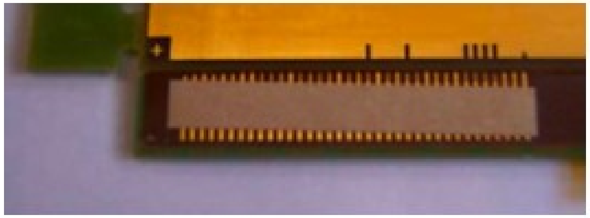
Length of layer:

1.5m for barrel
2.5m for endcaps

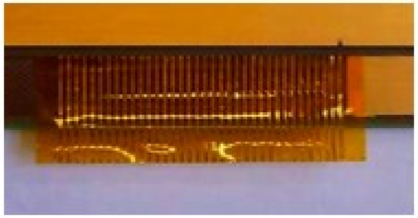
Details of interconnection method

The ACF 3M looks like double-sided tape

Put the ACF on FEV
Remove the protect film (brown)



Positioning of the comb
(It's possible to repeat the positioning)

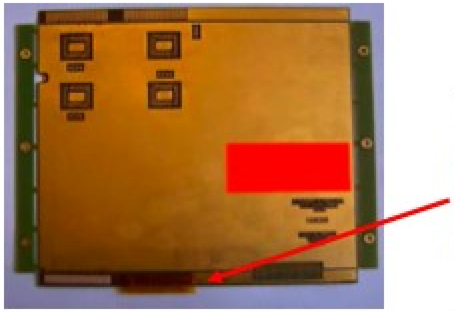


Using
Myachi
Thermode

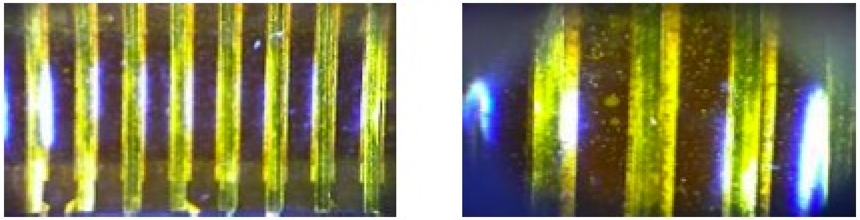
Temperature 150°C
Time 25 seconds
Pressure 18 Bar ◄

Pressure is an issue

alternatives exist



Kapton comb pictures with binocular



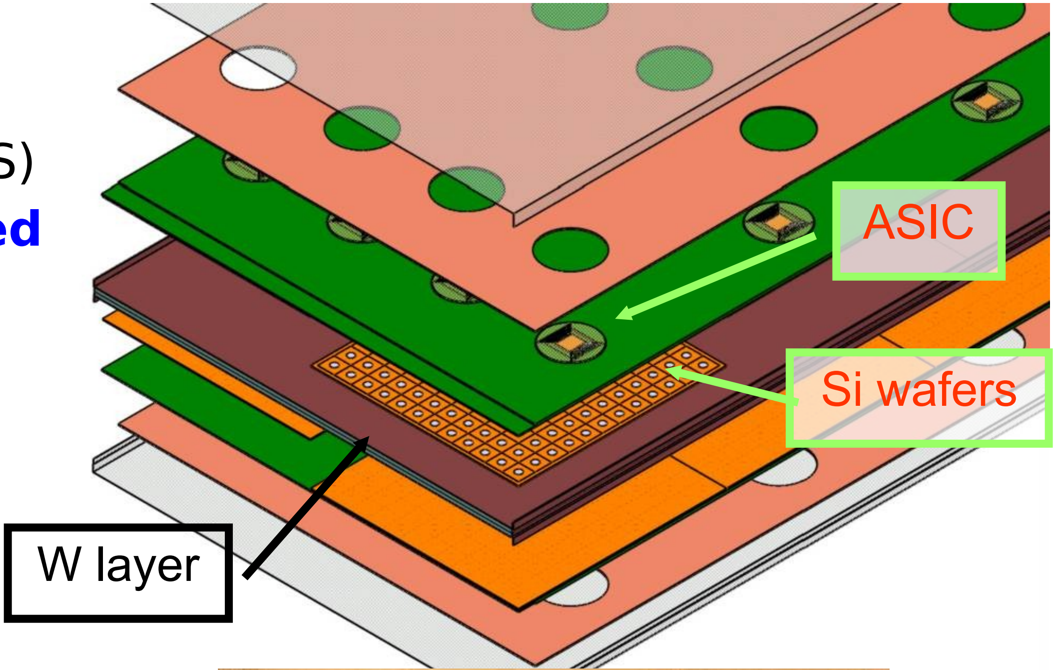
Resistance:
Across wires: 0.1 Ω
Between wires: ∞

Industrialisation is very easy

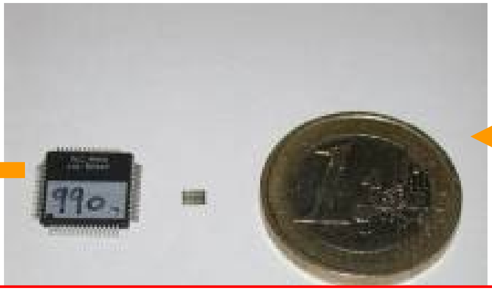
R&D Issues: Lifetime -> Aging tests

Front end electronics

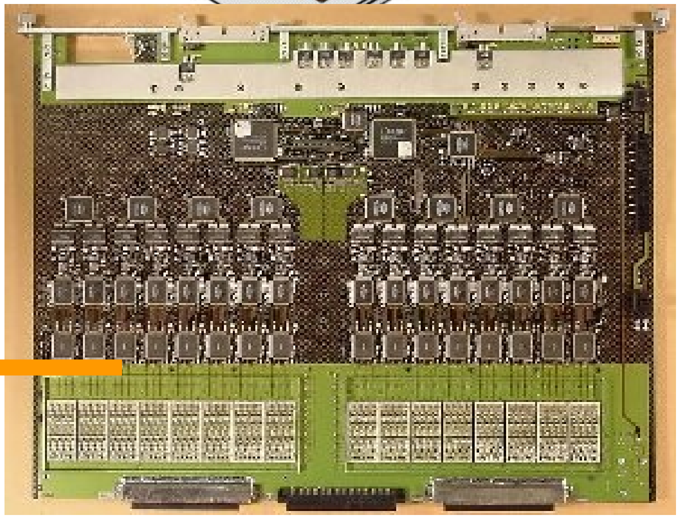
- Requirements to electronics
  - Large dynamic range (~2500 MIPS)
  - **Front end electronics embedded**
  - Autotrigger at ½ MIP
  - On chip zero suppression
  - **Ultra low power («25µW/ch)**
  - 10^8 channels
  - Compactness



ILC : **25µW/ch**



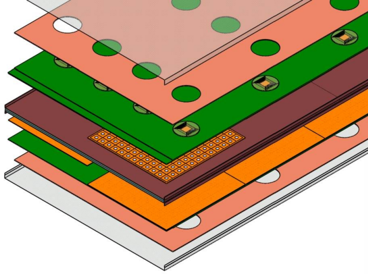
FLC_PHY3 18ch 10*10mm **5mW/ch**

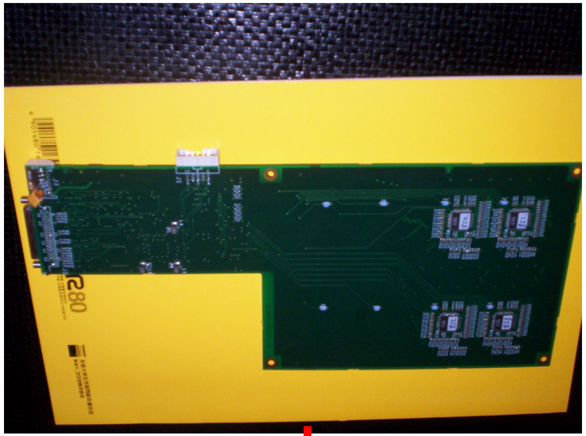


ATLAS LAr FEB 128ch 400*500mm **1 W/ch**

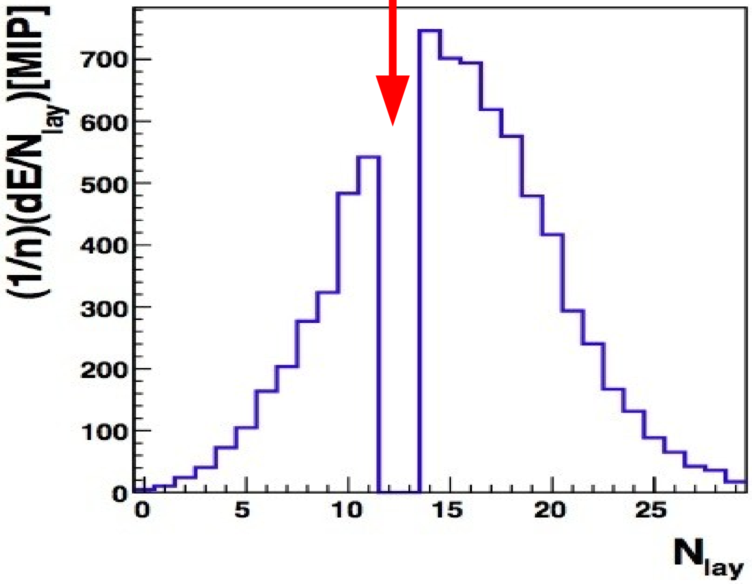
Embedded electronics - Parasitic effects?

Exposure of front end electronics to electromagnetic showers



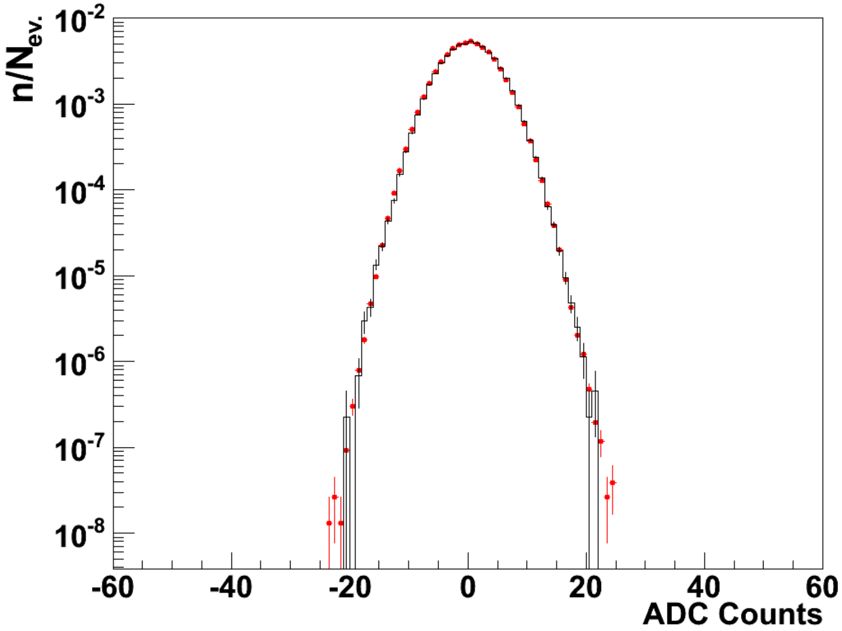


Chips placed in shower maximum
of 70-90 GeV elm. showers



Possible Effects: Transient effects
Single event upsets

Comparison: Beam events
(Interleaved) Pedestal events



- No sizable influence on noise spectra by beam exposure

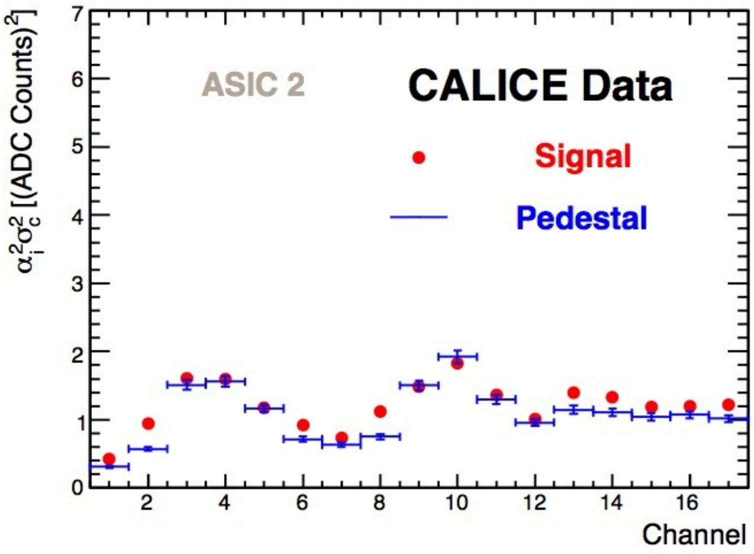
  ΔMean < 0.01% of MIP ΔRMS < 0.01% of MIP
- No hit above 1 MIP observed

  => Upper Limit on rate of faked MIPs: ~7x10^{-7}

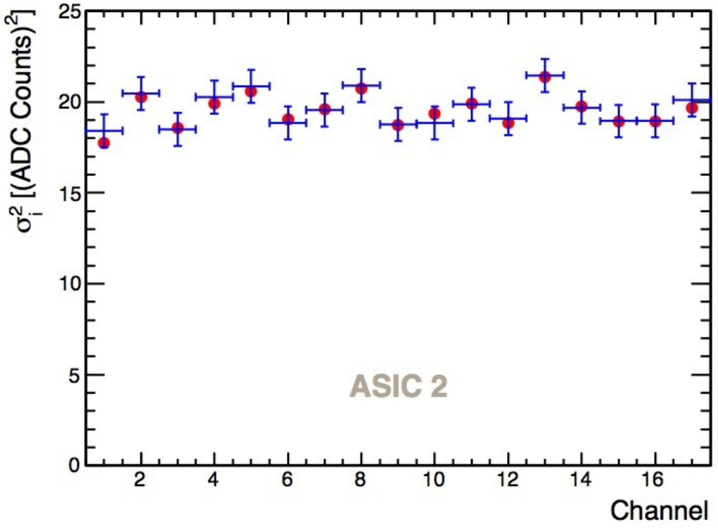
NIM A 654 (2011) 97

Detailed noise analysis

Coherent noise

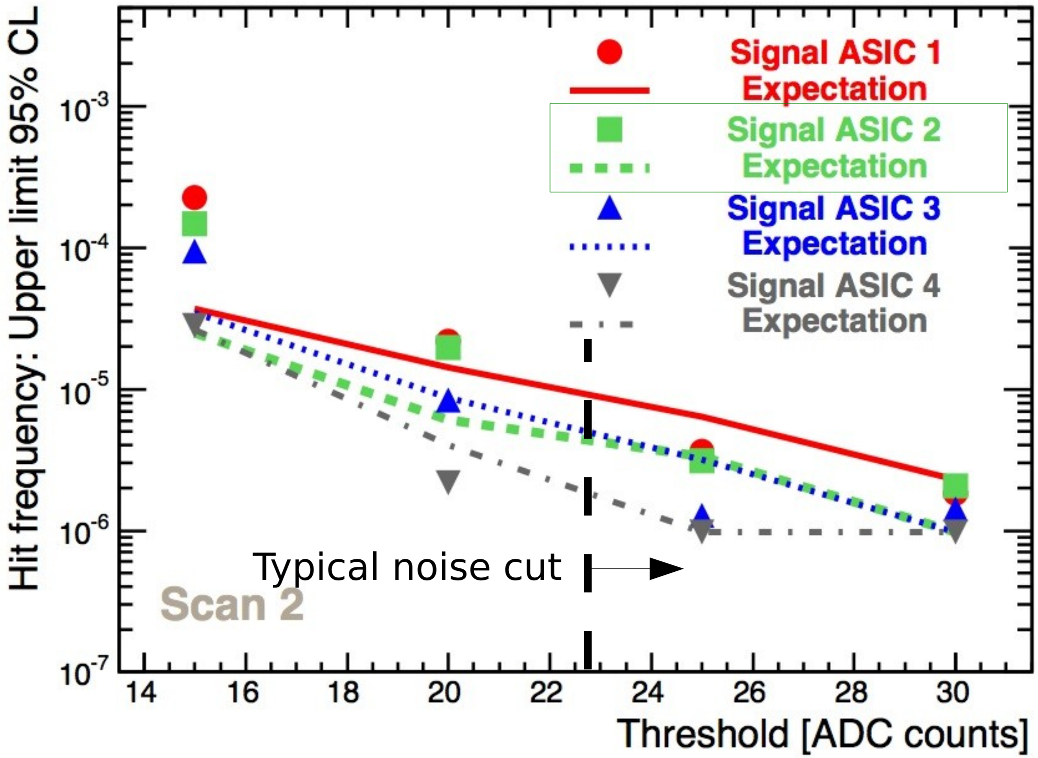


Incoherent noise



Noise pattern unchanged by shower particles

Upper limits on parasitic hits – 95% CL



Chip in beam

- Frequency of parasitic hits comparable with regular electronics noise
- < 10^{-5} above typical noise cut

Compare with 2500 cells in typical ee-> tt event

The Ecal ASIC - SKIROC

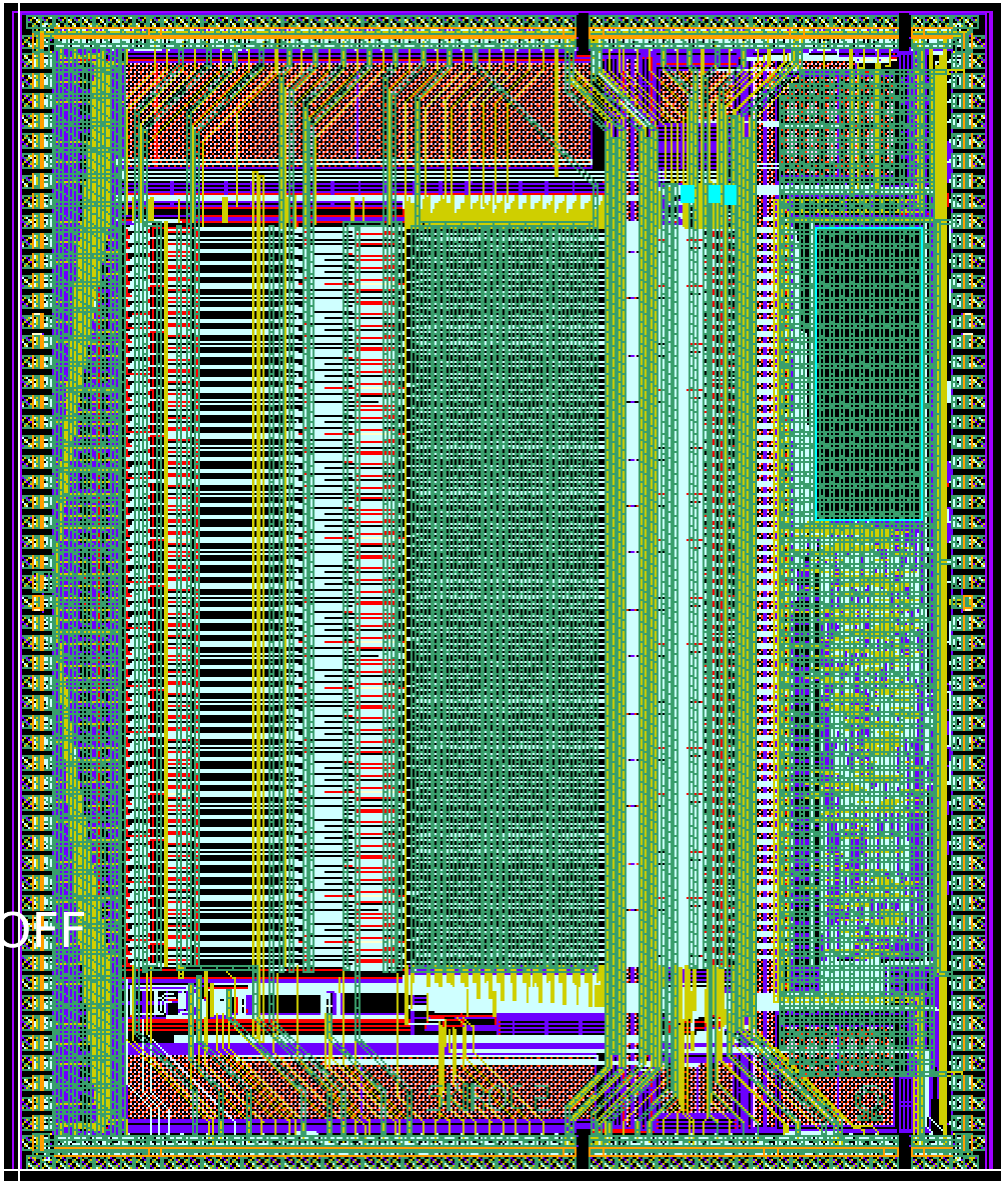
- 64 Channels

- Vss split :
  - Inputs
  - Analogue part
  - Mixed part
  - Digital part

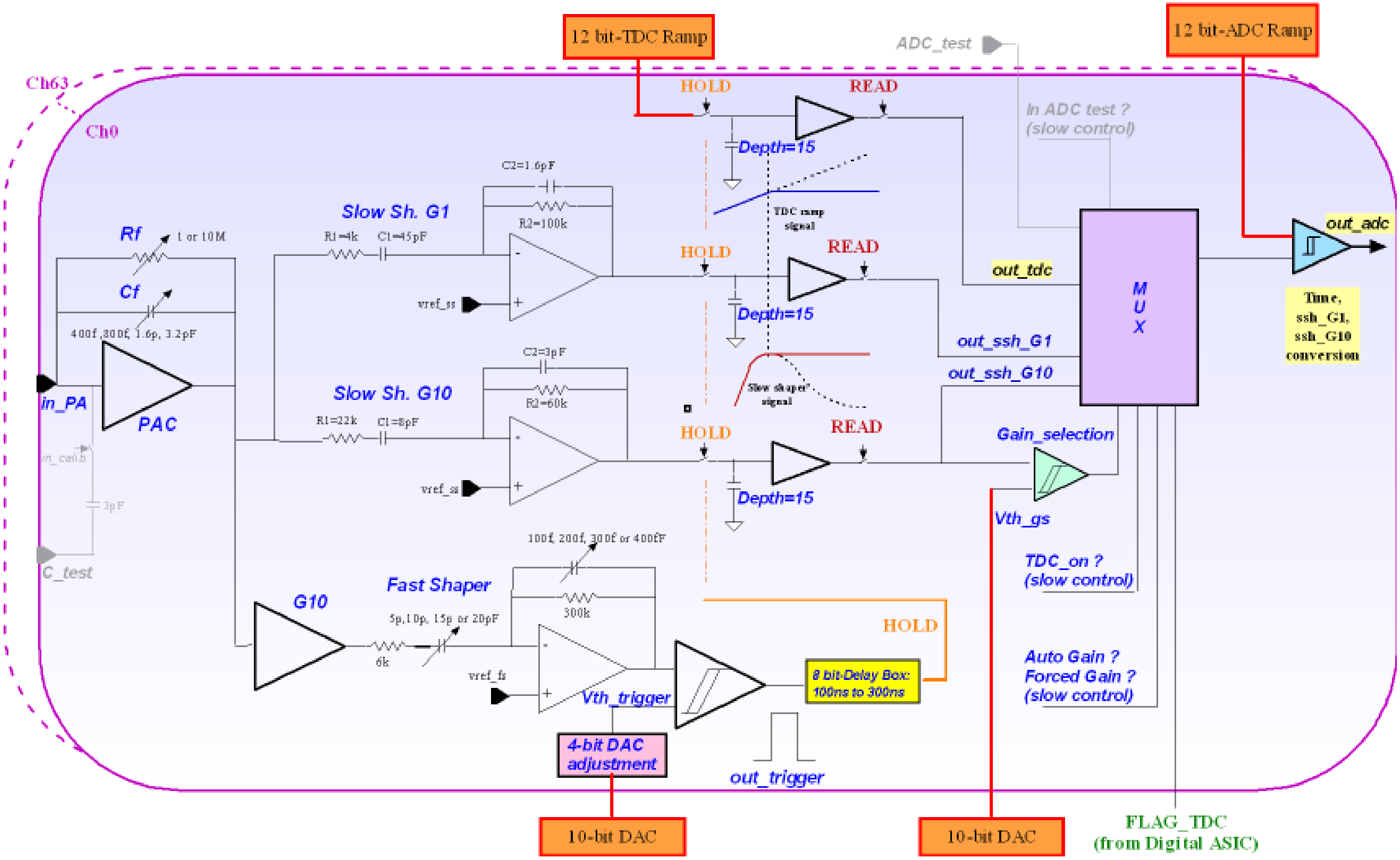
- 250 pads
  - 3 NC
  - 17 for test purpose only

- Enhanced Power control
  - Full power pulsing capability
  - Each stage can be forced ON OFF

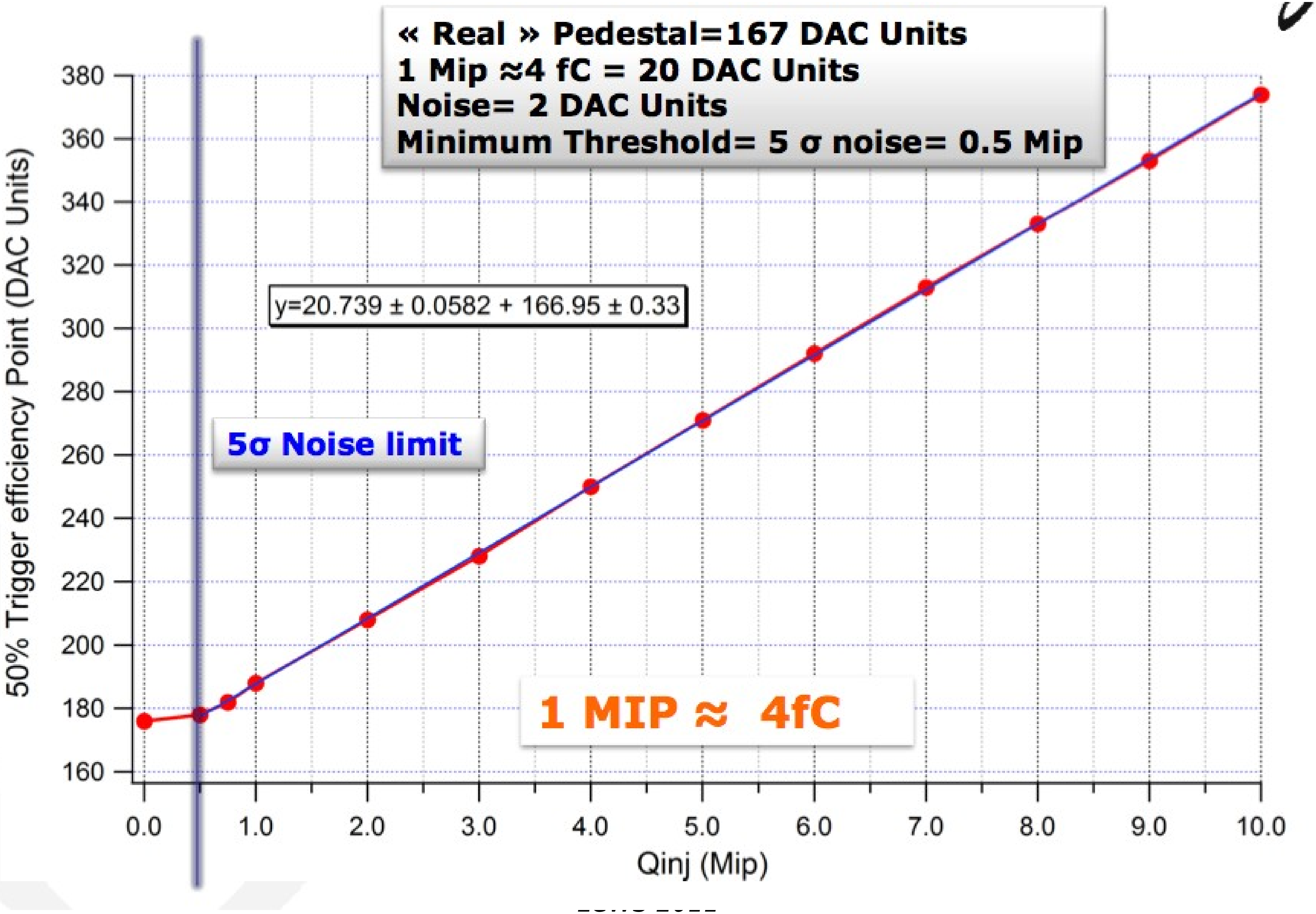
- Die size
  - 7229 µm x 8650 µm



SKIROC 2 block scheme



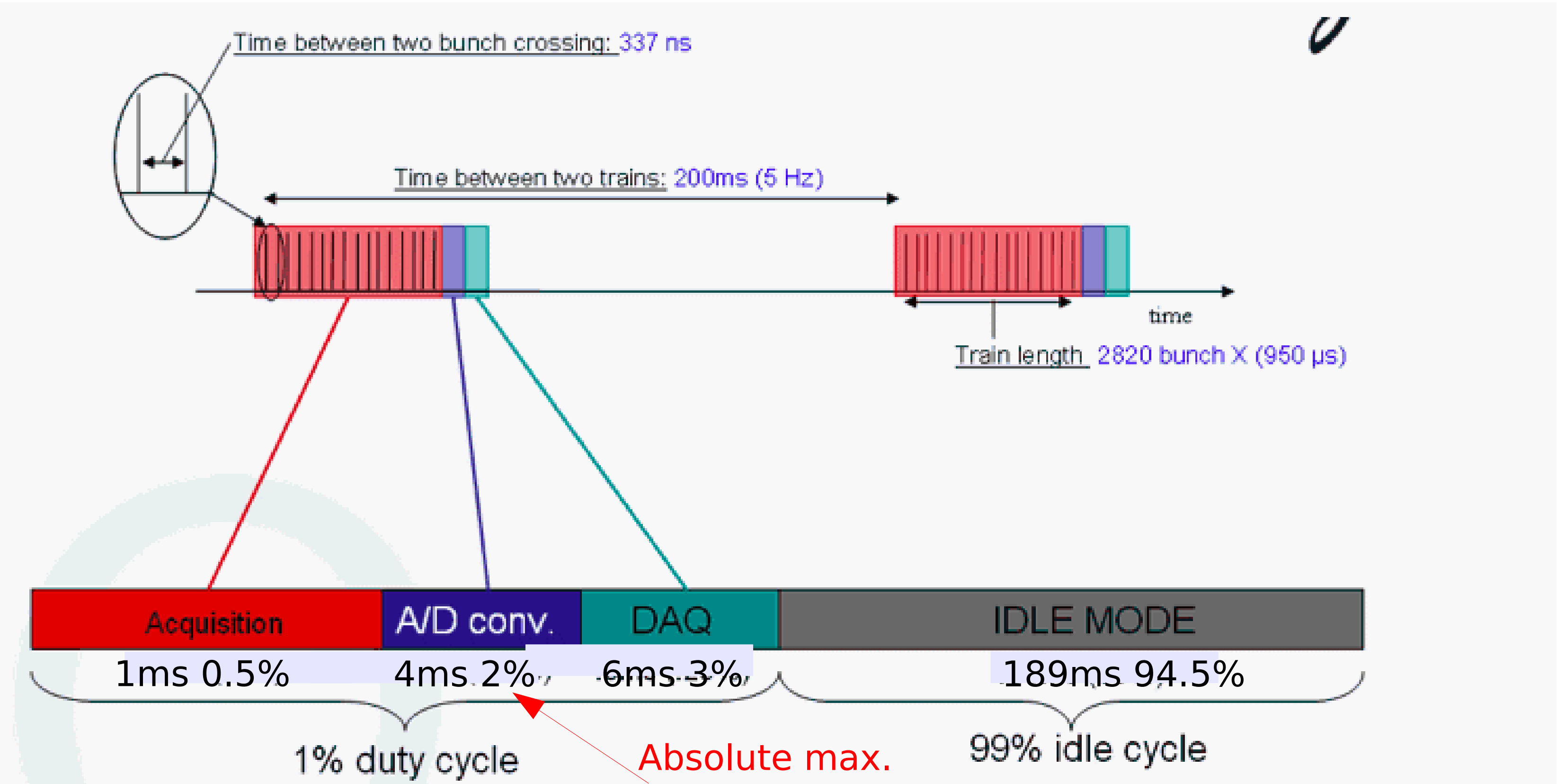
Example for SKIROC characterisation – Trigger efficiency



« Real » Pedestal=167 DAC Units
1 Mip ≈4 fC = 20 DAC Units
Noise= 2 DAC Units
Minimum Threshold= 5 σ noise= 0.5 Mip

1 MIP ≈ 4fC

Power pulsing (better power gating)



Absolute max.
Typically much smaller

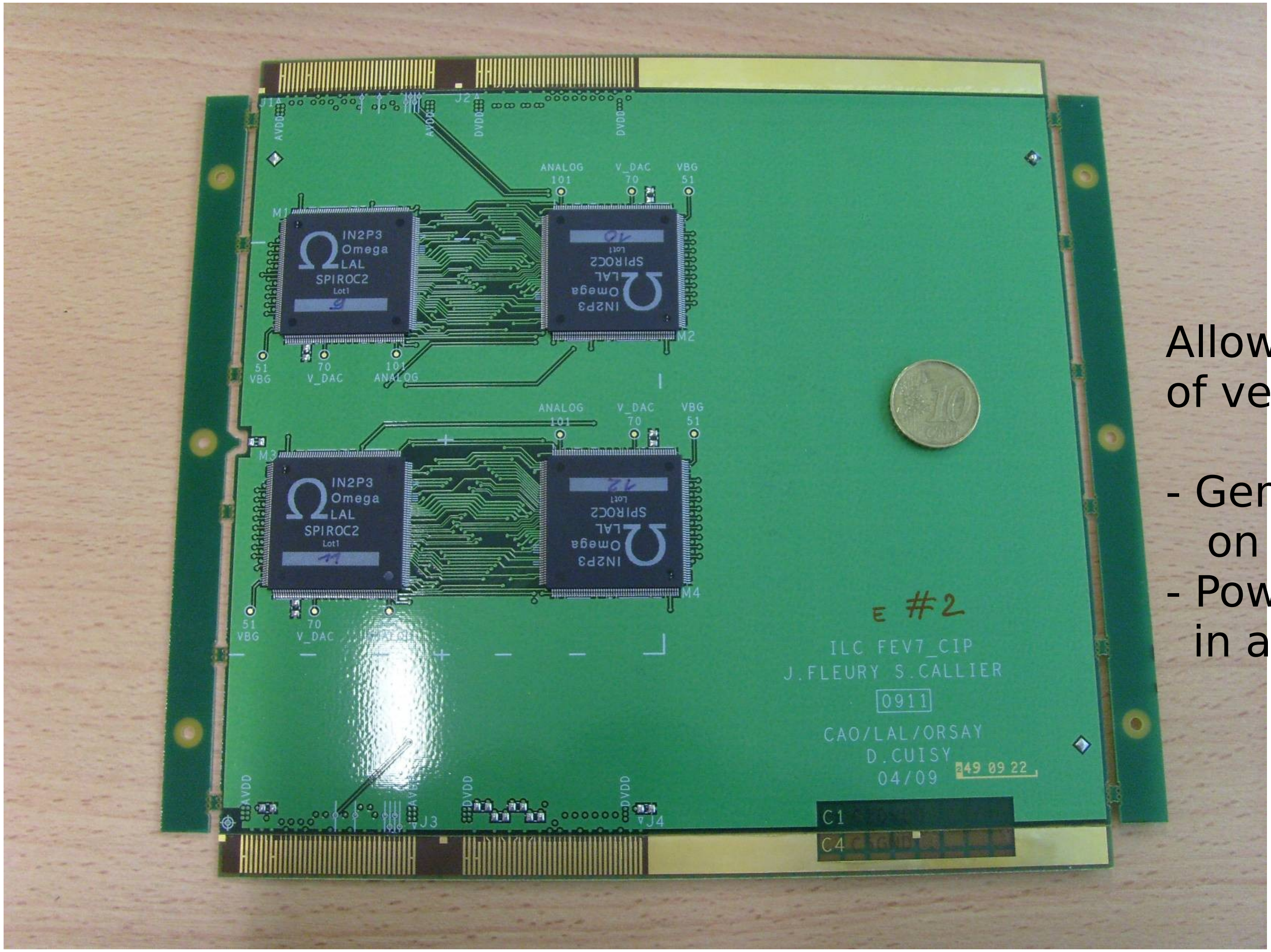
- Electronics switched on during 1ms of ILC bunch train and immediate data acquisition

- **Bias currents** shut down between bunch trains

- Mastering of technology is essential for operation of ILC detectors
  Measurements for SKIROC chip 1.7 mW <=> 27 uW/ch
  Encouraging results for SDCHAL with similar chip

R&D for PCBs

PCBs with 'conservative' technology FEV_CIP (Chip in Package)

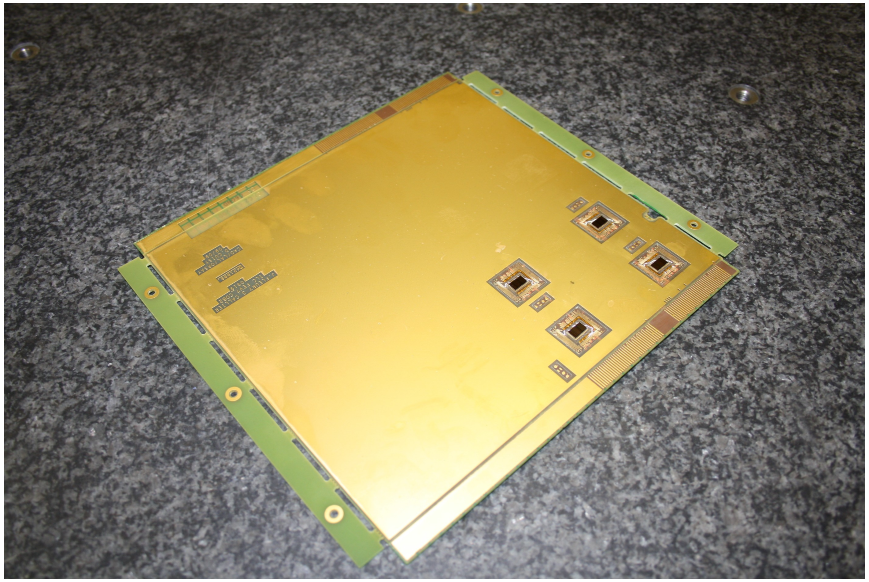


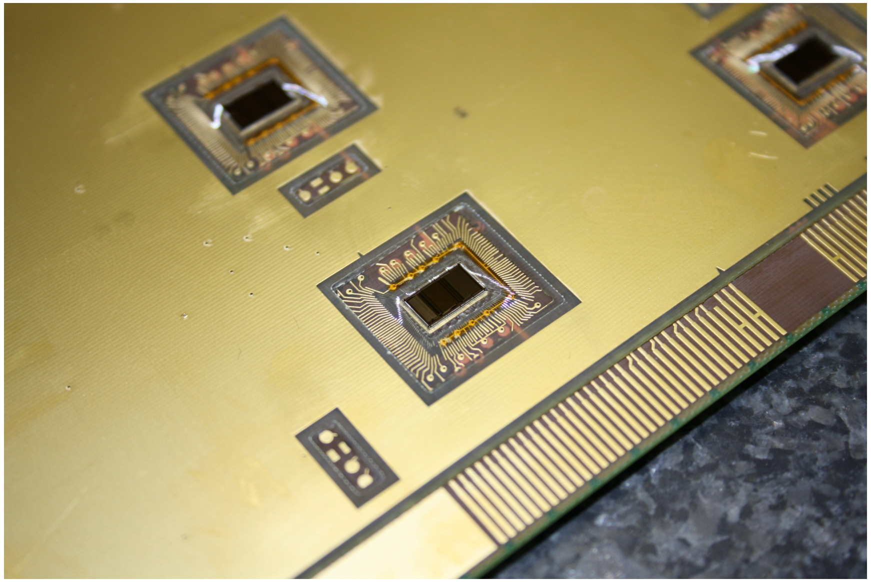
Allows us to realise a number of very useful tests

- General functionality of ASU on Cosmic bench and in beam
- Power pulsing in and outside of magnetic field

Stepwise approach to address R&D challenges

The next step FEV8 with COB – Chip on board





- Circuits wire bonded inside cavities

- Ultra thin

  9 layer board with max. 1.2mm thickness

- Ultra flat

  Deviation from total flatness max. 0.5mm
  Compare with industrial standard ~3mm

- Circuits need to be encapsulated with resine

  Non trivial to realise
  Long term effects of chips and wire bonds?

Mastering of these technological challenges is essential to meet LC detector design goals
-> A number of open points!!!

A generic DAQ system for the CALICE calorimeters (Technological Protoypes)

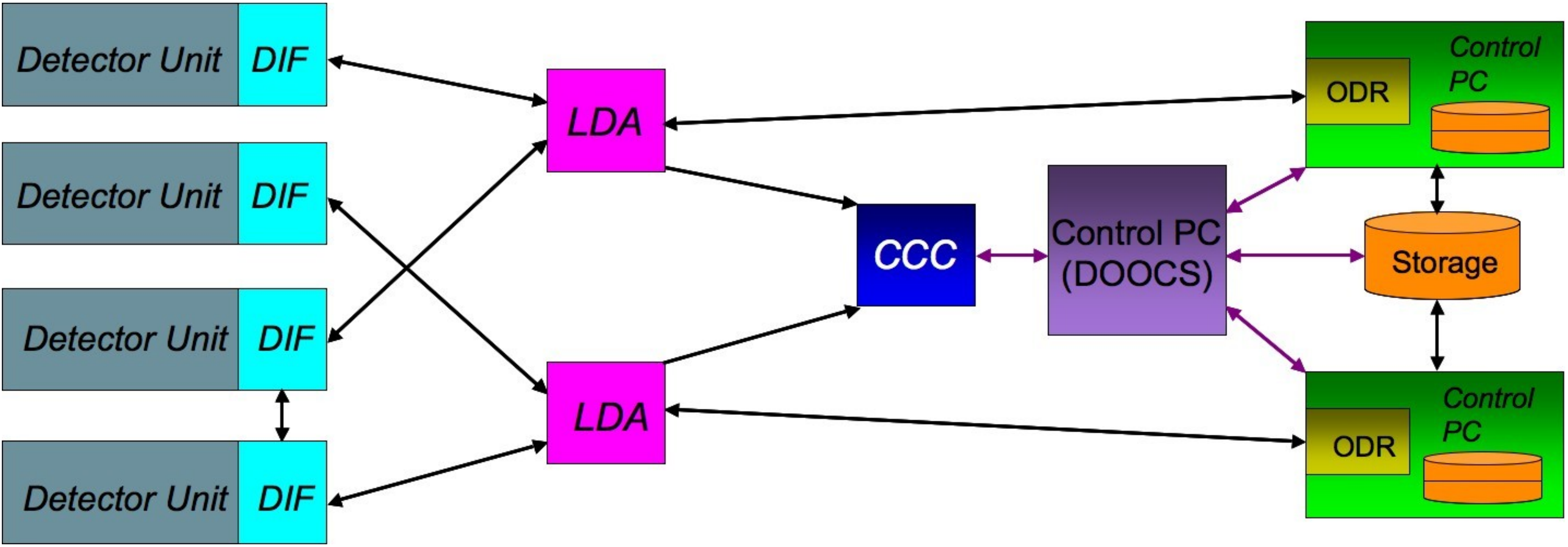
Standard

HDMI connectors
LVDS
GBEthernet
Optical links

Generic

FPGA

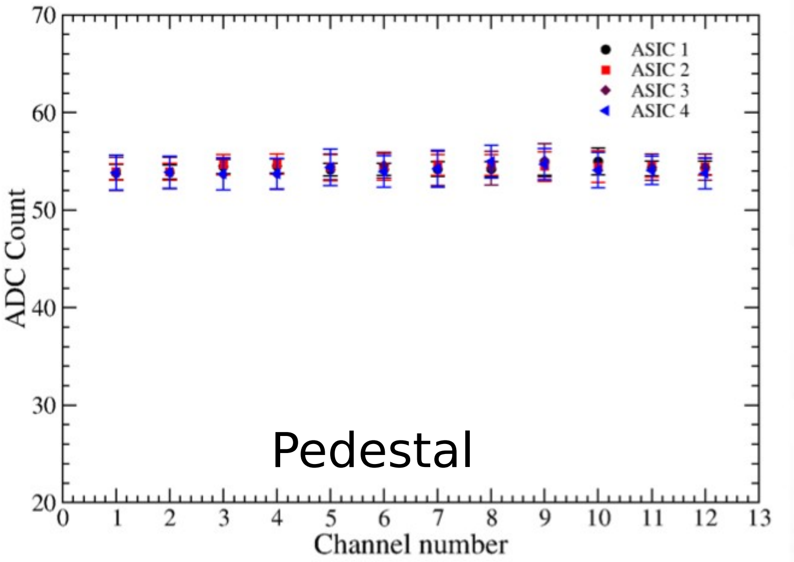
Scalable



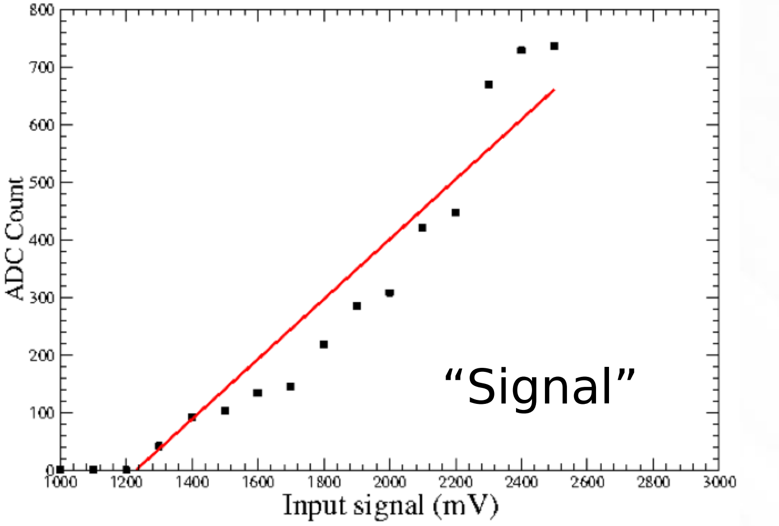
Test setup comprises currently FEV7_CIP and SPIROC

Interface Ecal <-> DAQ2 realised in summer 2011

Major step towards measurements with ASUs of Ecal techno. proto



Pedestal



“Signal”

In the middle of learning phase
Expect stable measurements in coming weeks

Summary and outlook

- Successful R&D for a highly granular electromagnetic calorimeter

- Detector concept is built on Particle Flow

Physics Prototype (2005-2011):
- Energy resolution ~17%/√E
- Signal to Noise Ratio ~8/1
- Stable calibration

- Capacity of separating particles impressively demonstrated by test beam analysis
- Unprecedented realistic views into hadronic showers thanks to high granularity 'Modern bubble chamber'

- Coping with huge amount of information is challenging

Potential to draw connection with other fields of science (algorithms)
The harvest is just starting

Technological Prototype (2010-...):
- Mechanical concept validated
- Silicon Wafer technology at hand
- Front End Electronics will be challenging
  Embedded into calorimeter layers: **No compromise for precision physics**
  Power gating
- Supported within EUDET (2006-2010), AIDA (2011-2015) and French ANR (2011-2014) + New Japanese ILC funding (2011-2016)

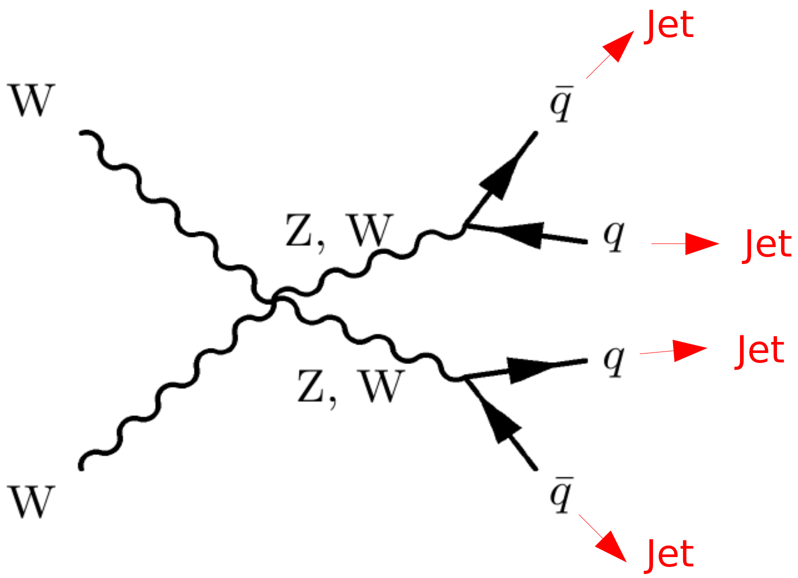
Backup Slides

Hadronic decays of W and Z Bosons

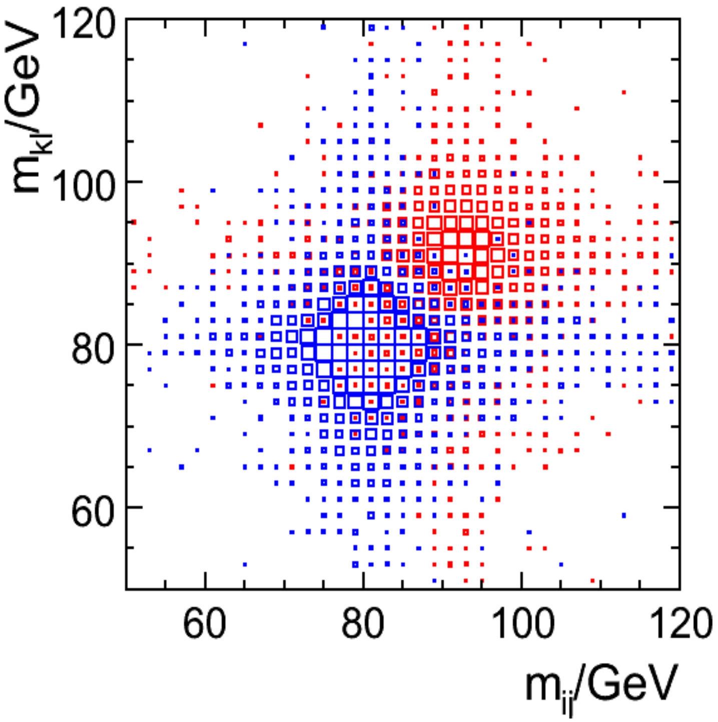
Boson Boson scattering

What if no Higgs?

Manifestation of new physics
Strong electroweak symmetry breaking



W, Z separation in the ILD concept



Remember: $M_Z - m_W \approx 10$ GeV

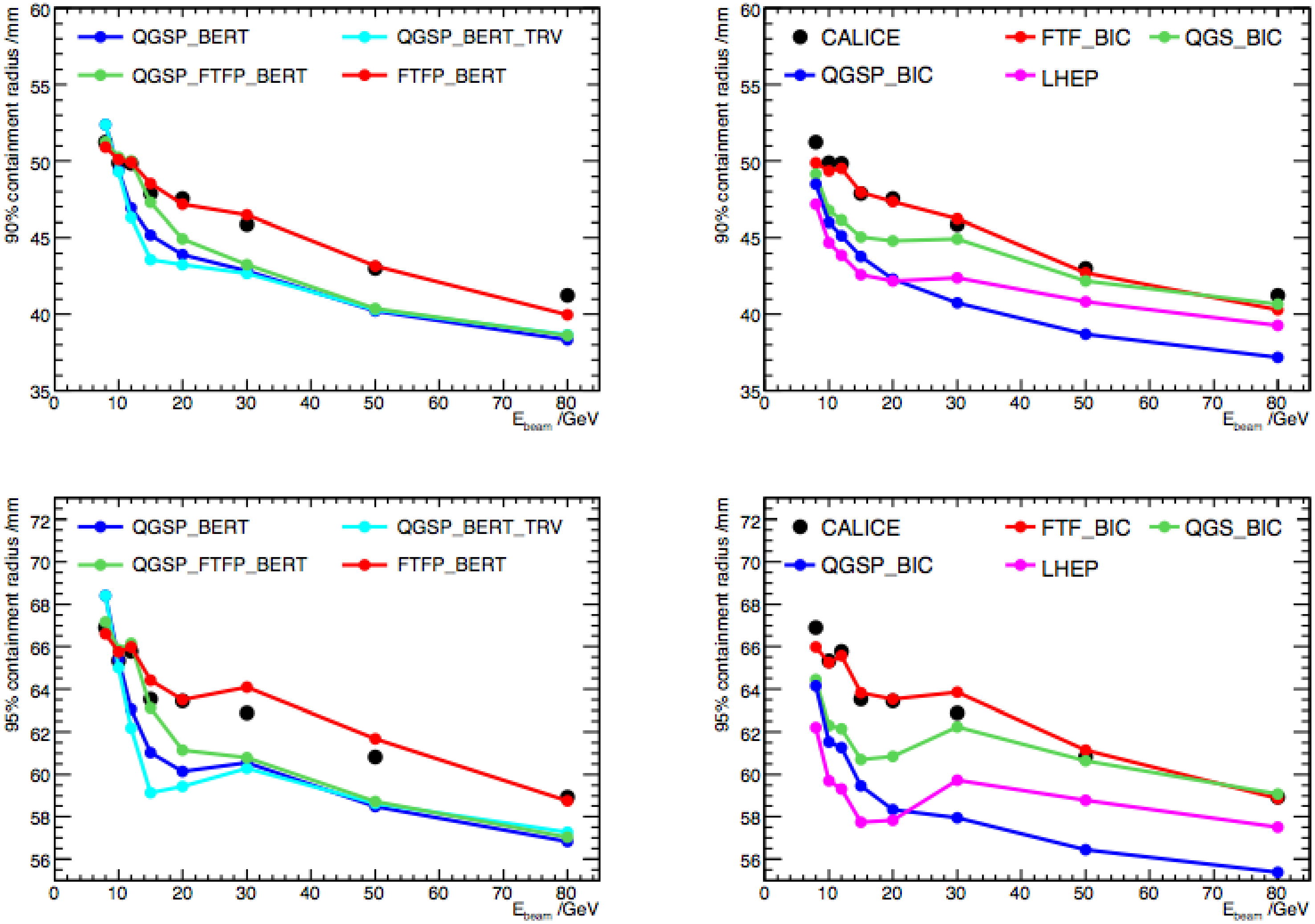
- Need excellent jet energy resolution to separate W and Z bosons in their hadronic decays
  $3\%/E_{jet}$-$4\%/E_{jet}$

Lateral shower containment

Radius of

90% containment

95% containment

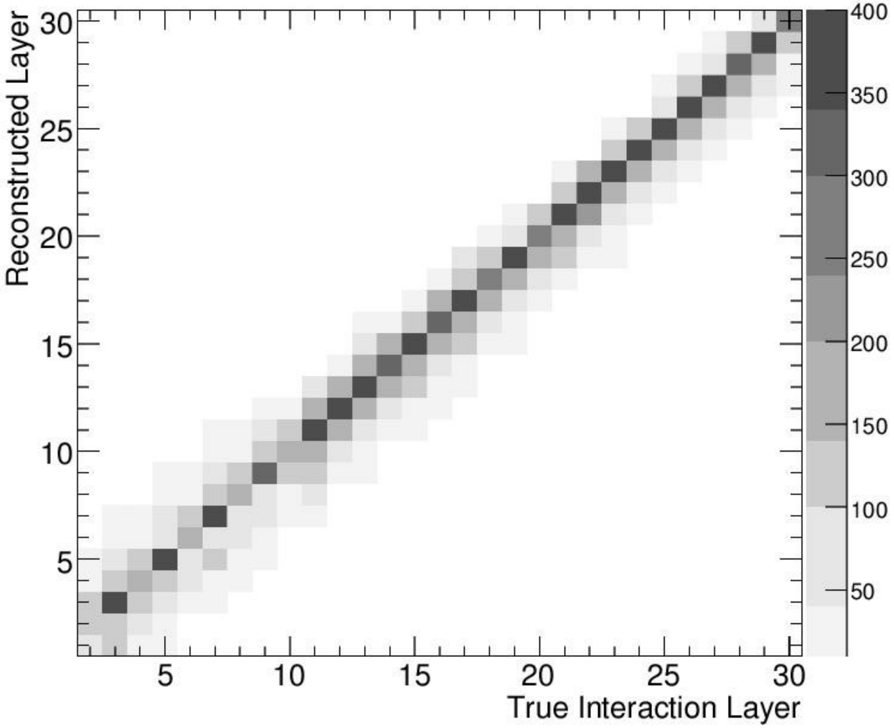


General underestimation of lateral shower extension

“FTF” models perform best

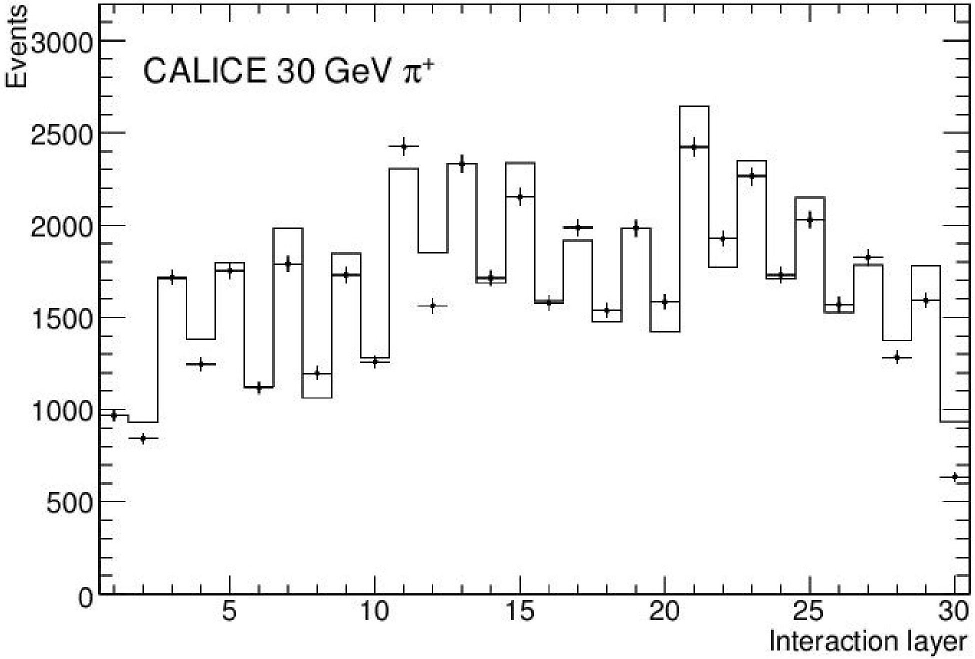
Finding the interaction in the SiW Ecal

Correlation:
True interaction <-> Found interaction



Determination precise to two layers
(Overall Layer thickness ~7mm max.)

Distribution of found interaction layers

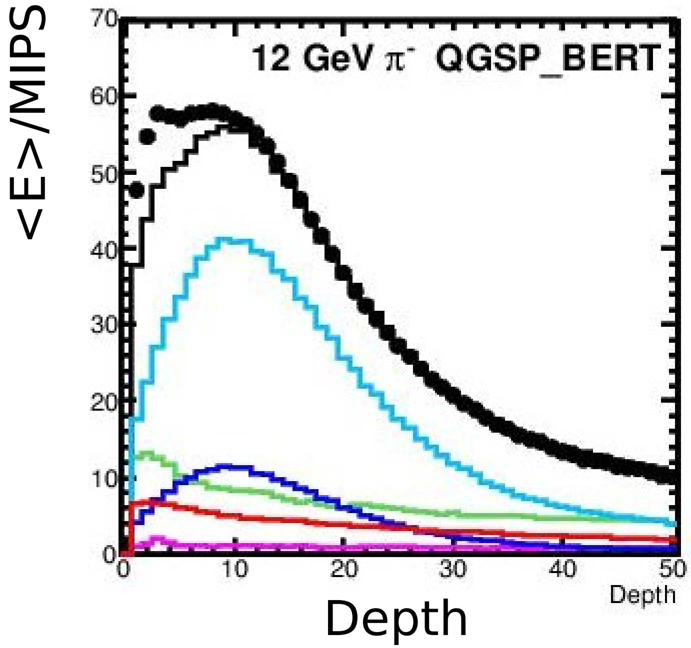


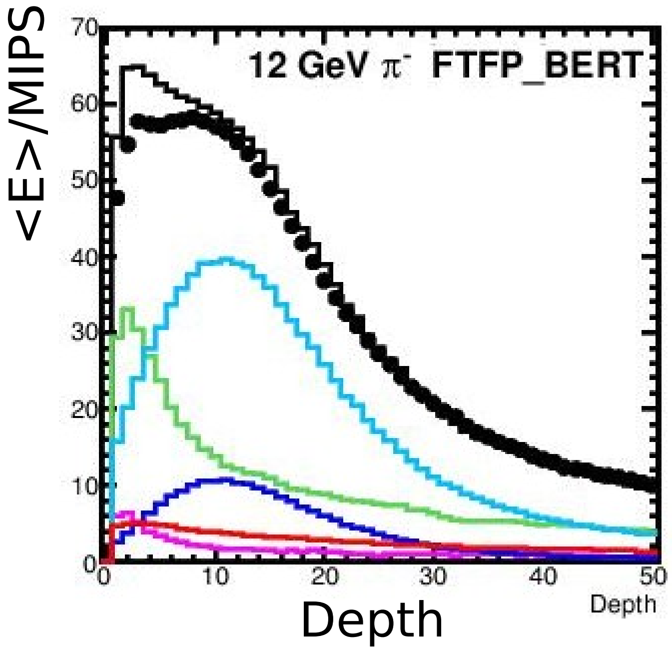
Good agreement between Data
and simulation (G4, here QGSP_BERT)

Granularity allows for resolving interaction layer with high resolution
High energy cross sections well implemented in G4 simulation

Longitudinal energy profiles

Sensitivity to different shower components





Shower components:

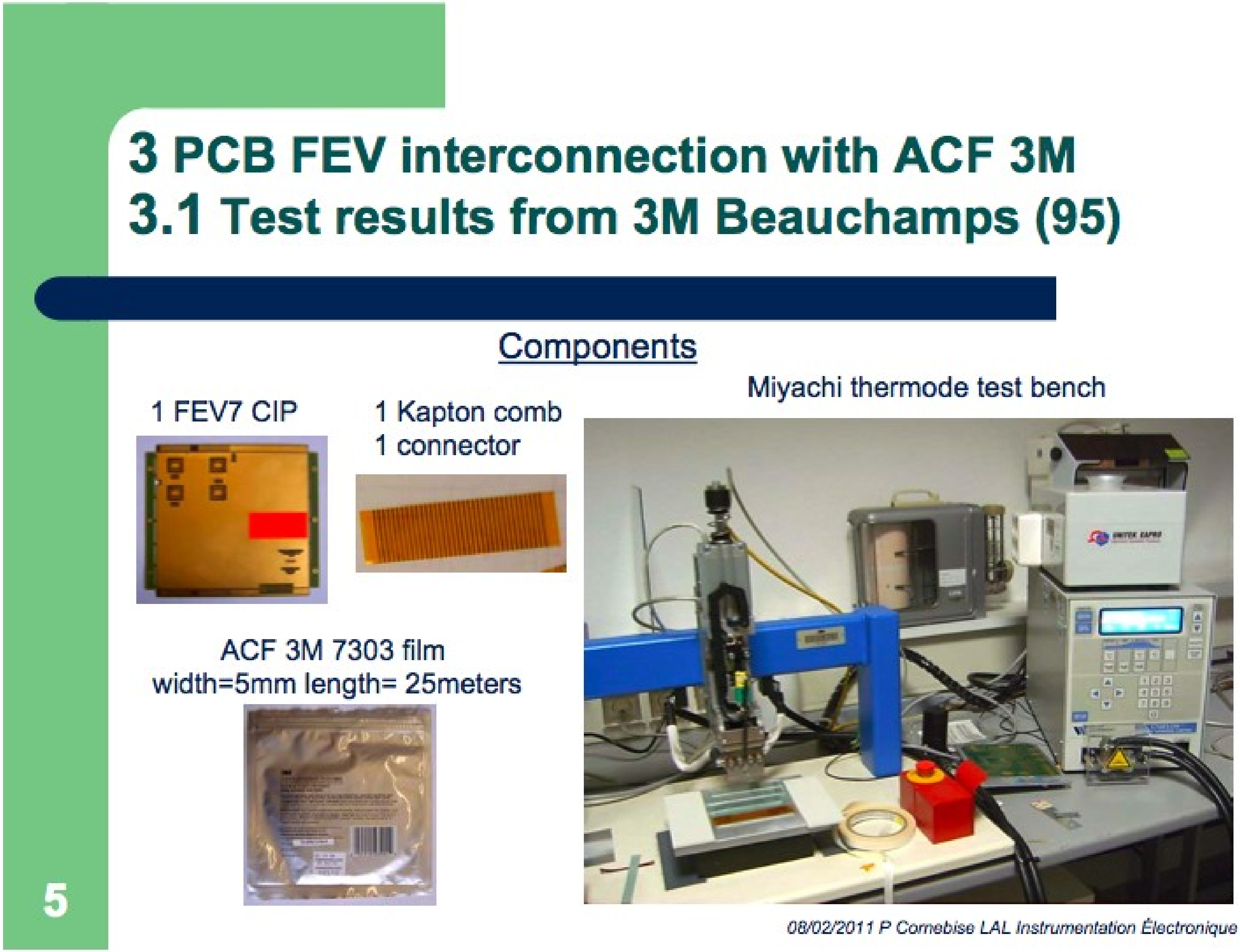
- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum

Significant difference between models

- Particularly for short range component (protons)

Granularity of SiW Ecal allows (some) disentangling of components

Further studies for shower decomposition are ongoing



3 PCB FEV interconnection with ACF 3M
3.1 Test results from 3M Beauchamps (95)

Components

1 FEV7 CIP

1 Kapton comb
1 connector

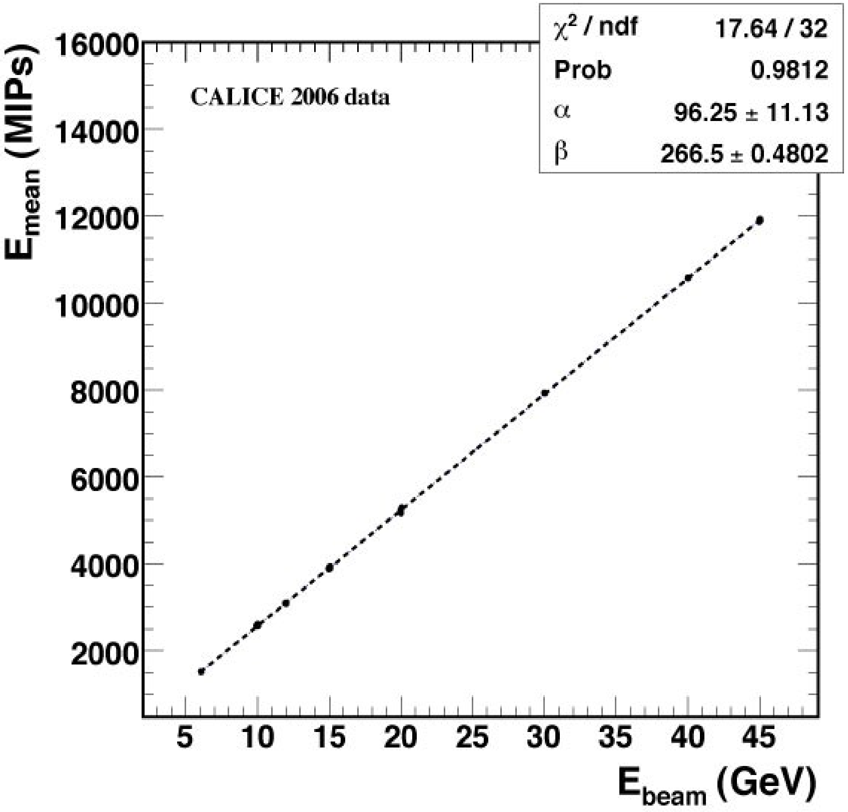
ACF 3M 7303 film
width=5mm length= 25meters

Miyachi thermode test bench

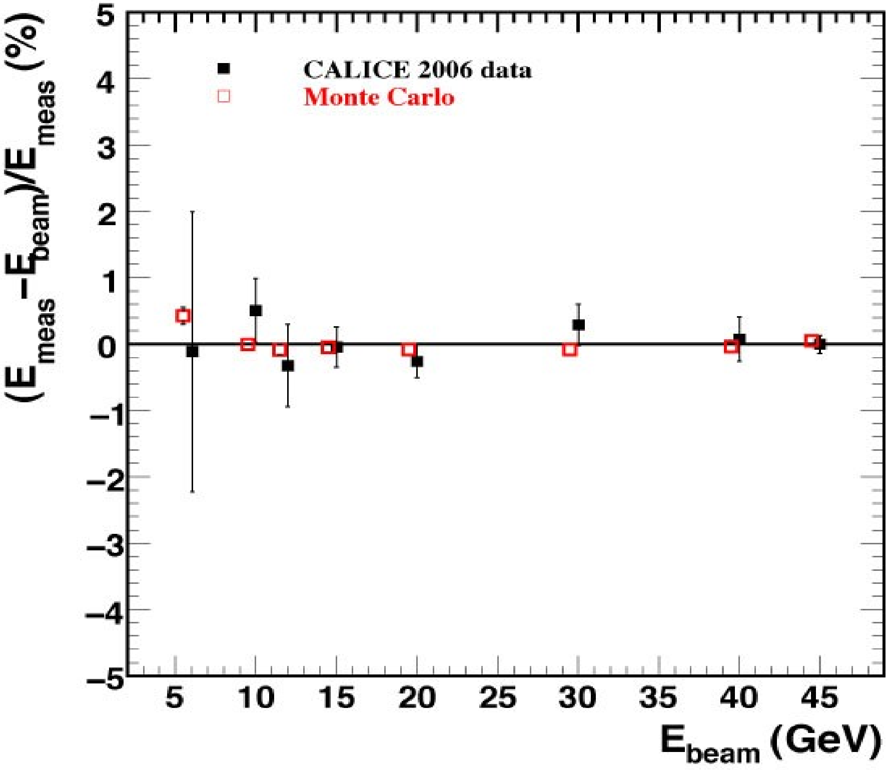
08/02/2011 P Cornebise LAL Instrumentation Électronique

Linearity of response

Overview



Residuals

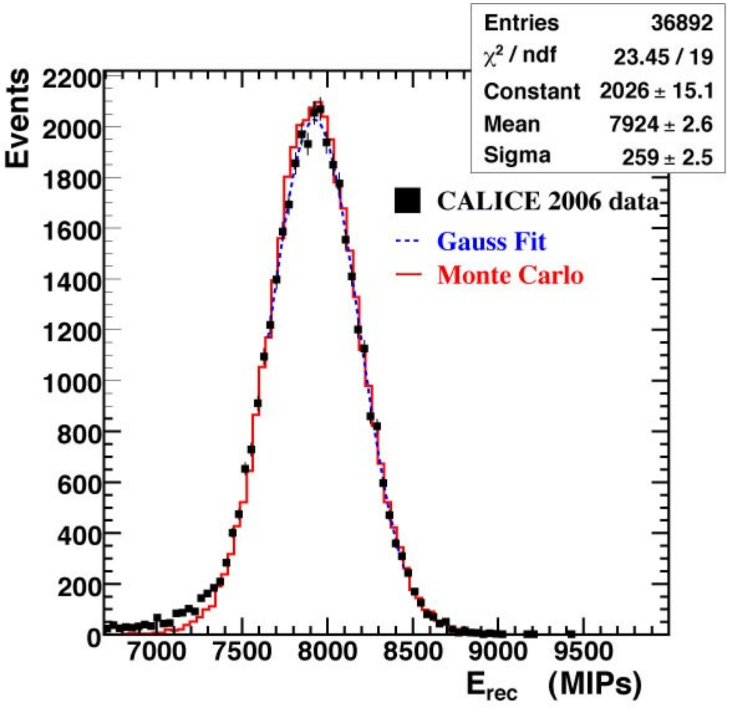


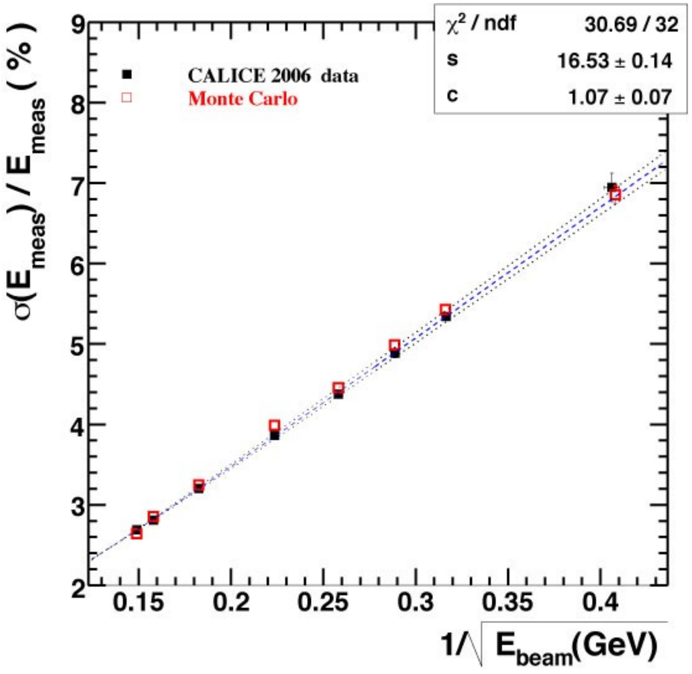
- Highly linear response over large energy range

- Linearity well reproduced by MC
  MIP/GeV ~ 266.5 [1/GeV]

- Non-linearity O(1%)

Energy resolution





Example 30 GeV electron beam:

Gaussian like calorimeter response

Resolution curve shows typical √E dependency

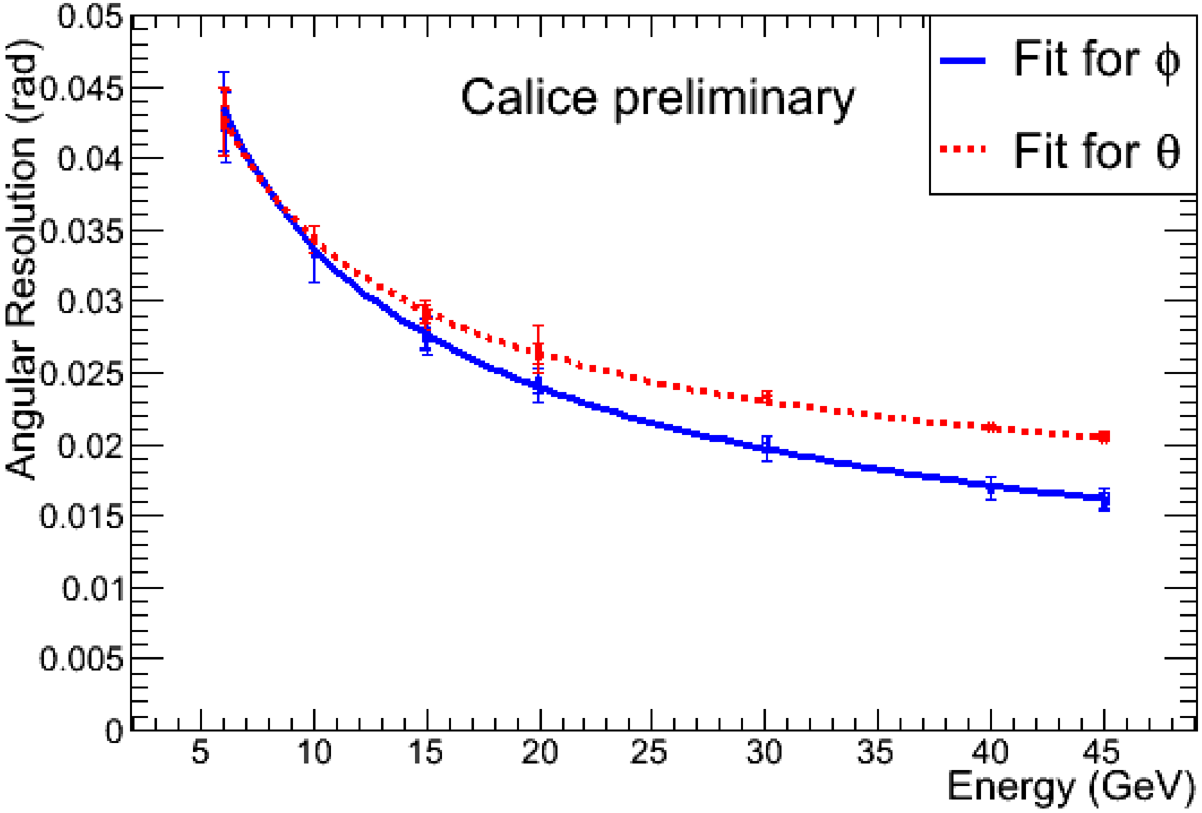
$$\frac{\Delta E_{meas.}}{E_{meas.}} = \left[\frac{16.6\pm 0.1\,(stat.)}{\sqrt{E\,[\mathrm{GeV}]}} \oplus (1.1\pm 0.1)\right]\%$$

- Resolution well described by MC
- Confirms value used in LOI

Design emphasises spatial granularity over energy resolution

Calorimeter for Particle Flow

Angular resolution



Fitted with:

$$\frac{p1}{\sqrt{E(GeV)}} \oplus p0$$

Φ, angle respect to X:

$$\left(\frac{106 \pm 2}{\sqrt{E(GeV)}} \oplus (4 \pm 1)\right) mrad$$

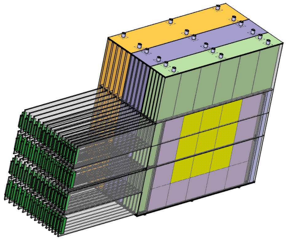
θ, angle respect to Y:

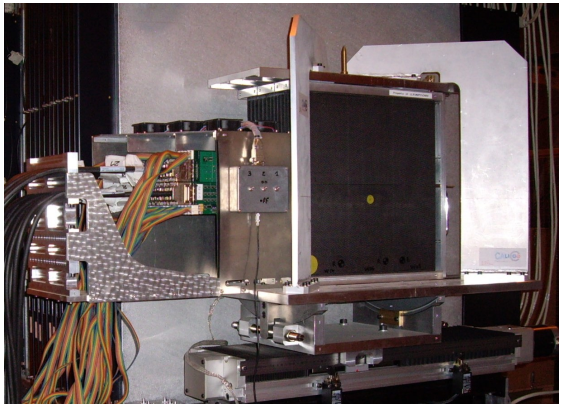
$$\left(\frac{100 \pm 2}{\sqrt{E(GeV)}} \oplus (14 \pm 1)\right) mrad$$

Differences due X and Y due to geometrical properties of prototype (staggering)

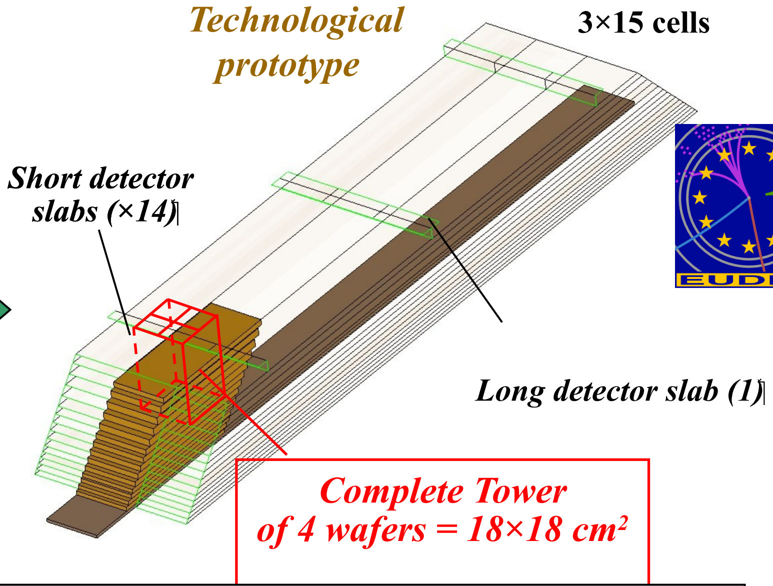
Technological Prototype

- Physics prototype: Validation of main concept
- Techno. Proto : Study and validation of technological solutions for final detector
- Taking into account industrialisation aspect of process
- First cost estimation of one module



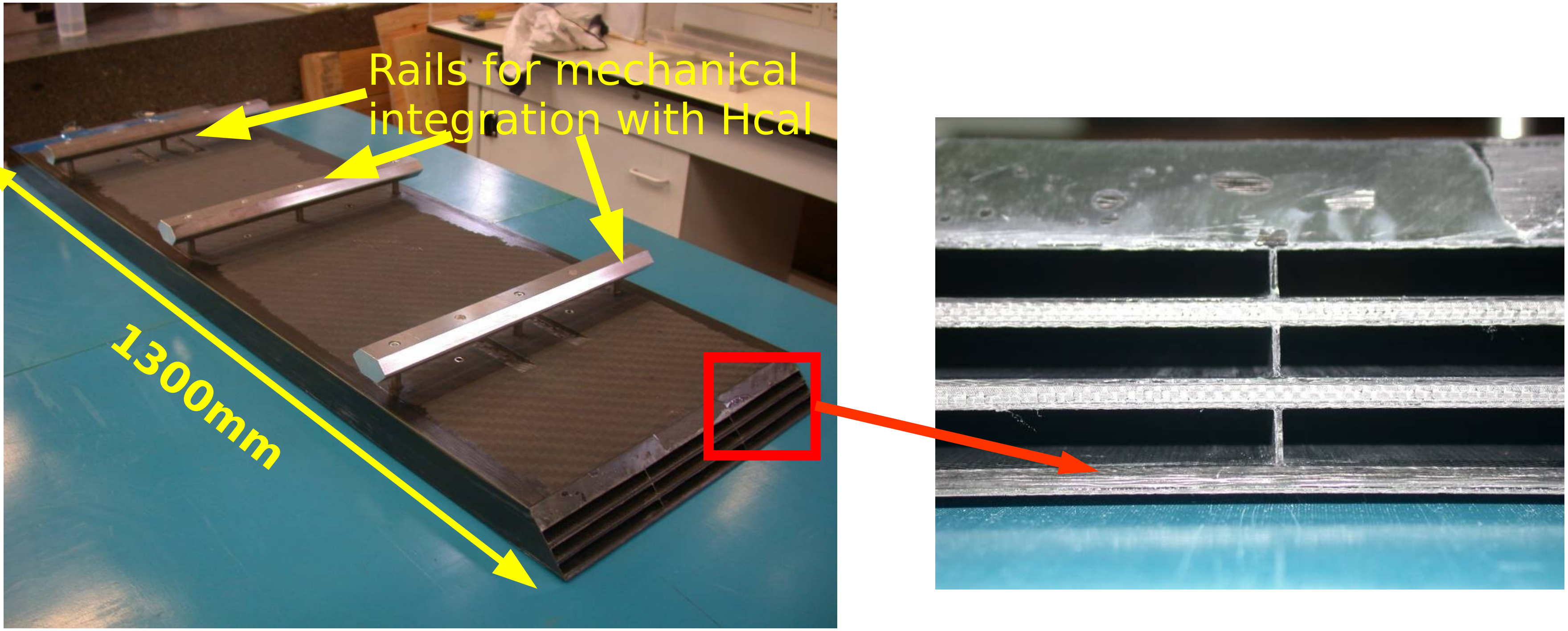


- **3 structures : 24 X_0 (10×1,4mm + 10×2,8mm + 10×4,2mm)**
- **sizes : 380×380×200 mm3**
- **Thickness of slabs : 8.3 mm (W=1,4mm)**
- **VFE outside detector**
- **Number of channels : 9720 (10×10 mm^2)**
- **Weight : ~ 200 Kg**

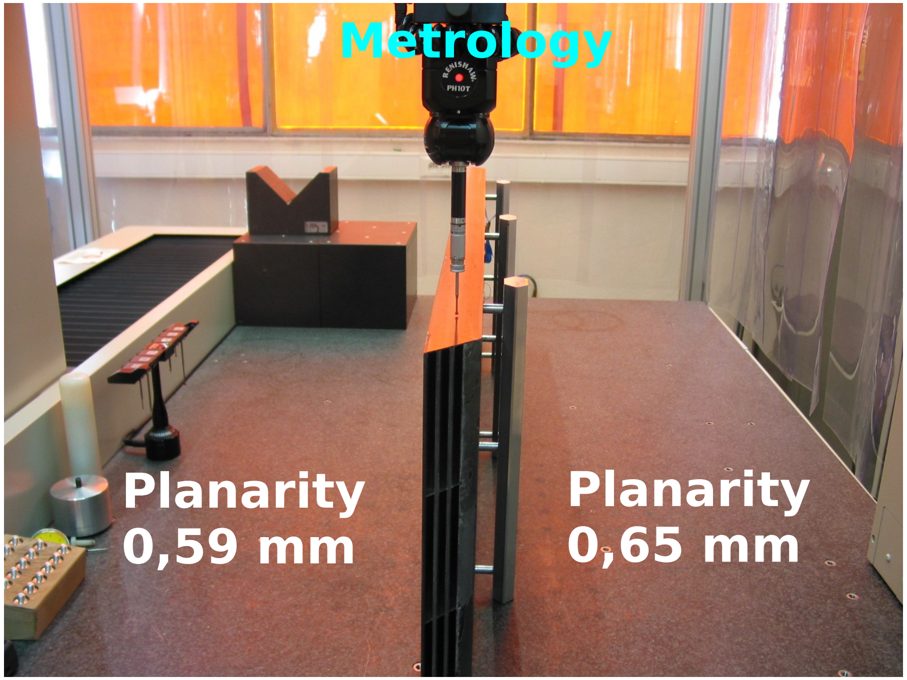


- **1 structure : ~ 23 X_0 (20×2,1mm + 9×4,2mm)**
- **sizes : 1560×545×186 mm3**
- **Thickness of slabs : 6.8 mm (W=2,1mm)**
- **VFE inside detector**
- **Number of channels : 45360 (5×5 mm^2)**
- **Weight : ~ 700 Kg**

First step: Demonstrator



Rails for mechanical integration with Hcal

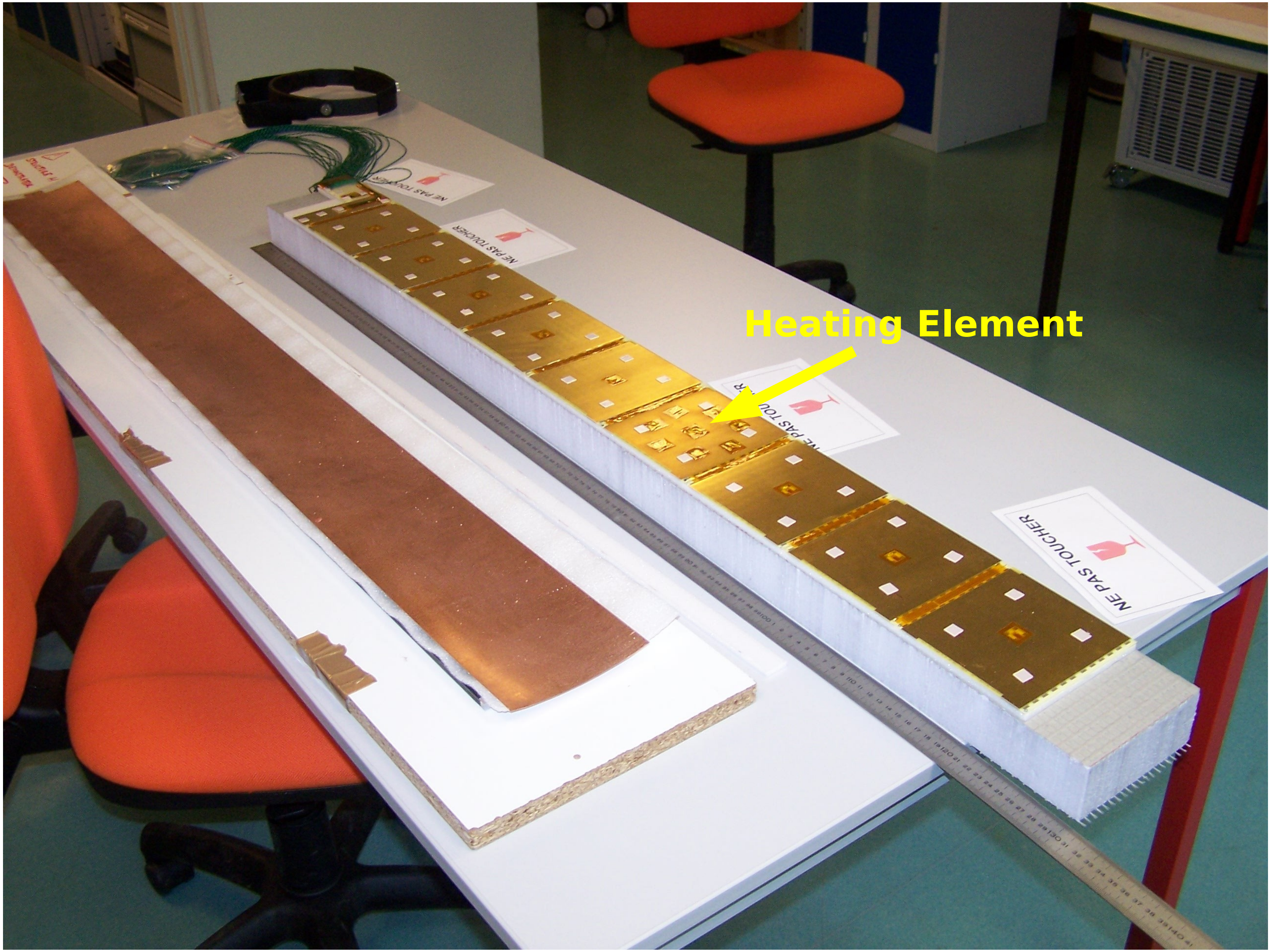


Metrology

Planarity 0,59 mm

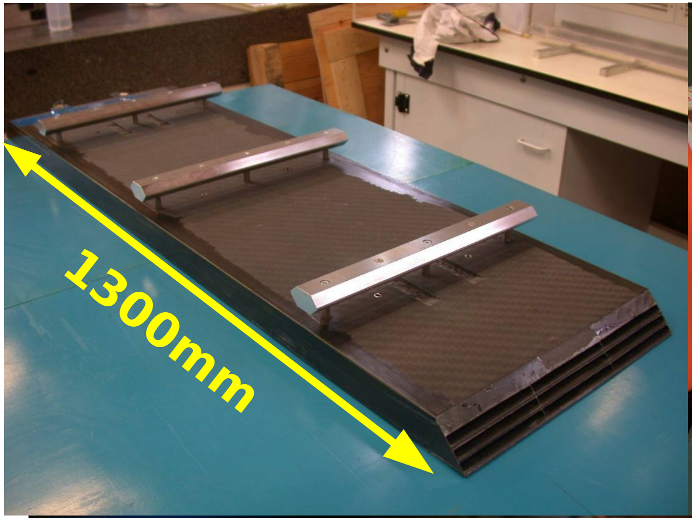
Planarity 0,65 mm

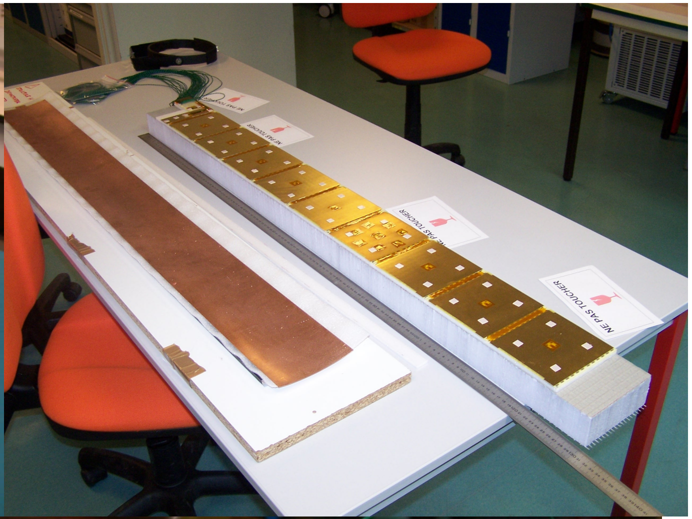
Developping the Techniques for Layer Construction – Thermal Layer

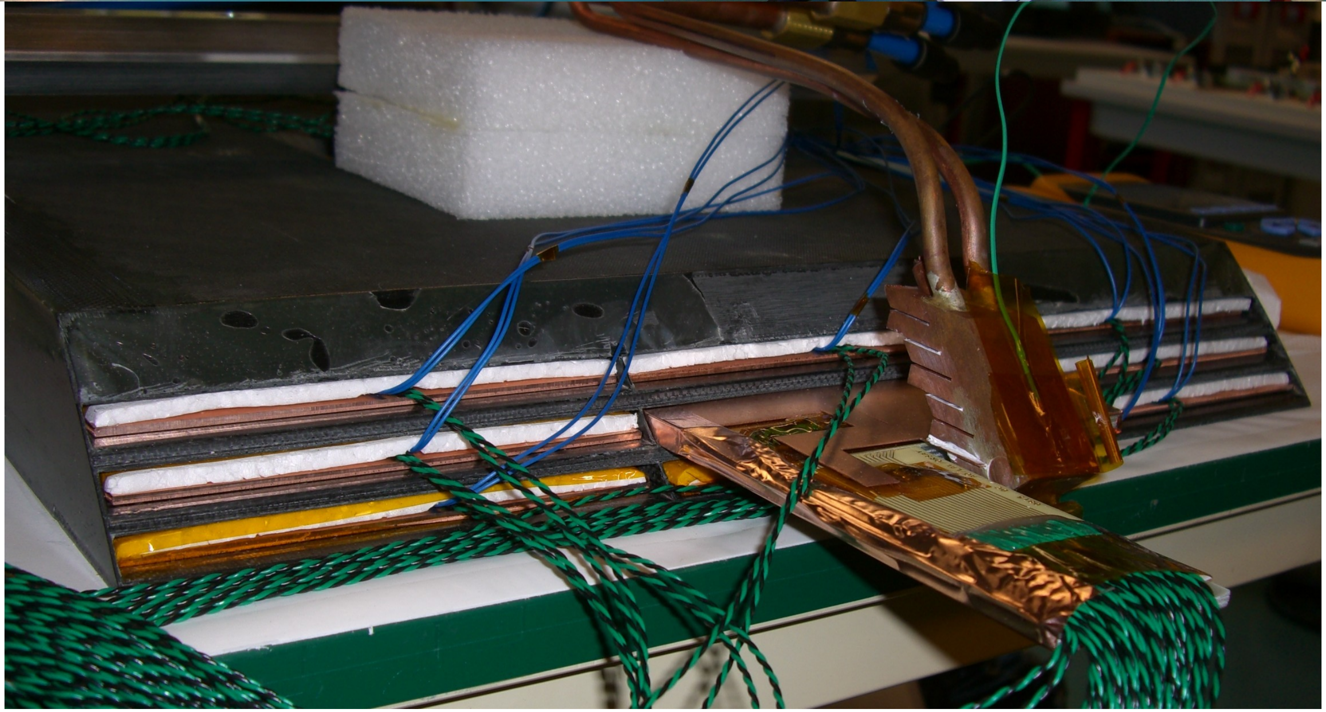


Proof-of-principle to build long layers

First step: Demonstrator



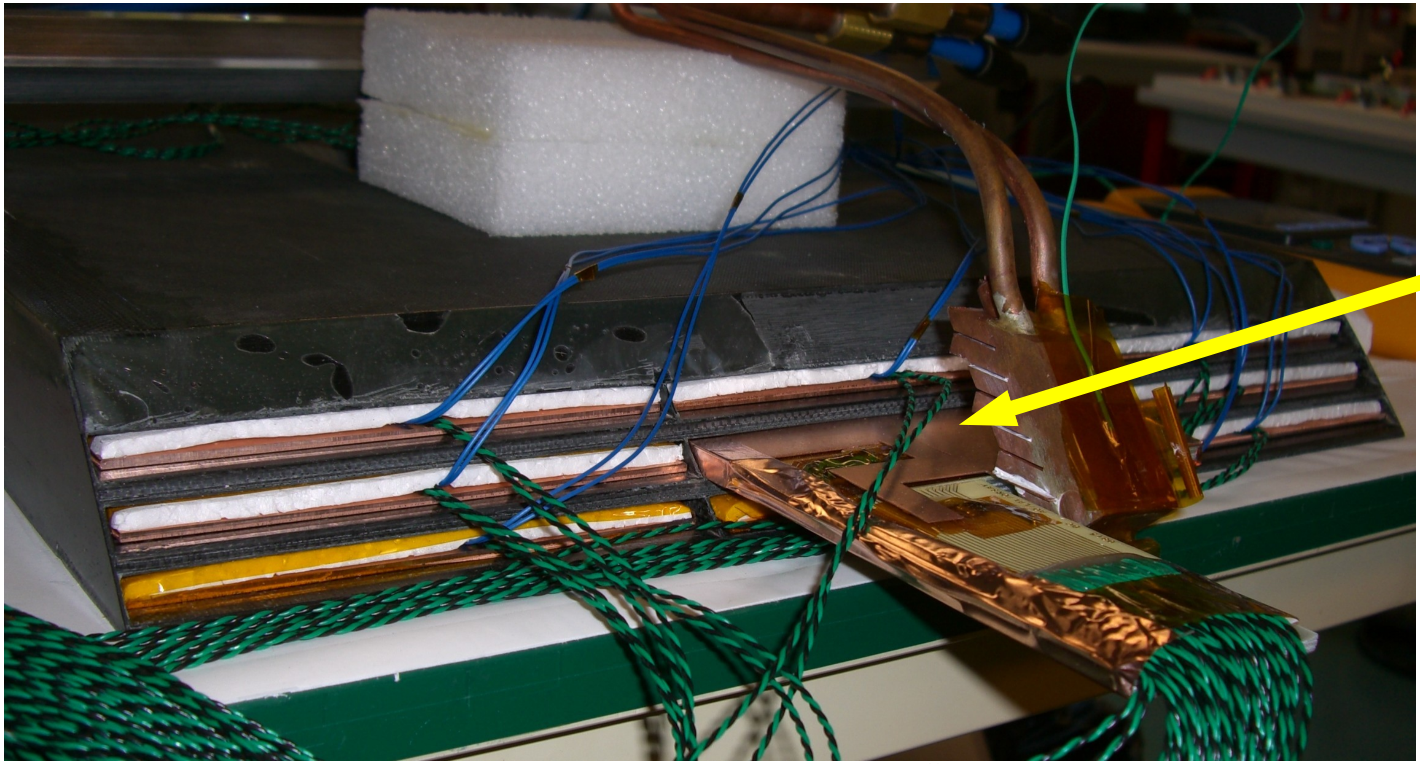




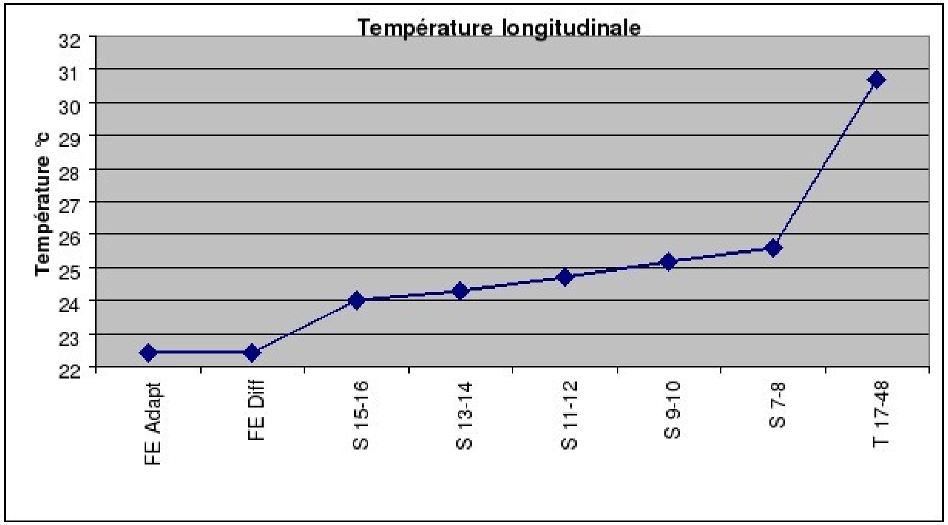
- Detector module realised (from mechanical point of view)
- Demonstrator subject to a thermal test

Thermal Test

To study thermal behaviour of detector module



Inserted Thermal Layer



Ambient Temperature	22		
Alveolar Slot	Left	Middle	Right
External		23.5	
Upper	24.8	24.8	24.6
Lower	25	30.7	25.2
Bottom	25.1	25.2	25.1

- Detector Module realised from mechanical point of view
- Thermal test important for DBD

Parties Involved

6 Laboratories are sharing out tasks in according to preferences and localization:

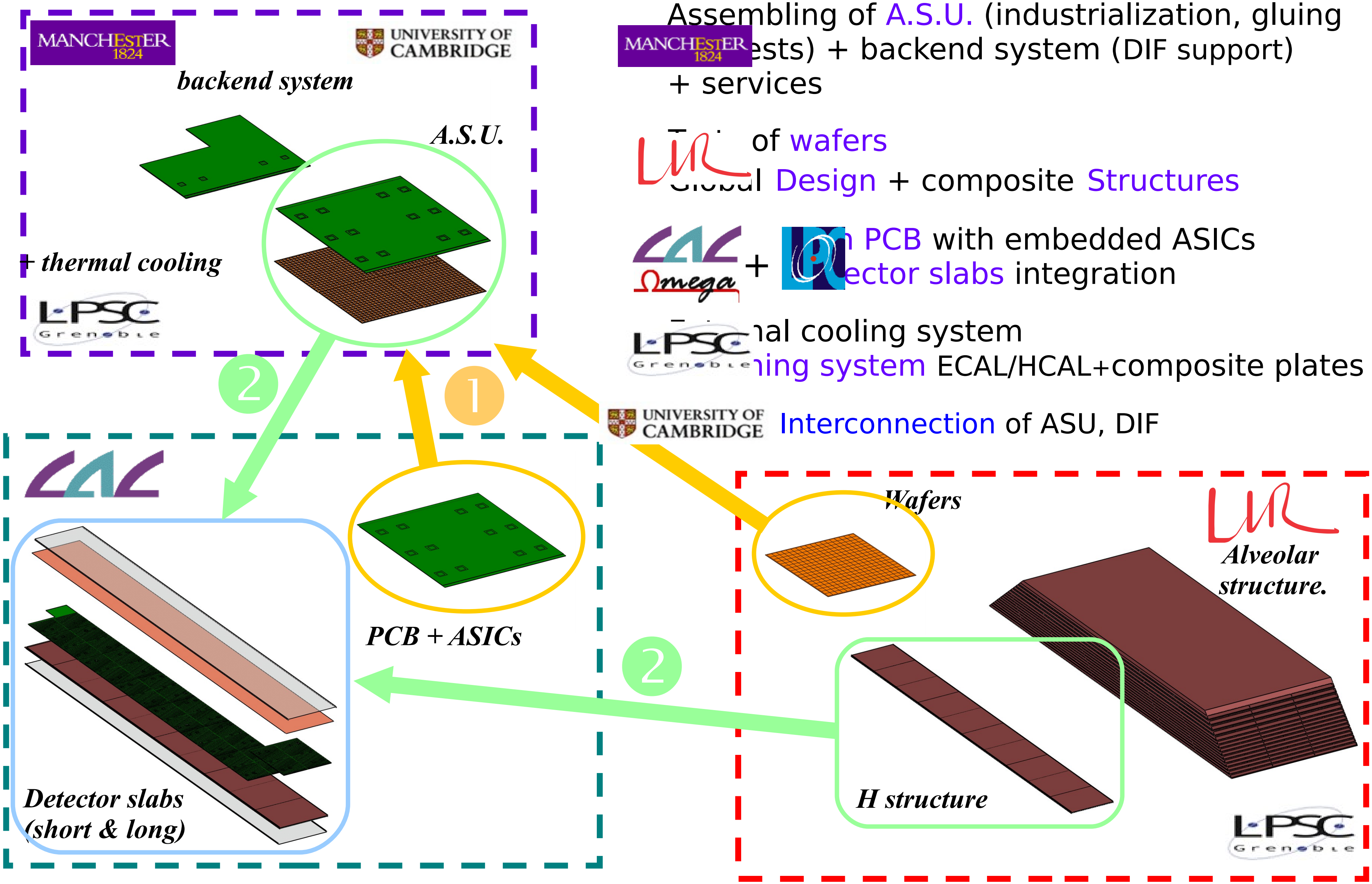
Assembling of A.S.U. (industrialization, gluing
ests) + backend system (DIF support)
+ services

of wafers
Global Design + composite Structures

n PCB with embedded ASICs
ector slabs integration

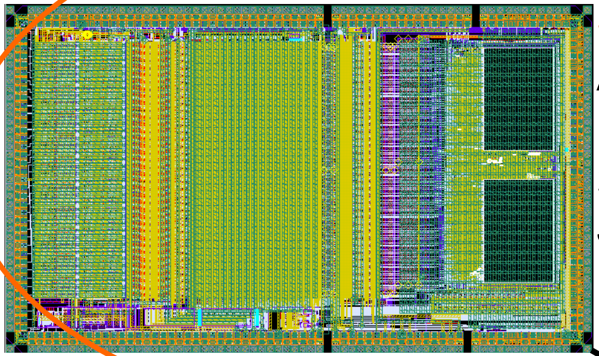
nal cooling system
ning system ECAL/HCAL+composite plates

Interconnection of ASU, DIF

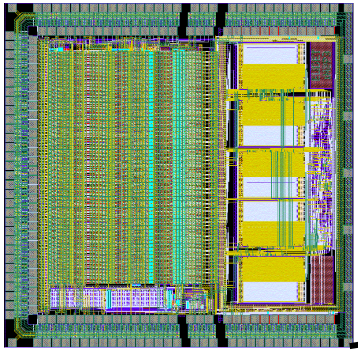


ASICs Frontales: Les Chips ROC

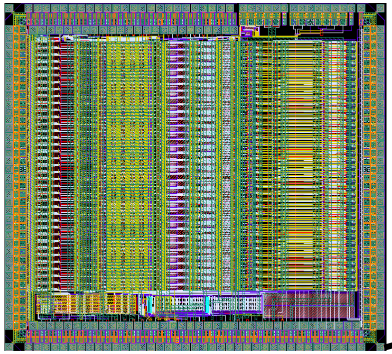
- Prototypes EUDET: modules à grande echelle (~2m)
- Financement partiel par EU (06-09)
- ECAL, AHCAL, DHCAL



SPIROC
Analog HCAL
(SiPM)
36 ch. 32mm²
June 07



HARDROC
Digital HCAL
(RPC, µmegas or GEMs)
64 ch. 16mm²
Sept 06



SKIROC
ECAL
(Si PIN diode)
36 ch. 20mm²
Nov 06