R&D for a SiW electromagnetic calorimeter for a future linear collider

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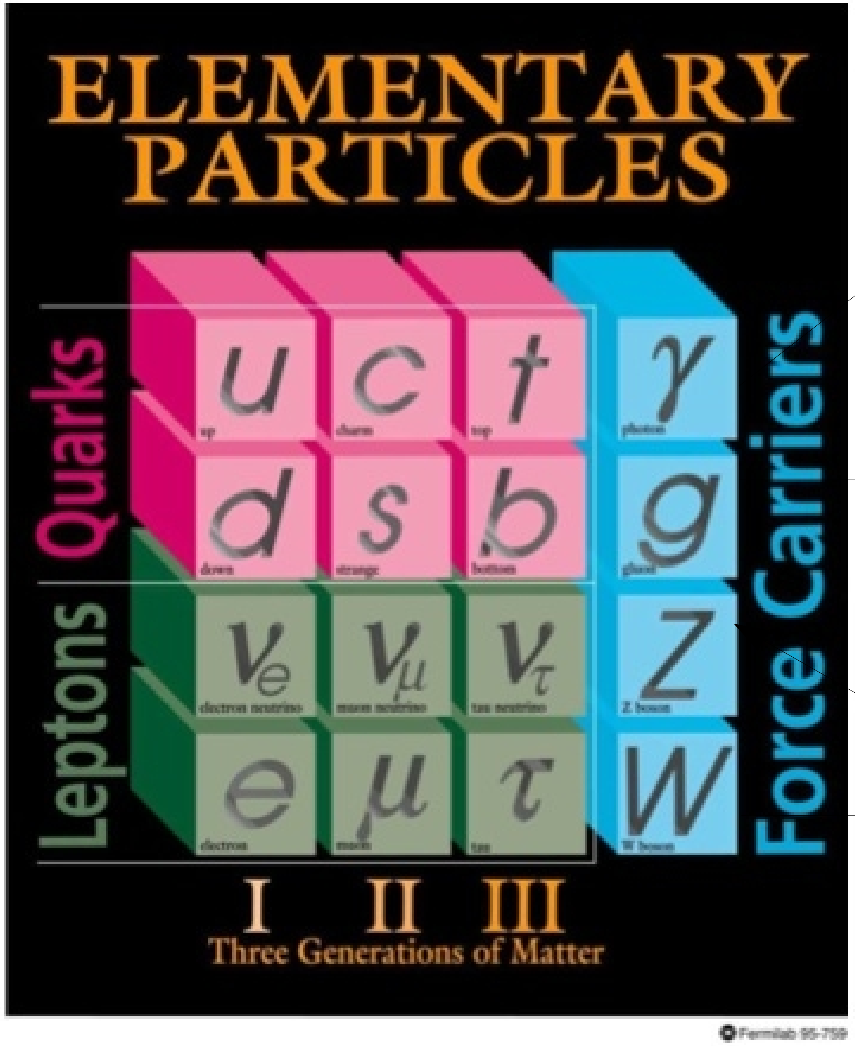
Seminar 3/3/2011 at LPNHE Paris

Scientific activities



Standard Model of particle physics

Electromagnetism (2003-2006)

Polarised positrons at E166

Instrumentation: Realisation of Compton polarimeter
s/w and Analysis: Data reconstruction
Magnetisation of analysers

Quantum chromodynamics at HERA (1994-2003, PhD 2000)

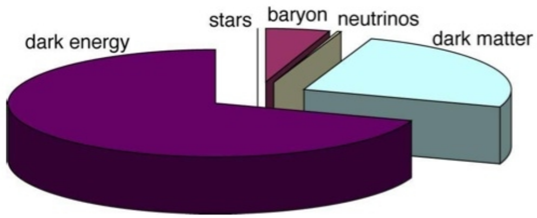
Analysis: Parton dynamics through di-jet rates
Instrumentation: Trigger level 2
Software: Reconstruction of backward H1 calorimeter (SpaCal)

Electroweak interactions at the ILC (since 2003)

Analysis: Higgs boson production
Instrumentation: R&D program of CALICE, Beam tests
Software: Developpement of tools for data reconstruction and grid exploitation

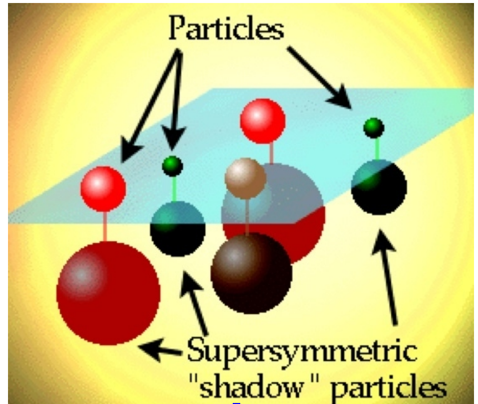
Beyond the Standard Model

Dark matter



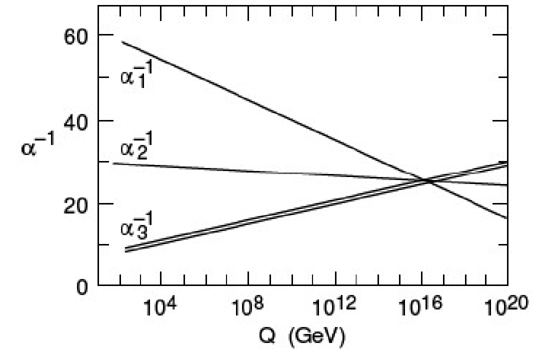
25% of the universe composed by dark matter

Supersymmetry?



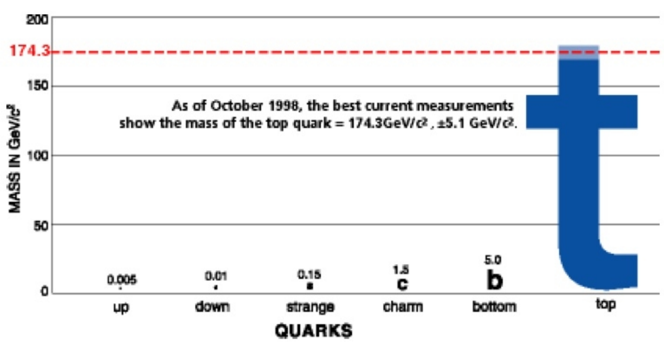
Higgs Boson

Unification of forces



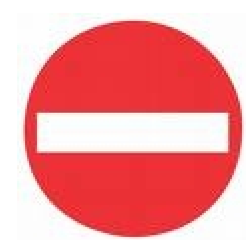
Do the forces become one?

Striking difference in fermion masses



Extra dimensions?

Higgsless models



Arguments for experiments at the TeV scale

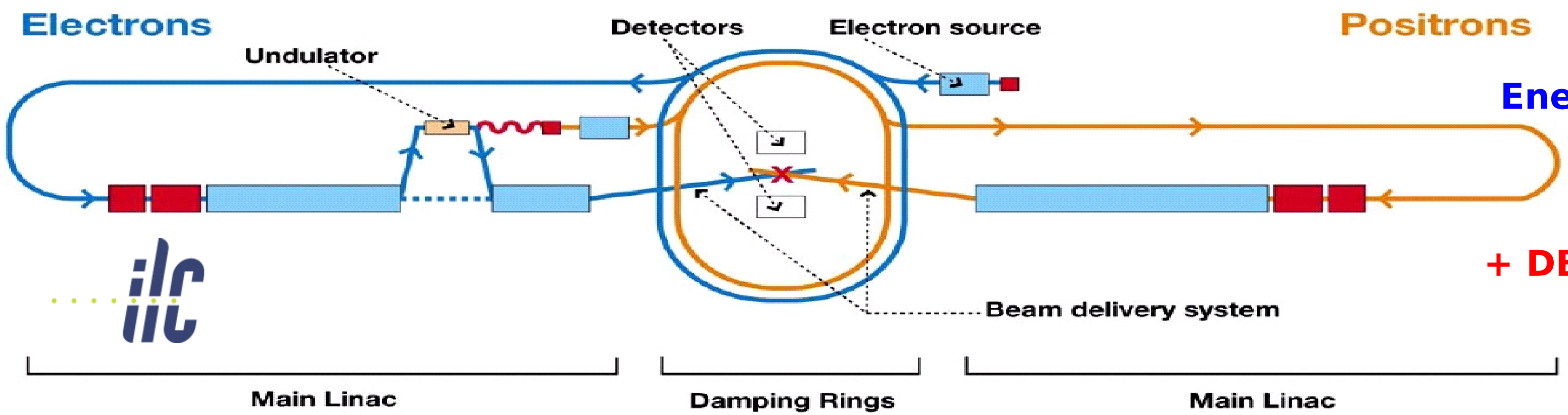
1) Compelling arguments for the existence of a light Higgs boson

$$114.4 \text{ GeV} < m_H < 1 \text{ TeV}$$

2) New physics in the domain 0.1 TeV – 1 TeV ?

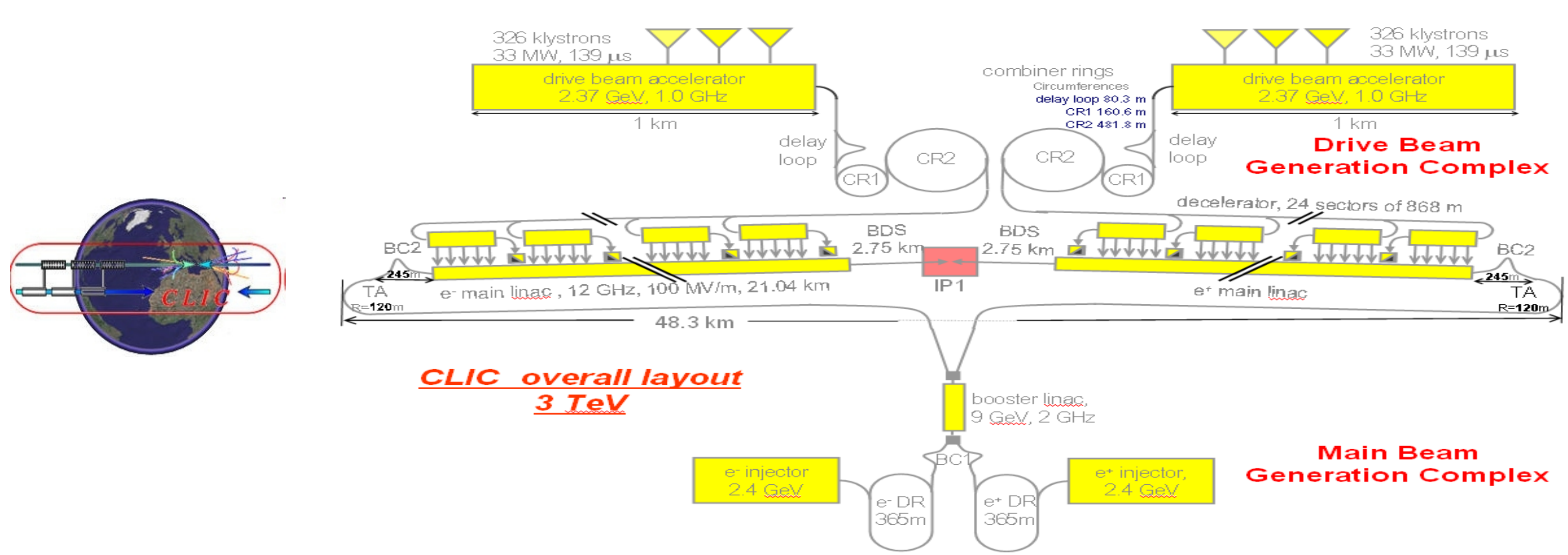
Exploration by new generation of accelerators

(Future) Linear electron-positron accelerators



Energy: 0.1 - 1 TeV

TDR in 2012
+ DBD for detectors



Energy: 0.5 - 3 TeV

CDR in 2011

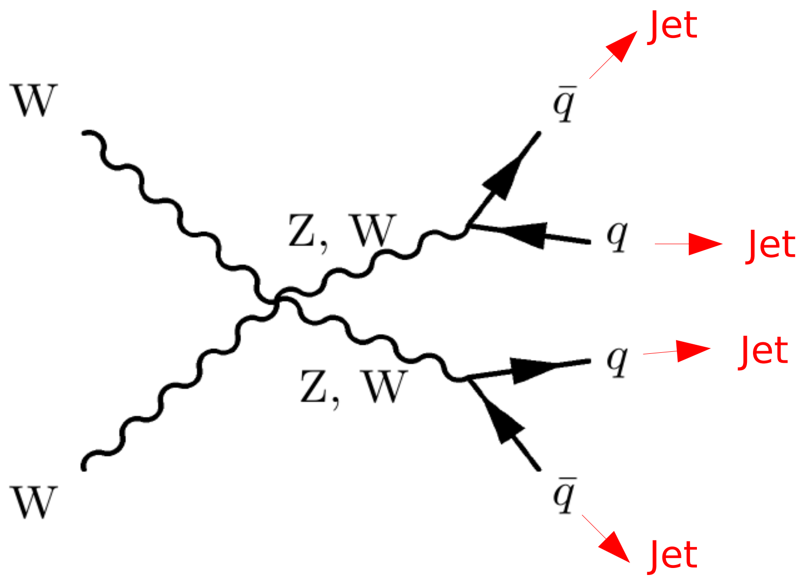
Linear collider is integral part of European Strategy beyond 2012

Hadronic decays of W and Z Bosons

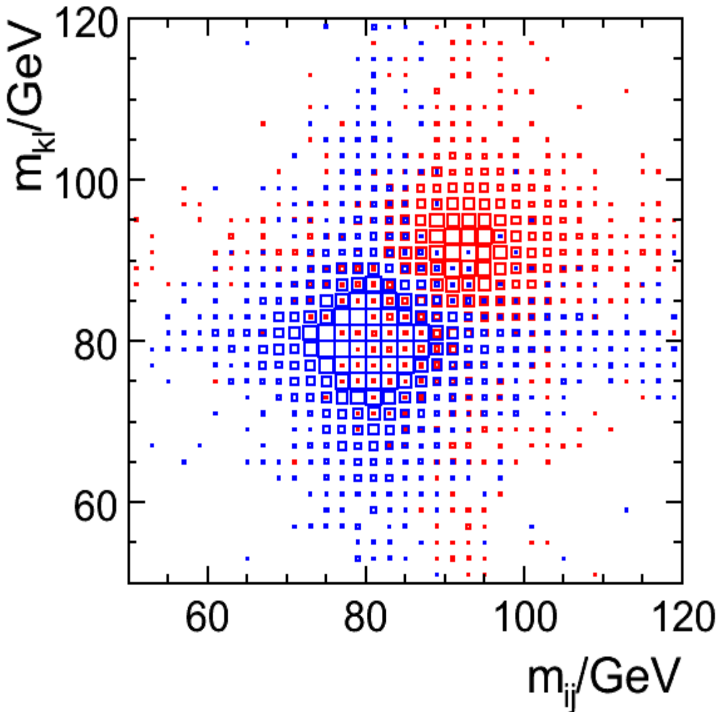
Boson Boson scattering

What if no Higgs?

Manifestation of new physics
Strong electroweak symmetry breaking



W, Z separation in the ILD concept

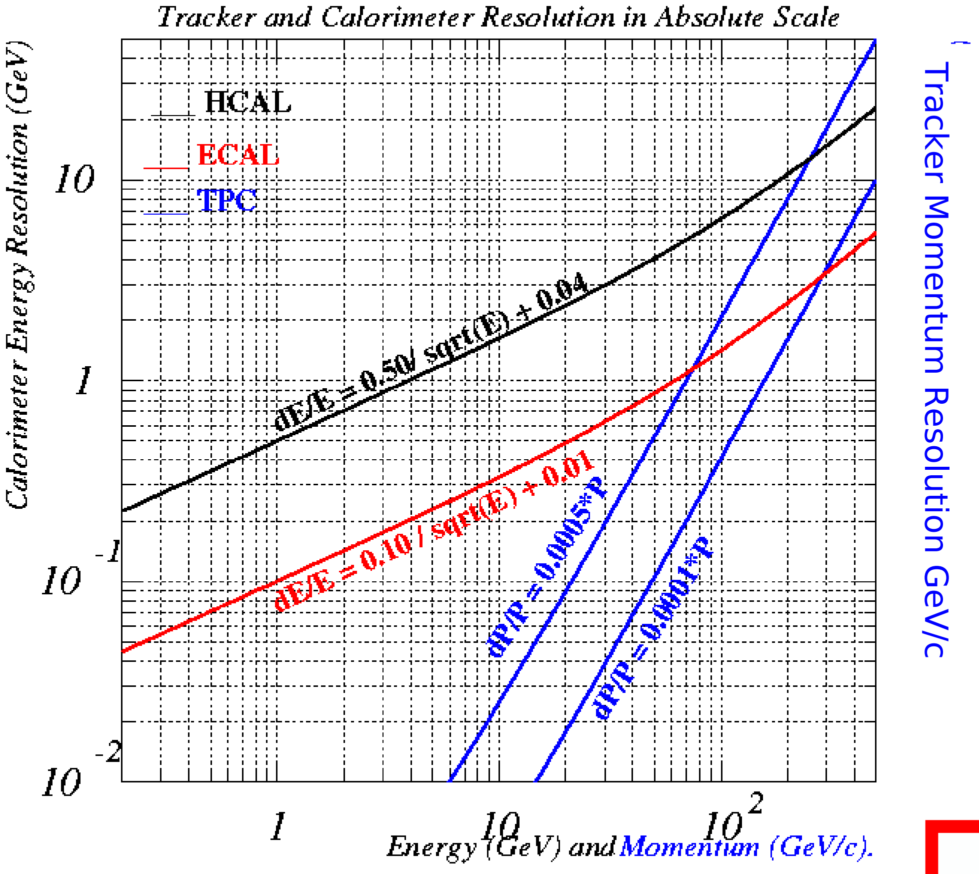


Remember: $M_Z - m_W \approx 10$ GeV

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

Jet energy resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the utmost precision !



Jet energy carried by …

- Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$)): 65%
  Most precise measurement by tracker
  Up to 100 GeV

- Photons: 25%
  Measurement by electromagnetic calorimeter (ECAL)

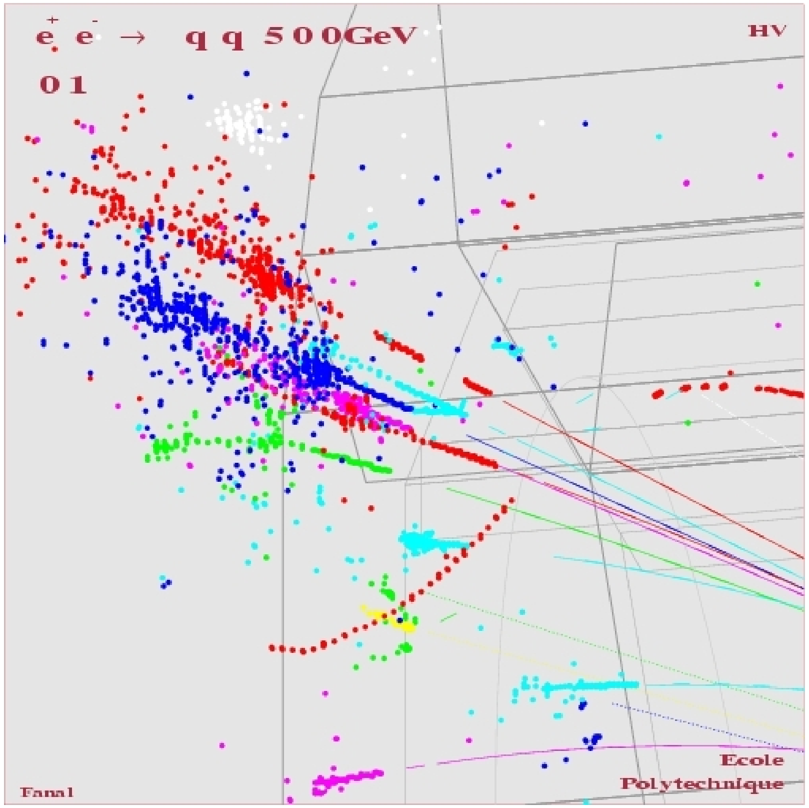
- Neutral Hadrons: 10%
  Measurement by hadronic calorimeter (HCAL) and ECAL

$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

Confusion term

- Base measurement as much as possible on measurement of charged particles in tracking devices

- Separate of signals by charged and neutral particles in calorimeter



- Complicated topology by (hadronic) showers

- Correct assignment of energy nearly impossible

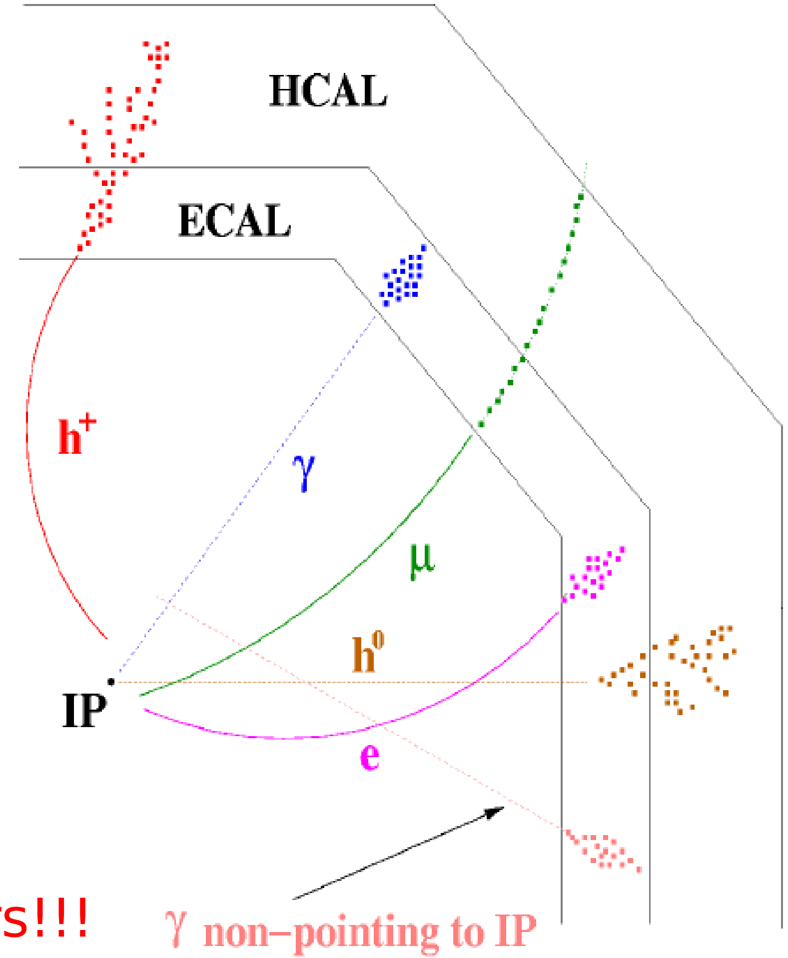
⇒ Confusion Term

Need to minimize the confusion term as much as possible !!!

Detector and calorimeter concept – Particle flow

Jet energy measurement by measurement of **individual particles**
Maximal exploitation of precise tracking measurement

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- "no" material in front of calorimeters
  - stay inside coil
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers

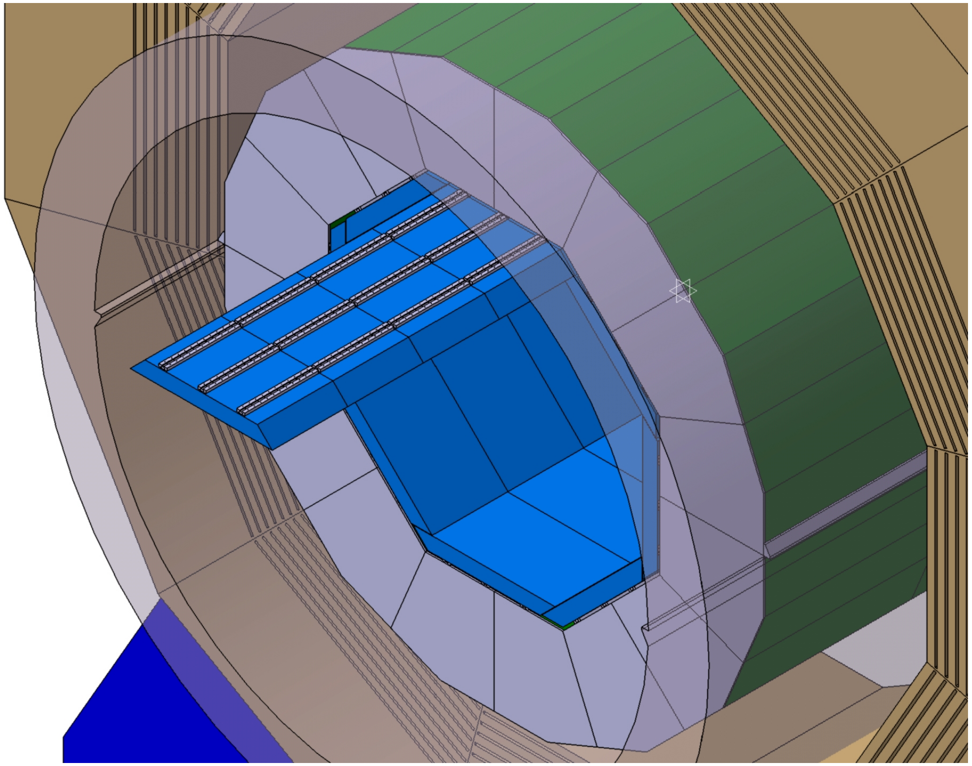


Physics goals at the ILC require the construction of highly granular calorimeters!!!

Emphasis on tracking capabilities of calorimeters

SiW Ecal - Basics

The SiW Ecal in the ILD Detector



Basic requirements

- Extreme high granularity
- Compact and hermetic

Basic choices

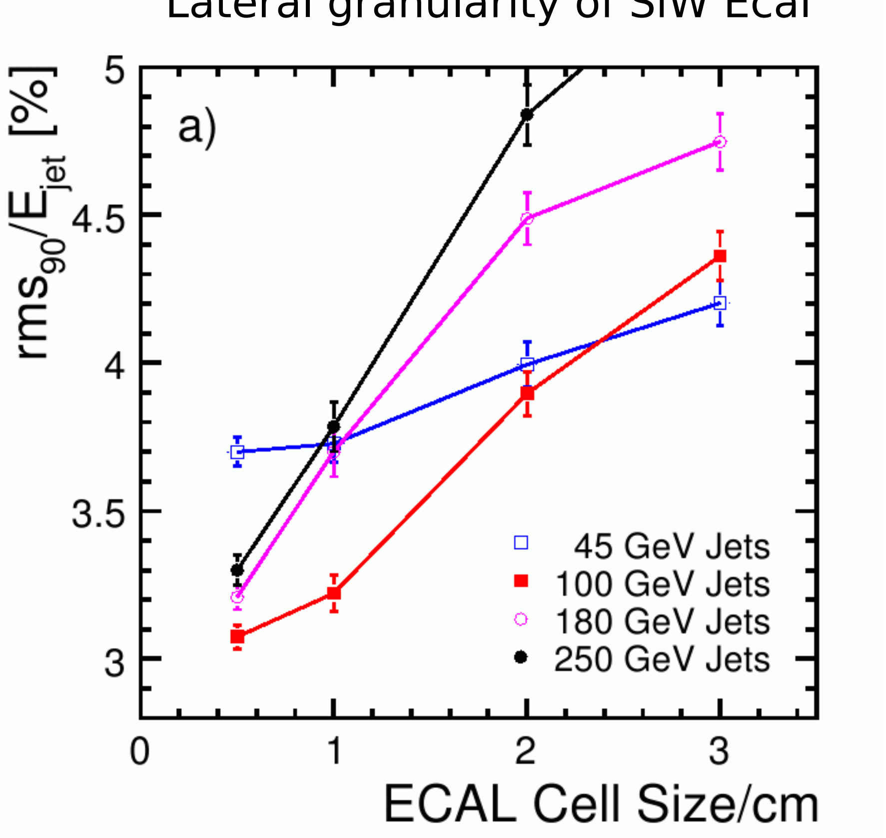
- Tungsten as absorber material
  - X_0=3.5mm, R_M=9mm, λ_I=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisation
  - Large signal/noise ratio

SiW Ecal designed as particle flow calorimeter

SiW Ecal optimisation

LOI for 2009 ILC Detectors
Optimisation using jet events and Pandora particle flow algorithm

Lateral granularity of SiW Ecal



Jet Energy resolution strongly sensitive on cell dimensions

- Better separation power
- Importance grows towards higher energies

High granularity of Ecal is crucial for precision measurements

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

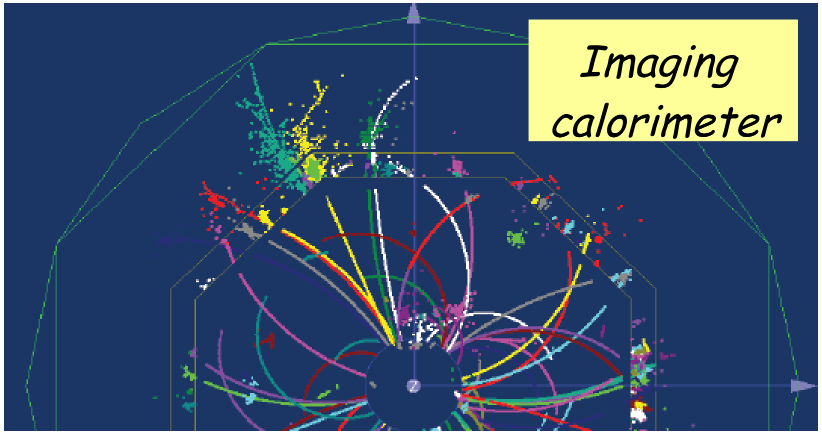
- Integrated R&D effort

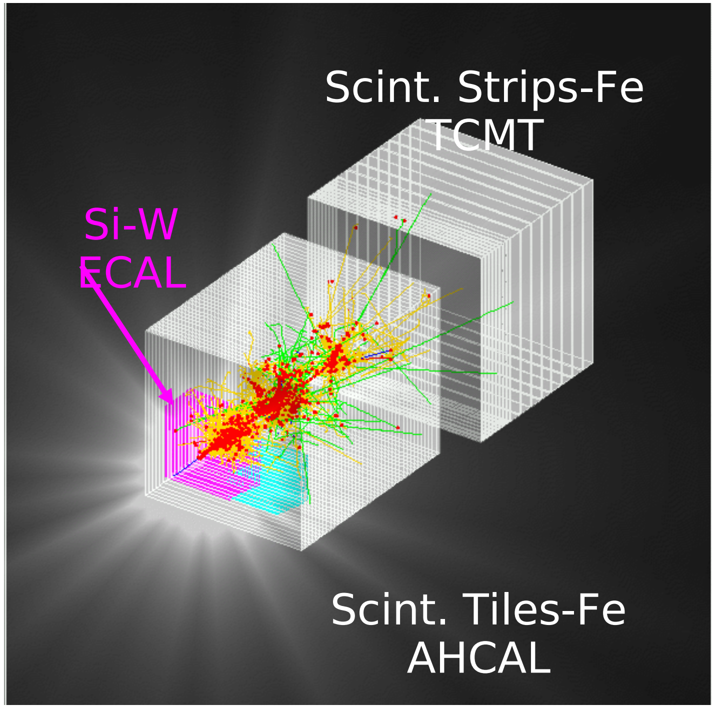
- Benefit/Accelerate detector development due to *common* approach

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

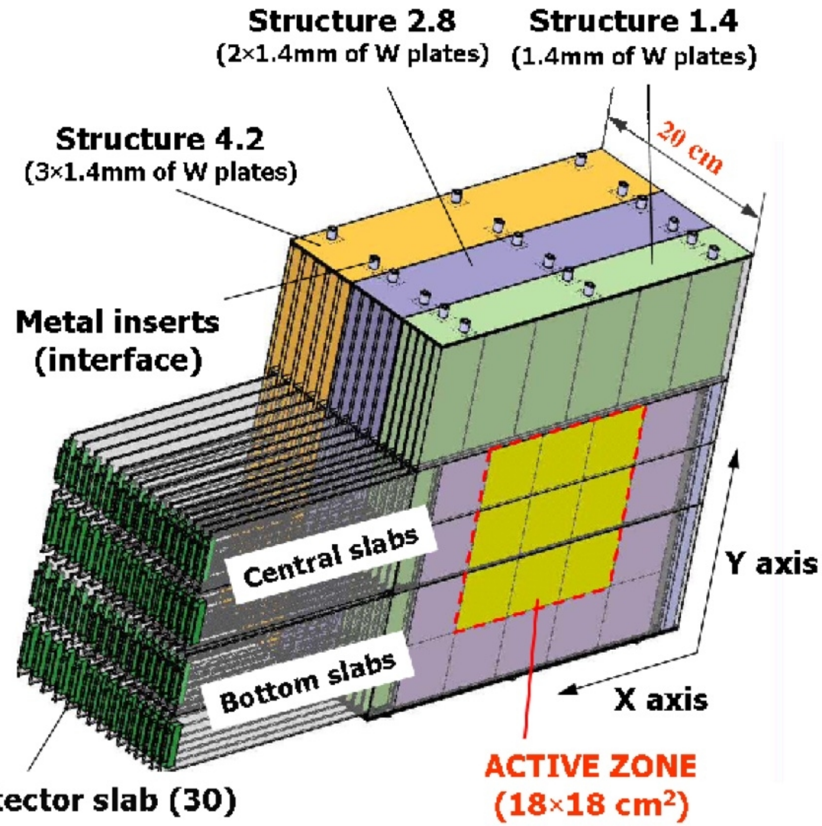




Intermediate task:

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

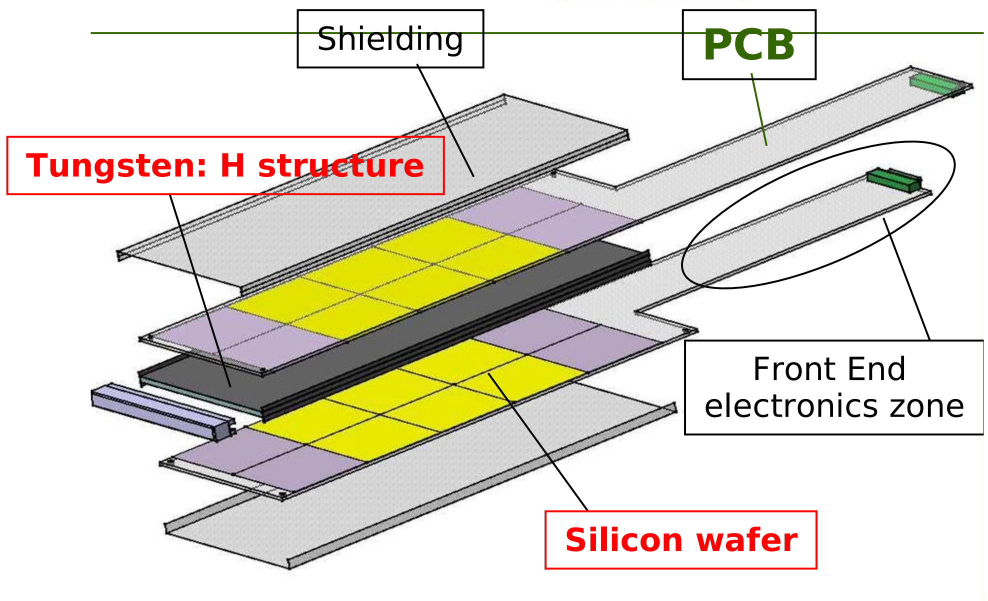
SiW Ecal Physics Prototype



30 layers of tungsten:

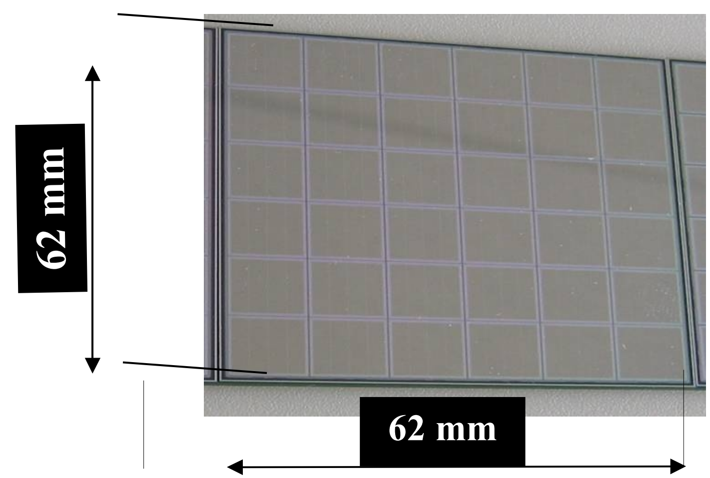
- 10 x 1.4 mm (0.4 X_0)
- 10 x 2.8 mm (0.8 X_0)
- 10 x 4.2 mm (1.2 X_0)
- 24 X_0 total, 1 λ_I

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

French groups working on SiW Ecal

Silicon sensors, DAQ, mechanics

Mechanical aspects – Cooling
Front end electronics

Silicon sensors
Front end electronics

Front end electronics,
Detector assembly and mechanics

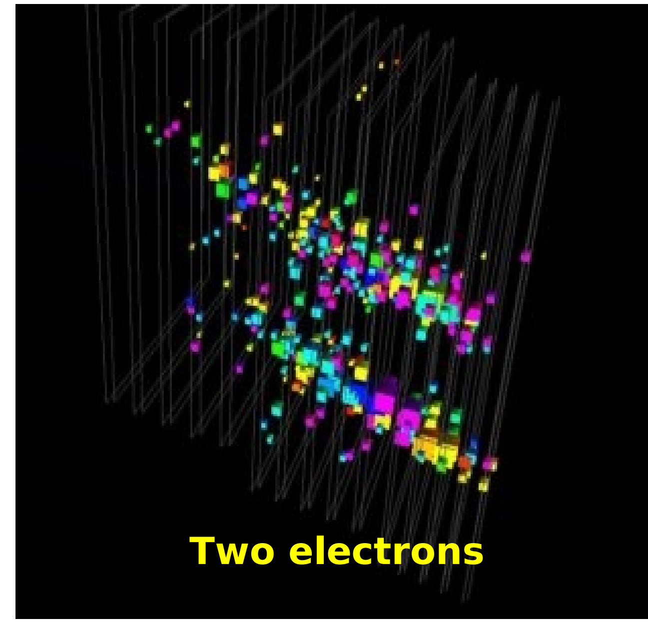
Envisaged, ongoing discussion

Large scale beam tests

Experimental setup

Zoom into Ecal

Particle distance~ 5 cm
→ No confusion !!!

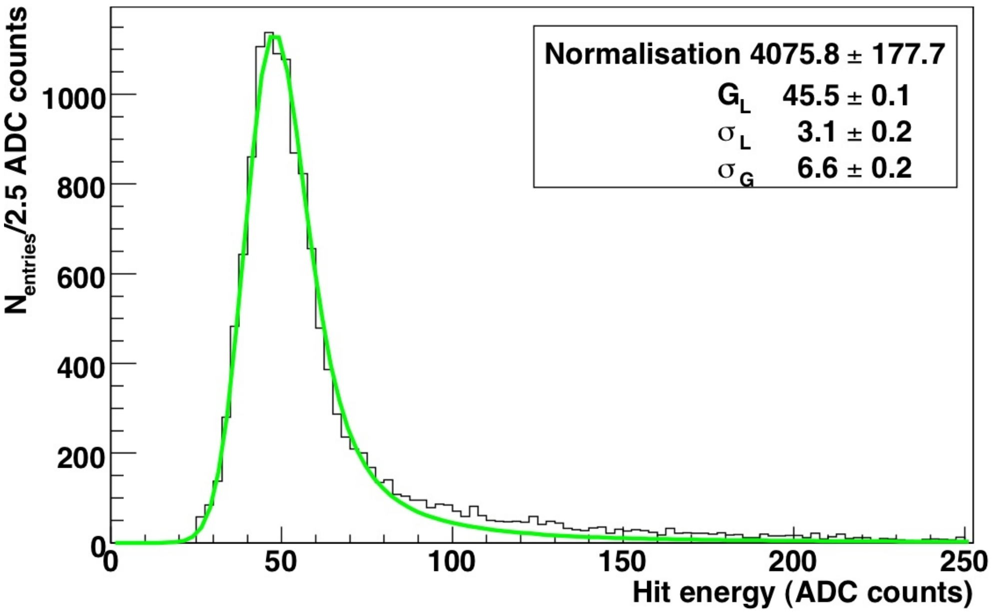


- 2006, Ecal 2 / 3 equipped
  Low energy electrons (1-6 GeV at DESY), high energy electrons (6-50 GeV at CERN)

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

- 2008 FNAL, Ecal completely equipped
  Pions at low energy,
  Data taking with Digital Hcal (>2010?)

Calibration – Uniformity of response

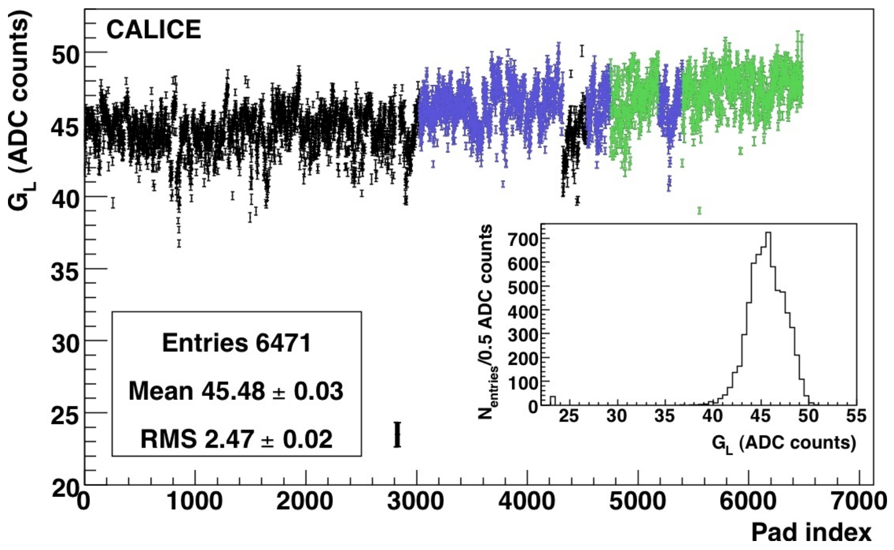


Calibration with with wide spread μ-beam

18 Mio. Events
Uniform response of all cells
only 1.4‰ dead cells

Differences in response can attributed to different

- Manufacturers
- Production series



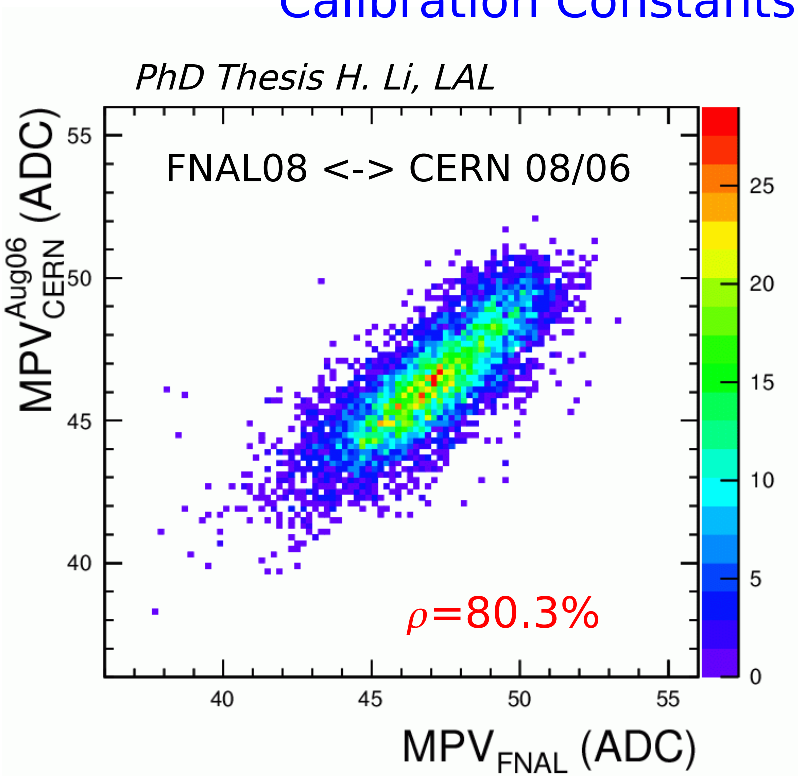
Experience to deal with different manufacturers and production series
Essential for final detector
~3000m^2 of Silicon needed

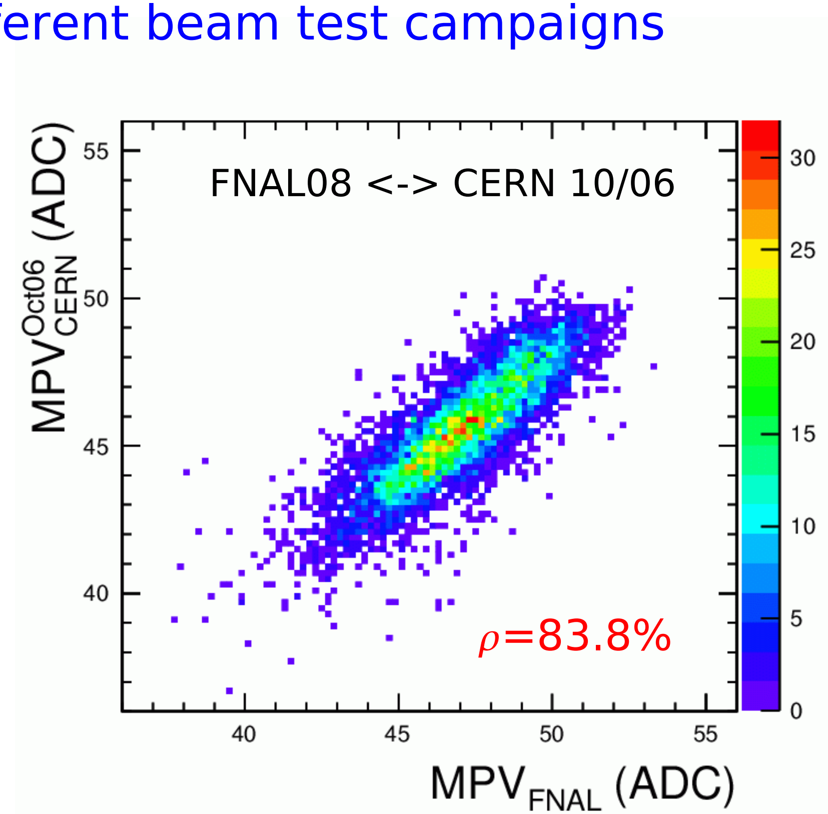
Stability of Calibration?

Important Criterium during evaluation process by IDAG

Affects both: precision and operability of detector: ~10^8 calo cells in ILC Detector

Calibration Constants in different beam test campaigns



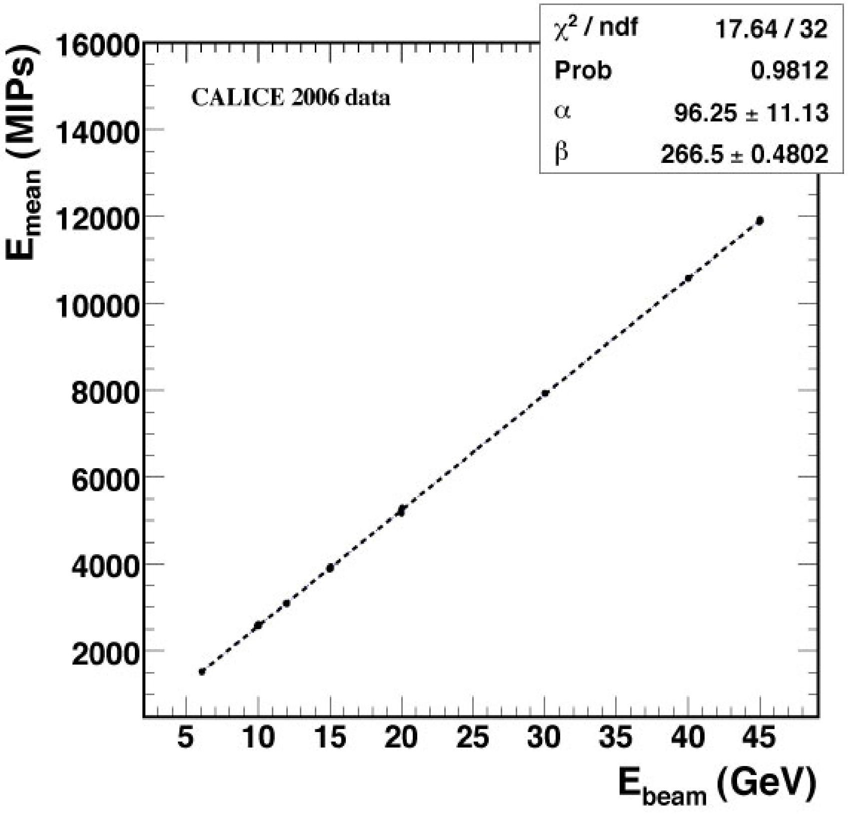


High Correlation between calibration constants

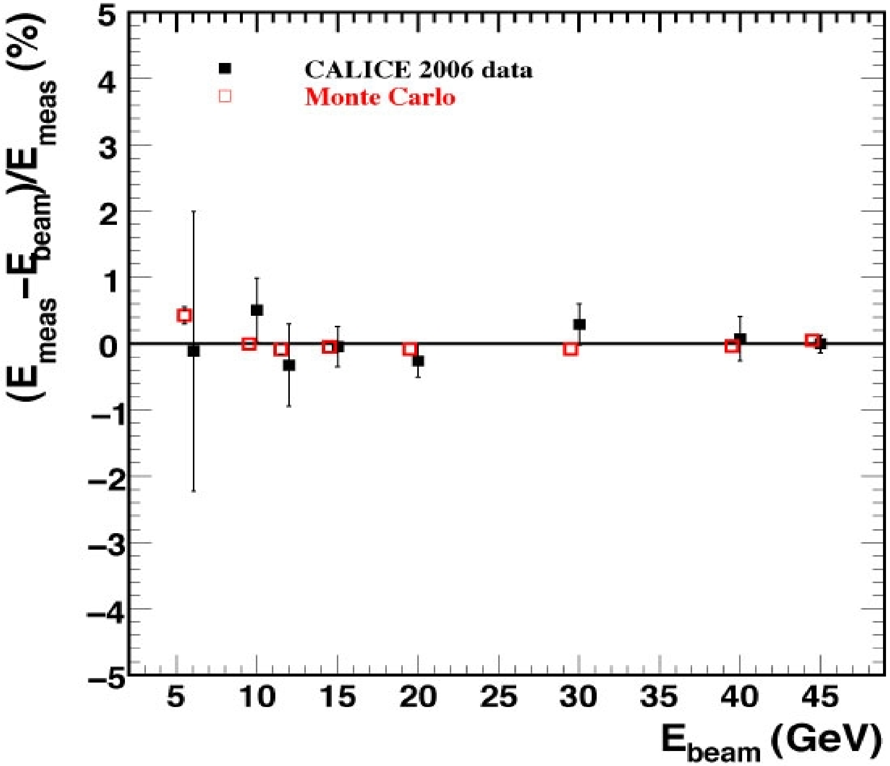
For "final" detector:
Detector modules can be calibrated in beam test prior to installation

Linearity of Response

Overview



Residuals

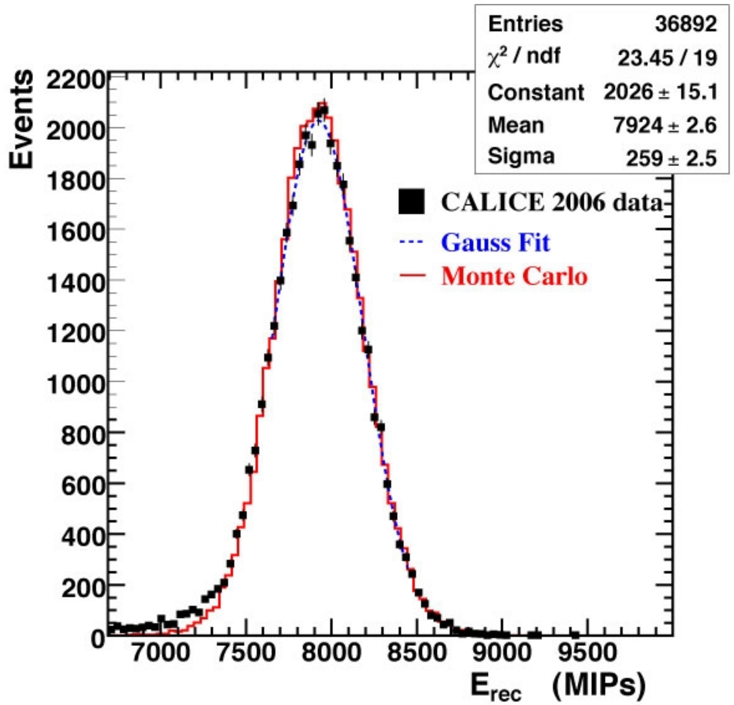


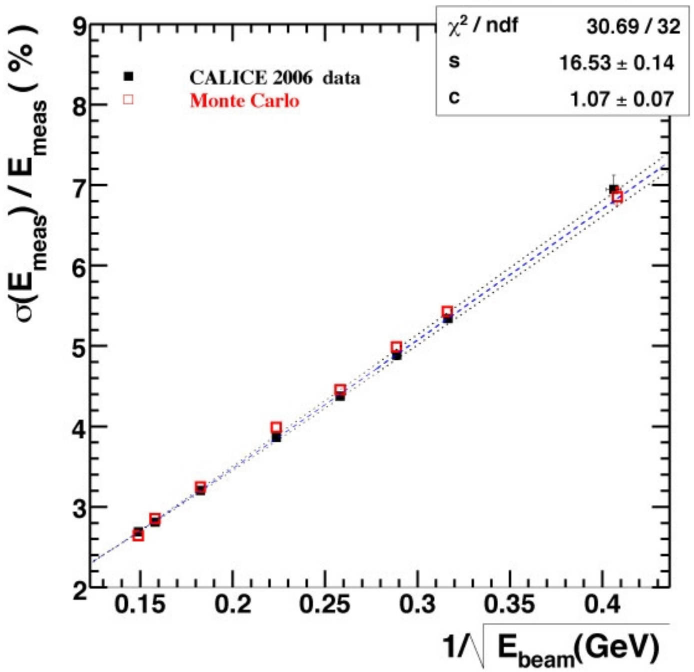
- Highly linear response over large energy range

- 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

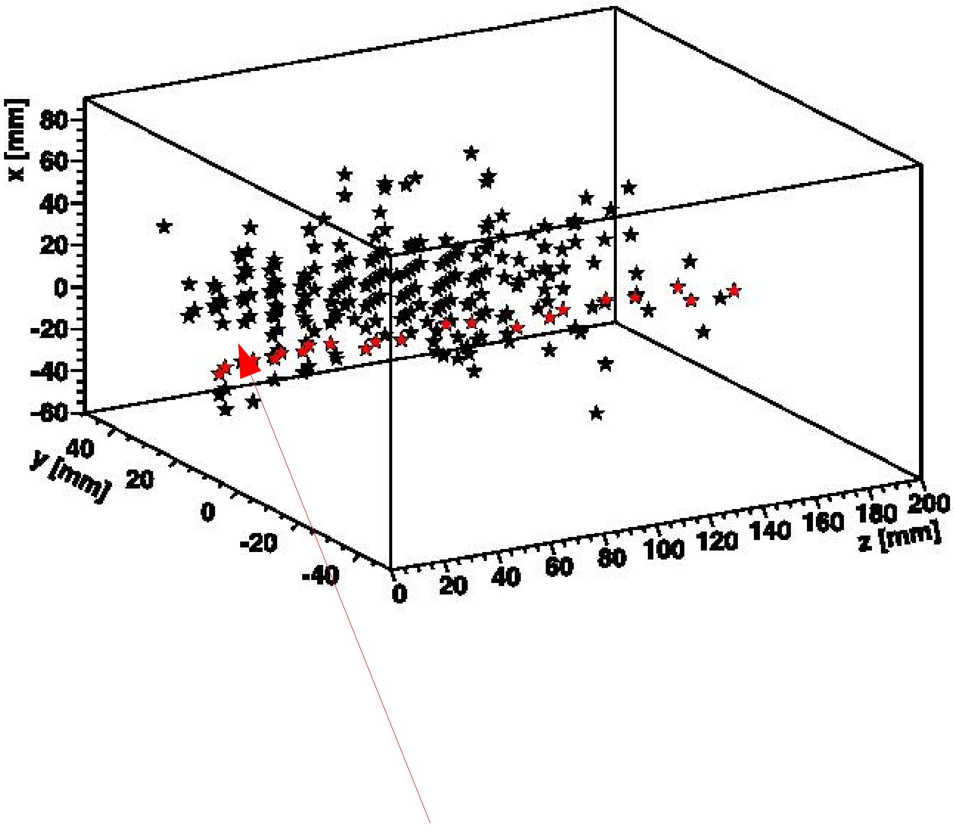
Calorimeter for Particle Flow

Exploiting the high granularity I – Particle separation

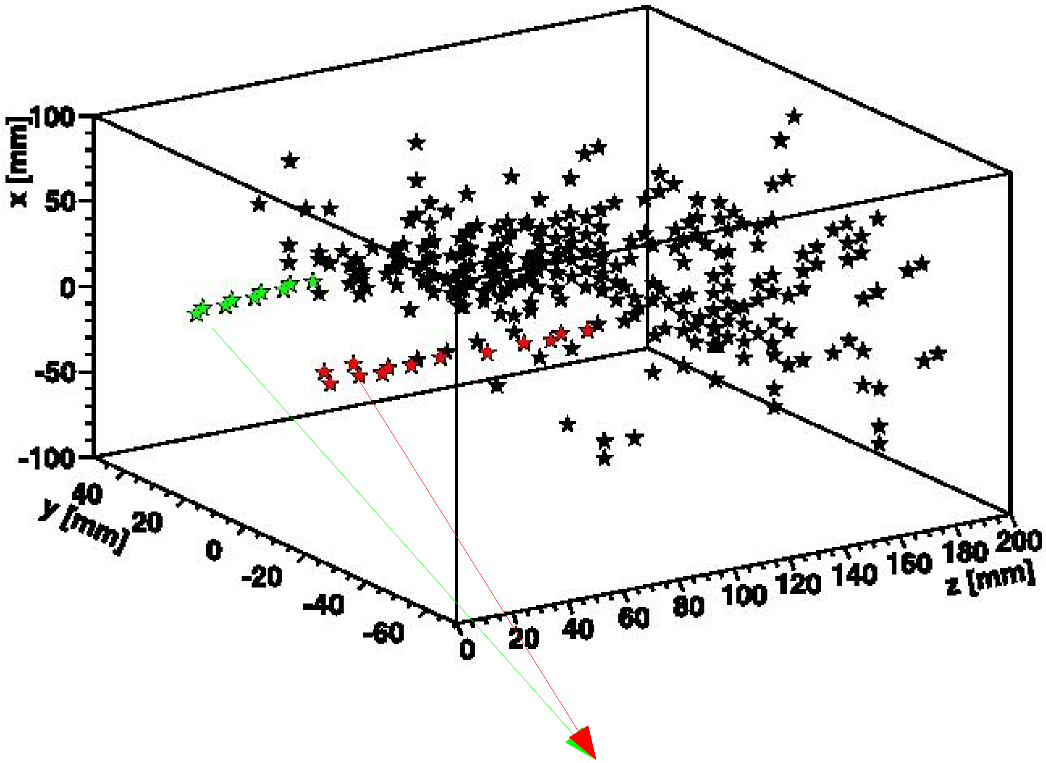
High granularity allows for application of advanced imaging processing techniques

E.g. Hough transformation

Events recorded in test beam



Secondary muon within electron shower

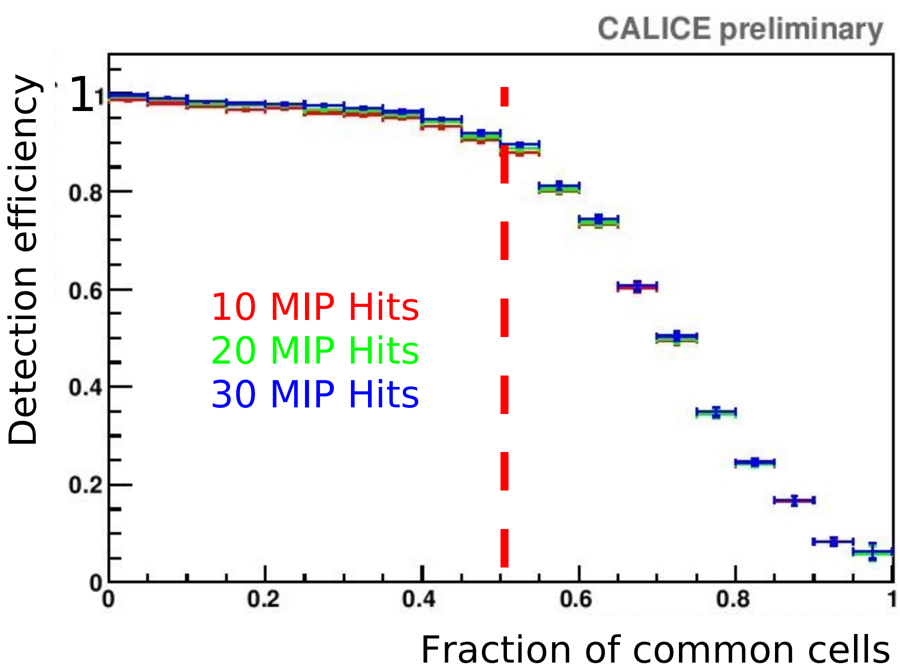


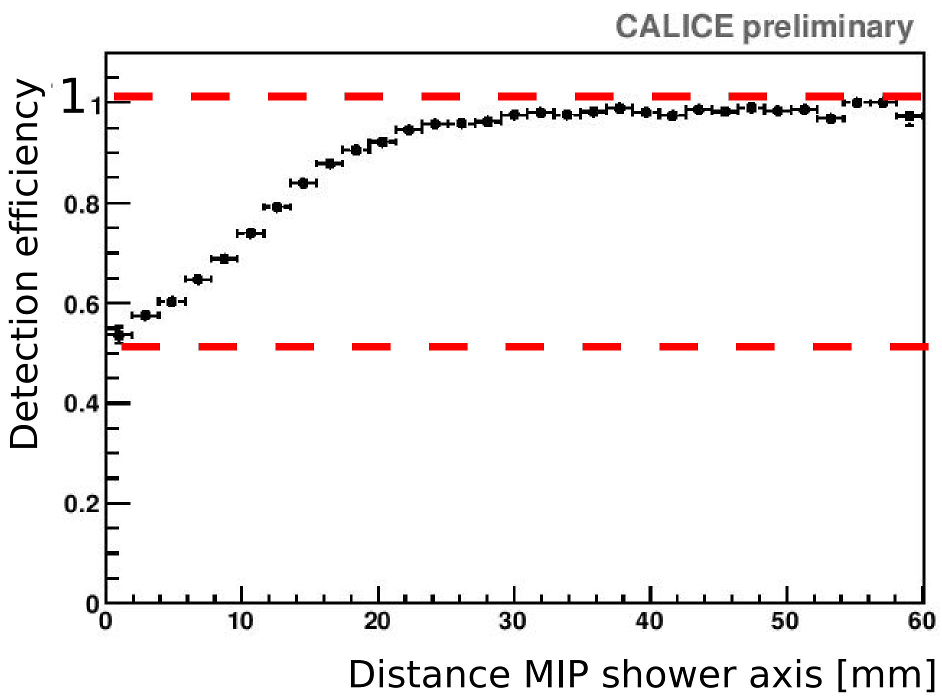
Two pions entering the SiW Ecal

Particle separation – cont'd

Efficiency of particle separation

Separation MIP <-> Electron





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

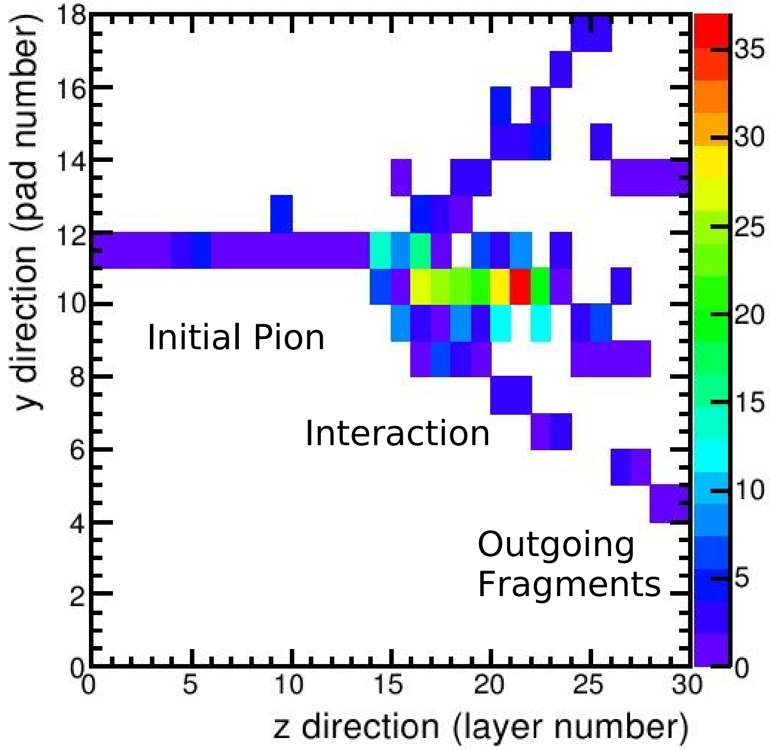
Independent of hits generated by MIP

Full separation for distances > 2.5 cm

Granularity and hadronic cascades

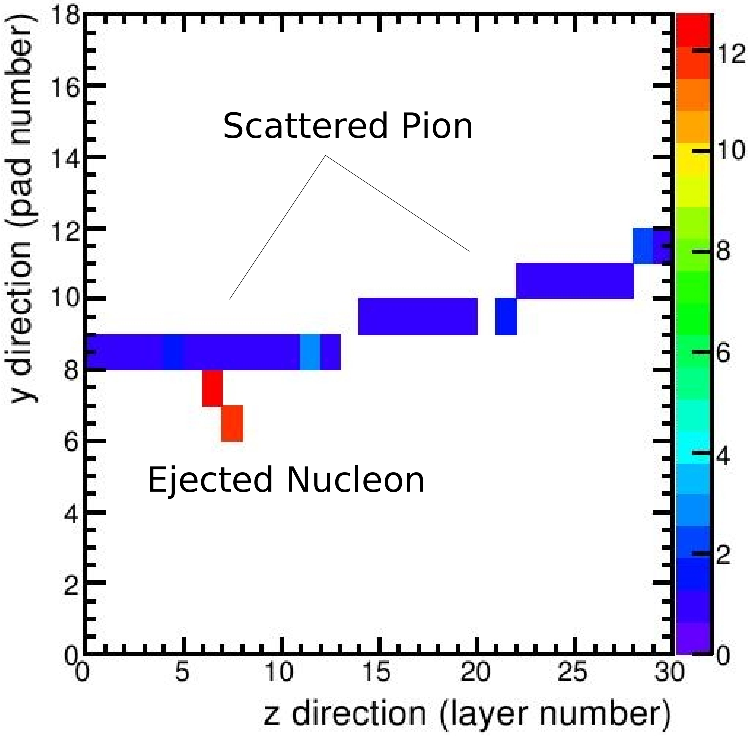
(Start of) Hadronic showers in the SiW Ecal

Complex and Impressive



Inelastic reaction in SiW Ecal

Simple but Nice

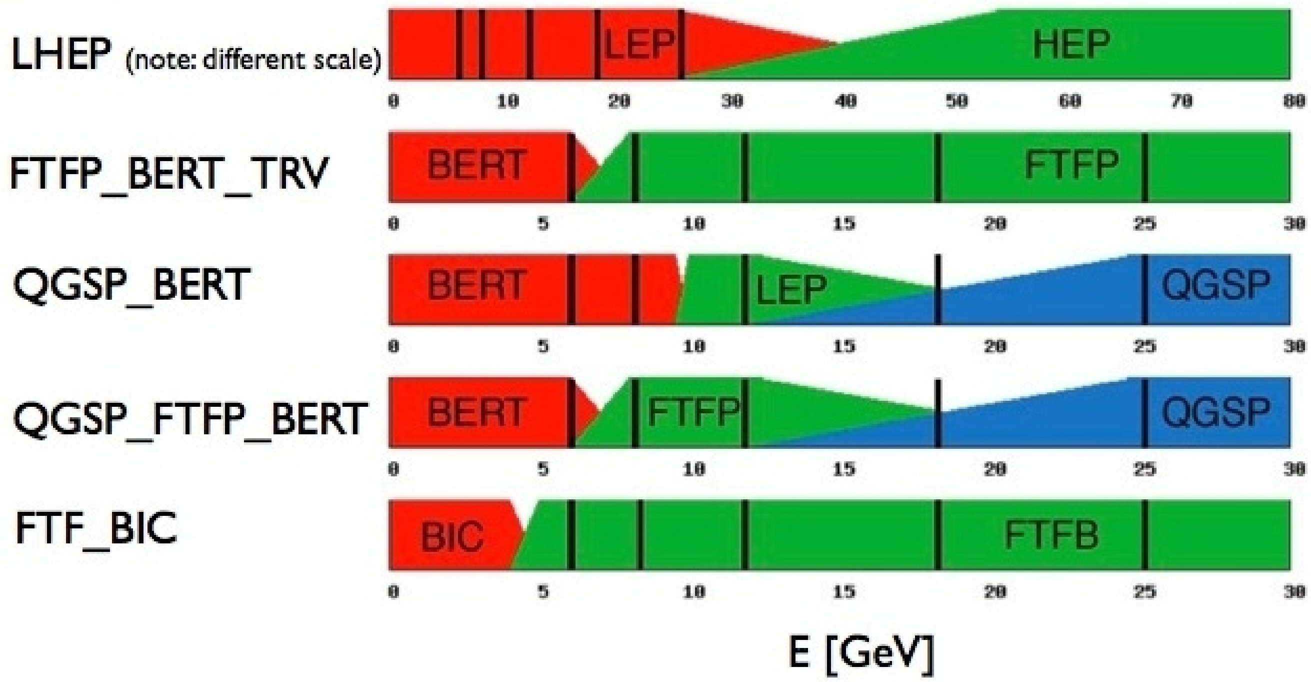


Nucleon ejection in SiW Ecal

High granularity permits detailed view into hadronic shower

Hadronic models in GEANT4

Variety of models available to describe hadronic showers

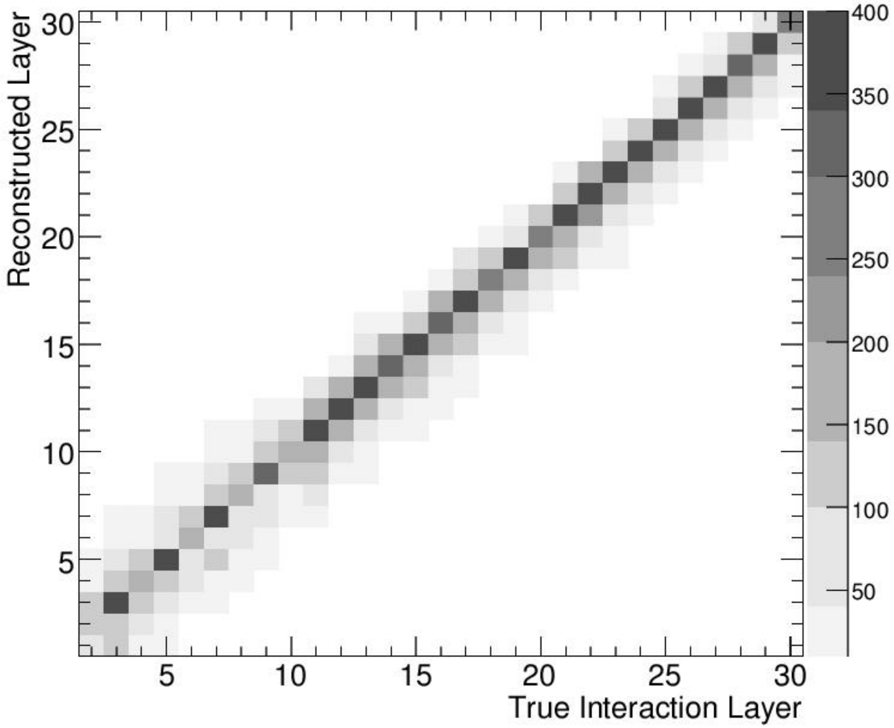


Discriminative power by high granularity !?

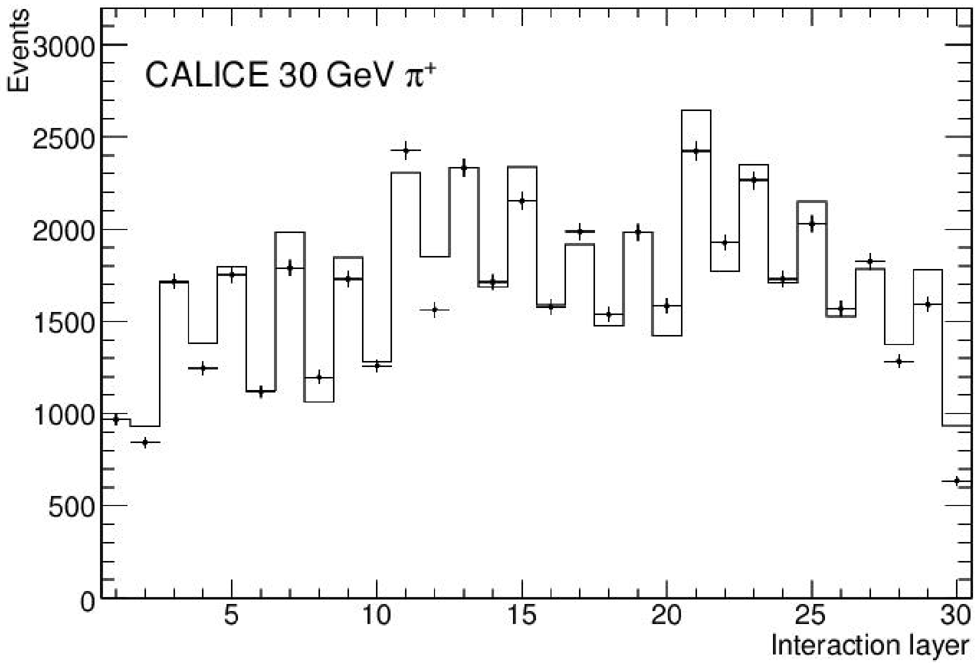
A. Dotti (G4 Collaboration): “Rough granularity of LHC calorimeters limits possibilities”
“CALICE is the perfect tool”

Finding the interaction in the SiW Ecal

Correlation:
True interaction <-> Found interaction



Distribution of found interaction layers



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

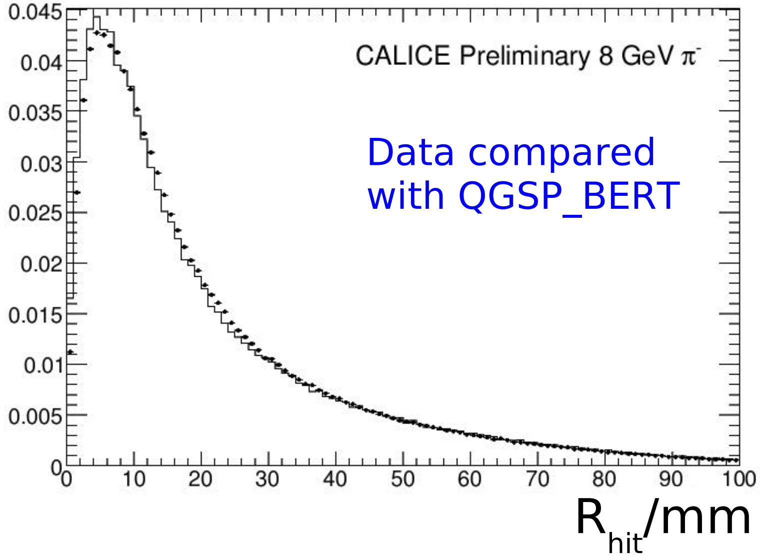
Good agreement between Data and simulation (G4, here QGSP_BERT)

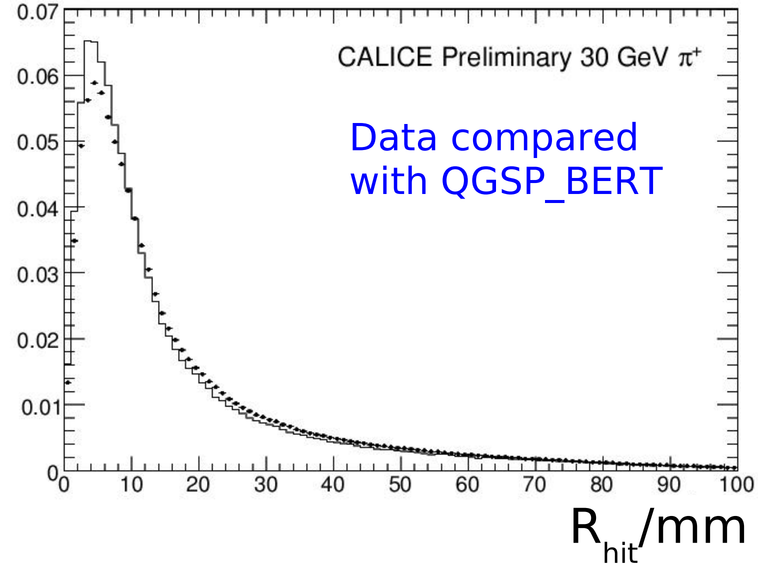
Granularity allow for resolving interaction layer with high resolution
High energy cross sections well implemented in G4 simulation

Transversal shower profiles and shower radius

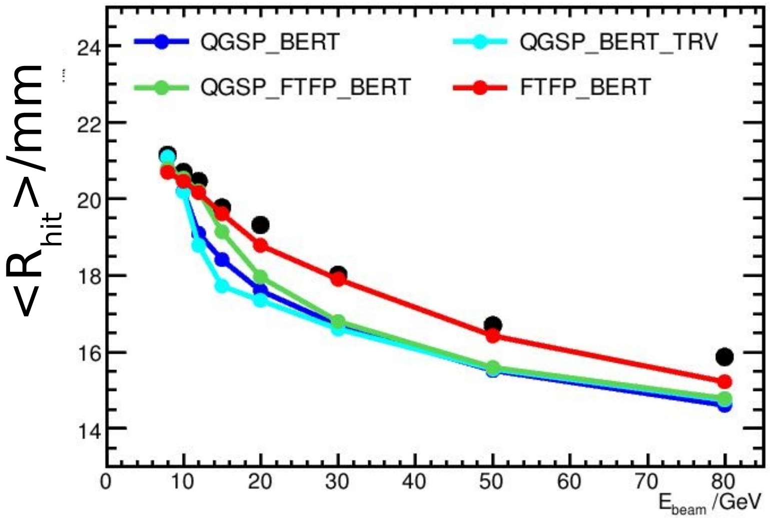
Affects overlap of showers <-> Importance for PFA

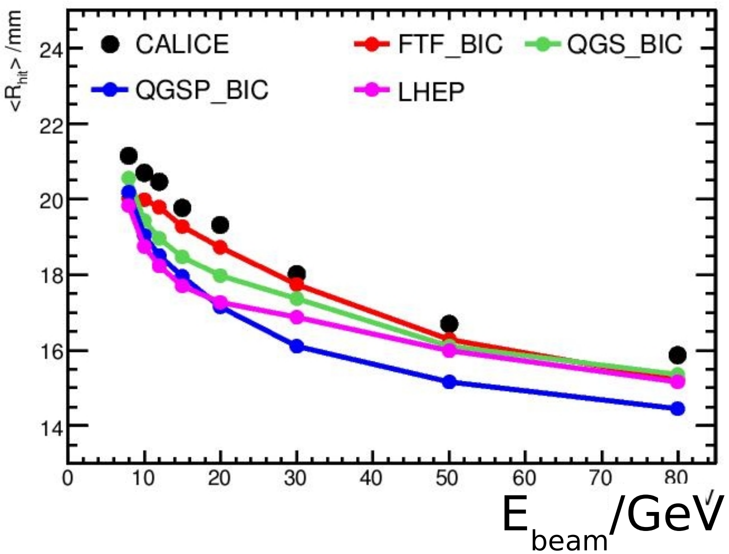
Transverse profiles





Shower radius

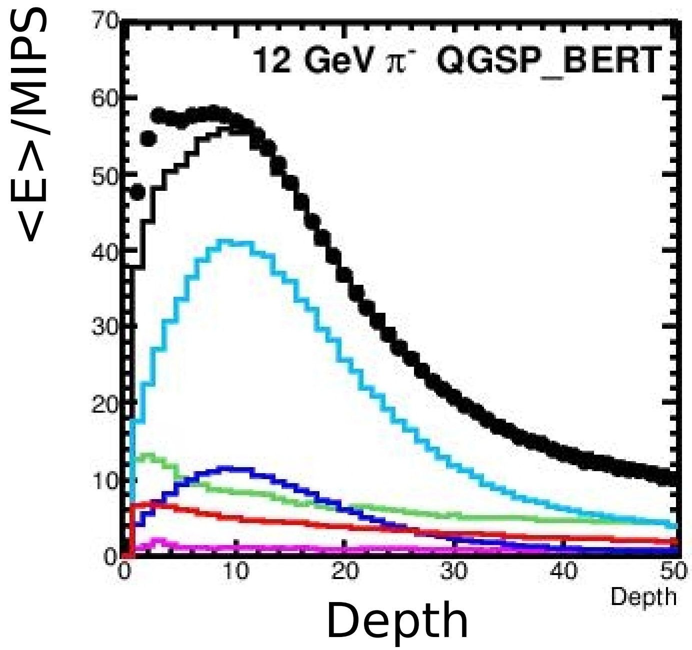




Small energy ok for 'BERT' models
Towards high energy: Underestimation of content in SiW Ecal
Relatively small difference between models (~15%)

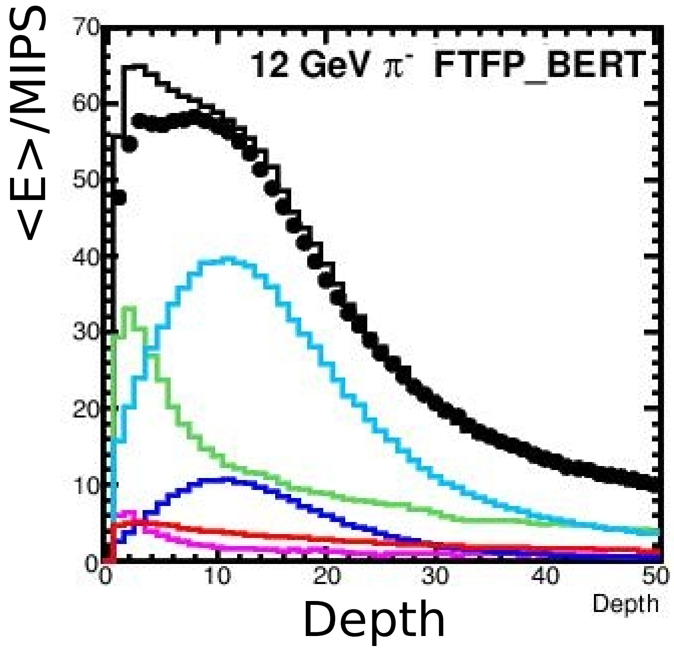
Longitudinal energy profiles

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

Energy depositions in different calorimeter depths

Layer 1-3:

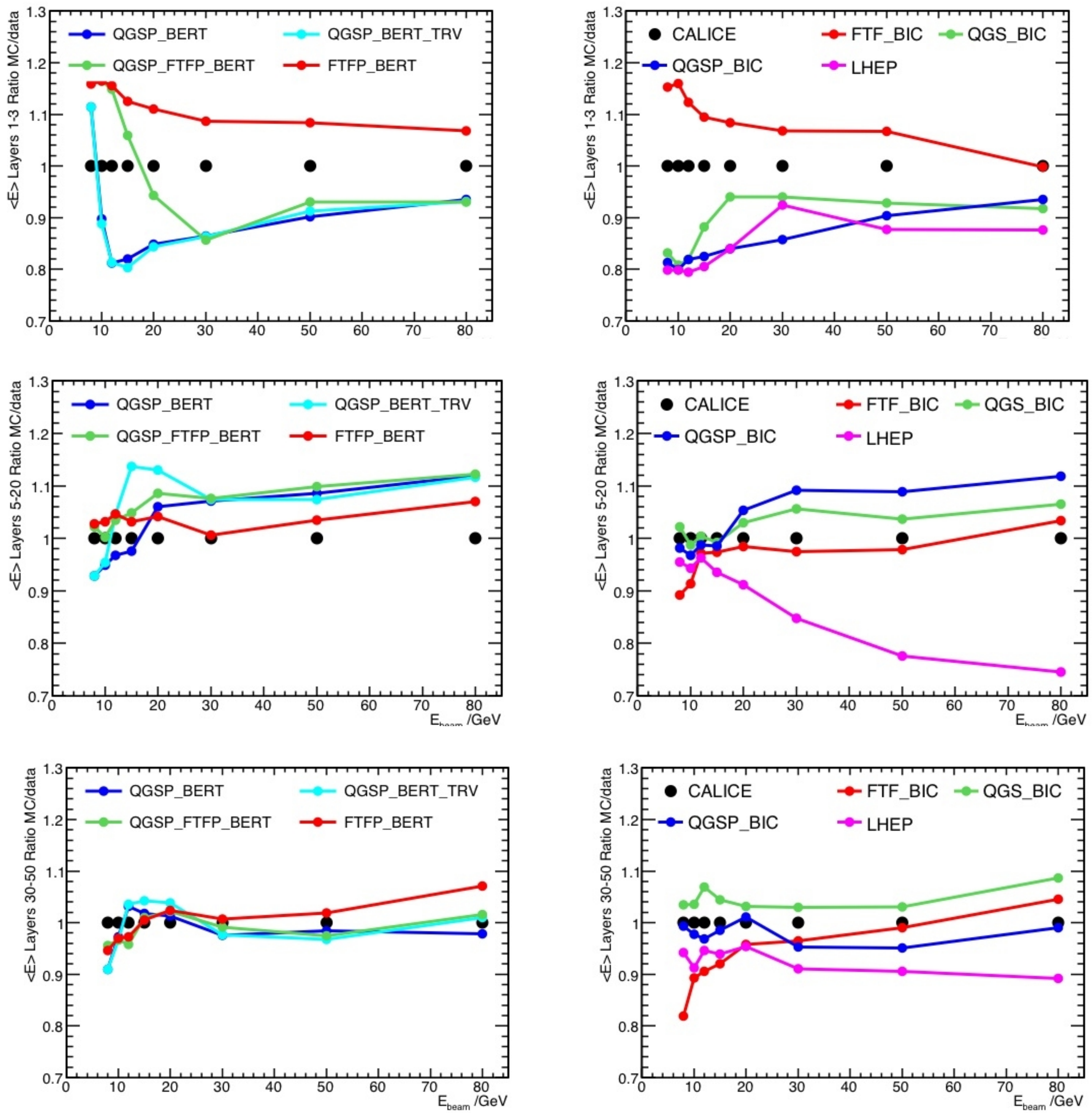
Nuclear breakup

Layer 5-20:

elm. component

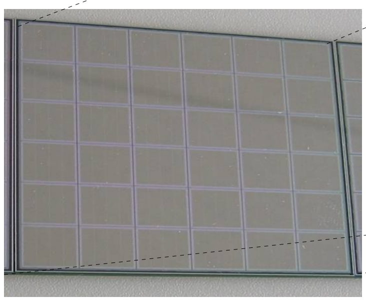
Layer 30-50:

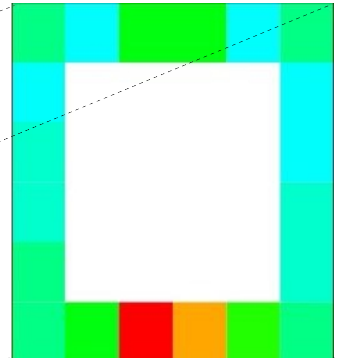
Shower hadrons



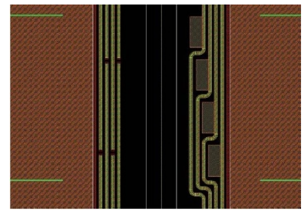
R&D for silicon wafers

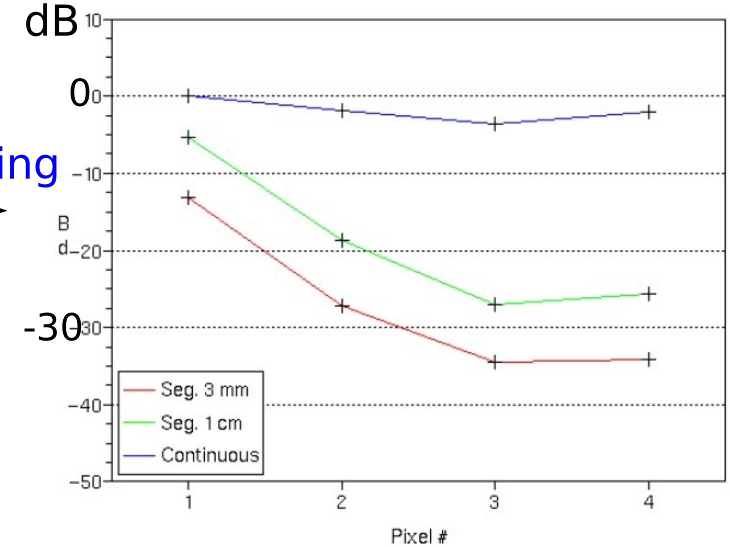
Square Pattern in Wafer Response





Segmented guardring



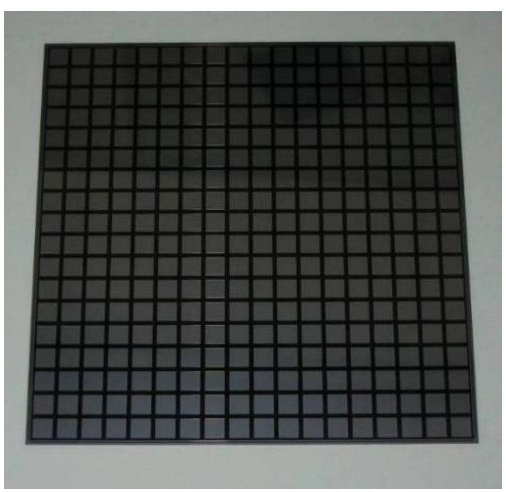


Xtalk continous guardring <-> Pixel

Attenuation of Xtalk

Beyond the physics prototype

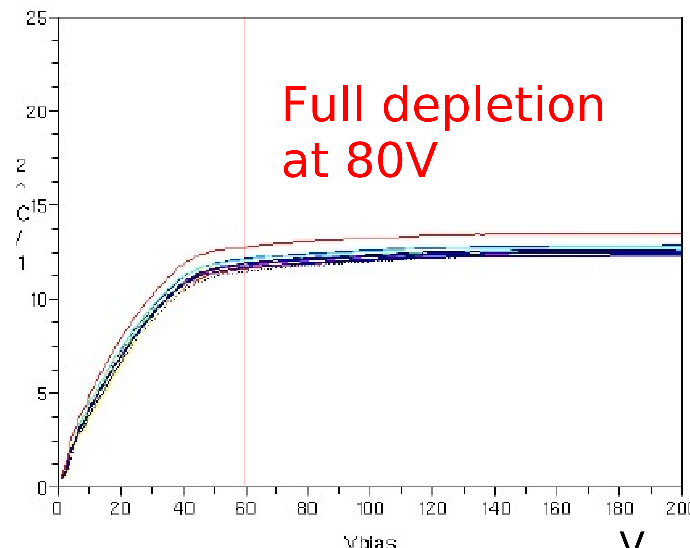
Wafers with smaller pixels



5x5 mm² pixels
~optimal "ILD width"

Thickness: 325 µm

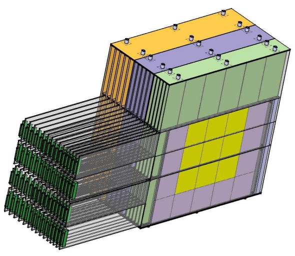
Characterisation

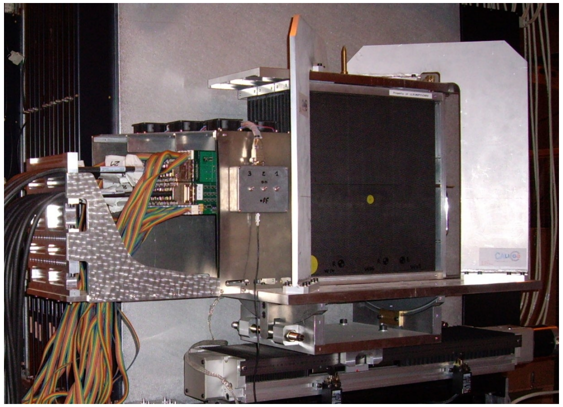


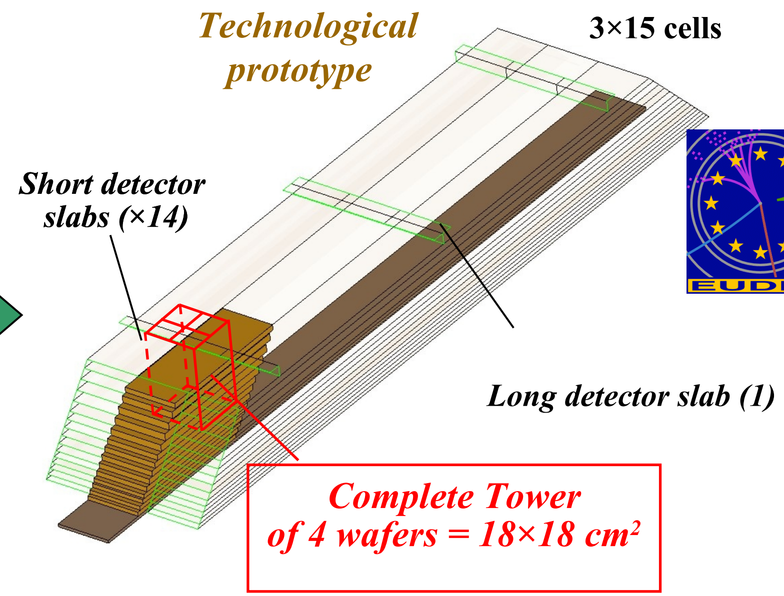
Breakdown at ~500 V

Technological Prototype

Technical solutions for the/a final detector







- Realistic dimensions

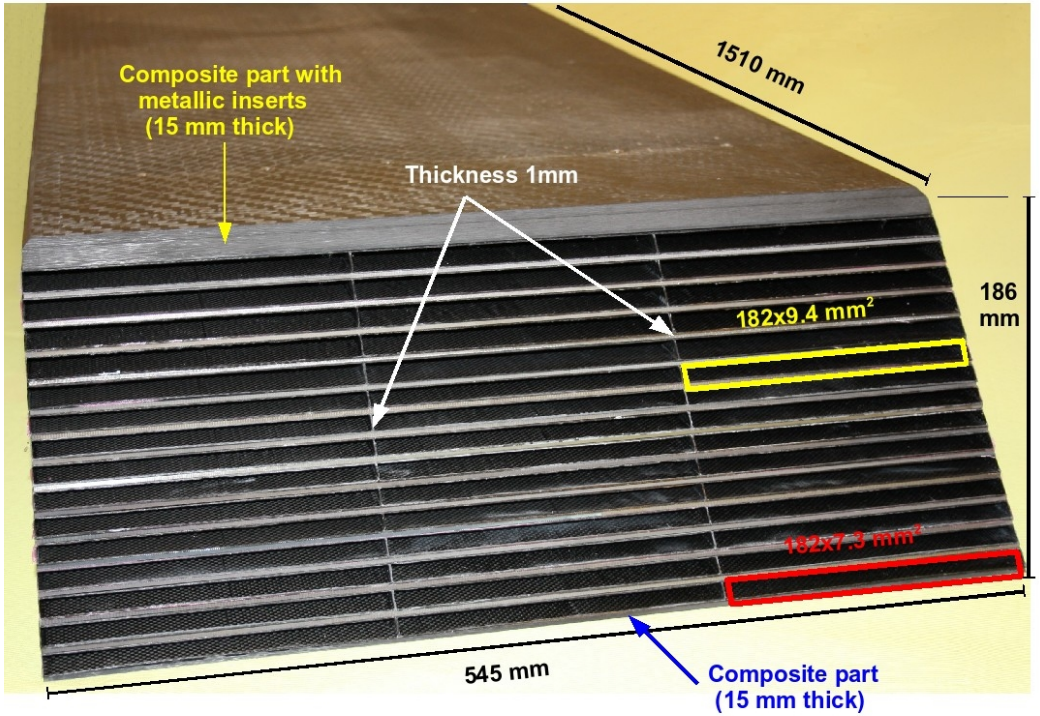
- Integrated Front End Electronics

- Small power consumption

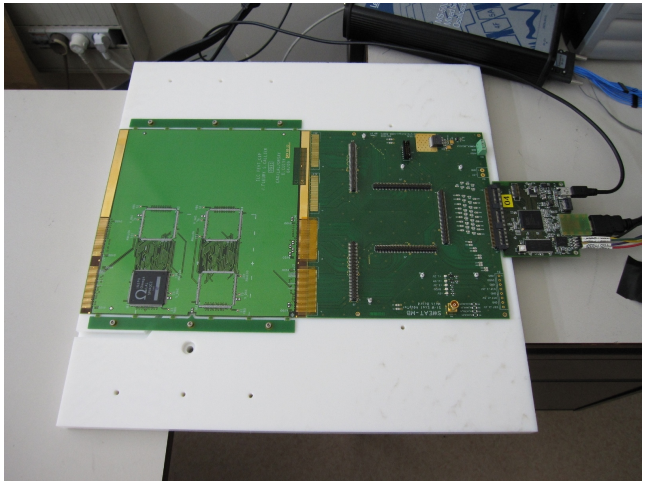
  Power pulsed electronics

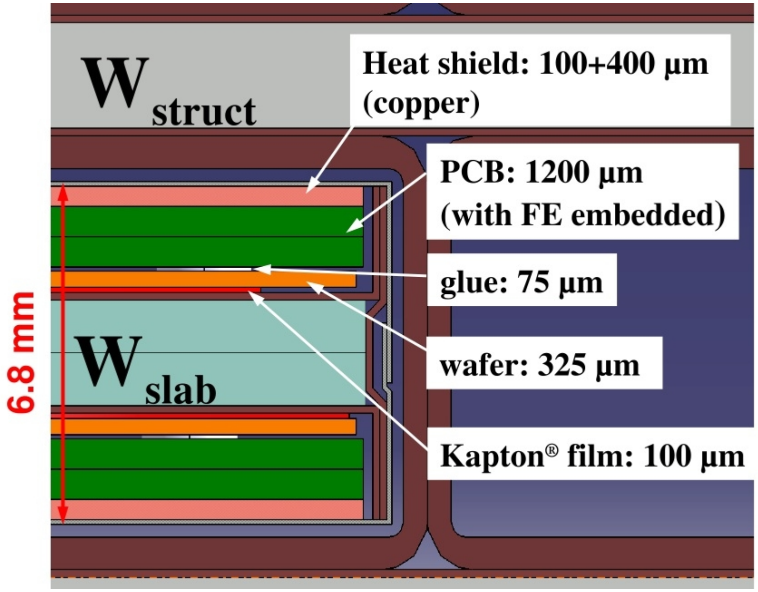
- Construction 2010 – 2012, Testbeams 2012-2013

Technological Prototype – Design



Slab prototype





- ⇨ 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)

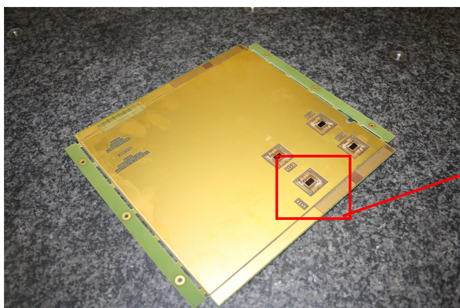
Ecal detector layer - principle

A layer is composed of several short ASUs:

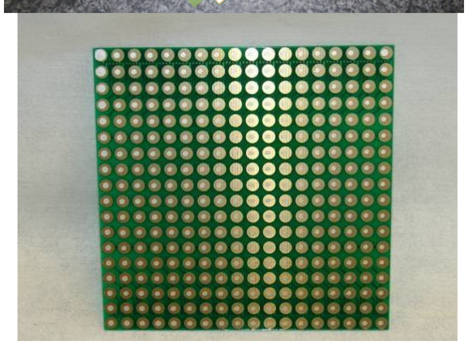
- A.S.U. : Active Sensors Units

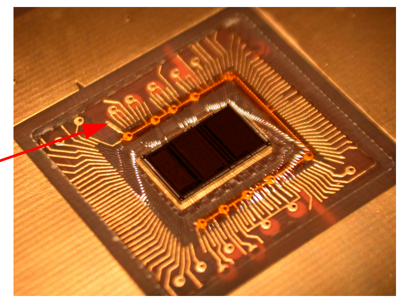
Interconnection
by FFC
(“Flat Flexible Cable”)

Chip+PCB+SiWafer =ASU

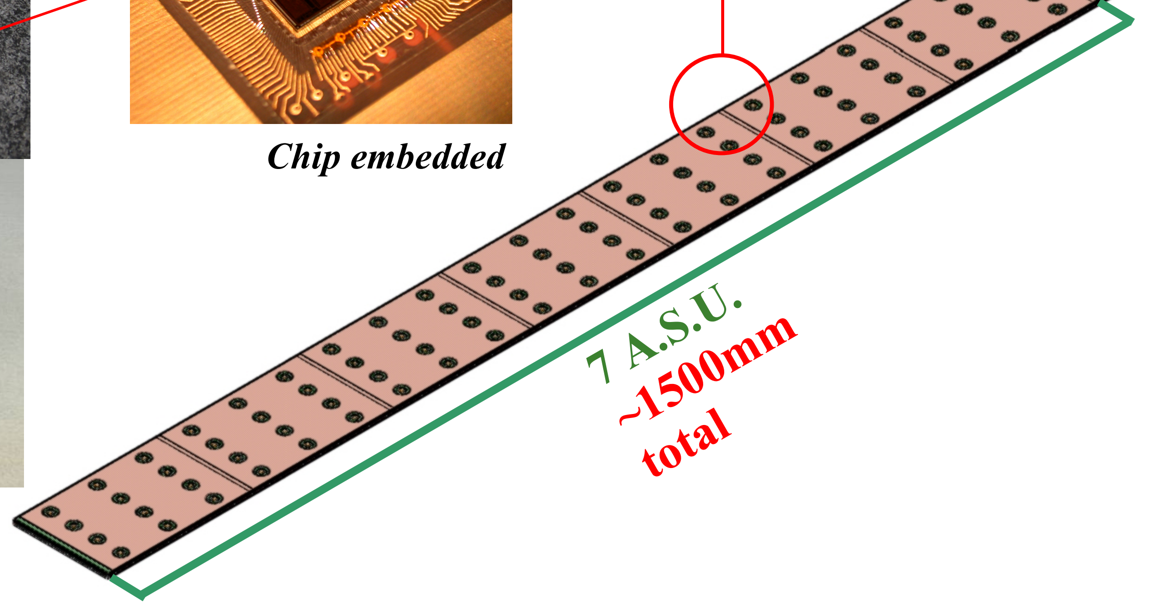


PCB
is glued
onto
SiWafers



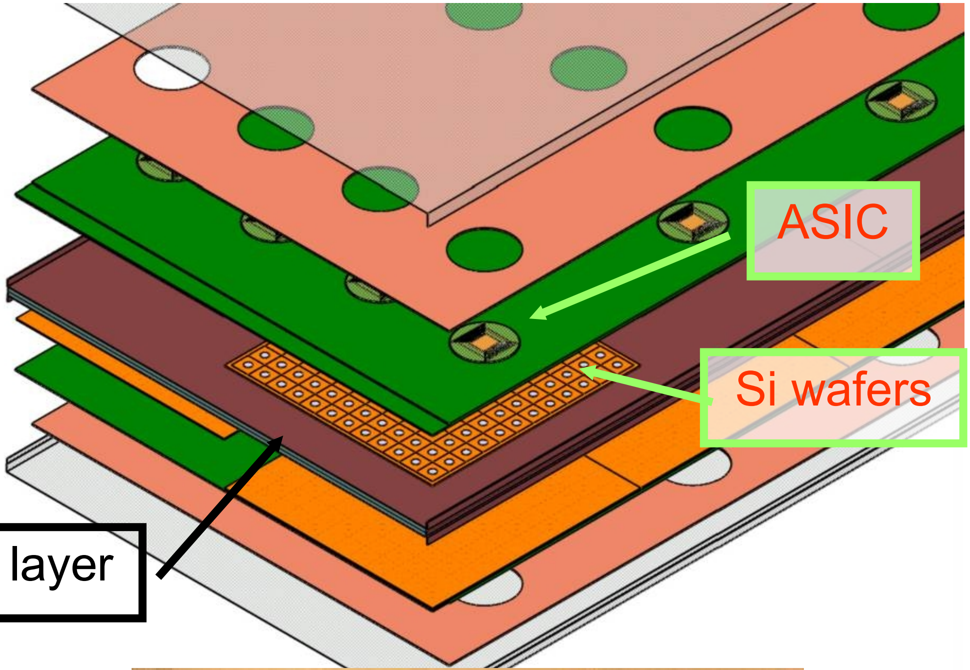


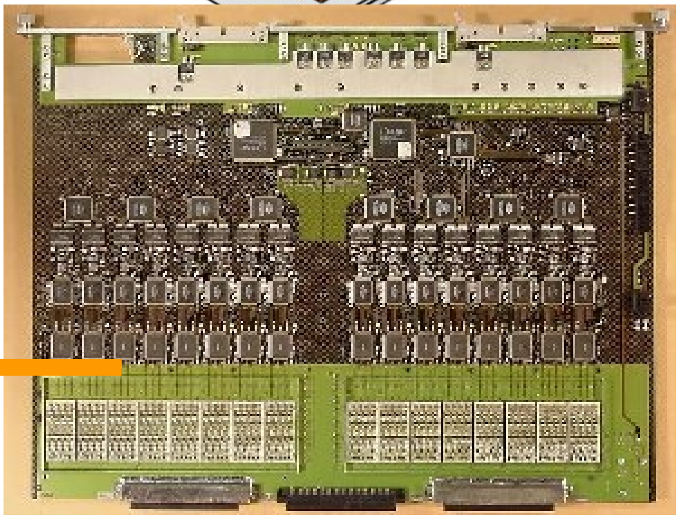
Chip embedded

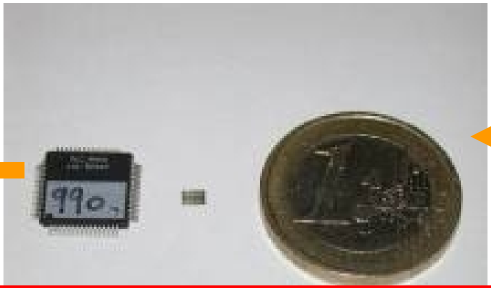


Front end electronics

- 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







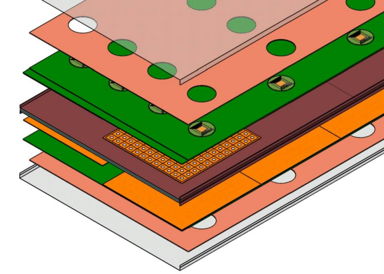
ILC : **25µW/ch**

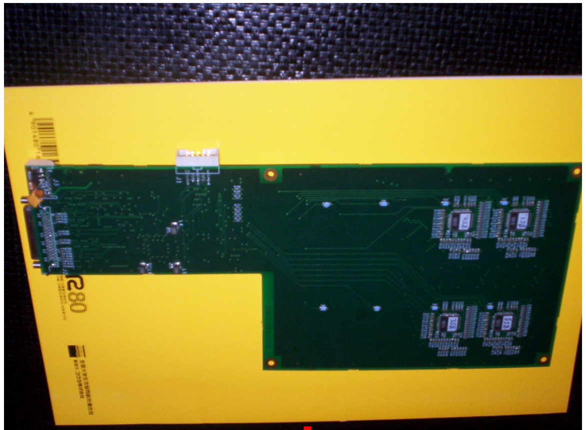
FLC_PHY3 18ch 10*10mm **5mW/ch**

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

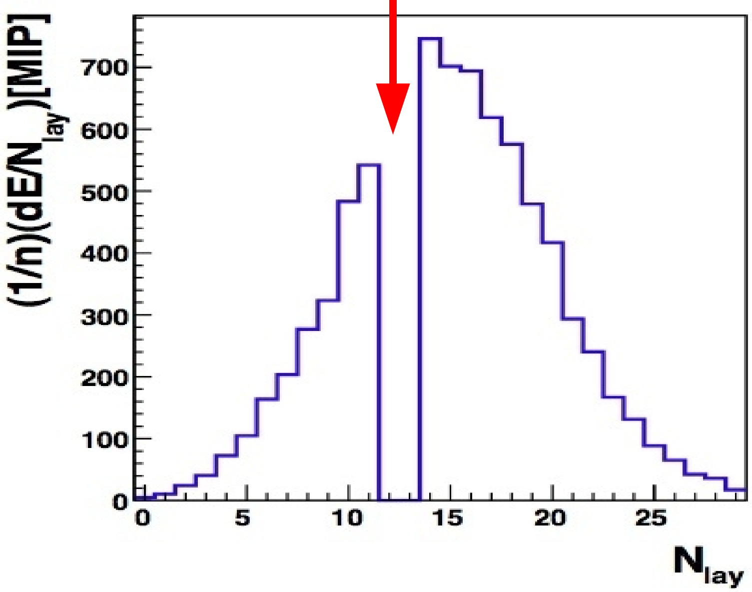
Embedded electronics - Parasitic effects?

Exposure of front end electronics to electromagnetic showers



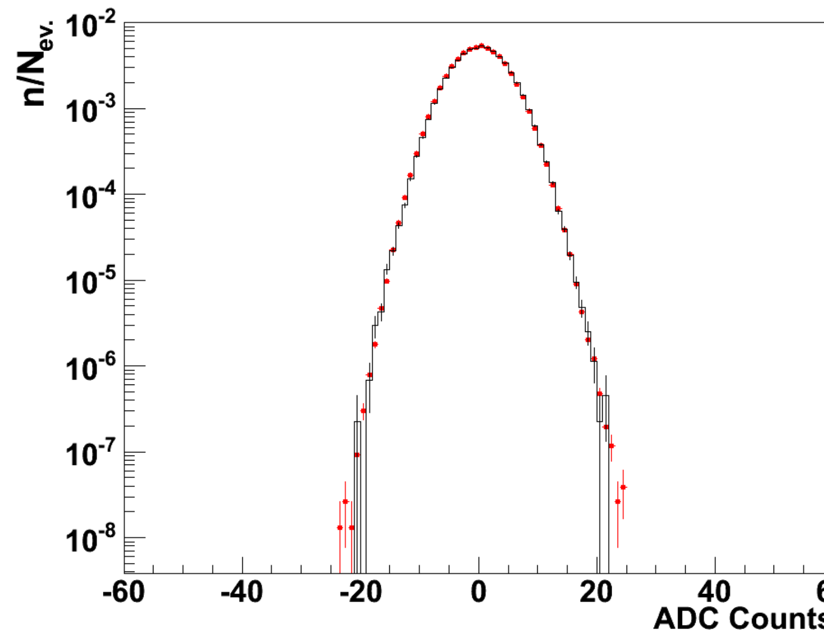


Chips placed in shower maximum of 70-90 GeV elm. showers



Possible Effects: Transient effects
Single event upsets

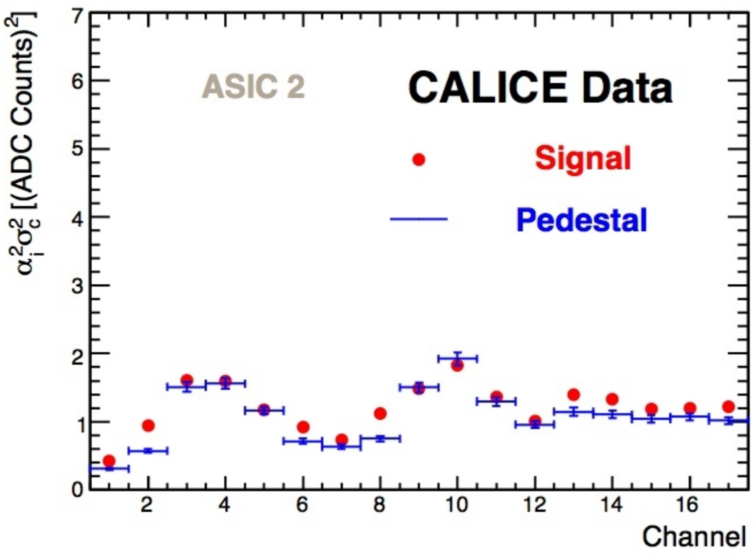
Comparison: Beam events
(Interleaved) Pedestal events



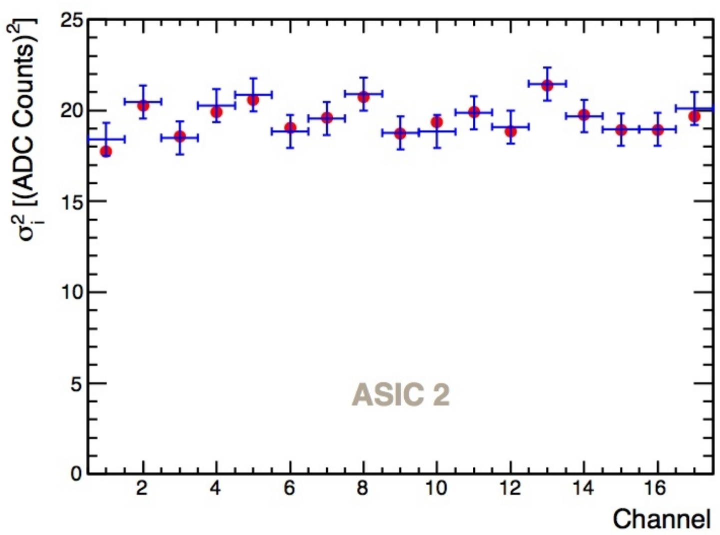
- No sizable influence on noise spectra by beam exposure
  ΔMean < 0.01% of MIP ΔRMS < 0.01% of MIP
- No hit above 1 MIP observed
  => Upper Limit on rate of faked MIPs: 5×10^{-7}

Detailed noise analysis

Coherent noise

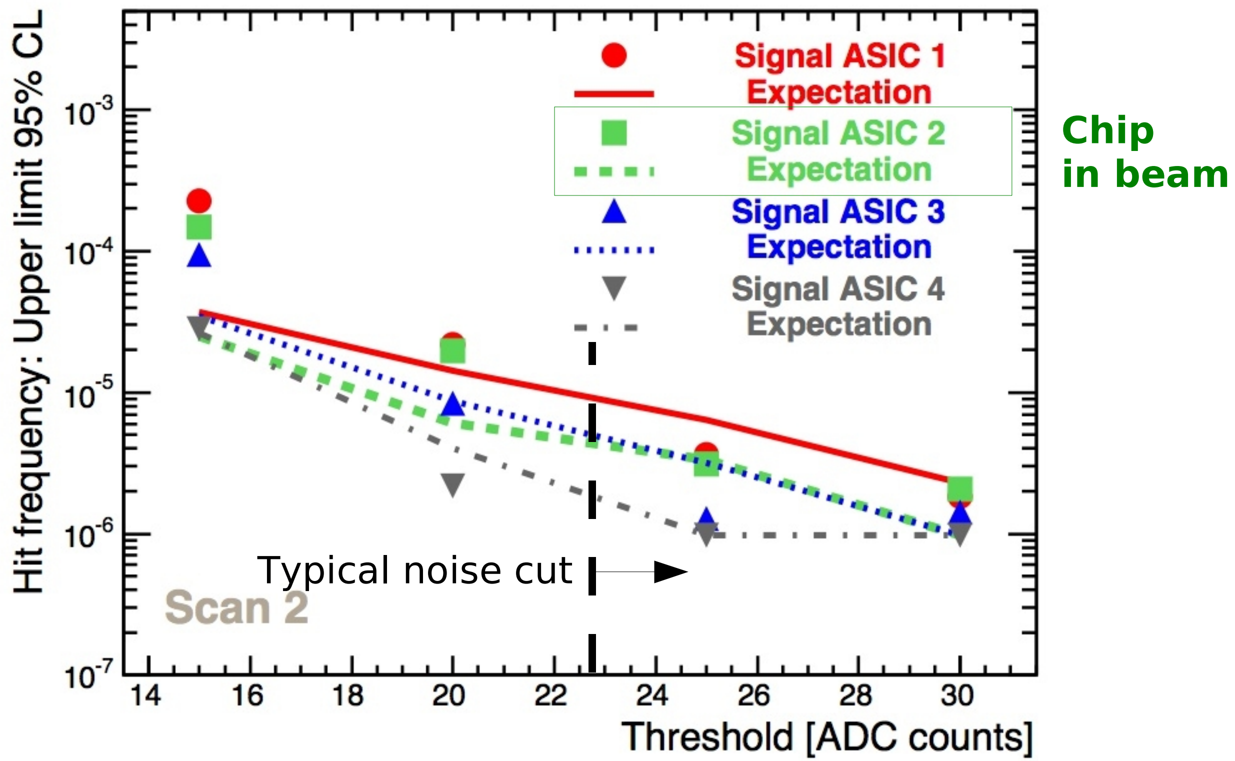


Incoherent noise



Noise pattern unchanged by shower particles

Upper limits on parasitic hits – 95% CL



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

Compare with 2500 cells in typical ee-> tt event

The Ecal ASIC - SKIROC

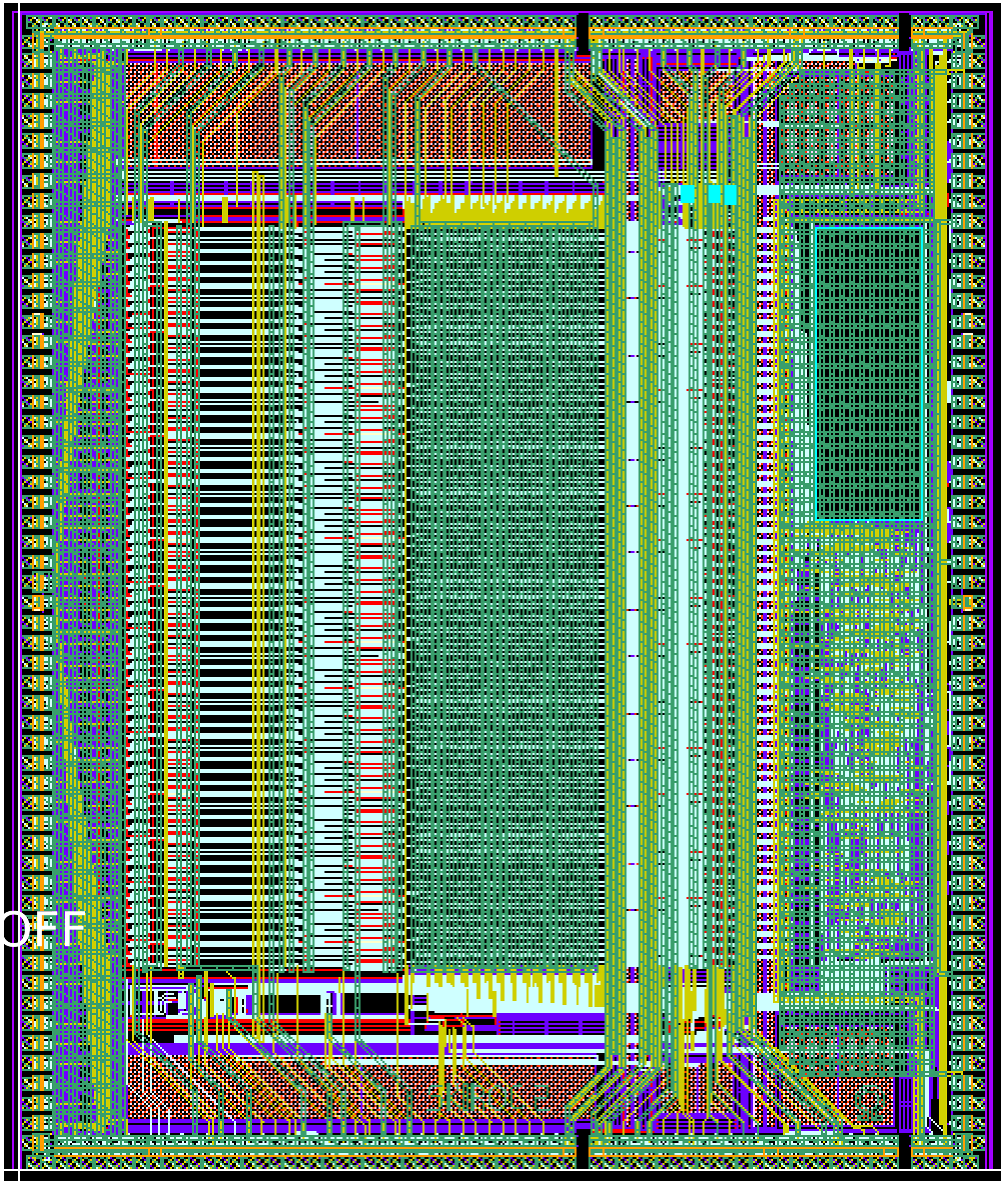
- 64 Channels

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

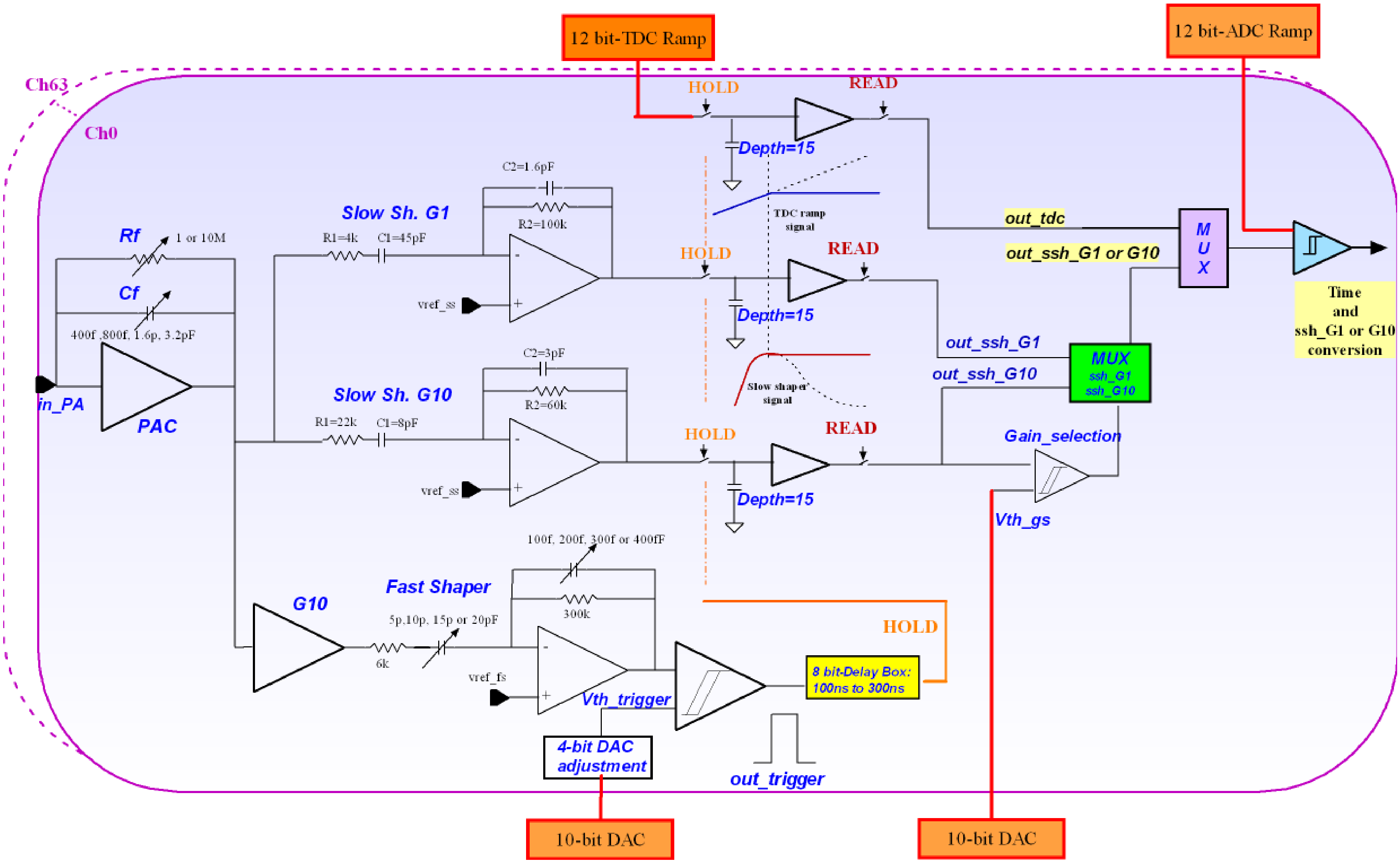
- 250 pads
  - 3 NC
  - 17 for test purpose only

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

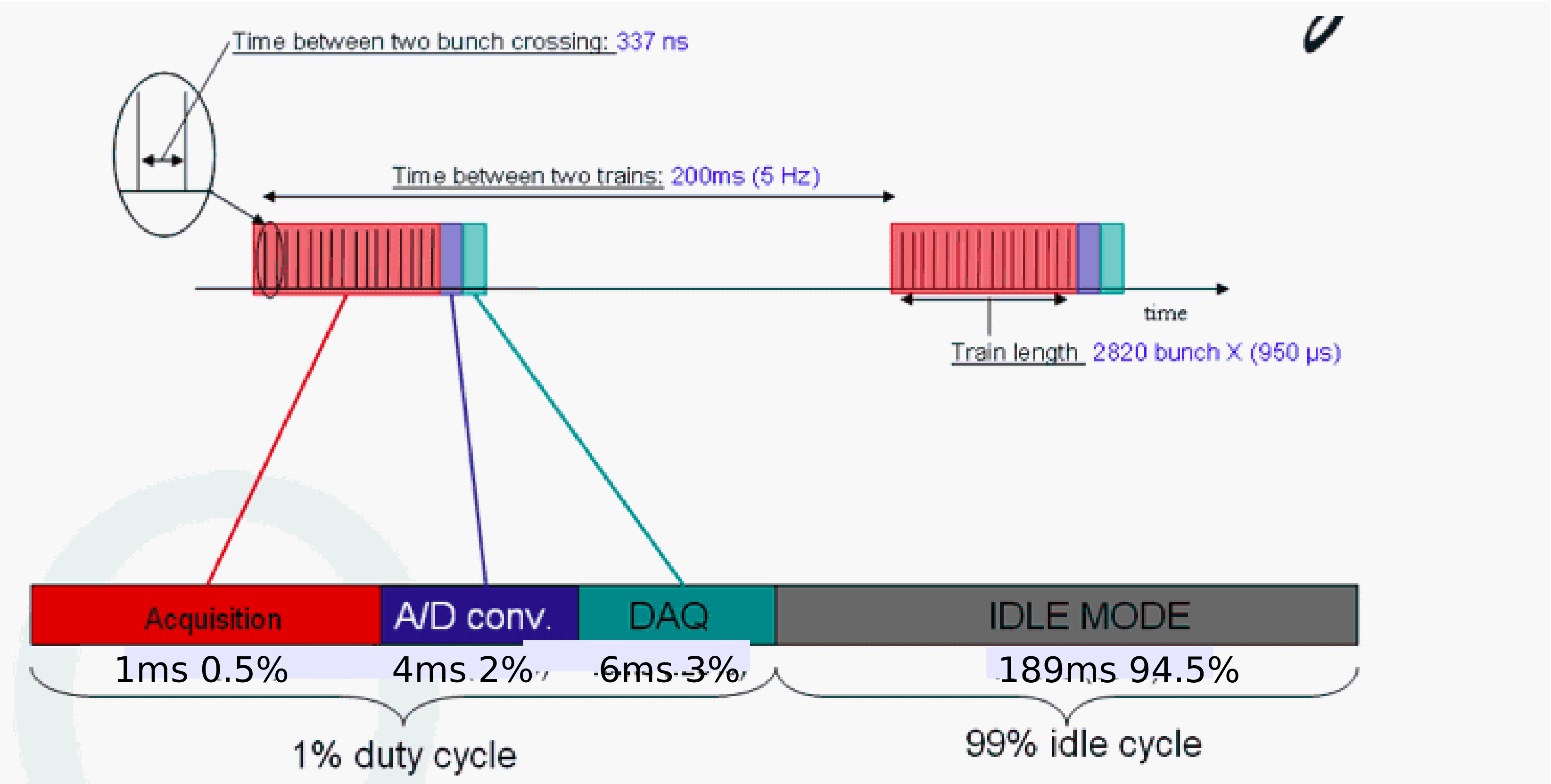
- Die size
  - 7229 µm x 8650 µm



SKIROC 2 block scheme



Power pulsing (better power gating)



- 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
  Encouraging results by IPNL group with similar chip

Summary and Outlook

- Successful R&D for a highly granular electromagnetic calorimeter

- Detector concept is built on Particle Flow

Physics Prototype (2005-2009):

- Energy resolution ~17%/√E
- Signal to Noise Ratio ~8/1
- Stable calibration

Technological Prototype (2010-...):

- Mechanical concept validated
- Silicon Wafer technology at hand
- Front End Electronics will be challenging
  Embedded into calorimeter layers, power gating
- Supported within EUDET (2006-2010) and AIDA (2011-2015)

- 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 vast amount of information is challenging
  The harvest is just starting

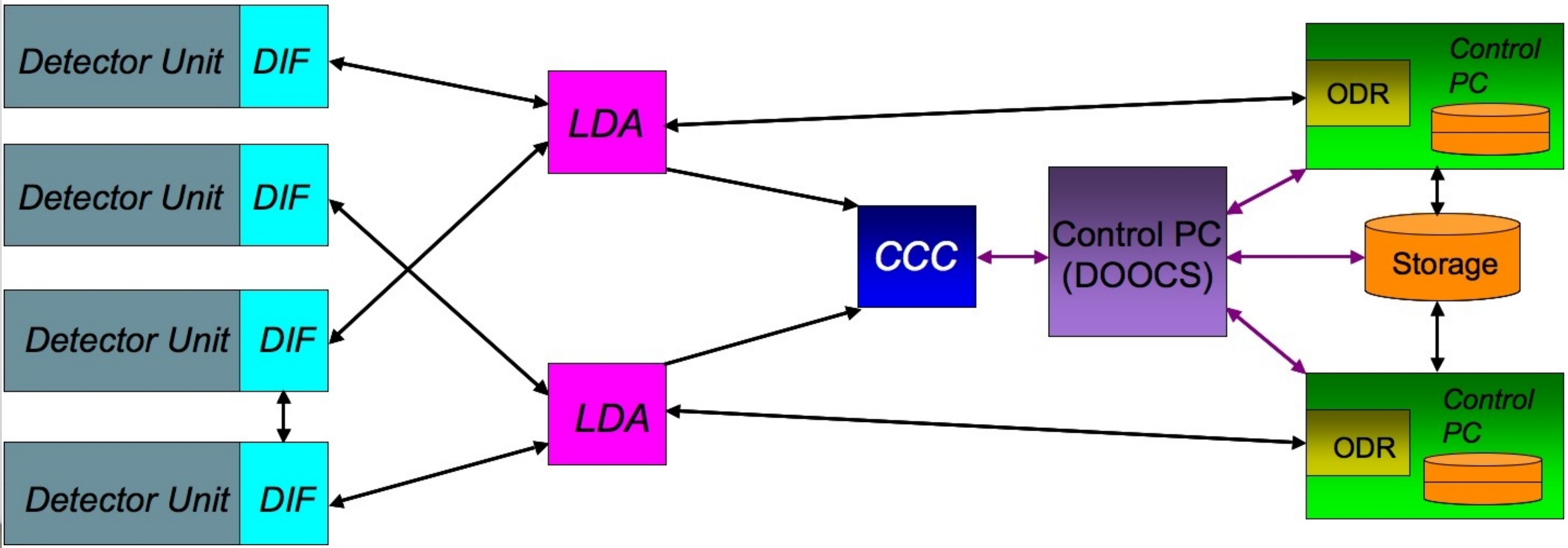
Backup Slides

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

Standard — HDMI connectors, LVDS, GB Ethernet, Optical links

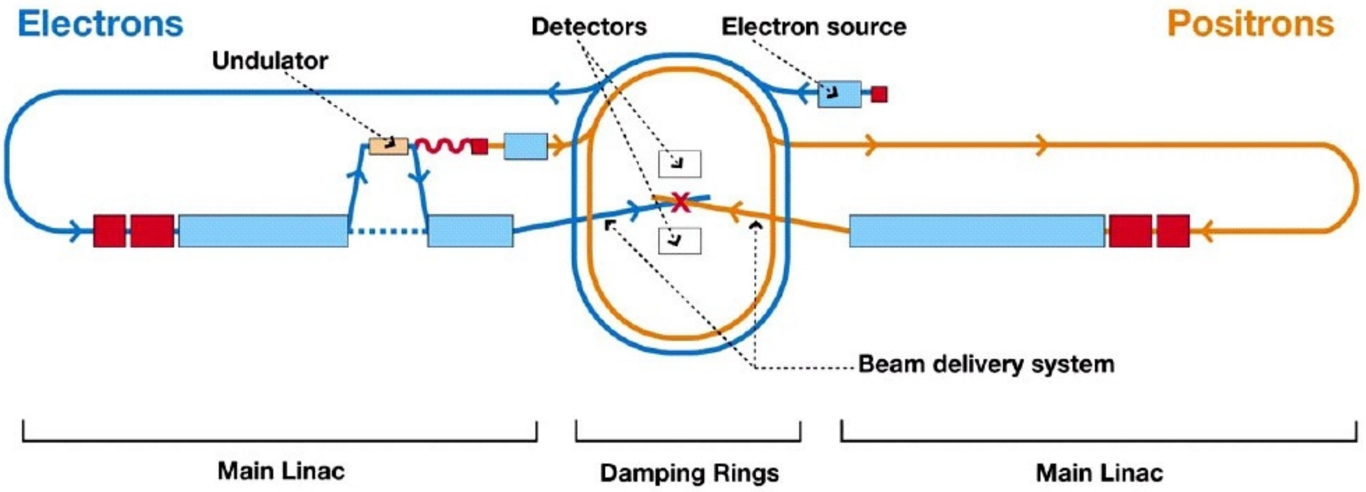
Generic — FPGA

Scalable



The International Linear Collider ILC

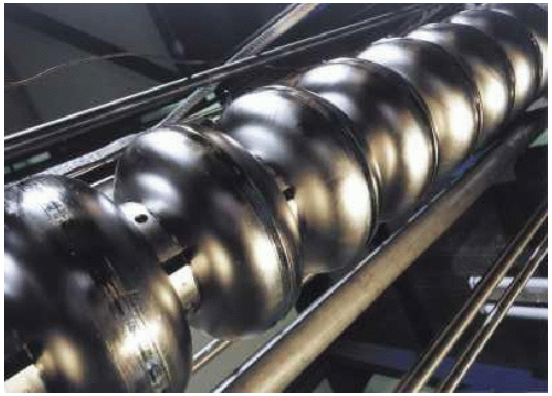
Linear Electron-Positron Collider



Total Footprint 31 km

Main parameters

- $\sqrt{s}$ adjustable from 200 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarisation of at least 80%
  Option: Polarised Positrons
- The machine must be upgradeable to 1 TeV



Technology for Main Linac

Superconductive RF cavity

ITRP Recommendation 2004

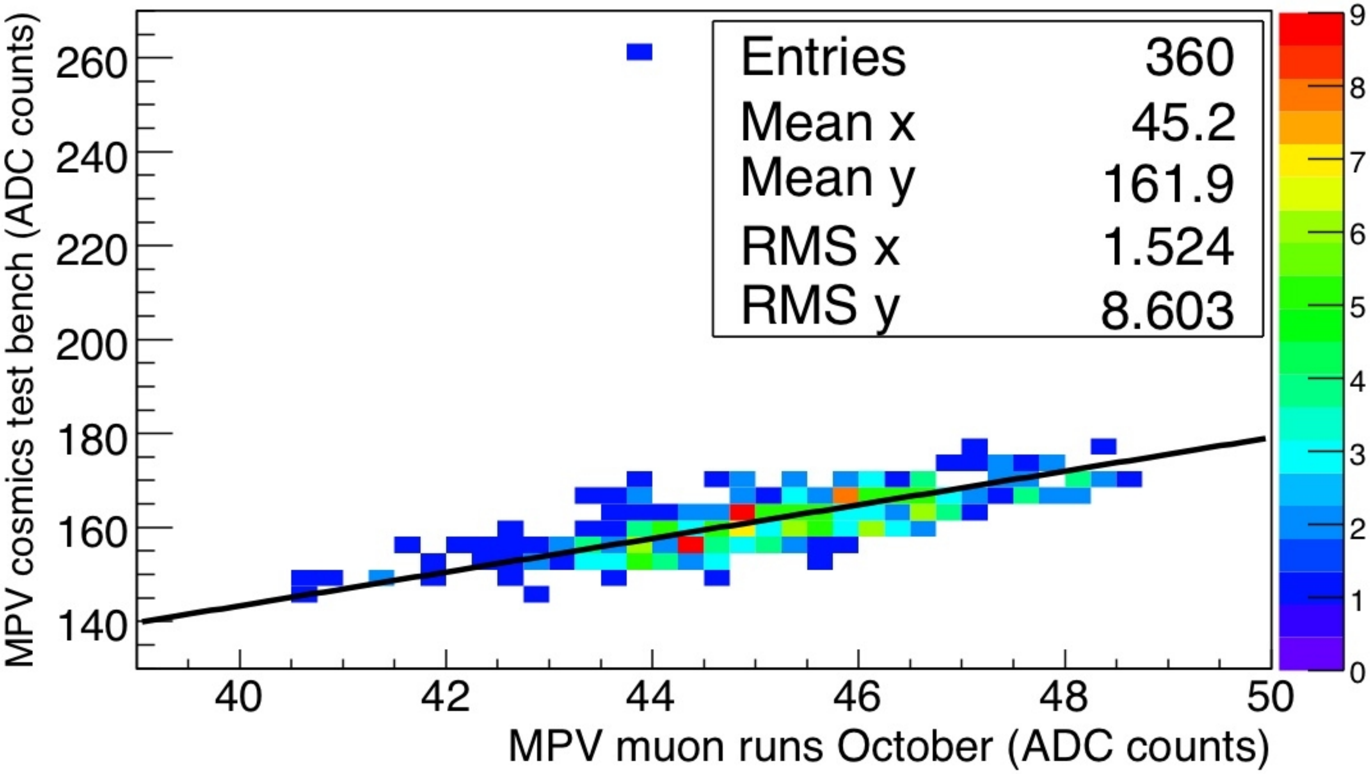
Present outlook
→ Technical design report 2012
→ R&D Project for higher Energies CLIC

Stability of calibration?

Important Criterium during evaluation process of detector concepts

Affects both: precision and operability of detector: ~10^8 calo cells in LC Detector

Calibration Constants on testbench and in beam test campaign

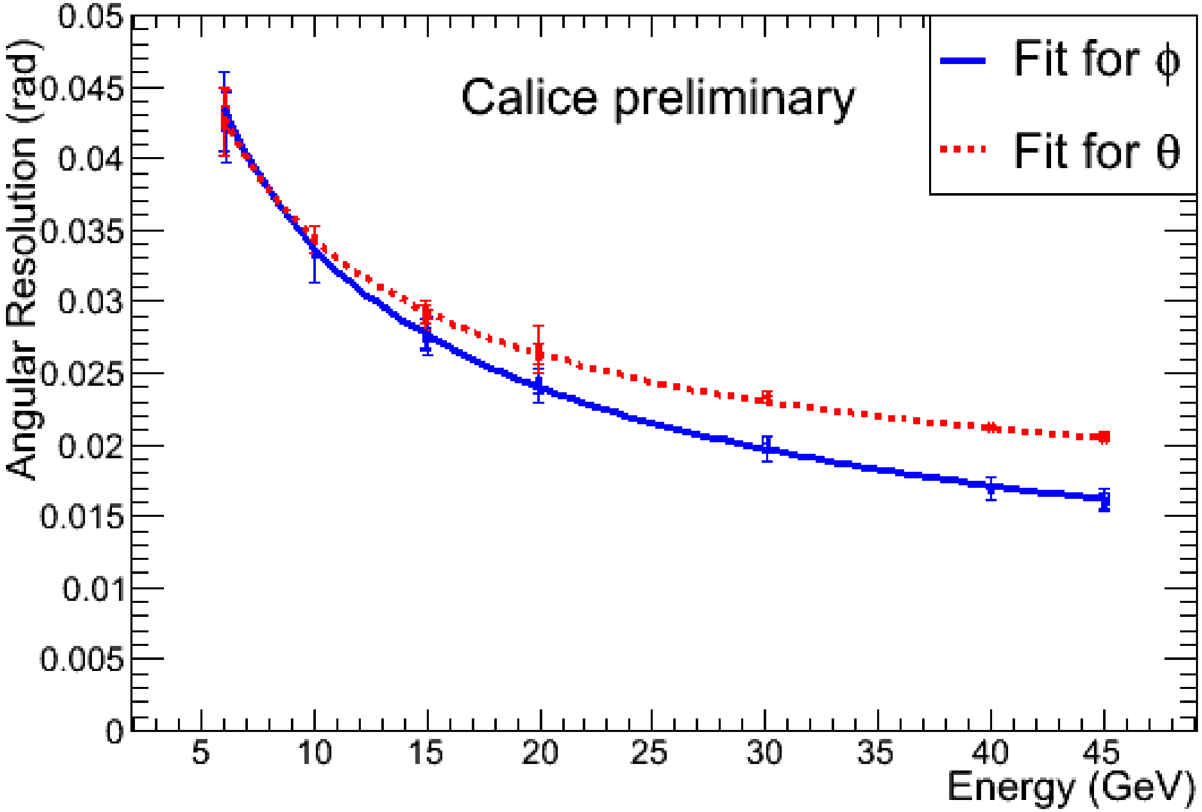


High Correlation between calibration constants

For “final” detector:

Detector modules can be calibrated in beam test prior to installation

Angular resolution



Fitted with:

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

Φ, angle respect to X:

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

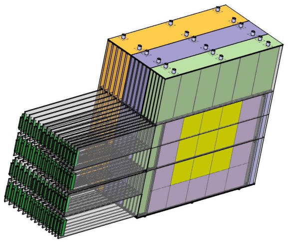
θ, angle respect to Y:

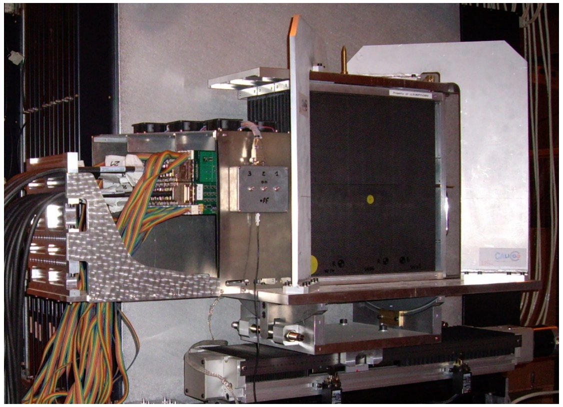
$$\left(\frac{100 \pm 2}{\sqrt{E(GeV)}} \oplus (14 \pm 1)\right) mrad$$

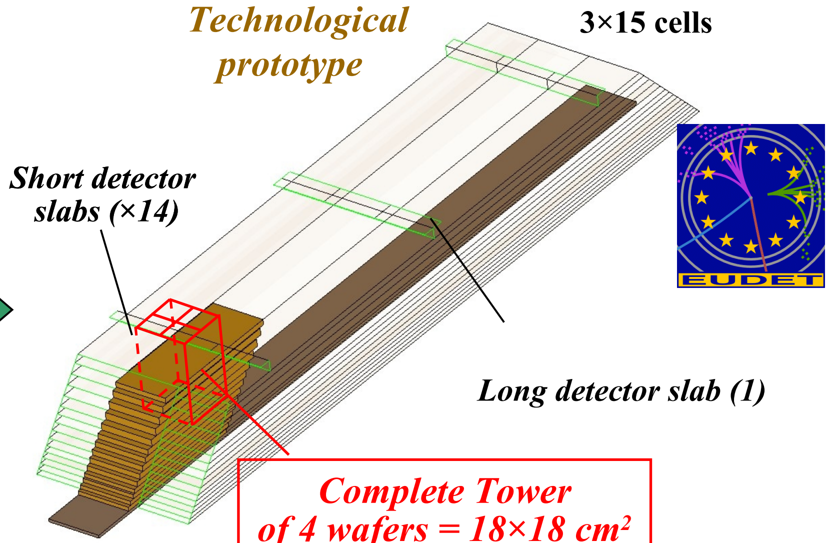
Differences due X and Y due to geometrical properties of prototype (staggering)

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



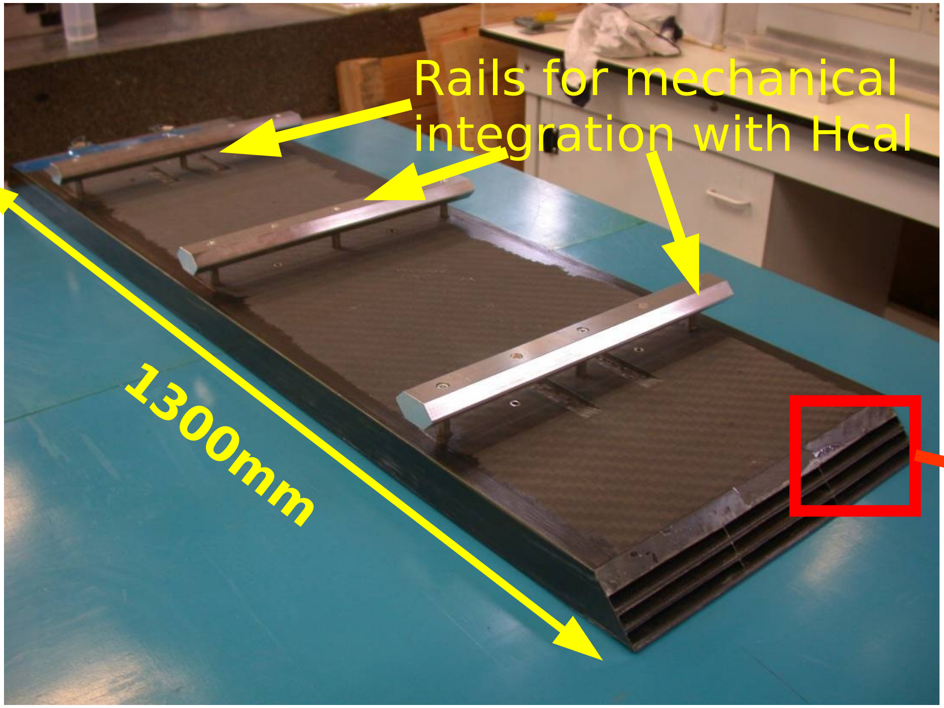


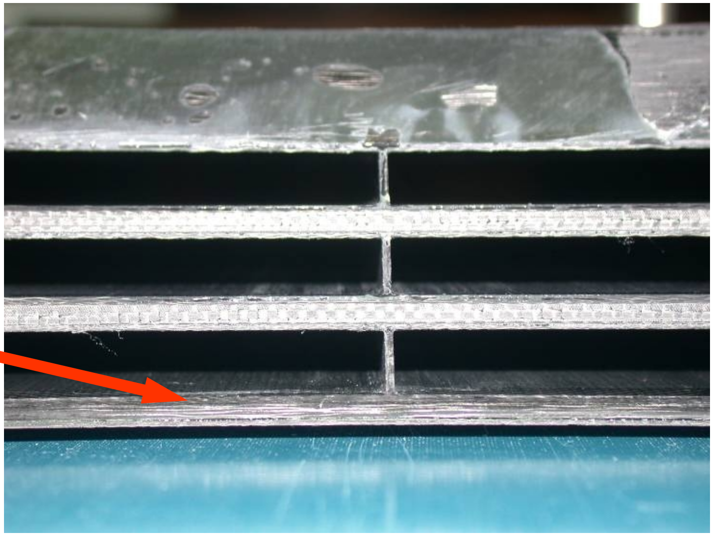


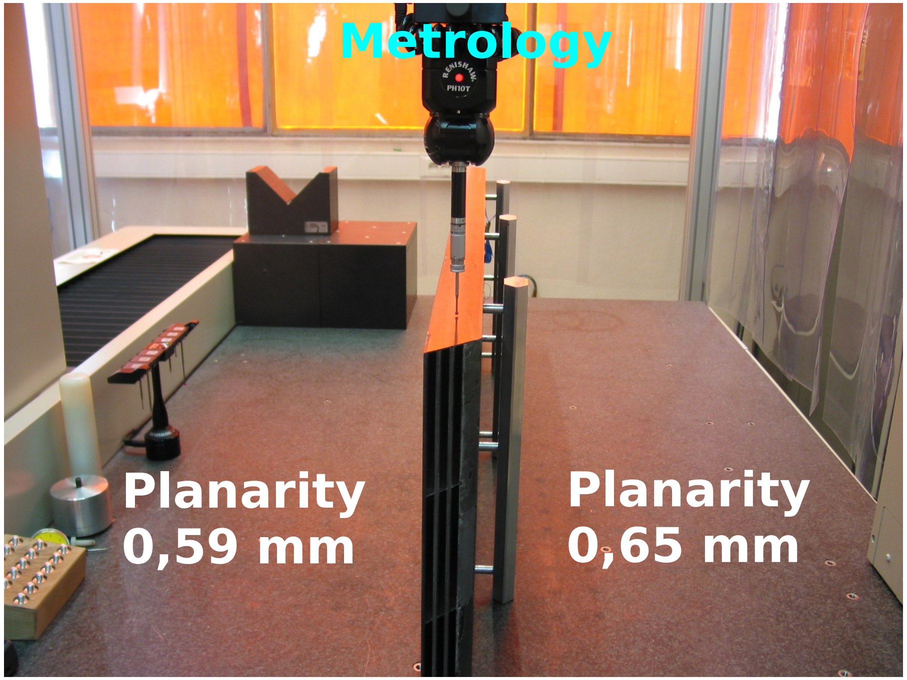
- **3 structures : 24 X_0 (10×1,4mm + 10×2,8mm + 10×4,2mm)**
- **sizes : 380×380×200 mm3**
- **Thickness of slabs : 8.3 mm (W=1,4mm)**
- **VFE outside detector**
- **Number of channels : 9720 (10×10 mm²)**
- **Weight : ~ 200 Kg**

- **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 mm²)**
- **Weight : ~ 700 Kg**

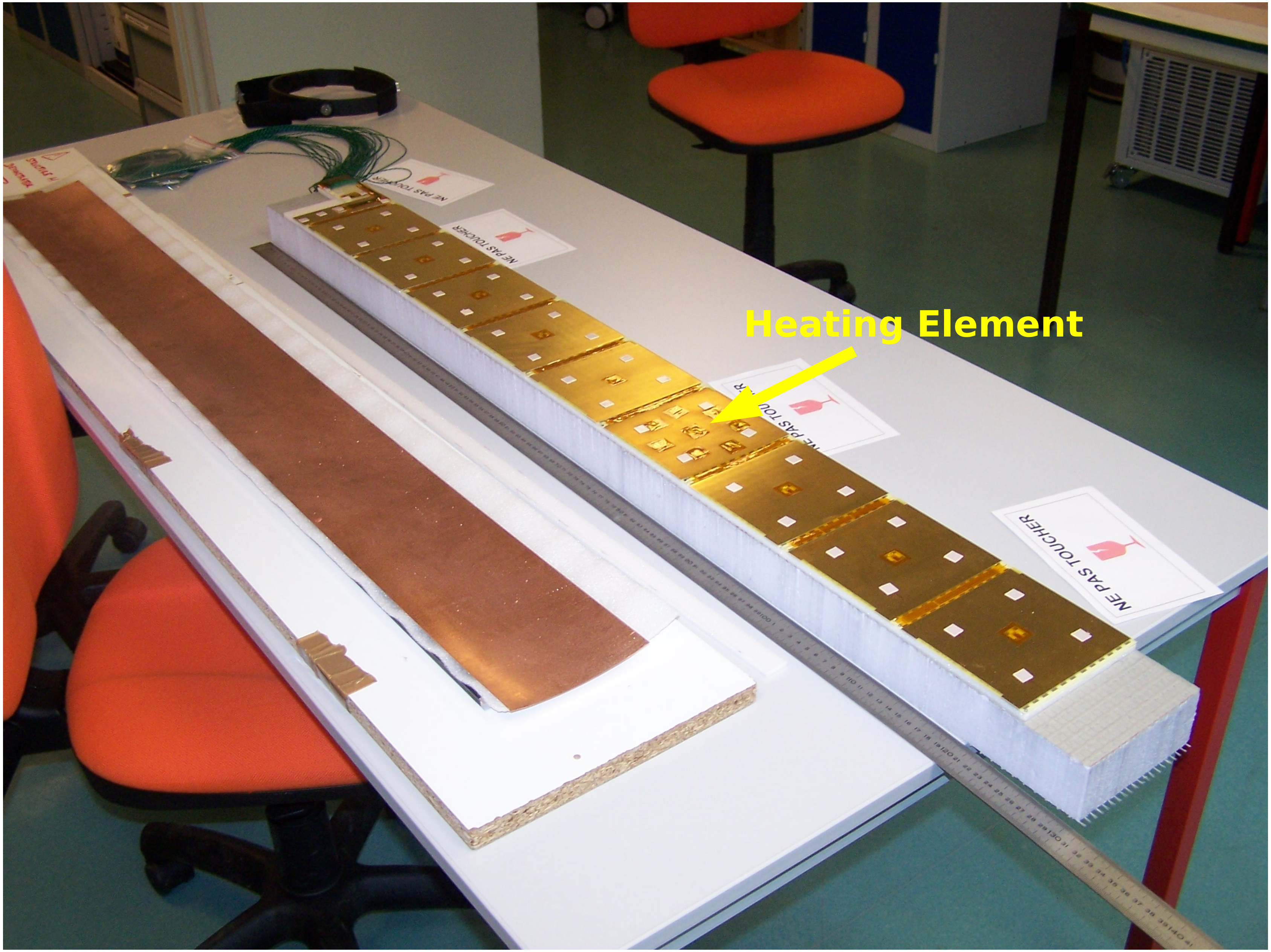
First step: Demonstrator





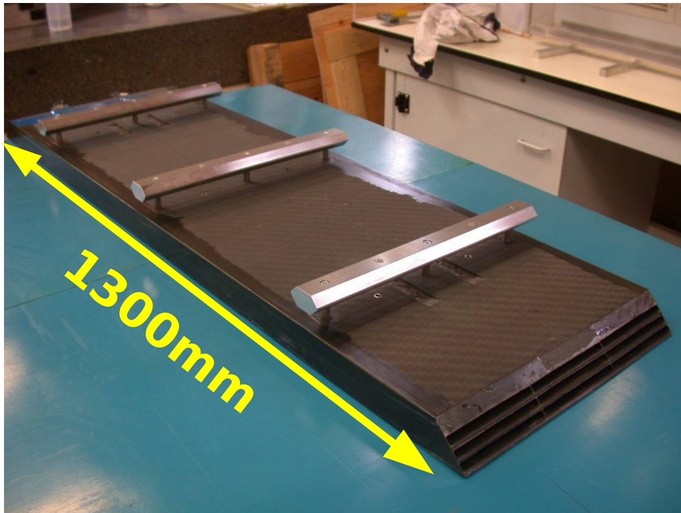


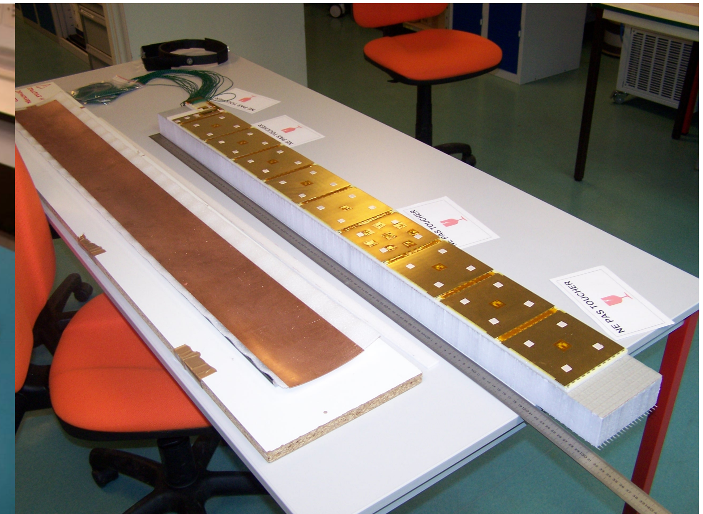
Developping the Techniques for Layer Construction – Thermal Layer

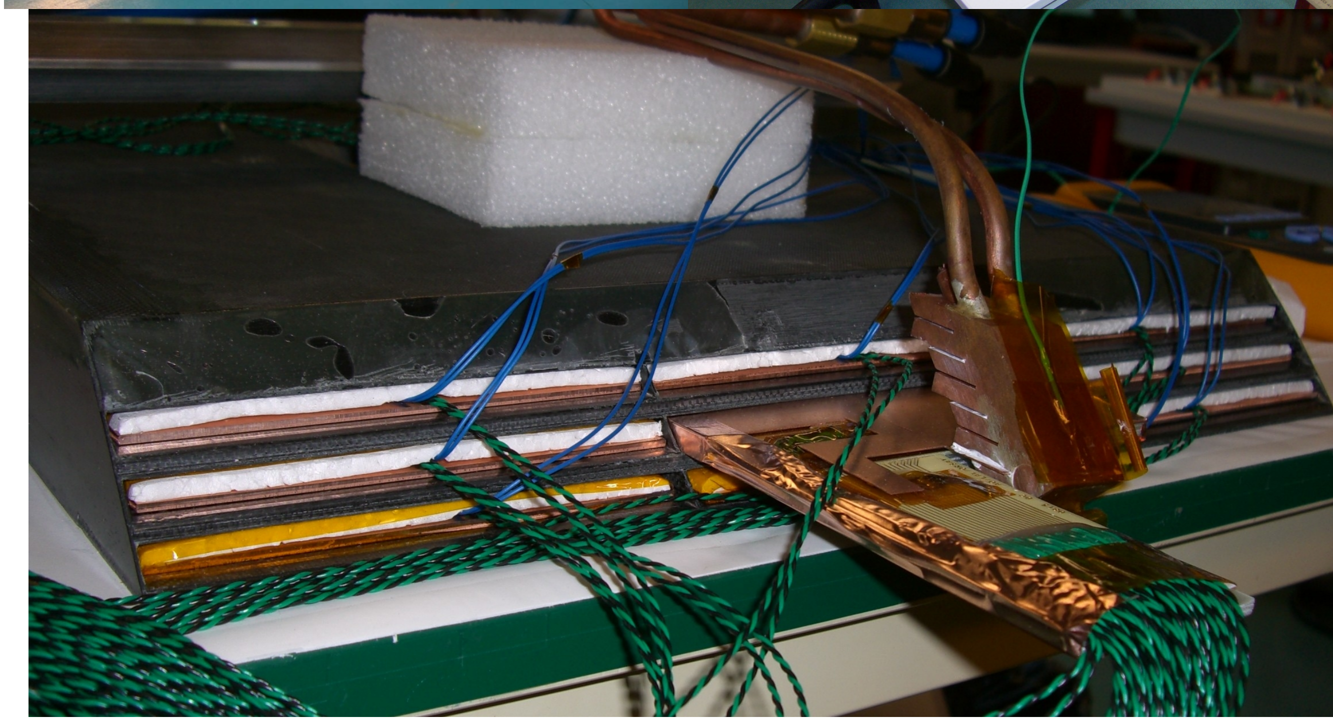


Proof-of-principle to build long layers

First step: Demonstrator



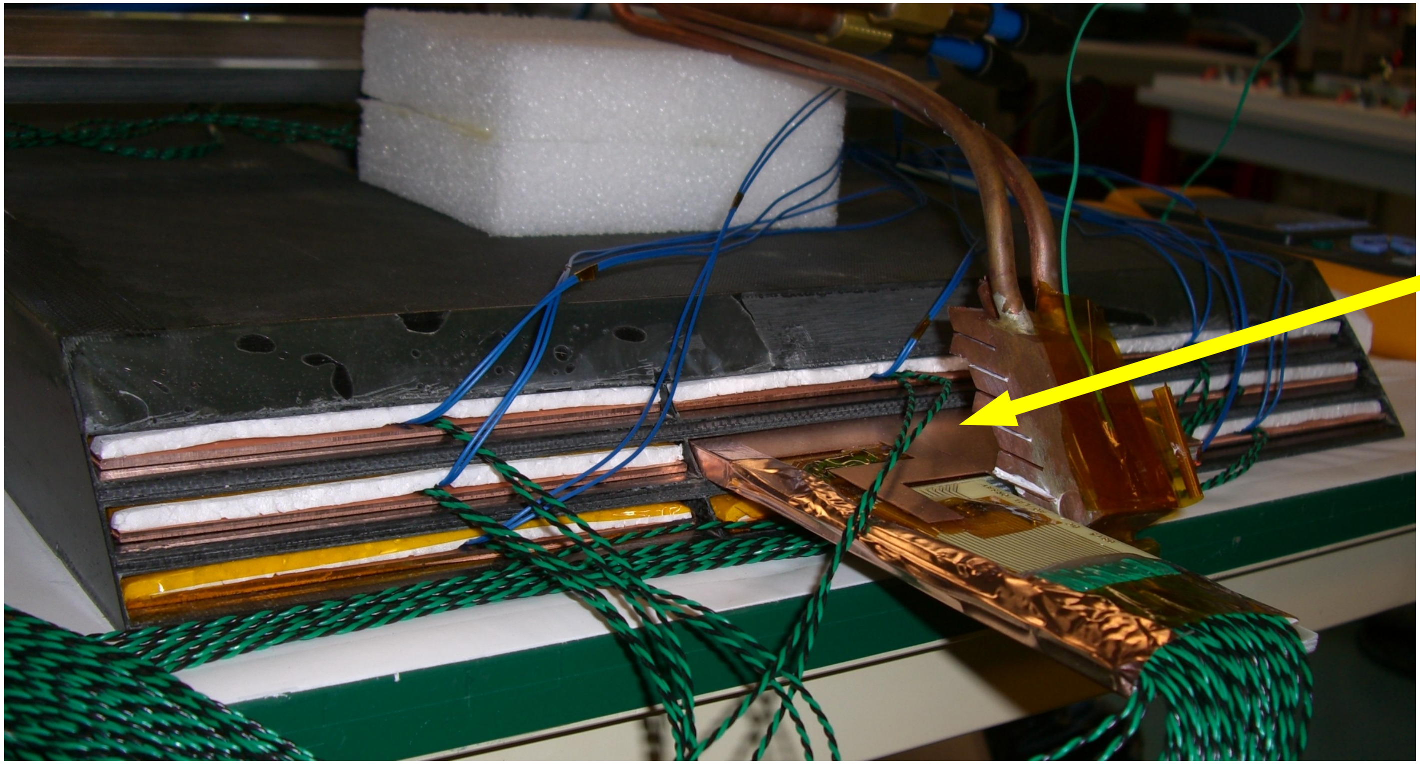


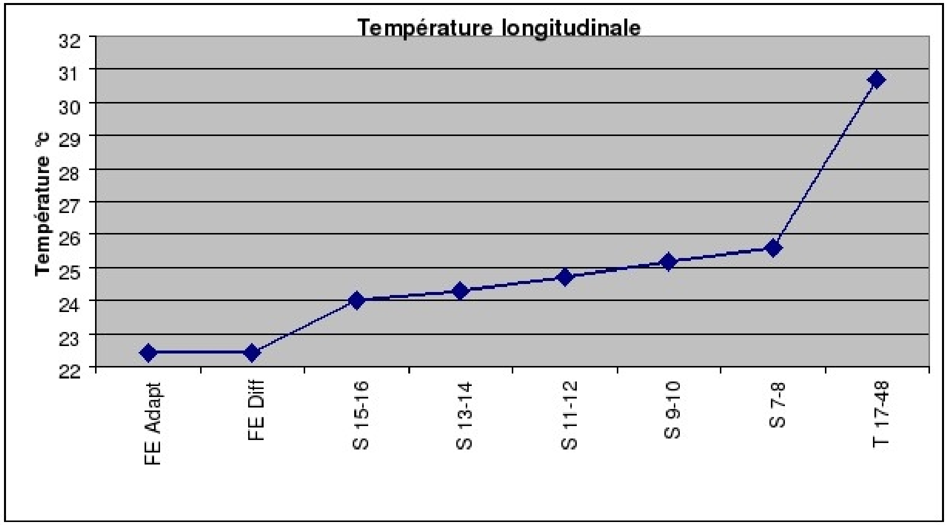


- Detector module realised (from mechanical point of view)
- Demonstrator subject to a thermal test

Thermal Test

To study thermal behaviour of detector module





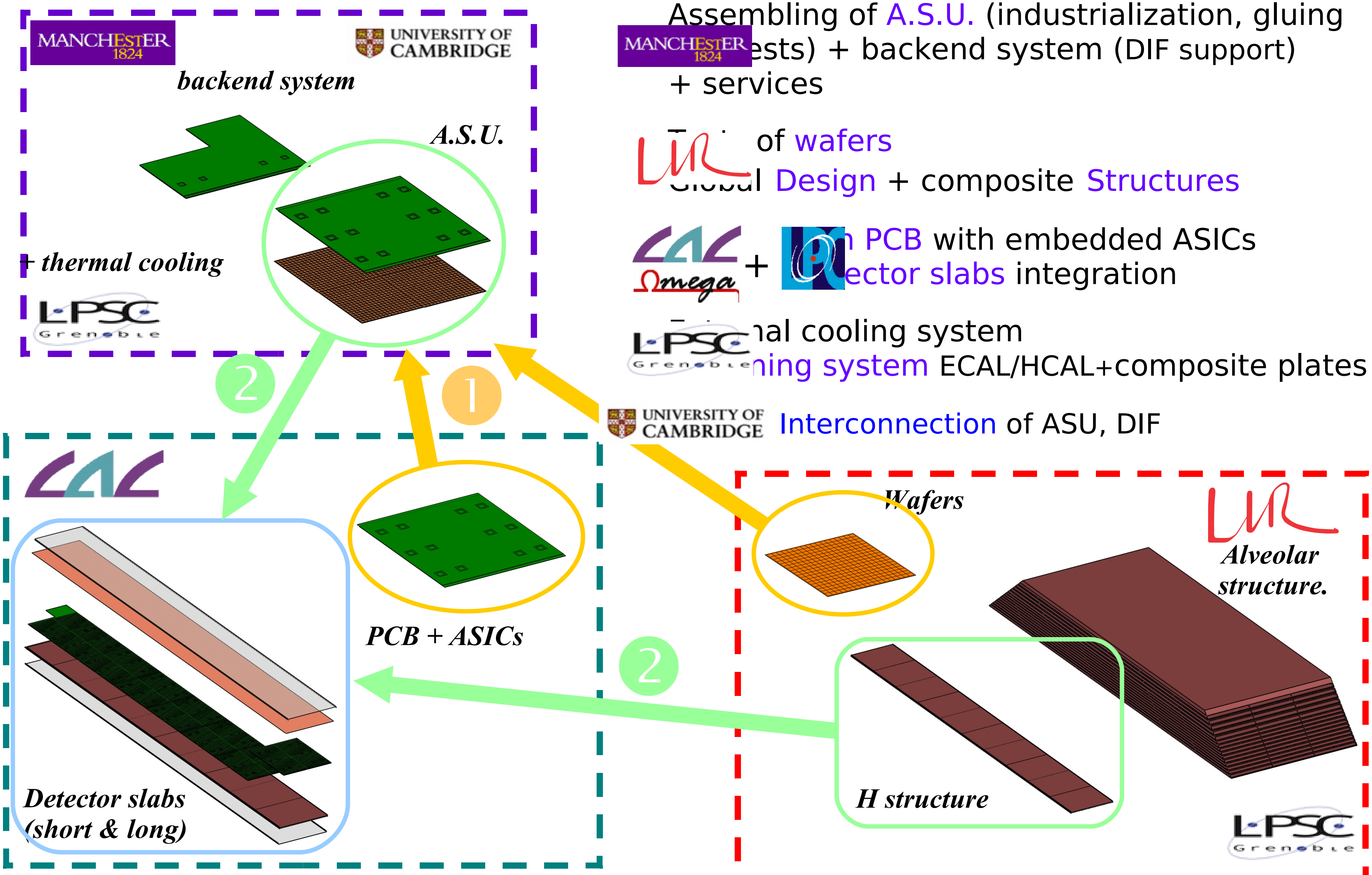
Ambient Temperature	22		
Alveolar Slot	Left	Middle	Right
External		23.5	
Upper	24.8	24.8	24.6
Lower	25	30.7	25.2
Bottom	25.1	25.2	25.1

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

Parties Involved

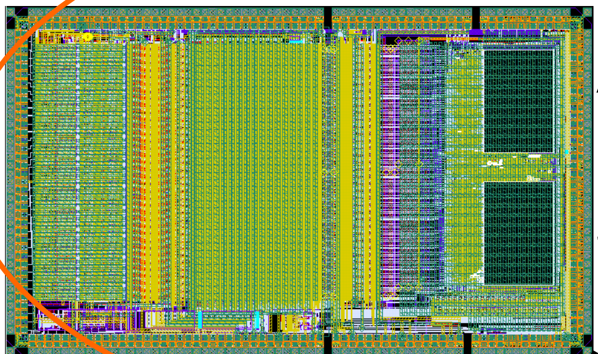
6 Laboratories are sharing out tasks in according to preferences and localization:

- Assembling of A.S.U. (industrialization, gluing …ests) + backend system (DIF support) + services
- …of wafers
- …l Design + composite Structures
- …PCB with embedded ASICs + …ector slabs integration
- …nal cooling system
- …ning system ECAL/HCAL+composite plates
- UNIVERSITY OF CAMBRIDGE: Interconnection of ASU, DIF

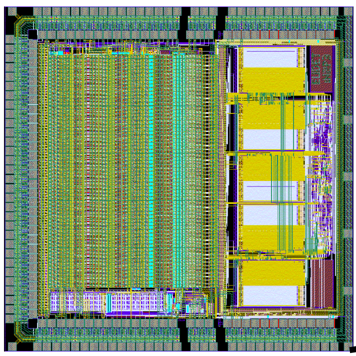


ASICs Frontales: Les Chips ROC

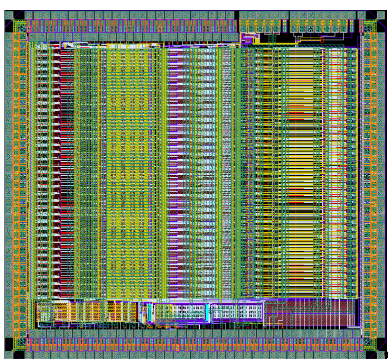
- Prototypes EUDET: modules à grande echelle (~2m)
- Financement partiel par EU (06-09)
- ECAL, AHCAL, DHCAL



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