CEPC Workshop – EU edition

Hadronic Calorimeters in CALICE

D. Boumediene on behalf of the CALICE collaboration

25/05/2018

CNRS dépasser les frontières

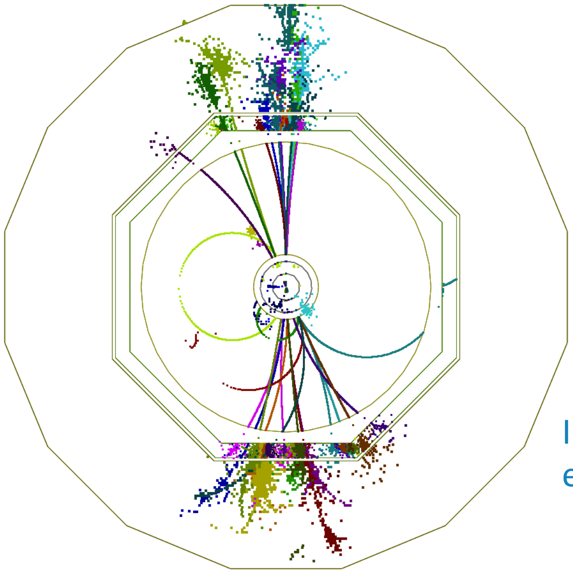
LPC Particules pLasmas Univers applicationS

Laboratoire de Physique de Clermont

CALICE Calorimeter for ILC

High granularity calorimeters

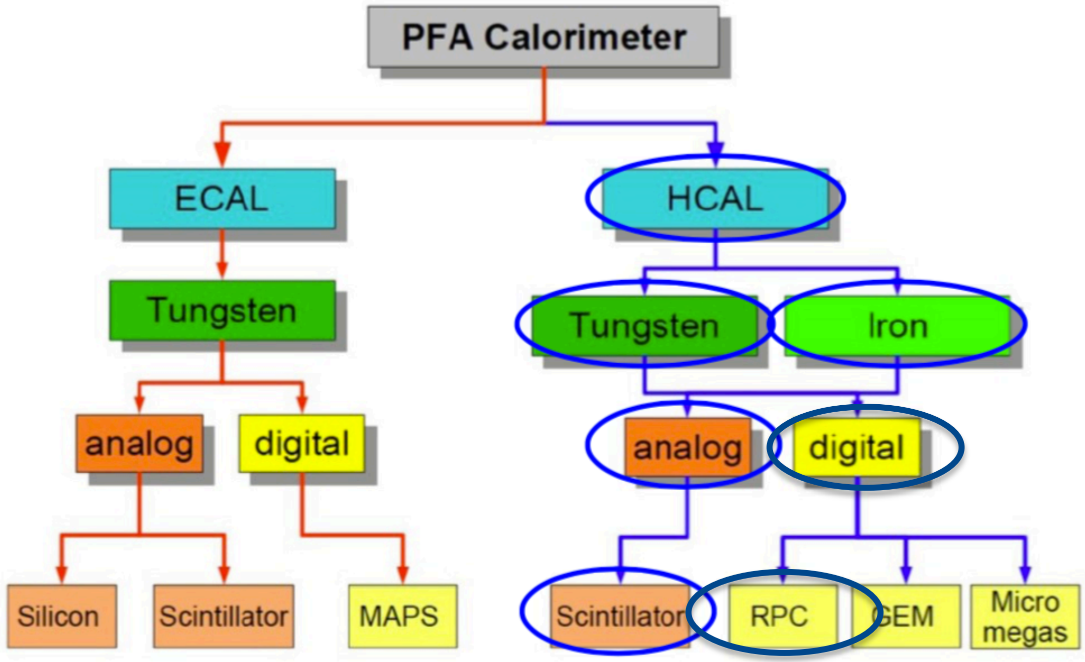
- Particle Flow analysis is an optimal way to reconstruct final states in e^+e^- collisions especially with τ, missing energy and jets…



ILD detector event display
$e^+e^- \rightarrow W^+W^- \rightarrow qqqq$

- A Particle Flow optimized hadronic calorimeter:
  - Has to be compact, fit in the magnet with negligible dead zones
  - The active component must allow fine segmentation of the signal while keeping a reasonable intrinsic energy resolution

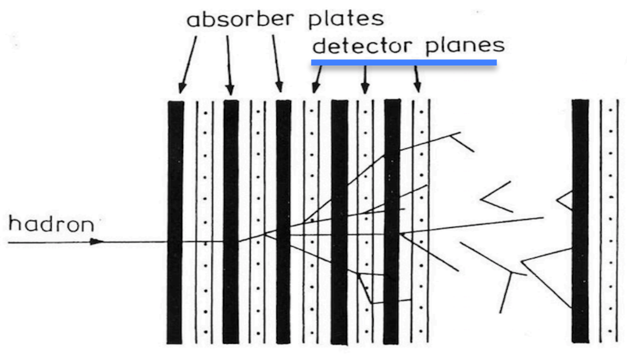
High granularity calorimeters



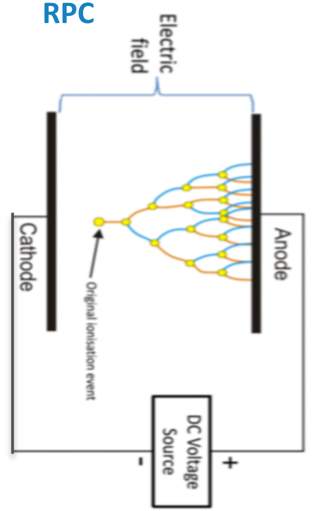
CALICE proposes Sampling hadronic calorimeters, optimised for PFlow Analysis

sDHCAL technology

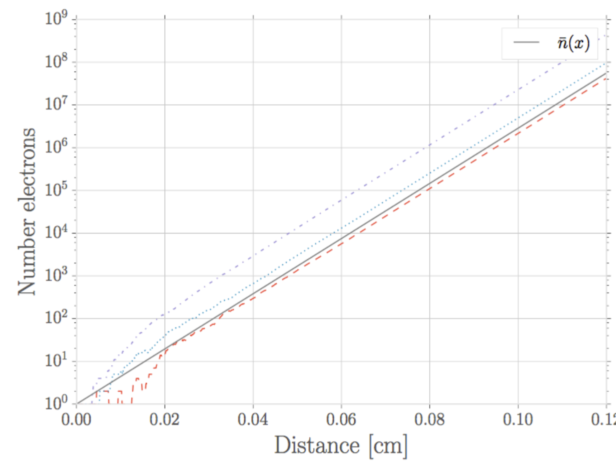
Sampling calorimeter



RPC



Charge amplification in a RPC



Advantages of Resistive Plate Chambers:

- High efficiency
- Linearity
- Low background

} → **energy resolution**

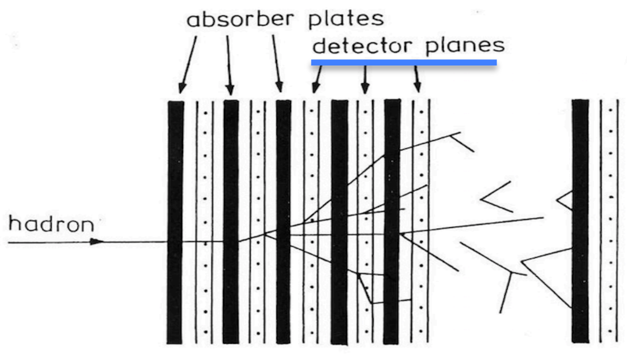
- Well contained avalanches → **fine granularity, energy resolution**
- Not expensive, robust, …

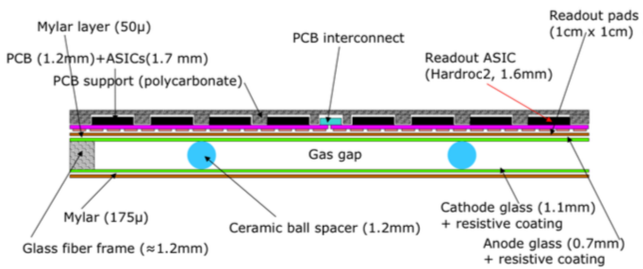
Requires:

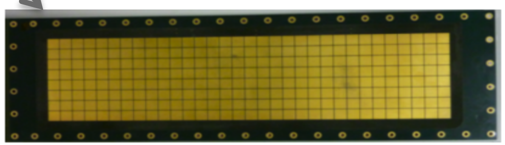
- Careful choice of the resistive material
- Control of the gas → **maintain avalanche mode, avoid saturations**

sDHCAL technology

Sampling calorimeter







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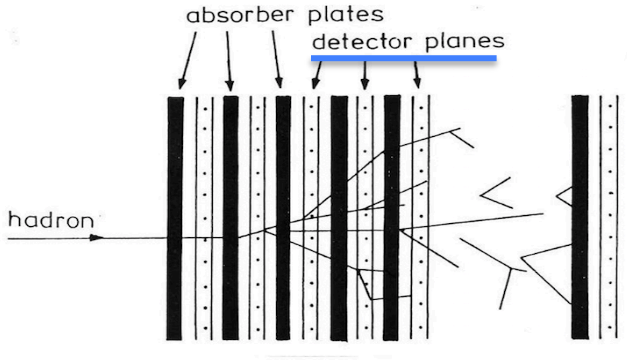
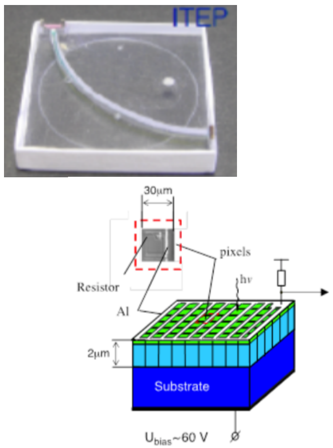
AHCAL technology

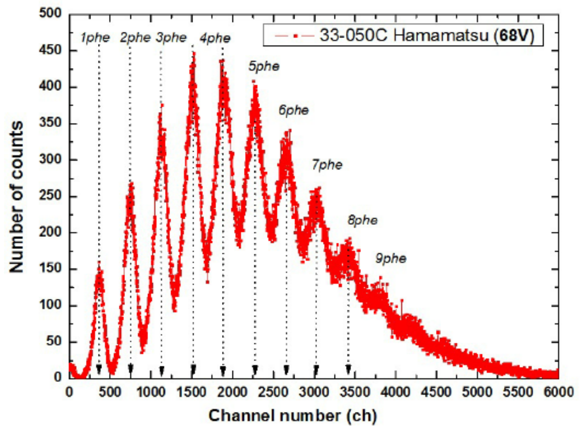
Sampling calorimeter



Scintillators + MPPC



Linearity in Phe measurement with MPPC



Advantages of scintillators and MPPC:

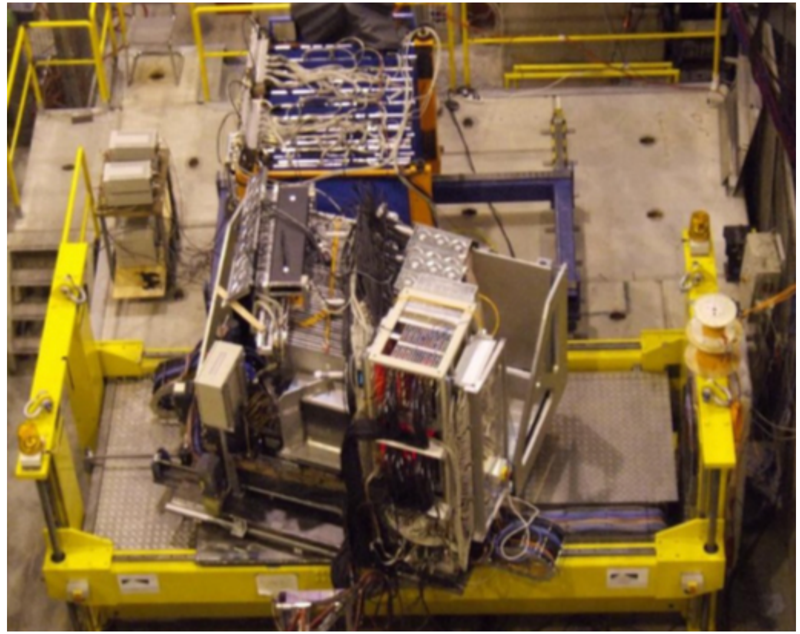
- High MPPC gain
- Scintillator linearity
- Fast resp.

} → **energy resolution**

- Scintillator segmentation → **fine granularity, energy resolution**
- MPPC Growing field

Requires:

- Careful calibration
- Study scalability



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The prototypes

The AHCAL physics prototypes

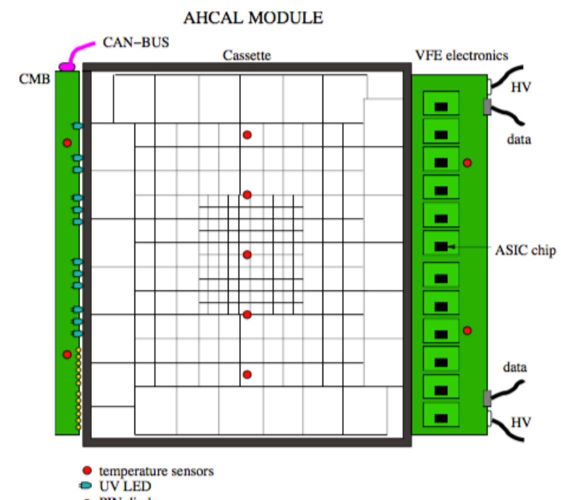
AHCAL prototype

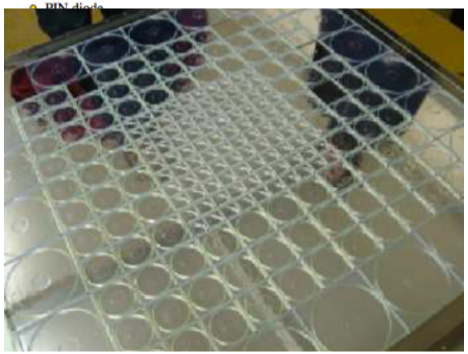
- Aim of the physics Prototype:
  - Used to validate the technology
  - Study hadronic showers
  - establish a reliable and robust calibration chain

- First large-scale application of SiPMs for scintillator calorimetry.

- AHCAL Active Layers:
  - Scintillator tiles with WLS fibers, read out by SiPMs
  - 38 m^2 Layers (5.3 λi)
  - 3x3 and 12x12 cm^2 tiles (0.5 cm)
  - no cooling within active layers

- AHCAL Readout and services:
  - voltage supply, LED system for calibration
  - front-end electronics, readout
  - 7608 channels
  - 12 bit analogue readout

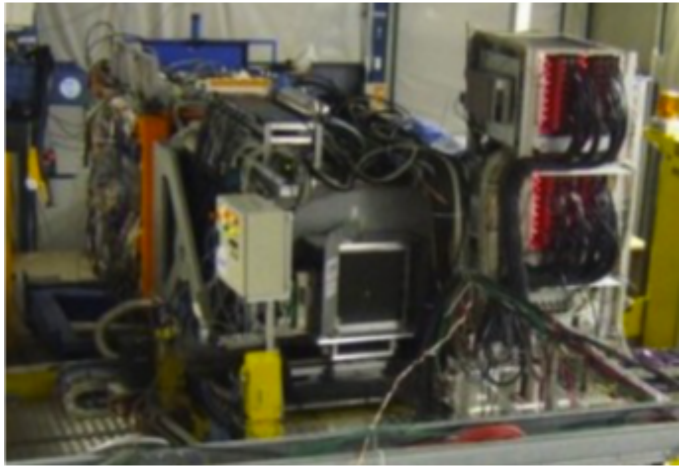




JINST 6, P04003 (2011)

AHCAL in test beam

- Test beam campaigns:
  - Since 2006 at DESY, CERN PS and SPS, FNAL
  - Exposed to hadron, muon, electron beams
- Readout:
  - Analogue readout with dedicated ASIC chip
  - 18 SiPMs per ASIC
- Calibration system:
  - Integrated calibration and monitoring system
  - Based on UV LED
  - Dedicated Boards distribute the LED light and control its amplitude



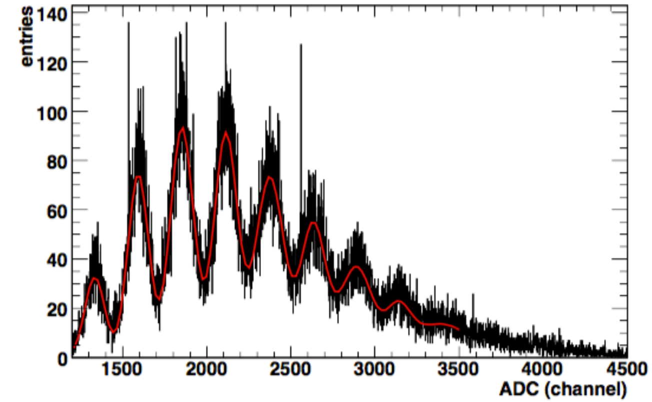
JINST 6, P04003 (2011)

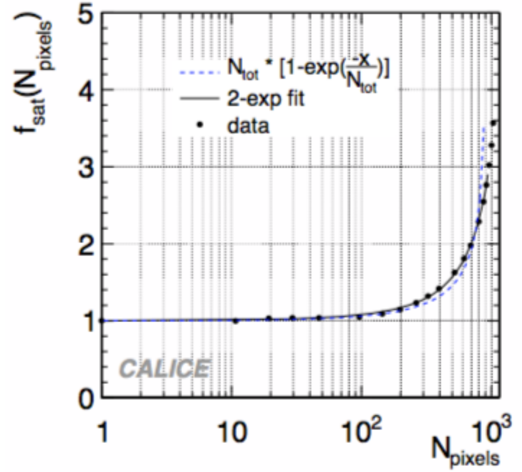
AHCAL calibration

- Approach:
  - calibration of the cell response and cell-to-cell equalization with MIPs
  - monitoring of the SiPM gain and corrections for the non-linear response;
  - calibration to an energy scale (in GeV) with electromagnetic showers.

- Regular inter-calibration of SiPM gain and electronics using:
  - Low intensity LED light
  - Single photoelectron spectrum

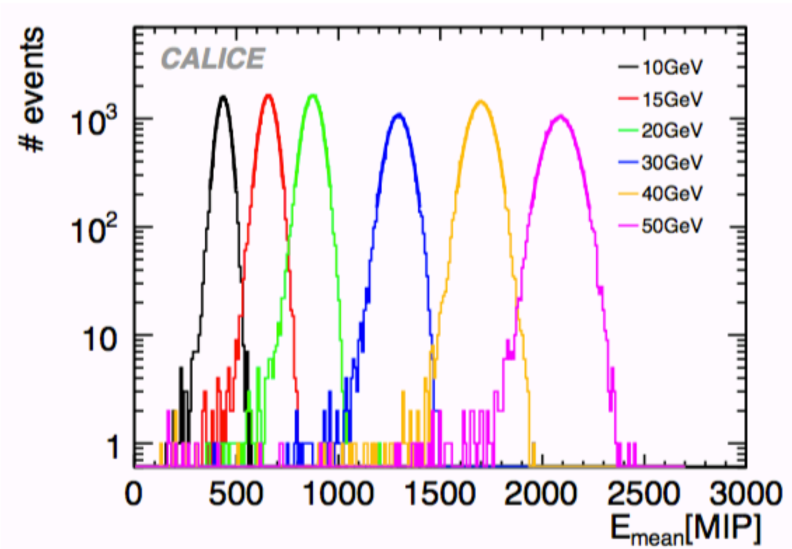
- Linearity corrections of SiPMs:
  - Intrinsically non linear devices
  - Behaviour well modelled, easily corrected

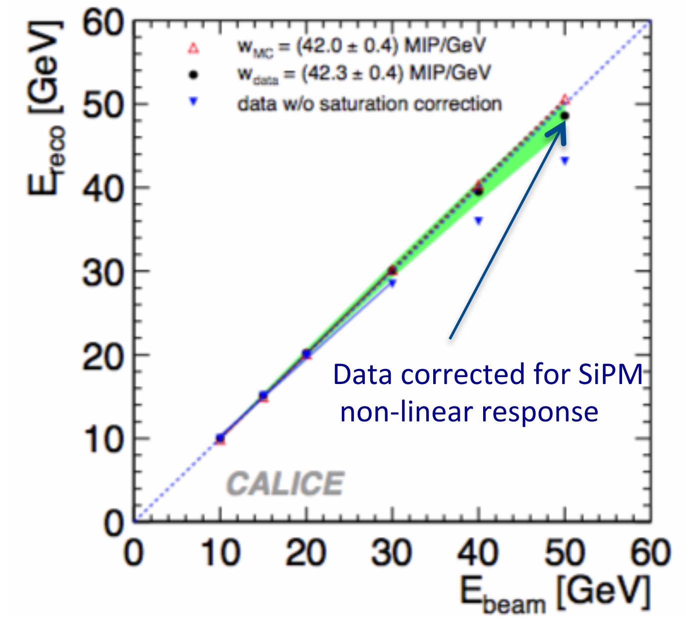




JINST 6, P04003 (2011)

AHCAL calibration





JINST 6, P04003 (2011)

- AHCAL calibration validated using positron beam at various energies
- Illustrates the MPPC linearity control and correction

AHCAL Energy reconstruction

- Energy resolution can be significantly improved with software compensating technique:
  - EM Origin of deposits characterised by the spatial density → take advantage of the spatial resolution of AHCAL
  - Assigning different weights to these components on an event by event basis

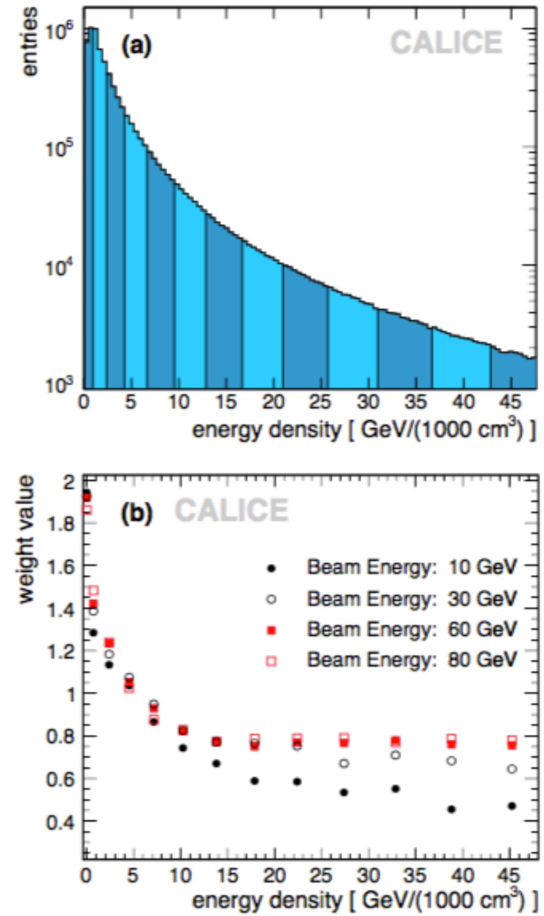
- Use of a local Corrections determined cell by cell:
  - Energy density ρ = energy of a cell / its volume
  - Each cell is weighted by:

$$\omega = p_0 + p_1 \cdot \exp(p_2 \cdot \rho)$$

  - Parameters $p_{0,1,2}$ determined by minimising:

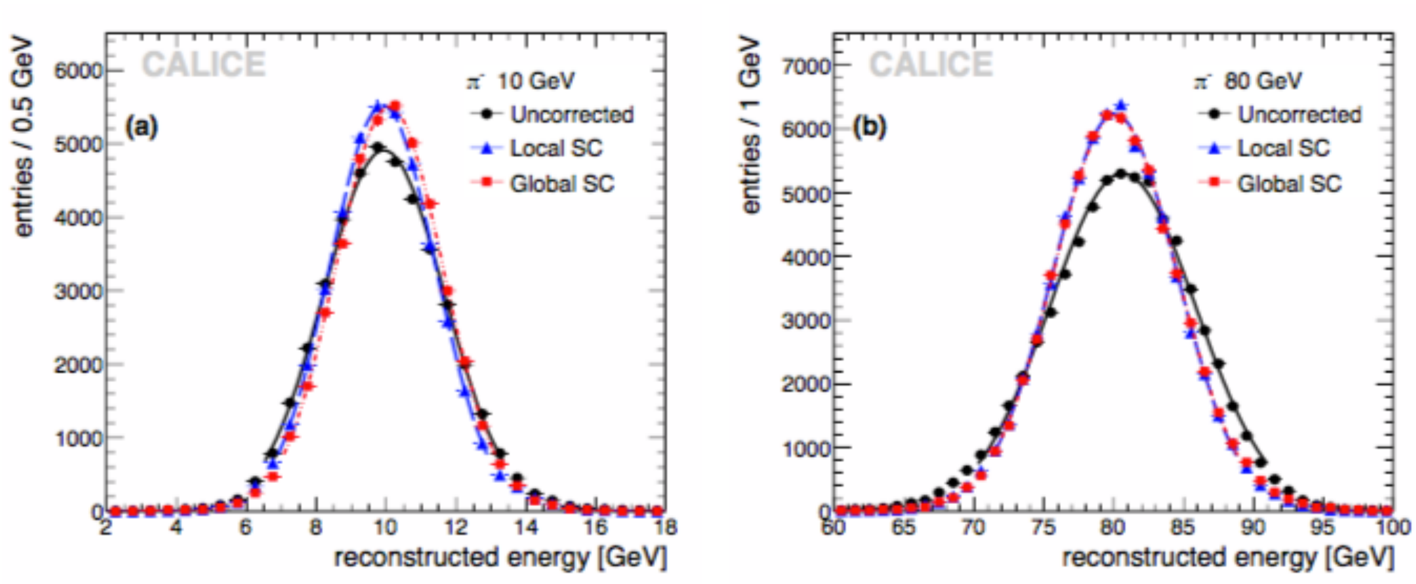
$$\chi^2 = \sum_i (E_{\mathrm{LC},i} - E_{\mathrm{beam}})^2$$

- Global software compensation, event by event: correct from EM fraction fluctuations



JINST 7, P00917 (2012)

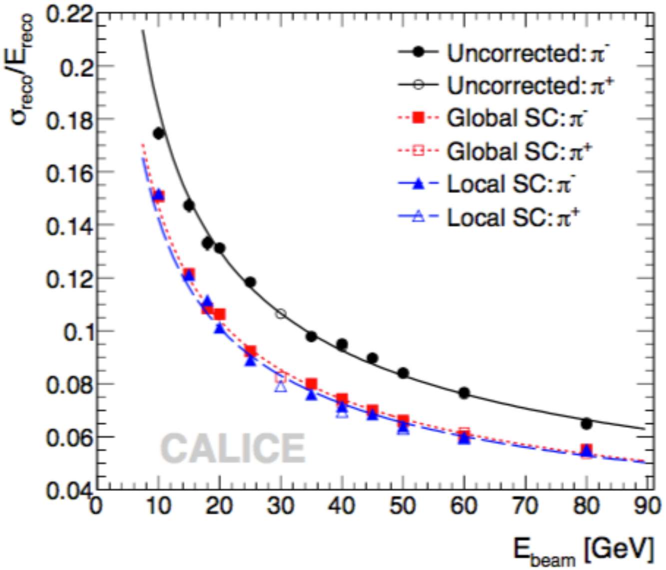
AHCAL Energy reconstruction

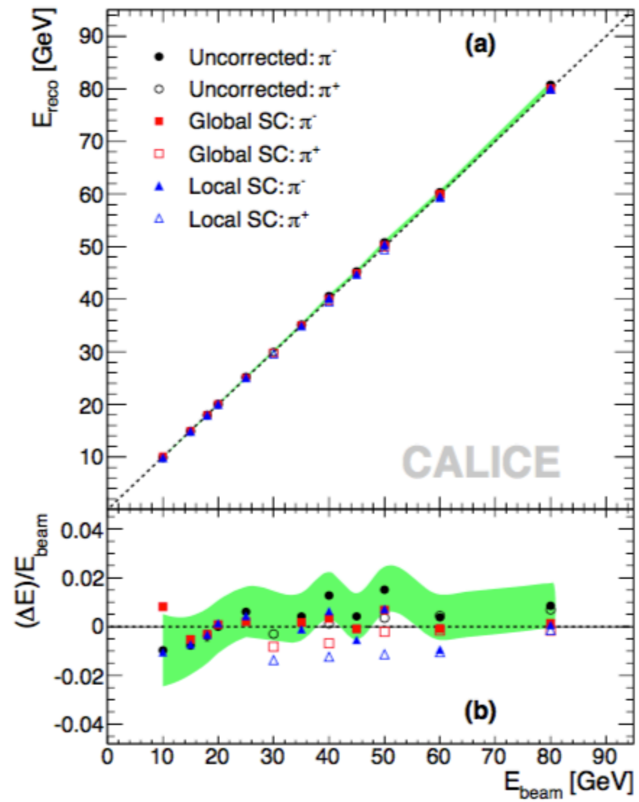


JINST 7, P00917 (2012)

Clear improvement of the reconstructed energy

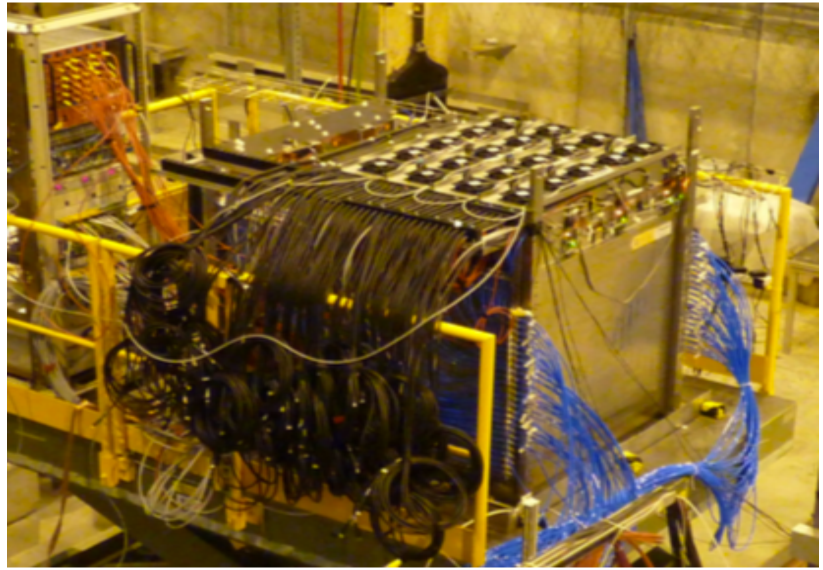
AHCAL Energy reconstruction





JINST 7, P00917 (2012)

- Comparison between direct and software compensated energy reconstructions
- **Significant improvement** of the energy resolution
- Good linearity



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The prototypes

The sDHCAL technological prototype

sDHCAL prototype

- sDHCAL Layers:
  - 48 Layers (48 GRPC) + 20 mm Stainless Steel Plates: structure of the modules and absorber

→ 50 plates, $\sim 6\lambda_I$
  - 1 m^2 layers
  - Gas mixture : 93%TFE ; 5%CO_2; 2%SF_6
  - HV ~6.9 kV → avalanche mode

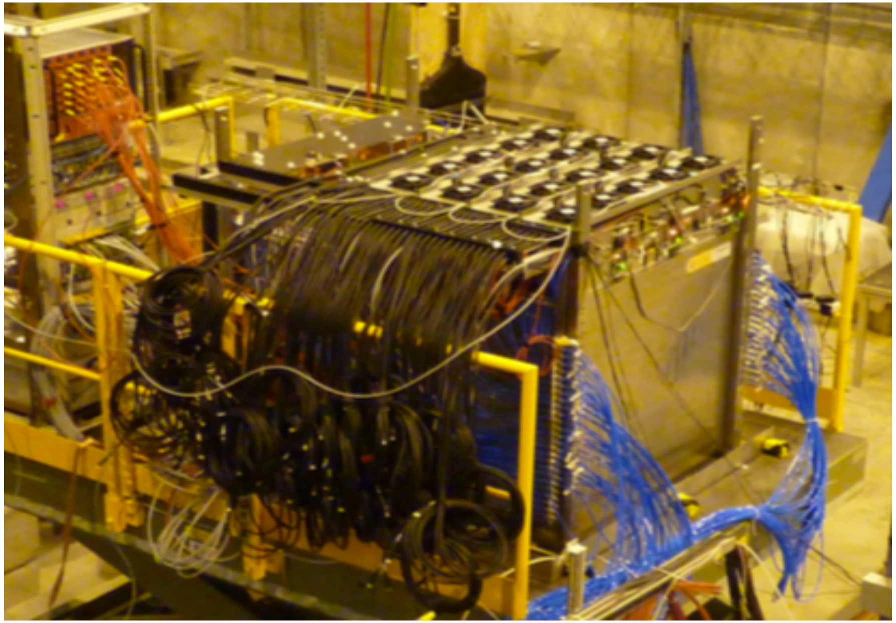
- sDHCAL Readout:
  - Embedded power-pulsed electronics
  - Semi DIGITAL → 4 states per pad (no signal, 3 levels of signal)
  - 9216 pads (1 cm^2) per chamber
  - 442k channels
  - 144×48 ASICs: Hardroc 2 (64 ch)

JINST 10 (2015) P10039

sDHCAL in test beam

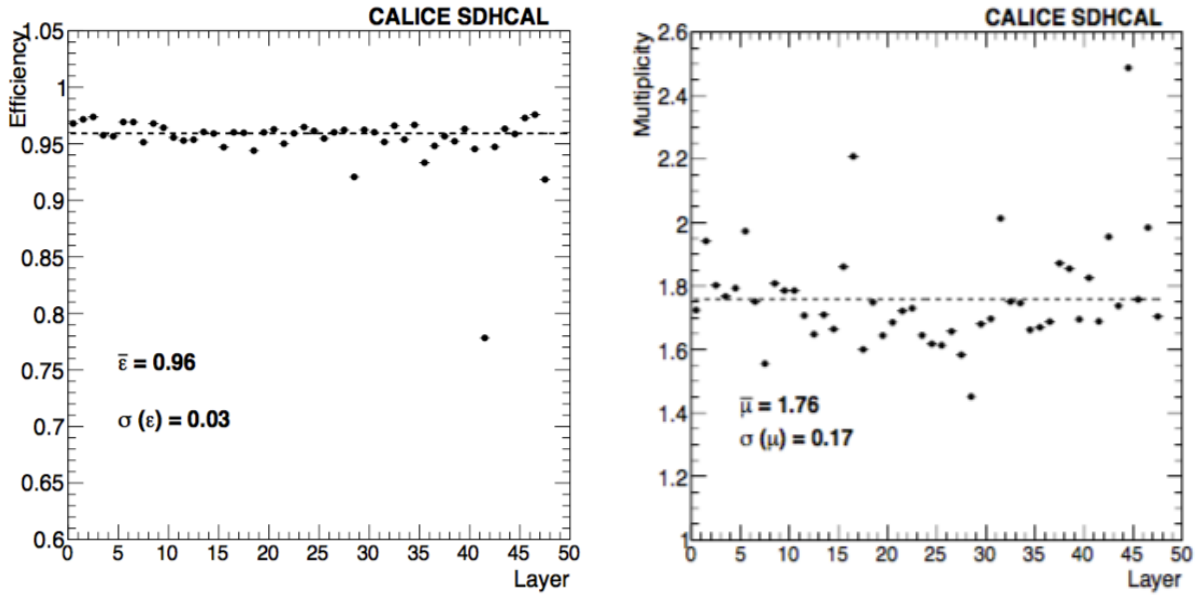
- Test beam campaigns:
  - 2012, 2015, 2016, 2017 at CERN PS and SPS
  - Exposed to hadron, muon, electron beams
- Use of power-pulsing:
  - Based on (S)PS spill structure
  - First test of the power pulsing with such a detector
- Readout:

  Different threshold configurations tested
- DAQ:
  - Based on USB & HTML protocols
  - Online monitoring

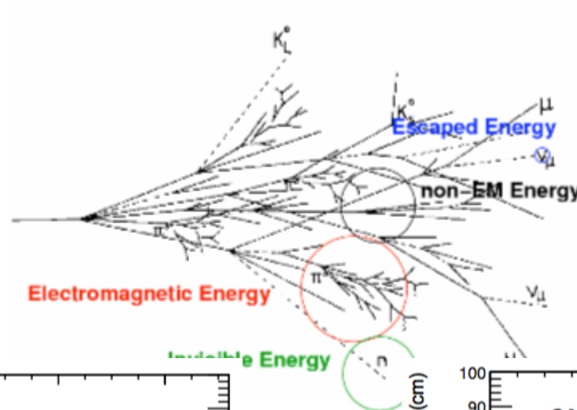


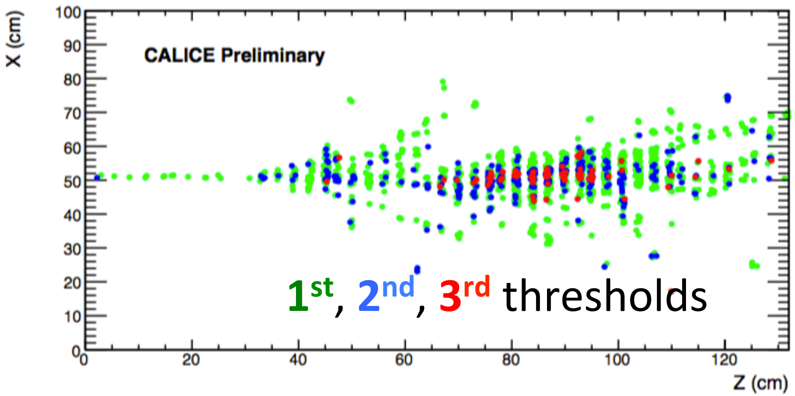
sDHCAL efficiency

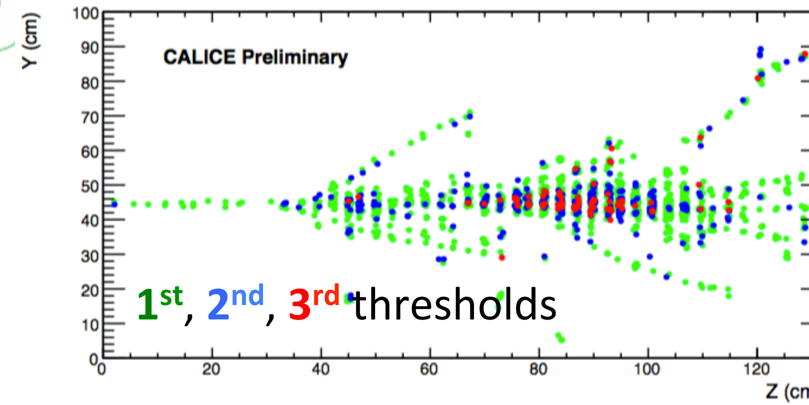
- **Detector efficiency** determined using muons
- Muons identified as tracks…
- Efficiency exceeds 90% for almost all the layers



sDHCAL: thresholds in use

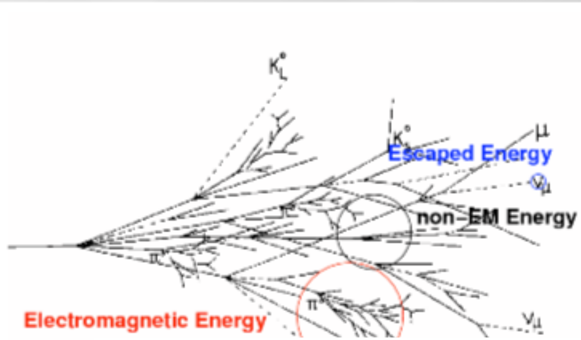


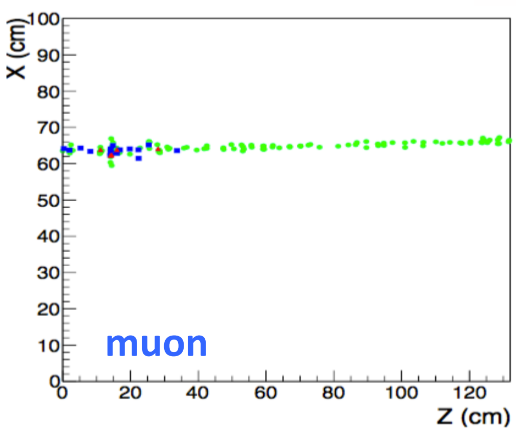


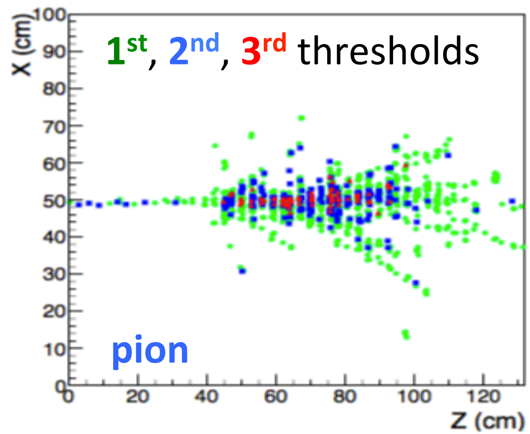


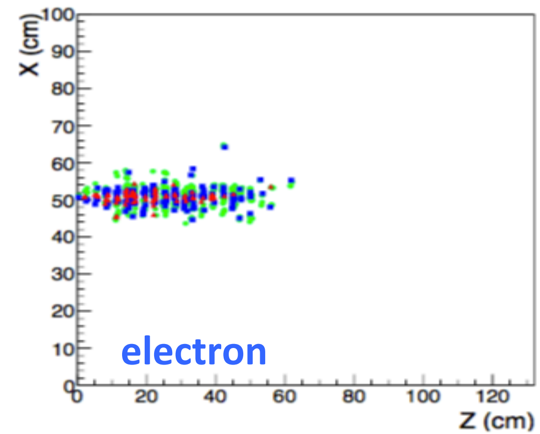
- Thresholds give a « count » of number of tracks passing a pad
- Used to create categories of hits: EM-like, tracks or hadronic-like

sDHCAL: thresholds in use









- Thresholds give a « count » of number of tracks passing a pad
- Used to create categories of hits: EM-like, tracks or hadronic-like

sDHCAL Energy reconstruction

Using binary mode:

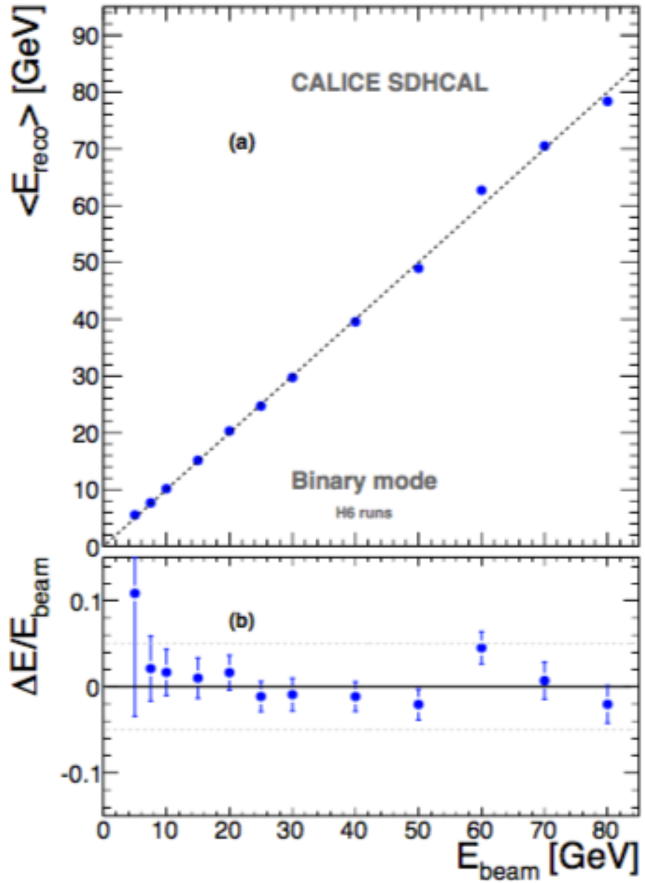
- Exploit proportionality between energy and total number of hits

$$E_{\rm reco} = A_1 N_{\rm hit} + A_2 N_{\rm hit}^2 + A_3 N_{\rm hit}^3$$

- Factors A_i measured by minimizing

$$\chi^2 = \sum_{i=1}^{N} \frac{(E_{\rm beam}^i - E_{\rm reco}^i)^2}{\sigma_i^2}$$

- Using π^+ data at various energies in the minimization



sDHCAL Energy reconstruction

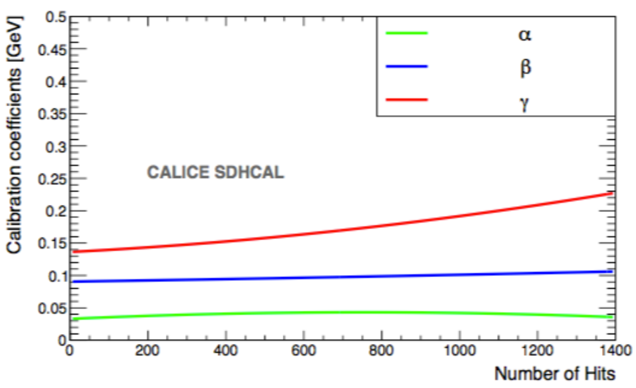
Using semi-digital mode:

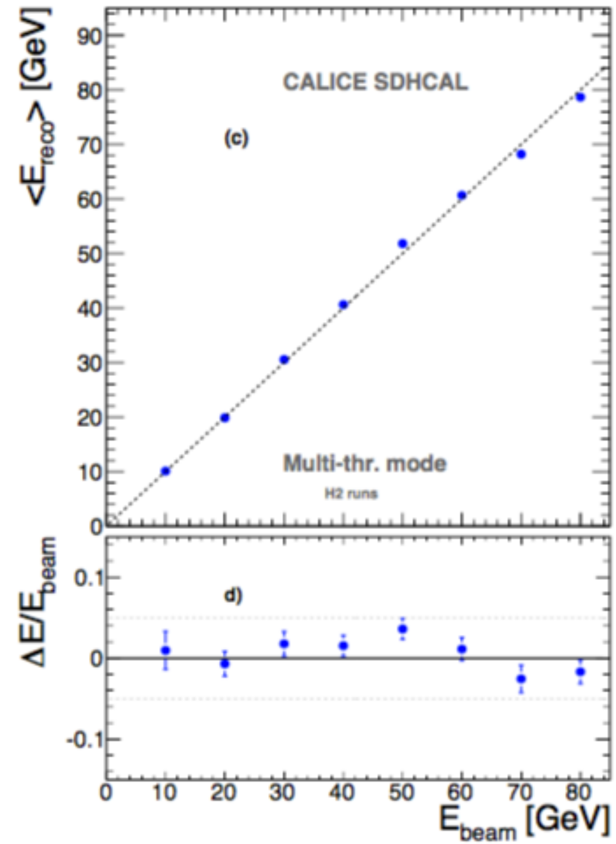
- Use the thresholds

$$E_{reco} = \alpha N_1 + \beta N_2 + \gamma N_3 \quad \text{with } \alpha,\beta,\gamma\,(N_{hit})$$

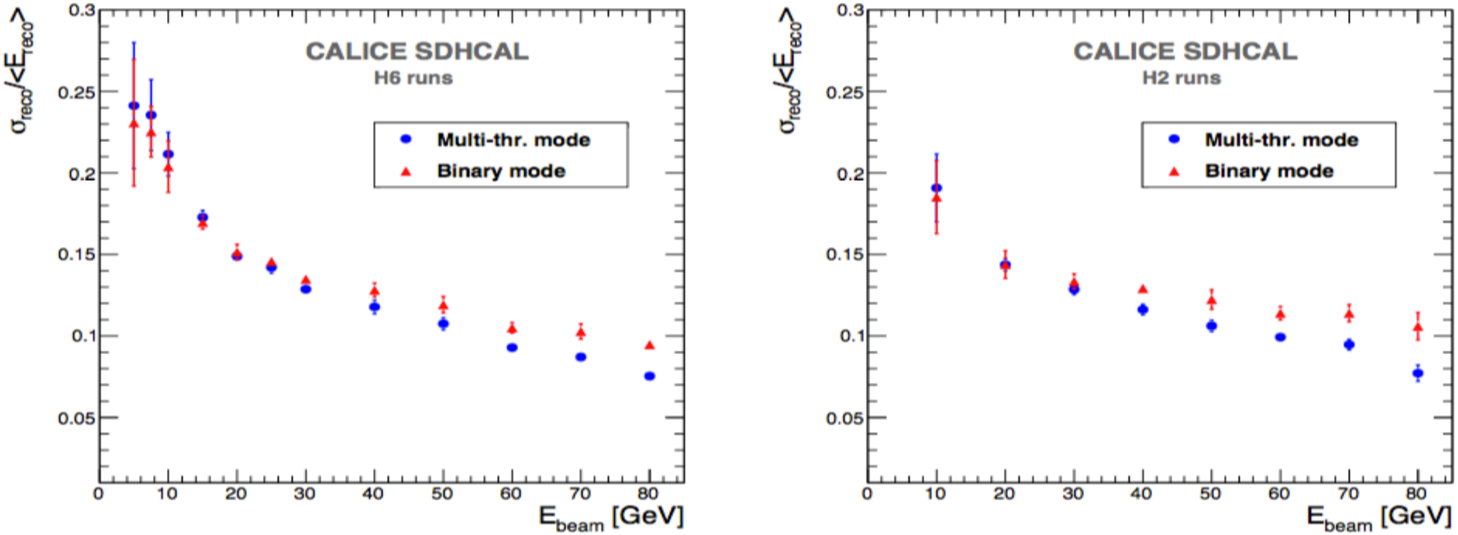
- Factors A_i measured by minimizing

$$\chi^2 = \sum_{i=1}^{N} \frac{(E^i_{beam} - E^i_{reco})^2}{\sigma_i^2}$$



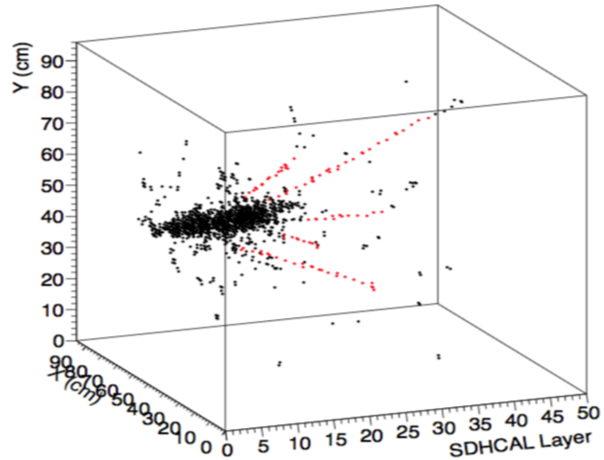


sDHCAL Energy reconstruction



JINST 11 (2016) P04001

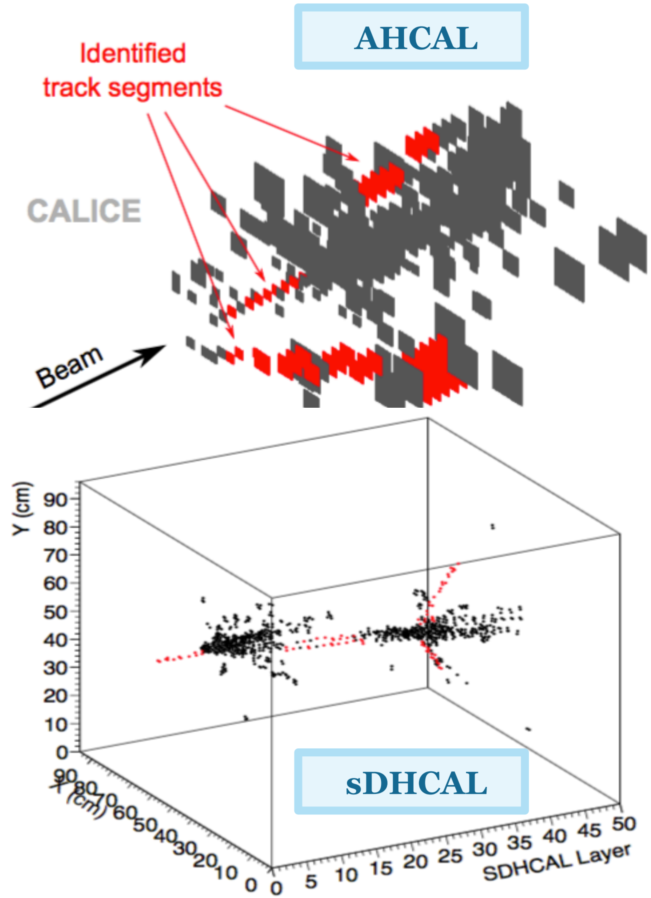
- Comparison between binary and Multi-threshold modes
- **Significant improvement** of the energy resolution for energies > 30 GeV



Imaging validation

Track reconstruction

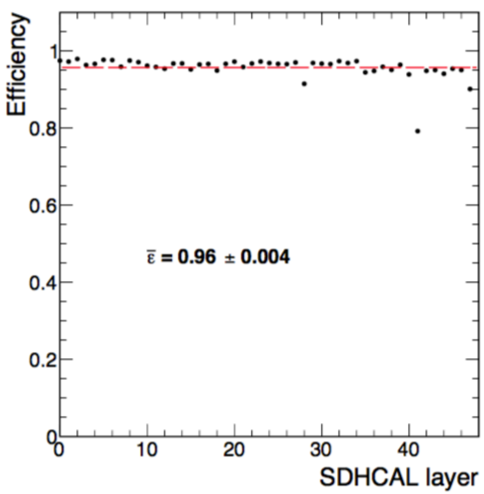
- Take benefit from the fine AHCAL/sDHCAL granularities
- **Reconstruct the tracks** in hadronic showers:
  - Can be be included in the energy reconstruction
  - Can improve PFA by connecting clusters
  - Can be used for In Situ efficiency measurements
- Use of the **Hough Transform method**



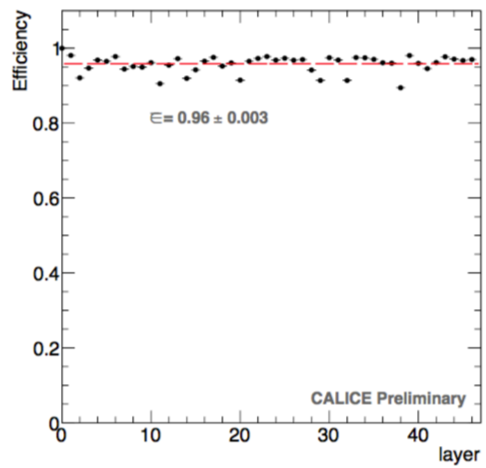
Track reconstruction

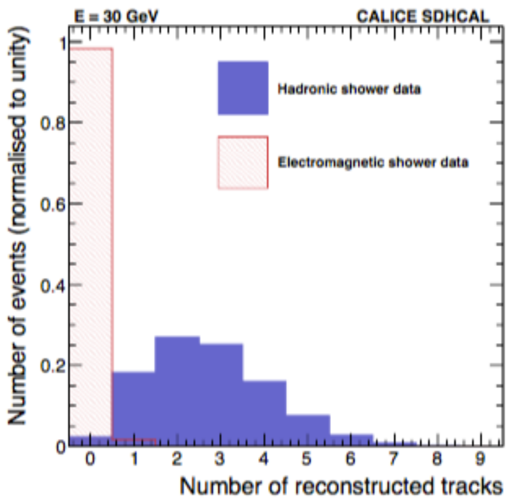
- Track reconstruction successfully applied to AHCAL/sDHCAL data
- eg., sDHCAL Efficiency estimate compared to muon data
- EM and Hadronic data compared

Efficiency estimated with beam muons



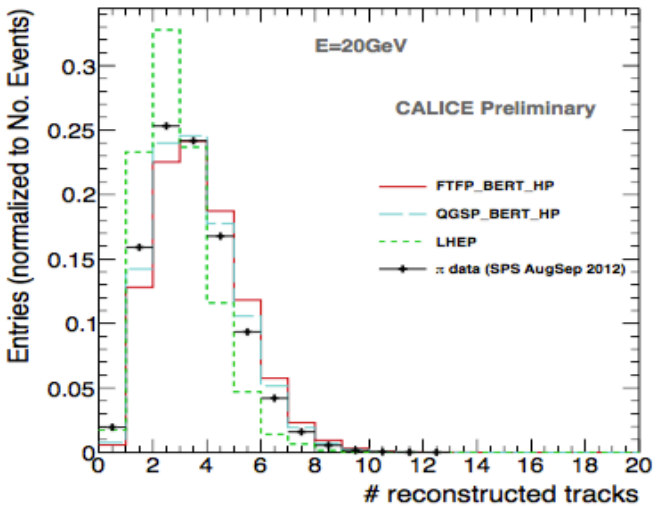
Efficiency estimated with HT tracks



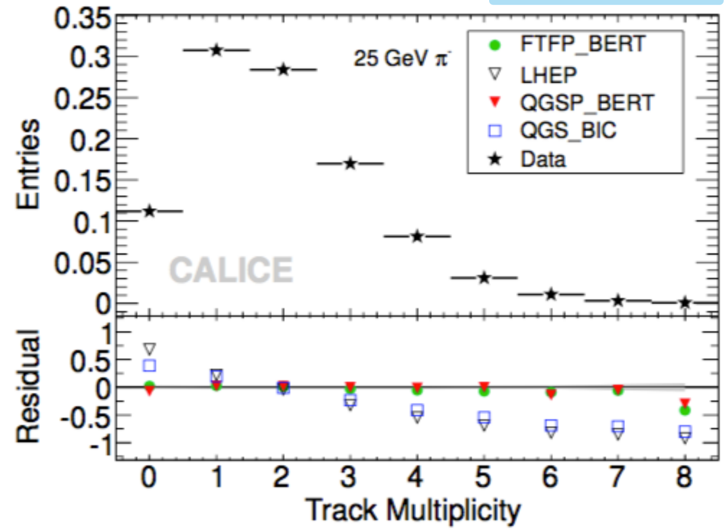


Track reconstruction

sDHCAL



AHCAL



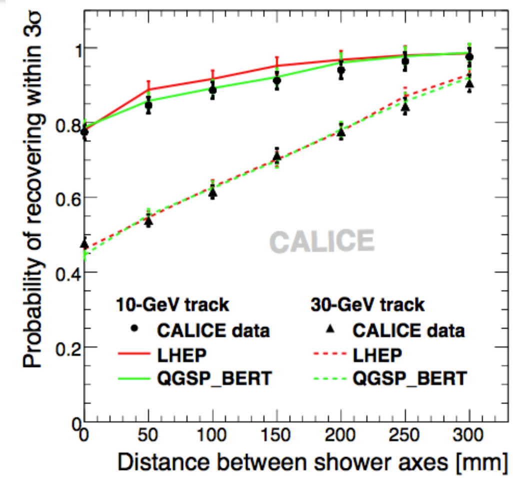
JINST 12 (2017) P05009 JINST 8

JINST 8, P09001 (2013)

- HT tracks can be used to distinguish between different hadronic shower models.
- Impact of the modelling of the detector response to be disentangled

Particle Flow Analysis

- Test PFA performances with real data :
  - Test the impact of the granularity
  - Efficiency, Purity, Energy of two adjacent hadrons
- Dedicated PFA algorithms connect hits and clusters
- Reconstruction is efficient: use of a particle PFA with this granularity was established with the prototype
- Critical distance in terms of efficiency



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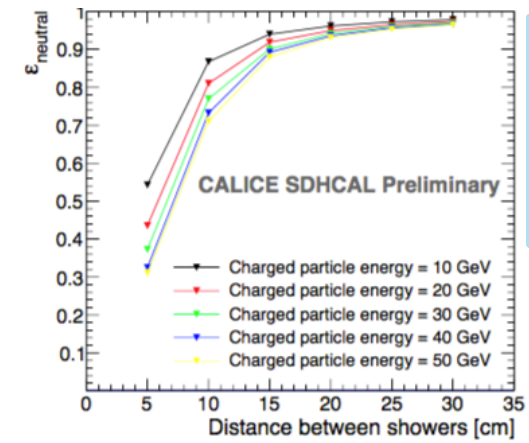
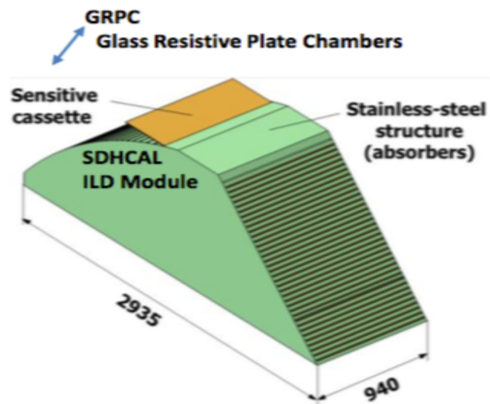
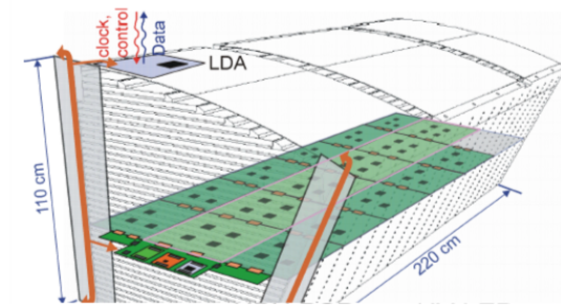


SDHCAL





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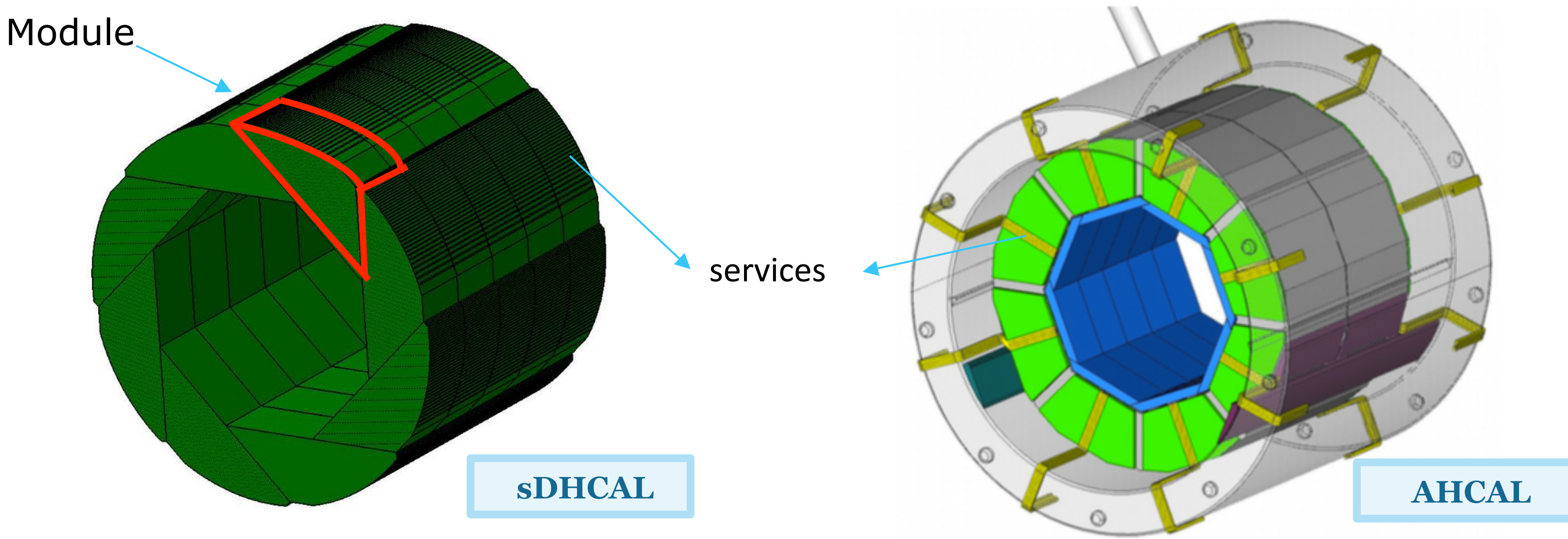
Scalability to large experiments

HCAL for ILC



- Prototypes: Clear establishment of the technologies (scintillator-SiPM or RPC) as a viable calorimetry option in a PFA-based detector
- However scalability issues:
  - Large detector planes including large surface readout
  - Large scale production

AHCAL technological prototype

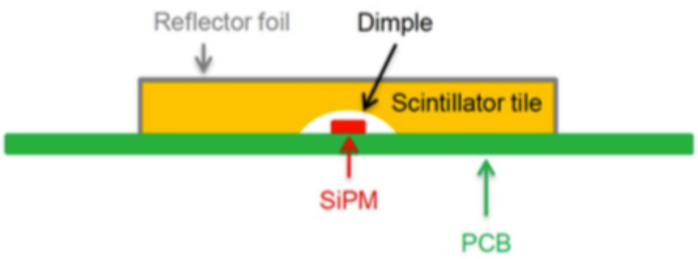
- AHCAL Physics prototype has excellent performances
- But not scalable to a collider detector:
  - external electronics
  - external LED calibration system
  - Difficult assembly

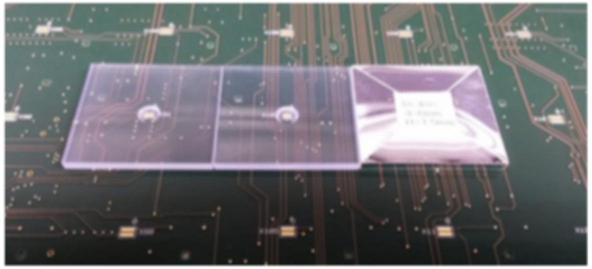
- Building of a technological prototype scalable to an ILC detector
- Interface Choices:
  - Scintillator – Sensor: With WLS fiber or direct (i.e. fiber-less) coupling
  - Sensor – PCB: In tile or surface-mounted on PCB
  - Scintillator – PCB: Individual tiles or tile arrays
  - Scintillator – LED: Light distribution or pulse distribution

AHCAL technological prototype

- Tiles with surface-mount SiPMs suitable for mass assembly
- SiPMs mounted directly on PCB
- Individually wrapped tiles

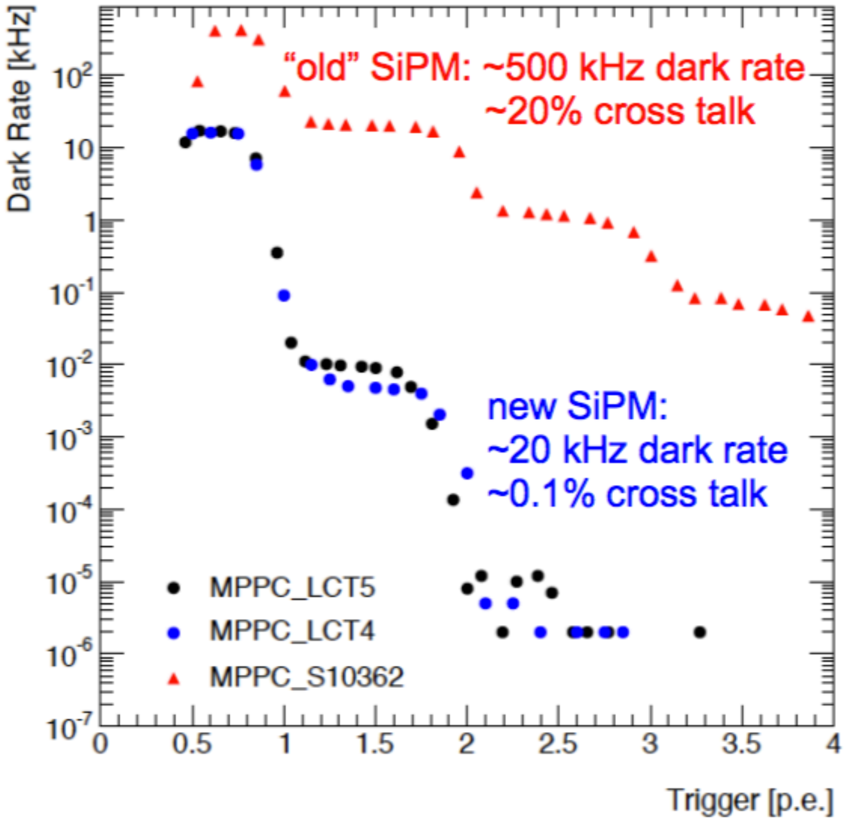
- Performance of this configuration tested:
  - In dedicated Testbeams
  - Using movable radioactive sources





AHCAL technological prototype

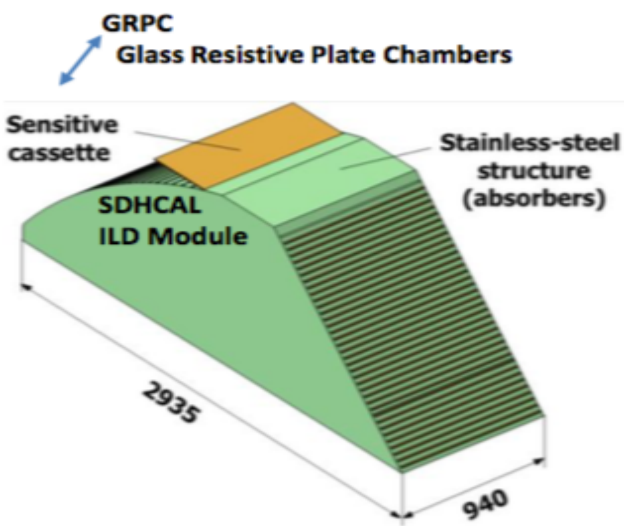
new generation of SiPMs: low noise and much improved sample uniformity



sDHCAL large prototype

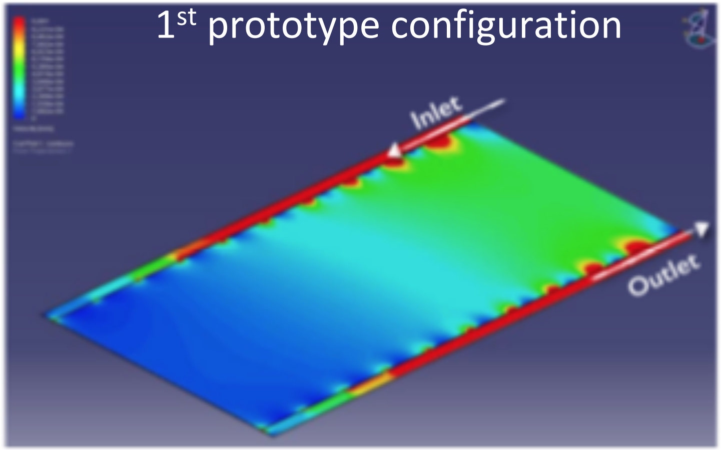
- **New prototype being produced because:**
  - Largest chambers will be 3×1 m → additional challenge
  - Electronic readout, DAQ system should be the most robust
  - Test the mechanical structure
  - Include options as timing

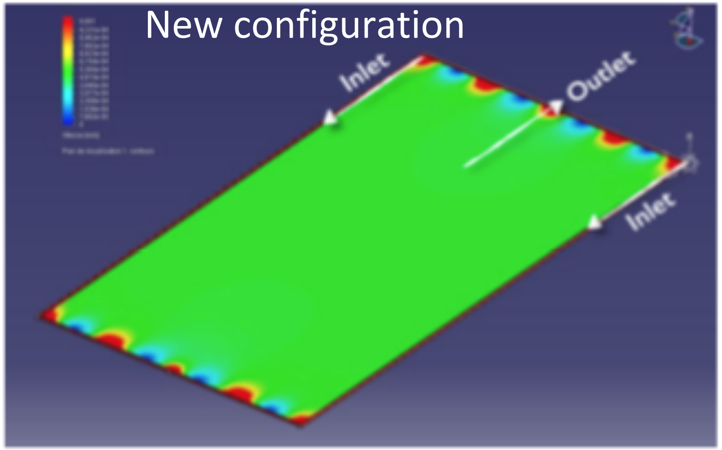
→ Produce an ILD module 0



sDHCAL mechanical improvments

- Change of gas circulation in large chambers → improved homogeneity





- Structure requirement: thickness tolerance under 50 μm and planarity under 500 μm → achieved with 1st prototype. Use of roller levelling technique to fulfil this requirement with 3 m planes

sDHCAL readout improvements

- DIFs link the DAQ to the ASICs:

  1 DIF handles 48 HARDROC2 chips in 1st prototype

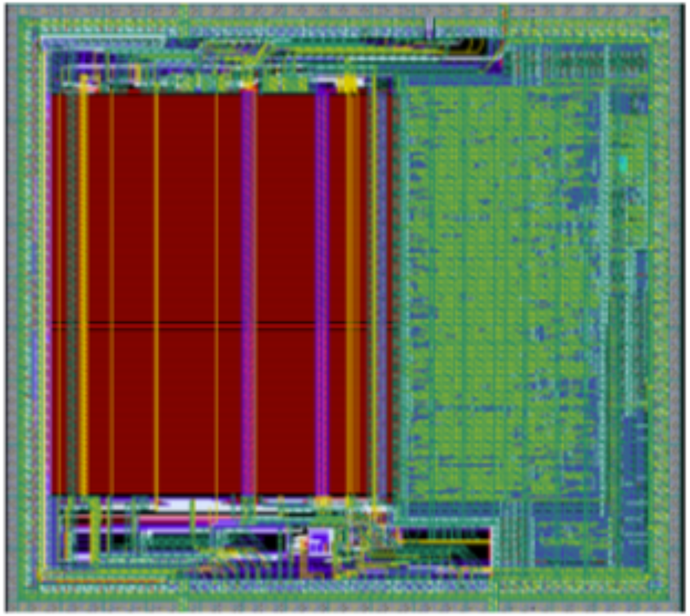
  → up to 432 HARDROC3 chips for the larger chamber

- Clock sent using HDMI in 1st prototype

  → change to fibre TTC signal

- HARDROC2 in 1st prototype

  → HARDROC3, dynamic range is extended from 15 pC to 50 pC, possibility to control each ASIC individually, fast clock generator inside the ASIC, independent channels with zero suppression, …



Summary & Outlook

- CALICE HCAL technologies optimised for future leptonic colliders: AHCAL and sDHCAL
- Two physics prototypes were produced
- Test beam data provided reach inputs:
  - Validation of the technologies
  - Bunch of results and ideas
- New prototypes being produced:
  - Will perform the last validation step (feasibility of largest chamber production)
  - Expect for the upcoming year
- sDHCAL was developed for ILD:
  - Further improvements are envisaged beyond ILC
  - Use of the timing, adding a cooling in the case of high inst. luminosity colliders (CEPC, …)
- Still many ideas to be tested or developed