Introduction

Motivation for Imaging Calorimeters

• The original motivation for CALICE: Develop highly granular calorimeters, optimised for particle flow reconstruction at future $e^+e^-$ colliders

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers

- $X_0 / \rho_M$ drive ECAL and HCAL (electromagnetic subshowers)
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  - $X_0 / \rho$ drive ECAL and HCAL (electromagnetic subshowers)
  
<table>
<thead>
<tr>
<th>Depends on material:</th>
<th>NB: Best separation for narrow showers particularly important in ECAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>• in W: $X_0 \sim 3$ mm, $\rho \sim 9$ mm</td>
<td>• Use W in ECAL!</td>
</tr>
<tr>
<td>• in Fe: $X_0 \sim 20$ mm, $\rho \sim 30$ mm</td>
<td></td>
</tr>
</tbody>
</table>

When adding active elements: ~ 0.5 cm$^3$ segmentation in ECAL, ~ 3 - 25 cm$^3$ in HCAL

- $O 10^{7-8}$ cells in HCAL, $10^8$ cells in ECAL for typical detector systems!
- fully integrated electronics needed
- requires active elements that support high granularity and large channel counts
- need technical solutions amenable to mass production & automatisation
Introduction & Overview

Phases of CALICE Development

• **Validation** of the concept of highly granular calorimetry:
  Physics prototypes with different ECAL and HCAL technologies in beam
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  • Development of reconstruction techniques for granular calorimeters
  • Comparison to and validation of GEANT4 simulations - providing input to development of physics lists
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  Technological prototypes, with fully embedded electronics, power pulsing,... tested in particle beams, partially with magnetic field
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• **Application** of CALICE technology in running experiments:
  • Use of CALICE detector elements
  • Full detector systems based on CALICE technology

... not discussed in any detail today
Validation & Exploitation

*The CALICE Physics Prototypes:*
Performance, Reconstruction Techniques, Shower Studies
A rich test beam program, with a variety of different prototypes

Electromagnetic - Tungsten absorbers

- analog: Silicon and Scintillator/SiPM
- digital: Silicon (MAPS)

39 Mpixels in 160 cm²

Hadronic - Steel and Tungsten absorbers

- analog: Scintillator/SiPM (Fe and W)
- (Semi)digital: RPCs (Fe, W digital only)

+ few-layer SD prototype with Micromegas
Silicon-Tungsten ECAL:

\[ \chi^2 / \text{ndf} = 30.69 / 32 \]

- CALICE 2006 data
- Monte Carlo

- stochastic term: 16.5%
- constant term: 1.1%

Scintillator-Tungsten ECAL:

\[ \sigma_E / E = 1.2\% + 12.5% / \sqrt{E_{\text{beam}}} \]

Scintillator provides better energy resolution due to larger sampling fraction, with a reduced compactness

[N.B. Detector optimized for particle separation, not single particle resolution]
Performance of Highly Granular Calorimeters

Energy resolution - Hadronic

Figure 29. Mean reconstructed energy for pion showers as a function of the beam energy (a) of the 2012 H2 (blue) and the 2012 H6 (red) data. The dashed line passes through the origin with unit gradient. Relative deviation of the pion mean reconstructed energy with respect to the beam energy as a function of the beam energy (b) of the 2012 H2 (blue) and the 2012 H6 (red) data. The reconstructed energy is computed using the three thresholds information as described in section 6.2.

(c) is the relative resolution of the reconstructed hadron energy as a function of the beam energy of the 2012 H2 (blue) and the 2012 H6 (red) data.

Finally, we think that the exploitation of the topological information provided by such a high-granularity calorimeter to account for saturation and leakage effects in an appropriate way as well as the application of an electronic gain correction to improve on the calorimeter response uniformity are likely to improve the hadronic energy estimation and should be investigated in future works.

8. acknowledgements

We would like to thank the CERN-SPS staff for their availability and precious help during the two beam test periods. We would like to acknowledge the important support provided by the F.R.S.-FNRS, FWO (Belgium), CNRS and ANR (France), SEIDI and CPAN (Spain). This work was also supported by the Bundesministerium für Bildung und Forschung (BMBF), Germany; by the Deutsche Forschungsgemeinschaft (DFG), Germany.

Software compensation (SC) and semi-digital reconstruction use weighting factors to optimise energy resolution.
Performance of Highly Granular Calorimeters

Particle Separation

- A key figure of merit for PFA performance
- studied with overlaid test-beam events for SiW ECAL + AHCAL

![Diagram showing probability of recovering within 3σ for 10-GeV and 30-GeV tracks for CALICE data and Monte Carlo simulations]

**Figure 5.** Probability of neutral 10 GeV hadrons energy recovering within 3σ (left) and 2σ (right) standard deviations from its real energy vs. the distance from charge d1 0 GeV (circles and continuous lines) and 30 GeV (triangles and dashed lines) hadrons for beam data (black) and for Monte Carlo simulated data, for both LHEP (red) and QGSP_BERT (green) physics lists.
Performance of Highly Granular Calorimeters

Particle Separation

- A key figure of merit for PFA performance
- studied with overlaid test-beam events for SiW ECAL + AHCAL

![Graph showing particle separation](image)

**Figure 5.** Probability of neutral 10 GeV hadrons energy recovering within 3σ (left) and 2σ (right) standard deviations from its real energy vs. the distance from charge d1 0 GeV (circles and continuous lines) and 30 GeV (triangles and dashed lines) hadrons for beam data (black) and for Monte Carlo simulated data, for both LHEP (red) and QGSP_BERT (green) physics lists.

Summary

To test the particle flow algorithm, PandoraPFA, we have mapped pairs of CALICE test beam events, shifted by the definite distances from each other, on to the ILD geometry. Then we modified the treatment of tracks in the PandoraPFA processor for the case of straight tracks. In this study we have investigated the hadron energy range typical for a 10 GeV jet. For jet fragmentation energies from 10 GeV to 30 GeV we estimated the confusion error for the recovered neutral hadron energy caused by the overlapping of showers.

We have confronted our result for test beam data with the result of Monte Carlo simulations for LHEP and QGSP_BERT physics lists. The results for the data and MC are in a good agreement.
Energy Reconstruction with Software Compensation

Exploitation: Algorithms

- Studying energy resolution in a “real-world” setting: A combined system of SiW ECAL, Scintillator/FE HCAL, Tail Catcher
- A combination of non-compensating systems with different active and absorber materials and varying longitudinal sampling
- Exploiting granularity: Local energy density can be used to improve energy resolution with software compensation methods

**ECAL (30 layers):**
Absorber: W; 1.4 mm, 2.8 mm, 4.2 mm
Active: Si; 525 µm

**HCAL (38 layers) / TCMT (8+8 layers):**
Absorber: Steel; ~ 21 mm (including cassettes)
Active: Plastic scintillator; 5 mm
Energy Reconstruction with Software Compensation

The Principle

• The basis of the technique: Local shower density depends on origin of energy deposits: higher density for electromagnetic subshowers
  ➤ Impact of non-unity e/h can be reduced by assigning energy-dependent weights to hits in global energy sum
Energy Reconstruction with Software Compensation

The Principle

- The basis of the technique: Local shower density depends on origin of energy deposits: higher density for electromagnetic subshowers
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weights are energy dependent: overall shower density changes with energy!
Energy Reconstruction with Software Compensation

Resulting Performance

- Substantial improvement in energy resolution:
  - SC in ECAL alone up to 8% improvement
  - SC in HCAL alone up to 23% improvement
  - Full SC up to 30% improvement, for a stochastic term of 42.5% and a constant term of 2.5%

\[ \text{CERN & FNAL TB, Fit: } a/V_{\text{GeV}} \oplus b \oplus 0.18 \text{ GeV/E} \]

- Standard Reco.: \( a=(54.25\pm0.13)\% \) \( b=(4.6\pm0.05)\% \)
- ECAL SC: \( a=(51.58\pm0.17)\% \) \( b=(3.52\pm0.07)\% \)
- HCAL SC: \( a=(46.58\pm0.16)\% \) \( b=(3.2\pm0.07)\% \)
- Full SC: \( a=(42.55\pm0.14)\% \) \( b=(2.5\pm0.07)\% \)

\[ \text{\textless The bulk of the improvement is achieved in the AHCAL} \]

- Software compensation also reduces tails and asymmetries in the energy distribution, in particular at lower beam energies

\[ \text{CALICE Preliminary} \]

\[ \text{Si-W ECAL + AHCAL + TCMT} \]
Energy Reconstruction with Software Compensation

Exploitation: Algorithms - Transfer to Particle Flow

- Particle flow algorithms make use of calorimeter energy at two main points
  - Track - calorimeter cluster matching, and iterative reclustering
  - Energy of neutral particles

transfer software compensation algorithm and training strategies from CALICE to full ILD detector simulations

em sub showers (in shower core) weighted less than hadronic periphery

ECAL not yet included: standard reconstruction used
Energy Reconstruction with Software Compensation

Exploitation: Algorithms - Transfer to Particle Flow

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Transfer software compensation algorithm and training strategies from CALICE to full ILD detector simulations

- Em sub showers (in shower core) weighted less than hadronic periphery

EcAL not yet included: standard reconstruction used

Graph showing RMS of energy resolution as a function of jet energy [GeV], with different correction methods: No energy correction, SC only neutral hadrons, SC for all at reclustering, Intrinsic energy resolution, Confusion term.
Different Schemes of Hadronic Energy Reconstruction

**Understanding the Performance of Highly Granular Calorimeters**

- CALICE hadron calorimeters use different schemes for energy reconstruction - depending on readout technology:
  - *scintillator*: analog & software compensation
  - *gas*: digital (1 bit), semi-digital (2 bit)

N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

- Different schemes tested on AHCAL data (3 x 3 cm² granularity)

---

**Figure 20**: Energy dependence of the relative energy resolution of the AHCAL test beam data in (a) and the simulation with 3 x 3 cm² granularity and the FTFP BERT physics list in (b), obtained using different approaches for the energy reconstruction of pions: analogue (black), digital (green), semi-digital (red) and applying the software compensation algorithm (blue). The dashed and dotted curves in (a) show the resolution achieved in [3] with and without software compensation techniques, using the energy deposits in the TCMT and in the ECAL in addition to the AHCAL. The plots on the top show the residuals to the beam energy with the bands indicating the systematic and statistical uncertainties. The purely statistical errors are smaller than the markers.

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**Understanding the Performance of Highly Granular Calorimeters**

N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

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N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

- Different schemes tested on AHCAL data (3 x 3 cm² granularity)
- Simulations used to study 1 x 1 cm² granularity (scintillator)
- Digital & fine granularity best at low energy: Suppression of fluctuations
- SC & semi-digital comparable

NB: Sampling fraction matters: Semi-digital reconstruction in RPCs does not reach the same resolution
Understanding Hadronic Showers

Highlights and Expectations

Hadronic showers are complex:

- **compact** - characterizes regions close to inelastic interactions
- **sparse** - results in MIP-like particles connecting regions of higher activity
- **extended in time**: few 10 ns from travel time of MeV-scale neutrons
  - longer delays up to µs (and more) from thermal neutron capture and subsequent photon emission
Understanding Hadronic Showers

Highlights and Expectations

• Hadronic showers are complex:
  
  compact - characterizes regions close to inelastic interactions

  sparse - results in MIP-like particles connecting regions of higher activity

  extended in time:
  • few 10 ns from travel time of MeV-scale neutrons
  • longer delays up to µs (and more) from thermal neutron capture and subsequent photon emission

• Simulation is crucial to optimise detectors and to analyse data

  → CALICE data with unprecedented granularity provides a new level of information to improve modeling of showers in GEANT4
Understanding Hadronic Showers

Selected Results on Spatial Structure
In version 9.6 of Geant4, the longitudinal energy profile of pions at 10 GeV was not predicted well by the FTFP BERT physics list. In contrast, its satisfactory prediction was observed in version 9.3 of Geant4. Some errors have been identified by the Geant4 developers in version 9.6, which are corrected in the new release. Recently, the latest version (version 10.1) of Geant4 became available for production within the CALICE simulation chain. In order to see if the prediction of the longitudinal energy profile was improved, a sample of 500 k events at 10 GeV has been generated and analysed in the same way as was done for the published analysis. Figure 1 shows the addition of the profile found in version 10.1 of Geant4. The result from version 10.1 is closer to the data than the result from version 9.6, however, the improvement is not sufficient to describe the data in a satisfactory manner. The fact that Geant4 physics lists are tuned exclusively on thin target scintillator data, could still be a cause that for silicon the prediction deviates from the data.
SiW ECAL - the first interactions

ΔE in layer [MIP]

Shower depth [pseudolayer]

0 10 20 30 40 50

10 GeV

- FNAL 2008
- FTFP_BERT G4 v9.3
- FTFP_BERT G4 v9.6
- FTFP_BERT G4 v10.1

NIM A794, 240 (2015)

CALICE Fe-AHCAL

JINST 11 P06013 (2016)

Frank Simon (fsimon@mpp.mpg.de)
Surprisingly good reproduction of data by Geant4

- The average hit energy per layer predicted in different versions of Geant4.
- The result from version 10.1 is closer to the data than the result from version 9.6.

FTFP_BERT physics lists are tuned exclusively on thin target scintillator data, could still be a cause that for silicon the prediction deviates from the data.

The parameter $\langle E \rangle_{/\text{pseudolayer}}$ [MIP] of the longitudinal energy profile was improved, a sample of 500 k events at 10 GeV became available for production within the CALICE simulation chain. In order to see if the prediction of the longitudinal energy profile was improved, a different version of Geant4 was used. The average hit energy per layer predicted in different versions of Geant4.

**Data**: FNAL 2008

**Physics lists**: FTFP_BERT

**CALICE**: Fe-AHCAL

**JINST**: 11 P06013 (2016)

**Frank Simon (fsimon@mpp.mpg.de)**
Surprisingly good reproduction of data by Geant4

Figure 1: Longitudinal energy profile for 10 GeV pions compared to predictions from the FTFP physics lists of version 9.6 and 10.1. Version 10.1 has a lower mean hit energy than version 9.6. Some errors have been identified by the BERT physics list. This in contrast to its satisfactory prediction of the profile of tracks of low energy that stop inside the calorimeter. In order to see if the prediction of the longitudinal energy profile was improved, a sample of 500 k events at 10 GeV have been generated and analysed in the same way as was done for the published analysis.

Selected Results on Spatial Structure

Many differences between the different versions. Version 9.6 has a lower mean hit energy than version 10.1. Portions of Geant4 have been modified to improve the prediction of the longitudinal energy profile. For silicon, the prediction deviates from the data.

Figure 2 shows a modification of Fig. 21 (c) from the paper; the data is now compared to FTF_BIC pi- and (a, b) data and (c, d) simulations with (a, b) data and (c, d) simulations with (a, b) data.

Track segment length as a function of the beam energy (a) and the relative difference between the number of hits that are above the third threshold.

Fit of function (1.30 ± 0.01) N_{hit} + 0.03 (d, 3) % to the number of hits that are above the third threshold. It decreases with energy, the decrease being (1.27 ± 0.01) N_{hit}.

Fit of function (1.1 ± 0.02) N_{hit} (d, 3) % to the number of hits that are above the third threshold. It decreases with energy, the decrease being (1.27 ± 0.02) N_{hit}.
Understanding Hadronic Showers

From 4D to 5D

- New technological prototypes (SiW ECAL, AHCAL) will provide cell-by-cell nanosecond-level timing:
  Studies of hadronic showers in space, amplitude and time
- Builds on first studies with a single strip of scintillator tiles
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• New technological prototypes (SiW ECAL, AHCAL) will provide cell-by-cell nanosecond-level timing: Studies of hadronic showers in space, amplitude and time
  • Builds on first studies with a single strip of scintillator tiles

• With the data taken this year and in the coming years: Scaling this up from a single strip of cells to a fully instrumented volumes - with both scintillator / SiPM and silicon
  ➷ Will further improve understanding of shower structure, and may provide interesting possibilities for improved reconstruction techniques
Technical Realization

The CALICE Technological Prototypes:
Towards realistic implementations - here focusing on the latest prototype: The AHCAL
Technical Realisation

Addressing real-world Constraints with new prototypes

- Common to all new developments: Embedded electronics, power pulsing

- Physics prototypes

- Large RPCs
  SDHCAL prototype

- SiW ECAL prototype

- AHCAL prototype

scalability to large areas, automatisation

W.Ootani, "AHCAL prototype: AHCAL Response to electron and muon"
Evolution of the SiW ECAL
From the Physics Prototype to a Technological Prototype

- Physics prototype: 6 x 6 cm$^2$
sensors, electronics outside of active volume
Evolution of the SiW ECAL

From the Physics Prototype to a Technological Prototype

- Physics prototype: 6 x 6 cm$^2$ sensors, electronics outside of active volume
- 9 x 9 cm$^2$ wavers, 5.5 x 5.5 mm$^2$ cells, mounted in 2 x 2 configuration for technological prototype
Evolution of the SiW ECAL

From the Physics Prototype to a Technological Prototype

- Physics prototype: 6 x 6 cm² sensors, electronics outside of active volume
- 9 x 9 cm² wavers, 5.5 x 5.5 mm² cells, mounted in 2 x 2 configuration for technological prototype
- First few layers technological prototype, fully integrated electronics
- Automatized assembly and QA chain
Evolution of the SiW ECAL

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- First few layers technological prototype, fully integrated electronics

- 9 x 9 cm² wavers, 5.5 x 5.5 mm² cells, mounted in 2 x 2 configuration for technological prototype

- Automaticized assembly and QA chain

Using these calibration values and enhancing the stats putting all cells together in one histogram we can fit the 2 & 3 MIP peaks (2 or 3 electrons crossing together)
Evolution of the SiW ECAL

Towards large-scale systems

- For a future linear collider detector, “slabs” with an active length of ~ 1.5 m are required
- Development ongoing, based on established assembly & QA procedures - making use of low-profile ASU-to-ASU interconnections
- Active elements with 2 silicon layers, integrated absorber, to be inserted in precision absorber frame - prototype available
Evolution of the Semi-Digital HCAL
Towards larger active elements & precision mechanics

- The first SDHCAL was already a technological prototype: Embedded electronics, …
- A key issue towards large-volume detectors: Size of active elements

- New large-area RPCs - 1 x 2 m² prototype - sizes ultimately beyond 3 m
- Improved gas circulation scheme to obtain uniform gas exchange in full volume
Evolution of the Semi-Digital HCAL
Towards larger active elements & precision mechanics

- Critical for highly granular calorimeters: Precision mechanics
- High sampling frequency in HCALs, embedded electronics
- At the same time: Compact detectors

- In construction: A multi-layer stainless steel demonstrator, electron beam welding for highest precision
- Excellent flatness of plates achieved by roller levelling (< 200 µm deviation from flatness over full area)
- 15 mm thick plates, 13 mm spacing, 1 x 3 m² size
Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

• From the first large-scale application of SiPMs to the “SiPM-on-tile” technology

2008 - 2016

Physics Prototype
Evolution of the Analog HCAL
A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- From the first large-scale application of SiPMs to the "SiPM-on-tile" technology

2008 - 2016

Physics Prototype

Direct coupling of tiles and photon sensors
Evolution of the Analog HCAL

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2008 - 2016
Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- Mass production for a new 0.5 m³, 22k channel prototype
- 24k tiles produced & wrapped

injection molding of PS based scintillator tiles

09/2017
Evolution of the Analog HCAL

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09/2017

Semi-automatic wrapping of scintillator tiles

10/2017 - 01/2018
Evolution of the Analog HCAL

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- Mass production for a new 0.5 m³, 22k channel prototype
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injection molding of PS based scintillator tiles

09/2017

automatic placement of tiles on electronics board (HBU), fully assembled with SiPMs and ASICs

10/2017 - 01/2018

semi-automatic wrapping of scintillator tiles

11/2017 - 02/2018
Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

• A multi-step QA procedure

spot testing of few % of 22k SiPMs, acceptance of 600 pc batches according to pre-defined criteria - all batches accepted
Evolution of the Analog HCAL
A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

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test of all ASICs (~80-90% yield)
test of all assembled boards using built-in LEDs
Evolution of the Analog HCAL
A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

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- test and calibration of all channels with cosmics

- test of all ASICs (~80-90% yield)
- test of all assembled boards using built-in LEDs
Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- A multi-step QA procedure

integration of layers & interfaces, test in beam at DESY

spot testing of few % of 22k SiPMs, acceptance of 600 pc batches according to pre-defined criteria - all batches accepted

test and calibration of all channels with cosmics

test of all ASICs (~80-90% yield) test of all assembled boards using built-in LEDs
The CALICE AHCAL Prototype

Successful Test Beams

• In May and June 2018: Test beam at CERN SPS - the smoothest CALICE test beams ever.
The CALICE AHCAL Prototype

Successful Test Beams

- In May and June 2018: Test beam at CERN SPS - the smoothest CALICE test beams ever.

- Analysis ongoing - first results soon

online data
50 GeV electron beam with pion and muon contamination
The Scintillator ECAL

Closely related to the AHCAL

- Channel count reduced by one order of magnitude wrt to Si-based ECAL, using crossed scintillator strips
- Apart from scintillator geometry, essentially identical to AHCAL, with higher channel density
The Scintillator ECAL

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- Investigating strip geometries for bottom coupling to SiPMs: Easier assembly
Application

Just one example...
Applications of CALICE Technologies

Highly granular calorimeters now widely adopted

- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

Most prominent: The CMS Endcap Calorimeter Upgrade HGCal
Applications of CALICE Technologies

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A wide range of other applications: ATLAS HGTD, essentially all future collider projects, long baseline neutrino detectors, …
Widening the Focus

A few thoughts on required design changes for circular colliders
Imaging Calorimeters for Circular Colliders

Modifications from the CALICE Concept

- On the technological side: Continuous readout, rather than bunch trains as for linear colliders
  - Does not allow to use power pulsing to reduce power budget: Cooling in the active volume?
  - Different ASICS?
    - Amenable to continuous readout
    - Different power optimisation

- A different detector optimisation: More focus on lower energies
  - What is the right granularity in ECAL and HCAL?
  - What is the right trade-off between granularity and electromagnetic energy resolution?
  - What is the right sampling in ECAL and HCAL, and where should the transition be?

... 

⇒ Many interesting questions to study - and lots of room for new contributions!
Summary & Conclusions

• Highly granular calorimetry is now widely accepted in HEP - as the solution of choice for optimal event reconstruction with particle flow, and to control backgrounds and pile-up

• CALICE has successfully demonstrated different technologies - the results from the beam tests provide important input for the development of reconstruction algorithms and for the validation and further development of GEANT4 shower simulations

• It does not end there: further development to address issues of scalability and realistic constraints in collider environments;
  • Fully embedded electronics with auto-triggering and time stamping
  • Larger active elements
  • Automatic assembly and testing

• And: Interesting challenges specific to circular colliders, still to be addressed!
Extras
Scintillator ECAL

Scintillator Strips, SiPMs

- Dynamic range is crucial for an ECAL: use small-pixel SiPMs
- Will profit from new HDR generation of MPPCs that are now becoming available
Extremes in Granularity
A MAPS based SiW ECAL

- In the context of the FoCAL upgrade of ALICE - identification and separation of very close-by photons in a dense environment

A 24 layer prototype built and tested in beam (39 Mpixel, 30 x 30 μm²)
- 28 X₀, 11 cm deep (3 mm W / layer), 40 x 40 mm² active area, total thickness / layer 4 mm
Extremes in Granularity
A MAPS based SiW ECAL

• In the context of the FoCAL upgrade of ALICE - identification and separation of very close-by photons in a dense environment

A 24 layer prototype built and tested in beam (39 Mpixel, 30 x 30 µm\(^2\))
- 28 X\(_0\), 11 cm deep (3 mm W / layer), 40 x 40 mm\(^2\) active area, total thickness / layer 4 mm
- Provides an even clearer look at shower structure, including fine details of electromagnetic showers
- pile-up in a 244 GeV mixed beam
Extremes in Granularity

A MAPS based SiW ECAL

CAL upgrade of ALICE - identification and separation of very close-by photons in a dense environment

Built and tested in beam (39 Mpixel, 30 x 30 µm²)

3 mm W / layer), 40 x 40 mm² active area, total thickness / layer 4 mm

pile-up in a 244 GeV mixed beam

radial shower profiles in HD:

• low energy: early shower maximum, profiles broaden and decay with depth
• high energy: profiles broaden with depth, increase up to shower maximum