Evolution and Performance of Highly Granular Calorimeters

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on behalf of the CALICE Collaboration

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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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<table>
<thead>
<tr>
<th>Depends on material:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• in W: X₀ ~ 3 mm, ρ_M ~ 9 mm</td>
</tr>
<tr>
<td>• in Fe: X₀ ~ 20 mm, ρ_M ~ 30 mm</td>
</tr>
</tbody>
</table>

| NB: Best separation for narrow showers particularly important in ECAL |
| Use W in ECAL! |

When adding active elements: ~ 0.5 cm³ segmentation in ECAL, ~ 3 - 25 cm³ in HCAL

- 0 \times 10^{-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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- **Technical Realisation** of detector systems satisfying collider constraints:
  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
A rich test beam program, with a variety of different prototypes

**Electromagnetic - Tungsten absorbers**

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

**Hadronic - Steel and Tungsten absorbers**

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

+ few-layer SD prototype with Micromegas

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**Validation**

39 Mpixels in 160 cm²
SiW ECAL:
[N.B. Detector optimized for particle separation, not single particle resolution]

Hadronic Calorimeters:
Analog (Scintillator + SiPM)

semi-digital (RPCs)

CALICE 2006 data
Monte Carlo

\[ \frac{\sigma_{\text{reco}}}{E_{\text{reco}}} \]

stochastic term: 16.5%
constant term: 1.1%

\[ \frac{\sigma_{\text{reco}}}{E_{\text{reco}}} \]

stochastic term: 57.6%
constant term: 1.6%

\[ \frac{\sigma_{\text{reco}}}{E_{\text{reco}}} \]

\[ \chi^2 / \text{ndf} = 30.69 / 32 \]
\[ s = 16.53 \pm 0.14 \]
\[ c = 1.07 \pm 0.07 \]
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
**Performance of Highly Granular Calorimeters**

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**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 10 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.

- If the charged hadron is situated in the vicinity of a neutral hadron with similar or higher energy, the confusion is typically less than in the reversed situation. In figure 6 we use the test beam data to estimate how the confusion depends on the energy of the neutral hadron. In jets in a full detector such as ILD, the charged particle will tend to obey separate from the neutral by the magnetic field. Therefore, in this figure the charged hadron is placed at a distance typical of its deflection in a 4 T magnetic field in the ILD geometry. The RMS deviation of the recovered neutral hadron energy from its measured energy does not depend significantly on the neutral hadron energy (see left plot in figure 6). The relative confusion is large for small neutral hadron energy. This results in a smaller probability of neutral hadron energy recovery for small neutral hadron energy (see right plot in figure 6).

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**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 100 GeV jet. For jet fragment 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.

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**Figure 9**

The ECAL + HCAL reconstruction efficiency of 30+10 GeV pion - electromagnetic clusters versus the distance between them (CERN'07). Other energy pairs may be found in Figs. 56, 57 in Appendix B.

**Figure 10**

The same as in Fig. 9 but for 20+6 GeV in ILD with 5×5 mm^2 ECAL pixels. Other energy pairs and the efficiency for 2×2.5 mm^2 granularity may be found in Figs. 58 - 61 in Appendix B.

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The criteria for the correct reconstruction of the mixed event for Garlic and Pandora are the same as in CERN'07 TB analysis. The Arbor requirements are the same as for Pandora with one exception. Arbor currently does not make a particle identification and does not distinguish between photons and other neutrals. Therefore, instead of one pion and one photon, we require one charged and one neutral cluster reconstructed in one 2×2 pixel window. For example, 0.00001 π+ phot. Other combinations may be found in Figs. 58 - 61 in Appendix B.
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
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pile-up in a 244 GeV mixed beam
Extremes in Granularity
A MAPS based SiW ECAL

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

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,
-124 mm total thickness / layer

pile-up in a 244 GeV mixed beam

Evolution & Performance of Highly Granular Calorimeters - CALOR, May 2018
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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:**
Absorber: W; 1.4 mm, 2.8 mm, 4.2 mm
Active: Si; 525 µm

**HCAL / TCMT:**
Absorber: Steel; ~ 21 mm (including cassettes)
Active: Plastic scintillator; 5 mm
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
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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%

- 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
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
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\[
\text{RMS}_{90}(E) / \text{Mean}_{90} \times 100 \%
\]

em sub showers (in shower core) weighted less than hadronic periphery
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 cm$^2$ granularity)

![Energy dependence of the relative energy resolution of the AHCAL test data in (a) and the simulation with 1 $\times$ 1 cm$^2$ 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.](image-url)
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)

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• 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

Figure 20: Energy dependence of the relative energy resolution of the AHCAL test

\[ \frac{\langle E_{\text{rec}} \rangle - E_{\text{beam}}}{E_{\text{beam}}} = \frac{\sigma_{\text{rec}}}{\langle E_{\text{rec}} \rangle} \]

- 0.04
- 0.06
- 0.08
- 0.1
- 0.12
- 0.14
- 0.16
- 0.18
- 0.2
- 0.22
- 0.24

E_{\text{beam}} [GeV]

0 10 20 30 40 50 60 70 80 90

1x1 Fe-AHCAL FTFP_BERT
1x1 Fe-AHCAL MC preliminary

Analogue
Digital
Semi-Digital
Software Compensation

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Technical Realisation
Addressing real-world Constraints with new prototypes

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

- Scalability to large areas, automatisation

- Large RPCs SDHCAL prototype

- SiW ECAL prototype

- AHCAL prototype (talk this morning)
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
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, 5.5x 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

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- First few layers technological prototype, fully integrated electronics

- Automatized assembly and QA chain
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- First few layers technological prototype, fully integrated electronics
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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

36 cm
boards cascaded to cover larger areas: up to 9 boards, covering 3.2 m
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
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
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• 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

![Diagram of hadronic shower components](image)
Selected Results on Spatial Structure

Fig. 1: Longitudinal energy profile for 10 GeV pions compared to predictions from the FTFP_BERT physics list in different versions of Geant4.

The average hit energy per layer predicted in different versions of Geant4 is also compared to data. Figure 2 shows a modification of Fig. 21 (c) from the paper; the data is now compared to only FTFP_BERT, but from 3 different Geant4 versions. Additionally the y-axis is shown with a log scale, so that small differences between the different curves can be more easily seen. This observable is overall best described in version 10.1, but near the shower start the energy per hit is too high in all studied Geant4 versions. Version 9.6 has a lower mean hit energy than version 10.1, which explains the improvement seen in the longitudinal energy profile.
For silicon the prediction deviates from the data. However, the improvement is not sufficient to describe the data in a satisfactory manner. The fact that the energy per hit only FTFP_BERT physics list in different versions. Version 9.6 has a lower mean hit energy than version 9.3 of Geant4. This is contrast to its satisfactory prediction of the profile well by the FTFP_BERT physics list in different versions. Version 9.6 of Geant4 is also compared to FTFP_BERT G4 v10.1. The result from version 10.1 is closer to the data than the result from version 9.6, which explains the improvement seen in the longitudinal energy profile. The average hit energy per layer predicted in different versions of Geant4 are corrected in the new release. Recently the latest version (version 10.1) of Geant4 BERT physics list in di- 

The behaviour of this parameter is shown in figure 4. It decreases with energy, the decrease being very slow above 30 GeV. It is well predicted by both physics lists below 30 GeV and for protons particle types above 30 GeV. Some errors have been identified by the developers in version...
Surprisingly good reproduction of data by Geant4.

Mean number of secondary tracks increases with beam energy.

10 GeV

10.1, which explains the improvement seen in the longitudinal energy profile.

Figure 1: Longitudinal energy profile for 10 GeV pions compared to predictions from the

FTFP physics lists are tuned exclusively on thin target scintillator data, could still be a

problem.

Understanding Hadronic Showers

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Mean number of secondary tracks increases with beam energy. In version 9.3 of Geant4, the y-axis is shown with different versions of Geant4. Additionally the y-axis is shown with the incoming hadron for simulation and for data at 10, 40 and 70 GeV. The behaviour of this parameter is shown in figure 5.2 "Core" and "short" parameters are parameterized as quadratic functions of the total number of hits (a, c) pions and (b) are respectively new quadratic functions of the total number of hits (a). The "long" component of the longitudinal profile which dominates in the shower tail, is probably related to the angular distribution of secondary particles above 30 GeV. The fact is too high in all studied is corrected in the new release. Recently the latest version (version 10.1) of Addendum to Paper 016: Longitudinal energy distribution in the BERT physics list in different versions of Geant4. Geant4 versions. Additionaly the y-axis is shown with different versions of Geant4.
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

![Image of electronics and cables]
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![Graph showing time of first hit vs. energy deposition for 60 GeV hadrons - tungsten](image)

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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 (partially even as we speak) 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
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 HGT, essentially all future collider projects, long baseline neutrino detectors, … some examples discussed at this conference.
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

• New data to come: intense test beam activities this year at CERN and DESY
Extras
Reconstructed Energy

Software Compensation, SDHCAL

Figure 10: Mean reconstructed energy and relative residual to the beam energy versus beam energy with standard reconstruction (blue circles) and Full SC reconstruction (red circles) of the combined (CERN+FNAL) dataset. The total (statistical and systematic) uncertainties are marked with '[]'. Dotted lines correspond to $E_{\text{reco}} = E_{\text{beam}}$.

7.1 Comparison between Dataset Results

Figure 11 presents the energy resolution for the different datasets with standard and Full SC reconstruction. The data points for the different datasets for both reconstruction methods agree within 3%. However, the fits for the standard reconstruction are different due to the different energy ranges. With the Full SC scheme the energy dependent improvement of the resolution reduces the constant term of the fit and results in an overall better description of the data points by the fit function.

7.2 Comparison between SC Schemes

In section 5.2 three SC schemes were described: Full SC, HCAL SC and ECAL SC. These schemes were applied to the different datasets, together with the standard reconstruction. Figure 13 presents the energy resolution for the combined dataset with the different reconstruction methods. The ECAL SC scheme gives a slight improvement of the resolution, from a stochastic term of (54.25 ± 0.13)% to (51.58 ± 0.17)%, the AHCAL SC reduces it further to (46.58 ± 0.16)% and the full SC gives the lowest stochastic term of (42.55 ± 0.14)%.