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CALICE highly granular calorimeters: imaging properties for hadronic shower analysis

M. Chadeeva on behalf of the CALICE collaboration

P.N. Lebedev Physical Institute of the Russian Academy of Sciences,
53 Leninskiy Prospekt, Moscow, Russia

E-mail: chadeevamv@lebedev.ru

Abstract: The CALICE collaboration pioneered the new trend in calorimetry — highly granular devices for high energy and particle physics applications. During the last fifteen years, several highly granular electromagnetic and hadron calorimeters based on different technologies were constructed and successfully tested. The technologies comprise optical readout, signal collection with semi-conducting devices and gaseous detectors. All current CALICE prototypes address technological aspects such as embedded electronics. Dedicated tools are developed for the analysis of test beam data collected with the standalone and combined setups of both physics and technological prototypes of highly granular calorimeters. The tools are described, which help to improve the precision of hadronic shower analysis including the implementation of a calorimeter-based particle identification.

Keywords: Calorimeters; Particle identification methods; Performance of High Energy Physics Detectors

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Contents

1 Introduction

The projects in the field of high energy physics proposed for the post-LHC era are focused presumably on lepton colliders such as the ILC in Japan, CLIC and FCCee at CERN, and CEPC in China. The lepton machines provide very clean environments and give many opportunities to carry out high precision measurements, in particular of the Higgs boson couplings, and perform model-independent analyses. An important part of the lepton collider programmes are detector concepts. The detector systems proposed for different collider machines differ in details but follow the common trend to design a detector as an instrument for particle flow (PF) reconstruction [1]. By means of the PF approach, which relies on a possibility to disentangle contributions from different particles within jets, one can expect to reach the 3–4% level of jet energy resolution and be able to identify dijets from hadronic decays of W and Z bosons [2, 3].

The particle flow reconstruction requires a high precision tracking and high longitudinal and transverse segmentation of calorimeters, which are the key features for effective application of the method. The CALICE collaboration pioneered a series of developments of highly granular calorimeter concepts including R&D, engineering, construction, commissioning and test beam studies of both electromagnetic and hadron calorimeter prototypes for future particle physics experiments.

2 Physics and technological prototypes of highly granular calorimeters

Two generations of highly granular calorimeter prototypes were developed and tested by the CALICE collaboration. The reliability of the concept was experimentally confirmed with the physics prototypes during several successful test beam campaigns at DESY, CERN and FNAL in 2006–2011 involving both standalone devices and combined setups of electromagnetic and hadron calorimeters [4–7]. The test beam programmes comprised the tests of readout technologies, development of calibration and reconstruction tools, study of shower development and validation of simulations. The simulations of the proposed ILD detector for the ILC (see ref. [2]) show that the optimal transverse segmentation results in more than 80 million channels in the electromagnetic calorimeter and

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about 8 million channels in the hadron calorimeter. The second generation of CALICE prototypes, called technological prototypes, is aimed at establishing and testing scalable solutions for mass production and assembling on the way to large-scale detectors such as the ILD. The technological prototypes of hadron calorimeters with embedded electronics were tested during test beam campaigns in 2012–2018 including the power pulsing operation mode [8, 9]. The power pulsing regime aims at noticeable reduction of power consumption by switching off the detector electronics during the idle time between collisions. The reduction is expected to be significant for the linear colliders such as the ILC where the idle time will comprise about 99% of the collider operation time.

Electromagnetic calorimeter (ECAL) prototypes. The physics prototypes of electromagnetic calorimeters constructed and tested by the CALICE collaboration represent two technological options: scintillator and semiconductor readout [4, 7]. Both prototypes are sampling calorimeters and consist of 30 layers with few millimetres of tungsten absorber to provide longitudinal compactness (about one nuclear interaction length, λ_I) together with enough depth to absorb electromagnetic showers (about 23 radiation lengths). The transverse size of prototypes is $18 \times 18\,\mathrm{cm}^2$. The active material of the Si-W ECAL are $1 \times 1\,\mathrm{cm}^2$ silicon pads. The Sc-W ECAL is comprised from $10 \times 45{\times}3\,\mathrm{mm}^3$ scintillator strips read out by silicon photomultipliers (SiPM), the strips in successive layers have an orthogonal orientation. The prototypes were tested in the combined setups with hadron calorimeters and exposed to muon, electron and hadron beams.

Scintillator-SiPM analog hadron calorimeter (AHCAL) prototypes. The CALICE analog hadron calorimeter is a layered structure with active layers assembled from scintillator tiles with SiPM readout as shown in figure 1. The tiles were produced using injection moulding technique by the Uniplast company in Vladimir (Russia). The first-generation prototype was tested in 2006–2011 with steel and tungsten absorbers [5, 10]. The main characteristics of both physics and technological prototypes are listed in table 1. The key differences of the second-generation prototype are embedded electronics and tiles with direct readout, which allow automatic wrapping, SiPM soldering and module assembly. The technological prototype with steel absorber was exposed to electron and pion beams in the energy range 10–200 GeV at CERN SPS in 2018. During the beam tests the prototype was also successfully operated in power pulsing mode and with electronic compensation of temperature changes. The calorimeter response was observed to be in good agreement between two modes, with and without power pulsing as shown in figure 2 for 20 GeV pions.

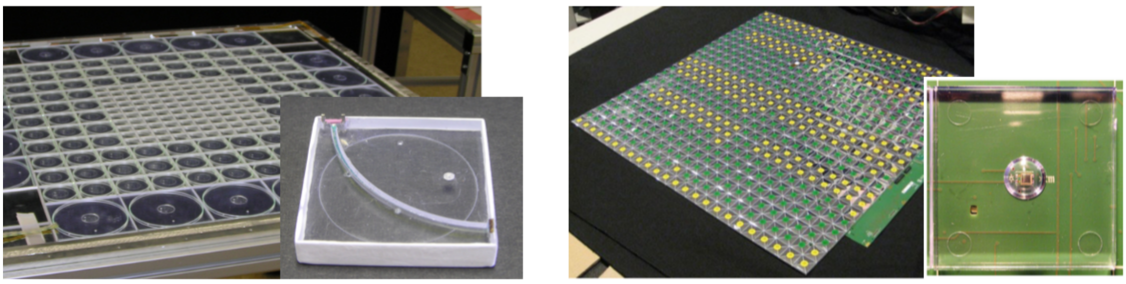

Figure 1. Active layers of the CALICE scintillator analog hadron calorimeters: (left) physics prototype layer assembled from tiles read out by SiPM coupled to WLS fiber; (right) technological prototype layer assembled from individually wrapped tiles with dimple and surface-mounted SiPM.

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Table 1. Characteristics of the CALICE analog hadron calorimeter prototypes.

	Physics prototype	**Technological prototype**
Total number of channels	7608	21888
Longitudinal parameters		
number of layers	38	38
scintillator depth per layer	0.5 cm	0.3 cm
total depth (steel, 2 cm/layer)	$\sim 4.5 \cdot \lambda_{\mathrm{I}}$	$\sim 4.5 \cdot \lambda_{\mathrm{I}}$
total depth (tungsten, 1 cm/layer)	$\sim 4.3 \cdot \lambda_{\mathrm{I}}$	—
Transverse parameters		
active plane size	$90 \times 90\,\mathrm{cm}^2$	$72 \times 72\,\mathrm{cm}^2$
tile size	3×3, 6×6, $12 \times 12\,\mathrm{cm}^2$	$3 \times 3\,\mathrm{cm}^2$
Tile design		
geometry	groove for fiber	central dimple
optical isolation	side coating	wrapping in foil
optical readout	SiPM coupled to WLS fiber	surface-mounted SiPM
Photodetectors and electronics		
number of SiPM pixels	1168	2668
SiPM sensitive area (pixel size)	$1.1 \times 1.1\,\mathrm{mm}^2$ (32 μm)	$1.3 \times 1.3\,\mathrm{mm}^2$ (25 μm)
SiPM dark count rate	~ 1 MHz	< 100 kHz
electronic boards	external	embedded
power pulsing option	no	yes
temperature monitoring	measurement	compensation
Assembly	by hand	automatic

GRPC (semi)digital hadron calorimeter prototypes. The highly granular gaseous RPC hadron calorimeters developed by the CALICE collaboration are sampling devices with unprecedented segmentation, which amounts to about half million readout channels ($1 \times 1\,\mathrm{cm}^2$ pads) in one cubic meter [6, 8]. The first tests of this technology were performed in 2010–2011 with the physics prototype DHCAL equipped by 1-bit readout electronics [6]. The technological prototype, SDHCAL, has embedded electronics with 2-bit readout and power pulsing option. The SDHCAL assembled from 48 layers with steel absorber ($5.7 \cdot \lambda_{\mathrm{I}}$) was exposed to test beams of electrons, muons and hadrons in the energy range 5–80 GeV in the series of experiments at CERN in 2012-2018 [8].

3 Tools for hadronic shower analysis with calorimeter prototypes

Large amount of experimental data were collected with the physics and technological prototypes of highly granular calorimeters. The extensive analysis of the data includes the study of hadron-induced showers, their global parameters and substructure, which is very helpful for validation of simulations. To perform the detailed study of hadronic showers, several tools were developed for test beam data analysis: shower start finding algorithm and methods of particle identification.

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3.1 Shower start finding algorithm in the AHCAL

A hadronic shower is a cascade process of multiplicative production of secondary particles after the first inelastic interaction of a primary particle with any nucleus of calorimeter materials. The position of the first inelastic interaction is called shower start and can be identified with the accuracy of longitudinal segmentation (layer width) in a sampling calorimeter. The identification of shower start on an event-by-event basis is helpful for studies of shower substructure and for estimates of the longitudinal leakage. The shower start position for hadrons is exponentially distributed along the particle direction and is characterised by the effective nuclear interaction length of the calorimeter in contrast to electromagnetic shower development or propagation of minimum ionising particles. Thus, the shower start observable can add discriminating power to particle identification algorithms.

The shower start finding technique was developed for the analysis of test beam data in the AHCAL physics prototype. The signal in each calorimeter channel (cell) is measured in units of MIP (corresponding to the response of minimum ionising particle), the cell responses being equalised during the MIP calibration with muons. The measured visible energy in a cell above 0.5-MIP threshold is called hit. The idea under the method is a comparison of two observables in several successive ranges along the particle direction with the MIP-like deposition. To make a conclusion about the calorimeter layer k, the following values are calculated: (a) visible energy sum, E_i, and number of hits, N_i, for each layer in a sliding window of m layers, $k-m+1 \leq i \leq k+1$ (the values $i < 1$ correspond to virtual layers before calorimeter, for which $N_i = 1$ and $E_i = 1.3$ MIP are assumed); (b) average visible energy in the sliding window $M_k = \sum_{j=0}^{m-1} E_{k-j}/m$. The sums of these values for two successive layers are compared with the thresholds M_{thr} and N_{thr}. If both inequalities, $(M_k + M_{k+1}) > M_{\text{thr}}$ and $(N_k + N_{k+1}) > N_{\text{thr}}$, are satisfied, the k-th layer is marked as a layer of the first inelastic interaction.

The thresholds M_{thr} and N_{thr} are tuned with simulations, the events with elastic and quasi-elastic interactions being removed from the simulated samples. While the energy threshold scales linearly with particle energy, the threshold for the number of hits exhibits logarithmic energy dependence. For test beam data analysis, both thresholds are calculated using beam energy. The averaging over the sliding window is applied to reduce the impact of noise, which increases fluctuations of MIP-like deposition. The AHCAL physics prototype was equipped with the first generation of silicon photomultipliers with relatively large dark count rate and the width of sliding window for shower start finding was set to $m = 10$. For the technological prototype, where dark count rate is much smaller, the optimal width of sliding window adjusted with simulations is found to be $m = 6$. An example event display of the simulated 10 GeV pion shower is shown in figure 3.

The shower start is found within ±1 layer from the true position of the first inelastic interaction for ∼ 80% of simulated pion events in the physics prototype in the energy range 10–80 GeV and ∼ 95% of the identified shower starts are within ±2 layers from the true position. The sliding window and threshold optimisations for the analysis of data from the AHCAL technological prototype allow improvement of the performance quoted above up to 85% and 96%, respectively. The important crosscheck of the algorithm is the estimation of an effective nuclear interaction length from the slope of the shower start position distribution. The extracted values of nuclear interaction length agree within uncertainties with the estimates obtained using material properties of the calorimeter components. Such an agreement confirms the performance of the approach.

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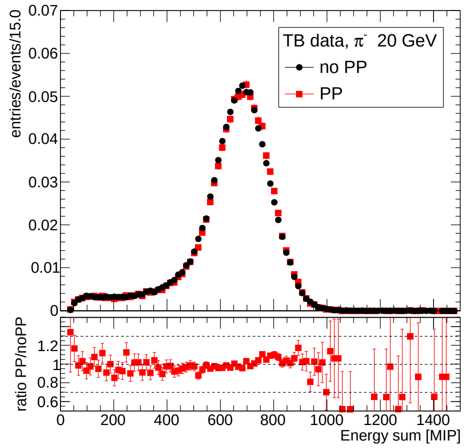

Figure 2. Energy sum distribution in the CALICE AHCAL technological prototype for 20 GeV pions from the CERN SPS test beam taken with (red squares) and without (black circles) power pulsing mode.

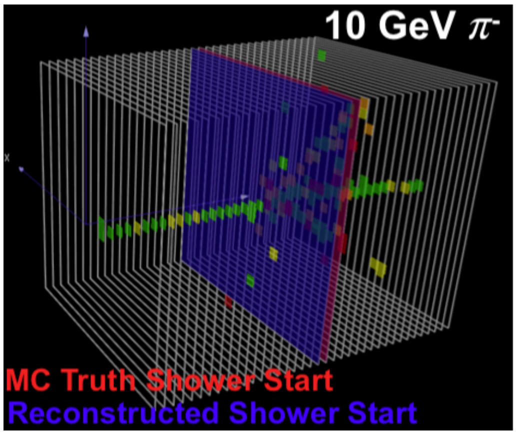

Figure 3. Event display of the simulated 10 GeV pion shower in the CALICE AHCAL technological prototype. The layers of the true and found first inelastic interaction positions are shown with red and blue planes, respectively.

3.2 Hadron identification algorithms

One of the goals of test beam experiments with highly granular calorimeters is the study of shower development and substructure, which are important for the validation of simulations. Hadronic shower studies require high purity data samples and reliable estimate of the non-hadronic admixture. Any test beam is typically a mixture of electrons, muons and hadrons. The discrimination between particle species is more challenging in the tests of standalone hadron calorimeters without electromagnetic calorimeter and tail catcher. In this case, the fine segmentation provides a set of observables, which can be used for calorimeter-based particle identification in test beam data analysis. Two multivariate techniques have been developed and implemented: a traditional cut-based approach and a more sophisticated approach based on machine learning of Boosted Decision Trees.

Analog hadron calorimeter. There are two groups of observables useful for classification task as no observable has enough discriminating power in the wide energy range. The counting variables are the number of hits in the event, N, and the shower start layer described in section 3.1. For the preselected single-particle events, all hits detected in the calorimeter volume are considered as cluster hits. Six discriminating observables use hit amplitudes: longitudinal centre of gravity, shower radius, energy fraction within a longitudinal depth of about 25 radiation lengths from the calorimeter front, energy fraction in the shower core, energy fraction in identified track hits. The nearest-neighbour-based search is performed to find a primary track and identify the in-shower track hits and shower core hits. The longitudinal centre of gravity, $zCoG$, and shower radius, R, are calculated as weighted sums $zCoG = \frac{\sum_{i=1}^{N} e_i \cdot z_i}{\sum_{i=1}^{N} e_i}$ and $R = \frac{\sum_{i=1}^{N} e_i \cdot r_i}{\sum_{i=1}^{N} e_i}$, where e_i and z_i are the amplitude and longitudinal coordinate of the i-th hit and r_i is its radial distance from the shower axis, which is defined from the primary track or transverse centre of gravity. The example two-dimensional distributions of the longitudinal centre of gravity and shower radius are shown in figure 4 for data collected with 10 GeV test beams in the CALICE AHCAL equipped with steel or tungsten absorber.

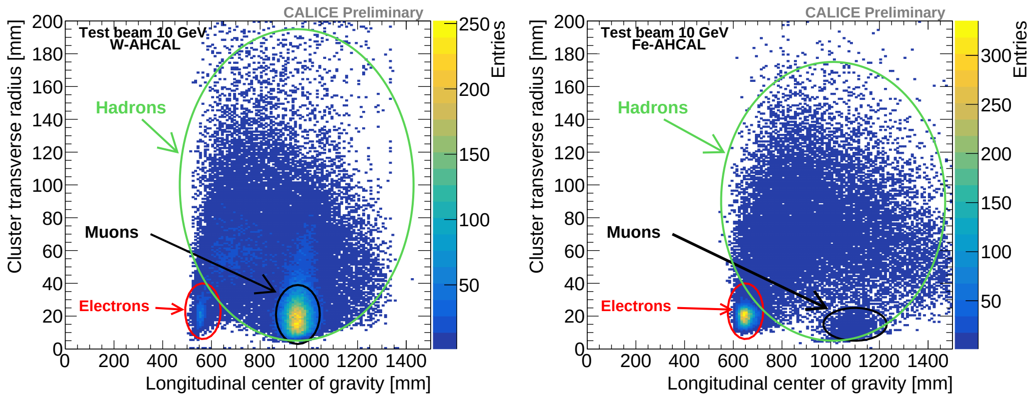

Figure 4. Two-dimensional distribution of the longitudinal centre of gravity and shower radius for events from the 10 GeV mixed test beam in the CALICE AHCAL with tungsten absorber at CERN (left) and with steel absorber at FNAL (right). The longitudinal coordinate of the AHCAL front is set at 485 mm.

The discriminating power of the observables shown in figure 4 differs for different absorber materials. The efficiency of hadron selection in the AHCAL with steel absorber was estimated using mixed samples of electrons, muons and hadrons simulated using Geant4 version 10.1. For the purity of hadron sample better than 99.5%, the efficiency of the cut-based approach is about 92%. The preliminary results from the BDT-based technique show that the identification efficiency can be increased up to 97%. Figure 5 shows the typical event displays in the AHCAL technological prototype corresponding to different particle species form the same test beam data sample.

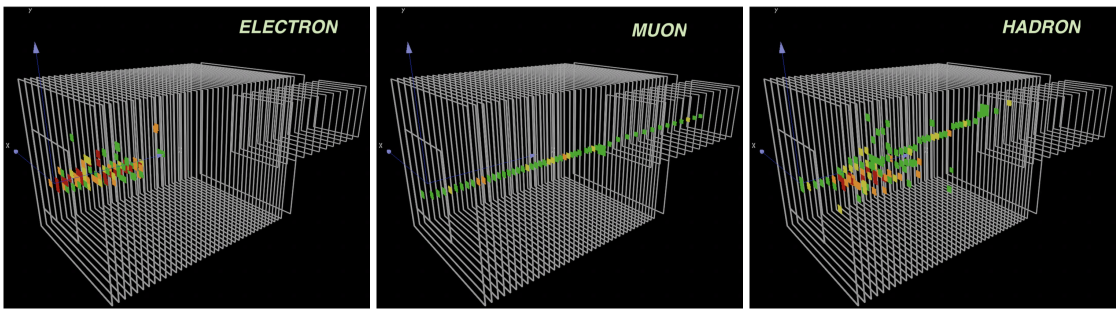

Figure 5. Typical event displays of the identified electron (left), muon (middle) and hadron (right) events from the same data sample collected for the mixed 10 GeV test beam at CERN SPS in 2018 with the CALICE AHCAL technological prototype.

Semi-digital hadron calorimeter. For the analysis of test beam data obtained with the standalone SDHCAL prototype, a sophisticated hadron selection procedure has been developed based on classification using Boosted Decision Trees. The simulated samples of pions, electrons and muons for the training of a BDT algorithm were produced using the version 9.6 of Geant4 package. Six observables were used as an input for the BDT including number of tracks within a shower, hit density extracted from the number of neighbour hits, shower radius and longitudinal position of the shower maximum. For the purity of hadron sample above 99%, the hadron selection efficiency from the sample with muon or electron contamination exceeds 98% and 97%, respectively [11].

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4 Conclusion

The detailed study of hadronic shower structure with highly granular calorimeters is accompanied by the development and implementation of sophisticated tools for test beam data analyses. The tools are tuned using simulated samples and are applied to the analysis of experimental data collected with the technological prototypes of the CALICE analog and semi-digital hadron calorimeters. The developed cut-based technique for hadron selection is used for the analysis of data from the CALICE AHCAL technological prototype providing the hadron identification efficiency of about 92% in the energy range 10–80 GeV, which is expected to be improved with the machine learning techniques under development. For the SDHCAL prototype, the BDT-based event selection technique helps to reduce statistical uncertainty by providing the relative increase up to $\sim$ 15% in the number of hadron events selected for analysis at the energies below 40 GeV compared to the cut-based approach.

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