CALICE scintillator HCAL - electromagnetic and hadronic shower analysis

Erika Garutti (on behalf of the CALICE collaboration)
DESY, Notkestr. 85, 22607 Hamburg, Germany
E-mail: erika.garutti@desy.de

Abstract. The CALICE test beam calorimeters operated at the CERN SPS facility have collected a large sample of hadronic and electromagnetic showers with unprecedented granularity. The calorimeters and beam line instrumentation are modeled in the MOKKA framework and full simulation of the test beam experiment is performed using GEANT4. Digitization is applied to each calorimeter to account for detector effects and noise. The scintillator-based hadronic calorimeter (AHCAL) is the center of the studies reported in this paper. The most important validation of the detector modeling and calibration chain is the test of the calorimeter response linearity and resolution for a large range on incident beam energies. Electromagnetic showers are the most demanding test since the energy deposited per single tile in an electromagnetic shower is larger than in a hadronic shower for the same beam energy. Results of the calorimeter response to muons and positrons are discussed and compared to Monte Carlo (MC). The analysis of single pion showers, recorded with the AHCAL offer the unique possibility to test hadronic shower models using a number of different observables. Total energy and longitudinal profiles have been studied at first and compared with two available shower models in GEANT4. Results of the effect of the shower leakage on the reconstructed energy and energy resolution are presented. Furthermore, studies of shower separation are performed using event mixing techniques. Shower separation is critical for the performance of modern particle flow algorithms, which here for the first time can be tested on experimental data.

1. Introduction
Three highly-granular prototype calorimeters constructed by the CALICE collaboration have been tested at the CERN SPS during 2006 and 2007. The Silicon-Tungsten electromagnetic calorimeter (ECAL, [1]) with 1×1 cm² readout pads; the Scintillator-Steel hadron calorimeter (AHCAL, [2]) with 3×3 cm² tiles analogically readout; and the Scintillator-Steel Tail-Catcher and Muon Tracker (TCMT, [3]) strip detector have been operated with a common data acquisition providing the readout of ~18000 channels. AHCAL and TCMT share not only the same sampling material but also the same photo-detector readout via SiPM [4]. Calibration and corrections of these two detectors are very similar. The AHCAL is a 38 layers sampling calorimeter, which alternates 2 cm of Steel to active layers assembled with 0.5 cm thick scintillator tiles. About 8000 SiPM are used for the individual readout or each tile. Details on the AHCAL calibration procedure are presented in [5]. In the first year of operation at CERN only 23 layers of the AHCAL have been instrumented. Full commissioning was achieved for the CERN run in 2007. Data from both periods is presented.
The validation of the calibration procedure and the MC digitization is obtained by the study of the calorimeter response to muons and electromagnetic showers. The analysis of single pion showers offers the unique possibility to validate MC hadronic shower models using a large number of well defined observables. Total energy and longitudinal profiles with very high resolution are studied in detail and compared with the available GEANT4 models. The ultimate goal of highly granular calorimeter is shower separation in a single event. To test the CALICE calorimeter system for shower separation quality two single pion events are overlaid and reconstructed with a track-wise clustering algorithm. The quality of shower separation is studied as a function of the distance between the two pions. Furthermore, a naive particle flow algorithm can be applied to the reconstructed clusters assuming one of the two pions to be charged and, therefore, having a perfectly determined momentum from the tracking system. The energy resolution of the second pion (playing the role of the neutral hadron here) is investigated.

2. Validation of MC digitization

The three calorimeters (ECAL, AHCAL and TCMT), as well as the full instrumentation of the SPS-H6 beam-line at CERN, have been implemented in MOKKA [6]. The true GEANT4 response of the detectors is digitized to include the SiPM response function, Poisson smearing and noise. Optical cross-talk between adjacent scintillator tiles is simulated.

In order to validate the digitization steps data is compared to MC for well understood physics processes sensitive the calibration procedure steps. All calorimeter cells are equalized using the signal from minimum ionizing particles (MIP). The response of the whole calorimeter and of the single cells to a MIP is investigated. To test the effect of non-linearity correction and the entire calibration procedure electromagnetic showers are investigated and compared to MC.

2.1. Simulation of muons

The energy deposited by a muon traversing 23 layers of the the AHCAL is shown in Fig. 1a. The distribution is compared to simulation both with and without digitization. In both cases the MC well reproduced the mean value and the spread of the distribution. This indicates that the Landau spread of the MIP energy in the 23 tiles is larger than the spread introduced by detector effects, i.e. Poisson smearing, noise, optical cross-talk. At the MIP energy amplitude the effect of non-linearity of SiPM is negligible.
Figure 2. a) Number of reconstructed hits in data and digitized simulation for 10 GeV positrons. Reconstructed data is shown in blue, digitized and reconstructed Monte Carlo in red. The excess in data at ~50 hits is due to muon contamination in the beam. b) Residual to a linear fit to the AHCAL response in the energy range 10-20 GeV. The green band indicates the influence of the calibration uncertainties on the saturation scale on the linearity hypothesis.

Fig. 1b shows cell-by-cell the MIP resolution correlation between data and digitized MC. The MIP width is influenced by Poisson smearing and noise. The correlation is good, but the MC width is about 10% smaller than for the data. This effect may be related to the tile non-uniformity, which is not yet included in the digitization.

2.2. Simulation of electromagnetic showers

For the analysis of electromagnetic showers a threshold cut of 0.5 MIP is applied to the energy deposited in each cell, after calibration. The total number of cells with hits above threshold is very sensitive to the MIP calibration and to the modeling of the noise and optical cross-talk between cells. Fig. 2a shows the total number of hits recorded in the AHCAL for a 10 GeV positron shower. The agreement is very good. The small excess at low number of hits in the data is due to remaining muon contamination in the positron sample, which is not simulated in the MC. For 50 GeV positron momentum the number of hits in MC is systematically 5% lower than in data. Besides the width of the MIP peak, the number of hits above threshold is influenced by light cross-talk between scintillator tiles. This value is assumed to be 10% summed up over all neighbors cells. Further studies will have to show if this disagreement can be improved tuning the amount of light cross-talk.

The integral response to single particles is reconstructed as the energy sum of all hits above threshold over the whole detector. The energy of positrons in the range 10-50 GeV has been reconstructed. Fig. 2b presents the residual to a linear fit in the energy range 10-20 GeV. The error bars include statistics and an uncorrelated systematics of 0.5% from the fit to the total energy distribution. The error band corresponds to the correlated systematic uncertainty of about 5% on the saturation scale. The reconstructed response is linear within errors up to 30 GeV beam momentum. A significant remaining non-linearity of about 4% is observed for 50 GeV positrons.

The energy resolution for positrons is evaluated for data and digitized MC and presented in Fig. 3. A sum in quadrature of noise (\(\propto \frac{1}{E}\)), stochastic (\(\propto \sqrt{E}\)) and constant terms is used to fit the points. The noise term is fixed from random trigger events to 2 MIP. The stochastic terms in data and MC are \(22.6\pm0.1_{\text{fit}}\pm0.4_{\text{calib}}\)%/\(\sqrt{E}\) and \(20.9\pm0.3_{\text{fit}}\)%/\(\sqrt{E}\), respectively. While...
Figure 3. Relative width of the reconstructed energy as a function of beam energy. The resolution is fitted excluding the data points at 40 and 50 GeV because of remaining non-linearity at high energies. The fit results are shown as red (black) line for data (simulation). The green band indicates the influence of calibration uncertainties on the saturation scale. Uncertainties on the MIP scale cancel in the width over mean ratio and are therefore not included.

both constant terms are consistent with zero with an error of 1.5% for data and 2.2% for MC. This preliminary data/MC comparison for electromagnetic processes is considered satisfactory and sufficient to move on to hadronic analysis. The remaining deviations are smaller than 10% and set the scale for the comparison data/MC of hadronic processes.

3. Hadronic showers response in the AHCAL
Hadronic data is calibrated, as electromagnetic data, to the MIP scale.

Pion events collected in October 2006 with a partially instrumented AHCAL are presented. Beam momenta from 6 GeV to 80 GeV have been analyzed. The range 6-20 GeV is a negative pion sample; the range 30-80 GeV is a positive pion sample. No correction for proton contamination in the positive pion sample is applied.
Pions with only MIP-like interaction in the ECAL are selected and the energy deposited in the AHCAL and TCMT are summed to reconstruct contained showers. The response of the calorimeter is shown in Fig. 4a). Data is compared to two MC models. The LHEP and QGSP\_BERT models have been chosen, for being the two most discrepant models in terms of total energy deposition. The MC is digitized and reconstructed with the same sampling factors and MIP/GeV conversion factor as for the data.
A discrepancy in the energy scale is observed of about 4% (20%) between data and LHEP (QGSP\_BERT).
The residuals to linearity are extracted fitting data and MC in the range 6-20 GeV. Above this range data is consistent with the linear hypothesis at the 2% level, while MC has a positive deviation of 6% (4%) for LHEP (QGSP\_BERT). This could be attributed to the non-compensating nature of the calorimeter. The remaining difference between data and MC can be the effect of not properly corrected SiPM non-linearity.
The longitudinal shower profiles of a 20 GeV pion shower is displayed in Fig. 5a and compared to the two MC models. The shower modeled in QGSP\_BERT appears to start later than in data and LHEP.
Figure 4.  a) Linearity of the AHCAL and TCMT combined response to pions. Black circles are data, open squares digitized LHEP and open triangles are digitized QGSP_BERT. Residual from a linear fit to the total energy in the range 6-20 GeV for data (b) and LHEP (c).

Figure 5.  a) Longitudinal shower profile of 20 GeV pions. The curve is a fit to the data points, excluding the last two layers which are known to have low efficiency. Energy dependence of the longitudinal shower maximum (b) and shower attenuation parameter (c). Black circles are data, open squares digitized LHEP and open triangles are digitized QGSP_BERT.

The shower maximum is determined with a fit to this distribution using the parameterization

$$\frac{dE}{dt} = k t^{a-1} e^{bt},$$

where $t$ is the depth in the calorimeter expressed in units of $\lambda_0$. The last two layers of the AHCAL are not included in the fit since they are known to have low efficiency. The energy dependence of the shower maximum $t_{\text{max}} = \frac{a-1}{b}$, and the shower attenuation $b$, are presented in Fig. 5b and Fig. 5c. The expected logarithmic increase of $t_{\text{max}}$ with energy is observed. The value of $b < 1$ is expected for pion showers.

The energy resolution obtained with the combined AHCAL and TCMT is presented in Fig. 6 for data and MC. The data lies in between the two models chosen for comparison, illustrating the
Figure 6. Energy resolution for pions in the combined AHCAL and TCMT detector as a function of the beam energy, \( E \) (a) and of \( 1/\sqrt{E} \) (b). Black circles are data, open squares digitized LHEP and open triangles are digitized QGSP\_BERT. The errors are statistical only.

large variations in the MC predictions. This plot is, at present, only a qualitative comparison.

4. Shower leakage

Hadronic shower development suffers from much larger fluctuations than electromagnetic ones. In particular the shower starting point varies over a much larger range in the calorimeter depth from event to event. The determination of the shower starting point is crucial to study hadronic shower shapes in detail and to address the problem of shower leakage. The definition of shower starting point is based on the topological resolution of the AHCAL. The track of the incoming pion is followed through the first layers of the detector until its first interaction takes place and an energy larger than minimum ionizing is released. The starting point identification method can be generalized to neutral hadron showers, but this study is restricted to charged hadrons.

Data is presented which was collected in a combined run of AHCAL and TCMT in 2007 at CERN. The fully instrumented AHCAL was rotated at an angle of 60 degrees with respect to the incoming beam. This gives the maximum depth of active detector achievable with the setup.

Fig. 7a shows the position of shower start in units of interaction length, \( \lambda_0 \). The decreasing exponential slope of 0.88 \( \lambda_0 \) agrees with the value extracted using a completely independent method and shown in Fig. 5c.

Fig. 7b shows the longitudinal profile for 10 GeV pion showers. Knowing for each event the shower starting point, it is possible to shift the single event profile to the same starting point. This is shown by the open symbols. The longitudinal shower profile becomes much shorter after correcting event-by-event for the variation of the shower starting point. A more meaningful and independent data to MC comparison will be possible using these profiles.

The knowledge of the shower starting point has been used to study the effect of shower leakage on the energy reconstructed and energy resolution of the calorimeter, shown in Fig. 8a and Fig. 8b, respectively. Fig. 8a has been used to determine a correction for the energy deposited as a function of the shower starting point. If this correction is applied to pion showers of 10 GeV
the mean value of the reconstructed energy better agrees with the expected beam momentum, but the energy resolution does not improve. This correction has no effect on the resolution of single particles, but can be potentially useful in the reconstruction of jets.

5. Showers separation

During test beam data taking single pion events are recorded. These events are selected and overlaid offline for the study of showers separation in the calorimeter. Calibrated pion events which interact in the ECAL as MIP-like particles are selected, which have no energy leaking to the TCMT. These fully contained showers in the AHCAL are selected according to their relative distance and overlaid on a cell basis. The energy of the overlaid event in each cell is the sum of the single pion energies. This method over-estimates the noise of the calorimeter by double counting it from the two events.
Figure 9. Energy distribution of reconstructed clusters $E_{\text{cluster}}$ (solid lines) for an overlaid event with a 8 GeV and a 12 GeV pions. The dash-dotted and dotted lines are the calorimeter energy distributions for single events, $E_{\text{calo}}^1$ and $E_{\text{calo}}^2$. In b) the cluster associated with the charged hadron has been replaced by the beam momentum, $E_{\text{track}}$ (dashed line).

The overlaid events are then input to a clustering algorithm which identifies the two clusters and measures their total energy. A track-wise clustering algorithm is used, which is an algorithm developed for particle flow in the full ILC detector [7]. The parameters of the code have been tuned for the AHCAL geometry to maximize the number of two identified clusters and minimize the difference between reconstructed and true cluster energy in the calorimeter.

An example is presented where two pions of 8 GeV and 12 GeV respectively are overlaid. The reconstructed cluster energies $E_{\text{cluster}}$ are shown in Fig. 9a as compared to the energy reconstructed in the calorimeter for the single pions, $E_{\text{calo}}$. One can see a broadening of the energy spectra of both pions due to the clustering procedure. The efficiency of two cluster separation with this method is more than 90% for two particles at a distance of 10 cm.

5.1. Naïve Particle Flow

Given the reconstructed clusters, an assumption can be made to test a naïve Particle Flow approach. One of the two pions is considered to be a charged hadron; its energy measured in the calorimeter is replaced by the tracker information, see Fig. 9b. For each overlaid event a “track” is defined by choosing the position of one of the mip stubs in the ECAL. The track’s energy, $E_{\text{track}}$, is the beam momentum of the corresponding event. The track is assigned to the cluster with cluster position (projection of the center of gravity to the $x-y$ plane) closest to the track.

To quantify the result of the particle flow approach compared to the ideal particle flow a quantity has been defined, the efficiency of shower separation. For events where exactly two clusters have been found the cluster energy $E_{\text{cluster}}$ in an interval of $\pm 3\sigma$ of $E_{\text{calo}}^1$ is integrated and compared to $E_{\text{calo}}^1$. The ratio of these two quantities defines the particle flow efficiency,

$$
eff_{\text{Pflow}} = \frac{\int_{-3\sigma}^{+3\sigma} E_{\text{cluster}}}{\int_{-\infty}^{+\infty} E_{\text{calo}}^1}.$$

The ideal particle flow case corresponds to infinitely separated clusters for which $E_{\text{cluster}} = E_{\text{calo}}^1$. Fig. 10 shows the efficiency of particle flow for 6 GeV charged particle (track). Neutral particles
with energy between 6 and 20 GeV are separated from the charged one. The efficiency increases for larger distances between particles and for lower energy of the neutral particle. The test of larger distances is not possible using the currently analyzed data set. This result can be compared to MC simulation studies [8] performed for the optimization of the AHCAL cell size. Comparing to the 3x3x1 cm$^3$ configuration (which is the one the AHCAL has been realized with) there is good qualitative agreement between data and MC trend. It has to be noted that in these studies one neutral and one charged particle were simulated, whereas in data we use two charged pions. This may be an advantage for the clustering algorithm since the MIP-like stab of the charged particle considered neutral is not removed before clustering. Detailed comparison with MC is still needed to validate particle flow in simulation with real data.

6. Conclusions
The calibration procedure of the AHCAL CALICE prototype has been tested on electromagnetic data. A linear response up to 30 GeV is obtained after correction of the SiPM non-linear response. A deviation of 4% from linearity is still visible for 50 GeV positrons, which will require more detailed studies.

The MC digitization procedure includes the effects of the SiPM response function, Poisson smearing and noise, and optical cross-talk between adjacent scintillator tiles. The digitization has been validated with muon and positron data at the level of better than 10%. This analysis shows a first comparison of CALICE hadron data to MC models including digitization. First results indicate that the digitized MC models agree in trend with the data in all observables studied. For the extraction of the total energy from the visible events it is observed that the two MC models have different MIP to GeV conversion factors or different sampling factors for hadrons. This effect will have to be investigated in more detail.

The deviation from linear behaviour at high energy is different in data and MC. While data is consistent with linearity up to 80 GeV at the 2.5% level, both MC models indicate a positive deviation. This effect could be due to an increasing $e/\pi$ at high energy, which is either not observed in data or compensated by a remaining non-linearity effect.

The two independent analysis of the longitudinal shower profile and the shower starting point determination yield consistent values for the interaction length of the calorimeter for pions to
be 0.88 \lambda_0.

The first application of a Particle Flow type of reconstruction to real data has been presented. This type of analysis is a powerful tool to compare various clustering algorithms in a realistic hadronic shower environment. Once these results have been validated by comparison to MC prediction they will be an important step in the verification of Particle Flow performance for physics events.

The shower separation efficiency obtained from these preliminary studies is consistent with the MC studies which have driven the design of the AHCAL prototype.

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