PROCEEDINGS OF SCIENCE

Analogue, Digital and Semi-Digital Energy Reconstruction in the CALICE AHCAL

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Within the CALICE collaboration different calorimeter technologies are studied for a future linear collider. These technologies differ in active material, ganularity and readout systems. The Analog Hadronic Calorimeter (AHCAL) reads out the signal proportional to the energy deposition in each calorimeter cell, while the digital HCAL detects hits by firing RPC pad sensors above a certain threshold. A 3 bit readout is provided by the semi-digital HCAL, which counts hits above three different thresholds per cell. For these three options different energy reconstruction procedures are developed. The analog data can also provide digital information, thus the advantages and disadvantages of different energy reconstruction procedures can be studied.
In this work such a comparison is done by applying these procedures to AHCAL beam test data, collected with the 1m^3 physics prototype at CERN, and simulated data, generated with GEANT4.

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1. Introduction

For a future linear electron-positron collider such as ILC or CLIC, the desired jet energy resolution of $3-4\,\%$ for a wide range of jet energies can be achieved by using Particle Flow Algorithms for the jet reconstruction. Within the CALICE collaboration, several concepts for a hadron calorimeter (HCAL) optimised for Particle Flow are studied and have been tested with large, $\sim 1\,\mathrm{m}^3$ prototypes: the so-called analogue, digital and semi-digital HCAL concepts. The concepts differ in active material for the shower detection, granularity, readout technology and reconstruction method. This makes it difficult to disentangle the influence of each of these components to the energy resolution of jets as well as of individual particles. Since the analogue HCAL prototype has a larger cell size than the other two concepts, and the digital and semi-digital HCAL prototypes do not provide analogue hit size information, it is impossible to study all different aspects in test beam data. For the data taken with the analogue HCAL prototype, a direct comparison of the reconstruction methods is possible, albeit with a cell size not optimal for the digital and semi-digital methods. The effect of the other differences can only be studied directly in simulation, where every aspect can be changed separately. For reliable results from the simulation it is important to validate the simulation of hadronic showers in the detector prototypes by comparing them to the measured test beam data, especially for the quantities that are relevant for the energy reconstruction.

2. Analogue Hadronic Calorimeter physics prototype in the CERN 2007 test beam

For this analysis the AHCAL test beam data from 2007 with steel absorber is chosen. The 2007 CERN test beam setup at the SPS consisted of 30 layers of CALICE silicon-tungsten ECAL, 38 layers of the scintillator-steel analogue HCAL and 16 layers of the scintillator-steel tail catcher and muon tracker (TCMT). The Absorber plate thickness for the HCAL was $\sim 2\,\mathrm{cm}$. A detailed description of the test beam setup can be found in [1].
The run list and event selection follows the published analysis [2] and consists of 29 runs at 11 energies for pions between 10 and 80 GeV. Negative pion events are selected by requiring the showers to start in the first 5 HCAL layers and by rejecting muons that have a smaller energy deposit than 150 MIP in the HCAL. One MIP is defined as the response of a minimum-ionizing particle like a muon in a single AHCAL cell. The value of a MIP is measured within calibration runs in ADC counts. For a detailed description of the event selection and the whole analysis see [3]. Additionally, the test beam runs are simulated using the software packages GEANT4 version 9.6 patch 1 with the conversion coefficients 846 keV/MIP and 15 % optical crosstalk between the AHCAL tiles. As the physics list FTFP_BERT from GEANT4 9.6 shows best performance for hadrons [4], it was chosen for comparisons in this analysis.

3. Energy Reconstruction

The goal of this analysis is a direct comparison of the three reconstruction methods, analogue, digital and semi-digital, applied to the same AHCAL data. This includes using the same methods to extract the mean energy and the resolution. Since the distributions of the energy reconstructed

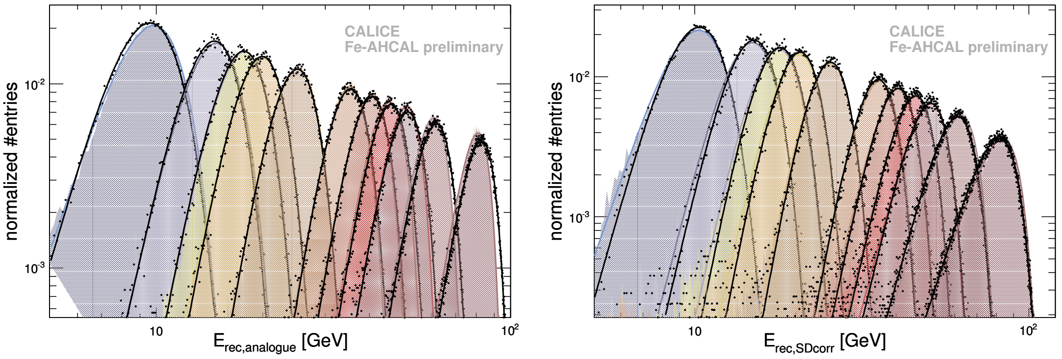

Figure 1: The analogue (left) and semi-digital (right) reconstructed energy distributions are shown for all energies, data in colored filled histograms and FTFP_BERT simulated data in black dots. The black and colored curves show Novosibirsk fits.

from the number of hits are expected to show a non-gaussian tail, the procedure to fit the distributions and to extract the mean and the width is discussed in the following.
In a first step, the Novosibirsk function $f(x) = A \cdot \exp\left(-\frac{1}{2}\left(\frac{\ln^2[1+\Lambda\tau(x-\mu)]}{\tau^2} + \tau^2\right)\right)$ with $\Lambda = \frac{\sin\left(\tau\cdot\sqrt{\ln 4}\right)}{\sigma\cdot\tau\cdot\sqrt{\ln 4}}$ is used to fit the reconstructed energy distributions. The fit range is determined as $\mu \pm 3\,\sigma$ from a pre-fit with a Gaussian. The fit consistently provided a χ^2/ndf value better than 3. In order to extract the mean and the width of this fit function, a histogram is filled with random values generated according to the Novosibirsk function with the extracted fit parameters μ, σ, τ and A. The mean and RMS of the histogram are used as response and resolution for the studied energy.
For each method the energy is reconstructed on an event-by-event basis.

3.1 Analogue

From the linear hit energy sum E_{sum} above 0.5 MIP threshold in the AHCAL the analogue energy is reconstructed as $E_{rec,analogue} = 0.3805\,\text{GeV} + \frac{e}{\pi}\,(\omega \cdot E_{sum})$ with the correction for the non-compensation with $e/\pi = 1.19$ and the electromagnetic calibration factor ω for the conversion from MIP to GeV scale. The approximately constant (within max. 10 % deviation) contribution of the track in the ECAL is taken into account using a constant value of 0.3805 GeV.

3.2 Digital

Within the digital energy reconstruction the non-linear digital response is linearised as follows. The mean number of hits $< N_{hits} >$ as a function of the beam energy E_{beam} is fitted with a power law $< N_{hits} >= a \cdot E^b_{beam}$. By constraining the digital reconstructed energy to show a linear behavior $E_{rec,digital} = E_{beam}$, the energy is reconstructed with the fit parameters of the power law to

$$E_{rec,digital} = \sqrt[b]{\frac{N_{hits}}{a}}. \tag{3.1}$$

3.3 Semi-Digital

The semi-digital energy reconstruction is done via the following equation

$$E_{rec,semi-digital} = \alpha N_1 + \beta N_2 + \gamma N_3, \tag{3.2}$$

with N_1 the number of hits with energy below 5 MIP, N_2 the number of hits above 5 MIP & below 15 MIP and N_3 the number of hits above 15 MIP. These threshold values are adopted from the MICROMEGAS SDHCAL analysis [5]. They were not optimised for the AHCAL geometry which has a much larger cell size. α,β and γ weight the hits depending on their energy content. Hadronic showers change their structure and evolution with energy, which is taken into account by parameterizing α,β and γ as quadratic polynomials of the total number of hits $N_{hits} = N_1 + N_2 + N_3$. To find the best parameterization of these so called calibration coefficients, a χ^2-like function of the form $\chi^2 = \sum_{i=1}^{N} \frac{\left(E^i_{beam} - E^i_{rec,semi-digital}\right)^2}{E^i_{beam}}$ is minimised, where i runs over all events. To achieve a reasonable linearity another linearisation step, similar to the digital reconstruction, was applied.
An example of the energy distributions is given in Figure 1, which shows the analogue in comparison to the semi-digital reconstructed energy distributions for data and MC.

4. Results

The resolutions obtained with the different reconstruction methods applied to the same AHCAL data are compared directly in Figure 2. In addition, the best resolution reached with AHCAL data, by applying software compensation techniques [2], is indicated. For the comparison one should keep in mind that in the earlier analysis, the TCMT is fully included and the track in the ECAL considered in the energy reconstruction, while here a simplified treatment of the ECAL is used and the TCMT contribution is neglected. The non-linearities of the three methods studied in this analysis are also shown in the lower part of Figure 2.
For the lowest energy points, the analogue and the digital reconstruction procedures show rather similar resolutions. For larger energies, the resolution of the analogue reconstruction method continues to decrease, while the digital resolution increases dramatically. The best resolution of all three methods for low energies up to about 35 GeV is found for the semi-digital reconstruction.
All three methods provide a reasonable linearity. The cell size of the AHCAL is not optimised for the digital and semi-digital reconstruction methods, leading to large saturation effects already below 30 GeV. The methods can correct for the shift of the mean number of hits due to the saturation, however the observed energy resolutions are significantly degraded. Of the three methods studied here, the semi-digital methods shows the best resolution below 30 GeV, while the resolution of the analogue reconstruction is best at large energies. None of the methods compares favourably with software compensation techniques using the full analogue information.
The results of this analysis are expected to depend significantly on the calorimeter cell size and thus are not directly applicable to the DHCAL or SDHCAL prototypes. But the impact of the cell size can be studied in simulation. Since it could be shown in this analysis that the simulated MC data set describes the recorded test beam data this simulated data will be used for the future cell size study.

References

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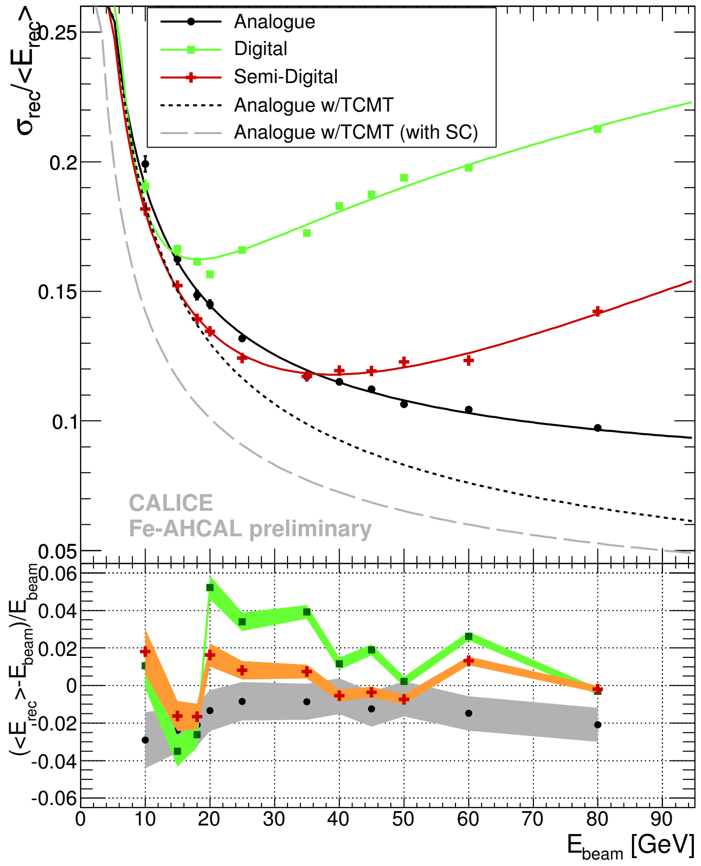

Figure 2: Energy dependence of the relative energy resolution of the AHCAL obtained using different approaches of the energy reconstruction for pions: analogue (black), digital (green) and semi-digital (red). The dashed and dotted curve show the resolution achieved in [2] with and without software compensation techniques, using the energy deposits in the TCMT (and of the track in the ECAL) in addition to the AHCAL. The bottom plot shows the residuals to beam energy with the bands indicating the systematic uncertainties and the statistical errors smaller than the markers.

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