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Highly granular hadron calorimeter: software compensation and shower decomposition

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Abstract. The highly granular analogue hadron calorimeter was developed and constructed by the CALICE collaboration. The active layers of the calorimeter are assembled from scintillator tiles with individual readout by silicon photomultipliers and are interleaved with absorber plates. The response and resolution of the calorimeter equipped with steel absorber was intensively tested in single particle beams. The application of software compensation techniques developed for the scintillator-steel prototype allows for reduction of the stochastic term of the single particle resolution from $58\%/\sqrt{E/GeV}$ to $45\%/\sqrt{E/GeV}$. The detailed study and decomposition of the longitudinal and radial profiles of hadron-induced showers in the energy range from 10 to 80 GeV are presented and compared to GEANT4 simulations.

1. Introduction

The experimental program proposed for future high-energy lepton colliders such as the ILC or CLIC puts unprecedented requirements on the detector systems [1]. To achieve a jet energy resolution of better than 4% at 100 GeV, the particle flow algorithm (PFA) was developed, which is based on the high granularity of a calorimeter system [2]. The CALICE collaboration has developed, constructed and tested a set of highly granular electromagnetic and hadron calorimeter prototypes. The main goals of this activity were the validation of calibration procedures, study of the calorimeter properties and experimental test of the particle flow concept. This study is focused on the properties of the analogue scintillator-steel hadron calorimeter prototype (Fe-AHCAL) [3]. The experimental response, energy resolution and shower profiles have been analysed and compared to GEANT4 simulations [4]. The high longitudinal and radial granularity of the prototype allows the hadronic shower development to be studied with high spatial resolution using shower decomposition.

2. Experimental setup, data and simulations

The CALICE Fe-AHCAL is a sampling structure of 38 active layers interleaved with 2 cm thick steel absorber plates. Each active layer has an area of $90 \times 90 \text{ cm}^2$ and is assembled from 5 mm thick scintillator tiles of varied transverse sizes, from $3 \times 3 \text{ cm}^2$ in the centre to $12 \times 12 \text{ cm}^2$ in the periphery. The tiles (cells) are individually read out by silicon photomultipliers (SiPM). The longitudinal depth of the Fe-AHCAL is about 5.3 nuclear interaction lengths. The response of



each calorimeter cell is calibrated using the visible signal of a minimum-ionising particle (MIP) as described in ref. [3]. To reject noise, only cells with a visible energy above a threshold of 0.5 MIP are used in the analysis.

The experimental data analysed here were collected at CERN SPS in 2007 with beams of charged hadrons with momenta from 10 to 80 GeV. The CALICE setup at CERN is described in detail in ref. [7] and comprised the silicon-tungsten electromagnetic calorimeter (Si-W ECAL) [5], the Fe-AHCAL, and the scintillator-steel tail catcher and muon tracker (TCMT) [6]. The depth of the Si-W ECAL is one nuclear interaction length at normal incidence and it has a very fine transverse segmentation equivalent to $1 \times 1 \text{ cm}^2$ cells. The TCMT is also a sampling calorimeter, it has 16 active layers assembled from scintillator strips with SiPM readout. The total longitudinal depth of the calorimeter setup amounts to ~ 11 nuclear interaction lengths.

The event selection procedure rejects muon-like and double particle events. The signal from the Čerenkov counter placed upstream of the calorimeters was used for the off-line separation of pions from protons in the positive hadron beams. For the current analysis, the Si-W ECAL was used as a tracker and pre-shower detector to select events with the first inelastic hadron interaction (shower start) at the beginning of the Fe-AHCAL. Such a requirement also helps to minimise the longitudinal leakage. The algorithm of the shower start identification is described in ref. [7]. The simulated single pion samples for the comparison with the experimental results were produced using different physics lists from GEANT4 version 9.6. The simulated samples were digitised taking into account the SiPM response, light crosstalk between neighbouring scintillator tiles in the same layer, and calorimeter noise extracted from data.

3. Energy resolution with software compensation

The reconstructed energy for each event is calculated as the sum of reconstructed energies in ECAL, Fe-AHCAL and TCMT as described in ref. [7]. The energy distributions were fit by Gaussian function in the range ± 2 r.m.s. of the sample mean to extract the mean reconstructed energy and resolution for the given energy. The response of the Fe-AHCAL to pions is observed to be linear in the energy range from 10 to 80 GeV. Two techniques of software compensation were developed, which allow the off-line correction of the reconstructed energy on an event-by-event basis [7]. The local software compensation technique uses local energy density information for a cell-by-cell re-weighting of energy deposits. The global software compensation technique exploits the distribution of cell energies to derive one overall weighting factor for the energy in the given event. Neither of the described techniques requires an a priori knowledge of the particle energy. The intrinsic energy resolution of the Fe-AHCAL for hadrons is measured to be $58\%/\sqrt{E/GeV}$ with a constant term of 1.6%. Both software compensation techniques show similar performance resulting in reduction of the stochastic term to $45\%/\sqrt{E/GeV}$. In contrast to data, the simulations predict larger improvement of the resolution with increasing energy.

4. Hadronic shower decomposition

The substructure of hadronic showers in the Fe-AHCAL can be studied using detailed longitudinal and radial shower profiles. The important advantage of the high granularity is the possibility to deconvolve the energy density distribution from the distribution of the shower start position. The longitudinal profiles from shower start represent the average visible energy in units of MIP measured per calorimeter layer, the first bin corresponding to the physical layer where the shower start is identified. An example longitudinal profile extracted from the experimental data for 40 GeV pions is shown in figure 1a where the bin width is ~ 0.14 in units of the nuclear interaction length λ_1^{eff} . The parametrisation of the longitudinal development of hadronic showers with a sum of two gamma distributions was proposed in ref. [8] as a natural extension of the parametrisation of electromagnetic shower profiles. In the frame of this approach, the longitudinal profile can be described with the two-component function

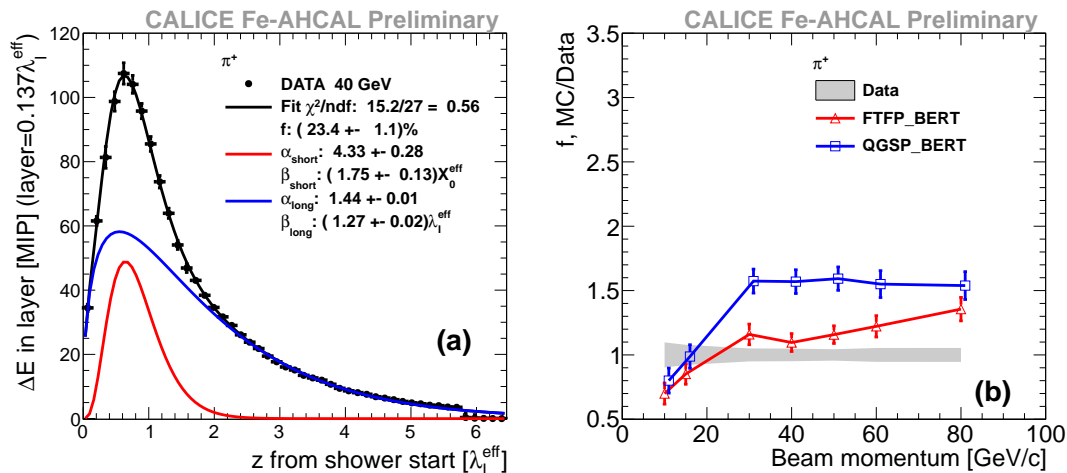


Figure 1. (a) Longitudinal profile of showers induced by positive pions from the test beam at 40 GeV in the Fe-AHCAL (black circles), fit to the profile with equation (1) (black curve) and its components corresponding to the “short” (red) and “long” (blue) contributions. (b) Ratio of the “short” component fraction extracted from simulations using the FTFP_BERT (red) and QGSP_BERT (blue) physics lists to that extracted from data versus beam momentum; the grey band shows the systematic uncertainty for data. Figures from ref. [9].

$$\Delta E(z) = A \cdot \left\{ \frac{f}{\Gamma(\alpha_{\text{short}})} \cdot \left(\frac{z}{\beta_{\text{short}}} \right)^{\alpha_{\text{short}}-1} \cdot \frac{e^{-\frac{z}{\beta_{\text{short}}}}}{\beta_{\text{short}}} + \frac{1-f}{\Gamma(\alpha_{\text{long}})} \cdot \left(\frac{z}{\beta_{\text{long}}} \right)^{\alpha_{\text{long}}-1} \cdot \frac{e^{-\frac{z}{\beta_{\text{long}}}}}{\beta_{\text{long}}} \right\}, \quad (1)$$

where A is the scaling factor, f is the fractional contribution of the “short” component with the shape parameter α_{short} and the slope parameter β_{short} ; α_{long} and β_{long} are the shape and the slope parameters of the “long” component.

The fit to the longitudinal profile with equation (1) is performed up to $4.5\lambda_1^{\text{eff}}$. Figure 1a shows the fit result together with the separate contributions of the “short” and “long” components. The slope parameter of the “short” component is ~ 1.5 in units of radiation lengths X_0^{eff} , which is similar to that of electromagnetic showers. A comparison of shapes of the “short” and “long” components leads us to the conclusion that they can be roughly interpreted as the electromagnetic and hadronic substructures within a hadronic shower. The estimates of the shape and slope parameters for both components agree within uncertainties between data and simulations in the energy range studied. At the same time, the parameter f rises faster in simulations than in data with increasing energy and is significantly overestimated by simulations from 30 GeV and above. The ratio of simulations to data for the parameter f is shown in figure 1b. The overestimation of this observable by simulations can be caused by the overestimation of π^0 production with increasing energy in the GEANT4 hadronic models.

Radial profiles describe the transverse distribution of the energy density within a shower integrated over the longitudinal direction. They are calculated as an average energy density at the distance r from the shower axis within a ring of width Δr . The unprecedented transverse granularity of the Fe-AHCAL allows the bin width for radial profiles $\Delta r = 10$ mm. The ratio of simulations to data of radial profiles is shown in figure 2 for 40 GeV pions and protons. The simulations significantly overestimate the energy density near the shower axis for pions. The

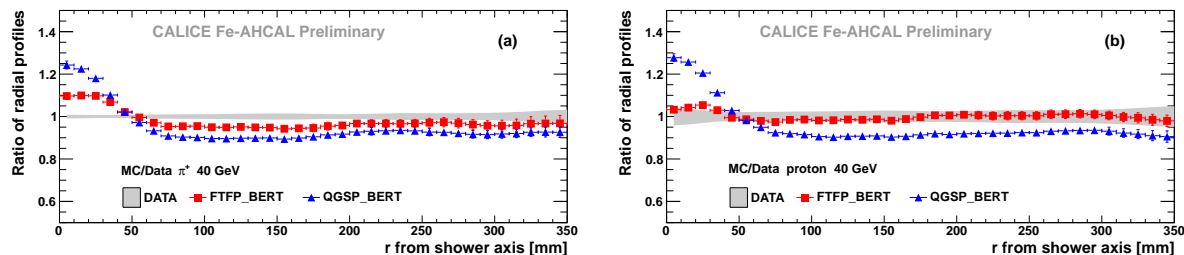


Figure 2. Ratio of radial profiles of showers induced by positive pions (a) and protons (b) at 40 GeV in the Fe-AHCAL extracted from simulations using FTFP_BERT (red) and QGSP_BERT (blue) physics lists to that extracted from test beam data; the grey band shows the systematic uncertainty for data. Figures from ref. [9].

FTFP_BERT physics list gives better predictions for pions and reproduces the behaviour for protons within uncertainties in the energy range studied.

The radial profiles can be parametrised with the sum of two exponential functions, which describe the behaviour in the shower core and far from the shower axis (in the halo region). A comparison of the fits to radial profiles reveals a good agreement of halo slope parameter between data and simulations. The observed underestimation of the core slope parameter is $\sim 5\%$ (10%) by the FTFP_BERT (QGSP_BERT) physics list above 15 GeV.

5. Conclusion

The development of hadronic showers in the highly granular scintillator-steel analogue hadron calorimeter has been studied in the energy range 10–80 GeV. The software compensation techniques developed for the Fe-AHCAL help to reduce the contribution from stochastic fluctuations to the energy resolution by 10–20% for single hadrons. In the frame of the particle flow approach, the software compensation applied to identified clusters in the calorimeter can contribute to the improvement of the jet energy resolution. A comparison of the longitudinal and radial shower development between data and GEANT4 simulations has been performed based on the shower decomposition. From the detailed comparison one can conclude that the observed discrepancy between data and GEANT4 simulations is most likely due to unprecise modelling of the energy dependence of π^0 production.

Acknowledgments

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