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Reconstruction and study of hadronic showers with highly granular calorimeters

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The physics and technological prototypes of imaging electromagnetic and hadronic calorimeters developed and operated by the CALICE collaboration have provided an unprecedented wealth of highly granular data of hadronic showers for a variety of active sensor elements and different absorber materials. The main goal of the CALICE research and development activities is to validate the performance of high-granular systems and study different reconstruction schemas. The very high longitudinal and transverse granularity of the constructed calorimeter prototypes opens the possibility to study the hadronic shower development and substructure and perform a detailed validation of the GEANT4 simulations. In this paper, the energy reconstruction and resolution for single hadrons in the analog and semi-digital hadron calorimeters is discussed. A comparison is provided of the standard and software compensation reconstruction in individual detectors and combined electromagnetic and hadronic systems. Several observables from test beam measurements, which characterise hadronic shower development, are confronted with the predictions of the simulations using GEANT4 hadronic physics models.

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1. CALICE prototypes for the PFA calorimetry

The main advantage of high longitudinal and transverse segmentation is the possibility to exploit the full power of the Particle Flow approach (PFA) for the energy reconstruction. The most matured and sophisticated particle-flow algorithms are being developed for future linear collider experiments where detectors are proposed to contain the calorimeter systems with unprecedented granularity [1]. The PFA-based reconstruction is currently mastered by the CMS collaboration and allow significant improvement of particle identification and energy reconstruction quality [2]. Several types of CALICE highly granular electromagnetic and hadronic calorimeter prototypes based on different readout technologies were designed, constructed and exposed to test beams during the last decade. Single-particle beams of muons, electrons and hadrons in the energy range from 1 GeV to 300 GeV were used, the overwhelming majority of collected data being positive and negative pions with momenta from 10 to 80 GeV/c. The calorimeters used in the presented analyses are listed in table 1. The test beam data were taken with either standalone calorimeters or combined setups, which are described in the corresponding references shown in table 1.

Table 1: The CALICE calorimeter prototypes used in the analyses discussed in this paper.

Calorimeter prototype	Active material and readout	Longitudinal size and segmentation	Transverse size (cell size)	Absorber
Electromagnetic SiW ECAL	Silicon pads	$\sim$1 λ_I 30 layers	18$\times$18 cm^2 (1$\times$1 cm^2)	Tungsten [3]
Hadronic AHCAL	Scintillator tiles with SiPMs	$\sim$5.3 λ_I 38 layers	90$\times$90 cm^2 (min. 3$\times$3 cm^2)	Steel [4] Tungsten [5]
Hadronic SDHCAL	GRPC	$\sim$5.8 λ_I 48 layers	100$\times$100 cm^2 (1$\times$1 cm^2)	Steel [6]
Tail catcher and muon tracker (TCMT)	Scintillator strips with SiPMs	$\sim$5.2 λ_I 16 layers	100$\times$100 cm^2 (5$\times$100 cm^2)	Steel [7]

2. Hadron energy reconstruction

Software compensation for calorimeters with analog readout. The sampling scintillator-SiPM-based analog hadronic calorimeter was tested with steel (Fe-AHCAL) and tungsten (W-AHCAL) absorbers. The tests of the Fe-AHCAL were performed in combined setups, including electromagnetic calorimeter and tail catcher. The W-AHCAL was tested without electromagnetic calorimeter and in the analysis of the W-AHCAL data the tail catcher was used for particle identification only. The Fe-AHCAL is noncompensating calorimeter with $e/\pi \sim$1.2, while the W-AHCAL is almost compensating calorimeter with $e/\pi \sim$1. The standard energy reconstruction in the AHCAL means that the signals above noise threshold (hits) are summed up and multiplied by one calibration factor. For the noncompensating Fe-AHCAL, two techniques of software compensation (SC) reconstruction were developed [4]. Both techniques work on an event-by-event basis and do not require the knowledge of initial particle energy. The first SC technique estimates the electromagnetic fraction in a hadronic shower using the shape of hit spectrum and reweights the energy sum. The second technique distinguishes the electromagnetic subshower within a hadronic shower and applies reweighting of the hit energies. It was demonstrated that the improvement of resolution due to software compensation for single pions in the Fe-AHCAL can be up to 20% in the energy range 10–80 GeV. The software compensation technique was implemented also to the energy reconstruction in the combined setup, where reweighting was applied not only to the hits in the Fe-AHCAL but also to the hits in the SiW ECAL [8]. The energy resolution for single pions from test beam data estimated for the combined setup using standard and SC reconstruction is shown in fig. 1. The achieved improvement of resolution with software compensation is about 15%.

A crosscheck of the software compensation approach was performed by implementing the software compensation reconstruction to the test beam data collected with the compensating W-AHCAL [9]. Figure 2 shows the relative resolution for single pions from test beam data estimated for the W-AHCAL using standard and SC reconstruction. The resulting improvement of resolution due to software compensation is observed to be much smaller for the compensating W-AHCAL (less than 5%) than for the noncompensating Fe-AHCAL (up to 20%). Such a comparison confirms our understanding that the software compensation techniques account presumably for the fluctuations of electromagnetic fraction in hadronic showers.

Energy reconstruction in a calorimeter with semi-digital readout. The GRPC-based semi-digital hadronic calorimeter prototype, SDHCAL, is a sampling calorimeter with gaseous readout and unprecedented transverse granularity (see table 1). The readout technology of the SDHCAL allows operation at 3-threshold mode (2-bit readout). In this mode, three ranges of cell amplitudes above noise threshold (hits) can be distinguished and three numbers of hits are saved for each event. Two reconstruction schemas were developed for the SDHCAL: binary and multithreshold [10]. For the binary mode, the reconstructed energy is a nonlinear function of the total number of hits in the event, N_{hit}. For the multithreshold mode, three different weights are applied to the detected number of hits in three amplitude ranges, the weights being nonlinear functions of N_{hit}. The improvement of resolution with multithreshold reconstruction with respect to the binary mode is comparable with the improvement due to software compensation for the calorimeter with analog readout.

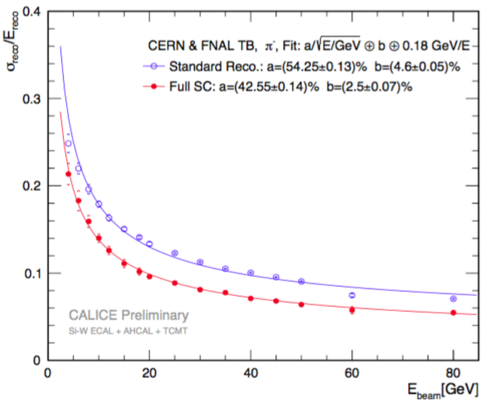

Figure 1: Relative energy resolution for the standard (blue circles) and SC (red circles) reconstruction in the combined setup [8]. The curves are plotted using the fit parameters from the legend. The overall uncertainties are shown.

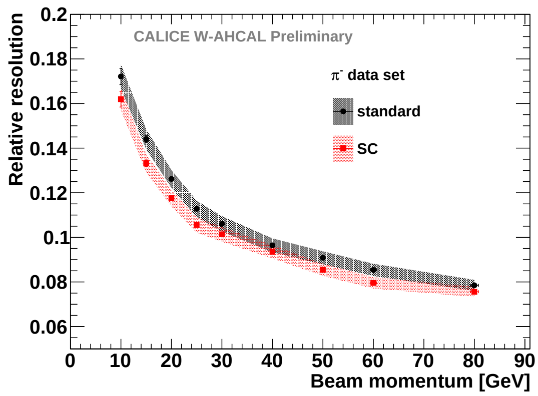

Figure 2: Relative energy resolution for the standard (black circles) and SC (red squares) reconstruction in the W-AHCAL [9]. The error bars (bands) show the statistical (systematic) uncertainties.

3. Validation of simulations

The tests of hadronic models from GEANT4 version 9.6 were performed using data collected with the highly granular calorimeters in the energy range from few GeV up to 100 GeV. The digitisation of simulations and detector specific effects were studied and tuned using electromagnetic showers. In the gaseous SDHCAL, the simulations underestimate both the total number of hits (by $\sim$15% at 80 GeV) and the number of identified track segments in hadronic showers [6, 10]. In the scintillator-based AHCAL, the overestimation by simulations of the energy fluctuations in pion showers increases above 20 GeV up to $\sim$15% at 80 GeV, while good predictions are given for the relative resolution. The detailed longitudinal and radial profiles of shower development show good agreement between data and simulations for pion energies below 20 GeV and discrepancies increase with energy above 20 GeV [11]. For both gaseous and scintillator calorimeters, the radial shower width is underestimated by simulations by $\sim$10% for pion energies above 20 GeV. For hadronic showers, the general trend is that the discrepancies between data and simulations increase with energy. The best predictions for most observables are given by the FTFP_BERT physics list.

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