

Pion Response of the AHCAL Prototype from Beam Tests and Simulation

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Abstract

The Circular Electron Positron Collider (CEPC) is a proposed next-generation collider designed for precision measurements of Higgs boson properties. A primary challenge for the CEPC detector is achieving a boson mass resolution (BMR) of 4%, which is essential for distinguishing Higgs, Z , and W bosons in their hadronic decay modes. The baseline detector design adopts the Particle Flow Algorithm (PFA) concept to satisfy this requirement, where BMR performance is largely governed by the shower separation capability and energy resolution of the calorimetry system. Consequently, a high-granularity hadronic calorimeter is required. In this study, we evaluate an Analogue Hadron Calorimeter (AHCAL) prototype—a scintillator-based option with analogue readout—which underwent beam tests at CERN. Fundamental parameters of the prototype were calibrated, and a Geant4-based simulation was developed to establish a digitization model of the detector response. By validating the simulation against reconstructed beam test data, we demonstrated that the energy linearity for pions is maintained within $\pm 1.5\%$ in the energy range of 10–100 GeV, achieving an energy resolution of $45.5\%/\sqrt{E[\text{GeV}]} \oplus 6.9\%$.

1 Introduction

The discovery of the Higgs boson at the LHC [1, 2] made the precise determination of its properties a central goal of particle physics [3, 4, 5, 6]. The Circular Electron–Positron Collider (CEPC), proposed by the Chinese high energy physics community, is designed as a Higgs factory dedicated to precision measurements of the Higgs boson [7, 8]. The CEPC is planned to operate at a center-of-mass energy of 240 GeV with a design luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ per interaction point, yielding approximately 10^6 Higgs bosons over a decade of operation [9].

A large fraction of physics events at the CEPC result in final states containing hadronic jets originating from the decays of the Higgs, Z , and W bosons. Precise jet energy reconstruction is therefore essential, with a target boson mass resolution (BMR) of about 4% in hadronic decay channels, enabling the separation of Higgs, Z , and W bosons. To meet this requirement, the baseline CEPC detector design is guided by the particle flow algorithm (PFA), in which individual particles in a jet are reconstructed separately, and their energies are measured using the most suitable subdetector [10, 11, 12]. The jet energy is then obtained by combining these measurements, aiming at a jet energy resolution of 3–4% for jets in the energy range of 50–100 GeV [13].

A critical requirement for the successful implementation of PFA at the CEPC is the efficient separation of nearby particles within jets in the calorimeter system. This necessitates a calorimeter with high spatial granularity. Several technological options have been proposed for the hadronic calorimeter (HCAL) of the CEPC detector to fulfill these requirements. One such

option is a scintillator–steel HCAL with analogue readout (AHCAL)[14, 15, 16]. The high granularity of the CEPC AHCAL provides the shower separation capability essential for PFA-based jet reconstruction. Following this approach, an AHCAL prototype has been developed and constructed; the study of its response to pions using beam-test data and simulation is the subject of this paper.

Based on the optimized AHCAL design, the prototype is expected to achieve an energy linearity of about 1.5% and an energy resolution of approximately $60\%/\sqrt{E}$ (GeV) for pion beams in the energy range of 10–80 GeV[17].

The prototype consists of 40 sampling layers, each comprising a 20 mm thick steel absorber and plastic scintillator tiles with dimensions of $40 \times 40 \times 3$ mm³ as the active material, as illustrated in Fig. 1, which shows the scintillator–steel sandwich structure with the tiles and readout board housed in a steel cassette that forms one sensitive layer. The total depth of the prototype corresponds to approximately $4.7 \lambda_I$, ensuring adequate containment of hadronic showers.

The sensitive area of the prototype is 720×720 mm², corresponding to a total of 12,960 scintillator tiles. Each scintillator tile is directly coupled with a SiPM individually, i.e. the "SiPM-on-Tile" design developed within the CALICE collaboration [18, 19]. The scintillation signals are read out by silicon photomultipliers (SiPMs) [20] and then processed using front-end chips (SPIROC2E) [21, 22, 23]. The scintillator tiles and front-end electronics are integrated into steel cassettes to form individual sensitive layers, which are assembled together with the absorber plates within a mechanical support structure[24]. The assembled prototype is shown in Fig. 2.

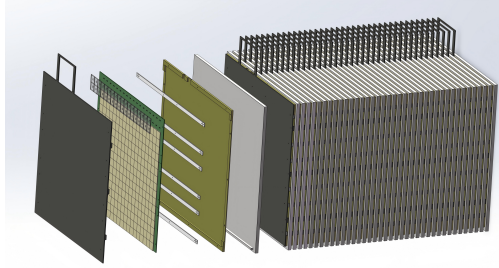


Figure 1: The scintillator-steel sandwich structure of the AHCAL prototype. The scintillator tiles and the readout board are housed in a steel cassette, forming one sensitive layer.



Figure 2: The AHCAL prototype installed at the SPS beamline.

2 Beam Test Setup

The AHCAL prototype has been tested three times at CERN with high-energy particle beams, using the H2 beamline at the Super Proton Synchrotron (SPS) and the T9 beamline at the Proton Synchrotron (PS). Each beam test lasted about two weeks. During these periods, the detector commissioning and the electronics calibration were completed and a large dataset was collected, including $\mu^\pm$ at momenta of 10 and 100 GeV/c and $\pi^\pm$ with momenta from 1 to 100 GeV/c.

Depending on the beam period, the prototype was operated either standalone or together with a prototype of the scintillator–tungsten electromagnetic calorimeter (ScW ECAL) mounted immediately upstream of it. In the combined configuration the beam first passed through the ECAL and then entered the AHCAL, so that the response of the two calorimeters could be studied jointly; in the standalone configuration only the AHCAL was exposed to the beam. The prototype was installed on a movable platform, which allowed different regions of the calorimeter to be positioned in the beam. The results presented in this paper are based on the standalone AHCAL data.

The beam-line layout for the standalone configuration is shown in Fig. 3. The beam enters from the upstream side and passes successively through the two scintillator detectors S1 and S2 before reaching the AHCAL prototype; the beam line continues on the downstream side of the prototype. The signals from S1 and S2 are sent to the trigger logic unit (TLU), which issues a trigger to the data-acquisition (DAQ) board whenever the two detectors are hit in coincidence. Upon receiving the trigger, the DAQ board reads out the AHCAL prototype and transfers the data to the PC.

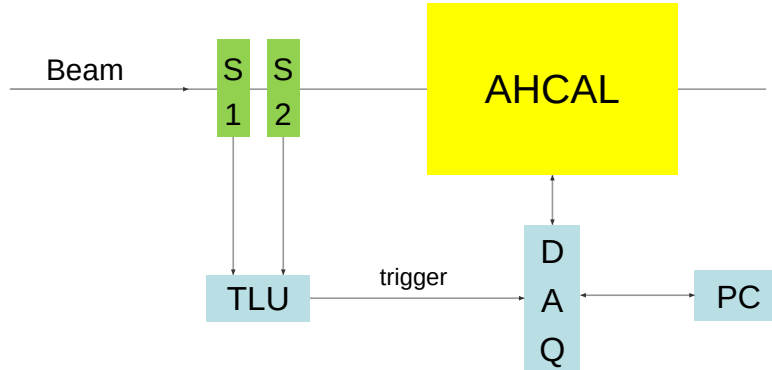


Figure 3: Beam test layout of the AHCAL prototype.

3 Calibration of Basic Parameters

To fully characterize the detector response and ensure data integrity across a wide dynamic range, a systematic calibration procedure was implemented. This process encompasses the determination of the electronic pedestal, the high-to-low gain (HG/LG) ratio, the energy scale via Minimum Ionizing Particles (MIPs), and the single photoelectron (SPE) gain. These quantities are the channel-dependent inputs to the energy-reconstruction formula given in Eq. (3): together they translate the raw ADC counts recorded in each cell into a calibrated deposited energy.

The pedestal is the ADC level recorded in the absence of a signal, and it originates from

the offset of the front-end electronics and the SiPM bias current. It must be subtracted from every measurement before the signal amplitude can be interpreted, and it is calibrated separately for the high- and low-gain branches of each channel. Its stability also serves as a probe of the operating conditions, since a drift of the pedestal reflects a change of temperature or bias voltage; the width of the pedestal distribution, in turn, measures the electronic noise of the channel. The pedestals of both gain branches were obtained through an external trigger. Figure 4 shows the pedestal calibration for both gain branches: panels (a) and (c) give the high-gain and low-gain pedestal distributions of a single channel as examples, and panels (b) and (d) show the fitted high-gain and low-gain pedestal values of all channels as a function of the layer, with the colour scale giving the number of channels. Within one layer, i.e. within one chip, the pedestal is rather uniform across channels, whereas it varies more strongly from layer to layer and from chip to chip; this reflects the fact that each chip is an independent front-end device with its own offset.

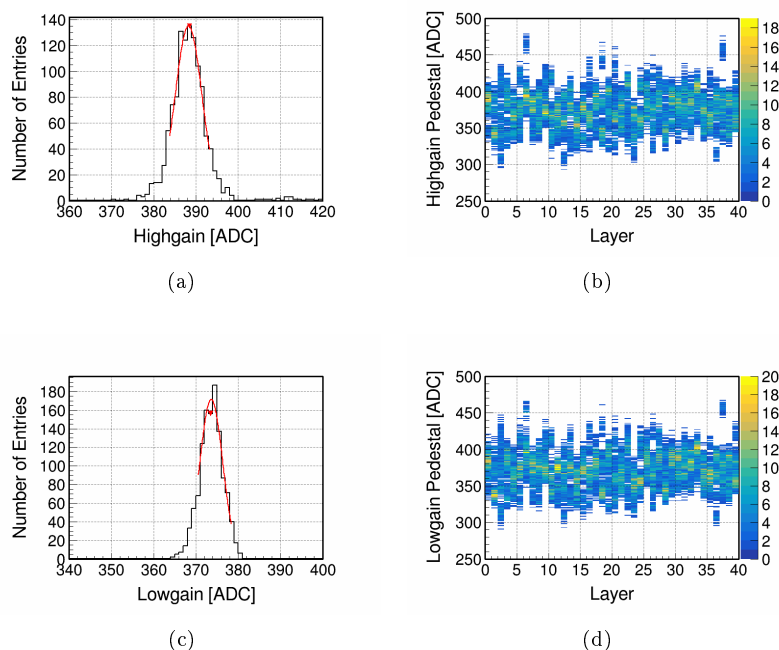


Figure 4: Pedestal of the AHCAL prototype. Upper row: (a) an example of the high-gain pedestal distribution and (b) the high-gain pedestal of all channels versus layer. Lower row: (c), (d) the same for the low-gain branch.

A single readout gain cannot simultaneously provide the fine resolution needed for small signals and the large dynamic range needed for high-energy showers. The SPIROC2E is therefore designed with two gain modes: a high-gain branch that resolves single photoelectrons but saturates at large charge, and a low-gain branch that extends the measurable range at the cost of a coarser resolution. Two channel-dependent constants are needed to combine them. The first is the high-to-low gain ratio $C_i^{\text{LG} \rightarrow \text{HG}}$, which rescales a low-gain reading onto the high-gain scale so that the two branches describe the same charge. The second is the high-gain saturation point SP_i , which marks the amplitude beyond which the high-gain response becomes nonlinear and above which the reconstruction must switch to the low-gain branch. Both were calibrated with

pion beams, which provide the large energy deposits required to drive the channels into saturation. Figure 5 shows the result: panel (a) gives an example of the low-gain versus high-gain correlation of a single channel, panel (b) the gain ratio of all channels as a function of the layer, and panel (c) the high-gain saturation point as a function of the layer. The gain ratio is uniform within a chip but varies between chips; the last two layers show a systematically higher gain ratio, because they are equipped with a different model of SiPM whose waveform differs.

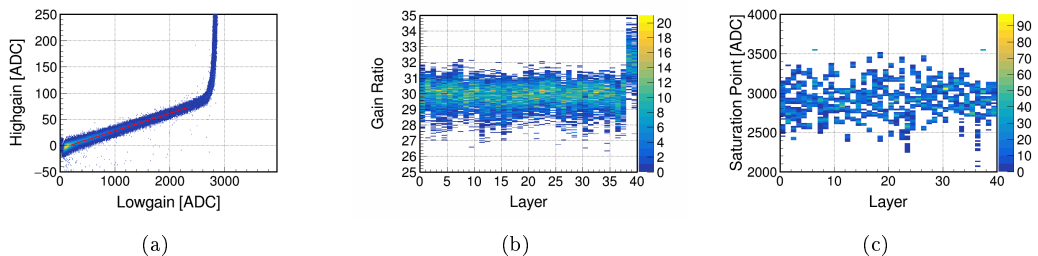


Figure 5: Gain ratio calibration of the AHCAL prototype: (a) an example of the low-gain versus high-gain correlation. (b) gain ratio of all channels as a function of layer. (c) high-gain saturation point of all channels as a function of layer

The Minimum Ionizing Particle (MIP) response defines the absolute energy scale of the detector. A relativistic muon traverses the scintillator with an almost constant energy loss, so its most probable energy deposition provides a stable, beam-energy-independent reference to which all measured amplitudes can be normalized; the resulting channel-dependent conversion factor $C_i^{\text{ADC} \rightarrow \text{MIP}}$ relates the measured ADC to the MIP scale. The MIP response for each channel was calibrated using a muon beam. During the beam test, the prototype was mounted on a translation stage, which was used to adjust its position and to scan the muon beam across all target areas. Consequently, sufficient statistics were obtained for MIP calibration in nearly all channels, with the exception of those at the periphery. The Most Probable Value (MPV) was extracted from the MIP spectra by performing a fit with a Landau-convolved Gaussian function, in which the Landau term describes the fluctuations of the energy loss in the thin scintillator and the Gaussian term accounts for the electronic noise. Figure 6 shows an example of the measured MIP spectrum together with the fit in panel (a) and the MPV of all channels as a function of the layer in panel (b).

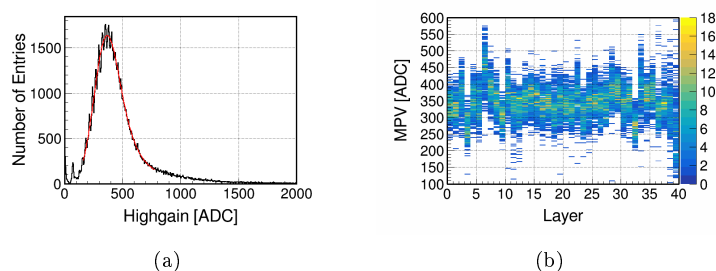


Figure 6: MIP calibration of the AHCAL prototype: (a) an example MIP spectrum and (b) the MPV of all channels versus layer.

The single photoelectron (SPE) gain sets the conversion between the measured charge and the number of detected photoelectrons, and it is therefore a key ingredient of the digitization model and of the saturation correction. It is calibrated from the response to individual photoelectrons, whose charge distribution is resolved into discrete peaks corresponding to zero, one, two, and more photoelectrons. The single photoelectron response was also calibrated using a muon beam. A multi-Gaussian function was employed to fit the SPE spectrum, allowing for the precise determination of the individual photoelectron peak positions. Figure 7 shows the procedure: the multi-Gaussian fit of a representative spectrum in panel (a) resolves the individual peaks, and a linear fit of the peak position versus the peak index in panel (b) yields both the SPE gain, given by the slope, and the pedestal, given by the intercept; panel (c) shows the resulting SPE gain of all channels as a function of the layer. As for the gain ratio, the last two layers differ from the others because of the different SiPM model, whose waveform differs.

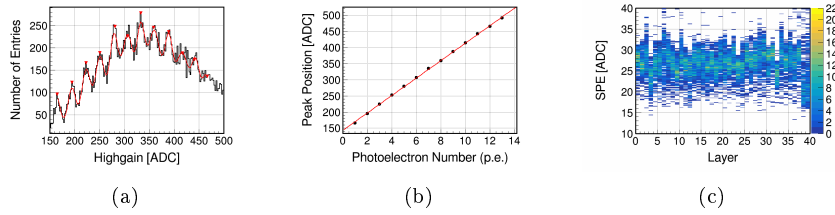


Figure 7: (a) Multi-Gaussian fit to the SPE spectrum. (b) Linear fit of the peak positions obtained from the multi-Gaussian fits. (c) SPE gain of all channels as a function of layer.

4 Simulation and Digitization

A Geant4-based simulation of the prototype was developed [25]. As shown in Fig. 8, the cassette geometry was modeled as a multilayer structure along the beam direction. Each cassette consists of two 2-mm absorber layers, a 3.5-mm plastic scintillator-and-ESR layer and a 6.5-mm PCB-and-air region. The plastic scintillator cells have dimensions of $4\text{ cm} \times 4\text{ cm} \times 3\text{ mm}$, and each cell is wrapped with an ESR film to improve the light collection efficiency. The PCB geometry was modeled in three dimensions and imported into the Geant4 simulation using CADMesh [26]. The incident particles were generated perpendicular to the cassette planes, passing successively through these material layers.

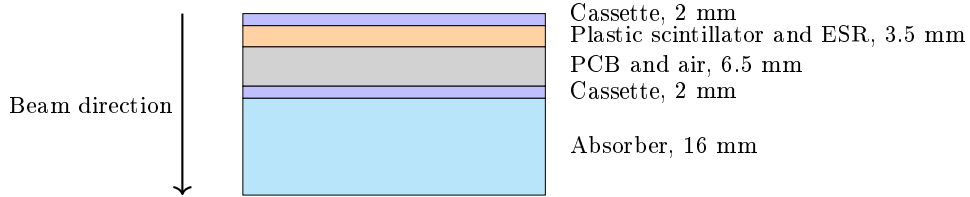


Figure 8: Structure of the cassette used in the Geant4 simulation.

To connect the simulated energy deposition to the experimental observables, a digitization model was developed to convert the energy deposited in each scintillator cell into the corresponding high- and low-gain ADC outputs. Two independent Gaussian fluctuations were first applied to the deposited energy to account for the scintillator-response nonuniformity (about

6%) and the temperature-induced variations (about 2%). The resulting energy deposition, E'_{dep} , was converted into the expected number of photons incident on the SiPM according to

$$\bar{N}_{\text{ph}} = \frac{E'_{\text{dep}}}{E_{\text{MIP}}} \frac{C_{\text{MIP}}}{\text{SPE} \times \eta_{\text{PDE}}}, \quad (1)$$

where E_{MIP} is the energy deposited by a minimum-ionizing particle as obtained from the simulation, C_{MIP} is the measured MIP response, SPE is the channel-dependent single-photoelectron gain, and η_{PDE} is the photon detection efficiency. Since $C_{\text{MIP}}/\text{SPE}$ represents the measured number of detected photoelectrons, the PDE correction in this expression is used only to infer the number of photons incident on the SiPM. The actual number of incident photons, N_{ph} , was then sampled from a Poisson distribution with a mean of $\bar{N}_{\text{ph}}$.

The response of the SiPM to these incident photons was modeled at the microcell level [27]; the procedure is shown in Fig. 9 (panel A: photon detection, panel B: cascading cross-talk). It loops over the $m = N_{\text{ph}}$ incident photons. In each iteration a microcell is selected by uniform sampling, and a Bernoulli trial with success probability η_{PDE} decides whether the photon is detected. If the photon is detected in a microcell that has not fired within the integration window, an avalanche is registered and the number of fired microcells, N_{fired} , is increased by one, whereas a photon assigned to an already fired microcell produces no additional signal; this reproduces the nonlinear saturation arising from the finite number of SiPM microcells. Each newly fired microcell may in addition induce an avalanche in an available neighbouring microcell with probability P_{CT} , and this optical cross-talk is applied recursively until no further microcell is triggered. After all m photons have been processed, the routine returns the final value of N_{fired} .

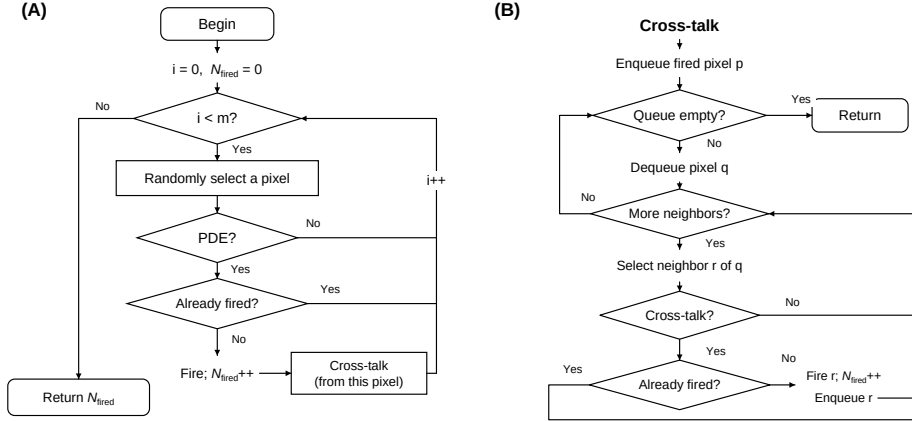


Figure 9: Flowchart of the microcell-level SiPM response simulation used to construct $P(N_{\text{fired}} | N_{\text{ph}})$. The model incorporates photon-detection efficiency, finite-microcell saturation, and optical crosstalk.

The simulation was repeated for different values of N_{ph} to construct the conditional SiPM response distribution

$$P(N_{\text{fired}} | N_{\text{ph}}), \quad (2)$$

which simultaneously incorporates photon-detection efficiency, microcell saturation, statistical fluctuations, and optical crosstalk. During event digitization, N_{fired} was sampled directly from

the corresponding pre-generated response distribution.

The SiPM signal amplitude was subsequently calculated from N_{fired} using the channel-dependent single-photoelectron gain. An additional Gaussian fluctuation with a standard deviation proportional to $\sqrt{N_{\text{fired}}}$ was introduced to account for the statistical broadening of the SiPM output. Finally, the resulting signal was processed through the high- and low-gain readout branches, including their respective pedestals, electronic noise, and gain-calibration parameters. The high-gain response was constrained by its measured saturation plateau, and both readout outputs were quantized into integer ADC counts. To validate the chain, the simulated response is compared with the beam data at the level of individual cells. Figure 10 shows, for a representative cell, the measured ADC spectrum of a MIP together with the digitized simulation, which reproduces the position and shape of the measured distribution.

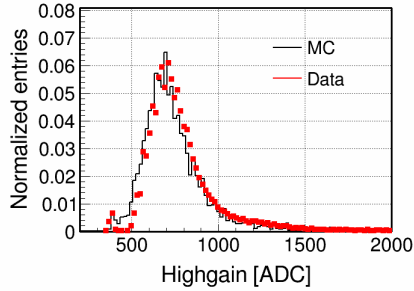


Figure 10: Measured ADC spectrum of a MIP compared with the digitized simulation.

5 Results

5.1 Energy reconstruction

After calibration above, we can reconstruct energy using formula 3

$$E_i^{\text{Dep}} [\text{MeV}] = \begin{cases} \frac{HS_i - HP_i}{C_i^{\text{ADC} \rightarrow \text{MIP}} \times C^{\text{MIP} \rightarrow \text{MeV}}}, & HS_i < SP_i \\ \frac{(LS_i - LP_i) \times C_i^{\text{LG} \rightarrow \text{HG}}}{C_i^{\text{ADC} \rightarrow \text{MIP}} \times C^{\text{MIP} \rightarrow \text{MeV}}}, & HS_i > SP_i \end{cases} \quad (3)$$

The deposited energy in the i -th sensitive cell, E_i^{Dep} , is reconstructed from the high and low-gain channel signals HS_i and LS_i , together with calibration parameters HP_i , LP_i , SP_i , $C_i^{\text{LG} \rightarrow \text{HG}}$, $C_i^{\text{ADC} \rightarrow \text{MIP}}$, and $C^{\text{MIP} \rightarrow \text{MeV}}$.

Here, HP_i and LP_i are the pedestals of the high and low-gain channels, respectively, and SP_i is the saturation point of the high-gain channel. When $HS_i < SP_i$, the deposited energy is reconstructed using the high-gain signal HS_i . When $HS_i > SP_i$, the low-gain signal LS_i is used, multiplied by the high-to-low gain conversion factor $C_i^{\text{LG} \rightarrow \text{HG}}$.

The conversion factor $C_i^{\text{ADC} \rightarrow \text{MIP}}$ is obtained from muon beam calibration data. The energy deposition spectrum of muons in each sensitive cell is fitted with a Landau distribution convoluted with a Gaussian function. The most probable value (MPV) of the Landau distribution is taken as $C_i^{\text{ADC} \rightarrow \text{MIP}}$.

The conversion factor $C^{\text{MIP} \rightarrow \text{MeV}}$ is determined from GEANT4 simulation of the AHCAL response to 100 GeV muons. The energy deposition spectrum of 100 GeV muons in a sensitive

cell is fitted with a Landau function, yielding an MPV of 0.461 MeV. Therefore, $C^{\text{MIP} \rightarrow \text{MeV}} = \frac{\text{MIP}}{0.461 \text{ MeV}}$.

After the detector signals were calibrated to energy, a saturation effect was observed in the high-energy region because the SiPM response becomes nonlinear when the number of detected photons is large. Because the dark noise of SiPM can be ignored, this effect was corrected using the formula 4, and the same correction procedure was applied to both the simulated data and the beam-test data.

$$N_{\text{ph}} = -N_{\text{pixels}} \ln \left(1 - \frac{N_{\text{fired}}}{N_{\text{pixels}}} \right) \quad (4)$$

The measured SiPM response becomes nonlinear at high light levels because the number of microcells is finite. The optical cross-talk probability of the SiPM used here is below 1%, so that the additional microcells fired by cross-talk are negligible and each detected photon can be treated as firing an independent microcell. Under this assumption, the expected number of fired microcells for N_{ph} detected photons is about $N_{\text{pixels}} [1 - \exp(-N_{\text{ph}}/N_{\text{pixels}})]$, which grows more slowly than N_{ph} and asymptotically approaches N_{pixels} . Inverting this relation gives Eq. (4), in which N_{pixels} is the total number of microcells of the SiPM (about 7.3×10^3 for the device used here), N_{fired} is the measured, saturation-distorted number of fired microcells, and N_{ph} is the corrected number of detected photoelectrons, i.e. the value N_{fired} would take in the absence of microcell saturation. This restores the linear relation between the deposited energy and the measured signal. The correction is reliable as long as the dark-count contribution is negligible and the photons are not concentrated on a small number of microcells.

5.2 Particle identification

The nominal pion beam is contaminated by electrons and by muons from the decay of pions in flight ($\pi \rightarrow \mu\nu$). A sequential event-selection and particle-identification (PID) procedure was therefore applied to obtain a high-purity pion sample. The first PID step exploited the correlation between the fractal dimension (FD) and the average deposited energy per fired cell, defined as $E_{\text{Hit}} = E_{\text{dep}}/N_{\text{Hit}}$. The FD quantifies the spatial topology of the calorimeter hits and is sensitive to differences between the compact, densely populated structure of electromagnetic showers and the more diffuse and fluctuating structure of hadronic showers [28]. As illustrated by the mixed simulated samples in Fig. 11, three characteristic populations can be identified in the FD- E_{Hit} plane. Electron-induced showers are concentrated in the upper-right region, with relatively large FD and E_{Hit} values, owing to their high local energy density and compact shower development. Interacting pions populate the intermediate region and exhibit a broader distribution because of event-by-event fluctuations in hadronic shower development. In contrast, minimum-ionizing particles and noninteracting beam particles are mainly located in the lower-left region, where both the shower complexity and the average deposited energy are small. A two-dimensional selection boundary, determined from the simulated samples, was therefore used to retain the pion-dominated region while suppressing the electron-rich region. Compared with independent one-dimensional requirements, this selection makes use of the correlation between the two observables and provides improved separation in their overlapping regions.

Requirements on the reconstructed shower-start and shower-end layers were then imposed, in order to reject events in which the hadronic shower is not sufficiently developed within the calorimeter. The shower-start criterion removes noninteracting particles and pions that interact only in the downstream part of the calorimeter, whose showers are poorly developed, whereas the shower-end criterion removes events with substantial longitudinal leakage or punch-through, for which the shower is not contained. An energy-dependent selection in the $N_{\text{Hit}}-E_{\text{Hit}}$ plane was

further applied to reject events with anomalously low hit multiplicities relative to their deposited energy, which are mainly associated with incomplete showers and detector noise. The evolution of the deposited-energy spectrum after each selection step is presented in Fig. 11. This sequential PID procedure suppresses the electron background and selects well-developed and sufficiently contained hadronic showers, thereby providing a high-purity pion sample for the subsequent calorimeter-response analysis.

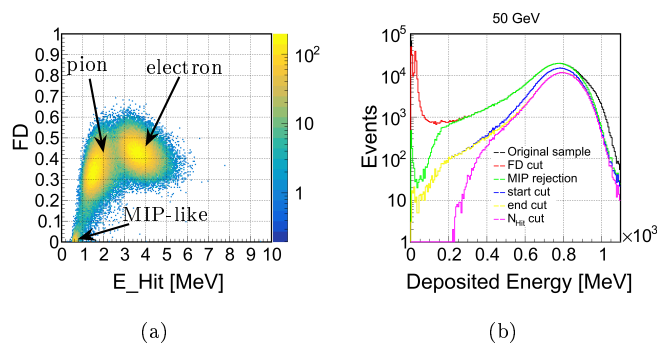


Figure 11: (a) Two-dimensional distribution of the FD and E_{Hit} . The electron-shower, pion-shower, and MIP-like populations occupy distinct regions of the distribution. (b) Evolution of the reconstructed deposited-energy spectrum for the 50 GeV pion-beam data throughout the event-selection procedure. The distributions correspond to the original sample and the samples remaining after the successive application of the FD- E_{Hit} selection, MIP-like event rejection, shower-start requirement, shower-end requirement, and the energy-dependent N_{Hit} - E_{Hit} selection.

5.3 Energy linearity and resolution

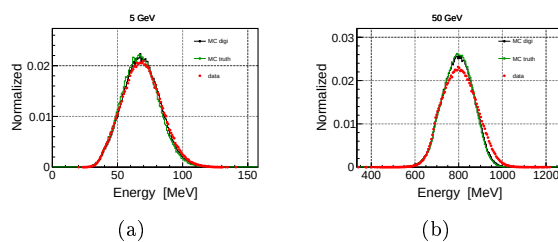


Figure 12: Reconstructed energy spectra of the pion beam: (a) 5 GeV at the PS and (b) 50 GeV at the SPS. The red points show the beam data, and the green and black lines the simulation before and after digitization, respectively.

At the PS, the pion beam energy ranges from 1 GeV to 15 GeV, and at the SPS from 20 GeV to 100 GeV. Since the SiPM dark-count contribution is very low, less than 1%, Eq. (4) can accurately describe and correct for the saturation effect. As shown in Fig. 12, which compares the beam data (red points), the simulation without digitization (green line), and the digitized simulation (black line) for 5 GeV (PS) and 50 GeV (SPS) pion events, the mean values of

the digitized simulation are consistent with the MC truth after the correction. In the beam-test data, the reconstructed peak positions agree well with the simulation at low energies, but show a slight downward deviation from the simulated values in the high-energy region. This results from the electronics saturation effect. Conversely, the saturation effect suppresses the high-energy region, effectively narrowing the energy spectrum and making the energy resolution appear smaller. Ultimately, the energy linearity for the pion-beam data was maintained within $\pm 2\%$ over the full 1–100 GeV range, and within $\pm 1.5\%$ above 10 GeV; an energy resolution of $45.5\%/\sqrt{E[\text{GeV}]} \oplus 6.9\%$ was achieved. The resulting energy linearity and energy resolution over the full 1–100 GeV range are shown in Fig. 13, with the linearity in panel (a) and the resolution in panel (b).

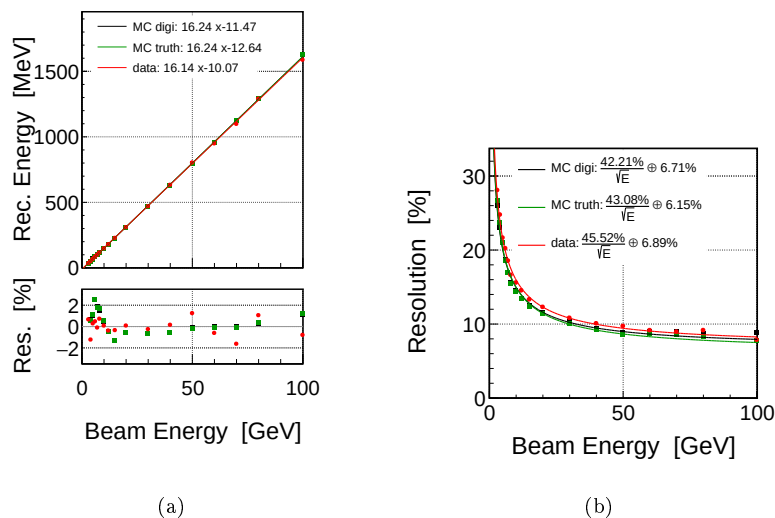


Figure 13: (a) Reconstructed energy versus beam energy, with the residual linearity shown in the lower panel, and (b) the energy resolution versus beam energy. The red points show the beam data, and the green and black lines the simulation before and after digitization, respectively.

6 Summary

Three beam tests were carried out for the AHCAL prototype at CERN. Environmental and operational stability was monitored through the temperature, the pedestals, the gain ratios, and the MIP responses. These tests provided a dataset comprising electronics test results and about 65 million particle events (μ, π, e). Calibration of channel-specific parameters—including the pedestals, gain ratios, saturation points, most probable values (MPV) and the single-photoelectron gain (SPE)—was performed to reconstruct the energy deposition in all sensitive cells. Particle identification (PID) based on energy and topological information was used to select a high-purity π^- sample. For π^- energies in the range of 10–100 GeV the saturation effect is not significant, and the prototype achieved an energy linearity of $\pm 1.5\%$ and an energy resolution of $45.5\%/\sqrt{E[\text{GeV}]} \oplus 6.9\%$. In the future, a refined electrical calibration could be performed for each individual cell: a known amount of charge would be injected into each cell and the corresponding signal response measured. In this way, the saturation curve of each cell

could be obtained and used for the corresponding corrections.

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