

Beam Tests of AHCAL Prototype

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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 indispensable. 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 comprehensive Geant4-based simulation was developed to establish a robust digitization model. By validating the simulation against reconstructed beam test data, we demonstrated that the energy linearity for pions is maintained within $\pm 1.5\%$, achieving an energy resolution of $48.8\%/\sqrt{E[\text{GeV}]} \oplus 4.5\%$.

1 Introduction

The discovery of the Higgs boson marked a major milestone in particle physics [1, 2]. The subsequent priority is the precise determination of its properties [3, 4, 5, ?]. 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 [6, 7]. The CEPC is planned to operate at a center-of-mass energy of 240 GeV with a design luminosity of $8.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, yielding approximately 10^6 Higgs bosons over a decade of operation [8].

A large fraction of Higgs production 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 [9, 10]. 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 [11].

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) [12, ?, 13]. The high gran-

ularity of the CEPC AHCAL provides the shower separation capability essential for PFA-based jet reconstruction. Considering these, a AHCAL prototype has been constructed.

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[?].

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. The total depth of the prototype corresponds to approximately 5λ , 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. The scintillation signals are read out by silicon photomultipliers (SiPMs) and then processed using front-end chips (SPIROC2E)[14, 15]. 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[16].

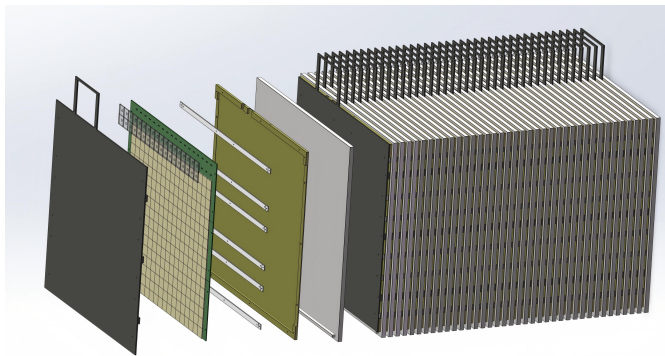


Figure 1: The scintillator-steel sandwich structure of the AHCAL prototype. The scintillator tiles and PCB board were housed within the steel cassette, creating a sensitive layer for the AHCAL.

2 Beam Test Setup

The AHCAL prototype has been tested three times at CERN using high energy particle beams, including H8 and H2 beamline at SPS and T9 beamline at PS. Each time of beam test last two weeks. During these periods, we completed detector commissioning and electronics calibration, and collected a large dataset of particles including $\mu^\pm$, $e^\pm$ and $\pi^\pm$ with the momentum of 1GeV to 120GeV

As Fig. 2 shows, The beam first passes through two Cherenkov detectors used for particle identification, followed by two scintillator detectors for coincidence measurements, and finally enters the AHCAL prototype. The signals from the two Cherenkov detectors (C1 and C2) are sent to the DAQ board, while the signals from the two scintillator detectors (S1 and S2) are sent to the TLU for coincidence processing. Based on the coincidence result, the TLU determines whether to issue a trigger to the DAQ board. Upon receiving the trigger, the DAQ board collects

AHCAL data and packages it together with the Cherenkov detector data for transmission to the PC.

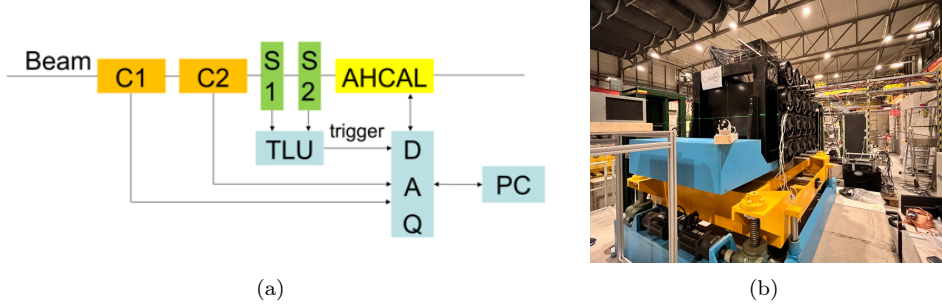


Figure 2: (a) Beam test layout of AHCAL prototype. (b) AHCAL prototype at H8 beamline of SPS

Table 1: Data Acquisition of Beam Tests

Beam line	Particle type	Energy(GeV)	Entries(M)
H8	μ^+	108, 160	10
	e^+	10, 20, 30, 40, 50, 60, 70, 80, 100, 120	2
	π^+	10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120	11
H2	μ^-	100	6
	e^-	10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 150, 200, 250	4.5
	π^-	10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 350	20
	proton	350	1
T9	μ^-	10	2
	e^-	0.5, 1, 2, 3, 4, 5	2.6
	π^-	1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15	8

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) ratios, the energy scale via Minimum Ionizing Particles (MIPs), and single photoelectron (SPE) gain.

The pedestals of both the high and low-gain channels were obtained through an external trigger. Figure 3 depicts the distributions of pedestals for all AHCAL high gain channels and low gain channels.

To cover wider dynamic range, SPIROC2E is designed to have two gain modes. The gain ratios between two modes and saturation points of all AHCAL channels were calibrated using pion beam. The distributions of the gain ratios and saturation points are shown in Fig. 4.

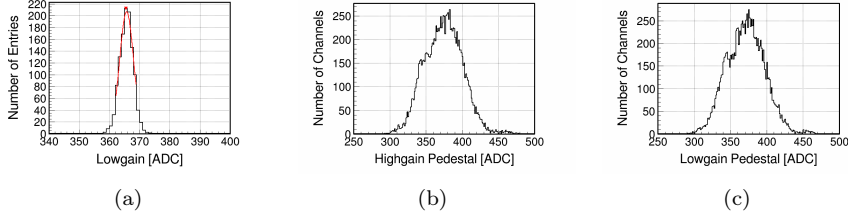


Figure 3: Pedestal of AHCAL prototype: (a) an example of pedestal distribution. (b) highgain channels. (c) lowgain channels

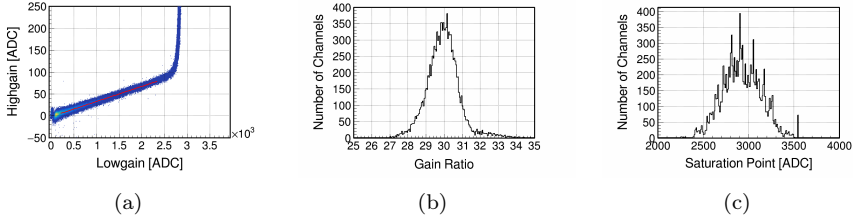


Figure 4: Gain ratio calibration of AHCAL prototype: (a) an example of lowgain v.s highgain. (b) gain ratio. (c) highgain saturation point

The Minimum Ionizing Particle (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 facilitate a comprehensive muon scan 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.

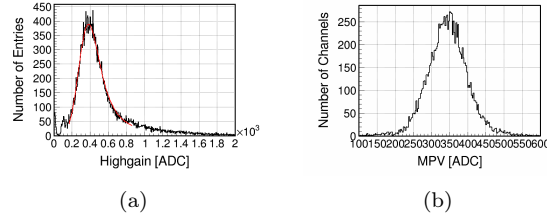


Figure 5: MIP calibration of AHCAL prototype: (a) an example of MIP spectrum. (b) MPV distribution

The single photoelectron (SPE) response for each channel 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.

Fig. 7 shows that the distribution of these basic parameters calibrated in layer level. Within the same layer—or more specifically, within the same chip—the parameter variation across different channels is relatively small, whereas the variation between layers or across different chips is more

significant. For gain ratio and spe, the last two layers seems different with others, this is because they use different model of SiPM, making the waveform is different.

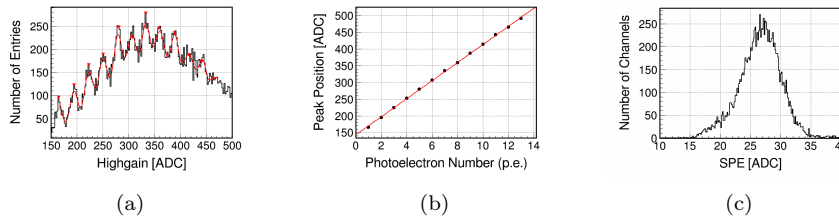


Figure 6: (a) Multi-Gaussian fit to the MIP spectrum. (b) Linear fit of the peak positions obtained from the multi-Gaussian fits. (c) SPE calibration of the AHCAL prototype.

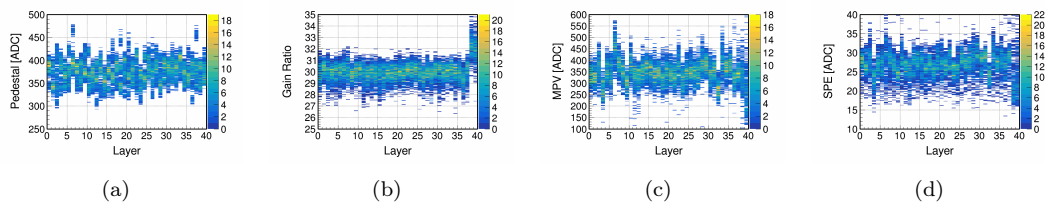


Figure 7: Layer distribution of basic parameters calibrated: (a) Highgain pedestal. (b) Gain Ratio. (c) MPV. (d) SPE

4 Simulation and digitization

A high-fidelity Geant4-based simulation was conducted. As shown in Fig. 8, the cassette geometry was modeled as a multilayer structure along the beam direction. Each cassette consists of a 2-mm absorber layer, a 3.5-mm plastic scintillator-and-ESR layer, a 6.5-mm PCB-and-air region, and an 18-mm absorber layer. 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 precisely modeled in three dimensions and imported into the Geant4 simulation using CADMesh. The incident particles were generated perpendicular to the cassette planes, passing successively through these material layers.

To bridge the gap between simulated energy deposition and experimental observables, a comprehensive digitization model has been developed. This model converts the simulation raw data into realistic detector responses by incorporating the fundamental calorimeter parameters calibrated previously. The digitization chain accounts for several critical physical effects: the statistical fluctuations of scintillation photons, the spatial non-uniformity of light yield within the scintillator, the SiPM photon detection efficiency, and the signal shaping and electronic noise of the readout system. The simulation results can be compared with the beam test data to validate the accuracy of the digitization model and the energy reconstruction algorithm.

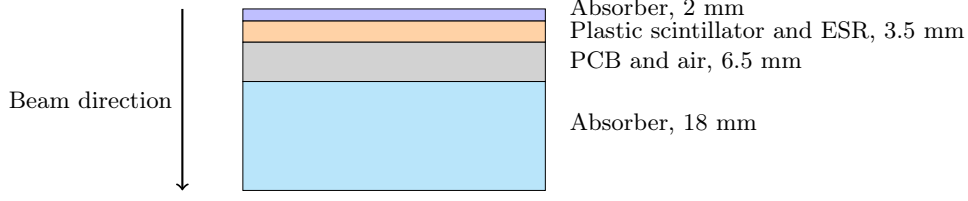


Figure 8: Structure of the cassette used in the Geant4 simulation.

5 Results

After calibration above, we can reconstruct energy using formula 1

$$E_i^{\text{Dep}} [\text{MeV}] = \begin{cases} \frac{HS_i - HP_i}{C_i^{\text{ADC} \rightarrow \text{MIP}} \times C^{\text{MIP} \rightarrow \text{MeV}}}, & HS_i < SP_i \\ \frac{(LS_i - LP_i) \times C_i^{\text{LG} \rightarrow \text{HG}}}{C_i^{\text{ADC} \rightarrow \text{MIP}} \times C^{\text{MIP} \rightarrow \text{MeV}}}, & HS_i > SP_i \end{cases} \quad (1)$$

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 2, and the same correction procedure was applied to both the simulated data and the beam-test data.

$$N_{\text{corrected}} = -N_{\text{pixels}} \times \ln\left(1 - \frac{N_{\text{photon}}}{N_{\text{pixels}}}\right) \quad (2)$$

Due to the presence of beam contaminants, a series of event selection criteria and Particle Identification (PID) techniques were applied to the raw beam data. Using these PID methods, we effectively suppressed the background[17]. This ensured that the energy spectra were reconstructed from a highly pure sample.

5.1 Pion Beam

At the PS, the pion beam energy ranges from 1 GeV to 15 GeV. At the SPS, the pion beam energy ranges from 20 GeV to 100 GeV. Since the SiPM dark-count contribution is very low,

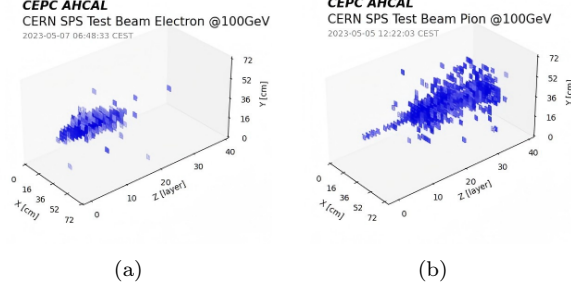


Figure 9: Beam test event displays of the AHCAL prototype: (a) a 100 GeV e^- beam event. (b) a 100 GeV π^- beam event.

less than 1%, formula. 2 can accurately describe and correct for the saturation effect. So as Fig 10 shows, after digitization and correction, the mean values of the simulated data are consistent with the MC truth. 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. It is resulted from 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 pions beam data was maintained within $\pm 2\%$, and an energy resolution of $47.1\%/\sqrt{E[\text{GeV}]} \oplus 6.6\%$ was achieved. And the saturation do not affect the number of hit, which is only related to the shape of shower, so the agreement of this between beam data and MC is good.

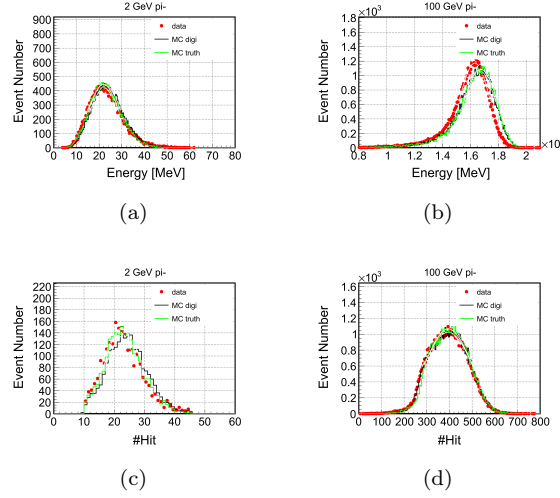


Figure 10: Total energy deposition and number of hit of pion beam, red point is the beam data, green line is the MC without digitization, black line is the MC with digitization: (a) energy deposition of 2 GeV at PS. (b) energy deposition of 100 GeV at SPS. (c) number of hit of 2 GeV at PS. (d) number of hit of 100 GeV at SPS

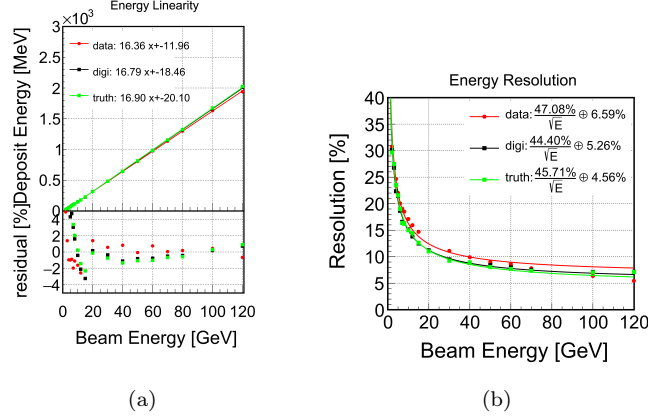


Figure 11: Energy linearity and energy resolution of electron: (a) energy range of 1 GeV-150 GeV. (b) Resolution of pion beam with energy range of 1 GeV-100 GeV

5.2 Electron Beam

At the PS, the electron beam energy ranges from 1 GeV to 5 GeV. At the SPS, the electron beam energy ranges from 10 GeV to 250 GeV. For electrons, the development of electromagnetic showers is more compact and the energy deposition is more localized. As a result, the energy deposited in the cell with the maximum response is larger than that in pion-induced hadronic showers, reaching up to 250 MeV per cell. Under such conditions, the electronics also begins to saturate and exhibit a nonlinear response, causing the total deposited energy measured in the beam-test data to be significantly lower than that predicted by the simulation at high energies. As shown in Fig. 12(d), the peak position of the beam data is notably lower than that of the MC. And as shown in 10(d), the visible deposit energy of beam data gradually bends downward and is significantly lower than the MC. Furthermore, variations between different channels introduce additional fluctuations that scale with the beam energy. This causes the energy resolution become worse at high energy.

6 Summary

A series of three beam tests were successfully conducted for the AHCAL prototype at CERN. Environmental and operational stability was ensured by monitoring temperature, pedestals, gain ratios, and MIP responses. These efforts yielded a comprehensive dataset comprising electronics test results and roughly 68 million particle events (μ , π , e). Calibration of channel-specific parameters—including pedestals, gain ratios, saturation points, Most Probable Values (MPV) and Single PhotonElectron (SPE)—was performed to reconstruct the energy deposition across all sensitive cells. Effective particle identification (PID) based on energy and topological information enabled the selection of a high-purity π^- sample. For π^- energies in the range of 10–100 GeV, the saturation effective is not obvious, so the prototype achieved a high energy linearity of $\pm 1.5\%$ and a energy resolution of $48.8\%/\sqrt{E[\text{GeV}]} \oplus 4.5\%$. But for e^- , because of the saturation effect of SiPM and electronics, the energy linearity become bad beyond 30 GeV, and the energy resolution increase along with the beam energy. In future, a refined electrical calibration could be carried out for each individual cell. A known amount of charge will be

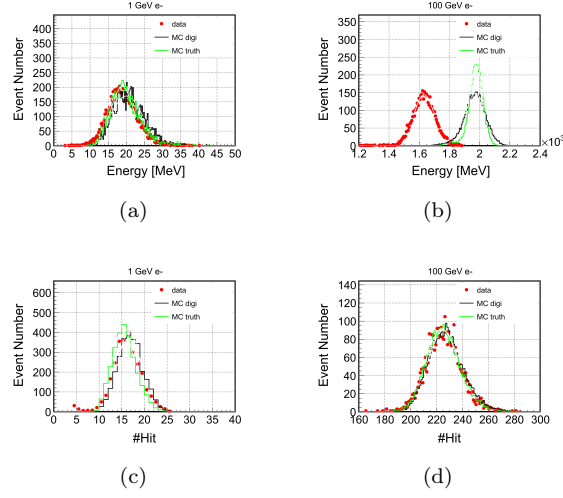


Figure 12: Total energy deposition and number of hit of electron beam, red point is the beam data, green line is the MC without digitization, black line is the MC with digitization: (a) energy deposition of 1 GeV at PS. (b) energy deposition of 100 GeV at SPS. (c) number of hit of 1 GeV at PS. (d) number of hit of 100 GeV at SPS

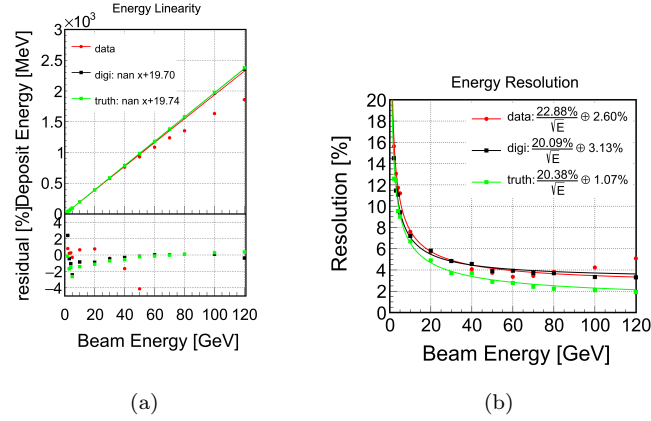


Figure 13: Energy linearity and energy resolution of electron: (a) energy range of 1 GeV-150 GeV (b) Resolution of electron beam with energy range of 1 GeV-100 GeV

injected into each cell and the corresponding signal response will be measured. In this way, the saturation curve of each cell can be obtained, enabling subsequent corrections.

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