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Beam-tests of CMS High Granularity Calorimeter prototypes at CERN

M. Bonanomi on behalf of CMS collaboration

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole polytechnique, Institut Polytechnique de Paris, Avenue Chasles, 91120 Palaiseau, France

E-mail: matteo.bonanomi@cern.ch

Abstract: As part of the HL-LHC detector upgrade programme, the CMS experiment is developing a High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeters. The HGCAL will be realised as a sampling calorimeter, including 36 layers of silicon pads and 14 layers combining silicon and scintillator detectors interspersed with metal absorber plates. Prototype modules based on 6-inch hexagonal silicon pad sensors with pad areas of 1.0 cm^2 have been constructed. Beam tests of different sampling configurations made from these modules have been conducted at the CERN SPS using beams of charged hadrons and electrons with momenta ranging from 20 to 300 GeV/c. The setup was complemented with a CALICE AHCAL prototype: a scintillator-based sampling calorimeter, mimicking the proposed design of the HGCAL scintillator part. These proceedings summarise the test beam measurements performed at CERN in 2018, including the calibration of the detector with minimum ionizing particles and energy reconstruction performance of electron- and hadron-induced showers. We also show measurements of the timing capabilities of this prototype system and the steps being taken towards electron and hadron identification.

Keywords: Calorimeters; Performance of High Energy Physics Detectors; Radiation-hard detectors; dE/dx detectors

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Contents

1 Introduction **1**

2 Beam tests of HGCAL prototype **1**

3 Calibration with minimum ionizing particles **3**

4 Reconstruction performance **4**
- 4.1 Electrons 4
  - 4.1.1 Energy resolution and shower shapes 4
  - 4.1.2 Position resolution 5
- 4.2 Pions 6

5 Timing performance **8**

6 Conclusions **9**

1 Introduction

The High-Luminosity phase of the LHC (HL-LHC) is expected to start after the third long shutdown (LS3. The HL-LHC it is planned to integrate about 3000 fb^{-1} by mid-2030s, with a corresponding pile-up of the order of 140–200 events. Studies based on simulations show that the detectors at HL-LHC will have to sustain fluences up to $10^{16}\,\mathrm{n_{eq}/cm^2}$ and doses around 2 MGy. In order to cope with such a harsh environment, the detectors need to undergo an upgrade phase, with the final aim of maintaining the current physics performance also during the high-luminosity campaign.

As part of the HL-LHC upgrade programme, the CMS Collaboration is planning to replace the current endcapt calorimeters with a high granularity calorimeter (HGCAL) [1]. The HGCAL will be a sampling calorimeter with a silicon-based electromagnetic compartment (CE-E) and a hadronic one (CE-H) based on a mixed technology involving silicon detectors (CE-FH) and scintillator tiles (CE-BH). It will be transversly segmented into hexagonal cells each with a surface of about 1 cm^2, for a total of over 6 million channels. A schematic view is given in figure 1. The CE-E will consist of 28 sampling layers in about 30 cm, for a total of 25 X_0 and about 1.3 λ. The CE-H will consist of 22 sampling layers, for a total of ~8.5 λ.

2 Beam tests of HGCAL prototype

Beam tests play a key role in the validation of the HGCAL design and of its innovative hexagonal silicon sensors. Two beam tests were done in 2016 at CERN and FNAL to validate the design of the CE-E section and to provide the first performance measurements. The results were reported in [2].

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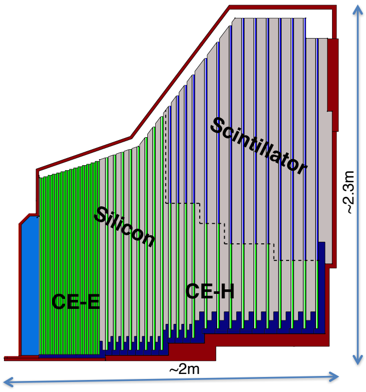
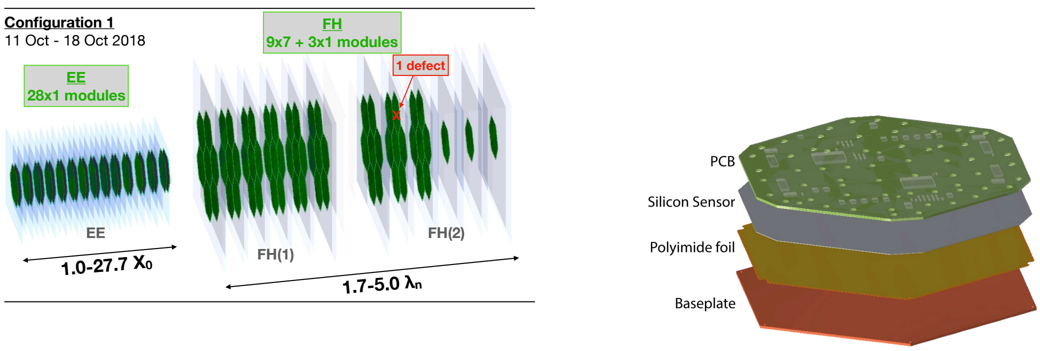


Figure 1. Schematic view of the High Granularity Calorimeter design.

In October 2018 the first full HGCAL prototype was assembled and its performance was studied in beam tests at the H2 CERN beamline.

The design of the detector used in the October 2018 beam test is shown in figure 2a and it consisted of 94 six inches hexagonal modules, referred as *Hexaboards*, with hexagonal Si pads of $\sim$1 cm^2 area. The electromagnetic section was equipped with 28 single modules, while the hadronic section comprised 9 layers with modules disposed in a *daisy* structure (i.e. a central module surrounded by 6 outer modules) and 3 layers equipped with single modules. The Hexaboards followed the same design as of 2016 [2], consisting of a stack of a copper-tungsten baseplate, a polymide foil, a silicon sensor of 300 or 200 µm and a readout PCB. A sketch of this structure is shown in figure 2b.



(a) Sketch of the HGCAL prototype configuration used in the October 2018 beam test.

(b) Schematics of the Hexaboard used in HGCAL beam tests.

Figure 2. The October 2018 beam test at CERN.

In addition, a better grounding and the new SKIROC2-CMS front-end chip [3] was used. This chip is equipped with a dual-gain amplification, a time-over-threshold technique (TOT) to cope with the low gain saturation and a time-of-arrival (TOA) measurement.

2020 JINST 15 C04001

Upstream the detector, several beam-quality monitoring systems were installed. In particular there were two Cherenkov detectors; four Delay Wire Chambers (DWCs), also used for the position resolution studies presented in section 4.1.2, and two micro channel plates (MCP), used as a timing reference for the analysis presented in section 5. A schematic view of the H2 beamline and of the experimental setup of the HGCAL prototype is depicted in figure 3.

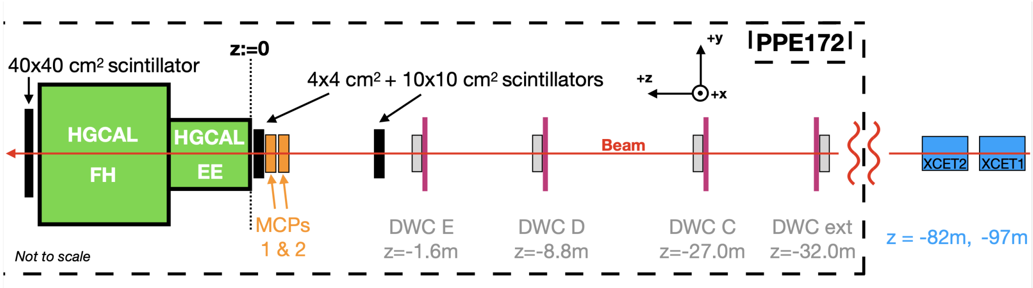


Figure 3. H2 beamline and HGCAL prototype experimental setup.

The HGCAL prototype was exposed to positron and pion beams in the momentum range 20–300 GeV/c, as well as 200 GeV/c muons used for the detector calibration. The use of MIP-like particles to calibrate the prototype and to determine a common energy scale is presented in section 3. The qualitative results of the analysis on the detector performance for electromagnetic and hadronic showers, as well as the comparison with a dedicated `GEANT4` simulation, are presented in section 4.1 and section 4.2, respectively. The preliminary measurement of the timing performance using the SKIROC2-CMS TOA is described in section 5.

3 Calibration with minimum ionizing particles

In order to have an adequate calibration accuracy, it is necessary for HGCAL to cleanly detect minimum ionizing particles (MIPs) in each cell. This requires a high enough signal-to-noise ratio (S/N), which can be achieved with a sufficiently fine lateral granularity. Hence, one of the purposes of beam tests was also to study the response of the HGCAL prototype to MIPs. In the October beam test, the tracking procedure developed for former beam tests was successfully applied and used to reconstruct MIP-like tracks in the detector. Figure 4 shows the reconstructed ADC spectrum, normalised to unity, for a sample channel: the blue histogram represents the ADC spectrum when the track is reconstructed using the HGCAL prototype and the tracking algorithm detailed in ref. [7]. The energy deposit by a MIP is described by a Landau distribution: the dashed red line in figure 4 represents the fit of the ADC spectrum for the given channel. The most probable value of this distribution was used to retrieve the ADC/MIP calibration factors used to calibrate the detector to a uniform response throughout all cells, defining a common energy scale for the HGCAL prototype under test.

The modules with 300 μm sensors were found to have a S/N $\simeq$ 7–8 for high gain and S/N $\simeq$ 4–5 for low gain configurations, whereas for 200 μm sensors the ratios were found S/N $\simeq$ 5 and S/N $\simeq$ 3 for high and low gains, respectively. In this beam test, MIP calibration was successfully performed for a total of ~85% of all cells using muons as MIP-like particles.

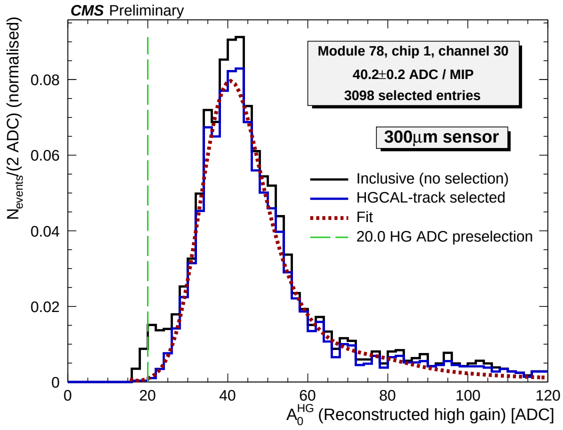


Figure 4. Distribution of reconstructed MIP signal amplitudes in high gain configuration for a readout channel, obtained using 200 GeV/c muons.

4 Reconstruction performance

In the following section, preliminary results on the electromagnetic and hadronic performance are shown, along with a comparison to the detailed `GEANT4` simulation developed for the October beam test.

4.1 Electrons

4.1.1 Energy resolution and shower shapes

The 28 layer electromagnetic section of the prototype used in the 2018 beam tests reflected the final HGCAL CE-E design. Hence it was an optimal *proof-of-concept* of the expected performance of such a sampling calorimeter. The measurement of the electron energy resolution was based on the reconstruction of the information in each Si pad, called *RecHits*. Each *RecHit* contains the deposited energy in the MIP energy scale, discussed in section 3. The energy deposit of an electromagnetic shower in the calorimeter was reconstructed as the unclustered sum of all selected *RecHits* in the 28 active layers.

The energy distributions were fitted with a Gaussian function within the range $[\mu - 1.0\sigma,\ \mu + 2.5\sigma]$. The asymmetric interval was chosen to avoid biasing mean and standard deviation estimators by the presence of a tail in the left-hand side of the energy distributions. The final electromagnetic energy resolution was estimated from the ratio between the mean energy response $\langle E \rangle$ and resolution σ_E extracted from the Gaussian fit. Figure 5a shows the comparison of the energy resolutions for data and simulation. The solid lines correspond to a fit using the function

$$\frac{\sigma_E}{\langle E \rangle} = \frac{S\ \left[\sqrt{\mathrm{GeV}}\right]}{\sqrt{E_{\mathrm{beam}}\ [\mathrm{GeV}]}} \oplus C,$$

where S and C are the stochastic and constant terms, respectively. The fit function did not take into account the noise term because its contribution was found to be negligible on the *RecHits* after the rejection of noisy channels and common-mode noise subtraction. A good qualitative agreement was found between data and simulation throughout the entire energy range.

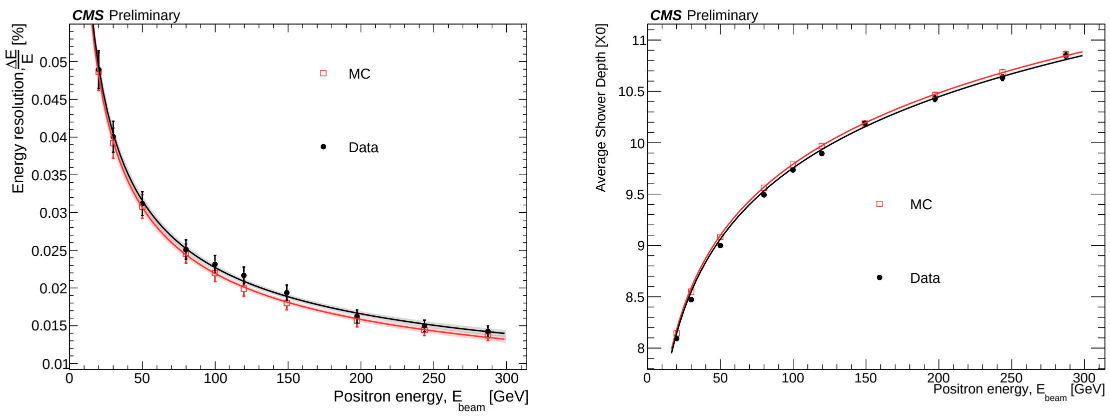
The longitudinal performance of the detector was assessed studying the center of gravity, or shower of depth, defined as:

$$SD_z = \frac{\sum_{i=1}^{28} E_i^{Si} \cdot z_i[X_0]}{\sum_{i=1}^{28}, E_i^{Si}}, \tag{4.1}$$

where E_i^{Si} is the deposited energy in the i-th layer and $z_i[X_0]$ is the total calorimetric radiation length up to layer i. The average value of the shower depth is expected to have a log dependece on the beam energy, as described in refs. [5, 6]. Figure 5b shows the values of $\langle SD_z \rangle$ determined from data and simulation starting from eq. (4.1). Also in this case, a qualitative agreement between the two sets of points was observed throughout the entire energy range. The solid lines represent the fit function

$$\langle SD_z \rangle = 1.5 + \log\left(\frac{E_{\text{beam}}}{E_c}\right),$$

where the offset 1.5 comes from refs. [5, 6] and E_c represents a first order approximation to the critical energy of the calorimeter.



(a) Reconstructed energy resolution for positrons in the energy range 20–300 GeV/c.

(b) Average shower depth for positron-induced showers in the energy range 20–300 GeV/c.

Figure 5. Preliminary results of the analysis on positron beams for the October 2018 beam tests.

4.1.2 Position resolution

A study of the position resolution for the individual layers of the electromagnetic section of the HGCAL prototype was also performed. The reconstruction of the impact position for each calorimeter layer was done using the same procedure developed for the 2016 beam test [2]. More precisely, the impact position was determined by means of a logarithmic energy weighted method:

$$x_{\text{reco}} = \frac{\sum_{i \in M} \omega\left(E_i^{Si}\right) \cdot x_i}{\sum_{i \in M} \omega\left(E_i^{Si}\right)}, \quad \text{and analogous for } y, \tag{4.2}$$

2020 JINST 15 C04001

where M denotes the set of all *RecHits* within two rings around the pad with the maximum energy deposit. The weighting function $\omega(E_i)$ is defined as:

$$\omega(E_i^{Si}) = \max\left(0,\ a + \ln\left(\frac{E_i^{Si}}{\sum_{j\in M} E_j^{Si}}\right)\right),\quad a = 3.5\ .$$

The expected impact position on each layer was inferred by propagating the delay wire chambers (DWC) track to the HGCAL prototype. These quantities were used to compute the position residuals, defined as the differences of the reconstructed position from eq. (4.2) and that extracted from the DWC track extrapolation. The residual distributions were derived for all layers and all positron energies. The final resolution per layer was taken as the standard deviation from a Gaussian fit of the residuals in the range $[\mu - 2.0\sigma,\ \mu + 2.0\sigma]$. Figure 6 shows the position resolution in x and y at a depth of 6.6 X_0, as a function of the incident positron energy. The dashed lines represent a fit with the function

$$\sigma_x = a \cdot E_{\text{beam}}^{-0.5} \oplus b, \quad \text{and analogous for } y.$$

We observed a good agreement of position resolutions from data and simulation, including in the latter the DWC resolution. Figure 6 shows the position resolution in simulation with and without DWC resolution. The reason is that the DWCs were not simulated as sensitive detectors, thus the impact positions on the DWCs were computed from a straight line extrapolation using the beam gun direction, adding a smearing according to their expected resolution.

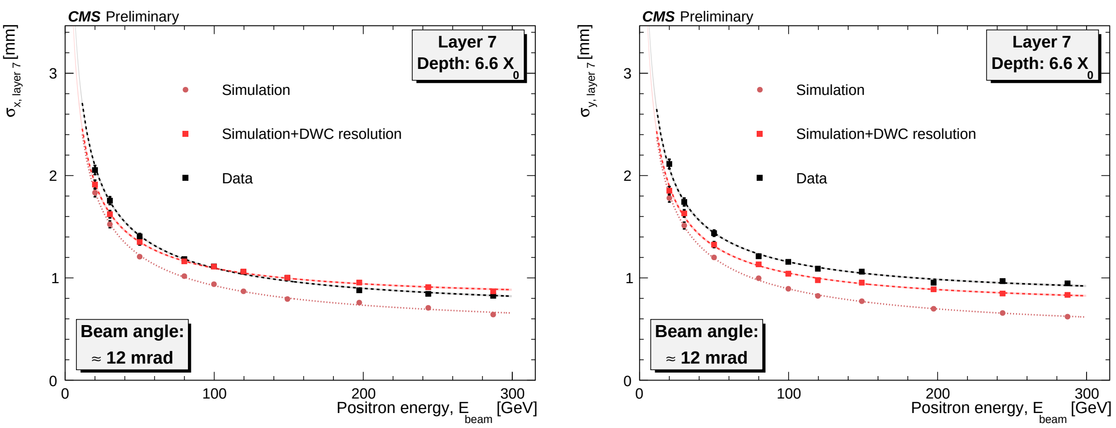


Figure 6. Reconstructed energy resolution (*left*) and average shower depth (*right*) for positrons in the energy range 20–300 GeV/c.

4.2 Pions

The study of charged pions estabilished the operational qualification of the hadronic section of the HGCAL prototype under test. This analysis, combined with the results on positrons beams presented in the previous section, contributed to the validation of the performance of the detector tested in October, which was the first full, large scale prototype close to the final HGCAL design.

2020 JINST 15 C04001

It was important to test the capability of this calorimeter in identifying the position of the first nuclear interaction starting the hadronic shower. This observable was reconstructed as presented in ref. [7]:

1. the sum of the *RecHit* energies was computed for each layer (E_l), limited to the hits around the incident particle trajectory;

2. if $E_1 > 20$ MIP, the first layer is identified as primary interaction layer (PI);

3. otherwise, if $E_2 > 20$ MIP and $E_2 > 2E_1$, the second layer is identified as the PI;

4. otherwise, if $E_l > 20$ MIP and $E_l > 2E_{l-1}$ and $E_l > 2E_{l-2}$, for any of the remaining layers, the l^{th} layer is identified as the PI;

5. otherwise, no layer is identified as the PI.

Figure 7a shows the distribution of the reconstructed PI depth from data and simulation for 200 GeV/c pions. A good agreement with the simulation was observed for all PIs. The solid lines represent the fit with the expected exponential law

$$\frac{dN}{\Delta\lambda_l} \propto \exp\left(-\frac{\lambda_l}{\lambda_0}\right)$$

where λ_0 is the pion interaction length and λ_l is the layer's depth in the calorimeter. The fit well describes the observed dependence. The only exceptions were found for the first layers and in the transition region between the electromagnetic and hadronic compartments. Notwithstanding this, the study confirmed the capability of the HGCAL prototype in identifying the PI of hadronic showers.

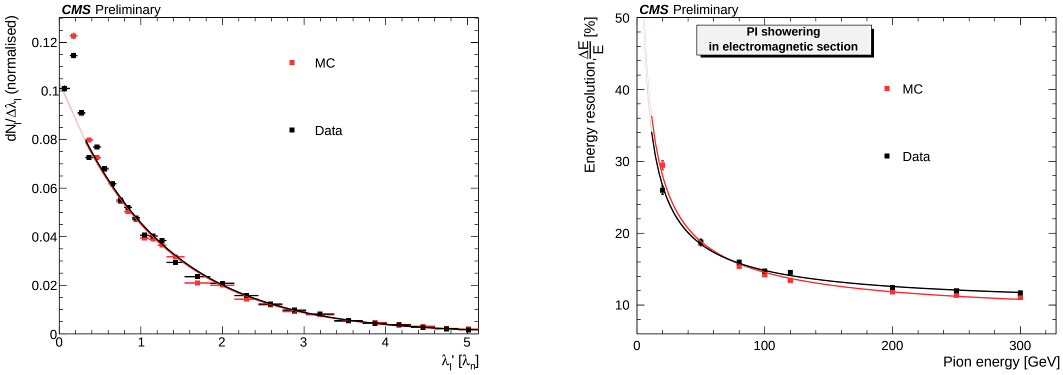
Having shown that the main features of a hadronic shower could be successfully reconstructed with the HGCAL prototype, it was used to study the energy resolution, similarly to what was done for positrons. However, for hadronic showers, the reconstructed energy distribution could not be computed as the bare unclustered sum of the *RecHits* in all Si pads, as the resulting distribution would not be centered around one value. Hence, the minimal energy reconstruction scheme had to take into account proper weighting of the energy sums in each compartment of the calorimeter:

$$E_{CE-EE} \coloneqq \sum_{i=1}^{N_{\text{hits}} \in CE-EE} E_i, \;\; E_{CE-H} \coloneqq \sum_{i=1}^{N_{\text{hits}} \in CE-H} E_i$$

$$E_{\text{Tot}} \coloneqq w_{CE-EE} \cdot E_{CE-EE} + w_{CE-H} \cdot E_{CE-H}.$$

The weights were retrieved from a regression on independent simulated samples of 5–350 GeV/c pions, exploiting the knowledge of the true particle energy in the simulation. These were found to be $w_{CE-EE} = 0.015$ GeV/MIP and $w_{CE-H} = 0.079$ GeV/c. A more extensive discussion of hadron shower energy reconstruction, along with additional methods to that presented here, can be found in ref. [7]. The study of the energy resolution was performed on pions showering in the electromagnetic compartment of the calorimeter. Figure 7b shows the results of this analysis. Even if these results have to be intended as preliminary, a good qualitative agreement was observed for data and simulation.

2020 JINST 15 C04001



(a) Normalised distribution of the identified primary interaction depth for 200 GeV/c pions.

(b) Energy resolution for pions showering in the electromagnetic section.

Figure 7. Preliminary results of the analysis on charged hadrons for the October 2018 beam tests.

5 Timing performance

The final HGCAL design foresees the precise timing measurement of the energy deposit, with expected resolutions of the order of tens of ps using the TOA information. This functionality was present also in the SKIROC2-CMS chips mounted on the prototype modules used for the beam tests. Hence a *proof-of-principle* analysis was performed for some sample channels, in order to study what has to be considered as an innovative measurement in calorimetry.

The timing resolution of the SKIROC2-CMS chips was measured using the time measured by the MCP-PMT as an external reference. More precisely, the resolution was extracted from the distribution of the difference between the TOA timestamp and the MCP reference, iterating over several events for a given channel. In order to maintain the MCP precision below 32 ps, only events with a reconstructed amplitude above 500 ADC counts were considered. Preliminary results were obtained for some channels close to the shower maximum, restricting the measurement to the linear region of the TOA. Figure 8 shows the values obtained for these channels, after the subtraction of

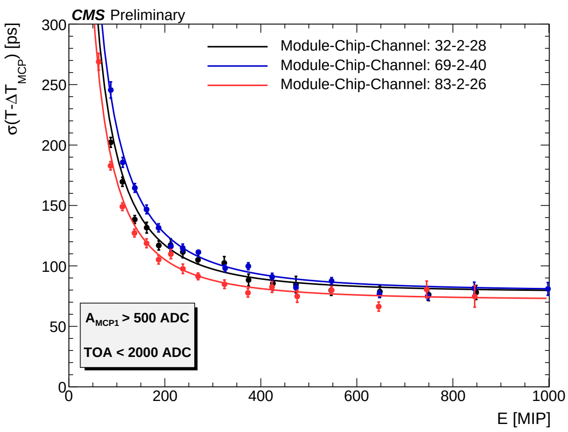


Figure 8. HGCAL prototype timing resolution extracted from the SKIROC2-CMS TOA using the MCP-PMT as a timing reference.

2020 JINST 15 C04001

the MCP reference time. Solid lines represent the fit with the function

$$\sigma(T - \Delta T_{\mathrm{MCP}}) = \sqrt{a^2 \cdot E_{\mathrm{hit}}^2 + b^2}.$$

This preliminary study reported the capability of extracting a timing resolution measurement using the TOA information from the SKIROC2-CMS ASIC. The resolutions obtained with this preliminary study were already close to the design value of 50 ps and no clear showstopper in the possibility of reaching this value with further and more detailed studies was found.

6 Conclusions

In October 2018 the first full large-scale prototype of HGCAL was tested at the CERN H2 beamline. This detector comprised an electromagnetic compartment with 28 layers and a hadronic compartment with 12 layers. The expertise acquired in previous beam tests, such as those described in refs. [2] and [4], was enhanced by the use of the SKIROC2-CMS ASIC, built specifically for beam tests of the HGCAL prototype.

The calorimeter was exposed to positron and pion beams of nominal energies ranging from 20 to 300 GeV/c, for a total of $O(10^6)$ events collected. Data were also acquired for 200 GeV/c muons and used for the MIP calibration. The same tracking procedure developped for [2] was applied, showing the capability of the detector to reconstruct tracks. These were also used to calibrate the response of the detector. A total of about 85% of the cells were successfully calibrated.

The performance of the HGCAL prototype was studied for both electromagnetic and hadronic showers and it was validated using an *ad-hoc* `GEANT4` simulation. The energy resolution of electrons was measured using the unclustered energy-sum distributions of the *RecHits* in all Si pads. Longitudinal shower shapes were studied by computing the electromagnetic center of gravity in the calorimeter. The expected log dependence of the average shower depth on the beam energy was also validated. For both these observables a good agreement of data and simulation was observed throughout the entire energy range. From the difference between the impact points on each layer of the electromagnetic compartment and the expected positions, extrapolated from the DWC tracks, the position resolution per layer was also measured.

The analysis of data with negative pions confirmed the capability of the HGCAL prototype to identify the primary interaction layer of hadronic showers. This information was exploited to measure the energy resolution of pions showering in the electromagnetic section of the calorimeter. For both these observables a good agreement between data and simulation was observed.

Using the time registered by the MCP-PMT as a reference, the TOA timing precision of the SKIROC2-CMS ASIC could be measured. Preliminary resluts for some example channels close to the shower maximum were shown, confirming the feasibility of such an innovative measurement for calorimetry.

The final results of the October 2018 beam test are going to be published in a set of 6 papers, which are under preparation at the time of writing this proceeding.

2020 JINST 15 C04001

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2020 JINST 15 C04001