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Calorimetry with Extremely Fine Spatial Segmentation

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Abstract. Particle Flow Algorithms (PFAs) attempt to measure each particle in a hadronic jet individually, using the detector subsystem that provides the best energy/momentum resolution. Calorimeters that can exploit the power of PFAs emphasize spatial granularity over single particle energy resolution. In this context, the CALICE Collaboration developed the Digital Hadron Calorimeter (DHCAL). The DHCAL uses Resistive Plate Chambers (RPCs) as active media and is read out with 1×1 cm^2 pads and digital (1-bit) resolution. In order to obtain a unique dataset of electromagnetic and hadronic interactions with unprecedented spatial resolution, the DHCAL went through a broad test beam program. In addition to conventional calorimetry, the DHCAL offers detailed measurements of event shapes, rigorous tests of simulation models and various analytical tools to improve calorimetric performance. Here we report on the results from the analysis of DHCAL data and comparisons with the Monte Carlo simulations.

1. Introduction

The High Energy Physics community has come to a consensus that the achievement of the high precision measurements aimed in future experiments, such as the ones envisaged at the International Linear Collider (ILC) [1], Compact Linear Collider (CLIC) [2] and Future Circular Collider (FCC) [3], can be made possible with the utilization of the Particle Flow Algorithms (PFAs) [4]. PFAs attempt to measure each particle in a hadronic jet individually, using the subdetector providing the best energy/momentum resolution in which the charged particles are measured with a high-precision tracker, photons with the electromagnetic calorimeter and the remaining neutral hadronic particles with the combined electromagnetic and hadronic calorimeters. A detector optimized for the implementation of PFAs requires calorimeters with extremely fine segmentation of the readout to separate showers from charged and neutral particles. In this context, the CALICE collaboration [5] developed several high segmentation calorimeters [6].

The large Digital Hadron Calorimeter (DHCAL) prototype was built in 2008-2010, following the successful completion of the test beam program of a small size prototype which produced a number of interesting results and enabled fine tuning of the details of the novel digital readout [7-12].

The DHCAL uses Resistive Plate Chambers (RPCs) as active media and is read out with 1 × 1 cm^2 pads and 1-bit resolution (digital). A single layer of the DHCAL measures roughly 1 × 1 m^2 and consists of 96 × 96 pads. Up to 52 layers were installed as a calorimeter stack during the beam tests. Each layer of RPCs was contained in a cassette with a 2 mm thick Copper front plate and a 2 mm thick Steel back plate. The details of the DHCAL are given in [13].

The DHCAL went through a broad test beam program and was tested with steel and tungsten absorber structures, as well as with no absorber structure, at Fermilab and CERN test beam facilities over several years. In addition to conventional calorimetric measurements, the DHCAL offers detailed measurements of event shapes, rigorous tests of simulation models and various tools for improved performance due to its very high spatial granularity.

Here, we report on the basic calorimetric measurements under various test conditions and also present detailed measurements of the electromagnetic and hadronic shower shapes. Results of comparisons with the Monte Carlo simulations are also reported.

2. Fe-DHCAL Tests at Fermilab

The DHCAL was tested at the Fermilab Test Beam Facility (FTBF) [14] with 120 GeV primary protons and 1 - 60 GeV secondary beams that are composed of muons, pions and positrons. The calorimeter consisted of a 38-layer structure (main stack) with 1.75 cm thick steel absorber plates and a 14-layer structure (tail catcher) with eight 2 cm thick steel plates followed by six 10 cm thick steel plates. This test setup is called the "Fe-DHCAL".

The mixed secondary beam and primary proton events were triggered by the coincidence of two 20 cm × 20 cm scintillator paddles located upstream of the DHCAL stack. The beam line houses Cerenkov detectors for particle identification for the mixed secondary beam. The DHCAL data contain the hit position information, the time stamp of the individual hits and the time stamp from the trigger and timing unit in addition to the discriminated signals of the Cerenkov counter and a muon tagger. The hits in each layer are combined into clusters using a nearest-neighbor algorithm and the cluster's x and y coordinates are calculated as the average of these coordinates over the constituent hits.

The calibration of the DHCAL involves several steps and multiple methods. The common method used in the publications so far is the full calibration in which the efficiency and the average pad multiplicity of a given RPC is normalized to the average efficiency and pad multiplicity of the DHCAL. The efficiency of an RPC is defined as the probability to measure at least one hit per traversing minimum-ionizing particle (MIP). The pad multiplicity of an RPC is defined as the average number of hits measured per traversing MIP. For Fe-DHCAL, the average efficiency was $\varepsilon_0 = 0.97$ and the average pad multiplicity was $\mu_0 = 1.69$.

Figure 1 (left) shows the response of the Fe-DHCAL to pions of energies from 6 to 60 GeV following the correction for nonlinearity. The grey bands indicate the statistical and systematic uncertainties of the data. The top panel shows the residuals to the beam energy, which are within 2 % for the entire energy range [15].

The DHCAL response was simulated in several steps as follows: The primary ionization locations in the gas gaps of the RPCs were obtained from Geant4 [16]. The ionization charges were sampled from the distribution obtained with the analog readout of a DHCAL RPC. A dedicated software called RPCSim was developed to distribute the generated charge over the pads, apply the threshold and reconstruct the hits. The tuning of the RPCSim parameters were done using the muon data simulation except one parameter which is called d_{cut}. The charges of the avalanches which originate within a distance of d_{cut} are limited using various approaches (see [15] for details). The tuning of the d_{cut} is performed using the positron data and simulation.

Figure 1 (left) shows the comparison of the DHCAL data with simulation. Three different electromagnetic physics lists of Geant4 were used after observing significant differences particularly in the shower shapes. FTBF_BERT is the hadronic physics list which uses the standard electromagnetic physics list, _EMY and _EMZ denote the alternative electromagnetic physics lists with increasing precision. There is no significant difference between different physics lists in terms of reproducing the DHCAL response to pions with the _EMZ list producing results with minimal residuals.

Figure 1 (right) shows the hadronic energy resolution of the Fe-DHCAL for pion energies from 6 to 60 GeV. The bottom panel shows the ratio of simulation and data. The energy resolution up to 32 GeV beam energy can be expressed as $(51.5 \pm 1.5)\%/\sqrt{E} \oplus (10.6 \pm 0.5)\%$. For single-particle energies higher than 32 GeV, the saturation effects dominate and the energy resolution degrades. On the other hand, it should be noted that the single-particle energies mostly lie below 20 GeV for e.g. the ILC.

The DHCAL is undercompensating for single-particle energies below 8 GeV, compensating around 8 GeV, and over-compensating above 8 GeV [15]. 8 GeV corresponds to the expected average energy of neutral hadrons at the ILC [17].

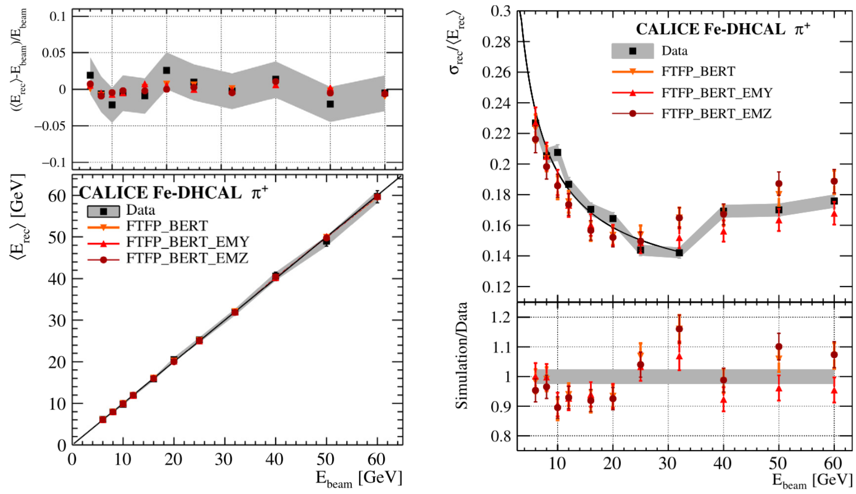

Figure 1. The response of the Fe-DHCAL to pions after nonlinearity correction (left) and the hadronic energy resolution of the Fe-DHCAL for pion energies from 6 to 60 GeV(right) [15].

3. W-DHCAL Tests at CERN

The DHCAL was tested at CERN PS with 1-10 GeV, and CERN SPS with 12-300 GeV electrons, positrons, positive and negative pions, muons and protons. The so-called “W-DHCAL” consisted of 54 active layers interleaved with Tungsten absorber plates [18]. The first 39 of these layers were inserted into the CERN tungsten absorber structure featuring 1 cm thick tungsten plates, named as the main stack. The distance between the plates was 15 mm, of which 12.85 mm were occupied by the cassette structure of the active layers. The remaining 15 layers were inserted into a steel structure, the tail catcher, which was located 23.5 cm behind the main stack. The first 8 absorber plates each measured 2 cm and the remaining plates each 10 cm. The active elements of the tail catcher were identical to the ones of the main stack. The first active layer was placed after the first 2 cm absorber plate. The total thickness of the 54-layer W-DHCAL (main stack and tail catcher) corresponded to approximately 183 radiation lengths or 11.1 nuclear interaction lengths.

Figure 2 (left) shows the uncalibrated mean response as a function of beam energy for the various particles in the beam. The responses to positive pions, negative pions and protons (after correction for the rest mass) show reasonable agreement. The response to electrons and positrons is significantly smaller than the response to hadrons, therefore W-DHCAL is strongly over-compensating even at low energies. This is in contrast to what was observed with steel absorber plates, where the response is compensating around 8 GeV/c and undercompensating (over-compensating) below (above).

Figure 2 (center) shows the energy resolution versus beam energy. The widths for both electrons and pions have been corrected for the observed non-linearity of the response. As expected, the through-going muon response shows a constant width, independent of the momentum selection. Fits of the quadratic sum of a stochastic and constant term seem to describe the measurements adequately.

For electrons, a stochastic term of 29.4 % and a constant term of 16.6 % are obtained. For pions, the stochastic term is 68.0 % and the constant term is 5.4 %. The large constant terms, in particular for electrons, are related to the saturation effects.

The mean response as function of beam energy over the entire momentum/energy range of the PS and SPS is shown in Fig. 2 (right). The effects of saturation noted with the PS data are also visible at higher energies. Empirical fits to a power law ($N = aE^m$) seem to describe the data adequately. The fit results obtained for pions, protons and electrons are 14.7 $E^{0.84}$, 13.6 $E^{0.86}$ and 12.7 $E^{0.70}$ respectively. The W-DHCAL is highly over-compensating. Smaller pad sizes would increase the electron response more than the hadron response and bring the calorimeter closer to compensation.

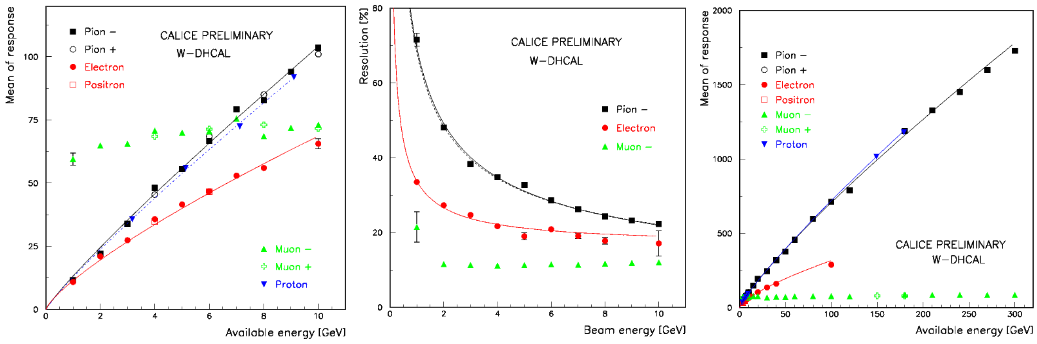

Figure 2. The uncalibrated mean response as function of beam energy (left) and the energy resolution (center) for the PS data; the mean response of W-DHCAL as function of beam energy over the entire energy range of PS and SPS [18].

4. Min-DHCAL Tests at Fermilab

The DHCAL was exposed to low energy particle beams of FTBF, as a 50-layer stack without being interleaved by absorber plates. The thickness of each layer corresponded approximately to 0.29 radiation lengths or 0.034 nuclear interaction lengths. This minimal absorber material configuration is called the “Min-DHCAL” [20].

Runs were taken with a selected momentum in the range of 1 - 10 GeV/c. The spatial segmentation of the DHCAL provides an unprecedented tool for the detailed study of the shape of electromagnetic showers. The measurements with the Min-DHCAL stack spread electromagnetic showers over the entire depth of the stack (approximately 1 m × 1 m × 1.3 m). This by itself means that the electromagnetic shower images are magnified by a factor of around 5000 compared to the conventional electromagnetic calorimeters. Figure 3 (left) shows the response as a function of beam energy. The data are compared to the results of the Monte Carlo simulation based on both the FTFP_BERT and the FTFP_BERT_EMY physics lists. Both are seen to be in good agreement with the data. The data/simulation are fit to a power law yielding N = 131.8 $E^{0.76}$ for the data indicating a strong saturation of the response. The saturation is mostly due to the large pad size compared to the density of particles in the core of the electromagnetic showers. The observed difference between data and simulation is due to a trend of the simulation to feature less hits at low energy and more hits at higher energy compared to the measurements.

Figure 3 (right) shows the electromagnetic energy resolution of Min-DHCAL. The measured widths are approximately 15% better than the corresponding resolutions obtained by the simulation based on the FTFP_BERT physics list, indicating a possible deficit in the simulation of the number of ionizations in the gas gap. On the other hand, the simulation based on the FTFP_BERT_EMY physics list reproduces the measurements quite well, but is in average about 6% better than the data. A stochastic term of 14.3 % and a constant term of 6.3 % were obtained for the data. The comparatively large constant term in both data and simulation is most likely due to the saturation effects, as the longitudinal leakage is relatively small.

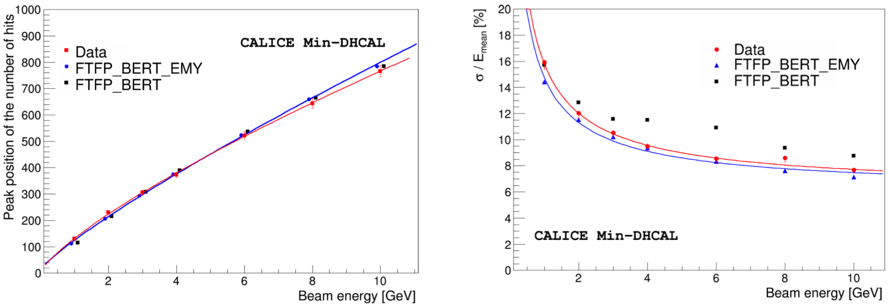

Figure 3. The response of the Min-DHCAL as a function of beam energy (left) and the energy resolution (right) [20].

5. Conclusions

The first Digital Hadron Calorimeter was built and tested successfully. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of Resistive Plate Chambers and extremely fine segmentation.

With various configurations, the DHCAL allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail. It also enables the utilization of various techniques not implemented in conventional calorimetry e.g. software compensation and leakage correction.

The DHCAL response was simulated with various versions of Geant4, and it was observed that the standard Geant4 simulation package fails to reproduce data well. Some optional packages allow big improvement in the agreement. The disagreements, on the other hand, are at the very fine level of detail which is not available in conventional calorimeters. The analysis of the data and the tests of simulation models are ongoing.

The concept of Digital Hadron Calorimetry is validated.

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