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DHCAL with minimal absorber: measurements with positrons

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Abstract. In special tests, the active layers of the CALICE Digital Hadron Calorimeter prototype, the DHCAL, were exposed to low energy particle beams, without being interleaved by absorber plates. The thickness of each layer corresponded approximately to 0.29 radiation lengths or 0.034 nuclear interaction lengths, defined mostly by the copper and steel skins of the detector cassettes. This paper reports on measurements performed with this device in the Fermilab test beam with positrons in the energy range of 1 to 10 GeV. The measurements are compared to simulations based on GEANT4 and a standalone program to emulate the detailed response of the active elements.

1. Introduction

This paper reports on special tests performed in the Fermilab test beam using the detector cassettes of the Digital Hadron Calorimeter prototype, the DHCAL [1], without absorber material interleaved between the active layers. The active layers of the DHCAL contained thin Resistive Plate Chambers (RPCs) with a readout featuring 1 x 1 cm^2 pads.

In its configuration without absorber plates, the so-called Min-DHCAL [2] provided the opportunity to study electromagnetic and hadronic showers with extremely fine segmentation, especially longitudinally, spreading the showers over the entire depth of the stack. This paper presents measurements with positrons in the energy range of 1−10 GeV. The experimental results are compared to detailed Monte Carlo simulations based on GEANT4. These comparisons provide an ideal tool to gain deeper insights into the response of an RPC-based calorimeter and into the physics of low energy showers.

2. Description of the DHCAL with minimal absorber

The DHCAL used Resistive Plate Chambers (RPCs) [3, 4] as active elements. The area of each plane was approximately 1 x 1 m^2 and was equipped with three 32 x 96 cm^2 chambers. The readout boards contained pads of 1 x 1 cm^2 and were placed on the anode side of the chambers. The chambers and the readout boards in turn were inserted into a cassette structure with a 2 mm thick steel front cover and a 2 mm thick rear copper cover. The thickness of each cassette was about 12.5 mm and corresponded to 0.29 radiation lengths X_0 or 0.034 nuclear interaction lengths λ_I. The DHCAL in this configuration with minimal absorber, consisted of 50 cassettes, spaced 2.54 cm apart. The total number of readout channels was 460,800. The electronic readout provided a single bit for each channel, corresponding to a single threshold. To first order, the energy of incoming particles was reconstructed as being proportional to the number of hits. This method works, as the noise rate in the stack was negligibly small [2]. For further details on the design, operation, and commissioning of the chambers and the electronic readout system, see ref. [1, 5].

3. Data collected at the Fermilab Test Beam Facility

The Min-DHCAL was exposed to the test beam at the Fermilab Test Beam Facility, FTBF [6]. The facility provides a primary 120 GeV proton beam and momentum selected secondary beams in the range of 1-66 GeV/c . The latter are a mixture of electrons, muons and pions, where the fraction of electrons is dominant at momenta below 5 GeV/c and tapers off for momenta above 32 GeV/c. The beamline included two Cerenkov counters for particle identification and two scintillator paddles (19 x 19 cm^2), located approximately two meters upstream of the Min-DHCAL. The data acquisition was triggered by the coincidence of these two paddles.

The data on which this paper is based were collected in November 2011. Runs were taken with a selected momentum in the range of 1-10 GeV/c.

4. Simulation of the test beam set-up

The simulation of the beam tests is based on the GEANT4 program [7] version 10.02. The simulated set-up includes the active elements with their cassette covers, resistive plates, the gas, and electronic readout boards. Any energy deposition generated by the simulation in the gas gap of the RPCs is used as a seed for the simulation of an avalanche. The latter is simulated by a standalone program, called RPC_sim [2], which is governed by six parameters. Five of these are tuned by comparing the distribution of the number of hits per layer in both measured and simulated muon track events. The remaining parameter, a distance cut, d_{cut}, introduced to suppress close-by avalanches, was tuned using the 3 and 10 GeV positron data [2].

Initially, the GEANT4 program utilized the FTFP_BERT physics list. However, this led to a unsatisfactory description of, among other measurements, the energy resolution, indicating a deficit in the generation of initial ionizations in the gas gap of the RPCs. A migration to the Option 3 or _EMY [8] based electromagnetic physics list, which is particularly appropriate for low energies, resulted in a significant improvement of the description of the experimental data, in particular, the energy resolution.

5. Hit and Event Selection

To ensure the high quality of the data, several loose cuts were applied to the selection of both hits and events. By requiring a signal in the upstream Cerenkov counter, the fraction of muon and pion induced events was effectively reduced to zero, due to the negligible rate of accidental hits in the counter. The acceptance for positrons was approximately 97.5% and independent of energy.

6. Equalization of the RPC responses

Through-going muons are used to measure and equalize the response of the 150 different RPCs in the stack. The equalization procedure is performed for each run individually using the admixture of muons in the beam.

The efficiency ϵ, the average pad multiplicity μ, and their product $\epsilon\mu$ are determined for each chamber individually and also averaged over the entire stack and all runs. For a given chamber, i, the calibration factor is calculated as the ratio of the product averaged over the entire stack, $\epsilon_0\mu_0$, and the product, $\epsilon_i\mu_i$, as measured for chamber i.

7. Systematic errors

The following systematic errors associated with uncertainties in the measurements have been considered: the residual non-uniformity in the calibrated response (dominant), the rate limitation of RPCs [9], contamination of the positron sample by muons and pions, and contributions from accidental noise hits in the chambers. All systematic errors pertaining to the experimental data are assumed to be independent and uncorrelated between energies, and are therefore added in quadrature.

The differences observed between the FTFP_BERT and FTFP_BERT_EMY physics lists point to some uncertainty in the simulation of electromagnetic showers in GEANT4. Additionally, uncertainties in the emulation of the RPC response lead to further systematic errors in the simulated results. However, since the 3 and 10 GeV measurements were used to tune the distance cut parameter of the RPC_sim program, d_{cut}, the simulation lost most of its predictive power and an assignment of systematic errors to the simulation of positrons has therefore become problematic.

8. Results

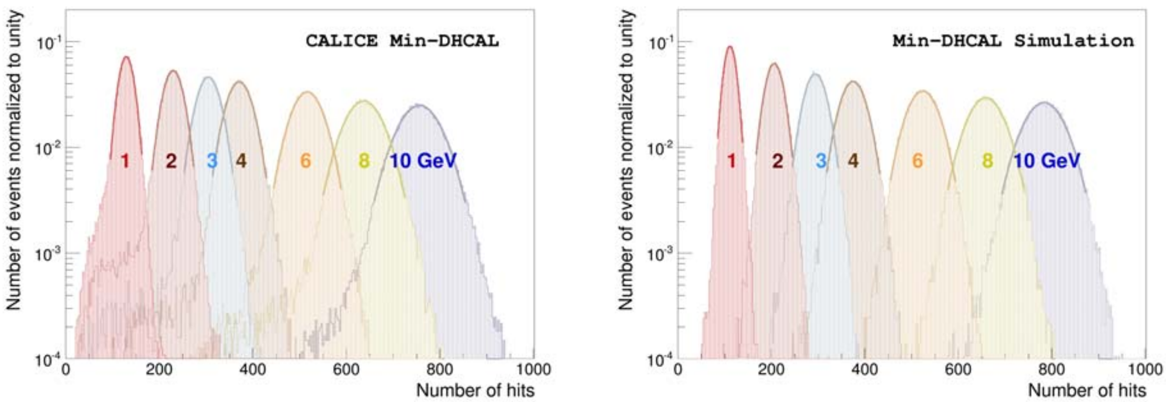

Figure 1. Distribution of the number of hits for all selected positron events for data (left) and simulation based on the FTFP_BERT_EMY physics list (right). The distributions are plotted separately for each beam momentum setting (1, 2, 3, 4, 6, 8, 10 GeV/c) and are each normalized to unity. The distributions are fit with a Gaussian function in the range of ±2 standard deviations. The results of the fits are shown as solid lines.

Figure 1 shows the distribution of the number of hits for all selected positron events for both data and simulation. The response curves have been normalized to unity for each momentum

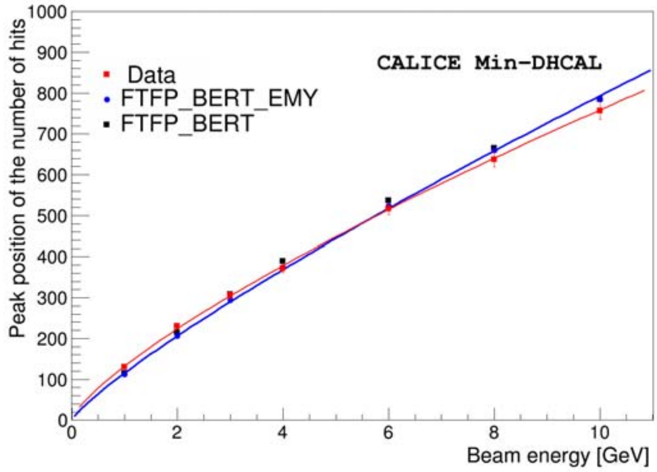

Figure 2. Peak position of the number of hits versus positron beam energy for both data (red) and simulation based on FTFP_BERT (black) and FTFP_BERT_EMY (blue). The experimental data points and the simulation based on FTFP_BERT_EMY have been fitted to a power law shown as solid lines. The error bars of the data include both the statistical and systematic (dominant) errors. The statistical error bars of the simulation are smaller than the marker size.

selection and are well described by fits of a Gaussian function in the range of $\pm 2\sigma$ around the peak value (determined iteratively).

The mean values obtained from the Gaussian fits are shown as function of beam energy in Fig. 2. 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 fitted to a power law

$$N_{hit} = a_0 (E_{beam}/GeV)^m \tag{1}$$

where the exponent m is a measure of the non-linearity (saturation) of the response. A value of unity would indicate a perfectly linear response. A value of $m = 0.76 \pm 0.02 (0.836 \pm 0.001)$ is obtained for data (simulation based on FTFP_BERT_EMY), 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 electromagnetic showers. The simulation based on the FTFP_BERT physics list produces similar results as the ones based on FTFP_BERT_EMY, as indicated by the black squares in Fig. 2. The inverse of the power law is utilized to reconstruct the energy of the positrons.

Figure 3 shows the resulting relative resolutions as function of beam energy for both data and simulation (based on both physics lists). The measured resolutions 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 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 are in average about 6% better than the data. The energy resolution versus beam energy was fitted to the standard parametrization with a constant and a stochastic term.

Table 1 summarizes the results of the fits, showing a reasonable agreement between the stochastic terms of data and simulation.

The imaging capabilities of the DHCAL provide an unprecedented tool for the detailed study of the shape of showers. As an example, Fig. 4 shows the distribution of the radial distance of

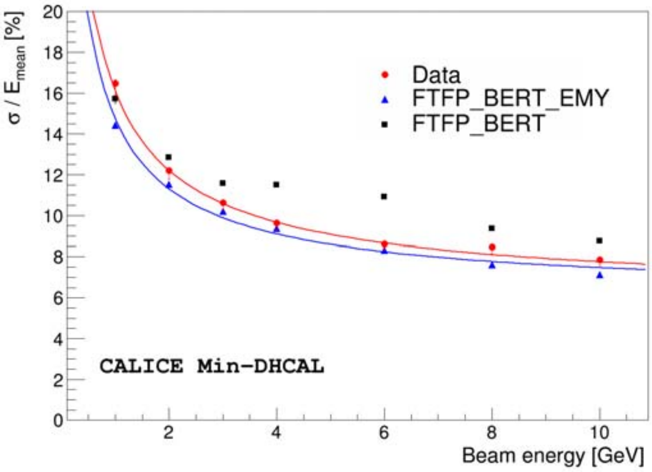

Figure 3. Energy resolution versus positron beam energy for data (red) and simulation based on FTFP (black) and FTFP_BERT_EMY (blue). The experimental points were corrected for the known momentum spread of the beam. The error bars of the data include both statistical and systematic uncertainties. The error bars of the simulation indicate the statistical uncertainty only. The curves are the results of fits to the quadratic sum of a constant and stochastic term.

	c [%]	α [%]
Data	6.3 ± 0.2	14.3 ± 0.4
Simulation (FTFP_BERT_EMY)	6.2 ± 0.1	13.4 ± 0.2

Table 1. Fit parameters for the constant and stochastic terms of the energy resolution for positrons.

each hit to the shower axis, as measured for 6 GeV positrons. The accelerated decrease in entries above a radius of 50 cm is an artefact of the square shape of the detector planes with dimensions of 96 x 96 cm^2. Excellent agreement between data and simulation is observed over the entire range of radii apart from a small depletion at small radii in the data. Note that the number of hits varies by six orders of magnitude over the entire range in radii. Both the statistical and systematic uncertainties of the data are very small and mostly invisible in the plots.

9. Conclusion

The Digital Hadron Calorimeter (DHCAL) detector planes without absorber plates, the Min-DHCAL, was exposed to particles in the Fermilab test beam. The response of the individual Resistive Plate Chambers in the calorimeter stack was equalized using through-going muon tracks. The response of the Min-DHCAL to positrons, its energy resolution and various electromagnetic shower shapes were measured in the energy range of 1 to 10 GeV. The results of a Monte Carlo simulation based on GEANT4 and a standalone program, RPC_sim, to emulate the response of the RPCs, were compared to the data. The RPC_sim program was tuned to reproduce the measured response to muons and to reproduce the measurements obtained with 3 and 10 GeV positrons. Due to the tuning process the simulation lost its predictive power for both muons and positrons.

The GEANT4 simulation utilized either the FTFP_BERT and the FTFP_BERT_EMY physics lists. The latter provides higher accuracy, in particular for the simulation of electromagnetic processes in thin layers. Despite tedious efforts of tuning of the RPC_sim parameters

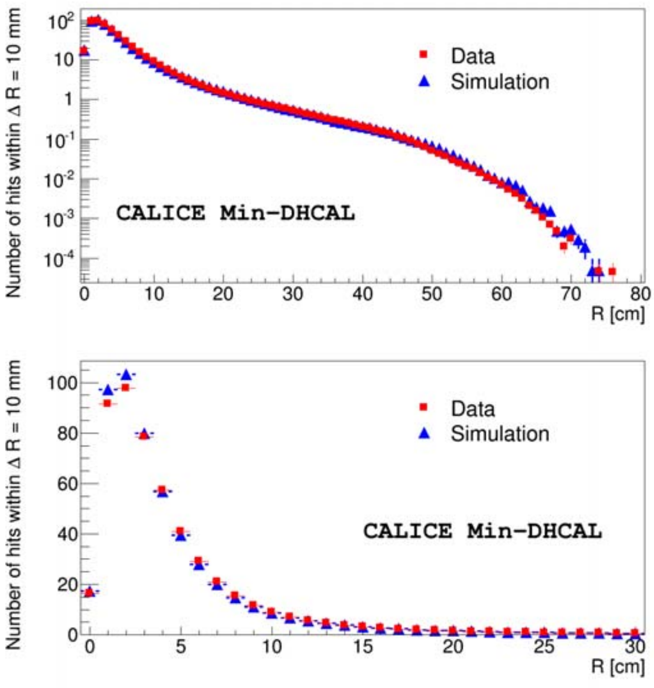

Figure 4. Distribution of the radial distance of hits from the shower axis for 6 GeV positrons. The upper (lower) plot uses a logarithm (linear) y-scale. The areas of both plots are normalized to one event. The error bars include the statistical and systematic uncertainties for the data and statistical uncertainties only for the simulation.

to reproduce the measurements, only a poor description of the data was obtained with FTFP_BERT, suggesting a deficit of ionizations in the gas gap of the RPCs. A significant improvement is seen with the use of FTFP_BERT_EMY, leading to a good to excellent agreement with the data.

References

[1] C. Adams et al., JINST 11 (2016), P07007.
[2] B. Freund et al., JINST 11 (2016), P05008
[3] R.Santonico and R.Cardarelli, Nucl. Instr. and Meth. **187** (1981)377-380.
[4] G.Drake et al., Nucl. Instr. and Meth, **A578**, 88-97, 2007.
[5] C. Adams et al., *Design, Construction, and Testing of the Digital Hadron Calorimeter (DHCAL) Electronics*, arXiv:1603.01654 [phys.ins-det](to be published).
[6] `http://ftbf.fnal.gov`
[7] E. Longo and I. Sestili, Nucl. Instrum. Methods **128**, 283 (1975)
[8] V.N. Ivanchenko et al.,*Recent Improvements in Geant4 Electromagnetic Physics Models and Interfaces* , Prog. Nucl. Sci. Technol. **2** (2011) 898.
[9] B. Bilki et al.: *Measurement of the rate capability of Resistive Plate Chambers*, JINST 4 P06003 (2009).