First Results from the CALICE Digital Hadron Calorimeter (DHCAL)

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On behalf of the CALICE collaboration

The Digital Hadron Calorimeter (DHCAL) is a prototype hadron calorimeter using Resistive Plate Chambers (RPCs) as active elements. The readout is finely segmented into 1 x 1 cm^2 pads, as required for a calorimeter optimized for the application of Particle Flow Algorithms (PFAs) to the measurement of hadronic jets. The prototype was exposed to particle beams at Fermilab and at CERN. After a short introduction, this talk reviews the first test beam results. The results are seen to validate the concept of a digital imaging calorimeter from both the physics point of view and as well as technically with its use of RPCs as active media together with a so-called digital or 1-bit readout.

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1. Introduction: PFAs, imaging calorimetry

Particle Flow Algorithms (PFAs) are proven to be powerful tools to improve the measurement of hadronic jets in colliding beam experiments [1, 2]. Currently PFAs are being applied to detectors, which, however, have not been designed with their application in mind. For a future lepton collider, detector concepts [3, 4] are being developed which are specifically designed to optimize the application of PFAs. Such detectors feature compact calorimeters with extremely fine segmentation of the readout. In this context, the CALICE collaboration [5] designed, built and tested, among others, a large scale prototype of a Digital Hadron Calorimeter with Resistive Plate Chambers as active media, the so-called DHCAL.

2. The DHCAL

The DHCAL was constructed in 2008-10 and consists of up to 54 active layers [6]. A layer contains three RPCs, each covering an area of 32 x 96 cm^2. The readout is segmented into 1 x 1 cm^2 pads, read out with the DCAL III chip, specifically developed for this project. A single threshold is applied to each channel (common to all 64 channels of a chip), corresponding to a 1-bit resolution. With a total of 497,664 readout channels, the DHCAL currently holds the world record in channel counts for both calorimetry and RPC-based systems. The DHCAL was exposed to particle beams at Fermilab and CERN.

At Fermilab [7] 38 DHCAL layers were inserted into the CALICE AHCAL structure containing Steel absorber plates [8]. In addition, up to 14 layers were inserted into a tail catcher [9] located downstream of the main stack and also featuring Steel absorber plates. Data were collected with the 32 GeV secondary beam and the beam dump lowered to provide a broadband muon beam covering the entire surface of the calorimeter. Momentum selected secondary beams with momenta in the range of 1 - 60 GeV/c provided mixed samples of charged pions and positrons. The latter were identified with the use of a Cerenkov counter located upstream of the experimental area. In addition, data were collected with the primary 120 GeV proton beam.

As an example illustrating the fine granularity of the DHCAL, Fig. 1 shows displays of events collected in the Fermilab test beam in a configuration without Steel absorber plates. In this particular case the mass of the calorimeter was dominated by the covers of the detector layers (2 mm Copper and 2 mm Steel per layer) and the glass of the RPCs (2 mm per layer).

At CERN the DHCAL layers were inserted into a structure containing Tungsten absorber plates, again followed by a tail catcher with Steel plates, similar to the one used at Fermilab. The tests were performed both at the PS and the SPS H8 test beams. The PS provided mixed particle beams up to 10 GeV/c, whereas the SPS covered the range from 10 to 300 GeV. Again, Cerenkov counters were utilized to identify electrons/positrons, or at higher energies, where the electron content is negligible, pions as opposed to protons.

Table 1 summarizes the number of events collected in the two test beam locations.

3. Noise measurements

There are three ways to measure the noise rate in the DHCAL: a) with random triggers, b) in trigger-less acquisition mode, where all hits are recorded, and c) using triggered data and counting

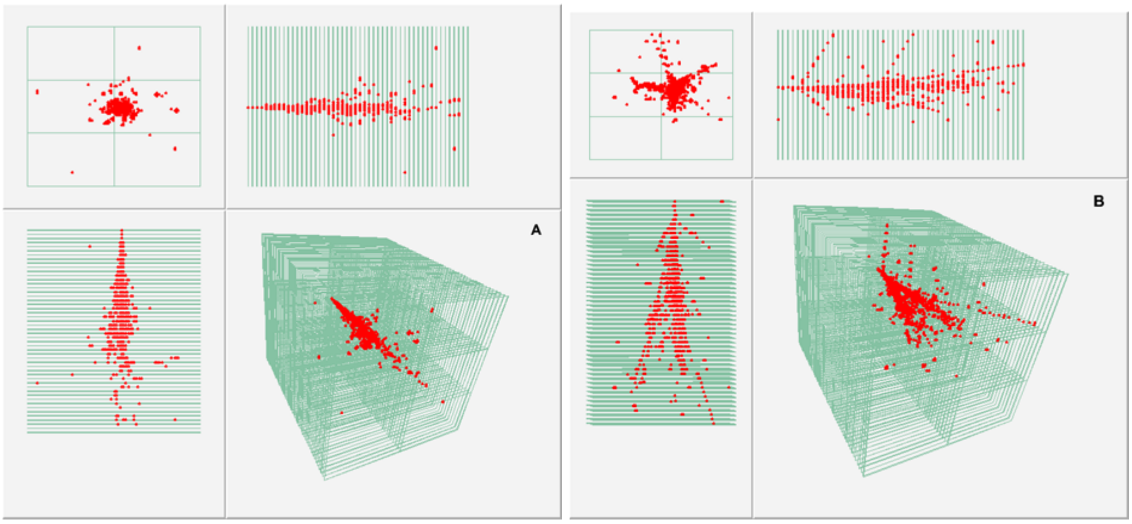


Figure 1: Event display of a 8 GeV e^+ in the DHCAL with minimal absorber material (*left*). Event display of a 16 GeV π^+ in the DHCAL with minimal absorber material (*right*).

Test Beam	Muon events	Secondary beam	Total
Fermilab	9.4M	14.4M	23.8M
CERN	7.6M	32.1M	39.7M
Total	17.0M	46.5M	63.5M

Table 1: Number of events collected in the Fermilab and CERN test beams.

the hits in the first two out of seven time-bins recorded. These first two bins correspond to times before incidence of the particle triggering the readout. The noise rate depends on environmental conditions (ambient temperature and atmospheric pressure) [10], the high voltage setting and on the high voltage connection to the resistive paint. Over larger periods of time, the latter was found to deteriorate for some of the chambers, leading to a loss of efficiency and thus also reducing the noise rate.

The three methods of measuring the noise rate provide consistent numbers: 0.01 to 0.1 hits per event for the entire DHCAL. As 1 GeV corresponds to 15 hits in average, the measured noise rate translates into at most a few MeV and, therefore, can be safely ignored for the following analyses of DHCAL data.

4. Response to muons

Broadband muons offer a great tool to assess the performance parameters of the RPCs: the efficiency for detecting a minimum ionizing particle (MIP), the average pad multiplicity for MIPs, and the product of the two, the calibration factors. Two methods have been developed to measure the performance of a given RPC. Excluding the layer containing the RPC to be measured, either tracks are reconstructed using all other layers in the stack or short track segments [11] are reconstructed using the neighboring layers upstream and downstream of that layer. Both methods provide similar results, but the latter offers the advantage of being also applicable to events containing hadronic showers. Emerging from inelastic reactions in the absorber material, hadronic showers frequently contain MIP stubs (see Fig 1), which can be used to establish the response of the chambers.

Figure 2 (left) shows the performance parameters as function of layer number as measured in November 2011 in the Fermilab testbeam. The performance of the RPCs is seen to be quite uniform with an efficiency around 95% and an average pad multiplicity of approximately 1.7.

The response to muons averaged over all layers is shown in Fig. 2 (right) compared to Monte Carlo simulations based on GEANT4 [12] and the digitization of the RPC signals by the so-called *RPCsim* [13] program. The latter contains six parameters controlling the generation of the signal charge, its spread over the pad surface and the electronic threshold. These parameters were tuned such as to reproduce the measured distribution of Fig. 2 (right).

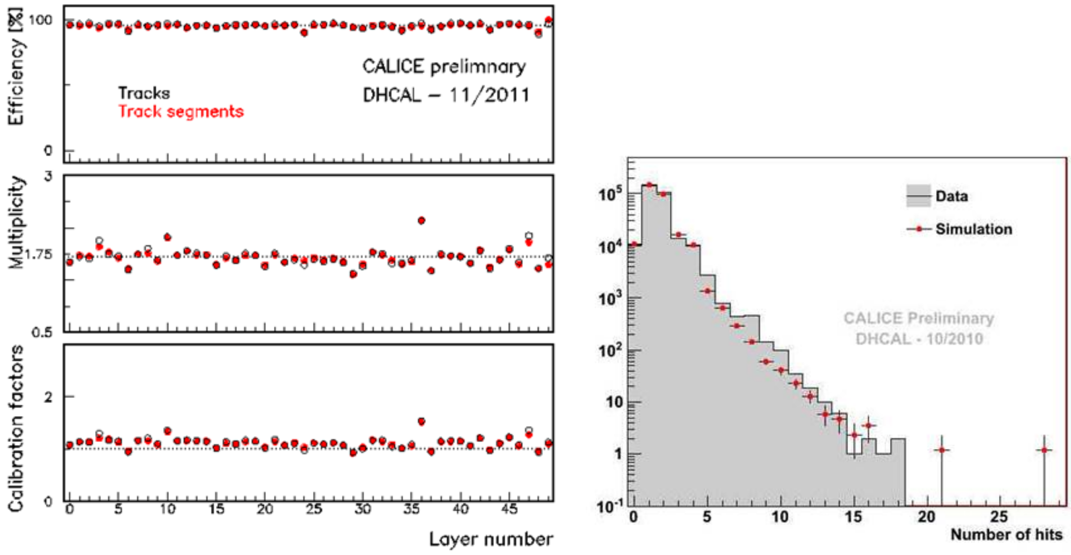


Figure 2: RPC performance parameters as function of layer number (*left*). Response to muons averaged over all layers: data (histogram) and simulation (red points) (*right*).

5. Response to pions/positrons with Steel absorbers

To first order, the energy of an incident particle in the DHCAL is reconstructed as being proportional to the number of pads firing. As an example Fig. 3 shows the number of pads firing for 8 GeV positrons (left) and pions (right), as measured at Fermilab with Steel absorber plates. The distributions are fitted with Gaussian functions, which reproduce the data reasonably well. Up to 60 GeV the hadronic response is found to be close to linear. On the other hand, the response to positrons is observed to be strongly non-linear, already at small energies. This leads to a peculiar behavior of the e/h ratio as function of energy, where at low energies the ratio is larger than unity, i.e. the response is overcompensating, at energies around 8 GeV the responses are equal (compensating) and at larger energies the ratio is smaller than unity (undercompensating), see Fig. 4 (left).

The hadronic resolution as function of beam energy is shown in Fig. 4 (right). Results are shown both before and after calibrating the response of the individual RPCs. The results are consistent with predictions based on Monte Carlo simulations [14].

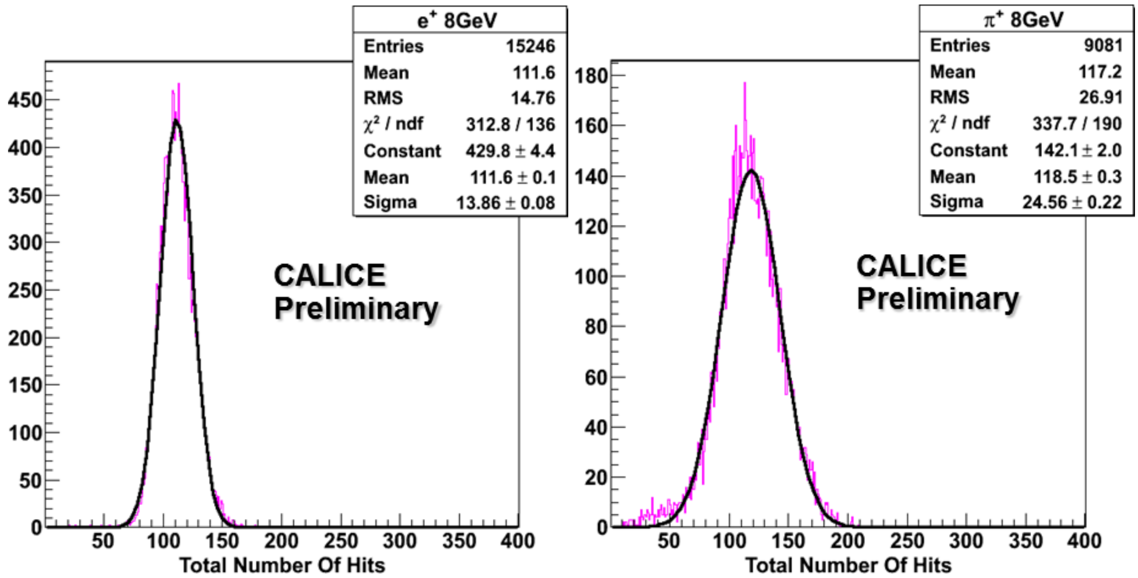


Figure 3: Response to 8 GeV e^+ in the DHCAL with Steel absorbers (*left*). Response to 8 GeV π^+ in the DHCAL with Steel absorbers (*right*).

6. Response to pions/electrons with Tungsten absorbers

In 2012 the DHCAL layers were transported to CERN, in order to perform measurements with Tungsten absorber plates. The setup consisted of a main structure containing 38 Tungsten plates with a thickness of 10 mm each, followed by a tail catcher with Steel absorber plates. Fig. 5 shows the response and resolution to various particle types as measured at the PS. Due to the increased thickness in radiation lengths of the Tungsten absorber plates (3.3 X_0), compared to the Steel absorber plates (1.0 X_0), the average number of pads is about 30% smaller for a given energy compared to the results obtained at Fermilab. This leads to a degraded resolution and a non-linear response for both electrons and hadrons. In the energy range tested at CERN, the response is seen to be over-compensating, even at the lowest energies probed.

Figure 5 shows the response versus beam energy up to the highest energies available in the SPS. A power law $N = \alpha E^{\beta}$ seems to fit the data adequately.

To restore the linearity of the DHCAL with Tungsten absorber plates, smaller pad sizes are required, e.g. 0.5 x 0.5 cm^2. These smaller pad sizes require RPCs with improved position resolution, such as 1-glass RPCs currently being developed and tested at Argonne (see below).

7. Current/future activities

The DHCAL group's current and future activities are concentrated in three areas:

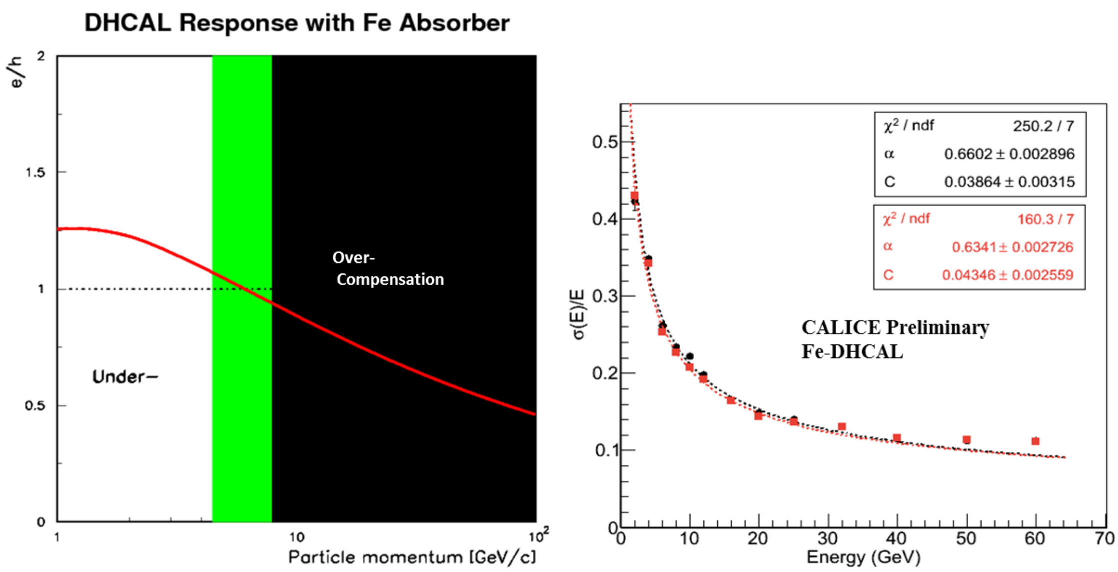
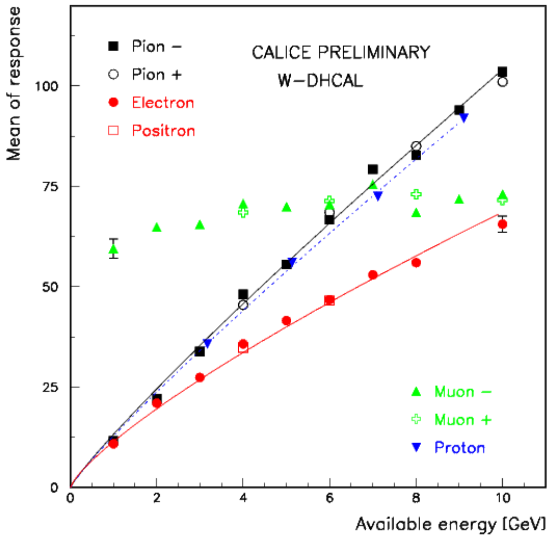


Figure 4: Ratio of the response to e^+ and π^+ versus beam energy in the DHCAL with Steel absorbers (*right*). Resolution measured with π^+ in the DHCAL with Steel absorbers: before (black) and after (red) calibration of the RPC response (*left*).

- *High-rate RPCs*
  At high particle rates RPCs loose efficiency for detecting particles [15]. The loss is proportional to the bulk resistivity of the resistive plates. The bulk resistivity of typical glass is of the order of 10^{13} $\Omega\dot{c}m$, leading to losses of efficiency above approximately 100 Hz/cm^2. Bakelite offers a bulk resistivity about 2 - 3 orders of magnitude lower, leading to rate capabilities between 10 to 100 kHz/cm^2.

  The DHCAL group is investigating low resistivity Bakelite (in conjunction with University of Michigan and the University of Science and Technology of China), as well as semiconductive glass (in co-operation with COE College in Iowa and University of Iowa). Prototype RPCs with these novel materials are being built and will be tested shortly in the Fermilab test beam. Rate capabilities in the range of 1 MHz/cm^2 are expected to be achieveable.

- *1-glass RPCs*
  Standard RPC designs feature two resistive plates. The DHCAL group proposes a novel design with a single glass plate, eliminating the resistive plate on the anode side [16]. Thus the signal pads are located directly in the gas volume. This design offers several distinct advantages: a reduced chamber thickness, an average pad multiplicity close to unity (with the extra advantage of simplifying the calibration and monitoring procedure), a higher rate capability (by about a factor of two), and a performance mostly independent of the surface resistivity of the resistive paint on the cathode plate. To date several prototype chambers have been built and are being tested with cosmic rays. Their performance is found to be excellent, with high efficiency and uniform response across the surface. Measurements in the Fermilab test beam are planned for later in the year, to establish their performance in



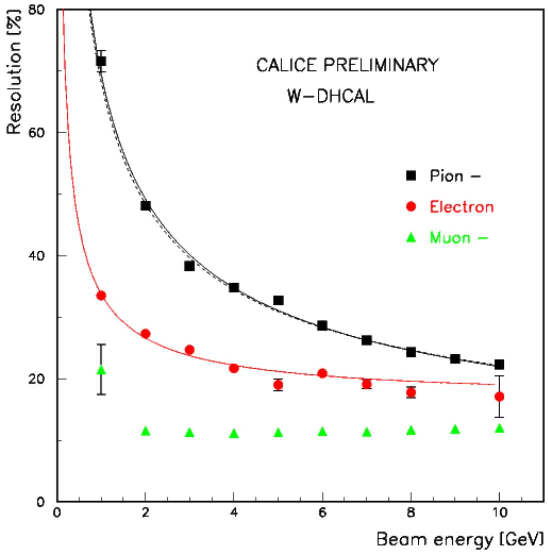


Figure 5: Response measured in the PS beam with Tungsten absorbers (*left*). Resolution measured in the PS beam with Tungsten absorbers (*right*).

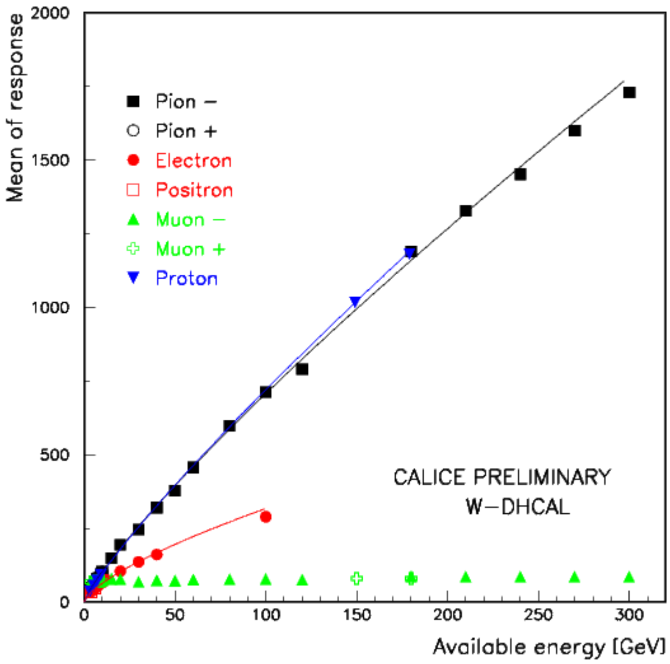


Figure 6: Response measured at the PS and SPS beams with Tungsten absorbers.

dense electromagnetic and hadronic showers.

- *HV distribution system*
  With of the order of 40 layers per module, a reliable, cost effective high voltage distribution

system is needed. The system will be connected to a High Voltage supply and will be able to control a yet to be specified number of channels, turning them on and off without affecting (tripping) the supply. In addition, the system will monitor both the voltage and the current of each channel individually. To date a first prototype able to control a single channel has been built and performed very well in bench tests. This development is being carried out at University of Iowa.

8. Conclusions

The DHCAL (Digital Hadron Calorimeter) is a novel, highly imaging hadron calorimeter prototype, based on Resistive Plate Chambers as active elements. The prototype was constructed in the years 2008 - 10 and was subsequently tested in the Fermilab (with Steel absorber plates) and CERN (with Tungsten absorber plates) test beams. The data from both test beams are currently being analyzed. The first results look very promising and validate the concept of a digital imaging calorimeter, from the physics point of view, as well as technically with its use of RPCs as active media.

Further R&D is aimed at improving the performance of the RPCs (increased rate capability and reduced average pad multiplicity). In addition, a High Voltage distribution system is being developed, with the potential to reducing drastically the cost of supplying high voltage to each layer of the calorimeter.

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