Journal of Physics: Conference Series

The CALICE digital hadron calorimeter: calibration and response to pions and positrons

The CALICE digital hadron calorimeter: calibration and response to pions and positrons

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Abstract. In order to measure the jet products of the hadronic decays of electroweak bosons in a future lepton collider with 3-4% resolution, a novel approach named Particle Flow Algorithms is proposed. The Particle Flow Algorithms attempt to measure each particle in a hadronic jet individually, using the detector providing the best energy/momentum resolution. The role of the hadronic calorimeters is to measure the neutral component of the hadronic jets. In this context, the CALICE Collaboration developed the Digital Hadron Calorimeter, which uses Resistive Plate Chambers as active media. The 1-bit resolution (digital) readout of 1 x 1 cm^2 pads achieves a world record in the number of readout channels already at the prototyping stage. Here we report on the results from the analysis of pion events of momenta between 2 to 60 GeV/c collected in the Fermilab test beam with an emphasis on the intricate calibration procedures.

1. Introduction

The CALICE Collaboration develops calorimeters that are optimized for the application of Particle Flow Algorithms (PFAs) for future linear colliders [1]. The large CALICE Digital Hadron Calorimeter (DHCAL) prototype was built in 2009-2010 with a design based on the preliminary work done with a small-scale prototype, which underwent a rigorous test program in the Fermilab test beam and resulted in numerous publications [2-7]. The active media of the DHCAL are Resistive Plate Chambers (RPCs), which are read out by 1 x 1 cm^2 pads with a 1-bit resolution (digital readout). A single layer of the DHCAL measures roughly 1 x 1 m^2 and consists of 96 x 96 pads. During the Fermilab beam tests, 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. In addition to the absorber plates, 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 can be found in [8, 9]. Further information about the CALICE detectors can be found in [10-16].

The DHCAL is a calorimeter with the following unique features: RPCs for calorimetry (no other hadron calorimeter uses RPCs as active medium); Pad readout of RPCs (RPCs are usually read out with strips); Digital readout; Embedded front-end electronics; Large channel count (a world record of ~ 0.5M channels). Here, we describe the basics of the intricate calibration procedures and their implementation in the analysis of the Fermilab data.

2. Calibration procedures

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. Additionally, discriminated signals from a beam Čerenkov counter and a muon tagger (a downstream scintillator 1 x 1 m^2 paddle) are integrated into the data stream by the data acquisition system.

The hits in each layer are combined into clusters using a nearest-neighbor algorithm. If two hits share a common edge, they are assigned to the same cluster. The cluster's x and y coordinates are calculated as the average of these coordinates over the constituent hits. Here, the x axis is the horizontal, the y axis is the vertical and the z axis is along the beam direction (a right-handed coordinate system with the origin at the center of the most upstream layer). The event selection requires at least five active layers (layers with at least one hit) in order to eliminate events with spurious triggers.

The calibration of the DHCAL involves several steps. To begin, the performance parameters of the individual RPCs, i.e. the efficiency and the average pad multiplicity, are measured. Here two methods are used: track fits and track segment fits. Dead or hot cells, if any, are identified on a run-by-run basis. In order to avoid a bias in the estimation of the performance parameters, regions within 1 cm of dead/hot cells or RPC edges are excluded from these measurements.

The track fits method uses dedicated muon calibration runs to assess the performance parameters of individual RPCs. This method starts with grouping the clusters that are laterally within a distance of 3 cm of each other in different layers for the events with tracks traversing the DHCAL. The group of clusters is then fit to the 3-dimensional parametric line $x=x_0+a_xt$; $y=y_0+a_yt$; $z=t$. For each layer, clusters within 2 cm of the point predicted by the fit are searched for. If a cluster is found, the layer is counted as efficient, and inefficient otherwise. If the layer is efficient, the pad multiplicity is given by the size of the found cluster. If multiple clusters are found in this search, the pad multiplicity is given by the size of the cluster that is closest to the fit point.

The track segment fits method is developed to measure the calibration parameters using the track segments within hadronic showers. With this method, the DHCAL provides another unique feature in calorimetry: For operation in a colliding beam environment, the DHCAL does not need a dedicated calibration system, as track segments can be used to monitor the performance of the RPCs. The method starts with searching for four clusters that are aligned within 3 cm in four different layers. The track segment is then fit to the parametric line defined above and this track segment is used to measure the performance parameters of a fifth layer (measurement layer). The measurement layer can either be within the layer span of the pick layers or outside, but only one measurement layer per track segment is allowed. In the measurement layer, clusters within 2 cm to the fit point are searched for. If a cluster is found, the layer is measured as efficient, and inefficient otherwise. If the layer is efficient, the pad multiplicity is measured as the size of the found cluster.

In the second step of the calibration, the number of hits measured in a given RPC is corrected for differences in its performance parameters using three different approaches: full calibration, density-weighted calibration, and hybrid calibration.

Using the track fits and track segment fits methods, the calibration factors per RPC per data taking run are obtained as $C_i= \varepsilon_i\mu_i/\varepsilon_0\mu_0$ where ε_i and μ_i are the efficiency and the average pad multiplicity of RPC i and ε_0 and μ_0 are the average RPC efficiency and pad multiplicity of the entire stack, 0.96 and 1.56 respectively [9].

Full Calibration: The hits in RPC i are weighted by $1/C_i$.

Density-Weighted Calibration: This approach takes into account that pads collecting charge from several nearby avalanches, for instance in the core of a shower, require a different calibration procedure than pads measuring single tracks. In other words, a pad in the core of a shower will register a hit with minimal dependence on the performance characteristics of this particular RPC and it should be calibrated in a different way than a pad e.g. along a MIP track in the same RPC. In this approach, the calibration factors of a pad may, in general, depend on the local hit density (as a measure of the number of avalanches contributing to the signal charge of that pad), the energy of the incident particle, and the type of incident particle, in addition to the performance parameters of the RPCs.

Hybrid Calibration: For the hits with 0 or 1 neighbor, the density effect is minimal. The hybrid calibration utilizes full calibration for density bins 0 and 1, and density-weighted calibration for the higher density bins.

Further details about the calibration approaches can be found in [17].

Figure 1 shows the application of the three calibration schemes to the 4 GeV π^+ (left) and 8 GeV e^+ (right) data. As expected, the uncalibrated data (black) show the largest amount of fluctuation in response between different runs. The full calibration (red), density-weighted calibration (green) and the hybrid calibration (blue) schemes all result in improved uniformity of the responses with significantly smaller fluctuations. All calibration schemes are successful in compensating for the slight differences in the RPC performance characteristics.

Figure 2 shows the χ^2/ndf for the constant line fits to the π^+ data collected in the Fermilab test beam. All calibration schemes improve the uniformity of the response across different runs and run periods. The three calibration schemes seem to perform at similar levels with no clear winner.

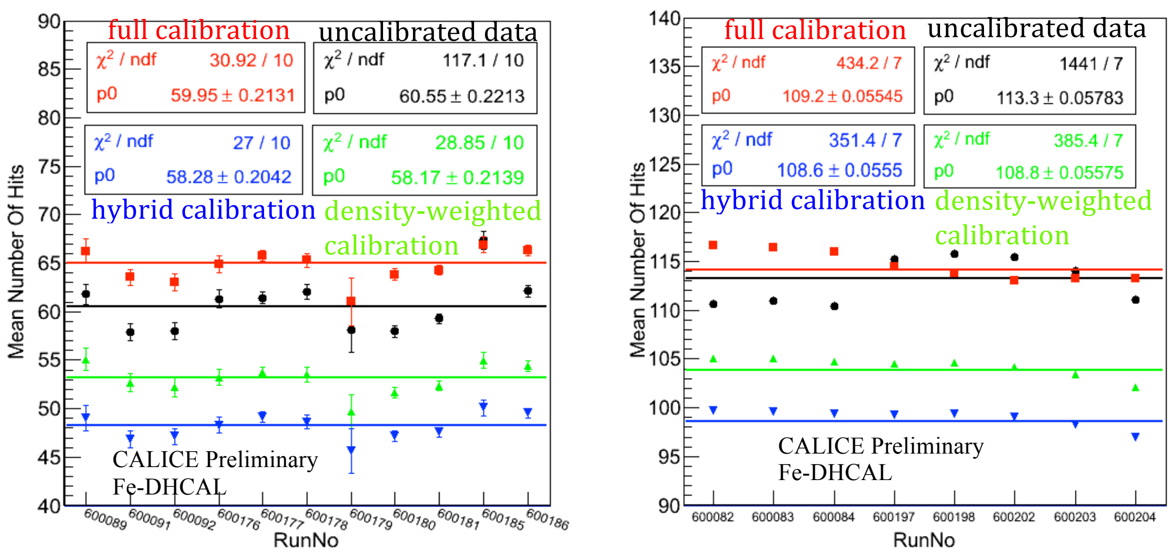

Figure 1. The results of the three calibration schemes applied to the 4 GeV π^+ (left) and 8 GeV e^+ (right) data. The uncalibrated data (black, 0), full calibration (red, 5), density-weighted calibration (green, -5) and the hybrid calibration (blue, -10) responses are all fit to a constant. The numbers in the parenthesis following the colors are the y-offsets applied to the data points in order to increase their visibilities. The error bars show the statistical errors on the means.

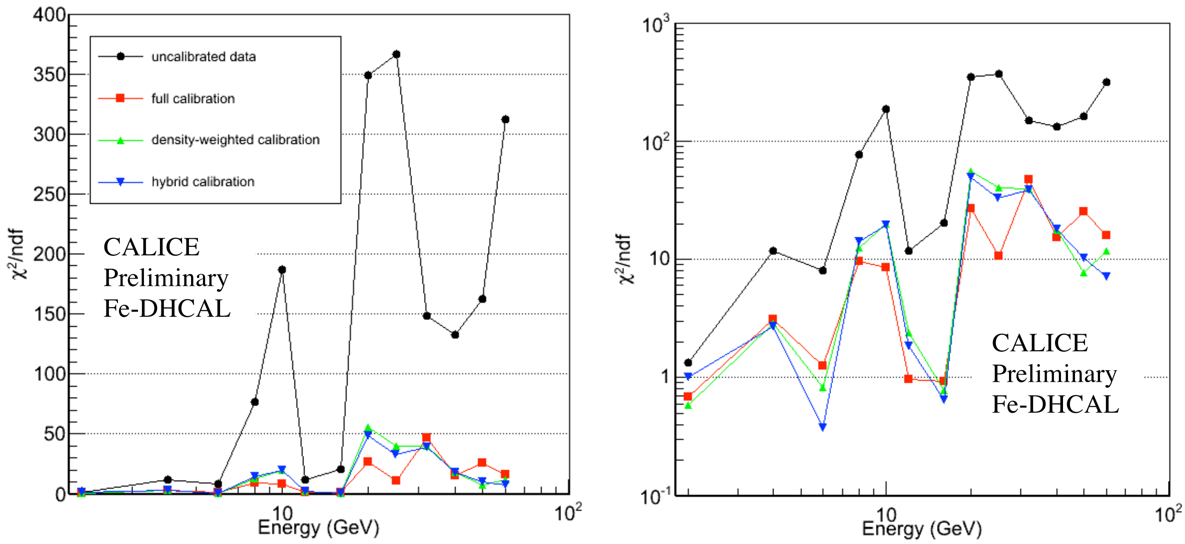

Figure 2. Normalized χ^2 of the fits of a constant to all the π^+ runs at a given energy (left), also in log-y scale (right).

3. Pion results

The event selection requires not more than 1 cluster in Layer 1 with at most four hits. This selection assures that upstream interactions are not included. The requirement of at least five active layers rejects events with spurious triggers. In order to separate the pions, positrons and muons in the beam, the Čerenkov counter in the beamline is utilized. In addition, a topological particle identification (PID) method is developed and implemented for 2, 4, 25 and 32 GeV data where the Čerenkov counter was not efficient. For details of the topological PID see [17]. The RPC performance parameters are calculated using the track segment fits method.

Figure 3 shows the mean response (a, c, e) and the energy resolution (b, d, f) for the uncorrected pion data (black in all plots), full calibration (red in a, b), density-weighted calibration (green in c, d) and hybrid calibration (blue in e, f). The mean response is fit to the power function $N=aE^m$ up to and including 60 GeV. The resolutions are fit to the generic $\frac{\sigma(N)}{N} = \frac{\alpha}{\sqrt{E}} \oplus C$ where α is the stochastic term and C is the constant term. The resolution fits are up to and including the 25 GeV point and they are extrapolated to 60 GeV. No additional corrections/selections are applied to the data (e.g. containment cuts, correction for response non-linearity). Therefore, the purpose of Figure 3 is to demonstrate the effect of the calibration schemes on the results.

All calibration schemes tend to normalize the mean response to the predefined DHCAL operating conditions. At lower energies, the methods agree with each other. However, at higher energies where the shower densities are large, the effect of employing the density weighting in the calibration procedure is clearly visible.

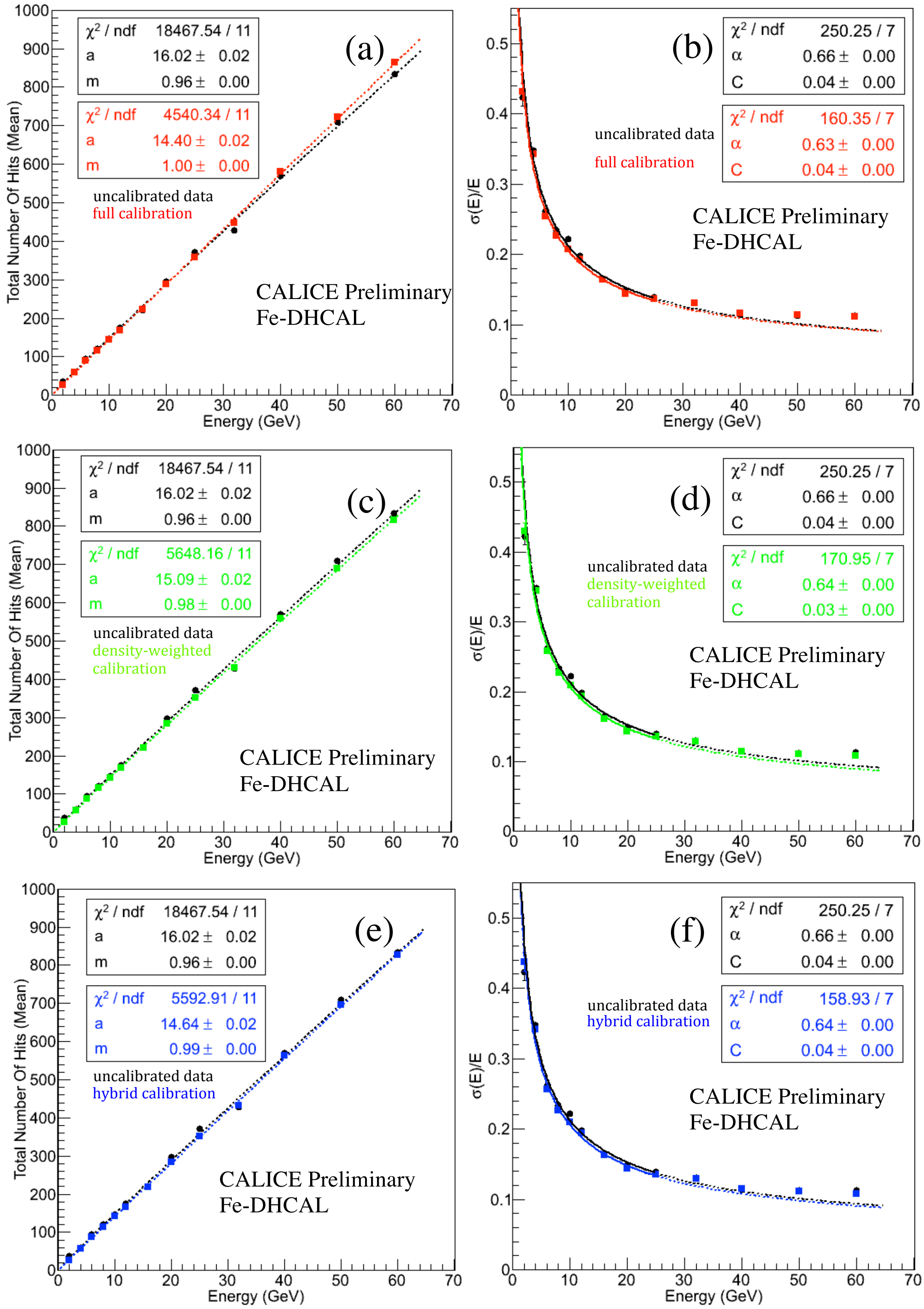

Figure 3. Mean response (a, c, e) and resolution (b, d, f) for the uncalibrated pion data (black) and the three calibration schemes (full calibration – red; density-weighted calibration – green; hybrid calibration – blue). For all calibration schemes, the fit quality is improved both for mean response (a, c, e) and resolution (b, d, f) compared to the fits to the uncalibrated data. The resolution fits (b, d, f) are up to 25 GeV (solid) and are extrapolated to 60 GeV (dashed).

4. Conclusions

The DHCAL recorded around 14 million secondary beam events over five test beam campaigns at Fermilab. The beam is a momentum-selected mixture of muons, pions and positrons. Data were collected at various energies between 2 and 60 GeV. The high granularity and the digital readout of the DHCAL enable the utilization of numerous topological event parameters for all purposes ranging from calibration to correcting the hadronic/electromagnetic response (software compensation) and improvements to the energy resolution measurements.

The calibration of the DHCAL is based on two performance parameters of the Resistive Plate Chambers: efficiency and average pad multiplicity. A simple multiplication of these parameters normalized to a reference value can serve as a calibration factor. However, the density of showering particles per pad impacts the calibration procedure in a complicated manner. As a result, the density-weighted calibration schemes provide better handles in understanding/manipulating response differences due to changes in individual RPC performances and operation conditions of the DHCAL.

All three calibration schemes, i.e. full calibration, density-weighted calibration and hybrid calibration, result in a more uniform response for all runs at each energy point when compared to the uncalibrated results.

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