Measurement of Hadron Shower Profiles from the Shower Start in the Rotated AHCAL

B. Lutz
for the CALICE collaboration

This note contains preliminary CALICE results, and is for the use of members of the CALICE Collaboration and others to whom permission has been given.

1 Introduction

This note describes a cluster based method to find the spacial position of the first hard interaction in a hadron shower and its application to measure longitudinal and radial development of the shower in the coordinate system of the shower itself. The treatment of the inhomogeneous sizes and rotation of the AHCAL cells is discussed in detail. Finally, first profile measurements of data and simulation are shown.

This note supersedes the results presented in [CAN-011, CAN-011a] in following aspects:

- Profiles are measured with respect to the shower axis and not along the layer orientation.
- The amount of detector material respective cell positions have been measured and updated in simulation and data.
- Birks’ law and electronics acceptance in time have been considered in digitisation.
- Calibration constants have been extrapolated to the temperature during measurement.

2 Shower Start Determination

Unlike electrons and photons, which start to shower practically immediately in a calorimeter, hadrons can travel a significant distance before a shower develops. The average distance a hadron travels before it undergoes a hadronic interaction, which typically starts the cascade of the shower, is called nuclear interaction length $\lambda_I$.

The measurement of the position of the first hadron interaction allows to disentangle the fluctuations of the shower start and the fluctuations in the hadronic cascade.
2.1 Definition

Generally, the shower start can be defined as the position of the first hard interaction a hadron undergoes in the detector. As the detector is not directly sensitive to the kind of the interaction that led to a signal, a definition based on the shape of the signal in the detector has to be found.

While neutral hadrons do not lose energy before interacting via the strong force, charged particles lose already some energy before showering and leave a signal in the detector due to ionisation and knock-on electrons. Additionally, the noise of the detector gives a certain amount of signal superimposed to the physics signal. Therefore, a practical method to detect the shower start has to be insensitive to the detector signal originating from a minimum ionising particle plus the detector random noise.

Based on these considerations, the energy deposition, that exceeds a certain threshold in amount and spatial size and is nearest to the origin of the particle, is defined as the shower start point. The exact algorithm is described in section 2.2.

2.2 Detection Algorithm

The detection algorithm works in several steps. First, possible regions of interest are searched in the calorimeter signal (see sec. 2.2.1). After this, the energy around these regions is collected into clusters (see sec. 2.2.2). The cluster that fulfills the requirements of both size and shape, and is nearest to the origin of the incoming particle, is considered the shower start cluster. The near end of the cluster main axis defines the shower start point.

2.2.1 Identifying Cluster Seeds

The signal of minimum ionising particles (MIP) follows a characteristic distribution. This distribution is measured during the calibration of the detector. The shape of this distribution is uniform enough for different cells to define a generic energy threshold, which identifies cells that are more likely traversed by more than one charged particle than by a single particle. The calibration of this threshold is described in detail in section 3.2.

All cells, where the recorded energy exceeds this threshold, are collected as seeds for the clustering. Before the clustering starts the hits are sorted ascending in z-position to ensure to find the cluster nearest to the origin of the incoming particle first.

2.2.2 Activity Based Clustering

During clustering all active cells surrounding the seed cell are added to the cluster independent of the signal size in these cells. Hereby all neighbour cells, typically 9 in front, 8 around and 9 behind the cell, are considered. If one or more of the newly added cells comply with the seed requirements the clustering continues around these cells until only cells below the seed threshold are added.

2.2.3 Selection of Clusters

For each cluster the total energy, the number of active cells and the main axis are calculated. The main axis is defined as the axis with minimum inertia. The calculation
is done using the external algorithm from ClusterShapes included in the MarlinUtil \[1\] package.

The first cluster matching the requirements for all three values is considered the cluster of the shower start. The identification of the best set of thresholds is described in section \[2.3\]

### 2.2.4 Point of Shower Start

The 3D position of the shower start is defined as the first point on the main principal axes within the cluster.

### 2.3 Optimisation of the Parameters

As described in section \[2.2.3\] the method provides three observables to identify the shower start: total energy, number of active cells, and direction of the cluster measured as the angle between cluster main axis and beam axis. To achieve the best performance for finding the first hard interaction, the thresholds respective limits for these values have to be optimised. This can be done using the shower start finding method on simulated data. The simulation provides the position where the incoming particle ends, which means that it took part in an identity changing interaction. This position is assumed to be the true shower start and compared to the result of the shower start finder.

In general it is expected that this optimisation depends on the chosen physics model in the simulation. To achieve the most realistic results, all optimisations have been done on simulation using the QGSP_BERT physics list. This model performed best in the description of showers at the low range of recorded energies \[CAN-011, CAN-011a\] which is the region most challenging for the shower start finder.

For all simulated events where the incoming particle ended within the detector, following quantities are calculated:

- **efficiency** The efficiency to find a shower start at all.
- **resolution** The RMS90 of the difference between reconstructed and real shower start z-position, where RMS90 is the root mean square of the range including 90% of the statistics with minimum root mean square.
- **offset** The mean difference between reconstructed and real shower start z-position, using the same range as for the resolution.

The thresholds for energy and number of hits are scanned each in 15 steps in the range of 2 to 16 hits for the number of hits and 4 to 32 MIP for the energy. The direction limit of the cluster is scanned in 9 steps from 5 to 85 degrees. Figure \[1\] shows the results for resolution and offset for an angle limit of 85 degree.

The scan shows, that limiting the cluster angle does not significantly improve the resolution or offset in the z-position, but reduces the efficiency of the method. In contrary to this, the x-y-position resolution can be improved when restricting the angle. In general, the x-y-resolution is at least a factor two better than the z-resolution, which means that the general position resolution will be dominated by the z-resolution. Therefore, the optimisation is done for energy and number of hits allowing the maximum possible angle. Depending on the requirements of the analysis, a different optimisation strategy might be more beneficial.
Figure 1: Resolution and offset of the shower start method for simulated 10 GeV $\pi^-$ and cluster angles up to 85 degree

Figure 2: Thresholds for hits and energy that give the best shower start position resolution at a given energy.

The configuration with the smallest RMS90 is selected for each energy point. Figure 2 shows the resulting thresholds for the different energy points. Both, the best hit threshold and the best energy threshold, increase with beam energy. The hit threshold is already at 30 GeV beam energy at end of the scan range (Figure 3(a)). This raise of the best threshold combination corresponds to the increasing size and density of the shower.

Some discontinuities are visible in the region between 10 GeV and 30 GeV. This energy range corresponds to the transition regions in the QGSP_BERT physics list. Figure 4 illustrates the composition of this Geant4 physics list [2, 3]. It is assumed that the discontinuities are rather the result of these transitions than of physical origin.

The resolution and offset obtained with the thresholds obtained from this optimisation is displayed in figure 3. While the increase in the resolution for low energies is understandable from the fact that the signal of low energetic showers is harder to separate from non showering particles and detector noise, the minimum around 15 GeV
Figure 3: Resolution and offset of the shower start method with the best thresholds for each energy point. Results are based on simulation with the QGSP\_BERT physics list.

seems to be unphysical. This region corresponds to the energy range where the rather simple parametrised model LEP is used in the simulation. More probable, the resolution is at least as large as the flat region for high energies.

Figure 4: Composition of the QGSP\_BERT physics list [3].

Figure 5: Best energy threshold when hit threshold is fixed to 4 hits.

While in the test-beam the energy of the incoming particle is known a priori, in a real detector this is not the case. Accordingly, a single threshold should be chosen for all energies. Additionally, the test-beam prototype of the AHCAL has a different granularity in the last eight layers. This leads to a different number of hits for the same shower shape depending on the start position. Thus, it is preferable to leave the hit threshold as low as possible to achieve a homogeneous response of the method along z.

Following these considerations, the energy threshold was optimised while the hit threshold was fixed at 4 hits. Figure 5 shows the best energy thresholds for the different beam energies. It becomes obvious that the energy is a weaker variable to identify the shower start than the number of hits. Still, a reasonable resolution can be achieved over the full range when choosing the best threshold of the lowest beam energy for the full energy range. The achieved resolution and offset for thresholds of 4 hits and 16 mip energy are shown in figure 6.
Energy [GeV] ± p

20 40 60 80

Z resolution (RMS90) [mm]

25 30 35 40

(a) resolution

Figure 6: Resolution and offset of the shower start method using global thresholds. Results are based on simulation with the QGSP,BERT physics list.

As already mentioned, the result of the shower start finding method depends on the chosen physics model in the simulation. For the analysis, a common set of thresholds was used for all physics models. Table 1 and table 2 summarise the results for the different models.

<table>
<thead>
<tr>
<th>physics list</th>
<th>energy [GeV]</th>
<th>shift [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>LHEP</td>
<td>-14</td>
<td>-10</td>
</tr>
<tr>
<td>QGSP,BERT</td>
<td>-15</td>
<td>-16</td>
</tr>
<tr>
<td>FTF,BIC</td>
<td>-7.6</td>
<td>-9.6</td>
</tr>
<tr>
<td>FTFP,BERT,TRV</td>
<td>-5.9</td>
<td>-4.3</td>
</tr>
<tr>
<td>QGSC,CHIPS</td>
<td>-4.2</td>
<td>-14</td>
</tr>
<tr>
<td>QGSP,FTFP,BERT</td>
<td>-5.9</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

Table 1: Offset between measured and real z-position of the first interaction. The accuracy of the measurement is better than 0.2 mm for all points and is not displayed for compactness.

<table>
<thead>
<tr>
<th>physics list</th>
<th>energy [GeV]</th>
<th>resolution [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>LHEP</td>
<td>29</td>
<td>27</td>
</tr>
<tr>
<td>QGSP,BERT</td>
<td>39</td>
<td>34</td>
</tr>
<tr>
<td>FTF,BIC</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>FTFP,BERT,TRV</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>QGSC,CHIPS</td>
<td>54</td>
<td>37</td>
</tr>
<tr>
<td>QGSP,FTFP,BERT</td>
<td>36</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 2: Resolution of the z-position of the first interaction. The accuracy of the measurement is better than 0.1 mm for all points and is not displayed for compactness.
3 Profiles in a Rotated Detector

The AHCAL is built from cells of three different sizes and uses a layout with reduced granularity for the last eight layers. This leads to a complex distribution of the positions and covered range of the cells when the layers are rotated with respect to the beam axis. To avoid artifacts of the detector geometry in the measurement of shower profiles some way of homogenising has to be used. This chapter describes an approach to distribute the cell energy over the cell size.

3.1 General Considerations

The AHCAL test-beam prototype allows to change the orientation of the layers with respect to the beam. Figure 7 sketches the AHCAL in such configuration. The beam enters the detector parallel to the z-axis. For better visibility, only 20 out of the 30 layers with finer core are drawn. This configuration is often referred to as rotated AHCAL even though the main calorimeter axis is still parallel to the beam direction.

When measuring shower profiles the detector layout and configuration has to be taken into account. One point is that the detector is built from square cells while the shower development is best described in a cylindrical coordinate system. Whenever a reasonable binning is chosen some cells will intersect more than one radial bin.

In the case of a rotated detector, the cells will cover a significant range in longitudinal direction. This not only implies that the cell might extend over more than one longitudinal bin, but also introduces some correlation between radial and longitudinal measurement. Finally, the rotated configuration introduces border regions where the detector is not sensitive in all positions.

Figure 8 shows the position of the detector cells in respect to the binning used for the measurement of the profiles. The radial binning is set to 3 cm which corresponds to the smallest cell size. This has the advantage, that the width of the bin corresponds approximately to the accuracy of the single cell position information. The longitudinal
bin width is set to the distance between two layer centres. This ensures that the number of cells contributing to the different bins stays constant over the detector except for the border regions.

3.2 Ansatz: Virtualisation

As described before, cells might cover more than one bin. Therefore, some strategy is necessary to distribute the cell energy to the different bins. A procedure, called virtualisation, is used to achieve this. Thereby, the main idea is to homogenise the detector geometry by separating the cells into virtual cells of $1\text{cm}^2$ size.

3.2.1 Estimation of the Number of Particles in a Cell

The distribution of the visible energy left by single minimal ionising particles (MIP) is recorded during detector calibration for each cell. Knowing this distribution allows to distinguish the thresholds for multiple MIPs. Figure 9(a) shows the simulated distributions for one to six MIPs. The crossing points where the $N + 1$-mip histogram becomes larger than the $N$-mip histogram corresponds to energy above which the signal is more likely generated by $N + 1$ mips than by $N$ mips. While the absolute scale varies significantly, the shape of this distributions changes only moderately from cell to cell.

The threshold positions were calculated for 500 channels. The resulting thresholds, expressed in units of MIP, are shown in figure 9. The threshold is a linear function of the order. The inverse is used to estimate the probable number of particles in a cell.

3.2.2 Distribution of Energy

It is assumed that the cell was hit by as many particles as estimated in section 3.2.1. The total energy is equally distributed to these virtual particles. Each virtual particle is randomly assigned to one of the $1\text{cm}^2$ virtual cells within the cell area.
Figure 9: Estimation of the number of particles in a cell from the recorded energy.

This method ensures that the energy of the cell is in average distributed over the full space. In contrary to other methods of distribution, it ensures that neither the full energy of a highly active cell is assigned to a single space point nor the energy of a single minimal ionising particle is distributed to many space points.

3.2.3 Border Regions and Normalisation

When the detector is in a rotated configuration, regions exist that have no full coverage along the longitudinal or radial bins. Figure 10 shows the front part of the detector with two regions marked. In the orange region the detector response is reduced, as some part of the space is not instrumented. In the red region the detector does not cover all radial positions anymore.

Figure 10: Front region of the rotated AHCAL.

It is assumed that in average the showers develop symmetrically along the direction of the incoming particle. Under this assumption one can consider some re-weighting to recover the response. But, it should be taken into account that the insensitive part is not equally spread over all radial positions. For the orange region, where all radial positions...
are still covered, a simple re-weighting using the fraction of the sensitive detector in each bin of $z$ and $r$ is applied. For the red region, where the response would have to be extrapolated to the not covered radial positions, a more sophisticated method would be necessary. Currently, only showers that start after the red region are considered and the data from the cells in the red region is neglected.

3.2.4 Crosscheck

The method to measure profiles for an arbitrary angle was crosschecked with data measured in the zero degree configuration. The longitudinal profile obtained with this method was compared to a simple layer-wise energy sum profile. The results were exact identical.

3.3 Profiles from Shower Start

Knowing the shower start point allows to measure the shape of the hadron shower development independent of the fluctuations in the first nuclear interaction.

3.3.1 Shifting Cell Positions

In first approximation the found shower start point $\vec{r}_{\text{start}}$ has to be subtracted from the cell positions $\vec{r}_{\text{cell}}$:

$$\vec{r}'_{\text{cell}} = \vec{r}_{\text{cell}} - \vec{r}_{\text{start}}$$

This neglects the systematic difference between real and measured shower start point. More accurately, this offset $\vec{r}_{\text{offset}}$ should be taken into account:

$$\vec{r}'_{\text{cell}} = \vec{r}_{\text{cell}} - (\vec{r}_{\text{start}} - \vec{r}_{\text{offset}})$$

Figure 11 displays the offsets predicted by different simulation models. $\vec{r}_{\text{offset}}$ depends significantly on the energy and the physics model chosen in the simulation. It is assumed that the offset present in data lays in the range of the simulation predictions. The mid of the range of each energy is substracted as reference value from data. The high and low limit of the range are used to calculate the systematic uncertainty on this assumption.

![Figure 11: Predictions for the systematic shift from different simulation models and assumption for data.](image)

![Figure 12: Side view of AHCAL (no rotation)](image)
3.3.2 Normalising for Detector Acceptance

When overlaying shower start point corrected events, it is important to consider that the detector acceptance relative to the start point changes with the position of the shower start. Figure 12 shows an illustration of two showers with same longitudinal development but different shower start points. While the full response is recorded for the blue shower, the red shower is recorded only partly as the detector ends.

The virtualisation ansatz gives an elegant way of keeping track of the different measurement ranges in the events. The three dimensional positions of all virtual $1\text{cm}^2$ cells representing the active detector are known.

A normalisation histogram with identical binning of the measurement histogram is filled with the positions calculated with equation 1 for all not masked (see 3.2.3) virtual cells independent of the state of the cells. The resulting histogram represents the sum of the active detector area for each bin. This allows to normalise the measurement bin by bin to energy density per event.

4 Result of the Shower Profile Measurement

A comprehensive collection of data were recorded during the CALICE CERN 2007 test-beam campaign, covering the energy range from 8 GeV to 80 GeV.

A set of runs which were recorded without ECAL in front of AHCAL has been chosen to achieve high statistics and reduce the selection and energy uncertainties when analysing pions in the AHCAL. Furthermore, runs have been selected where the beam hits the detector centrally to achieve a good radial symmetry. The only data set fulfilling all the requirements was taken with a detector configuration of 28.3 degree. This set also has the advantage that it comes from a period of stable detector running.

Geant4 based simulations with six different physics lists have been generated for comparison. The simulation includes the following detector specific effects:

- saturation effects in the scintillator (Birks' law)
- limited acceptance in time of the detector electronics
- light crosstalk between scintillator tiles
- non-linearity of the SiPM
- statistical fluctuation on the pixel scale
- superposition of SiPM and DAQ noise
- variation of the detector calibration with temperature

Due to the generation process, the particle beams in the experiment can contain a significant fraction of muons. These pass the detector as minimal ionising particles without generating showers. To remove events where a muon was recorded, only events where a shower start is found are selected. The simulations have been generated with pure pion beams.

Currently, some of the systematic uncertainties are yet unknown. The error bands display only the uncertainty of the systematic shift between found and real shower start point in data. Due to this, a fully quantitative comparison of measurement to simulation
is not possible at the moment. Therefore, only two energy points will be discussed here and the differences will not be quantified bin by bin. The reader should keep in mind that there is the possibility of a scale uncertainty between measurement and simulation.

4.1 10 GeV and 80 GeV Pion Showers

4.1.1 Two Dimensional Profiles

![Graphs showing 2D profiles of 10 GeV and 80 GeV pion showers](image)

Figure 13: 2D profiles of 10 GeV $\pi^-$ and 80 GeV $\pi^+$.  

Figure 13 shows the measured profile of 10 GeV negative pion and 80 GeV positive pion showers in two dimensional representation. The energy density per event is plotted versus the radius $r$ of the radial ring and its longitudinal position $z$. While 13(a) and 13(b) show the profile as it is recorded within the detector, 13(c) and 13(d) show the measurement from shower start point normalised to the effective detector response.
4.1.2 Longitudinal and Radial Profile

The longitudinal and radial projections of the two dimensional profile are shown in figures 14 and 15. The plots also include the predictions of the different simulation models.

Peak position and shape of the theory driven models match the longitudinal profile already quite well for 10 GeV. In contrary to this, the parametrised model LHEP cannot describe the longitudinal shape. The radial profile includes some additional discrepancies for QGSC,CHIPS, which shows a too wide radial distribution. An exact definition of the systematic measurement errors is necessary to select a favourite from the remaining models.

In the case of 80 GeV pions the results is not as clear as for the low energy case. Measurement shows significant differences to all simulation models. This is partly due to artifacts in the measurement that are not reproduced in the digitisation of the simulation. The size of these discrepancies can be seen in figure 15(b) where the shower max is deformed and the jumps in the tail are not always coherent between measurement and simulation. Nevertheless, these effects seem not to be large enough to explain the discrepancy in the peak shape of the theory driven models and the measurement. These
models seem to predict more compact showers, too. LHEP gives again quite different predictions in respect to the other models and the discrepancies to data have opposite sign.

4.1.3 Differential Longitudinal Profiles

The fact that the data are available versus \( r \) and \( z \) allow to compare not only integrated longitudinal and radial profile but also differential profiles. This gives more possibilities to test the quality of the predictions from simulation. Figures 16 and 17 show the longitudinal profiles measured from shower start for different ranges of the radial distance \( r \).

At 10 GeV, the longitudinal shape is reproduced well for all simulation models in the shower core, if one neglects some differences in the energy scale. But several models show significant differences for larger radii.

The sensitivity of this comparison becomes more obvious in the case of the 80 GeV data. Here the picture changes more dramatically between the different radial slices. The integrated longitudinal profile (Fig. 14(b)) is strongly dominated by the development in the shower core where all models, except LHEP, give similar results. But, the predictions for the larger radial positions differ significantly and can be used to understand where the different approaches describe the measurements more realistically.
Figure 16: Longitudinal profiles from shower start for different radial positions of 10 GeV $\pi^-$. 

(a) $0 \text{ cm} \leq r < 6 \text{ cm}$  
(b) $6 \text{ cm} \leq r < 12 \text{ cm}$  
(c) $12 \text{ cm} \leq r < 18 \text{ cm}$  
(d) $18 \text{ cm} \leq r < 24 \text{ cm}$
Figure 17: Longitudinal profiles from shower start for different radial positions of 80 GeV $\pi^+$. 

(a) $0 \text{ cm} \leq r < 6 \text{ cm}$

(b) $6 \text{ cm} \leq r < 12 \text{ cm}$

(c) $12 \text{ cm} \leq r < 18 \text{ cm}$

(d) $18 \text{ cm} \leq r < 24 \text{ cm}$
5 Summary

A new method to measure the position of the first interaction in a hadronic shower has been developed. The accuracy of this method has been quantified with simulated hadronic showers.

Additionally, a new algorithm to measure shower profiles in the AHCAL with rotated layer orientation was developed.

These two developments give the basis for the measurement of profiles from the shower start for arbitrary configuration angles.

A first qualitative comparison of profiles measured with the described methods has been shown for different simulation models and data recorded during the CERN 2007 test-beam campaign.

References


