CERN - European Organization for Nuclear Research

Particle ID Studies in a Highly Granular Hadron Calorimeter

C. G. Reichelt* †,

* *CERN, Switzerland,* † *Technical University of Denmark*

September 6, 2013

CERN Summer Student Program: 1. July - 6. September 2013

Supervisors: J. F. Strube and C. Grefe

Abstract

Highly granular hadronic calorimeters optimized for the Particle Flow Paradigm are being developed for future linear colliders. A new algorithm for identifying shower starts has been developed for analyses of data from the CALICE tungsten DHCAL prototype. The new algorithm improves the linearity between the reconstructed and generated interaction layers in Monte Carlo simulations, and it is applied as part of the particle identification of muons and pions. Additionally, the effective nuclear interaction length for pions in the DHCAL is estimated by analysing the distribution of interaction layers.

1 Introduction

A linear TeV-scale $e^+ e^-$ collider (CLIC), allowing for high precision measurements of the Standard Model and the discovery of potential new physics, has been proposed as a future complement to the LHC [7]. In addition to unprecedented center-of-mass energies for a lepton collider, the aim is to achieve a jet energy resolution between 3.5% and 5%. This jet energy resolution is obtained by implementing the Particle Flow Paradigm, which reconstructs the individual particles that make up the jets and thereby enables measurements of energy and momenta in the most favourable detectors for a high energy resolution: Charged particles in the tracker, photons in the electromagnetic calorimeter and neutral hadrons in the hadronic calorimeter. With a jet energy carried on average by 62% charged particles, 27% photons, 10% neutral hadrons and 1.5% neutrinos, this reduces the dependence on energy measurements in the hadronic calorimeter significantly [8].

The introduction of the Particle Flow Paradigm has driven research into highly granular detectors, and this note describes work on the particle identification in the CALICE tungsten Digital Hadronic Calorimeter (DHCAL). The DHCAL uses tungsten as the absorber material and Resistive Plate Chambers (RPCs) as the active elements. The RPCs are read out by 1×1 cm^2 pads, subject to a single threshold, and the unprecedented high number of read out channels (497,664 for the prototype) makes the DHCAL well suited for the Particle Flow Paradigm. The focus of this note is the identification and separation of muons and pions from the CERN test beam data, as part of the continuing work on the calibration of the DHCAL.

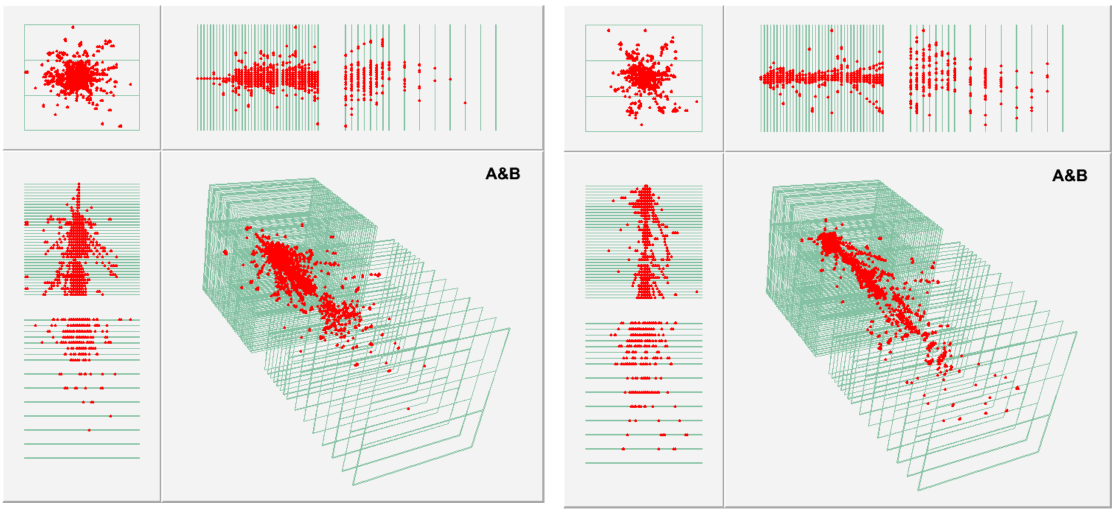


Figure 1: Visualisation of the distribution of recorded hits in two events from a 300 GeV beam with negative polarity at the SPS showcasing the high granularity of the DHCAL [6].

2 The DHCAL prototype

The data analysed in this note was obtained in the SPS test beam (10-300 GeV) with the DHCAL prototype. The prototype consisted of a total of 54 active layers, with each layer featuring Resistive Plate Chambers (RPCs) and an absorber plate. The first 39 layers constituted the 'main stack', and each each layer consisted of a 10 mm thick tungsten absorber plate and 12.5 mm cassettes, resulting in a layer spacing of approximately 25 mm. The cassette structure housed three RPCs per layer and read-out electronics (see Figure 6a). The last 15 layers were assembled as the 'Tail Catcher and Muon Tracker' (TCMT) and placed 23.5 cm behind the main stack. While the RPCs in the TCMT were identical to those in the main stack, the first 8 layers were equipped with 2 cm steel absorbers, and the last 7 layers featured 10 cm thick steel absorbers. A more detailed description of the DHCAL prototype, and the test beam line can be found in other studies [6].

Monte Carlo simulations of the DHCAL prototype set-up and the RPC response will also be used to test the performance of the applied analysis methods in this note. Currently the Monte Carlo simulation only features the main stack, i.e. the first 39 layers.

In all analyses in this note data has been cleaned to remove electronics noise and out-of-time hits. Further information on the cleaning of events can be found elsewhere [6].

3 Interaction Layer Identification

The interaction layer of the DHCAL in each event is defined as the layer at which the hadronic shower starts, i.e. the hadron interacts and secondary particles are created and detected. In earlier analyses of the DHCAL data an algorithm based on the number of hits in consecutive layers was used to identify the interaction layer [6]. However, this definition was found to be biased towards finding interaction layers too early, and to be sensitive to hit multiplicities, which have to be calibrated. Therefore, a new algorithm for identifying the interaction layer has been developed. The aim of the algorithm is to be less sensitive to smaller fluctuations such as hit multiplicities. This is achieved by exploiting the rapid increase in the number of hits in the layers following an interaction. The algorithm is summarized in the following steps:

Assumptions and computed quantities:
- A running 'three-layer hit average' (TLHA) is computed iteratively through all layers.
- Prior to the first layer the assumption is TLHA = 2, i.e. a track like a MIP.
- If a layer has no hits, it is weighted with 2 hits in the TLHA.
- If the first layer has more than 30 hits no interaction layer is computed.

Conditions checked:
- Over three consecutive TLHAs, the THLA has increased by a factor of 2.
- The current TLHA ≥ 4.
- The sum of hits in the next two layers is greater than or equal to the number of hits in the current layer.

Decision:
- If all conditions are satisfied the interaction layer is set to the layer before the current layer in the iteration.

It should be noted that the condition of an increase by a factor of 2 in the TLHA is empirically chosen by inspection of the data. Smaller and bigger values of the factor have also been tested without improving the results.

The new definition was tested by computing the interaction layer in simulated pion events, and comparing it with the known endpoint for the pions. The correlation between the two, as well as a distribution of the discrepancies, is shown in Figure 2. The new definition leads to an improved linearity between the reconstructed and generated interaction layers, although the algorithm in this particular example is prone to identifying the interaction layer as the preceding layer. Overall the distribution of the discrepancy between the reconstructed and generated interaction layers shows an improved mean value and standard deviation.

4 Particle Identification

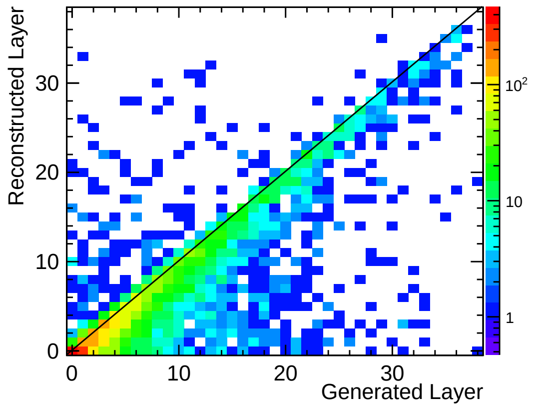
The identification of the incoming particles in each event is important for the further understanding of the DHCAL prototype data. By separating the particles it is possible to analyse and understand the response of the RPCs to each type of particle, and in particular to the hadronic showers.

Analysis of the separate samples will improve the understanding of hit multiplicities and inefficiencies in the detector, including the agreement with simulations. For the DHCAL the calibration of the total number of hits is especially of great importance since the energy measurement is proportional to the total number of hits in the detector. These studies are new for a DHCAL with tungsten as the absorber material as opposed to steel [3] [2].

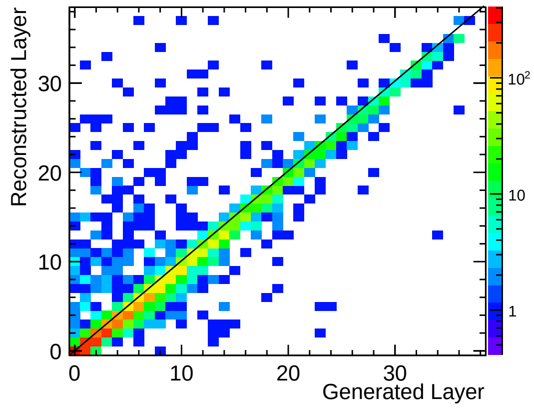
4.1 Muon Selection

The muon is considered a minimum ionizing particle (MIP) when operating at the energies of the SPS test beam data (10-300 GeV). In principle muons therefore leave a straight track with one hit in each layer in both the main stack and the TCMT. However, more hits are frequently detected in each layer, i.e. the 'hit multiplicity' for the layers is greater than one.

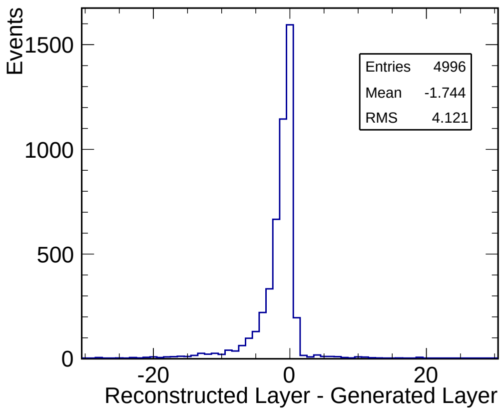
Despite the variation in the total number of hits per event, the identification of muons at energies above approximately 30 GeV is straightforward. With increasing energies the distribution of number of hits per event for the muons stays relatively constant, while the number of hits for pions increases significantly. This leads to a separation of the muon and pion distributions, and a cut applied to the total number of hits in the event yields a simple energy dependent separation of muons and pions, but at energies below 30 GeV it is not applicable. A more generic, energy



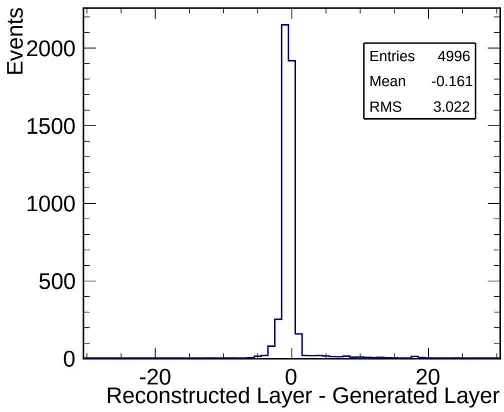
(a) Old definition



(b) New definition



(c) Old definition



(d) New definition

Figure 2: Plots comparing the performance of the old and new algorithms for identifying the interaction layer for Monte Carlo simulations of 50 GeV pions. Figures (a) and (b) show the correlations between the reconstructed and simulated interaction layers, while Figures (c) and (d) show the distributions of discrepancies between the reconstructed and the generated interaction layers.

independent selection of muon events has therefore been developed based on the topology of muon hits in the detector:

Muon Selection:

- No interaction layer was found (i.e no shower start).
- A total of at least 30 hits in the event.
- A minimum of 2 hits in the last 5 layers.

Muon Runs	Events	Muons identified	Efficiency
5 GeV	10000	9969	99.09%
10 GeV	10000	9832	98.32%
30 GeV	10000	9640	96.40%
50 GeV	10000	9508	95.08%
180 GeV	10000	9107	91.07%

Table 1: The efficiency of the muon selections as applied to simulated muon runs. The efficiency decreases with higher energies as radiative effects become more prominent, and these interactions can trigger the interaction layer identification.

The main criteria for the selection of muon events is that no interaction layer was found, as this rejects the events with interacting pions. The additional criterias for the number of hits in total and in the last layers insure that there is a full track through the detector.

The efficiency of the muon selection was tested on simulated runs of muons in the main stack as presented in Table 1, where the efficiency of the muon selection is defined as the percentage of muons identified out of the the total number of events. For energies below 50 GeV, the efficiency is above 95%, but a clear trend is observed: The efficiency decreases with higher energies. By inspecting some of the events for the unidentified muons, it was found that most of these were exhibiting radiative effects (e.g bremsstrahlung and knock-off electrons). With increasing energy these effects become more probable and trigger the interaction layer identification, which explains the decrease in efficiency.

Two examples of the muon selection applied to data at energies of 15 GeV and 30 GeV are shown in Figure 3. The selection successfully rejects most pion events while retaining most of the muon events which are part of the distributions to the left, centred around 70-75 total hits per event. The distribution of selected muons is slightly skewed towards higher total hit counts, but this is expected due to the radiative effects.

4.2 Pion Selection

With an effective nuclear interaction length of about 20 cm for pions in the DHCAL[1)], more than 99% of all pions are expected to shower within the main stack. The selection of pions is therefore made by requiring the identification of an interaction layer in the event, and by doing so effectively reject muon events. Furthermore, the interaction layer is restricted to be identified as one of the 10 layers following the first layer. The first layer is excluded as systematic errors in the interaction layer algorithm are more likely here, and the upper limit for the layers is set to minimize leakage of showers out of the the main stack and TCMT. In addition, to optimize the rejection of muon events, a hit density above 2. The hit density is defined as the total number of

[1]This value is motivated and discussed later in the note.

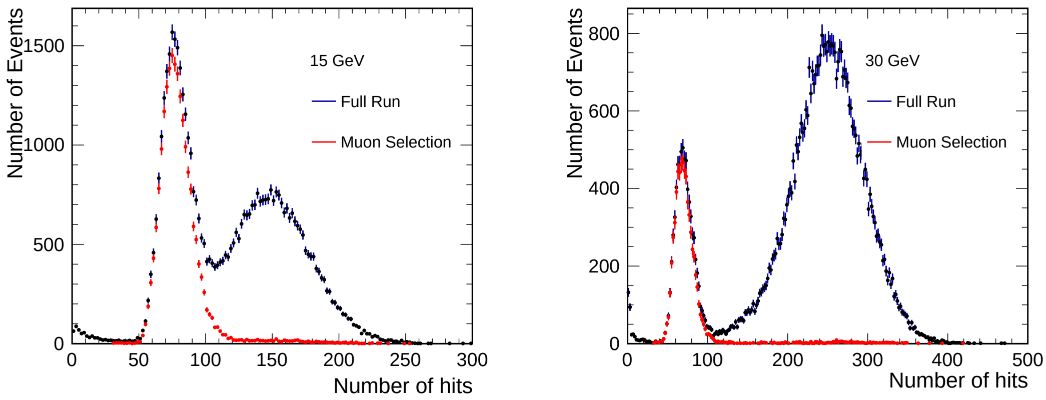


Figure 3: Example of identification and separation of muons from 15 GeV and 30 GeV runs. The separation of the two distributions increases for higher energies.

hits divided by the number of active layers. In summary the cuts applied for pion identification are:

Pion Selection:
- An interaction layer was found.
- The interaction layer was not identified as the first layer.
- The interaction layer is less than 11.
- Hit density > 2.

Figure 4 shows two examples of the pion selection at energies of 15 GeV and 30 GeV, respectively, and two Gaussian fits have been added to the selection.

4.3 Nuclear Interaction Length and Shower Development for Pions

The identification of the interaction layer of pions enables the study of the nuclear interaction length and the longitudinal shower development in terms of the number of hits. This also serves as a test of the algorithm for finding interaction layers and its ability to reproduce the expected distributions.

In the top row of Figure 5 two examples of the reconstructed distribution of interaction points for pions are shown. The interaction point has been calculated by multiplying the reconstructed interaction layer with the layer thickness, and the distributions are well described by an exponential decay. However, systematic fluctuations are observed in several independent runs, e.g. around 780 mm, due to layers that are consistently over active or inefficient. Resolving these fluctuations is outside the scope of this note.

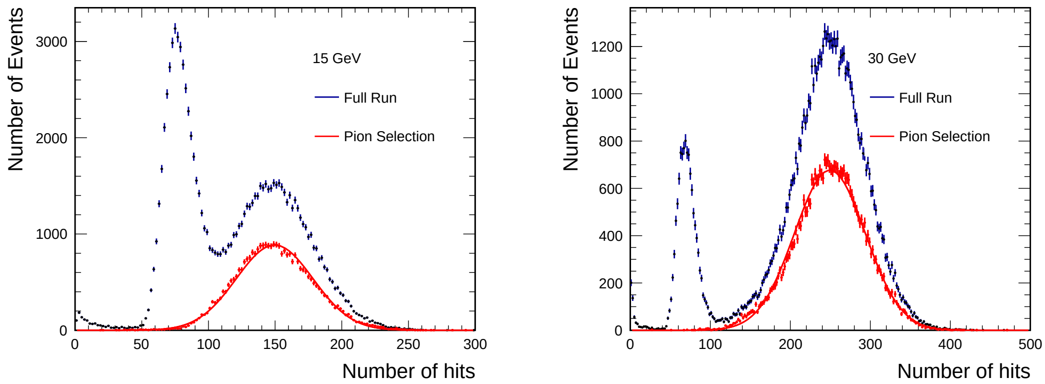


Figure 4: Example of identification and separation of pions from 15 GeV and 30 GeV runs, with Gaussian distributions fitted to the selection.

The nuclear interaction length is defined as the mean path length travelled by a hadron before showering. When assuming an exponential dependence of the interaction point on the travelled distance z

$$\text{interaction point} \propto \mathrm{e}^{-z/\lambda_{\text{eff}}} \quad , \tag{1}$$

the effective nuclear interaction length in the detector is λ_{eff}. A distribution of the interaction lengths obtained from the exponential fits at different energies is shown in Figure 6b, where the red line indicates a mean value of approximately $\lambda_{\text{eff}} = 20.9$ cm. The calculation of these values revealed much higher uncertainties on the interaction length at energies above approximately 120 GeV. This suggests that the algorithm can be optimized for higher energies.

For pure tungsten the nuclear interaction length for pions is 11.33 cm [1], but the other constituents of each layer will make the effective length significantly larger. For comparison, the approximate effective nuclear interaction length was calculated based on the layer and material structure shown in Figure 6a, by using the approximate formula [4]

$$\lambda_{\text{eff}} = \frac{1}{\chi_1/\lambda_1 + \chi_2/\lambda_2 + \ldots + \chi_n/\lambda_n} \quad , \tag{2}$$

where χ_i are the ratios of the respective material thickness to the layer thickness, and λ_i is the pion interaction length for the specific material[2)]. For the DHCAL this was found to be 20.0 cm. The interaction length estimated from the data is therefore slightly higher, but discrepancies within 1 cm is satisfactory when comparing with similar analyses for the steel AHCAL [5]).

In the bottom row of Figure 5 the hit distribution in each layer relative to the interaction layer

[2] All material parameters were obtained from the Particle Data Group [1].

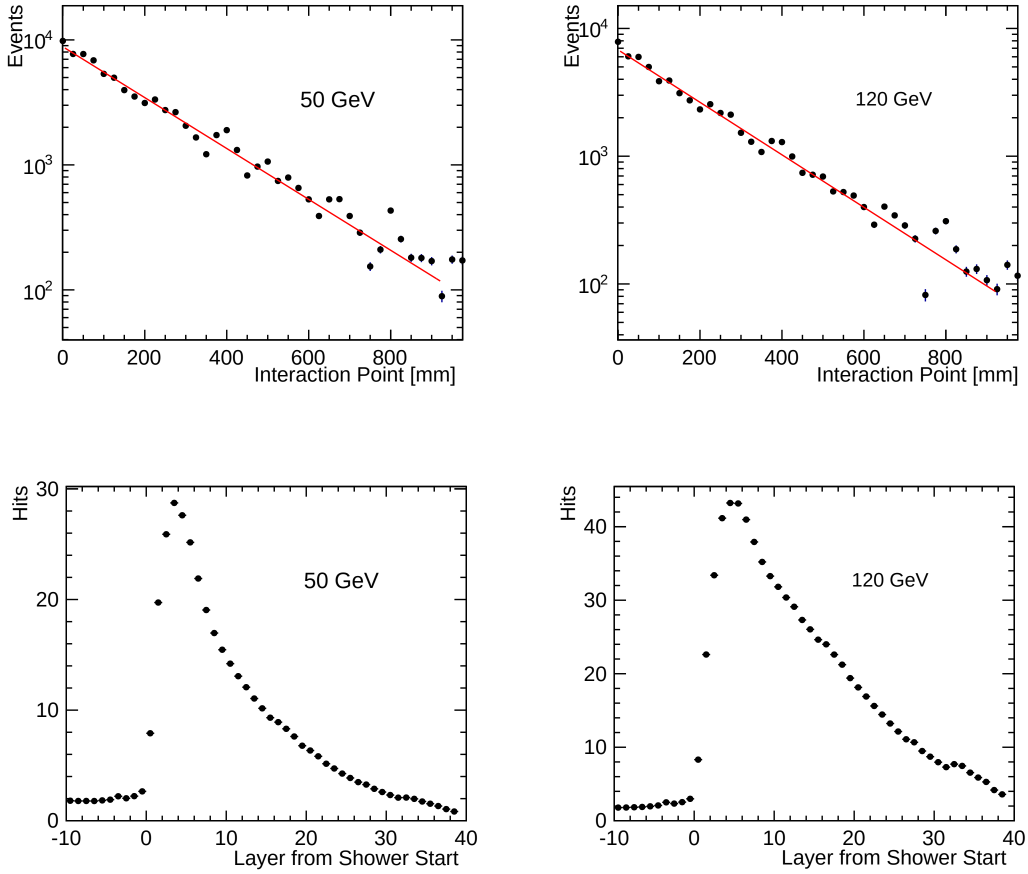
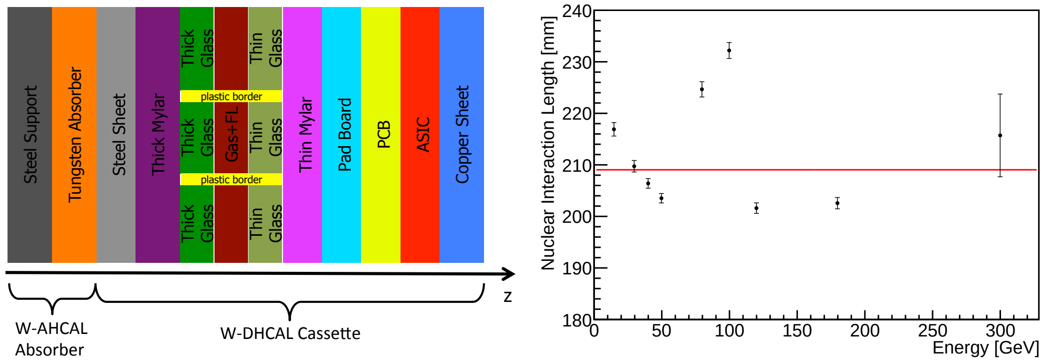


Figure 5: Top row: Distribution of the interaction point for pions calculated from the obtained interaction layer and fitted with an exponential function. An interaction point at 0 mm corresponds to the first layer, and error bars only represent errors from the exponential fit.Bottom row: The number of hits in each layer is shown relative to the interaction layer.

as averaged over a whole run is shown. As desired by the algorithm, the hit distribution looks like a MIP until the interaction layer, and a rapid increase in the hits per layer follows. A clear shower maximum in terms of the number of hits per layer is quickly reached, and the number of hits per layer then slowly decrease.



(a) Layer structure (b) Effective Nuclear interaction length

Figure 6: The schematic structure of materials in each layer in the DHCAL, and the calculated effective nuclear interaction length from pion data. The red line indicates the mean value, $\lambda_{\text{eff}} = 20.9$ cm.

5 Summary and Conclusion

A new improved algorithm for identifying interaction layers has been developed. There are indications that the algorithm works best for low energies (below 120 GeV), and further adjustments may have to be done in order to improve the performance at higher energies. In addition, the identification of interaction layers was used as an effective and energy independent way to separate muons and pions, combined with only few additional cuts. A good identification of the shower start will also improve future analyses as it serves as natural reference point. This was exemplified in the analyses of the nuclear interaction length and the longitudinal shower development.

6 Acknowledgements

I would like to thank all the members of the CERN PH-LCD group for welcoming me in their group, and making my stay a truly great experience. A special thank you should be directed to my supervisors Jan Strube and Christian Grefe for their help, guidance and physics discussions, from which I have benefited greatly throughout this project.

References

[1] J. Beringer et al. Review of Particle Physics (RPP). *Phys.Rev.*, D86:010001, 2012.

[2] B. Bilki, J. Butler, G. Mavromanolakis, E. May, E. Norbeck, J. Repond, D. Underwood, L. Xia, and Q. Zhang. Hadron showers in a digital hadron calorimeter. *JINST*, 4:10008, October 2009.

[3] B. Bilki, J. Butler, E. May, G. Mavromanolakis, E. Norbeck, J. Repond, D. Underwood, L. Xia, and Q. Zhang. Measurement of positron showers with a digital hadron calorimeter. *JINST*, 4:4006, April 2009.

[4] Yu.A. Budagov, Y.A. Kulchitsky, V.S. Rumyantsev, N.A. Rusakovich, V.B. Vinogradov, et al. Study of the hadron shower profiles with the ATLAS tile hadron calorimeter. 1997.

[5] CALICE collaboration. Pion Showers in the CALICE AHCAL Prototype, 2011. CALICE Analysis Note CAN-026, available at http://twiki.cern.ch/twiki/bin/view/CALICE/CaliceAnalysisNotes.

[6] CALICE collaboration. Analysis of Tungsten-DHCAL Data from the CERN Test Beam, 2012. CALICE Analysis Note CAN-039, available at http://twiki.cern.ch/twiki/bin/view/CALICE/CaliceAnalysisNotes.

[7] P. Lebrun, L. Linssen, A. Lucaci-Timoce, D. Schulte, F. Simon, S. Stapnes, N. Toge, H. Weerts, and J. Wells. The CLIC Programme: Towards a Staged e+e- Linear Collider Exploring the Terascale : CLIC Conceptual Design Report. *arXiv e-prints*, September 2012.

[8] J.S. Marshall, A. Münnich, and M.A. Thomson. Performance of Particle Flow Calorimetry at CLIC. *Nucl.Instrum.Meth.*, A700:153–162, 2013.