Hadronic models validation in GEANT4 with CALICE highly granular calorimeters

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Abstract. The CALICE collaboration has constructed highly granular hadronic and electromagnetic calorimeter prototypes to evaluate technologies for the use in detector systems at a future Linear Collider, and to validate hadronic shower models with unprecedented spatial segmentation. The electromagnetic calorimeter is a sampling structure of tungsten and silicon with 9720 readout channels. The hadron calorimeter uses 7608 small plastic scintillator cells individually read out with silicon photomultipliers. This high granularity opens up the possibility for precise three-dimensional shower reconstructions and for software compensation techniques to improve the energy resolution of the detector. We discuss the latest results on the studies of shower shapes and shower properties and the comparison to the latest developed GEANT4 models for hadronic showers. A satisfactory agreement at better than 5% is found between data and simulations for most of the investigated variables. We show that applying software compensation methods based on reconstructed clusters the energy resolution for hadrons improves by a factor of 15%. The next challenge for CALICE calorimeters will be to validate the 4th dimension of hadronic showers, namely their time evolution.

1. Introduction
The CALICE collaboration has been performing research and development on calorimeters intended for precision measurements at a future lepton collider. Prototypes of electromagnetic and hadronic calorimeters optimised for the Particle Flow approach have been built aiming for a jet energy resolution of 3-4% at the International Linear Collider [1, 2, 3]. As well as testing the hardware concepts, the CALICE data are able to test simulation models of particle showers in unprecedented detail owing to the highly granular readout of the calorimeters. Extensive comparisons of hadron data obtained in the 8 GeV - 80 GeV range, with the most recent GEANT4 physics lists are presented, with particular interest in the 4 GeV - 30 GeV transition region between the cascade models (QGS, FTF) and the string models (Bertini, Binary) [4, 5, 6]. New observables are reported, including energy profiles after the identified interaction point, providing feedback for further improvement of the models. Unless otherwise specified, version 9.3 of GEANT4 was used for all physics lists except for CHIPS, for which the patched version 4.9.3p01 was used.

2. The calorimeters
In this paper data taken in 2007 in the CERN H6 test beam are reported. The layout of the CALICE calorimeters and the beam instrumentation are discussed in [7, 8]. Two calorimeters
had been used:

- the Si-W ECAL [9], an electromagnetic calorimeter composed of 30 layers of tungsten wrapped in carbon fibers as absorber and silicon wafers each segmented in a $6 \times 6$ array of $1 \text{ cm} \times 1 \text{ cm}$ diode pads as sensitive detectors for a total depth of 23 radiation lengths ($X_0$) and about one interaction length ($\lambda_{\text{int}}$);
- the Fe-AHCAL [8], an analog hadronic calorimeter, composed of 38 layers 18 mm thick iron absorber and plastic scintillator tiles ($3 \text{ cm} \times 3 \text{ cm}$ in the shower core) with analog readout (using Silicon Photomultipliers) as a sensitive detector, for a total depth of 47 $X_0$ and 5.3 $\lambda_{\text{int}}$.

The extremely high granularity of the CALICE prototype allows to acquire three-dimensional pictures of hadronic showers. An impression of the granularity is provided by the following numbers. One ECAL cell is about $1 \times 1$ Moliere radii ($R_M$) in size and the average longitudinal segmentation is $1 X_0$ or $0.03 \lambda_{\text{int}}$. In the AHCAL one cell has a size of about $0.85 \times 0.85 R_M$ and a longitudinal segmentation of $1 X_0$ or 0.15 $\lambda_{\text{int}}$. This granularity can be exploited to determine precise shower properties (e.g. the position of the first hadronic interaction, the energy density, the shower shape) and hence to validate different physics aspects implemented in Monte Carlo models.

3. Validation of models using testbeam data

The data presented in this publication had been acquired at CERN SPS H6 testbeam area, where positive and negative pion showers in the 8 - 80 GeV energy range had been recorded. Various observables are used to compare simulations to data, but the following analysis will focus on the shower spatial development, thus restricting to the study of radial and longitudinal profile and the identification of the position of the first hadronic interaction. More details on the calorimeters calibration and comparison between data and Monte Carlo simulation can be found in [10, 11, 12].

3.1. First hadronic interaction

The high granularity of the CALICE calorimeters provides the capability for topological reconstruction within a shower, allowing the accurate localization of the first hard interaction layer using simple algorithms based on the energy deposition [11, 12]. Using the information of the starting point of the shower, we select only events which have their first interaction in the first $\lambda_{\text{int}}$ of the calorimeter to minimize the effect of the leakage. As shown in figure 1, the shower...
Figure 2: Mean shower depth in unit of interaction lengths for the ECAL (a) and for the AHCAL (b) from data (black) for different pion energies, compared with mean Monte Carlo predictions obtained from QGSP-based physics lists (red and brown).

longitudinal profile can be studied either from the calorimeter front face (filled histogram) or from the layer of the first hadronic interaction (black line histogram): this second distribution is equivalent to the first one deconvoluted from the probability distribution of the first hadronic interaction, governed by the pion-nucleon cross-section. Therefore, the information of the first interaction point can easily be used to validate the cross-section implementation in the different physics lists [10, 11, 12].

Moreover, the calorimeters fine granularity allows a further analysis based on the energy deposition profile for incoming hadrons in the 2 GeV - 10 GeV range, providing a classification of the first hadronic interaction and a cross-check on the hadron-nucleon cross-section [11, 12].

3.2. Longitudinal development
In order to conveniently compare different physics lists at different energies, two energy-weighted parameters are introduced:

\[
\langle z \rangle = \frac{\sum_i z_i E_i}{\sum_i E_i}, \tag{1}
\]

\[
\sigma_z = \sqrt{\langle z^2 \rangle - \langle z \rangle^2}, \tag{2}
\]

representing respectively the mean shower depth, and the variance of the longitudinal distribution, where \( \langle z^2 \rangle = \sum_i z_i^2 E_i / \sum_i E_i \).

In figure 2 (a) and figure 2 (b) mean shower depths for ECAL and AHCAL respectively are plotted: values increase non-linearly as expected up to about 1 \( \lambda_{int} \) in case of the AHCAL, while it reaches lower values of about 0.3 \( \lambda_{int} \) for the ECAL. This is due to the fact that, as mentioned, the total depth of the ECAL is \( \sim 1 \lambda_{int} \) and thus is not capable of full containment of a hadronic shower.

In comparing data with Monte Carlo results (see figure 3), it can be first of all noted how simulations in general predict shorter hadronic showers. FTF-based model show a less pronounced energy dependence and a global better agreement with data with respect to the QGSP-based models, whose agreement with data is nonetheless within the 10% and the energy dependence is at the 5% level. CHIPS physics lists, instead, exhibit a completely different behaviour, overestimating the shower length with a dependency from the energy of the 15% in case of the ECAL and slightly larger than 10% in the AHCAL. A similar behaviour can be noted studying the variances of the longitudinal distribution as shown in figure 4.
3.3. Radial development

Good modeling of the transverse shower width is of importance for the development of particle flow algorithms, since it affects the degree of overlap between showers, and therefore the efficiency for separating them. For each calorimeter hit, the radial coordinate is computed as $r_i^2 = (x_i - x_C)^2 + (y_i - y_C)^2$, where $(x_C, y_C)$ correspond to the center of gravity coordinates in case of the ECAL or the incoming pion track coordinates as measured by the tracking system in case of the AHCAL and $(x_i, y_i)$ are the coordinates of the hit cell. As in case of the longitudinal profile, energy-weighted first and second momenta of the radial distribution have been introduced, to better compare different physics lists at different energies with data:

$$\langle R \rangle = \frac{\sum_i r_i E_i}{\sum_i E_i},$$

$$\sigma_R = \sqrt{\langle R^2 \rangle - \langle R \rangle^2},$$

where $\langle R^2 \rangle = \sum_i r_i^2 E_i / \sum_i E_i$.

In figure 5 (a) and (b) the mean radial shower extension for ECAL and AHCAL respectively are plotted: once again ECAL shows sensibly lower values due to the fact that the shower is not fully contained neither in the radial direction.

Looking at the comparison between data and Monte Carlo for the mean shower radii in figure 6, it can be seen how FTF-based models are, in general, closer to data and show a less pronounced energy dependence with respect to the QGS-based models, though both underestimate the shower radial extension. CHIPS physics list, instead, shows the best agreement with data (within...
Figure 5: Mean shower radius in millimeters for the ECAL (a) and for the AHCAL (b) from data (black) for different pion energies, compared with mean Monte Carlo predictions obtained from CHIPS physics lists (green).

3% for the ECAL and 5% for the AHCAL) and a less pronounced variation with incoming pion energy. Similar consideration can be drawn studying the variances of the radial profile as shown in figure 7.

Figure 6: Ratio between mean shower radius from data and from Monte Carlo from different physics lists for the ECAL (a) and for the AHCAL (b) for different pion energies.

Figure 7: Ratio between variance of the radial profile from data and from Monte Carlo from different physics lists for the ECAL (a) and for the AHCAL (b) for different pion energies.
4. Conclusions
The CALICE collaboration has built finely granular electromagnetic and hadronic calorimeters which allow in-depth studies of hadronic shower properties and validation of Monte Carlo models on an unprecedented level. With these imaging calorimeters it is possible to investigate shower profiles and to determine the position of the first hard interaction in a shower. Summarizing the comparison between data and GEANT4 9.3p01 Monte Carlo simulations for different physics list it can be concluded that:

- the best agreement at the level of 5% is found for most of the selected observables in both ECAL and AHCAL data with the FTF-based physics lists, with the prediction for the longitudinal shower extension narrower than data only slightly less than 5%;
- QGSP-based lists are performing worse than FTF-based ones on the whole energy range covered: in particular the QGSP-FTFP-BERT physics list shows no clear improvement over the combination which still includes LEP as a stop-gap between QGSP and BERT;
- in the description of the radial extension of the hadronic shower, the CHIPS model is closest to data in terms of mean shower radius, showing in general less artifacts related to the transition between different models and therefore proving to be an interesting model, although still experimental and in a testing phase.

The following step will be the commissioning of new technological prototype of the CALICE calorimeters with timestamping capabilities, which will allow the exploration of the time structure of hadronic showers.

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