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Hadrons in the CALICE silicon-tungsten electromagnetic calorimeter

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Abstract. A detailed study of hadronic interactions is presented using data recorded with the highly granular CALICE silicon-tungsten electromagnetic calorimeter. The predictions of several Monte Carlo \textsc{Geant4} models are compared with experimental data, taken at FNAL in 2008. The contribution recaps results published in 2015 and a set of new results available since the beginning of 2016. The published results present a detailed analysis of hadronic showers in terms of radial and longitudinal hit and energy distributions. For the most recent analysis a simple track-finding algorithm was developed to study tracks left by secondary particles, emerging from hadronic interactions in the highly granular electromagnetic calorimeter prototype. Present Monte Carlo simulations provide a good description of the experimental data in terms of new observables, available through the detailed analysis of secondary particles; the Monte Carlo predictions are within 20\% of the data, and for many observables much closer.

1. Introduction

The physics at future high-energy lepton colliders requires jet energy reconstruction with unprecedented precision. Detector concepts for the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) rely on Particle Flow Algorithms \cite{1, 2} to achieve the necessary precision. This event reconstruction technique requires highly granular calorimeters to deliver optimal performance. Such calorimeters are developed and studied by the CALICE collaboration.

To develop realistic Particle Flow Algorithms, the interactions of hadrons must be modelled reliably in Monte Carlo simulations and the detector response to hadrons must be well-understood. Highly granular calorimeter prototypes provide a unique means to test and to further develop models of hadronic cascades.

The response of the CALICE silicon-tungsten electromagnetic calorimeter prototype (Si-W ECAL) \cite{3} is used to test hadronic shower models at low energies. The depth of the Si-W ECAL corresponds to approximately one interaction length ($\lambda_I$), which means that, although the complete shower is not recorded, the first hadronic interaction can be studied in great detail because of the fine longitudinal and transversal sampling. The Si-W ECAL was operated in a test beam at Fermi National Accelerator Laboratory (FNAL) with negatively charged pions ($\pi^-$) in the energy of range 2 – 10 GeV. The majority of charged pions and other hadrons within high energy jets have energies in this range and therefore it is of considerable interest to validate...
the performance of Monte Carlo simulations. Results of a study of global observables such as radial and longitudinal hit and energy distributions of hadronic showers, have been published in [4]. As an extension of this analysis this article presents new results that become available due to the high granularity of the Si-W ECAL [5].

2. The CALICE silicon-tungsten electromagnetic calorimeter

The Si-W ECAL prototype consists of a sandwich structure of 30 layers of silicon as active material, alternating with tungsten as the absorber material. The active layers are made of silicon wafers segmented into $1 \times 1 \text{ cm}^2$ pixels (or pads). Each wafer consists of a square of $6 \times 6$ pixels and each layer contains a $3 \times 3$ matrix of these wafers, resulting in an active zone of $18 \times 18 \text{ cm}^2$.

The Si-W ECAL is divided into three modules of ten layers each. The tungsten thickness per layer is different in each module, increasing from 1.4 mm in the first module (layers 1–10), to 2.8 mm in the second (layers 11–20) and 4.2 mm in the third (layers 21–30). The total thickness corresponds to 24 radiation lengths ($X_0$) and approximately one interaction length. More than half of the hadrons traversing the Si-W ECAL prototype undergo a primary interaction within its volume.

3. Global observables of hadronic showers

Test beams were conducted in May and July of 2008 at the Fermilab Test Beam Facility at FNAL. The presented analysis uses data from runs with $\pi^-$ mesons at energies of 2, 4, 6, 8 and 10 GeV. Monte Carlo simulations corresponding to the recorded test beam data have been produced using the simulation tool kit Geant4 (version 9.6 patch 1). The full geometry of the CALICE test beam set-up is taken into account in the simulation via the mokka framework which provides the geometry interface to Geant4. Four different physics lists, ftfp_bert, ftfp_bert_hp, qgsp_bert and qbbc, are compared to the data in order to study the different hadronic models which are implemented in the physics lists for different energy ranges.

As a first step in the analysis a pure data sample is selected. Residual contamination from electron events and events with multiple incoming particles is corrected for. Subsequently interacting events are selected based on the deposited energy in individual layers of the Si-W ECAL. The starting layer of the hadronic shower can be reconstructed with an accuracy of $\pm 2$ layers at an efficiency of at least 50% at 2 GeV and 87% at 10 GeV. The same event selection criteria as used for the data are also applied to the simulated events. The predictions from the simulations are then compared to the data. The fraction of interacting events and the total deposited energy are studied, as well as radial and longitudinal shower profiles, the size and energy density of the interaction region, and the distribution of secondary particles from the first hard interaction. As an example for the results Fig. 1 shows the longitudinal shower profile and the mean hit energy per layer for $\pi^-$ mesons with an energy of 10 GeV compared with different implementations of the physics list ftfp_bert [6]. While the older version 9.3 of Geant4 describes the data well, a successor version 9.6 fails to describe the data. The situation improves slightly with a more recent version 10.1 of Geant4.

4. Studying the structure of the first hadronic interaction

After the study of general observables of the hadronic shower as outlined in the previous sections the analysis goes one step further demonstrating the outstanding potential of the CALICE Si-W ECAL physics prototype to obtain a detailed picture of the interactions of hadrons with matter. Figure 2 shows the event display of a primary pion of 10 GeV that interacts in the Si-W ECAL. Visible are the incoming primary hadron, the interaction zone and secondary particles emerging from it.
Figure 1. Longitudinal shower profile (left) and Mean hit energy per layer (right) for 10 GeV pions compared with predictions from the FTFP.BERT physics list in different versions of GEANT4.

Figure 2. Event display of the interaction of a primary pion with an energy of 10 GeV in the Si-W ECAL. The interaction leads to a dense interaction region and secondary particles that can be reconstructed as outgoing tracks.

The following results are obtained with a new simple track-finding algorithm for the Si-W ECAL. This algorithm allows for the reconstruction of tracks produced by secondary particles created in the interaction of hadrons with the absorber material, and hence to study the interaction region of hadronic showers in the Si-W ECAL. The track-finding algorithm produces a new set of differential observables, based on reconstructed tracks of secondary particles and the interaction region of the hadronic cascades. The results are stable w.r.t. small variations of the main parameter of the track-finding algorithm.

The accuracy with which the simulation describes the data varies with the beam energy and the chosen physics observable. In most of the cases data and Monte Carlo agree within 10%
without revealing a clear preference for one of the chosen physics lists. The largest source of discrepancy between data and Monte Carlo is the energy and radius of the interaction region. As shown in the left part of Fig. 3, the measured energy deposition in the interaction region is up to 20% higher than predicted by the Monte Carlo simulation.

Figure 3. **Left**: Relative energy deposition in the interaction region of hadronic interactions in the Si-W ECAL. **Right**: Number of secondary tracks emerging from hadronic interactions in the Si-W ECAL.

The distributions of the number of secondary tracks, see right part of Fig. 3, and the number of hits per track for data are well described by the tested physics lists. The polar angles of reconstructed tracks in the Monte Carlo simulation agree with data within 8% on average and the distribution of azimuthal angles is well reproduced by the Monte Carlo simulations even in view of the non-trivial detector geometry.

With respect to a more general outlook future work aims at transferring the insights about the interaction region and the secondaries emerging from it to the optimisation of Particle Flow Algorithms. The comparatively simple algorithm as presented in this contribution will allow to judge on the performance of more involved algorithms such as PandoraPFA [2] or ARBOR [7].

A tighter track selection leads to clean MIP-like tracks. The detector response is stable to about 1-2% over the tested energy range with an expected good agreement with Monte Carlo simulations. This observation can be exploited in the future as a starting point for a study on the possibility of an in-situ calibration or at least a regular monitoring of the detector by means of the selected tracks.

References