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Test beam performance and detailed studies of the structure of hadronic showers with highly granular calorimeters

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The highly granular calorimeters developed and tested by the CALICE collaboration have provided large data samples with precise three-dimensional information on hadronic showers with steel and tungsten absorbers and silicon, scintillator and gas detector readout. The calorimeters have been operated in extensive test beam campaigns at DESY, CERN and FNAL in the energy range from 1 GeV to 300 GeV. The selected results are presented obtained with the highly granular hadron calorimeter prototypes with semi-digital and analogue readout. The performance of the RPC-based semi-digital hadron calorimeter in terms of pattern recognition and the comparison with GEANT4 simulations including a detailed modelling of the RPC response are discussed. We also present the results of spatial shower development studies in the scintillator-steel analogue hadron calorimeter. The component of hadronic showers related to π^0 production is analysed using the shower decomposition technique. The influence of granularity on the resolution obtained with digital, semi-digital and analogue reconstruction methods is demonstrated based on the analogue hadron calorimeter data and simulations. We also show the results of the performance studies of the combined scintillator-based calorimeter system (scintillator electromagnetic, hadronic and tail catcher calorimeters), including the study of the single hadron energy resolution using both classical energy reconstruction and software compensation techniques in comparison with the predictions of GEANT4 simulations.

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1. Hadronic shower analysis in the SDHCAL

The CALICE semi-digital hadron calorimeter (SDHCAL) [1] is a sampling calorimeter with 48 glass resistive plate chambers (GRPC) used as active media. The transverse segmentation of the SDHCAL is 1×1 cm^2, it uses a three-threshold readout and its total depth is about $6\lambda_\mathrm{I}$. The response of the SDHCAL to hadrons and electrons was studied using test beam data in the energy range 5–80 GeV. The GEANT4 simulation of the SDHCAL is followed by a digitisation procedure to simulate the GRPC response. The tuning of the digitiser parameters (charge distribution and repartition, charge screening effect, etc.) is done using muon tracks and electromagnetic shower data. The number of hits in electromagnetic shower data is well reproduced by the simulation. Above 40 GeV, the simulation underestimates significantly the total number of hits in hadronic showers.

A new reconstruction algorithm, ArborPFA, is proposed to separate nearby hadronic showers in the SDHCAL prototype. The algorithm utilises the tree-like structural features of hadronic showers to associate hits belonging to each shower in order to reduce confusions between two nearby showers. Two pion-induced showers from different events are overlaid with varied distance between shower entry points and varied energy of the second particle. Figure 1 shows the efficiency of single particle reconstruction by the ArborPFA for pions at 10–80 GeV, which demonstrates the powerful separation of nearby showers down to distances of 5 cm between the shower axes and the capability of highly granular hadron calorimeters to efficiently apply Particle Flow Algorithms.

2. Decomposition of shower profiles in the Fe-AHCAL

The CALICE scintillator-steel analogue hadron calorimeter (Fe-AHCAL) is a 1 m^3 sampling calorimeter comprised from 38 active layers interleaved by stainless steel absorber plates. The longitudinal depth of the Fe-AHCAL is $\sim5.3\lambda_\mathrm{I}$ with the segmentation of $0.14\lambda_\mathrm{I}$ per layer, which allows a precise identification of the shower start position on an event-by-event basis. The test beam setup comprised the Si-W ECAL, the Fe-AHCAL and the tail catcher calorimeter (TCMT) is described in detail in Ref. [2]. The response of the Fe-AHCAL to hadrons, the energy resolution and spatial shower development were studied with the single hadron test beams in the energy range 10–80 GeV.

The longitudinal profiles of hadron-induced showers represent the mean detected energy depending on the distance from the shower start position. The longitudinal profiles were parametrised with the sum of two Gamma-functions, describing the shower development near the shower start position ("short" component) and in the shower tail ("long" component). The extracted parameters of the "short" component was observed to be consistent with the parameters of electromagnetic showers. The position of the maximum of "short" component, $Z_\mathrm{max}^\mathrm{short}$, is plotted in figure 2 versus the energy deposited in that component for both data and simulations. For comparison, the dependence of the shower maximum position on the particle energy for electron-induced showers measured in the Fe-AHCAL prototype is also shown as well as the phenomenological predictions for electron-induced and gamma-induced showers. The GEANT4 hadronic models overestimate the fraction of the "short" component related to π^0 production by 5–10%.

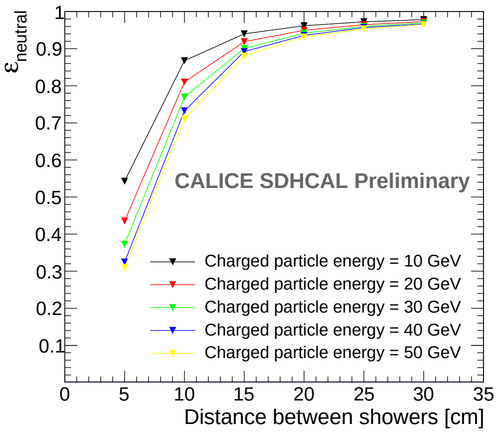

Figure 1: Efficiency of the reconstruction of 10 GeV neutral particle in the vicinity of charged particles with different energies versus the distance between shower axes.

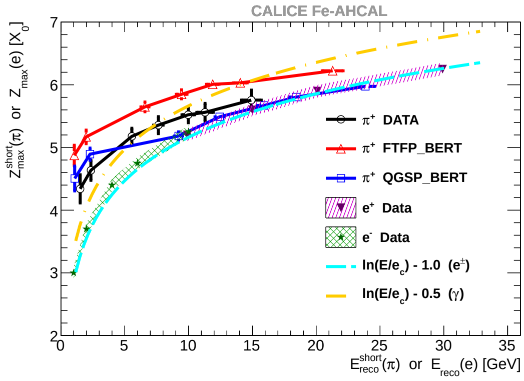

Figure 2: Position of the shower maximum of "short" component of pion-induced showers for test beam data (black circles) and simulations with FTFP_BERT (red squares) and QGSP_BERT (blue triangles) physics lists from GEANT4 9.6. See text for details.

3. Comparison of energy reconstruction schemes in the Fe-AHCAL

Different energy reconstruction algorithms are used to reconstruct the incident particle energy from the measured depositions of the different CALICE prototype detectors. The DHCAL only registers whether any signal was detected in a given cell (*digital reconstruction*) [3], the SDHCAL classifies hits into four different amplitude bins (*semi-digital reconstruction*) [1], and the AHCAL does a full 16 bit digitisation of the sensor output in each cell (*analogue reconstruction*). There is also an option for analogue readout of applying a weight for each hit based on the hit energy to correct the non-compensating nature of the AHCAL (*software compensation* — SC) [4].

All three energy reconstruction algorithms were studied on the same data set taken with the Fe-AHCAL by artificially reducing the amplitude information per hit according to the reconstruction scheme. Figure 3 shows a comparison between the different reconstruction algorithms. All algorithms result in satisfying reconstructed response linearities with less than 5 % deviation. For particle energies above around 20 GeV the digital reconstruction performs significantly worse than the other options due to response saturation. The semi-digital reconstruction yields better energy resolutions than the analogue reconstruction for all energy points due to the implicit hit energy weighting applied in the optimisation of the semi-digital weighting factors. The software compensation approach utilising the full analogue readout information gives the best single particle energy resolutions in the Fe-AHCAL.

4. Energy resolution of a combined scintillator-SiPM calorimeter system

A full calorimeter system prototype based on plastic scintillators with SiPM readout, consisting of the ScECAL [5], the Fe-AHCAL and the TCMT has been operated in a test beam campaign at FNAL in 2008–2009. The resulting single pion energy resolutions for an unweighted standard energy reconstruction as well as a software compensation reconstruction are shown in figure 4 in comparison to simulations with different GEANT4 physics lists and versions. Software compensation reconstruction improves the measured energy resolution of the calorimeter system by $\sim$2 % for all beam energies. The resolutions obtained with the standard energy reconstruction are well reproduced by the given simulation models. Using software compensation, all tested simulation models tend to overestimate the possible improvements in energy resolution by 1–2 %. Even though the combined calorimeter system consists of sub-detectors of very different sampling ratios and absorber materials, the energy resolutions obtained with the whole system are very similar to the energy resolutions obtained in the AHCAL+TCMT configuration.

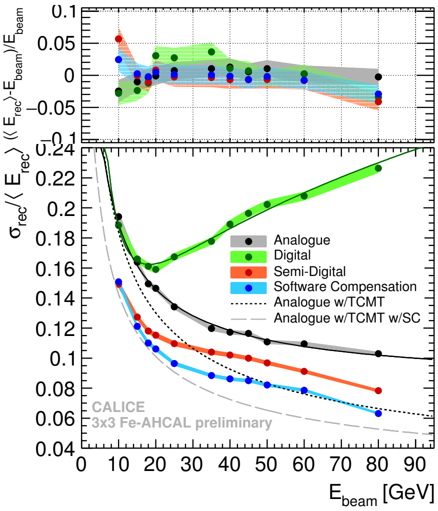

Figure 3: Response to pions (top) and fractional resolution (bottom) for the AHCAL (grey), DHCAL (green) and SDHCAL (red) reconstruction schemas, the AHCAL+TCMT option (dotted) and the SC approach (dashed).

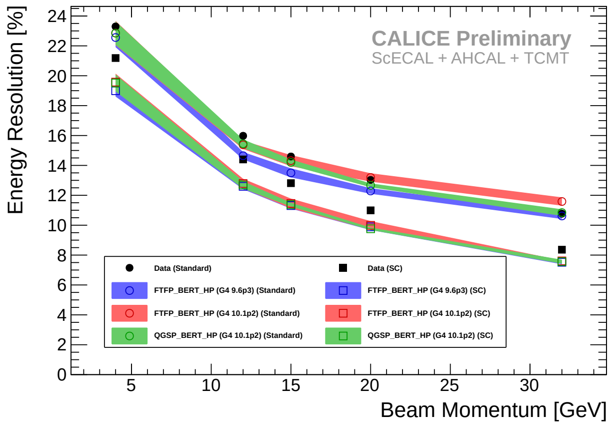

Figure 4: Pion energy resolution of the scintillator-SiPM calorimeter prototype system as a function of the incident pion energy for both standard (unweighted) energy reconstruction and software compensation energy reconstruction. Data points taken in the FNAL test beam are shown with filled black markers. Different Geant4 physics list simulations are shown with open coloured markers.

References

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