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Shower characteristics of particles with momenta up to 100 GeV in the CALICE scintillator-tungsten hadronic calorimeter

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Abstract. We present a study of showers initiated by 1–100 GeV positrons, pions, kaons, and protons in the highly granular CALICE analogue scintillator-tungsten hadronic calorimeter. The data were taken at the CERN PS and SPS. The analysis includes measurements of the calorimeter response to each particle type and studies of the longitudinal and radial shower development. The results are compared to several Geant4 simulation models.

1. Introduction
A hadron sampling calorimeter with highly granular readout, as required for Particle Flow Analysis [1], and with tungsten as absorber, is proposed as barrel hadronic calorimeter for experiments at future multi-TeV e+e− colliders such as the Compact Linear Collider (CLIC) [2]. The usage of the dense absorber material tungsten allows, on the one hand, for a deep calorimeter system which can cope with TeV-jets and on the other hand, it limits the diameter of the surrounding solenoid of the experiment.

Test beam experiments are used to characterise this detector concept. The results are compared to predictions of Monte Carlo simulations in order to estimate the accuracy of the simulation models used in detector development studies for CLIC.

2. Experimental setup
The CALICE collaboration has built a sandwich calorimeter prototype with alternating layers of tungsten (W) absorber plates [3] and scintillator readout planes of the CALICE Analogue Hadronic Calorimeter (AHCAL) [4]. Each tungsten absorber layer is 1 cm thick and is made of a tungsten alloy with an admixture of 5.25% nickel and 1.76% copper. The alloy has a nuclear interaction length of $\lambda_I = 10.80$ cm and a radiation length of $X_0 = 0.39$ cm.

Each AHCAL layer contains a 0.5 cm thick scintillator layer that is subdivided into tiles read out with wavelength shifting fibres and silicon photomultipliers (SiPM). In the central part of an AHCAL layer, the tiles have the highest granularity of $3 \times 3$ cm$^2$. Towards the outer part of the readout layer, the granularity decreases to $6 \times 6$ cm$^2$ and $12 \times 12$ cm$^2$.

The initial W-AHCAL prototype used in 2010 consisted of 30 layers. For the 2011 experiments at higher beam momenta, this was extended to 38 layers. The full dimensions of the W-AHCAL prototypes are $0.9 \times 0.9 \times 0.75$ m$^3$ and $0.9 \times 0.9 \times 1$ m$^3$. This corresponds to 3.9 (4.9) nuclear...
interaction lengths, 85 (107) radiation lengths, and 6480 (7608) readout channels.

In the following, we present results from W-AHCAL test beam experiments performed in 2010 at the CERN PS with beam momenta from 1 GeV to 10 GeV and in 2011 at the CERN SPS at 10–100 GeV. Mixed beams of e, µ, π, K, and p were provided in both test beam campaigns. At the SPS, also dedicated e beams were provided. In order to select events based on particle type and trajectory, information from two in-beam Cherenkov counters, three wire chambers, and two trigger scintillators were used [3, 5]. For the rejection of muons from in-flight decays, information from the highly granular W-AHCAL itself could be exploited. The W-AHCAL response was calibrated using dedicated muon beams to create signals from minimum ionizing particles (MIP) [6]. Results of the W-AHCAL test beam measurements are compared to Geant4 simulations [7]. Here, physics lists with a data driven high precision (HP) model for neutron simulations are used as neutrons are expected to play an important role in the neutron-rich tungsten absorber.

3. Shower characteristics

3.1. Positrons

Due to the dense absorber material tungsten, electromagnetic showers in the studied momentum range deposit energy only in a few W-AHCAL cells. At low beam momenta, this results in a non-Gaussian energy sum distribution with tails at high energies as shown in figure 1. This behaviour is reproduced by simulations. The signal shape can be described well by the Novosibirsk fit function [8]

\[ f(x) = A \cdot \exp \left[ 0.5 \cdot \left( \frac{\ln^2[1 + \Lambda \cdot \tau \cdot (z - \mu)]}{\tau^2} + \tau^2 \right) \right] \]

with \( \Lambda \equiv \frac{\sinh(\tau \cdot \sqrt{\ln 4})}{\sigma \cdot \tau \cdot \sqrt{\ln 4}} \) (1)

in which \( \mu \) is the peak position, \( \sigma \) the width, and \( \tau \) the tail parameter. The fit is used in the following to extract the mean visible energy, \( \langle E_{\text{vis}} \rangle = \mu_{\text{Novosibirsk}} \), and the width of the energy sum peak, \( \sigma_E = \sigma_{\text{Novosibirsk}} \).

Figure 2 shows the positron mean visible energy as a function of the beam momentum for data and simulations for the two beam momentum ranges. The shaded error bands indicate the systematic uncertainties of the data points dominated by the uncertainty of the MIP scaling.
Figure 3. $e^+$ energy resolution as a function of the beam momentum at 1–6 GeV [9] (left panel) and at 15–40 GeV [10] (right panel).

factor, the stability of the detector response, and the uncertainty of the SiPM saturation scaling factors. The bottom panels of the figures display the ratio of simulation over data. Within the uncertainties, data and simulation agree with each other. The visible energy increases linearly with the beam momentum, as expected.

Figure 3 shows the positron energy resolution as a function of the beam momentum. The energy resolution in the beam momentum range 1–6 GeV (left panel) is fitted with the fit function

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E_{\text{GeV}}}} \oplus b \oplus \frac{c}{E_{\text{GeV}}},$$

where $a$ is the stochastic term, $b$ is the constant term, and $c$ is the noise term. In the following, the noise term is fixed to the measured noise in the fiducial volume of the positron shower of $c_{e^+} \approx 36$ MeV. The results of the positron energy resolution fit are $a_{e^+} = (29.6 \pm 0.5)\%$ and $b_{e^+} = (0.0 \pm 2.1)\%$, which are in agreement with the values extracted from a fit of the simulated positron energy resolution of $a_{e^+} = (29.2 \pm 0.4)\%$ and $b_{e^+} = (0.0 \pm 1.5)\%$. The positron energy resolution for the high momentum data set is not fitted as the energy range 15–40 GeV is too small to obtain stable fit results.

3.2. Hadrons

At low beam momenta, the hadron energy sum distributions have a non-Gaussian shape with a high-energy tail (cf. figure 4). This tail is reproduced by Geant4 simulations and decreases with increasing beam momentum. The visible energy and the width of the energy sum distribution at low beam momenta are therefore estimated using the mean and the RMS of the energy sum histogram. At high beam momenta, $\langle E_{\text{vis}} \rangle$ and $\sigma_E$ are extracted using Gaussian fit functions of the 80% most central entries of the energy sum distributions. Figure 5 shows the $\pi^+$ mean visible energy as a function of the available energy $E_{\text{available}} = \sqrt{p_{\text{beam}}^2 + m_\pi^2}$ for the low momentum data and as a function of the beam momentum for the high momentum data. The Geant4 physics list QGSP_BERT_HP gives the best description in the low momentum range. For the high momentum data, QGSP_BERT_HP and FTFP_BERT_HP describe the data equally well.

Figure 6 shows the $\pi$ energy resolution. For the low momentum range, the energy resolution fit results are $a_{\pi^+} = (61.8 \pm 2.5)\%$ and $b_{\pi^+} = (7.7 \pm 3.0)\%$, for positive pions and
Figure 4. W-AHCAL energy sum distribution of 3 GeV $\pi^+$ [9].

Figure 5. Mean visible $\pi^+$ energy as a function of the beam momentum at 3–10 GeV [9] (left panel) and at 25–100 GeV [10] (right panel).

Figure 6. Energy resolution for $\pi^\pm$ as a function of the beam momentum at 3–10 GeV [9] (left panel) and for $\pi^+$ at 25–100 GeV [10] (right panel).

$a_{-\pi} = (63.9 \pm 2.4)\%$ and $b_{-\pi} = (3.2 \pm 6.9)\%$ for negative pions. The noise term is fixed to the measured noise of $c_{\pi} \approx 70$ MeV. In the right panel of figure 6, the $\pi^+$ energy resolution measured at 15–100 GeV is compared to Geant4 model predictions. QGSP_BERT_HP and FTFP_BERT_HP show slightly smaller energy resolutions. The high momentum pion energy resolution is not fitted as the limited beam momentum range does not allow constraining the fit parameters sufficiently.

Figure 7 shows the longitudinal shower development relative to the measured shower start for 100 GeV $\pi^+$. QGSP_BERT_HP overestimates the energy deposition in the first part of the shower but reproduces well the energy deposition after one $\lambda_t$. On the contrary, FTFP_BERT_HP underestimates the energy deposition in the first part of the shower and overestimates the...
energy deposition after one $\lambda_I$.

The radial shower development for 100 GeV $\pi^+$ is shown in figure 8. Both models predict a slightly higher energy deposition in the core of the shower than observed in data. In the radial shower tail, QGSP_BERT_HP underestimates the energy deposition slightly while FTFP_BERT_HP shows a good agreement with data at this energy.

The calorimeter response of $e^+$, $\pi^+$, $K^+$ and $p$ are compared to each other in figure 9. The response is similar for all hadrons in the studied momentum range while the electrons show a slightly steeper slope. This behaviour is reproduced by Geant4 simulations (figures not shown).

4. Summary

We have presented analysis results of test beam experiments with beam momenta up to 100 GeV recorded with a highly granular scintillator-tungsten HCAL prototype. The W-AHCAL response increases linearly with the available particle energy. The response is similar for $e$, $\pi$, $K$, and $p$ for the studied particle energy range. The stochastic term of the W-AHCAL energy resolution is found to be $a_e \approx 30\%$ for positrons and $a_\pi \approx 62\%$ for pions. The pion energy resolution of the W-AHCAL is similar to that achieved by the steel AHCAL ($a_\pi$, Fe-AHCAL, 10–100 GeV $\approx 58\%$ [11]), while the W-AHCAL has a larger positron energy resolution than the Fe-AHCAL ($a_e$, Fe-AHCAL, 10–50 GeV $\approx 22\%$ [6]). These alterations in the energy resolution are expected due to the larger number of $X_0$ per layer in the tungsten AHCAL. The Geant4 W-AHCAL detector simulation is validated using electromagnetic showers. For a good agreement between data and simulation results of hadron showers in the W-AHCAL, the HP model extension for high precision neutron tracking is needed. The agreement between measured hadron shower characteristics and predictions of the QGSP_BERT_HP and FTFP_BERT_HP models are on the percent level.
Figure 9. Mean visible energy as a function of the available energy for $e^+$, $\pi^+$, and p at 1–10 GeV [9] (left panel) and for $e^+$, $\pi^+$, $K^+$, and p at 10–100 GeV [10] (right panel).

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