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Exploring the structure of hadronic showers and hadronic energy resolution with highly granular calorimeters

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On behalf of the CALICE Collaboration

The CALICE Collaboration pioneers past and present developments of highly granular calorimeters. The prototypes provide unprecedented 3D images of hadronic showers with up to 500000 cells. This article presents highlights of the physics results of the CALICE research programme in terms of energy reconstruction of hadronic showers via software compensation and the analysis of fine details of hadronic showers that are uniquely accessible because of the high granularity. The high granularity in combination with different absorber and sensitive materials lead to a deep understanding of hadronic showers. This is valuable input to the improvement of simulation models of hadronic showers e.g. as implemented in the simulation toolkit GEANT4. The data were recorded with the different prototypes since 2005 at the beam test facilities of CERN and FNAL.

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1. Introduction

Table 1 gives an overview of the prototypes for which results are presented in this article. For more details the reader is referred to [1].

Project	Absorber	Sensitive part	Segmentation	Readout
AHCAL	Stainl. steel/Tungsten	Scintillator	38 layers, 5-6 λ_I (long.) $3 \times 3\,\mathrm{cm}^2$, $6 \times 6\,\mathrm{cm}^2$, $12 \times 12\,\mathrm{cm}^2$ (later.)	Analogue
TCMT	Stainl. steel	Scintillator	12 layers, 5.5 λ_I (long.) $5 \times 100\,\mathrm{cm}^2$ (later.)	Analogue
DHCAL	Stainl. steel/Tungsten	RPC (GEM)	up to 52 layers, 5.3 λ_I (long.) $1 \times 1\,\mathrm{cm}^2$ (later.)	Digital (1-threshold)
SDHCAL	Stainl. steel	GRPC (µMegas)	48 layers, 5.8 λ_I (later.) $1 \times 1\,\mathrm{cm}^2$ (later.)	Semi-digital (2-thresholds)
SiW ECAL	Tungsten	Silicon	30 layers, 1λ_I (long.) $1 \times 1\,\mathrm{cm}^2$ (later.)	Analogue
ScW ECAL	Tungsten	Scintillator	30 layers, 1λ_I (long.) $1 \times 5\,\mathrm{cm}^2$ (later.)	Analogue

Table 1: *Overview of CALICE prototypes relevant for this article. The prototypes for hadron calorimeters called AHCAL, TCMT, DHCAL and SDHCAL feature a typical overall size of* $1\,\mathrm{m}^3$*. The prototypes for electromagnetic calorimeters called SiW ECAL and ScW ECAL feature a typical size of* $20 \times 20 \times 20\,\mathrm{cm}^3$*. 'Analogue' Readout indicates that the analogue information is digitised into much more than 2-bits.*

2. Energy reconstruction

The example of the DHCAL, left part of Fig. 1, shows the linearity of the energy response as a function of the beam energy after the application of a correction function to compensate for saturation effects [2]. Reference [3] demonstrates that the additional threshold available in the SDHCAL moderates the saturation effect.

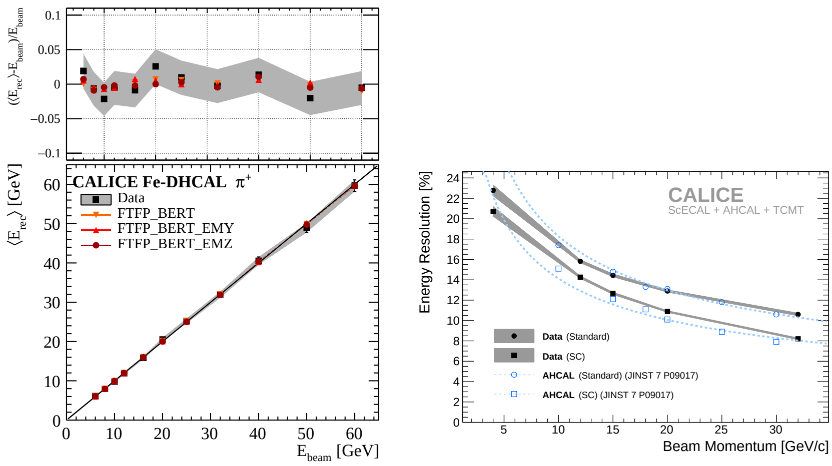

Figure 1: *Left: Linearity of the DHCAL [2]. The GEANT4 version is v10.1. Right: Energy resolution of a system ScW ECAL/AHCAL/TCMT before and after the application of software compensation [4].*

Using data taken in a combined beam test of ScW Ecal, AHCAL and TCMT, the right part of Fig. 1 demonstrates that the application of software compensation improves the energy resolution by about 10-20% [4].

3. Global shower analysis

The SiW ECAL has been used to study the longitudinal shower profile [5]. Recent versions (i.e. v10.1) of the standard GEANT4 simulation model FTFP_BERT do not describe the longitudinal profile at the shower start until the shower maximum.

The CALICE SDHCAL has been used to study the radial shower profile. As shown in Ref. [6] the average lateral extension of recorded π showers is wider than the prediction of the simulation models in GEANT4 (v9.4 here) over most of the available energy range of 10-80 GeV.

The hadronic interaction lengths for π, λ_π, and for p, λ_p, have been extracted from the longitudinal shower development for energies of the primary particle between 10 GeV and 80 GeV in the AHCAL [7]. For π showers the data are reproduced by the simulation using GEANT4 Version 9.6p01. In the case of p showers the extracted λ_p is systematically below the data. The measured values are however close to the expected values of $\lambda_\pi = 282$ mm and $\lambda_p = 231$ mm respectively [8].

4. Detailed shower analysis

The number of secondary tracks has been analysed using AHCAL and SDHCAL data. In both cases there is the tendency that simulation models underestimate the measured track multiplicity. For details see Refs. [9, 10].

A recent analysis has also measured the number of secondary tracks in the SiW ECAL [11]. The measured distribution is reasonably well described by the GEANT4 simulation models, see left part of Fig. 2. The right part of Fig. 2 shows the distribution of the azimuthal angle of the tracks. Here all the recent GEANT4 simulation models give an accurate description.

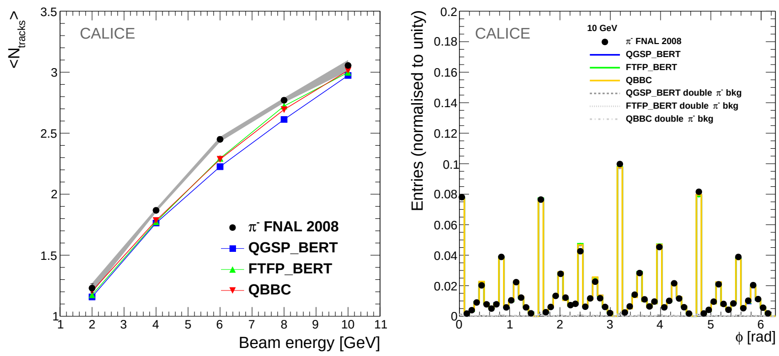

Figure 2: *Left: Mean track multiplicity measured in the SiW ECAL. Right: Distribution of the azimuthal angle of secondary tracks measured in the SiW ECAL. Both figures have been taken from Ref. [11]. The* GEANT4 *version is 10.1.*

5. Particle separation and identification

Using multi-variate analysis techniques, the achieved purity of the π selection in the SDHCAL is more than 98% at μ and e rejection rates of up to 99% [12]. The quality of the results depends on the purity of the data sample. The high granularity allows for the selection of e.g. a clean π sample. Reference [13] demonstrates how, by means of the granularity of the SiW ECAL, a data sample recorded at the Fermilab Testbeam Facility in 2008 has been analysed in order to provide a clean π sample.

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