PROCEEDINGS OF SCIENCE

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

Wataru OOTANI[†,*]

ICEPP, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

E-mail: wataru@icepp.s.u-tokyo.ac.jp

Electromagnetic and hadronic calorimeters with an unprecedented high-granularity are being developed by the CALICE collaboration based on a variety of active sensor elements and absorber materials. We present the detailed structures of hadronic showers measured by the CALICE calorimeter prototypes to characterise the different stages of hadronic cascades in the calorimeters as well as comparisons with GEANT4-based simulations using different hadronic physics models. The high granularity of the detectors is exploited in the reconstruction of hadronic energy, both in individual detectors and combined electromagnetic and hadronic systems, making use of software compensation and semi-digital energy reconstruction. The performance of the reconstruction techniques for different electromagnetic and hadronic calorimeters, with silicon, scintillator and gaseous active elements are discussed.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

[†]on behalf of the CALICE Collaboration
[*]Speaker

PoS(ICHEP2020)862

1. Introduction

An excellent jet energy resolution is required to accomplish the physics goals of future electron-positron colliders. The Particle Flow Approach (PFA) is proposed to achieve an unprecedented jet energy resolution of 3–4 % over a wide energy range[1–3]. High granularity calorimeters required for PFA are under development in the framework of the CALICE collaboration based on various sensor technologies. The concept of the high granularity calorimeters has been validated with full layer prototypes in test beam campaigns. The test beam data provide us not only with the proof-of-principle of the concept but also with a unique opportunity for the detailed studies on the development of the hadronic shower including the validation of the hadronic shower models in GEANT4. The selected results from the test beam data with an emphasis on the studies on the structures of the hadronic showers are presented.

2. CALICE Test Beam Prototypes

The early CALICE prototypes which were developed for the proof-of-principle of the high-granularity calorimeter concept and extensively tested in beams are summarised as follows.

SiW-ECAL The "physics prototype" of the SiW-ECAL is based on 30 layers, each of which is composed of a tungsten absorber plate and a sensor layer of $18 \times 18\,\mathrm{cm}^2$ with a matrix of silicon PIN diode of $1 \times 1\,\mathrm{cm}^2$, totalling 9720 cells. The total material depth is $24\,X_0$.

ScW-ECAL The required high granularity is achieved in the ScW-ECAL by scintillator strips aligned alternately in horizontal and vertical orientations. The physics prototype of the ScW-ECAL consists of 30 layers of a tungsten absorber plate and a sensor layer of $180 \times 180\,\mathrm{mm}^2$ with $45 \times 10 \times 3\,\mathrm{mm}^3$ scintillator strips, each of which is read out by a wavelength-shifting fibre coupled to SiPM. The total material depth is $24\,X_0$.

AHCAL The physics prototype of the analogue hadron calorimeter (AHCAL) is composed of 38 layers of a steel absorber plate (later tested also with a tungsten absorber) and a layer of scintillator tiles of $30 \times 30 \times 5\,\mathrm{mm}^3$ in the central region and larger tiles in the outer region. Each tile is read out by a wavelength-shifting fibre coupled to SiPM. The active area of the scintillator layer is $90 \times 90\,\mathrm{cm}^2$ with 7608 tiles for the whole prototype. The total material depth amounts to $5.3\,\lambda_{\mathrm{int}}$.

DHCAL The prototype of the digital hadron calorimeter (DHCAL) based on GRPC sensor layer read out by $1 \times 1\,\mathrm{cm}^2$ pad with a 1-bit digital resolution is composed of up to 54 layers of a steel absorber plate (later tested also with a tungsten absorber) and the sensor layer. The transverse size is $96 \times 96\,\mathrm{cm}^2$, and the longitudinal depth corresponds to about $6\,\lambda_{\mathrm{int}}$.

SDHCAL The semi-digital hadron calorimeter (SDHCAL) is also based on GRPC sensor layer read out by $1 \times 1\,\mathrm{cm}^2$ pad, but with a 2-bit digital resolution. The prototype with 48 layers of a steel absorber plate and a $100 \times 100\,\mathrm{cm}^2$ sensor layer has a material depth of about $6\,\lambda_{\mathrm{int}}$.

3. Hadronic Shower Studies

The spatial development of hadronic showers was studied with the test beam data taken at CERN and FNAL by the Fe-AHCAL for positive pions and protons with different initial energies of 10–80 GeV[4]. Fig. 1 shows the longitudinal profiles of showers initiated by (a) pions and

(b) protons of 30 GeV. The shower-start was evaluated on an event-by-event basis with the high longitudinal granularity. The measured profiles are fitted with a two-component function with the parameterisation proposed in Ref.[5]. The profiles are decomposed into "short" and "long" components, and the short component is considered to be the contribution of the electromagnetic component in the hadronic shower. The ratios of the hadronic and electromagnetic response h/e are estimated from the extracted parameters, as shown in Fig. 2 for pions with different initial energies. It shows an only weak energy dependence below 30 GeV and agrees with simulations within 5%.

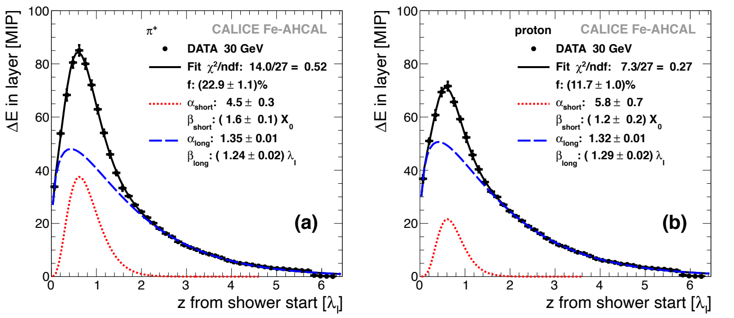

Figure 1: Longitudinal profiles of hadronic showers measured by the AHCAL prototype[4].

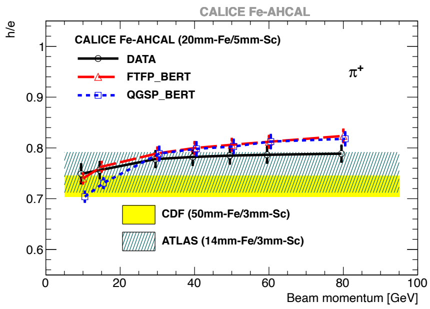

Figure 2: Energy dependence of the h/e estimated by the measured longitudinal profiles[4].

The radial profiles of hadronic showers were studied in more detail with the SDHCAL prototype taking advantage of the finer transverse segmentation[6]. The prototype was exposed to pions at different energies between 5–80 GeV. Fig. 3 shows the radial profiles measured for 20 and 70 GeV pions. The shower barycenter is estimated on an event-by-event basis from the intersection of each layer and the shower axis evaluated by a straight line fit of the unweighted shower hit positions. A smaller width of the profile is observed in the simulation, which is not fully understood.

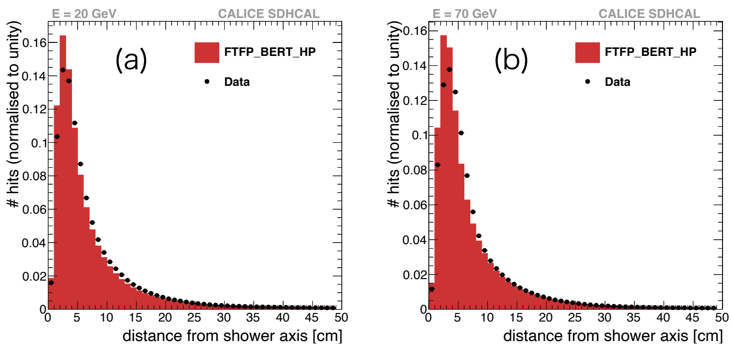

Figure 3: Radial profiles measured with the SDHCAL prototype for (a)20 GeV and (b)70 GeV[6].

The longitudinal profiles of hadronic showers at lower energies were studied with the SiW-ECAL prototype exposed to negative pions of 2–10 GeV at FNAL[7]. Fig. 4(a) shows the measured longitudinal profile for negative pions with an initial energy of 10 GeV. The means of the longitudinal profiles for hit and energy are shown in Fig. 4 (b) and (c), respectively. The measured profiles are in agreement to within 20%, but with a much better agreement for most observables. The longitudinal hit distribution is well described by simulations, while the largest discrepancies are observed in the longitudinal and radial distributions of the reconstructed energy. It is also observed that the discrepancies depend on the hadronic shower models in GEANT4.

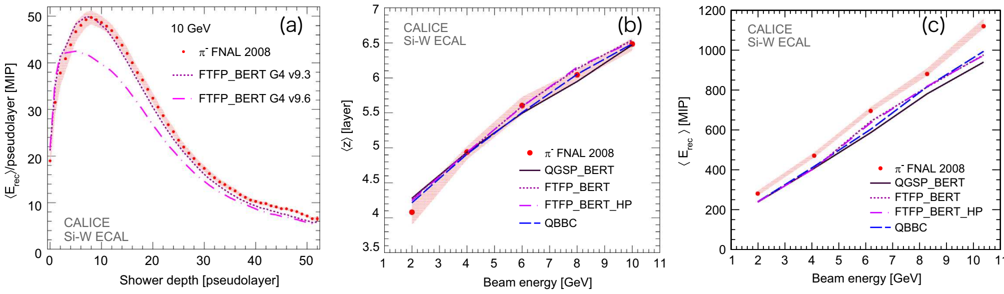

Figure 4: (a) Longitudinal energy profile measured with the SiW-ECAL prototype for negative pions of 10 GeV and the means of the longitudinal hit (b) and energy (c) distributions[7].

The high granularity of the CALICE prototypes allows us to study the fine structure of the hadronic showers using the track segments. Fig. 5(a) shows the typical hadronic shower observed by the SDHCAL prototype for 50 GeV pions, where the track segments identified by Hough transform technique are shown in red[8]. The means of the numbers of tracks and the track lengths are shown in Fig. 5(b) and (c), respectively. They show a reasonably good agreement with the predictions by simulations, although a slight discrepancy in the number of tracks is seen at high energies. Similar studies were also done with the AHCAL and SiW-ECAL prototypes[9, 10].

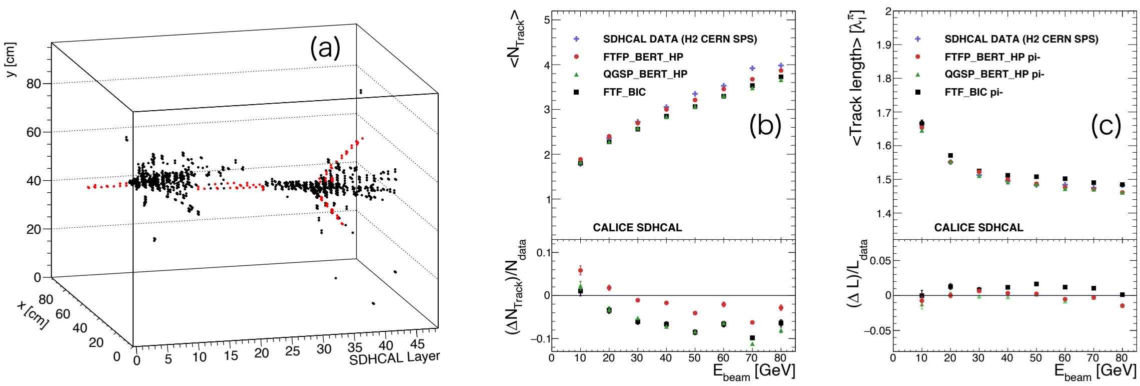

Figure 5: (a) Typical shower observed by the SDHCAL prototype for 50 GeV pion where the track segments identified by Hough transform technique are shown in red; the means of the numbers of tracks (a) and the track lengths (b)[8].

4. Hadronic Energy Reconstruction

The energy reconstruction for hadronic showers is not trivial due to the complicated processes for shower development. In particular, the large event-by-event fluctuation of the electromagnetic and hadronic components in hadronic showers is a crucial limiting factor for non-compensating calorimeters. A software compensation technique has been applied to the test beam data collected with the combined Sc-ECAL and AHCAL prototypes and Tail Catcher exposed to negative pions with an energy range of 4–32 GeV at FNAL[11]. The electromagnetic component has a higher shower density than the hadronic component. The software compensation technique is based on reweighing individual energy depositions according to the hit energy to compensate for the difference between the electromagnetic and hadronic response.

Fig. 6(a) shows the hit energy spectrum of the AHCAL prototype for 15 GeV pions where the weights are optimised for each hit energy bin. The hit energy bin weights for each energy bin as a function of the reconstructed particle energy are shown in Fig. 6(b). Fig. 6(c) shows the energy resolutions with the standard and the software compensation technique for the combined system (Sc-ECAL, AHCAL and Tail Catcher). It can be seen that the energy resolutions are significantly improved by 10–20% with the software compensation technique.

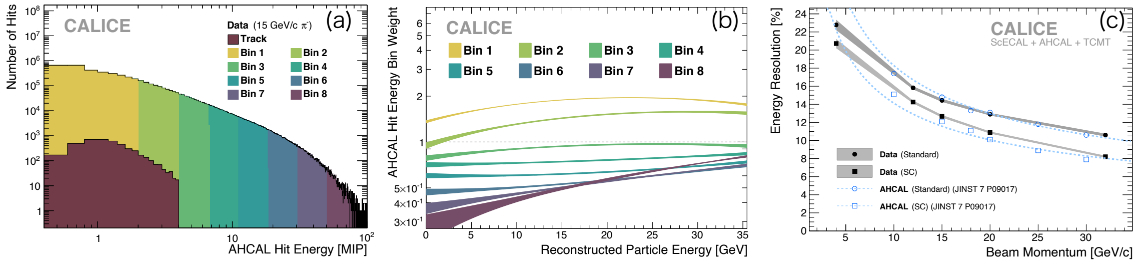

Figure 6: (a) Hit energy spectrum of AHCAL prototype for 15 GeV negative pions[11]. The energy bin weights are optimised for the hit energy bins with different colours. (b) Optimised energy weights for each energy bin as a function of the reconstructed particle energy[11]. (c) Energy resolutions with the standard and the software compensation technique for the combined system (Sc-ECAL, AHCAL and Tail Catcher)[11]. The resolutions only with the AHCAL and Tail Catcher are also shown.

The energy reconstruction at the SDHCAL prototype is based on counting the number of hits but with a multi-threshold readout. The energy is reconstructed as $E = \alpha N_1 + \beta N_2 + \gamma N_3$, where N_1, N_2 and N_3 are the exclusive number of hits associated to the first, second and third thresholds, respectively and α, β and γ are optimised as quadratic functions of the total number of hits. Fig. 7(a) shows a typical event display for 70 GeV pion. The hits above the third threshold are concentrated at the shower core and are essentially related to the electromagnetic shower component. Fig. 7(b) shows the optimised coefficients as a function of the total number of hits. The measured energy resolutions for pions are shown in Fig. 7(c) where the resolutions with a single threshold (binary mode) are also shown for comparison. It can be seen that the saturation of the resolution improvement with the binary mode is mitigated with the multi-threshold mode.

5. Summary and Prospects

The high granularity calorimeter is a key element to the unprecedented jet energy resolution with the particle flow calorimetry and is under development based on different sensor technologies by the CALICE collaboration. Detailed studies on the structures of hadronic showers providing a validation of the hadronic shower modelling in GEANT4 are carried out with the test beam data collected by the prototypes of the CALICE high granularity calorimeters. More results are expected

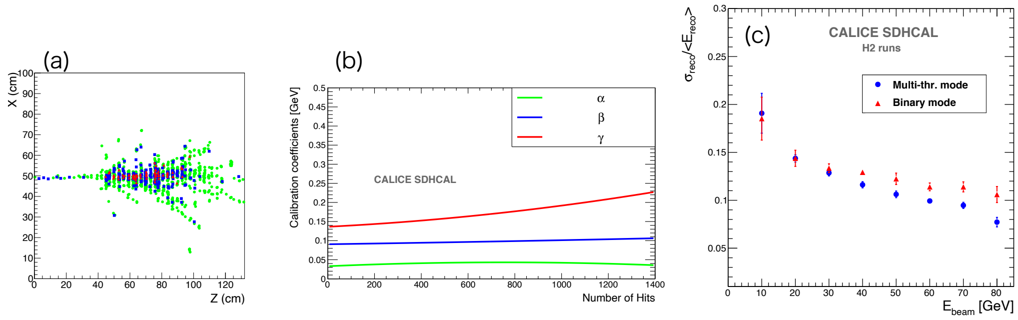

Figure 7: (a)Typical event display for 70 GeV negative pion where the red triangles, the blue squares and the green circles show the hits for the highest, the middle and the lowers thresholds, respectively[12]. (b) Optimised coefficients as a function of the total number of hits[12]. (c) Relative resolutions with the multi-threshold mode where the resolutions with the binary mode is also shown for comparison[12].

to come soon from the recent test beam experiments using technological prototypes with improved performances[13].

References

[1] J.-C. Brient and H. Videau, *eConf* **C 010630**(2001)E3047 [hep-ex/0202004].

[2] V.L. Morgunov, *X International Conference on Calorimetry in High Energy Physics (CALOR2002)*, Pasadena, California, U.S.A., 25–29 March 2002.

[3] M. Thomson, *Nucl. Instrum. Meth.* **A 611**(2009)25.

[4] CALICE collaboration, G. Eigen et al., 2016 *JINST* **11** P06013.

[5] R.K. Bock, T. Hansl-Kozanecka and T.P. Shah, *Nucl. Instrum. Meth.* **186**(1981) 533.

[6] CALICE collaboration, Z. Deng et al., 2016 *JINST* **11** P06014.

[7] CALICE collaboration, B. Bilki et al., *Nucl. Instrum. Meth.* **A 794**(2015)240.

[8] CALICE collaboration, Z. Deng et al., 2017 *JINST* **12** P05009.

[9] CALICE collaboration, C. Adloff et al., 2013 *JINST* **8** P09001.

[10] CALICE collaboration, G. Eigen et al., *Nucl. Instrum. Meth.* **A 937**(2019)41.

[11] CALICE collaboration, J. Repond et al., 2018 *JINST* **13** P12022.

[12] CALICE collaboration, Z. Deng et al., 2016 *JINST* **11** P04001.

[13] V. Boudry on behalf of CALICE collaboration, *Implementation of large imaging calorimeters, 40th International Conference on High Energy physics (ICHEP2020), Jul. 28–Aug.6, 2020, Prague, Czech Republic (virtual meeting).*

PoS(ICHEP2020)862