

# Hadron shower decomposition in a highly granular calorimeter

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**Abstract.** The spatial development of showers induced by positive hadrons with momenta 10-80 GeV in the highly granular CALICE scintillator-steel analogue hadronic calorimeter is analysed. The parametrisation of both longitudinal and radial shower profiles with the two-component functions are fit to the test beam data and simulations using the physics lists QGSP\_BERT and FTFP\_BERT from GEANT4 version 9.6 patch 01. The shower parameters, describing the longitudinal tail and radial halo, are in good agreement between data and simulations and are similar for pions and protons. For the longitudinal development, the most significant difference between data and simulations is in the relative containment of the separated components. For the radial development, the core slope parameter is underestimated by simulations. The physics list FTFP\_BERT gives a very good description of proton showers in the studied energy range and gives better predictions of the pion shower development than QGSP\_BERT.

## 1. Introduction

The CALICE collaboration has developed and constructed highly granular electromagnetic and hadronic calorimeter prototypes to evaluate detector technologies for future linear collider experiments. The linear collider physics program requires a very high jet energy resolution, which can be achieved using the particle flow approach based on the precise tracking and the possibility to disentangle showers induced by different particles in the calorimeter system [1, 2, 3]. The understanding of hadronic showers and their parametrisation is important for the estimation of leakage from the calorimeter, for the validation of hadronic shower models in simulations [4] and for the development of the particle flow algorithms [5].

The CALICE analogue hadronic calorimeter prototype (AHCAL) is the first experience of a large-scale application of silicon photomultipliers (SiPM) in the field of high energy physics [6]. The prototype was extensively studied during several test beam campaigns in two configurations: with tungsten (W-AHCAL) or steel (Fe-AHCAL) as an absorber material. The unprecedented granularity of the AHCAL allows to identify the position of the first inelastic interaction and deconvolve the distribution of the energy density inside the shower from the distribution of the shower starting point. The calorimeter response and resolution for pions are described in detail in [7] including the implementation of the developed software compensation techniques. The validation of several hadronic models from GEANT4 version 9.4 is discussed in [4], where the detailed comparison of the longitudinal centre of gravity, radius and profiles of pion-induced showers is shown.



Here we present the study of showers induced by positive pions and protons with initial momenta 10-80 GeV in the CALICE Fe-AHCAL, which is based on the parametrisation of shower profiles. The longitudinal and transverse shower profiles are decomposed into the core and halo contributions by fitting an empirical parametrisation to the energy density distributions extracted from both data and simulations. The fitted parameters and the extracted core shower fractions are compared to simulations using the physics lists QGSP\_BERT and FTFP\_BERT from GEANT4 version 9.6 patch 1 [8].

## 2. Data samples, event selection and simulations

The positive hadron data were collected during CALICE test beams campaigns at CERN in 2007 in the momentum range from 30 to 80 GeV/ $c$  and at FNAL in 2009 in the momentum range from 10 to 15 GeV/ $c$ . The CALICE calorimeter setup comprised the Fe-AHCAL and the scintillator-steel tail catcher and muon tracker (TCMT) [9]. The Si-W electromagnetic calorimeter (ECAL) [10] was placed in front of the AHCAL during CERN runs and is used as a tracker in this analysis. The information from a Čerenkov counter upstream of the calorimeter setup was used for off-line discrimination between pions and protons on an event-by-event basis.

The AHCAL is a sampling structure of 38 active layers interleaved with absorber plates. Each active layer is assembled from the small scintillator tiles ( $3\times 3$ ,  $6\times 6$  and  $12\times 12$  cm<sup>2</sup>) individually read out by SiPMs. The longitudinal depth of the Fe-AHCAL is  $\sim 5.3\lambda_1^{\text{eff}}$  ( $\lambda_1^{\text{eff}} = 231$  mm). The TCMT is also a sampling calorimeter with 16 active layers assembled from strips with SiPM readout. The first section (9 layers) of the TCMT has the same sampling as the Fe-AHCAL ( $\sim 0.14\lambda_1^{\text{eff}}$  per layer) and is shown in the plots of the longitudinal profiles but is not used for fits. The effective radiation length  $X_0^{\text{eff}}$  of the Fe-AHCAL is estimated to be 25.5 mm.

The visible signal in each calorimeter cell is obtained in units of MIP (minimum-ionising particle) as described in [6]. Only cells with a signal above 0.5 MIP were used in the analysis and are called hits. The hadron sample cleaning includes the rejection of muons and positrons with the resulting purities of better than 99% and 98%, respectively. The additional selection of events was applied to minimise the leakage into the TCMT and to reduce the fraction of remaining positrons in the sample: the events with an identified shower start in the physical layers 2, 3, 4, 5, 6 (3, 4, 5, 6) of the Fe-AHCAL were selected for run taken with (without) ECAL. Hereinafter the profiles from the identified shower start are analysed.

The following sources of systematic uncertainties were found to affect the comparison of shower profiles: (a) layer-to-layer variations of the response in test beam data due to saturation correction issues (up to  $\sim 10\%$  at 80 GeV); (b) accuracy of the identification of a shower axis for the data samples collected without ECAL (up to 10%); (c) pion contamination of the proton samples (estimated purity of the proton samples is from 74% to 95%). The uncertainties due to positron contamination of the samples taken without ECAL, accuracy of the shower start identification and leakage from the Fe-AHCAL were found to be negligible, provided the event selection described above. The statistical and systematic uncertainties are summed up in quadrature for the fit of the studied shower profiles.

The simulations were performed with GEANT4 version 9.6 patch 1, the test beam profile of each particular data run being closely reproduced. The simulated samples were digitised by taking into account the SiPM response, inter-tile crosstalk, map of calorimeter dead cells and noise from the corresponding data runs.

## 3. Parametrisation of hadron shower profiles

The parametrisation is an instrument for quantitative comparison of the observed shower development with the predictions of the Monte Carlo models. To obtain a stable fit procedure and reliable error estimates, no parameter limits were applied during the minimisation. Instead,

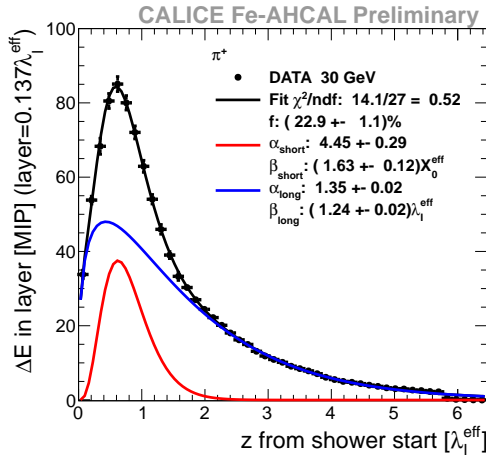
a random variation of initial values for the minimisation procedure was used. From the sample of 100 attempts the best fit was chosen, the results with unphysical values were rejected.

### 3.1. Fit to longitudinal profiles

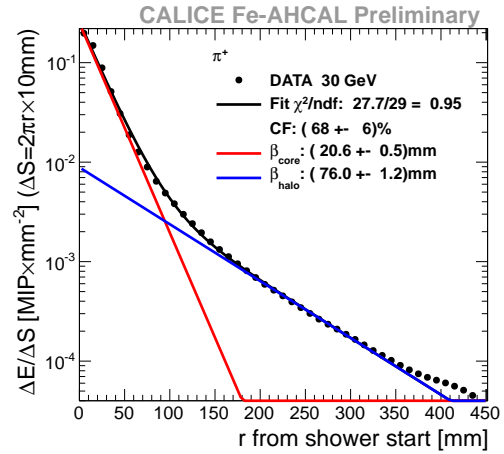
The parametrisation of the longitudinal development of hadronic showers with a sum of two gamma distributions was proposed in [11] as a natural extension of the parametrisation of electromagnetic shower profiles. The energy distribution  $\Delta E(z)$  along the longitudinal coordinate integrated over the radial direction (longitudinal profile) is parametrised as a sum of the "short" and "long" components:

$$\Delta E(z) = A \cdot \left\{ \frac{f}{\Gamma(\alpha_{\text{short}})} \cdot \left( \frac{z}{\beta_{\text{short}}} \right)^{\alpha_{\text{short}}-1} \cdot \frac{e^{-\frac{z}{\beta_{\text{short}}}}}{\beta_{\text{short}}} + \frac{1-f}{\Gamma(\alpha_{\text{long}})} \cdot \left( \frac{z}{\beta_{\text{long}}} \right)^{\alpha_{\text{long}}-1} \cdot \frac{e^{-\frac{z}{\beta_{\text{long}}}}}{\beta_{\text{long}}} \right\}, \quad (1)$$

where  $z$  is the longitudinal distance from shower start,  $A$  is the scaling factor. The smaller slope parameter from the fit is called  $\beta_{\text{short}}$  with the corresponding shape parameter  $\alpha_{\text{short}}$  and the fractional contribution  $f$  of the "short" component. The parameters  $\alpha_{\text{long}}$  and  $\beta_{\text{long}}$  characterise the shape and slope of the "long" component. The fit range is from 0 to  $\sim 4.5\lambda_1^{\text{eff}}$  with the step of  $\sim 0.137\lambda_1^{\text{eff}}$ . An example of the fit to the pion longitudinal profile is shown in Fig. 1.



**Figure 1.** Fit (black curve) of the function (1) to the longitudinal profile (points) of showers initiated by the test beam pions with initial energy 30 GeV. The red and blue curves show the contributions of the "short" and "long" components, respectively. See text for details.



**Figure 2.** Fit (black curve) of the function (2) to the radial profile (points) of showers initiated by the test beam pions with initial energy 30 GeV. The red and blue curves show the contributions of the core and halo components, respectively. See text for details.

### 3.2. Fit to radial profiles

A transverse distribution of the energy density  $\frac{\Delta E}{\Delta S}$  integrated over the longitudinal direction (radial profile) can be parametrised with a sum of the "core" component near the shower axis and the "halo" component far from the shower axis:

$$\frac{\Delta E}{\Delta S}(r) = A_{\text{core}} \cdot e^{-\frac{r}{\beta_{\text{core}}}} + A_{\text{halo}} \cdot e^{-\frac{r}{\beta_{\text{halo}}}} \quad (2)$$

where  $\Delta S = 2\pi r \Delta r$  is the area of the ring of width  $\Delta r$  at the distance  $r$  from the shower axis,  $A_{\text{core}}$  and  $A_{\text{halo}}$  are the scaling factors,  $\beta_{\text{core}}$  and  $\beta_{\text{halo}}$  are the slope parameters. The fit range is from 0 to 340 mm with the bin width  $\Delta r = 10$  mm (the perimeter  $12 \times 12$  cm<sup>2</sup> cells of the AHCAL were excluded from the fit). The estimated accuracy of the determination of the position of the shower axis is  $\sigma_r = 2$  mm. An example of the fit to the radial profile is shown in Fig. 2. The fractional contribution of the core component is called "core fraction" (CF) and is calculated as a ratio of the integral under the core component (the red curve in Fig. 2) to the total shower energy.

### 3.3. Comparison of shower parameters extracted from profiles parametrisation

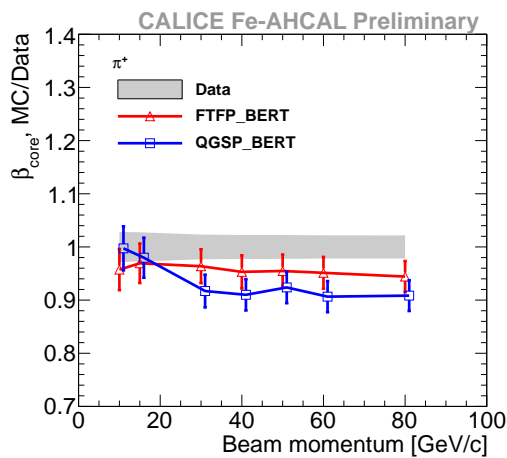
The behaviour of the shape parameter  $\alpha_{\text{long}}$  does not depend on the particle type, is well predicted by Monte Carlo and rises logarithmically with energy. The values and behaviour of the slope parameters  $\beta_{\text{long}}$  and  $\beta_{\text{halo}}$  are also predicted by simulations within uncertainties. They demonstrate no energy dependence and are very similar for pions and protons. Such a behaviour supports the general idea that both tail and halo of the hadronic shower consist of secondaries, which have already "forgotten" the energy and type of the initial particle.

The radial parameter  $\beta_{\text{core}}$  characterises the transverse shower development near the shower axis and is probably related to the angular distribution of secondary  $\pi^0$ s from the first inelastic interaction. The estimated value of this parameter is of the order of magnitude of one effective Molière radius of the Fe-AHCAL ( $R_{\text{M}}^{\text{eff}} = 24.5$  mm), which is comparable with the spatial parameters of electromagnetic showers. It decreases with energy and is well predicted by both studied physics lists below 20 GeV and for protons by FTFP\_BERT in the full studied energy range. The ratio of parameters  $\beta_{\text{core}}$  extracted from the test beam data and simulations is shown in Fig. 3. The underestimation of the parameter  $\beta_{\text{core}}$  above 20 GeV is  $\sim 5\%$  by FTFP\_BERT for pions and  $\sim 10\%$  by QGSP\_BERT for both types of particles.

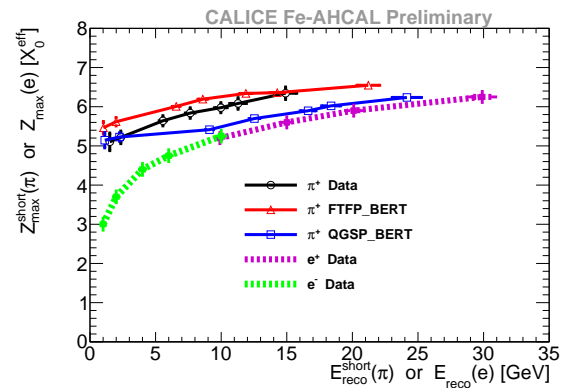
The "short" component of the longitudinal profile describes the part of the shower, which develops immediately after the first inelastic interaction. The slope parameter of the "short" component is about  $1.5 \cdot X_0^{\text{eff}}$ . Both "short" parameters for pions are well predicted by Monte Carlo except for by FTFP\_BERT at 10 GeV and are energy independent above 20 GeV. The fractional contribution of this component for protons is significantly smaller than for pions and cannot be reliably estimated for the energies below 20 GeV.

The position of the maximum of the "short" component  $Z_{\text{max}}^{\text{short}}(\pi)$  can be calculated as follows:  $Z_{\text{max}}^{\text{short}}(\pi) = (\alpha_{\text{short}} - 1) \times \beta_{\text{short}}$ . Figure 4 shows the comparison of  $Z_{\text{max}}^{\text{short}}(\pi)$ , extracted from the "short" component of pion showers, with the estimation of the shower maximum position  $Z_{\text{max}}(e)$ , obtained from the pure electromagnetic showers induced by single electrons or positrons in the Fe-AHCAL [12, 13]. The position of the maximum of the "short" component for pions is calculated w.r.t. the shower start that corresponds to the estimates of  $Z_{\text{max}}(e)$  from the calorimeter front for single electrons. In case of pions, the reconstructed energy, corresponding to the integral under the "short" component,  $E_{\text{reco}}^{\text{short}}$  is calculated using the factor 42.3 MIP/GeV [13]. The maximums of the longitudinal profiles obtained for single electrons or positrons are shown versus the mean reconstructed energy  $E_{\text{reco}}$  of the corresponding particles, which coincides with the beam energy within 1-2%. The difference between  $Z_{\text{max}}^{\text{short}}(\pi)$  and  $Z_{\text{max}}(e)$  increases with decreasing energy for both data and simulations.

While the slope and shape longitudinal parameters extracted from the test beam data and simulations coincide within uncertainties, the fractional contribution  $f$  of the "short" component is overestimated by both studied physics lists above 20 GeV for pions and is slightly underestimated below 20 GeV. The behaviour of the parameter  $f$  is shown in Fig. 5a. The



**Figure 3.** Energy dependence of the ratio of the radial slope parameter for pion showers  $\beta_{\text{core}}$  extracted from simulations with the FTFP\_BERT (red) and QGSP\_BERT (blue) physics lists to that extracted from data. The grey band corresponds to the uncertainties for data.



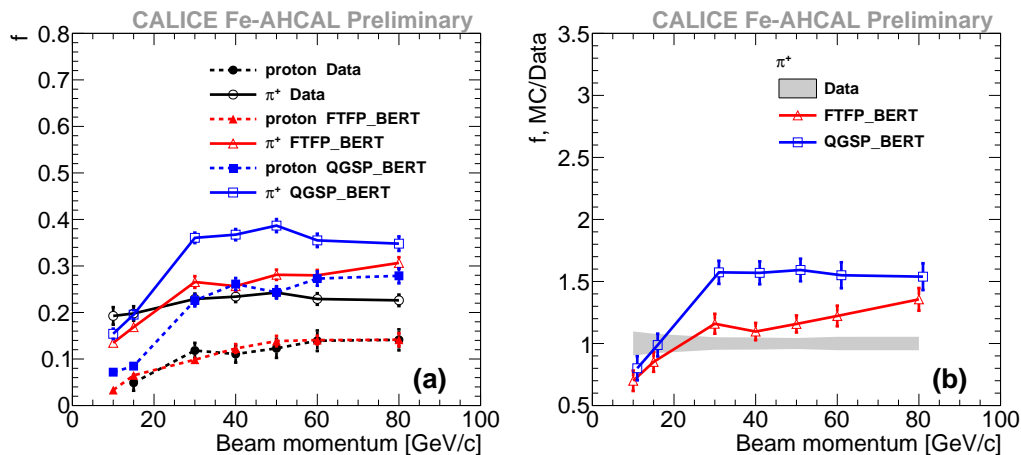
**Figure 4.** Solid lines: maximum of the "short" component versus energy of the "short" component estimated from the fit to pion shower profiles from data (black) and simulations with FTFP\_BERT (red) and QGSP\_BERT physics list (blue). Dashed lines: maximum of the longitudinal profile obtained for electromagnetic showers induced by single electrons (green) [12] or positrons (magenta) [13] in the Fe-AHCAL versus the mean reconstructed energy.

FTFP\_BERT physics list gives a good prediction for protons while overestimates the parameter for pions at higher energies by 5-25%. The QGSP\_BERT physics list significantly (up to 50%) overestimates the contribution of the "short" component above 20 GeV for both pions and protons. The fractional contribution of the "short" component in proton showers is roughly twice lower than in pion showers, which can be explained by a smaller electromagnetic fraction in proton showers due to lower amount of produced  $\pi^0$ s.

#### 4. Conclusion

The spatial development of hadronic showers in the CALICE scintillator-steel analogue hadronic calorimeter was studied using the parametrisation technique. The positive hadron test beam data collected at beam energies from 10 to 80 GeV were analysed and compared with simulations performed using FTFP\_BERT and QGSP\_BERT physics lists from GEANT4 version 9.6. The energy density distributions within hadronic showers were deconvolved from the distributions of the shower starting point through the possibility to identify the position of the first inelastic interaction on an event-by-event basis.

The longitudinal profiles are parametrised with the sum of two gamma distributions. The parameters of the "short" component are comparable with those of electromagnetic showers induced by single electrons in the Fe-AHCAL. Hence the "short" component can be considered to represent the contribution of the electromagnetic showers from the decays of  $\pi^0$ s produced in the first inelastic interaction. The spatial parameters of the longitudinal tail are reproduced by simulations within uncertainties, do not depend on the type and energy of the initial particle. Proton profiles are characterised by a smaller fractional contribution of the "short" component. The parameter  $f$  for pions is overestimated by simulations above 20 GeV and exhibits a much steeper rise than observed in the test beam data.



**Figure 5.** Energy dependence (a) of the "short" component fraction  $f$  for pions (solid curves) and protons (dotted curves) and (b) of the ratio of  $f$  extracted from simulations with the FTFP\_BERT (red) and QGSP\_BERT (blue) physics lists to those extracted from data for pion showers. The grey band corresponds to the uncertainties for data.

The radial profiles are parametrised with the sum of two exponential functions, which describe the behaviour near the shower axis ("core" region) and in the periphery ("halo" region). While the halo slope parameter is well reproduced by simulations, the core slope parameter is underestimated by  $\sim 5\%$  for pions by FTFP\_BERT and by  $\sim 10\%$  by QGSP\_BERT for both types of hadrons resulting in an underestimation of the shower width (shower radius) observed in the previous studies [4].

The tendencies observed in the current analysis for the models from GEANT4 version 9.6 are similar to those demonstrated in [4] for the version 9.4: the overestimation of the shower core and underestimation of the shower radius for pions increase with energy. The FTFP\_BERT physics list from GEANT4 version 9.6 gives very good predictions of both longitudinal and radial shower development for protons over the full studied energy range and shows better agreement with data than the QGSP\_BERT physics list for both pions and protons.

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