Longitudinal shower profile of an electromagnetic shower in the CALICE calorimeter prototype

Valeria Bartsch for the CALICE collaboration

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E6BT, UK

E-mail: `bartsch@hep.ucl.ac.uk`

Abstract. This paper studies the longitudinal shower profile of an electromagnetic shower in the CALICE ECAL prototype. Data from the CERN test beam in 2006 are analysed. The electron energy goes from 6 GeV to 45 GeV. The longitudinal shower profile is compared with Monte Carlo samples and shows that we understand our detector very well. This is due to some cuts performed on the data and some small changes in the Monte Carlo generation introduced last year. The longitudinal shower profile can be fitted very well. In order to get such a good fit result, the sampling fraction has been studied and a dependency of the sampling fraction on the layer, in other words the development of the shower, has been taken into account. It is important to understand basic features of the electromagnetic shower like the longitudinal profile for more sophisticated studies using the transversal segmentation of the CALICE calorimeter prototype. In addition important quantities for the calorimeter like the shower maximum and the leakage energy have been extracted from the longitudinal shower profile.

1. Modifications to MOKKA and event selection

For the study the geometry description of the CALICE test beam in August 2006 at CERN has been chosen. The MOKKA [1] description has been changed so that the energy deposited in the tungsten and the G10 detector components was recorded. It has been checked that over 90% of the total energy is deposited in the tungsten and G10 elements of the ECAL prototype. The energy deposited in the other parts of the support structure is negligible. The program can be found at [2] . Samples for 6 GeV, 10 GeV, 20 GeV, 30 GeV and 45 GeV have been generated with steering files which can be found at [2]. In order to plot the sampling fractions versus the radiation length the radiation length, X0, of the calorimeter has been extracted from the calorimeter simulation. All materials have been accounted for including the support structure for the tungsten absorbers and the silicon sensors. It turns out that this adds about 3 X0 to the naive calculation of the radiation length based on the tungsten thickness.

The study of the longitudinal profile of the electromagnetic shower applies the following criteria to collect electron events. The events have to have a total energy measured in the ECAL within 50% of the nominal beam energy and all hits to have a minimum energy equivalent to 0.6 MIPs. To reduce contributions from events in which significant showering starts before the beam is incident upon the first layer of the ECAL, potentially biasing the longitudinal profile, a cut has been applied which identifies clusters and rejects the events if more than one cluster with

beam energy	selected runs
45 GeV	300195, 300208, 300384
40 GeV	300235
30 GeV	300197, 300207, 310059
20 GeV	300205, 300236, 300379, 310046, 310062, 310064
15 GeV	300202, 300238, 300674, 310047, 310048, 310053
12 GeV	300673, 310052, 310055
10 GeV	300200, 300383, 310051, 310054, 310056
6 GeV	300670

Table 1. Selected runs ordered by beam energy,

an energy above 2.5% of the cluster with the highest energy appears. In this analysis no correction is made for the reduced efficiency in the region between each wafer, the measured mean transverse position of all hits above threshold is required to be between -10 cm and 15 cm in x and between -40 cm and -25 cm or between 5 cm and 25 cm in y. A possible contribution of pions created upstream is suppressed by a cut using the particle identification of the Cerenkov counter.

For the analysis the data collected in the 2006 CERN test beam have been used. The test beam energies for the electrons varied between 6 GeV and 45 GeV. The run selection is summarised in table 1. The data have been compared with Monte Carlo generated with the MOKKA device simulation. For the longitudinal shower profile of the electrons the momentum of the beam energy has been smeared. The values for the smearing have been obtained from the H6 beam line description [6]:

$$\frac{\Delta p}{p} = \frac{\sqrt{C3^2 + C8^2}}{19.4}[\%] \tag{1}$$

C3 and C8 are the full widths opening of these collimators in mm. From which results that a gap of about 3 mm in the momentum collimators results in a $\frac{\Delta p}{p} \approx 0.2\%$. The Monte Carlo events have not been digitised, in other words the detector effects and noise have not been taken into account.

2. Sampling fraction determination

In a sampling calorimeter the total deposited energy (E^{tot}) can be estimated from the energy deposited in the active medium (E^{act}) by dividing by the sampling fraction (f_{samp}):

$$f_{samp} = \frac{E^{act}}{E^{act} + E^{pas}} \tag{2}$$

where E^{pas} is the energy deposited in the passive material.

For a minimum ionising particle the sampling fraction is a fixed number which can be calculated from the known energy deposits in the active and passive materials due to ionisation e.g. caused by muons. Particles produced in the electromagnetic shower interact differently with the detector at the beginning and the end of the shower development. At the end of the shower a large number of low-energetic photons are produced, which have a higher probability to produce low energy electrons in the tungsten absorber than in the silicon. Since the range of these electrons is typically smaller than the tungsten absorber thickness, the energy deposit in the absorber increases relative to the energy deposit in the active material towards the end of the shower and the sampling fraction decreases. This effect is studied for the test beam data taken with the CALICE physics prototype.

Fig. 1 shows the sampling fraction for several energies. The sampling fraction has been determined using:

$$f_{samp} = \frac{E_{Si}}{E_{Si} + E_W + E_{G10}} \tag{3}$$

where E_{Si} is the energy deposition in silicon, E_W in the tungsten, E_{G10} in the G10 part i.e. the support structures of the calorimeter prototype. For the Monte Carlo samples with a 30 GeV electron beam it has been estimated that 95% of the energy is deposited in the monitored parts of the calorimeter whereas 99% of the electron beam energy has been deposited in the calorimeter. One can clearly see the three zones with different tungsten thickness. Within the three stacks it can be seen that the sampling fraction slightly changes between odd and even layers. This is due to a small change in the radiation length X0 between those layers which is caused by a small change in the support structure. Except the changed sampling fraction no other method has been used to level the odd/even layer difference. The sampling fraction changes and the slope of the change of sampling fractions changes (see Fig. 1). The sampling fraction is also depending on the test beam energy. As shown at [5] the energy dependence can be taken into account and a calibration for unknown particle energies can be found.

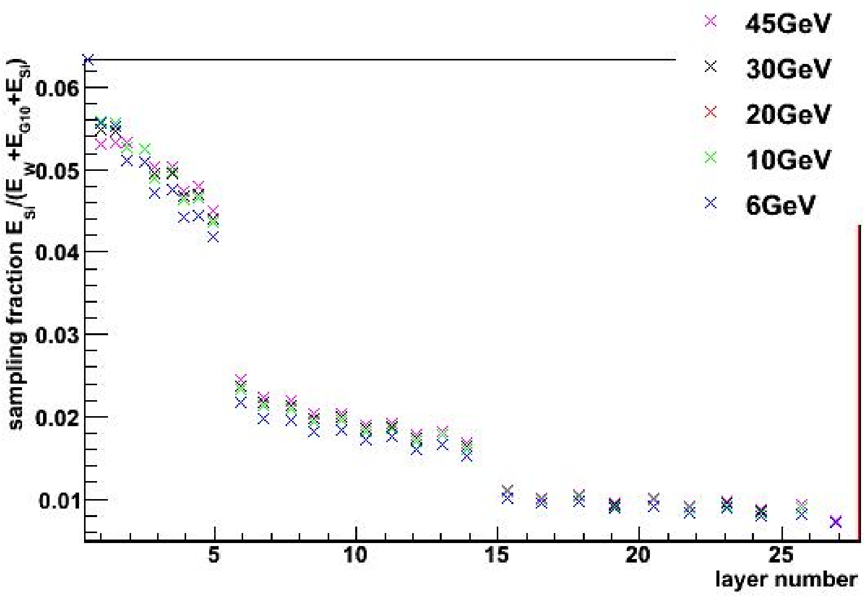


Figure 1. sampling fraction determined by Monte Carlo

3. Longitudinal shower profile

When comparing the longitudinal profile of the Monte Carlo sample and the data (Fig. 2) one can see that the Monte Carlo describes the data very well. This is due to several improvements in the Monte Carlo description which were introduced last year including the description of the momentum distribution of the electron beam which can be deduced of the collimator setting of the test beam setup and the improvements of the density of the G10 support structure.

The correction factor for the different tungsten thicknesses in each stack has been more sophisticated than the simple estimate by only taking the tungsten thickness into account. The tungsten thickness ratio is 1.4 mm/2.8 mm/4.2 mm, thus a ratio of 1/2/3. However taking all materials into account one arrives at a ratio of 4.92 X0/8.99 X0/12.91 X0, i.e. 1/1.83/2.64 for the radiation lengths of each stack. These corrections have been used for Fig. 2.

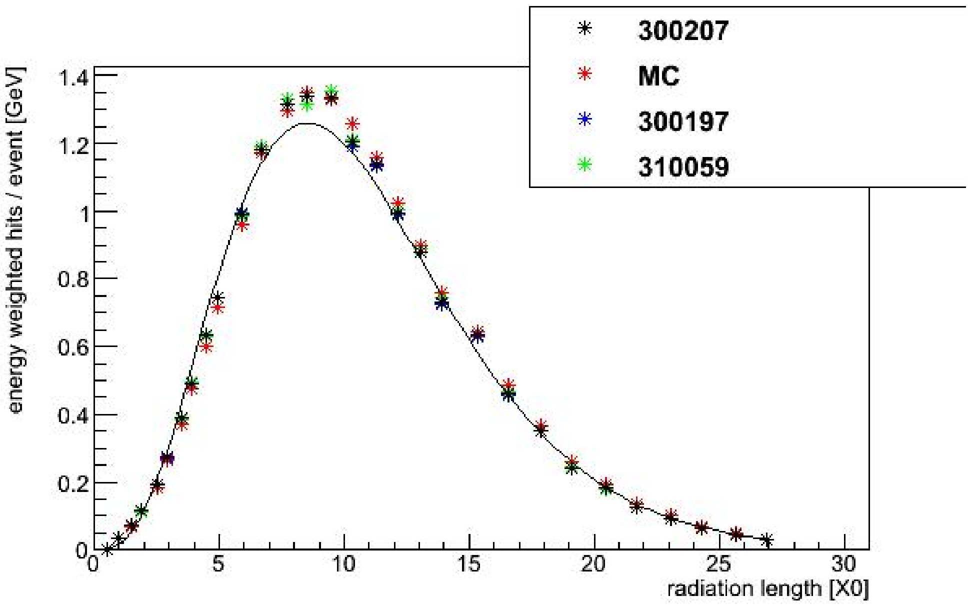


Figure 2. longitudinal shower profile of the 30 GeV runs

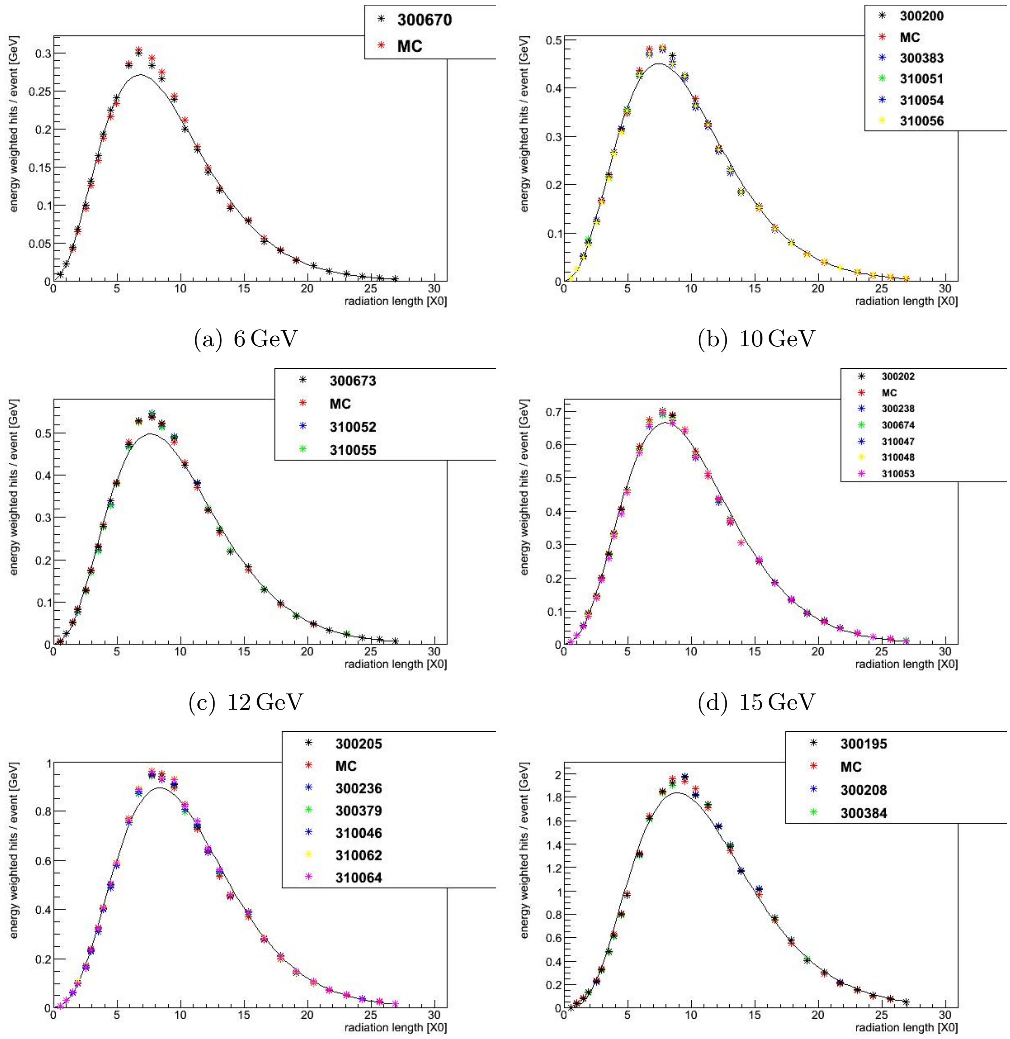
The statistical error of the longitudinal shower profile have been estimated using the distribution of energy deposits for each event in each layer. The energy deposits for each event show a Gaussian distribution as shown in Fig 4. The error for each layer is the sigma of the distribution, σ_{ev} divided by the square root of the number of events, n, in the samples.

$$\sigma = \sigma_{ev}/\sqrt{n} \tag{4}$$

I have tested that this equation describes the statistical error correctly on several different data runs. I assume that in 68% of the layers the difference of the energies deposited in each layer is smaller than the sum of the errors for each layers. In general this is not true, the value is closer to 30%. However the RMS divided by the square root of events is only the statistical error, a systematic error still needs to be added. So I looked at two runs which were taken immediately after each other at the same energy (run 310062 and 310064). I assume that these runs might not have a change in systematic like a change in the test beam conditions and the conditions of the calorimeter prototype. In fact for these two runs 57% of all layers the difference of the energy deposits is smaller than 1 sigma. This goes to 100% for 2 sigma.

In addition to the statistical error one needs to estimate the systematic error. Several sources of systematic errors in the test beam setup have been identified:

- A slight rotation of the calorimeter prototype could change the radiation length of the setup. For a rotation of 1 degree the change would be 0.01%. So this error is negligible.



(a) 6 GeV (b) 10 GeV

(c) 12 GeV (d) 15 GeV

(e) 20 GeV (f) 45 GeV

Figure 3. *Longitudinal shower profile for various energies*

- The momentum spread of the test beam is slightly different for each data run. Usually $\frac{\delta p}{p}$ is about 0.25%. For three runs it is about 0.73% (300200, 300202, 300670). The difference for each layers for these runs compared to runs with $\frac{\delta p}{p}$=0.25% has been estimated using the data samples and extracting the quantity:

$$\sigma_{sys} = (|E_{dep1} - E_{dep2}| - (\sigma_1 + \sigma_2))/E_{dep1} \tag{5}$$

  E_{dep1} and E_{dep2} are the energy depositions at a given layer of two different data runs. The systematic error obtained is on average 1%.

- The error on the electron energy at the test beam area is [6]:

$$\frac{\delta E}{E} = 0.5\% + \frac{150MeV}{E} \tag{6}$$

  That means that at 45 GeV one expects an uncertainty on the beam energy of 0.4 MeV. This uncertainty is negligible and does not need to be taken into account.

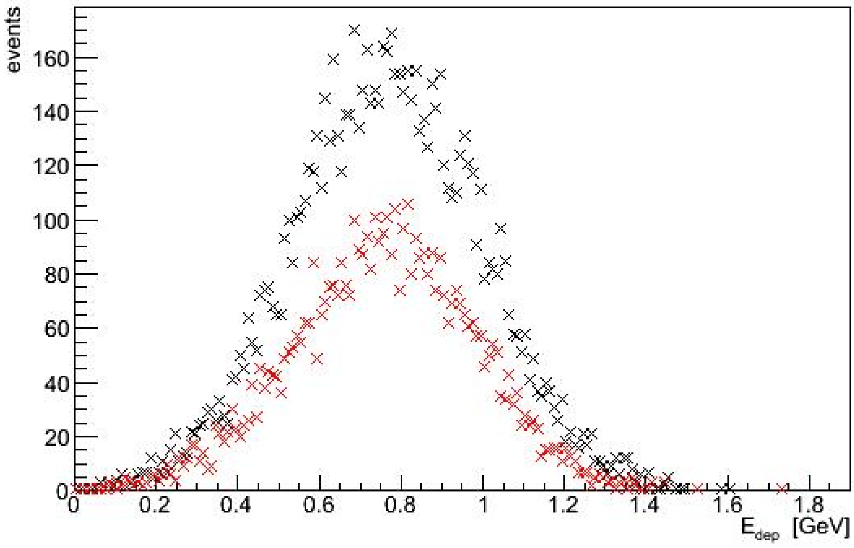


Figure 4. distribution of the energy deposits per event for layer 10, Monte Carlo in red, data in black

- It has been checked that the tungsten thickness is known to about 1% and it is assumed that the density is uniform.

According to this estimate the systematic error is about 1% for each layer. This error however might be too naive. I can see from the fit that the fit underestimates the data at the X0 of the shower maximum. This occurs due to the 1% error being applied to every layer. So we might need to add a more precise systematic error.

4. Fit of the longitudinal shower profile

Fig. 2 is fitted with the function:

$$f(X0) = Const. \times (X0 - \beta)^{\alpha} \times exp(-\gamma \times (X0 - \beta) \tag{7}$$

The fitting function can be found in [7]. The parameter β has been added to take account of the material in front of the calorimeter prototype which can not be accounted for. As can be seen in Fig. **??** the fitting function describes the Monte Carlo very well.

With the help of the fit to the longitudinal shower profile several important quantities can be extracted:

- The total energy deposited in the calorimeter is the integral over the longitudinal profile. This parameter can be used to cross check the analysis.
- The parameter β could be a measure of the radiation length in front of the calorimeter. Thus it has to be independent of the beam energy.
- The integral downstream the end of the calorimeter prototype is an estimate of the average leakage energy. This parameter is important for the final layout of the electromagnetic calorimeter.
- The maximum of the fit of the longitudinal shower profile corresponds to the shower maximum. The shower maximum goes with the logarithm of the beam energy.

5. Errors on the fit parameters

To extract these quantities an estimate of the error of the quantities has to be given. Usually one would take the error of the fit parameter given by MINUIT. However for parameter like the leakage energy this is not possible. So a more sophisticated methods to extract the errors has to be found.

A method to estimate the errors of the fit parameters divides the Monte Carlo sample and the data into subsamples of a given number of events. The fits are performed on the subsamples and the fitting parameters are extracted for each fit. Running over the total sample means that there is a distribution of fit parameter values as shown in Fig. 5. The mean value of the parameters is quite stable as shown for the example of β in Fig. 6. The mean value varies by 4% at a subsample size of 20 events compared to a subsample size of 1000 events. The errors on the fit parameters can be extracted as the RMS of the fits. This method should be independent of the subsample size. However when changing the subsample size from 20 events per sample to 1000 events per sample one can see a clear dependency of the error on the subsample size (sss) (see Fig. 7). The dependency can be parametrized as:

$$f(sss) = \frac{a}{\sqrt{sss}} + b \qquad (8)$$

The values for a and b have been extracted in Tab. 2. The error decreases with a larger number of events in a subsample and then reaches a point where the error is independent of the subsample size, i.e. converging to value a. I expect the dependence of the error $f(sss)$ on $\sqrt{sss}$ for the statistical error. However I do not understand the dependence on b. I propose that in order to understand this dependence better, one should make a sample which can be perfectly fitted by the fitting function and repeat the procedure described on it. So I can validate this procedure. I can also validate the procedure by comparing the error on the fit parameters extracted by this procedure with the error on the fit parameter from MINUIT.

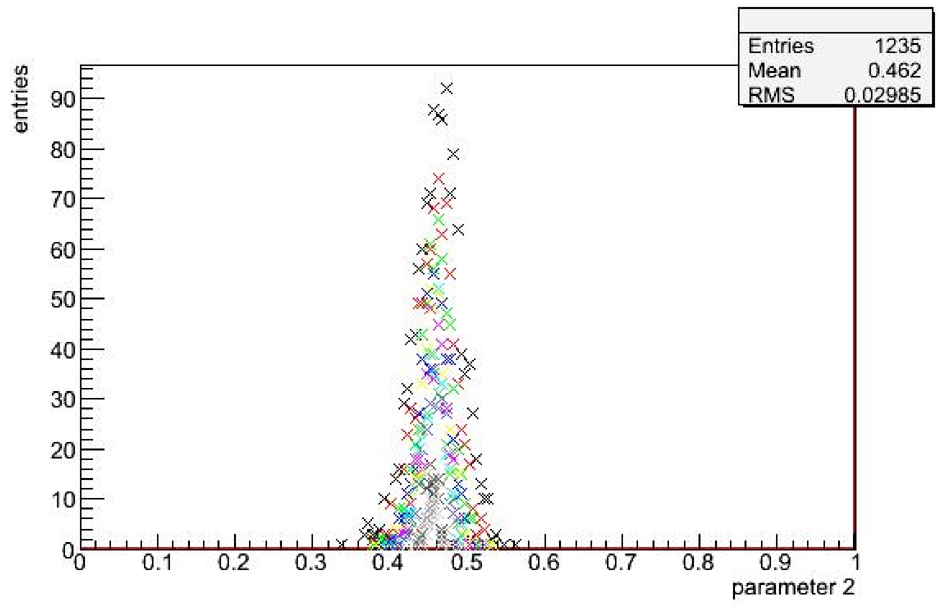


Figure 5. Distribution of the fit parameter γ. The different colours belong to different subsample sizes.

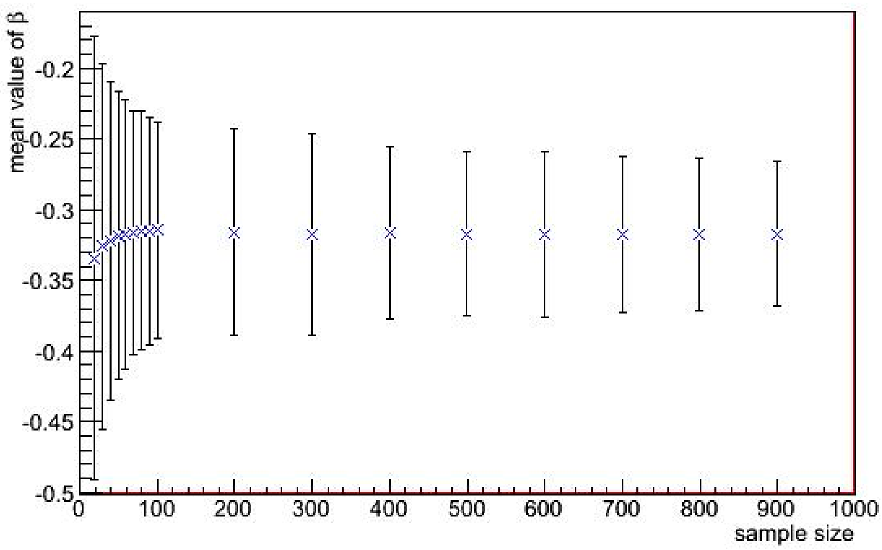


Figure 6. Fit parameter β versus subsample size

fit parameter	a	b
β.	1.44	0.12
γ	0.27	0.01
α	0.34	0.01
Const.	6.28	0.06

Table 2. Fit parameter for the error dependency of the fit parameter RMS versus subsample size

6. Conclusion

The longitudinal profile of the Monte Carlo sample and the data run agree very well. The correction of the sampling fraction has resulted in a much smoother profile. The odd/even layer variations have vanished. The factors taking into the account the different tungsten thicknesses in the stack can be corrected for using the real radiation lengths. The longitudinal shower profile can now be fitted with one curve.

The error estimates of the longitudinal shower profile still pose a problem. The errors on the fit parameter need to be understood better in order to extract errors e.g. on the leakage energy.

Finally the mean values and errors on the shower maximum and leakage energy need to be extracted, the analysis needs to be written up in a CALICE note.

7. References

[1] Mokka homepage, `http://polywww.in2p3.fr/activites/physique/geant4/tesla/www/mokka/mokka.html`

[2] LFC catalogue server, `lfc:/grid/calice/bartsch/calice_sampling`

[3] CIN-002, "Radiation length of the Si-W calorimeter components and impact on the energy resolution" , D. Boumediene

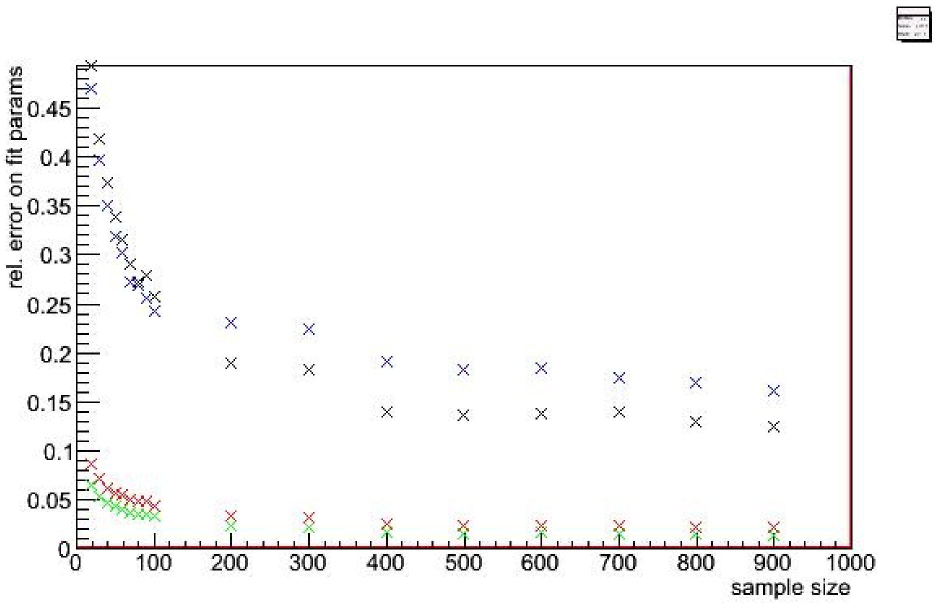


Figure 7. RMS of the fit parameter versus subsample sizes.

[4] Wigmans, Shower Simulation Workshop, FNAL 2006

[5] Aharrouche et al., Energy linearity and resolution of the ATLAS electromagnetic barrel calorimeter in an electron test-beam, ATLAS Electromagnetic Barrel Calorimeter Collaboration, Aug 2006, Nucl.Instrum.Meth.A568:601-623,2006.

[6] H6 beam line description, `http://ab-div-atb-ea.web.cern.ch/ab-div-atb-ea/BeamsAndAreas/h6/H6manual.pdf`

[7] E. Longo and I. Sestili, Nucl. Instrum. Methods 128, 283, 1975