DESY 95-005

# Simulation of the ZEUS calorimeter*

Yoshihisa Iga†
*DESY, Notkestrasse 85*
*22603 Hamburg, Germany*

for ZEUS Collaboration

ABSTRACT

The simulation of the ZEUS uranium-scintillator calorimeter is presented. It is based on the GEANT and GHEISHA Monte Carlo packages. To simulate the high resolution calorimeter with adequate precision and feasible execution time, two fast, tunable shower terminators have been developed. One of them (electromagnetic shower terminator) is applied for electromagnetic particles and the other (neutron shower terminator) for hadronic interactions inside the uranium calorimeter. The calorimeter simulation was tuned and verified with extensive data, obtained with prototype and production modules in test-beams at CERN and Fermilab. The simulation reproduces the energy resolution and $e/h$ ratio for momenta down to $0.5\ GeV/c$. The simulated longitudinal and transverse shower profiles also agree reasonably well with data. Effects caused by the boundary between read-out cells and by extra material in front of the calorimeter are also reproduced well by the simulation. The shower terminators reduce the execution time by a factor of about 15.

## 1. Introduction

The ZEUS detector has been taking data at the electron-proton collider, HERA, at DESY since summer 1992. Details about the ZEUS detector are described elsewhere [1,2]. One of the main components of the ZEUS detector is the hermetic, high resolution calorimeter. The sampling structure consists of $1X_0$ depleted uranium plates interleaved with plastic scintillator tiles. The ratio of the thickness of the scintillator to the absorber was chosen to yield $e/h = 1$ (compensation), hence achieving excellent energy resolution of hadronic showers [3].

The ZEUS collaboration uses the GEANT [4] and GHEISHA [5] packages to simulate the ZEUS detector. We started with GEANT 3.11 and GHEISHA7, and afterwards updated to GEANT 3.13.

Although GEANT simulated most features of the ZEUS detector well, it did a poor job with the ZEUS uranium-scintillator calorimeter response. For example, test-beam data with the prototype at CERN gave a resolution, excluding the contribution of photostatistics, of $15\%/\sqrt{E}$ for electron beams [3,6]. On the other hand, the Monte Carlo, with electrons and photons tracked down to $1\ MeV$, gave $\sim 17.5\%/\sqrt{E}$ [7]. For

*presented at the V International Conference on Calorimetry in High Energy Physics
Brookhaven National Laboratory, Upton, NY
September 25 - October 1, 1994
†e-mail address: iga@desy.de

hadronic showers, the Monte Carlo, with charged hadrons tracked down to $10\,MeV$ and neutrons down to $10\,keV$, gave the resolution $\sim 45\%/\sqrt{E}$ with $e/\pi \sim 1.2$ for 100 ns gate width [7], to be compared to the measured values of $35\%/\sqrt{E}$ with $e/\pi \sim 1.0$ [3,6].

To overcome the discrepancies between test-beam data and the Monte Carlo simulation, we have developed two fast, tunable shower terminators [7,8]. In this approach the general features of GEANT, like the cross sections, dynamics and so on, are kept, and GEANT simulates most components as before. The first terminator, called the *E/M shower terminator*, operates on $e^-$, $e^+$ and $\gamma$ with kinetic energy less than $200\,MeV$. The *E/M shower terminator* is of general use both inside and outside the calorimeter, although it is not used in the ZEUS inner tracking region. The second terminator, or the *neutron shower terminator*, operates on the evaporation energy [‡] of excited nuclei at nuclear interactions simulated with GHEISHA and on neutrons with energy below $50\,MeV$. The *neutron shower terminator* acts only in the interior of the ZEUS calorimeter.

The ZEUS calorimeter simulation with shower terminators gives reasonable agreements with test-beam data for $e/h$, for energy resolution of both electromagnetic and hadronic showers, and for shower profiles in the momentum range of $0.5 - 100\,GeV/c$. The shower terminators also make the program execution faster by a factor $\sim 15$.

Precision measurements from the prototype with CERN test-beam enabled us to tune the shower terminators, and to include some geometrical effects, e.g. the inefficiency near boundaries. Correct simulation of such detailed but important effects reduces the errors due to calorimeter simulation systematics in the physics analysis.

The ZEUS calorimeter is described briefly in Section 2, and the shower terminators are described in Sections 3 and 4. The comparisons between data and Monte Carlo with shower terminators are shown in Section 5. Finally we summarise the ZEUS calorimeter simulation.

## 2. ZEUS Calorimeter

The ZEUS calorimeter is divided into three parts: the forward (FCAL), barrel (BCAL), and rear (RCAL), which cover $2.2° < \theta < 39.9°$, $36.7° < \theta < 129.1°$, and $128.1° < \theta < 176.5°$ respectively. (The downstream proton direction defines $\theta = 0$.) The calorimeter covers 99.7% of the total solid angle.

The basic read-out unit in the ZEUS calorimeter is a tower, whose cross-section is approximately $20\,\text{cm} \times 20\,\text{cm}$. For read-out, each tower is subdivided longitudinally into an electromagnetic (EMC) and hadronic (HAC) sections. FCAL and BCAL have two HAC sections and RCAL has one. Each EMC section is subdivided transversely into 4 cells $5\,\text{cm} \times 20\,\text{cm}$ ($\sim 5\,\text{cm} \times 25\,\text{cm}$) for FCAL(BCAL), and 2 cells $10\,\text{cm} \times 20\,\text{cm}$ for RCAL. HAC sections are not subdivided transversely and so the transverse cell size is $\sim 20\,\text{cm} \times 20\,\text{cm}$. The scintillators of each cell are read out on each side through a wave-length shifter (WLS) coupled by a light guide (LG) to a photomultipliers (PMT).

[‡] Evaporation energy makes very low energy ($K.E \leq 20\,MeV$) neutrons or protons.

The sampling structure consists of $3.3\,mm$ thick uranium plates and $2.6\,mm$ thick scintillator tiles for each cell. An EMC section has a depth of $25X_0$, and a HAC section has $3\lambda$ for FCAL and RCAL and $2\lambda$ for BCAL. The innermost EMC section in RCAL also has silicon diode planes to assist hadron-electron separation (HES). The unit size of HES, at $3\,\mathrm{cm} \times 3\,\mathrm{cm}$, is much smaller than the EMC cell, thus providing more accurate position information. Equivalent devices will also be installed in FCAL, and possibly also in BCAL, at a future date. Further details of the ZEUS calorimeter can be found elsewhere [10,11,12,13].

In order to investigate the performance of the ZEUS calorimeter, an FCAL prototype was built and thoroughly tested in CERN test-beams in momentum range between 0.5 and $120\,GeV/c$. The prototype size is $4 \times 4$ towers, with the same structure as FCAL. The measured energy resolution is $35\%/\sqrt{E(GeV)}$ for hadrons and $18\%/\sqrt{E(GeV)}$ for electrons, and $e/h$=1 [3,6]. Similar tests were made at FNAL with BCAL production modules.

## 3. E/M Shower Terminator

The calorimeter provides information on energy, position, timing, and particle identification. The energy resolution depends on the sampling fraction. The position resolution depends upon the longitudinal and transverse shower profiles, which also give information useful for particle identification. It is important for the simulation code to reproduce accurately the sampling fraction and shower profiles.

The essential problem of shower simulation is to reproduce the measured shower characteristics without prohibitive use of CPU time in tracking the myriad shower particles and their interactions. Electromagnetic ($em$) showers have a remarkable feature, namely tight longitudinal collimation due to the characteristics of electromagnetic physics processes. For simulation purposes, the highly collimated nature suggests that a low energy shower below $\Delta$ (e.g. $\Delta = 200\,MeV$), called *showerlet*, could be described by one representative since all the shower particles are almost parallel. while a lower threshold $\delta$ (e.g. $\delta = 1\,MeV$) might be necessary to reproduce the longitudinal shower profile. This characteristic of the $em$ showers allows us to use the following prescription for the *E/M shower terminator* [7].

For the $em$ interactions at energy below $\Delta$, the *E/M shower terminator* keeps one secondary and discards the others, instead of tracing every shower particle. The *E/M shower terminator* also keeps account of energy left, called undistributed energy, of the original *showerlet* to take care of energy conservation. The retained particle is tracked by GEANT as usual. Each energy deposit during GEANT tracking is scaled up by the ratio of undistributed energy of the original *showerlet* to that of the survivor, so that the *E/M shower terminator* also deposits contributions from discarded particles, and then the undistributed energy is updated.

The *E/M shower terminator* continues to apply this discard algorithm for each $em$ interaction, until the retained secondary particle's energy is less than $\delta$.

This basic prescription of the *E/M shower terminator* describes only very crudely

the correct shower profile. In order to generate energy deposits by GEANT, the survivor is chosen from among the $e^-$ and $e^+$, excluding the $\gamma$. The resulting energy losses by charged particles, instead of by photons, makes longitudinal penetration too shallow.

In order to compensate for this problem, a "stretched" path length phase was introduced [8]. The origin of the *showerlet* is replaced by a photon with an empirically longer mean free path of pair-production, even when it was actually an electron or a positron. After this "stretched" photon has an interaction, the original discard algorithm takes it over.

On the other hand, the basic *E/M shower terminator* also makes the transverse shower profile narrower due to discarding half of the binary products. To recover the correct transverse shower profile, a post *E/M shower terminator* procedure is carried out. When the retained particle's energy falls below $\delta$, the undistributed energy of the parent *showerlet* is still relatively large, typically $0.5\Delta$. This undistributed energy is spread along the *showerlet* axis using a GEANTINO (a fictitious particle provided by GEANT) according to an empirical formula which parameterises the transverse shower profile as a function of radiation length.

Inside the ZEUS calorimeter, an additional procedure is necessary to reproduce the measured energy resolution. The basic *E/M shower terminator* prescription gives too wide energy distribution, since in effect the signal from low energy showers fluctuates as though showers consisted of one particle rather than many. To correct this sampling problem, the visible energy deposited in scintillator is compared to the expected energy based on the sampling fraction, which is 0.037 from an EGS study [9]. Deviations in the energy resolution for electrons are then scaled by a factor of 15/17.5 (see section 1) [7].

## 4. Neutron Shower Terminator

The *neutron shower terminator* was introduced to overcome the discrepancies in hadronic showers between the test-beam data and Monte Carlo simulation. The main uncertainty, which plays a major role in $e/h$ and the energy resolution of hadronic showers, comes from the complex nuclear processes.

The ratio $e/h$ was measured as a function of the incident kinetic energy with the FCAL prototype at CERN. At high energies $e/h = 1$. As the incident kinetic energy decreases below $4\,GeV$, $e/h$ also decreases, eventually approaching $e/mip$, where *mip* stands for minimum ionising particles [6]. When GEANT generates a hadronic or nuclear interaction inside the ZEUS calorimeter using GHEISHA, the *neutron shower terminator* intercepts

- the evaporation energy, and
- the energy of any spallation neutrons below $50\,MeV$.

To simulate the measured $e/h$ behaviour at low kinetic energy, an energy dependent scale factor is applied to the evaporation energy in GHEISHA interactions. Most

of the evaporation energy is distributed isotropically by one or more GEANTINOs, according to the form $e^{-\Delta x/\sigma}$ where $\Delta x$ is the distance in $x$ from the interaction point and $\sigma$ is set to $7\,cm$, and similarly in $y$ and $z$. It is also distributed in time, $t$, according to the "lethargy plot" based on results of very detail shower simulation [7,14]. To represent the penetrating component in the evaporation energy, the rest is thrown as a proton or neutron randomly chosen according to the target's nuclear composition, whose direction is the same as that of the incident hadron.

Spallation neutron energy is also thrown with the same prescription, except in the spatial distribution, which is biased toward the neutron's direction, and the time distribution, which is prompt.

The energy distributed as GEANTINOs by the *neutron shower terminator* has a sampling fraction empirically chosen to yield $e/h = 1$ for $10\,GeV/c$ $\pi^-$. The GEANTINO energy deposits are also smeared to reproduce the overall hadronic energy resolution of $\sim 35\%/\sqrt{E}$ at this energy.

The *neutron shower terminator* is used only inside the ZEUS calorimeter, and is limited to the above mentioned components of nuclear interactions. GHEISHA takes care of the energy dependence and many other features in hadronic showers, including fluctuations and correlations.

## 5. Comparisons to Data

### *5.1. Electromagnetic showers*

First, we compare Monte Carlo simulations with and without the *E/M shower terminator*. In fig. 1, the longitudinal distribution simulated with the *E/M shower terminator* for $5\,GeV/c$ electrons is compared to that from normal GEANT (i.e. without the *E/M shower terminator*), where tracking is done to $100\,keV$ for $\gamma$, and to $1\,MeV$ for $e^-$ and $e^+$. They agree very well.

In order to study the transverse shower profile, data were collected in three adjacent electromagnetic cells (EMC1, EMC2, and EMC3), each measuring $5\,\mathrm{cm} \times 20\,\mathrm{cm}$. The ratio of energy deposited in EMC1 to the sum of the three, as the electron beam normal to the EMC's face is scanned across the central cell (EMC2), characterises the transverse shower profile. This ratio is shown, for both data and Monte Carlo simulation, for $15\,GeV/c$ $e^-$ in fig. 2, as a function of beam position. The Monte Carlo results are in reasonable agreement with the data. We should note that the *E/M shower terminator* was already tuned to the test-beam for some of the light propagation effects.

### *5.2. Hadronic showers*

An important feature in the ZEUS calorimeter is the excellent energy resolution for hadronic showers due to the compensation mechanism, giving $e/h = 1$. Fig. 3

shows $e/h$ as a function of kinetic energy. Data were taken from the FCAL prototype with CERN test-beam for $h = \pi$ and $p$. The corresponding Monte Carlo results are also shown in fig. 3 for both of pions and protons. The energy dependence of $e/h$ is reproduced very well, even in the energy region below $4\,GeV$.

The energy resolution of hadronic showers is plotted as a function of incident particle momentum in fig. 4. Proton and pion data are presented separately, along with Monte Carlo results. The CERN test-beam data shows a resolution of $\sim 35\%/\sqrt{E}$ in the high energy region. The Monte Carlo reproduces this behaviour, even in the low energy region, for both protons and pions.

To study the longitudinal shower development, fig. 5 shows the fraction of the energy deposited by incident $\pi^+$s in the EMC, HAC1 and HAC2 sections, of the FCAL prototype, as a function of incident beam momentum. An EMC section is $25X_0$ thick, and HAC1 and HAC2 are each $3\lambda$ thick. Monte Carlo simulations are in fair agreements with data for each section in the momentum range of $0.5 - 100\,GeV/c$. The ZEUS barrel calorimeter (BCAL) has thinner HAC sections: HAC1 and HAC2 are each $2\lambda$ thick. In fig. 6 the same quantity is shown for BCAL as a function of the incident $\pi^+$ momentum. Simulation results are shown to agree well with data across the entire momentum range, from 20 to $100\,GeV/c$, where BCAL test-beam results are available.

The lateral spread of $30\,GeV$ hadronic showers is presented in fig. 7a and 7b for data and Monte Carlo, respectively. The FCAL prototype consists of $4 \times 4$ towers, with the beam incident on the tower positioned in the third column and the second row. Each box shows the ratio of energy deposited in that tower to the sum from all 16 towers. The data and Monte Carlo agree with each other at the level of $\pm 0.5\%$.

### *5.3. Calorimeter response*

In this section we describe the simulation of various more detailed aspects of the ZEUS calorimeter response.

The mechanical structure includes cracks between towers, and between cells, consisting of air gaps, wrapping papers, and spacers. Such cracks reduce signal output near the boundaries. CERN tests with production modules measured this crack effect precisely. In fig. 8 the signal reduction in RCAL for $10\,GeV/c$ $e^-$ is shown as a function of beam position. The solid curve represents the CERN test result, while dots are the simulation results. The dip in the right side corresponds to the crack between EMC cells, and the left dip is from the crack between neighboring towers. In this worst case, the beam is perpendicular to the calorimeter surface. The signal reduction at the tower boundaries is $\sim 10\%$. At the cell boundaries the effect is $\sim 7\%$, because there are small spacers between towers which protect scintillator tiles. The crack effect is very well duplicated by Monte Carlo. In practice, this effect is not as serious for the ZEUS physics data, because the incident particles are not generally normal to the FCAL and RCAL surface.

There is a similar effect at the boundary between modules, where WLSs and LGs

transport scintillation light to the PMTs. When charged particles deposit energy in WLS and LG, there is no scintillation light, but there can be Čerenkov light under the appropriate circumstances. In order to compensate the reduced scintillation light by Čerenkov light in the WLS, there is a single lead sheet of $2.5\,mm$ thickness between each pair of modules in the ZEUS calorimeter. This thickness was chosen on the basis of a CERN test [3,15]. In the simulation code the factor for Čerenkov light in WLS was adjusted to reproduce this test-beam data. Fig. 9 shows Monte Carlo results with this configuration. The contribution from WLSs and scintillators are individually shown in fig. 9a and 9b respectively, and the total is in fig. 9c as a function of the impact position of electrons. The position of $x = 30$ corresponds to an intermodule boundary, with the $e^-$ shot from the ZEUS interaction point. Based on the test-beam data, the predicted fluctuation is less than 5%.

There is also the problem of extra material in front of the calorimeter, e.g. other components, signal cables and beampipes. In the CERN test with the prototype, this "dead material effect" was investigated [16]. The results are compared to the simulation in fig.10 for 1, 5 and $30\,GeV/c$ electrons, where the signal reduction ratio is plotted against the radiation length of the extra material in front of calorimeter. Monte Carlo and data agree reasonably well at each momentum.

## 6. Conclusions

The ZEUS calorimeter simulation is based on GEANT and GHEISHA, and two fast, tunable adaptations, *E/M shower terminator* and *neutron shower terminator*. The *neutron shower terminator* is necessary to reproduce $e/h = 1$ and the excellent energy resolution of the calorimeter. The *E/M shower terminator* is needed for the correct shower profile. Using these shower terminators also makes the CPU execution faster by a factor of $\sim 15$.

Data and Monte Carlo were compared for several distributions, the ratio $e/h$, energy resolutions for both hadronic and electromagnetic showers, and shower profiles. The Monte Carlo simulations agree well with the measured data in the momentum range, $0.5 - 100\,GeV/c$, where the test-beam data is available.

An important application of the extensive test-beam data was for fine tuning the shower terminators. Geometrical effects due to the boundary between cells, towers, and modules are nicely reproduced, as well as the effect of extra material in front of the calorimeter.

This calorimeter simulation is currently used to generate useful Monte Carlo data samples for physics analysis in the ZEUS collaboration.

## 7. References


1. The ZEUS detector, Status Report 1993, DESY (1993).
2. ZEUS collab., M.Derrick et al, *Phys. Lett.* **B293** (1992) 465.

3. ZEUS Calorimeter Group, U.Behrens et al, *Nucl. Inst. and Meth.*, **A289** (1990) 115.
4. R.Brun et al, GEANT 3, CERN/DD/EE/84-1 (1987).
5. H.C.Fesefeldt, *Simulation of Hadronic Showers*, PITHA 85-02, RWTH Aachen (1985).
6. ZEUS Calorimeter Group, A.Andresen et al, *Nucl. Inst. and Meth.*, **A290** (1990) 95.
7. G.F.Hartner, ZEUS-Note 88-49 (1988).
8. G.F.Hartner and Y.Iga, ZEUS-Note 90-84 (1990).
9. B.J.Stacey, G.F.Hartner and J.F.Martin, ZEUS-Note 88-29 (1988).
10. A.Andresen et al, *Nucl. Inst. and Meth.* **A309** (1991) 101.
11. A.Bernstein et al, *Nucl. Inst. and Meth.* **A336** (1993) 23.
12. A.Caldwell et al, *Nucl. Inst. and Meth.* **A321** (1992) 356.
13. J.A.Crittenden, *The Performance and Understanding of the ZEUS Calorimeter*, in this proceedings.
14. H.Brückmann et al, *On the Theoretical Understanding and Calculation of Sampling Calorimeters*, DESY 87-170 (1987).
15. J.A.Crittenden and R.Yoshida, Proceedings of the Workshop 'Physics at HERA' vol.1, DESY (1992) 121.
16. J.Krüger, *Length of Calorimeter and Effect of Absorbers in Front of Calorimeters*, DESY 90-163 (1990).

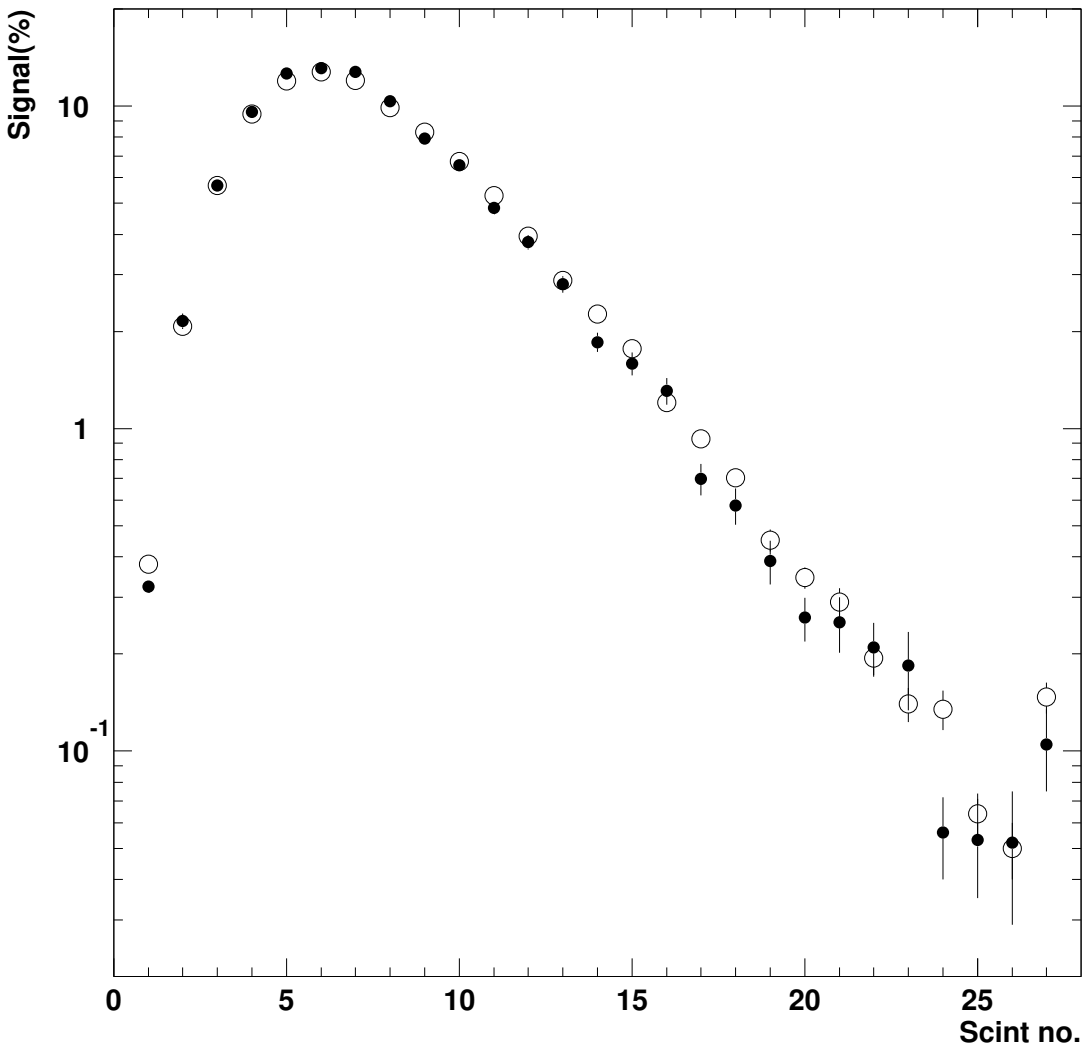


Figure 1: *Mean percentage of FCAL signal in each EMC layer for 5 GeV/c electron. The summed HACs is in the last point.* ○ *: with E/M shower terminator and* ● *: without E/M shower terminator*

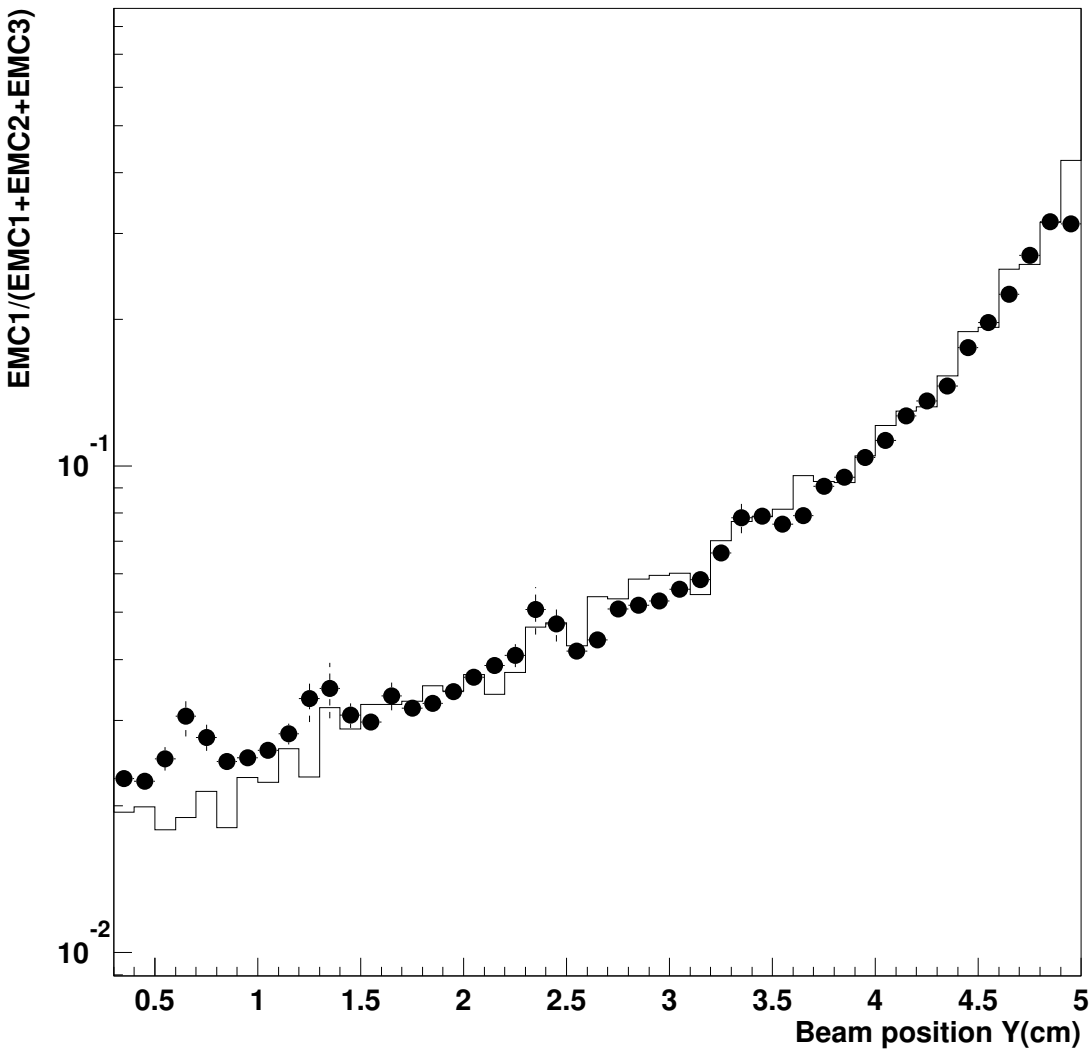


Figure 2: *Transverse shower profile for 15 GeV/c $e^-$. Ratio of energy deposited in the right side (EMC1) to the sum of three adjacent EMC cells as a function of the beam position. Y=0 to 5 is corresponding to the central cell (EMC2). Histogram is for MC result and dots for data.*

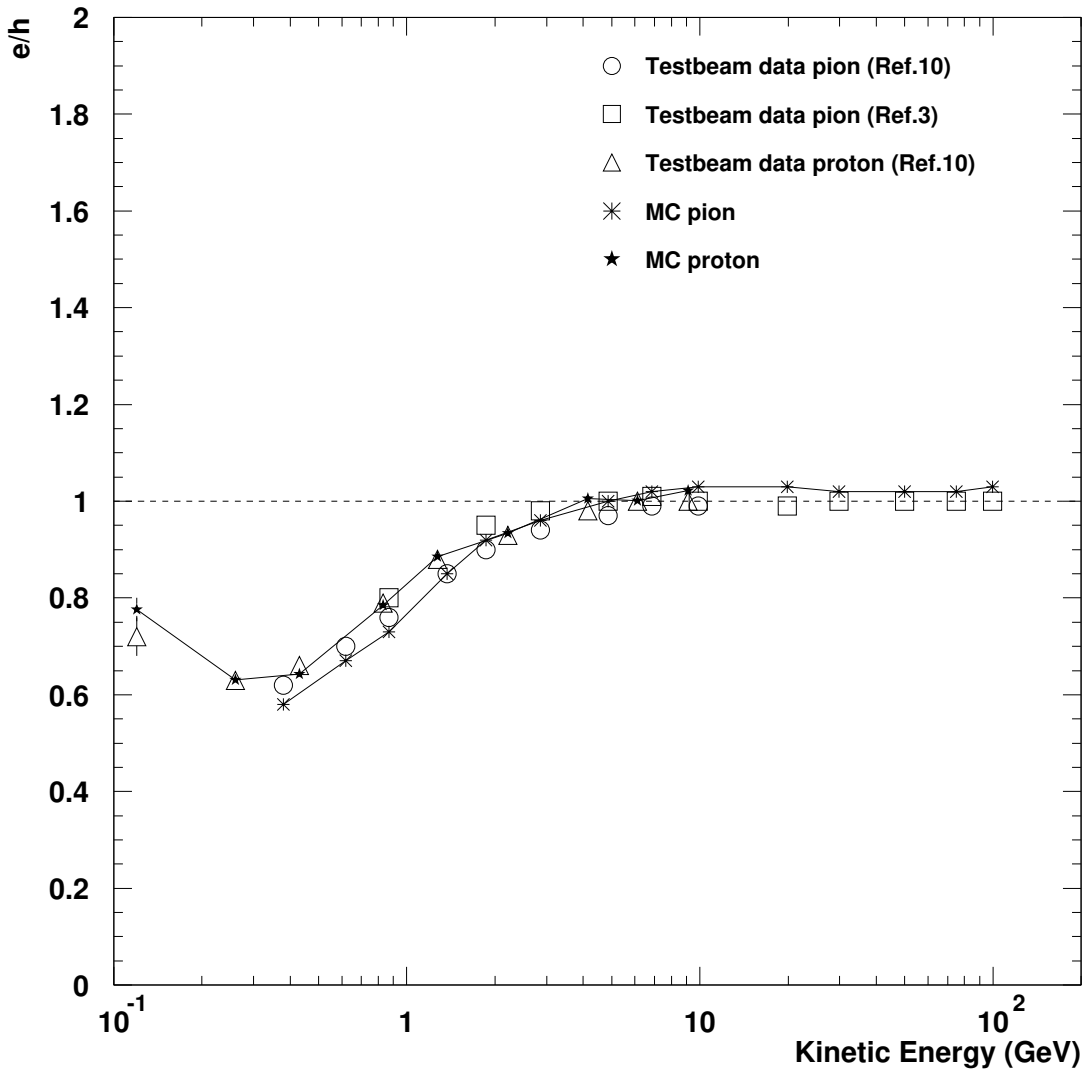


Figure 3: *e/h ratio as a function of kinetic energy for pions and protons. Testbeam data are shown with open symbols and MC points are connected by solid lines.*

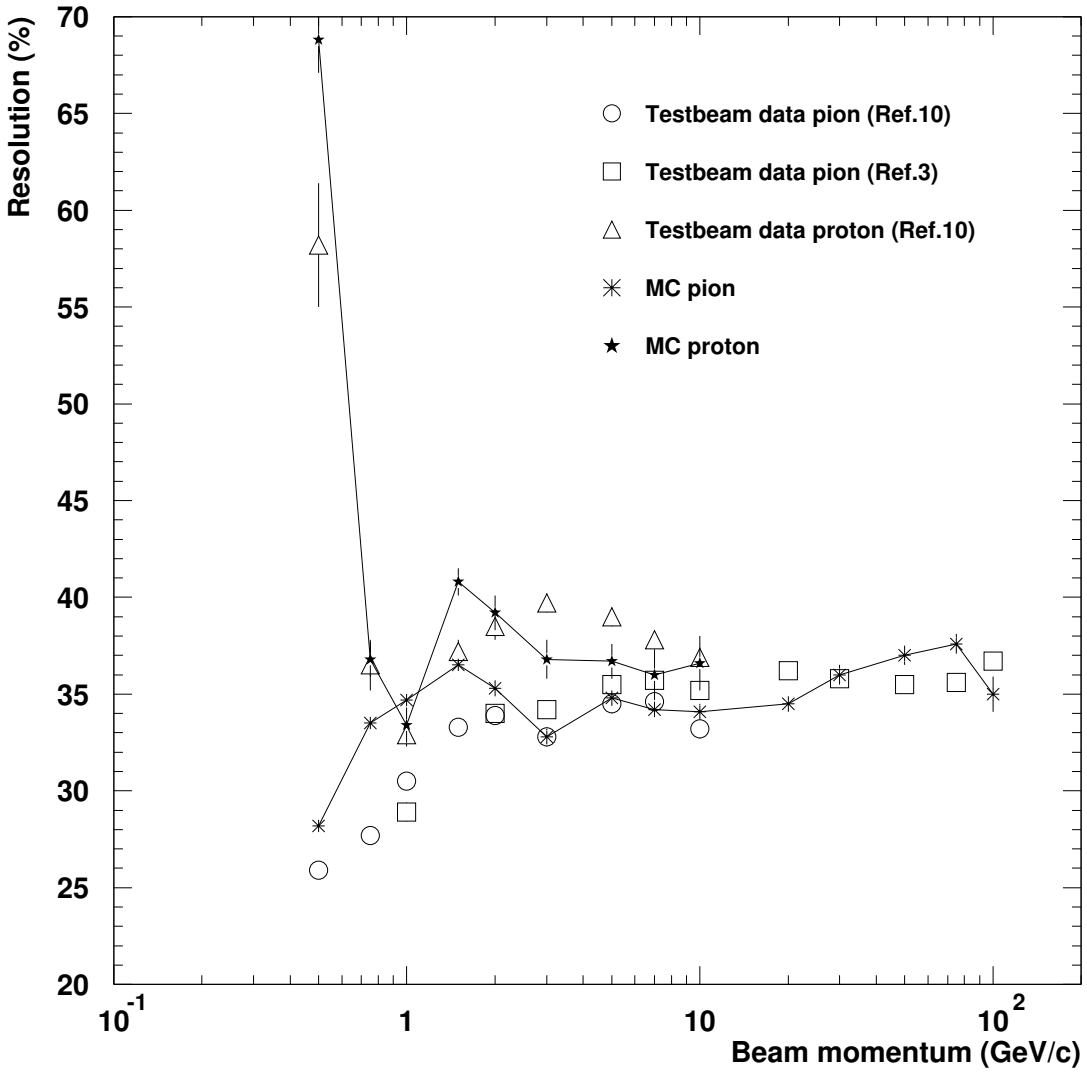


Figure 4: *Energy resolution of hadronic showers as a function of beam momentum. Testbeam data are shown with open symbols and MC points are connected by solid lines.*

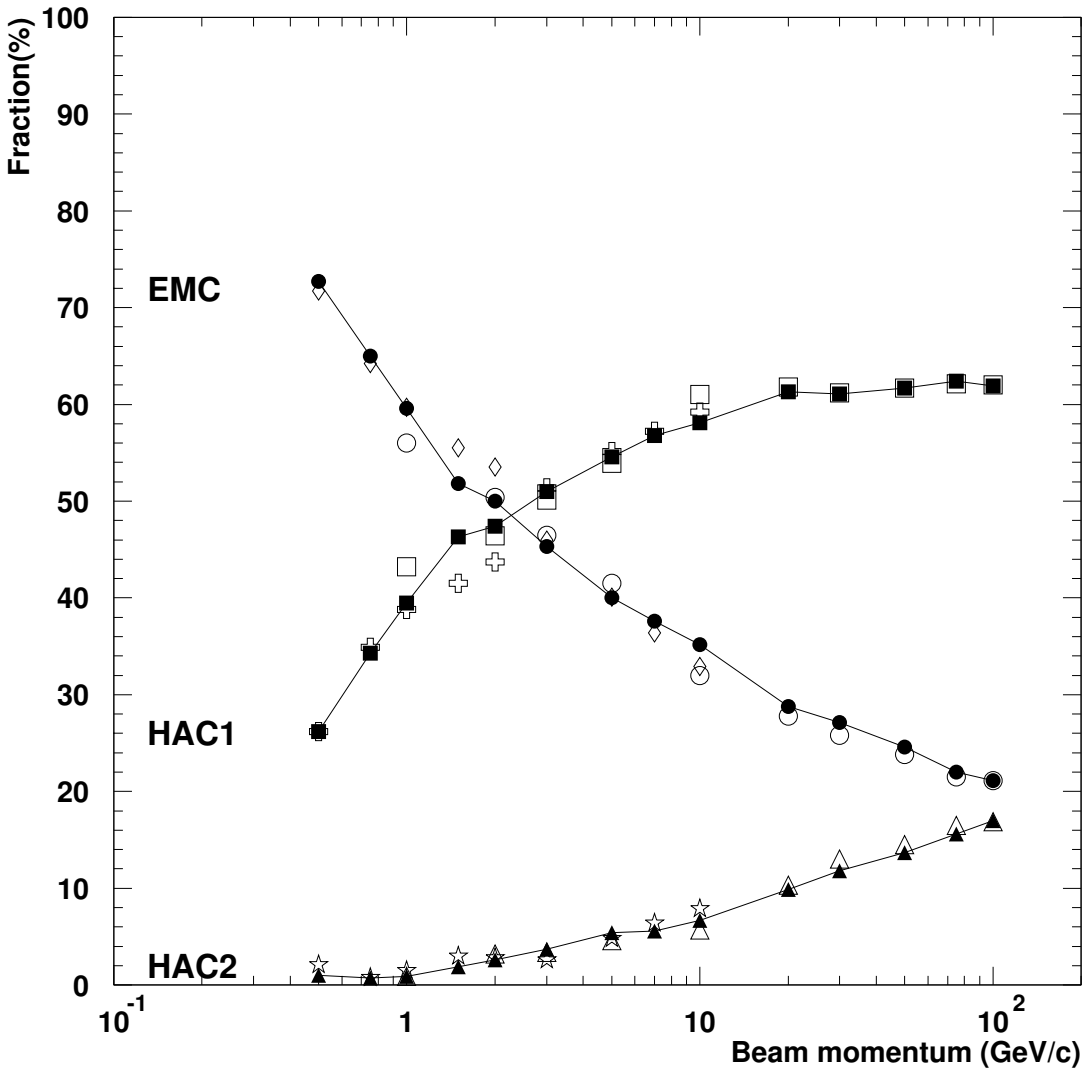


Figure 5: *Longitudinal shower profile in FCAL for $\pi^+$. The fraction of energy deposited in each section to total deposited energy are shown as a function of beam momentum. Open symbols are for testbeam data (Refs.3 and 10) and closed symbols for MC results with solid lines.*

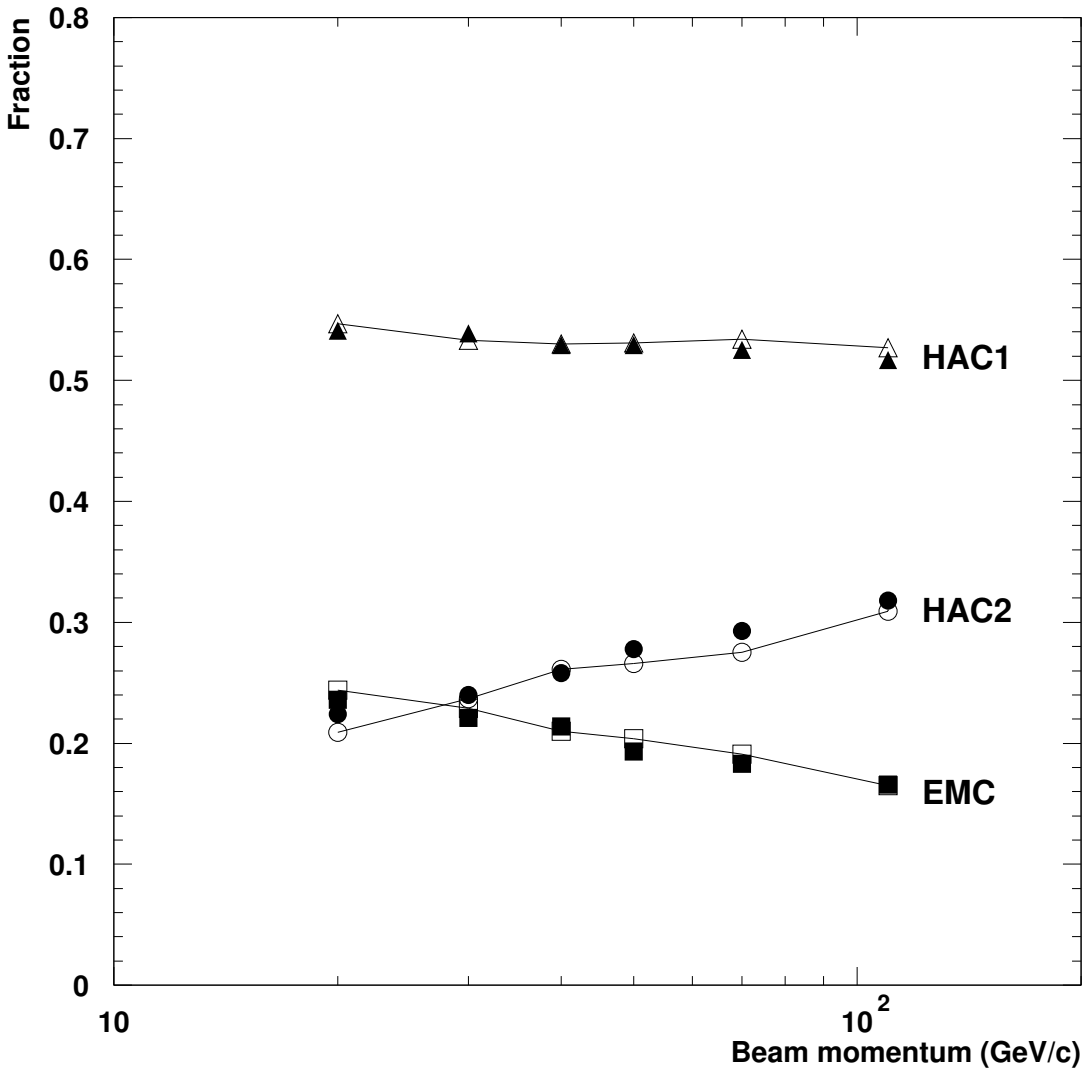


Figure 6: *Longitudinal shower profile in BCAL for $\pi^+$. The fraction of energy deposited in each section to total deposited energy are shown as a function of beam momentum. Open symbols are for testbeam data and closed symbols for MC results with solid lines.*

| | | | |
|---|---|---|---|
| 0.26 | 1.3 | 3.8 | 1.3 |
| 0.31 | 3.8 | 77.7 | 3.8 |
| 0.26 | 1.3 | 3.8 | 1.3 |
| 0.09 | 0.26 | 0.31 | 0.26 |

(a)

| | | | |
|---|---|---|---|
| 0.15 | 1.2 | 4.5 | 1.2 |
| 0.34 | 4.3 | 76.4 | 4.3 |
| 0.16 | 1.2 | 4.5 | 1.2 |
| 0.05 | 0.16 | 0.36 | 0.16 |

(b)

Figure 7: *Lateral spread of 30 GeV hadronic shower. (a) Testbeam data and (b) Monte Carlo result. Beam position is in the third column and the second row. Each box shows the ratio of energy deposited in that tower to the sum of all 16 towers.*

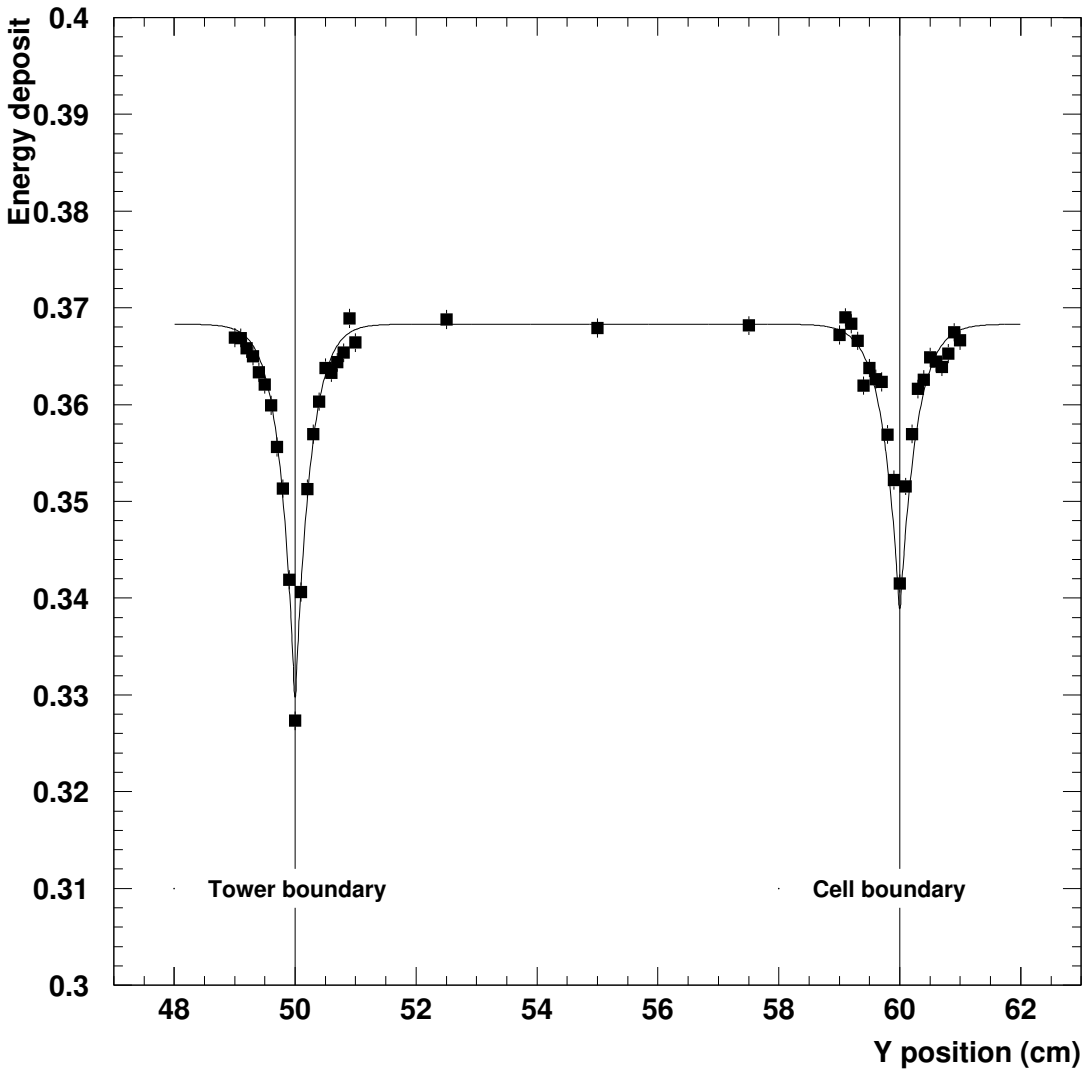


Figure 8: *Signal reduction due to cracks in RCAL for 10 GeV/c $e^-$ as a function of beam position. Y=50 corresponds to the tower boundary and Y=60 to the cell boundary. Solid line shows testbeam data and square symbols present Monte Carlo result.*

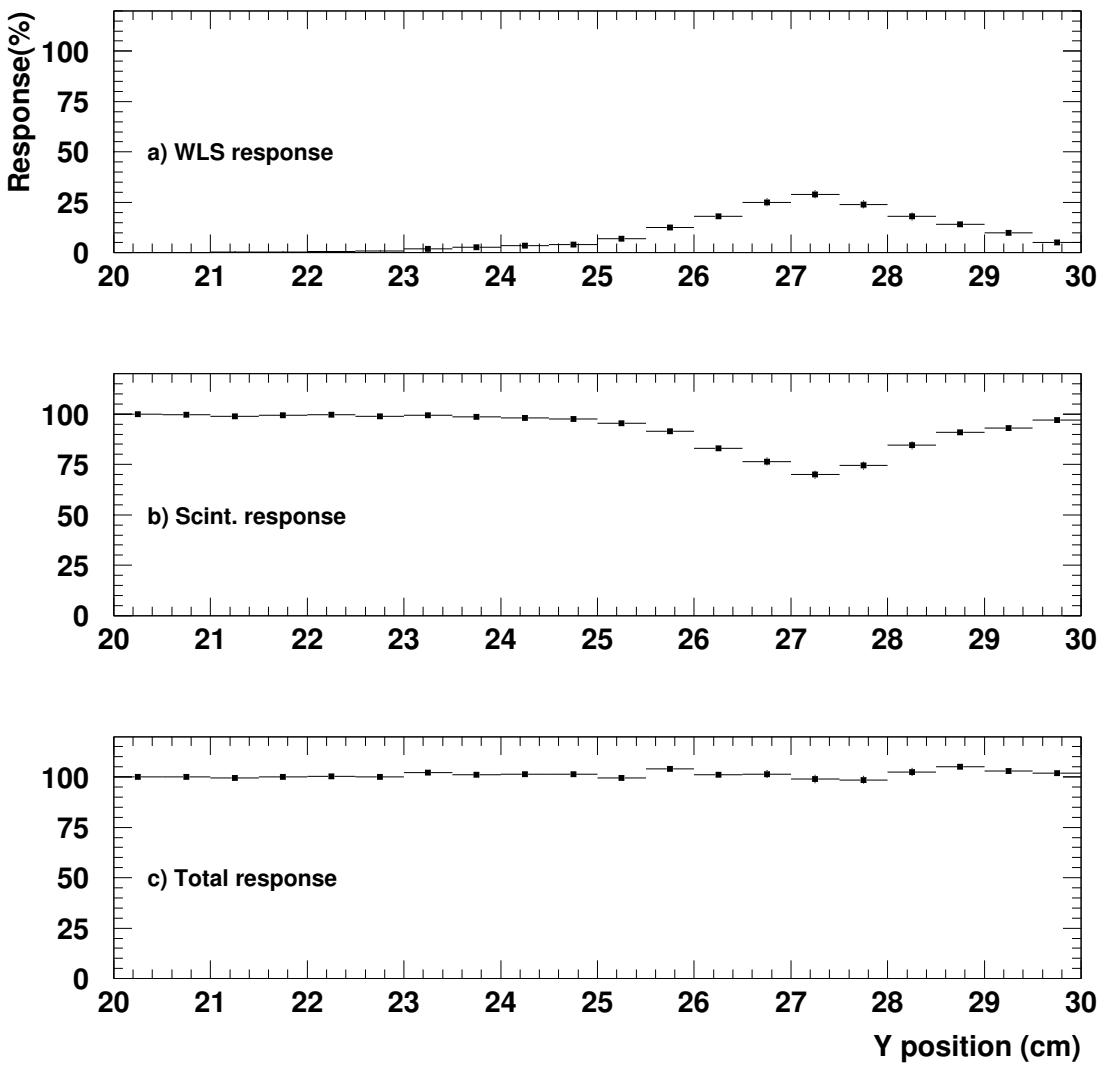


Figure 9: *Calorimeter response in the module boundary for electrons as a function of beam position from Monte Carlo, normalised to incident beam energy. a). WLS, b). Scintillator and c). Total response.*

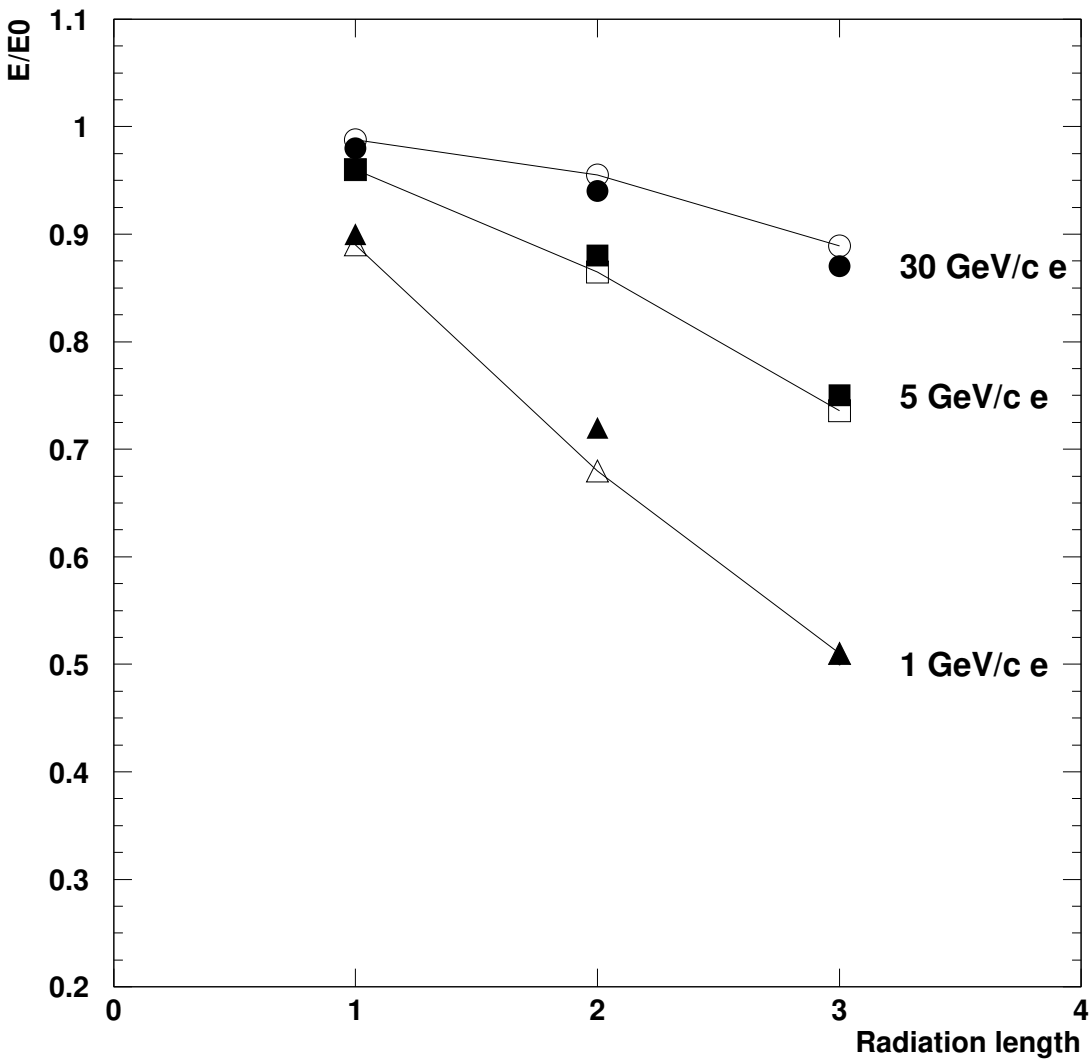


Figure 10: *Signal reduction ratio as a function of the radiation length of extra material in front of the FCAL prototype. Closed symbols show the testbeam data in ref.16 and open symbols present Monte Carlo results and they are connected by solid lines.*