

Beam Test of an Imaging Calorimeter Prototype Module

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Abstract

Results are summarized for the beam test of a Pb/scintillating fiber module with pixelated sampling. The device was exposed to photons and electrons with energies in the range 0.15 - 10 GeV. Resolutions for energy and reconstructed angle are measured and compared to Monte Carlo simulations.

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1 Introduction

In June of 1996, a beam test of calorimeter technologies for GLAST was conducted. The parasitic electron/positron beamline into End Station A was used to study the response of CsI(Tl) and scintillating fiber calorimeter modules to electrons and photons. This Note reports on one analysis of the scintillating fiber module, together with Monte Carlo modelling of imaging calorimeter methods.

2 Beamline and Test Module

Electrons of 1.33, 1.93, 5.07, and 9.49 GeV were momentum selected and steered into a test area in End Station A. The electron/positron bunches had a frequency of 120 Hz, with intensities ranging from 0.25 to 2 electrons per bunch. For photon running, a 3.5% radiation length Cu target was used to induce bremsstrahlung, and a magnetic spectrometer measured the electron (and thus photon) momentum. For the studies reported in this paper, photons in the range 0.35 - 0.55 GeV were studied, in addition to the primary electrons.

In order to study the properties of modern scintillating fiber calorimeters, and to check the Monte Carlo modelling of such materials, a crude calorimeter module was constructed at the University of Chicago. Pb/fiber material in the volume ratio 42%:58% was donated (courtesy of Prof. G. Barbiellini) by the KLOE Collaboration, which is has constructed a large HEP calorimeter with this material¹. Enough material was obtained to construct a rectangular block measuring 14.9 cm \times 14.9 cm \times 18.8 cm, with the fiber axis along one of the shorter axes; this machining was performed at the University of Chicago. The KLOE material has $L_{rad} = 1.6cm$ and $R_{Moliere} = 3.8cm$, giving depths of 9.3 L_{rad} transverse to the beam and 11.75 L_{rad} along the beam direction.

Because of time and funding constraints, compromises had to be made in choosing readout for the device. Photomultiplier tubes were chosen for readout in order to best assess the light output of the scintillator. Adequate granularity of sampling was obtained by pulling 4 Winston light concentrators measuring 0.5 inch \times 0.75 inch (also courtesy of KLOE) at the first radiation length, followed by 18 coarser 1 inch \times 1 inch Winston cones (manufactured at Chicago) at intervals throughout the remaining material. Only one view of the shower development is obtained this way. For the smaller light concentrators, Hamamatsu R5600 PMTs having 0.5 cm aperture were used; for the larger pixels, RCA C31005 tubes having 0.75 inch aperture were employed. A schematic of the module is shown in Figure 1.

The SciFi module was mounted on an x-y translator stage which could be positioned remotely from the operator console; module position resolution of about 0.2 cm was obtained with the device. Two sets of beam defining scintillators were located in front of the module + translator stage. A set of 1 cm wide "finger counters" in the vertical and horizontal directions was used to steer the beam and to define a 1 cm \times 1 cm beam aperture. A thick, large aperture scintillator "paddle" was used to select beam bunches having only single electrons (used only for incident electron mode).

A 20 L_{rad} -long NaI(Tl) crystal was placed behind the SciFi module in order to measure the shower leakage.

¹ Antonelli et al, NIM A354 (1995) p352.

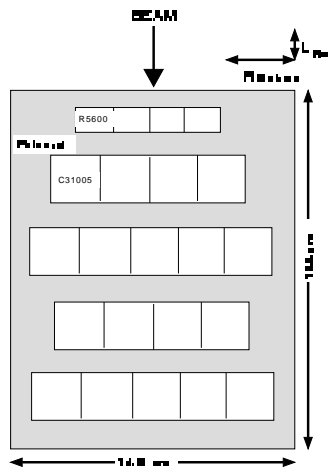


Figure 1: Layout of the scintillating fiber module. The white boxes indicate the pixels read out with Winston light-concentrators and phototubes.

3 Calibration and Energy Resolution

The calibrations were performed using incident electrons of energies 1.33, 1.93, and 5.07 GeV. In special calibration runs, the SciFi module was oriented so that each readout pixel was centered on the beam, with the pixel axis (i.e., the fiber axis) along the beam direction. The module was mounted on an x-y translator so that the 22 pixels could be centered remotely. One of the calibration spectra is shown in Figure 2.

Showers incident along the fiber axis can develop differently from those transverse to the fiber axis; this phenomenon is known as "channelling". While informal reports suggest the difference is not large (few percent), the calibration runs in our case show a severe non-linearity; this is shown in Figure 3. This non-linearity is the same for both of the phototube types used in the calorimeter, indicating that the non-linearity is indeed due to channelling. Because of the problem, only the 1.33 GeV calibration was used for the remainder of the analysis.

At 1.93 GeV, the beam intensity was rather high, resulting in a large number of pulses having multiple electrons; this is shown in Figure 3, and these "multis" events are used in the energy resolution measurement later. With the SciFi module in "shower position" (i.e., oriented so the pixel axes are transverse to the beam direction), the sum-energy spectrum is shown in Figure 4, where the calibration is corrected for the 50% pixel sampling area. A fit to 4 Gaussians is shown on the figure. The centroids of the peaks are plotted in Figure 5, which shows some saturation of the PMTs at the gain used in the test. In the analysis which follows, no correction is made for this non-linearity.

5.07 GeV electrons, cut on singles

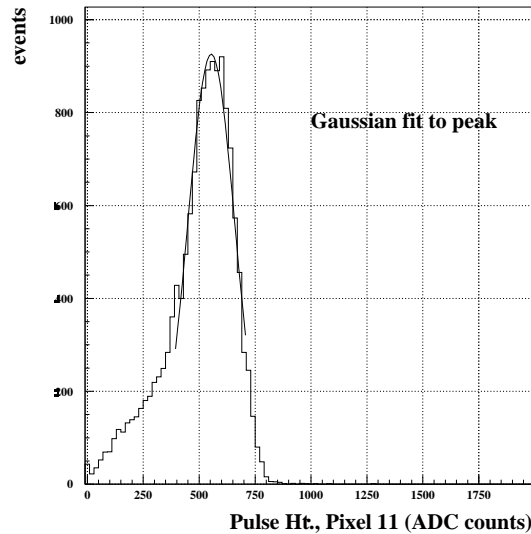


Figure 2: Calibration spectrum of the central pixel.

The energy resolution is degraded by shower leakage out of the back of the module. Figure 6 shows a comparison of the total SciPi energy with that of the NaI "tail catcher". No correction for the shower leakage is made in the analysis which follows; rather, the data is compared with Monte Carlo simulations which incorporate the leakage.

The energy resolution in "shower orientation" was obtained using the various incident electron energies, the multi-electron events, and lower energy photons (0.35 - 0.55 GeV) from the radiator-in runs. The resolution is shown in Figure 7. Note that no corrections have been made for shower leakage (about 20% for the test module), and that the dominant contribution to the resolution is from the readout sampling. The resolution obtained from the test module is much worse than what would be obtained with complete readout coverage, but the results are useful for comparison to Monte Carlo simulations (next section of this Note).

The transverse containment of the showers is quite good. Figure 8 shows the transverse energy profiles in rows 2-5 (the 1 inch pixels) for 5 GeV electrons.

At this point, most of the useful information from the test module has been discussed and awaits comparison to MC in the next section. A crude measurement of the reconstructed angle is shown in Figure 9, with the caution that data was taken at only one angular orientation of the test module, and we know from MC studies that the test module pixel arrangement was too coarse for good angle reconstruction. The figure shows reconstructed angles using the energy-weighted "moment of inertia" of the pixels (more sophisticated techniques are discussed later). The

Pixel 11 Calibration

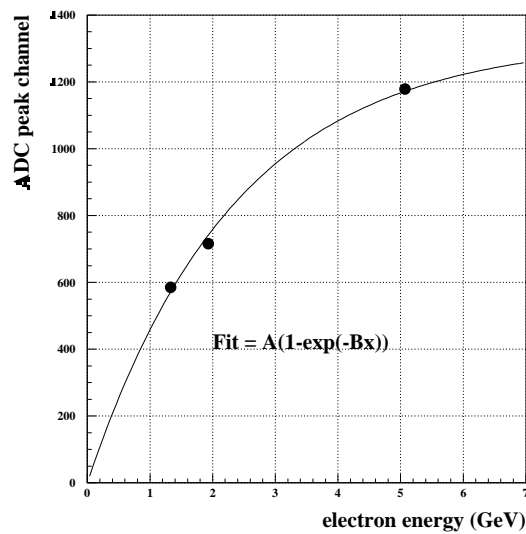


Figure 3: Peak ADC channel for single- e peaks in calibration mode. The electrons are incident along the fiber axis. Extreme non-linearity is due to shower "channelling" in fibers.

asymmetric profiles are due to the location of the beam axis with respect to the location of the pixel boundaries; for large pixel sizes near shower maximum, there are "pulls" in the center of gravity which bias the angle reconstruction. Anti-bias corrections are discussed in a later section.

1.93 GeV electrons

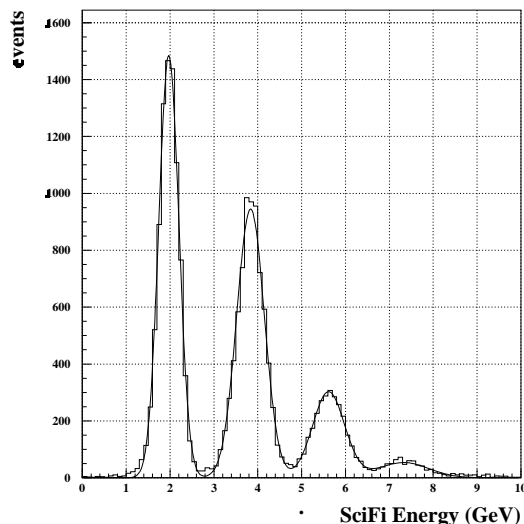


Figure 4: Sum energy spectrum for 1.93 GeV electrons.
The multiple peaks are n -electron pulses.

4 Comparison with MC

Monte Carlo simulations of the SciFi module were performed using the GEANT² package from CERN. In order to simplify the geometry, individual fibers were not simulated. Rather, the geometry consisted of a sandwich of Pb and scintillator slabs having the same volume ratios as the KLOE material, namely 48% Pb and 52% scintillator. (Actually, the KLOE fibers consist of 42% scintillator and 10% glue, but this distinction is not made in the MC.)

Cutoffs on the propagation of electromagnetic showers can have a significant impact on the results, especially in plastic scintillator. For the MC described here, a 100 KeV cutoff on photons and electrons was used for propagation in both the Pb and plastic.

Figure 10 shows a comparison of the longitudinal shower profile for 1.93 GeV electrons. While the MC does mimic the data fairly well, it is clear that the true radiation length is somewhat smaller than that simulated in the MC. A further consequence of this is somewhat better MC energy resolution than that in the data (Figure 11).

For the MC model of the test-beam module, the RMS energy resolution is predicted to be $14.6\%/\sqrt{E}$ for E in GeV; this compares well with the measured value of $15\%/\sqrt{E}$ (see Figure 7). The conclusion to be drawn from these comparisons is

²GEANT 3.21 is described in the CERN Program Library.

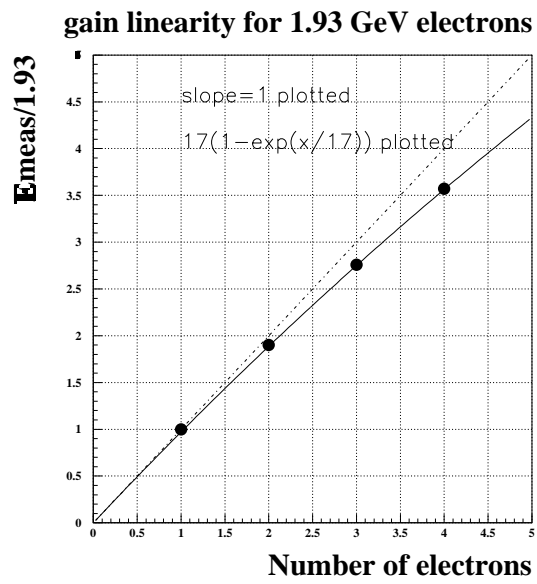


Figure 5: Measured energy of multi-electrons at 1.93 GeV. This demonstrates non-linearity of the PMTs.

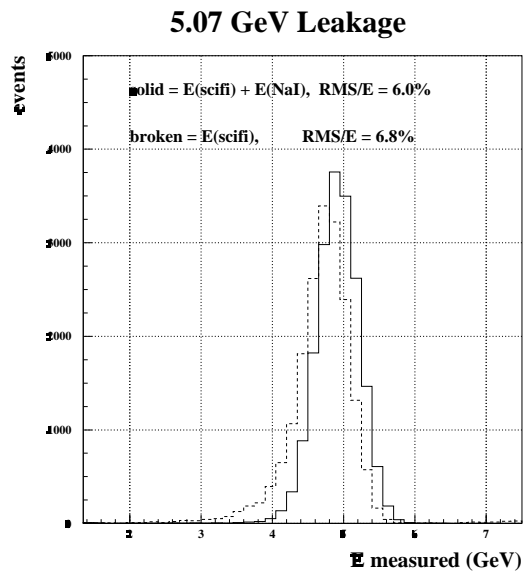


Figure 6: Comparison of total energy at 5.07 GeV for SciFi-only and SciFi+Nal.

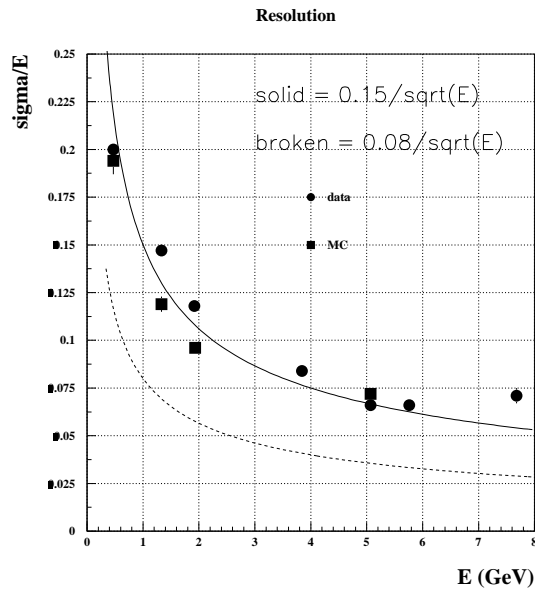


Figure 7: RMS energy resolution for all energies. Data points include electrons, photons, and multi-electrons. The broken curve shows the resolution expected with 1 cm pixels.

that module of 11.75 X_{rad} depth with *complete* sampling coverage would have an energy resolution of 8.3%; this is to be compared to the KLOE figure of $5\%/\sqrt{E}$ for a calorimeter with good shower containment.

In the following sections, angle and energy reconstruction techniques are studied using a MC which assumes complete readout coverage of the module and with 1 cm pixels.

5.07 GeV transverse profiles

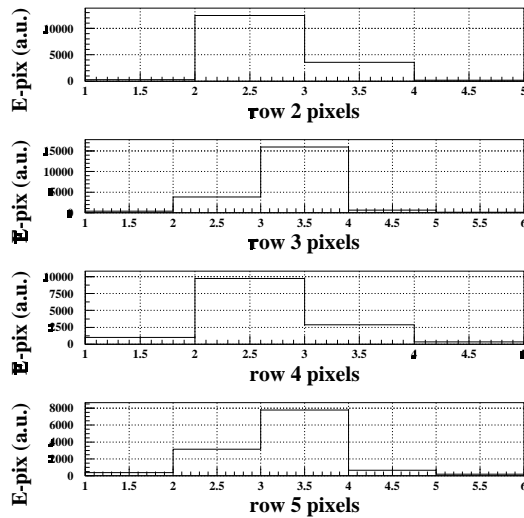


Figure 8: Transverse energy profile in row-3 at 5.07 GeV. The showers are well-contained transversely in the test module.

5 Angle Reconstruction

The most naive angle reconstruction method is to find the center of gravity (COG) of the energy profile in the calorimeter, and then to diagonalize the energy-weighted inertia tensor having the origin at the COG. This method is not dependent on an assumed beam axis. However, for pixellated sampling, the COG is "pulled" into the pixel centers, a well-known bias for this method. Figure 12 shows the bias for 1 cm and for 3 cm pixels.

The bias can be partially corrected by using the hyperbolic tangent function suggested by the previous figure. Figure 13 shows the reconstructed angles for various energies, using this bias correction. For these studies, the incident photons had angles in the range ± 0.4 rad and an entrance position distributed over the face of the central pixel. This method realizes an RMS angle resolution of $66 \text{ mrad}/\sqrt{E}$, for E in GeV; this is shown in Figure 14.

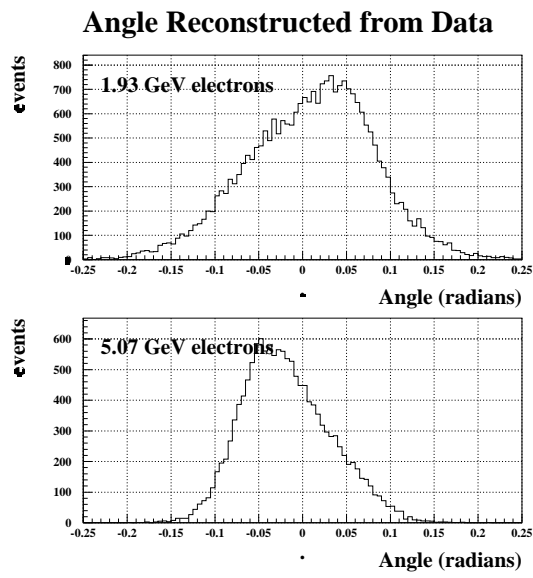


Figure 9: Reconstructed angle for 1.93 and 5.07 GeV. The non-gaussian shapes are due to limited sampling in the module.

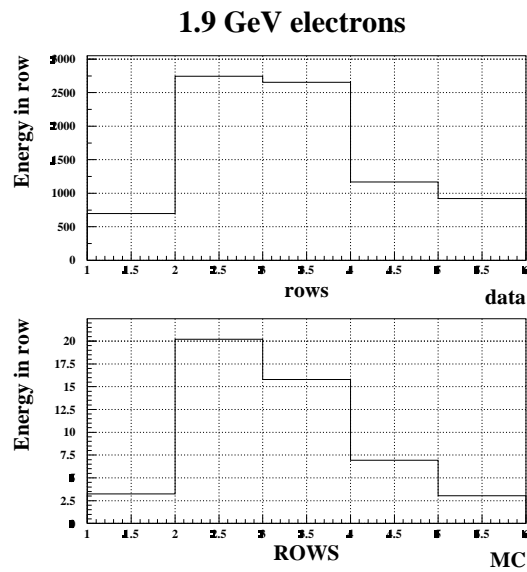


Figure 10: Longitudinal energy profile for 1.93 GeV data and MC.

1.93 GeV electrons: data and MC

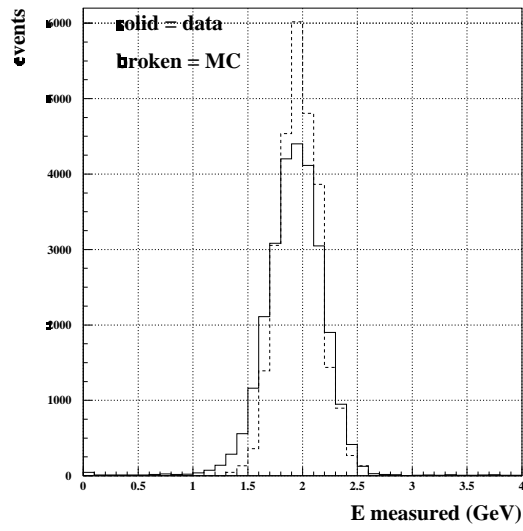


Figure 11: Total measured energy for 1.93 GeV data and MC.

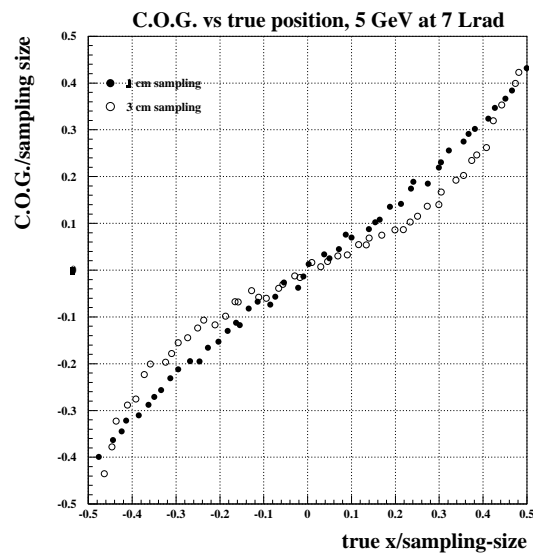


Figure 12: True position versus C.O.G. reconstruction.
Sampling sizes of 1 cm and 3 cm are shown.

Angle Reconstruction (moment method), 1 cm sampling

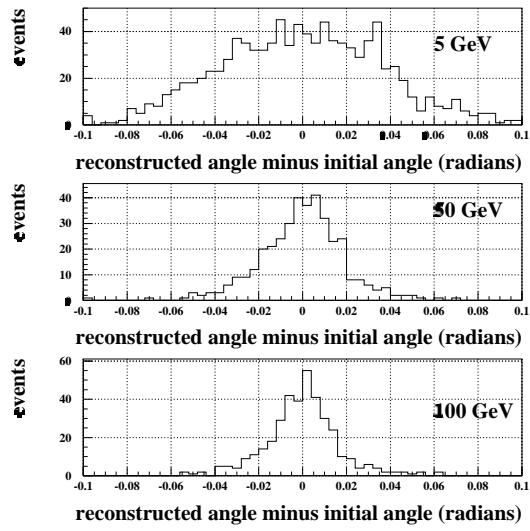


Figure 13: Reconstructed angle using 1 cm pixels. The moment method is used with 1 cm pixels.

Moment method, 1cm sample, bias-corrected

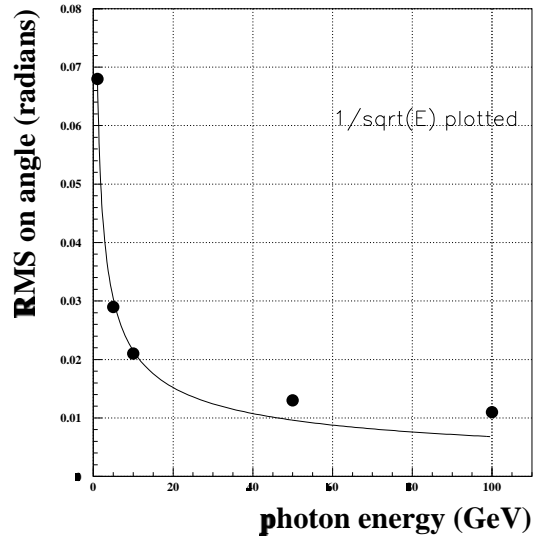


Figure 14: Angular resolution as function of photon energy.

6 Energy Correction

Showers of energy larger than several GeV have shower-maxima which fluctuate over many centimeters, and are often ill-contained in the calorimeter. Figure 15 shows the longitudinal profile of two showers from 50 GeV photons. The distribution of shower maximum for the 11.75 L_{rad} module is shown in Figure 16.

50 GeV photons

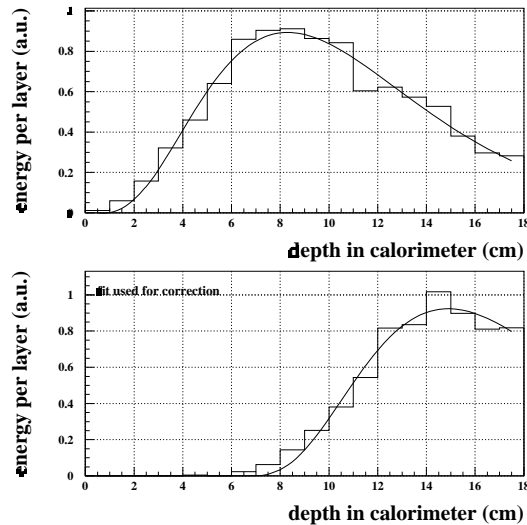


Figure 15: Longitudinal energy profiles for 50 GeV photons.
1 cm sampling is used.

For 1 cm pixels, the shower profile at all energies is fitted well by a gamma function. This fitted shower maximum can be used either to reject high energy events having "late" showers, or to correct the energy using the fitted parameters. Figure 17 shows the raw fiber energy and the corrected energy for 50 and 100 GeV photons. While the RMS on the fitted energy is not much improved, the low energy tail is eliminated. Figure 18 shows the RMS energy for raw energy, corrected energy, and raw energy for events with "good" fitted shower-maximum.

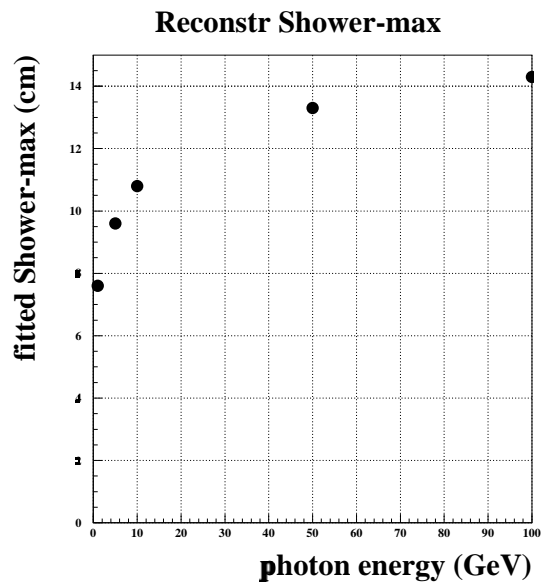


Figure 16: Fitted shower-maximum position at 50 GeV. 1 cm sampling is used.

7 Conclusions

The results from the beam test of the Chicago scintillating fiber module support the characteristics published by the KLOE collaboration and are well simulated by the Monte Carlo. Imaging calorimetry clearly has a number of advantages over monolithic or longitudinally segmented calorimetry. Profiling of the shower allows for good angle reconstruction of multi-GeV particles without the use of a conversion-tracker, and also permits tagging of high-energy shower fluctuations.

50 and 100 GeV photons

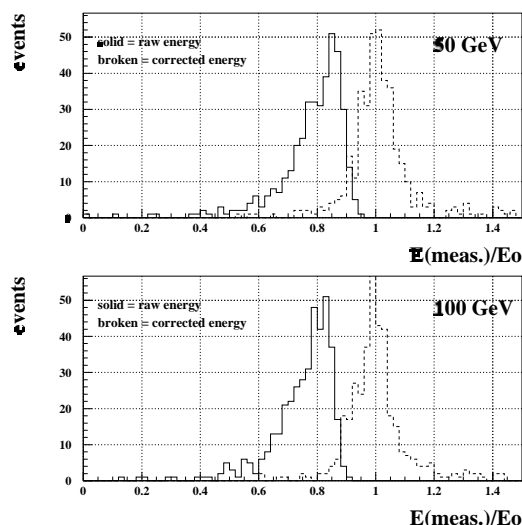


Figure 17: Comparison of raw and corrected energy distributions. Correction is based on 1 cm sampling.

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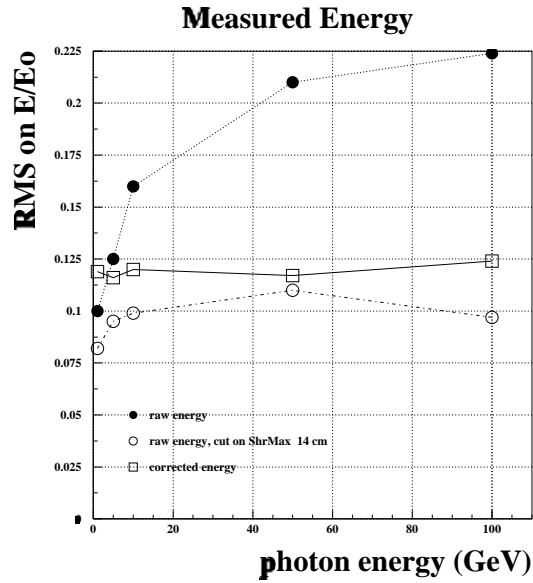


Figure 18: Measured and corrected energy resolution.
 The raw energy has good resolution when shower-maximum is less than 14 cm.