Simulation of analog and digital energy measurements in the LDC electromagnetic calorimeter end-caps

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Abstract

The energy resolution of the electromagnetic end-caps of the future LDC detector has been studied using two methods: the analog method, using the energy deposited in the active layers; and the digital one based on the number of hitted cells. The simulations show that for electron energies above 4 GeV, the energy resolution is better for the analog method while for low energies ($E < 4$ GeV), the digital method gives a better resolution. Other techniques, i.e. an hybrid method combining analog and digital methods or a modified digital method, have been tested to improve the energy resolution.

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1 Introduction

The primary goal of a detector at a futur e^+e^- linear collider will be to make precision measurements and the discovery of new physics signals. Detailled studies of the detector components, including simulations and tests of detector prototypes, are crucial to understand the detector response and estimate its resolution.
In a previous work [1], the energy resolution has been studied for the electromagnetic calorimeter end-caps, using the energy deposited in 10×10 mm^2 cells (analog method). The energy can also be measured using the number of tracks (digital method) which gives an energy resolution depending on the cell size. In a recent version of the LDC electromagnetic calorimeter, smaller size detection cells (3×3 mm^2) are used, which makes interesting a comparison between analog and digital methods.
The simulated end-caps version is made by 500 μm thick active silicon layers. The 30 active layers are preceded by 1.4 mm of tungsten (W) and the last 10 by 4.2 mm of W. Simulations were performed using Mokka simulation software [2], for electrons energy from 1 to 300 GeV. For the detector configuration, only the electromagnetic calorimeter has been taken into account (-s ecal07 option). Except when it is mentionned, the size of detection cells was 3×3 mm^2. All simulations were done with a polar angle equal to 21.80 degrees.

2 Analog and digital methods for energy resolution study

2.1 Analog and digital methods

In the analog measurement, the energy deduded from the electromagnetic end-cap is given by the relation:

$$E_{anal} = \alpha(E_1 + \beta E_2)$$

Where E_1 represents the energy deposited (in MeV) in the first compartment, i.e. in the first 30 active layers of silicon, and E_2 the energy deposited (in MeV) in the last 10 layers (compartment 2).
The α parameter is an overall coefficient of normalization and β represents the relative weight of the 2 compartments which sample the energy deposit of the incident electron. The value of β is obtained by minimizing the energy resolution for each considered energy.

In the digital measurement, one uses the number of the hitted cells to reconstruct the beam energy. The correlation between the average number of hitted cells and the incident energy (figure 1) shows a linearity at low energy (E $\leq$ 20 GeV) while for dense showers, a non-linear behavior is observed.

The energy deduced from the electromagnetic end-cap is given by the relation:

$$E_{dig} = \alpha(N_1 + \beta N_2)$$

where N_1 represents the number of hitted cells in the first compartment, and N_2 the number of hitted cells in the second compartment. Alpha and β have the same signification as in the analog method.
The energy resolution σ/E dependence on the cell size in the digital measurement is shown in figure 2. The resolution strongly changes from 10×10 mm^2 to 3×3 mm^2 detection cells with an improvement up to 25%. The same behavior has been observed for a digital hadron calorimeter with K_L^0 [3]. The cell size effect is however smaller for K_L^0 than for electrons, the hadron showers are less dense than electromagnetic showers, so effects of multiple hits in a digital calorimeter should be stronger for electrons.
We also noticed that the value of $N_T = N_1 + N_2$ is almost three times larger for 3×3 mm^2 detection cells than for 10×10 mm^2.

2.2 Analog-Digital methods comparison

Figures 3 and 4 show the evolution of α and β parameters according to the energy E for the two methods, respectively. One can notice that, for the analog method, the value of β is approximatly constant "around 3.0" (which is compatible with the ratio between the W thicknesses in the two compartments); while a strong correlation between β and E is observed for the digital method. A similar behavior is observed for the α parameter (figure 3). The difference between the maximum and minimum values of α doen't exceed 1% for the analog method wheras a difference of 200% is observed in the digital case. It results that in the analog method, one can use the average values of α and β whereas for the digital method, the procedure should be more complicated.
In spite of the strong dependence of α and β on energy, it is possible to rebuild the energy from the number of hitted cells if the relations binding α and β to the energy are known with a good accuracy.

The resolutions obtained with the two methods according to the electrons energy are compared in figure 5. It can be clearly seen that for low energies (E $<$ 4 GeV), the digital method is better than the analog one whereas for high energies, the analog method leads to better resolutions. The behavior observed at low energies is due to the Landau fluctuations in the energy loss process which affect the analog method energy resolution. The use of the digital method could be therefore of a big interest at low energy which can concern several physical processes succeptible to be studied at the ILC.

The energy resolution obtained with each method was fitted by the function:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus c$$

One obtains:

Method	a(% $GeV^{1/2}$)	c(%)
analog	12.1 $\pm$ 0.16	0.57 $\pm$ 0.039
digital	13.19 $\pm$ 0.18	2.03 $\pm$ 0.032

One can remark that the classical parametrization of the fit for the analog method seems not to be the optimum for the digital method, see for example figure 2.

3 Analog-Digital hybrid method

In this part we proposed a new method which consists in using the two previous methods together to increase the energy resolution. The use of an hybrid method is possible since even if an analog energy measurement is adopted, the digital information will always be disponible.
The energy deduced from the electromagnetic end-cap will be then given by the relation:

$$E = \alpha_1 E_{anal} + \alpha_2 E_{dig}$$

$$with \quad \alpha_1 + \alpha_2 = 1$$

α_1 and α_2 are the relative weights of the analog and digital methods respectively. α_1 (α_2) is obtained by minimizing the energy resolution for each considered energy. Figure 6, shows the evolution of α_2 according to energy: the observed evolution is in perfect agreement with the results shown in figure 5, i.e. at low energy, the two methods are close to each other other giving $\alpha_2 \geq 50\%$. The weight of the analog method increases with the energy.
Figure 7 shows the energy resolution obtained with the three methods (analog, digital and analog-digital). By comparing to the analog method, the analog-digital hybrid method gives an improvement of about 8% at low energy and 2% at high energy.
The fit parameters a (sampling term) and c (constant term) are compared below:

Method	a(% $GeV^{1/2}$)	c(%)
analog	12.1 $\pm$ 0.16	0.57 $\pm$ 0.039
digital	13.19 $\pm$ 0.18	2.03 $\pm$ 0.032
analog-digital	11.27 $\pm$ 0.22	0.63 $\pm$ 0.047

4 Multiweight digital method

The resolution in energy obtained with the digital method can be improved while assigning an individual weight to every layer (40 weights to optimize). This can be made by using neural networks. In this work, we start by a simpler method which consists in subdividing the 40 layers in 8 blocks of 5 active layers and assigning a weight to every block (8 weights to optimize).
The total energy is given by:

$$E = \alpha \sum_{i=1}^{8} (\beta_i E_i)$$

The optimization is made by steps: one starts to assign the same weight to all blocks (β calculated for the considered energy), then one optimizes successively the weights of the different blocks. The β_i evolution with energy is given below:

E (GeV)	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8
5	0.88	1.08	1.08	1.12	1.00	1.00	1.79	1.47
10.	0.52	1.00	1.04	1.08	1.04	1.04	1.80	2.41
15	0.45	0.88	1.00	1.08	0.96	1.08	1.72	1.87
20	0.48	0.88	1.00	1.12	1.00	1.12	1.92	2.36
60	0.30	0.33	0.92	1.00	1.08	1.24	2.20	2.20
100	0.29	0.82	1.14	1.14	1.46	1.94	3.36	3.12
150	0.20	0.74	1.06	1.14	1.22	1.54	3.65	3.39
200	0.16	0.88	1.04	1.12	1.16	1.72	3.60	3.60
300	0.00	0.76	1.04	1.16	1.16	1.42	4.88	4.08

Figure 8 shows the energy resolution improvement between the digital and the multiweight method. A marked improvement, up to 15%, can be reached at high energy. In figure 9 are compared the resolutions given by the analog and the multiweight digital method, the same behavior is observed, as in figure 5, with a clear difference between the two methods at high energy.

The following table gives a comparison between the fit parameters a and c obtained for the four methods tested in this work:

Method	a(% $GeV^{1/2}$)	c(%)
analog	12.1 $\pm$ 0.16	0.57 $\pm$ 0.039
digital	13.19 $\pm$ 0.18	2.03 $\pm$ 0.032
analog-digital	11.27 $\pm$ 0.22	0.63 $\pm$ 0.047
multiweight digital	12.96 $\pm$ 0.27	1.90 $\pm$ 0.030

4.1 Conclusion

The energy resolution of the electromagnetic end-cap for the future LDC of the ILC was studied in this note thanks to the MOKKA simulation software. Two methods were used: the classical analog method (measurement of the deposited energy) and the digital method (number of hittd cells). In general, the results indicate that the energy resolution obtained with the analog method is better than what can be deduced from the digital one. However, at low energy (E $<$ 4 GeV), the digital method gives better resolutions because of the Landau fluctuations which contribute and degrade the analog resolution. The use of a digital method will be very helpful for low energy electrons and photons.
Since the digital information will be always available, we can exploit it to improve the analog resolution. Results show that an improvement of 8% can be reached at low energy with an analog-digital hybrid method.

Many efforts have been done to enhance our understanding of the electromagnetic digital measurement which is specific to finely-segmented hadronic calorimeters where a perfect linearity between the energy and the number of hitted cells is obseved. We proposed a simple method with a longitudinal segmentation of the calorimeter in blocks having different weights. The modified digital measurement gives a marked improvement of the resolution at high energy. A better improvement can be reached with the neural network method. Other investigations are in progress in order to find the best way to exploit the digital measurement.

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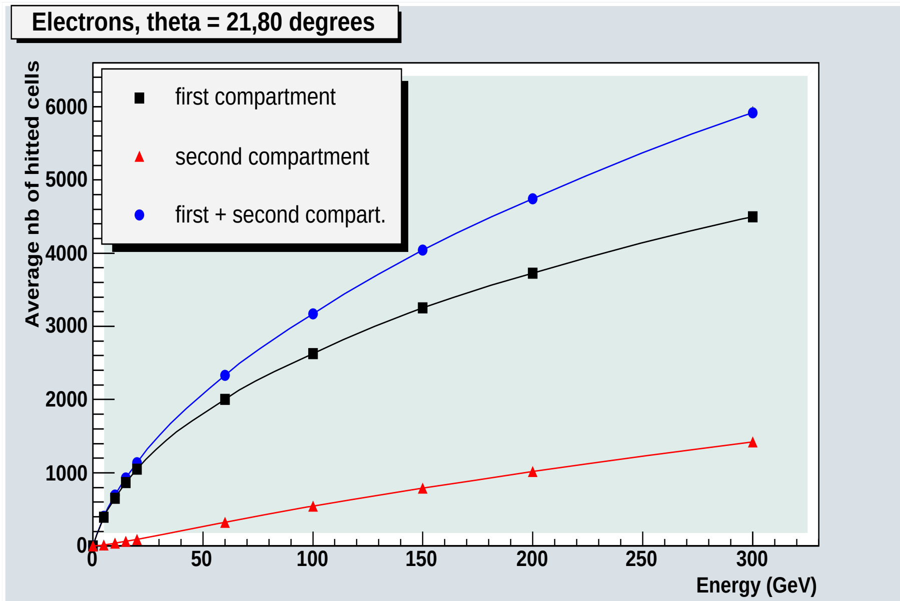

Figure 1: Number of hitted cells as a function of the incident energy.

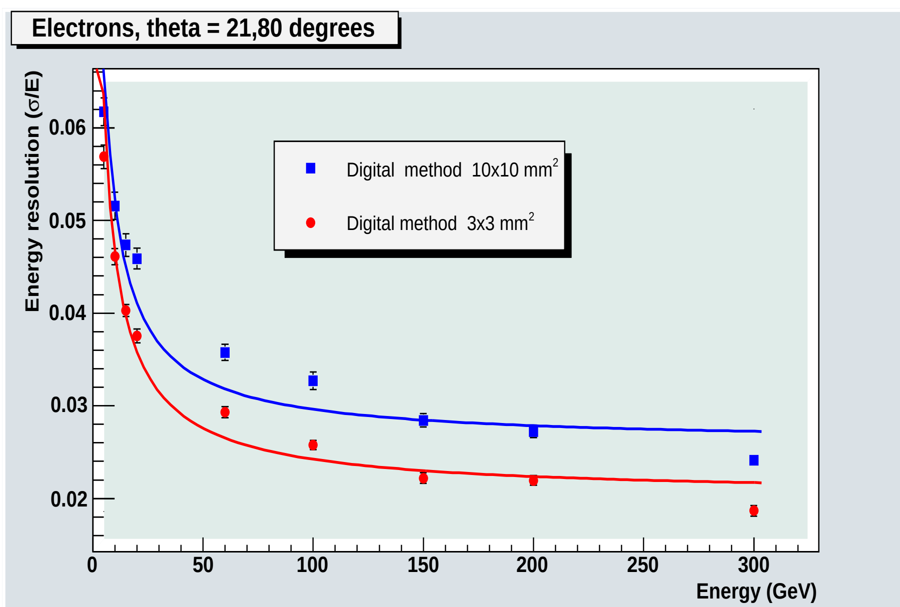

Figure 2: Digital energy resolution for 10×10 mm^2 and 3×3 mm^2 detection cells. The fit parametrization is described in section 2.2.

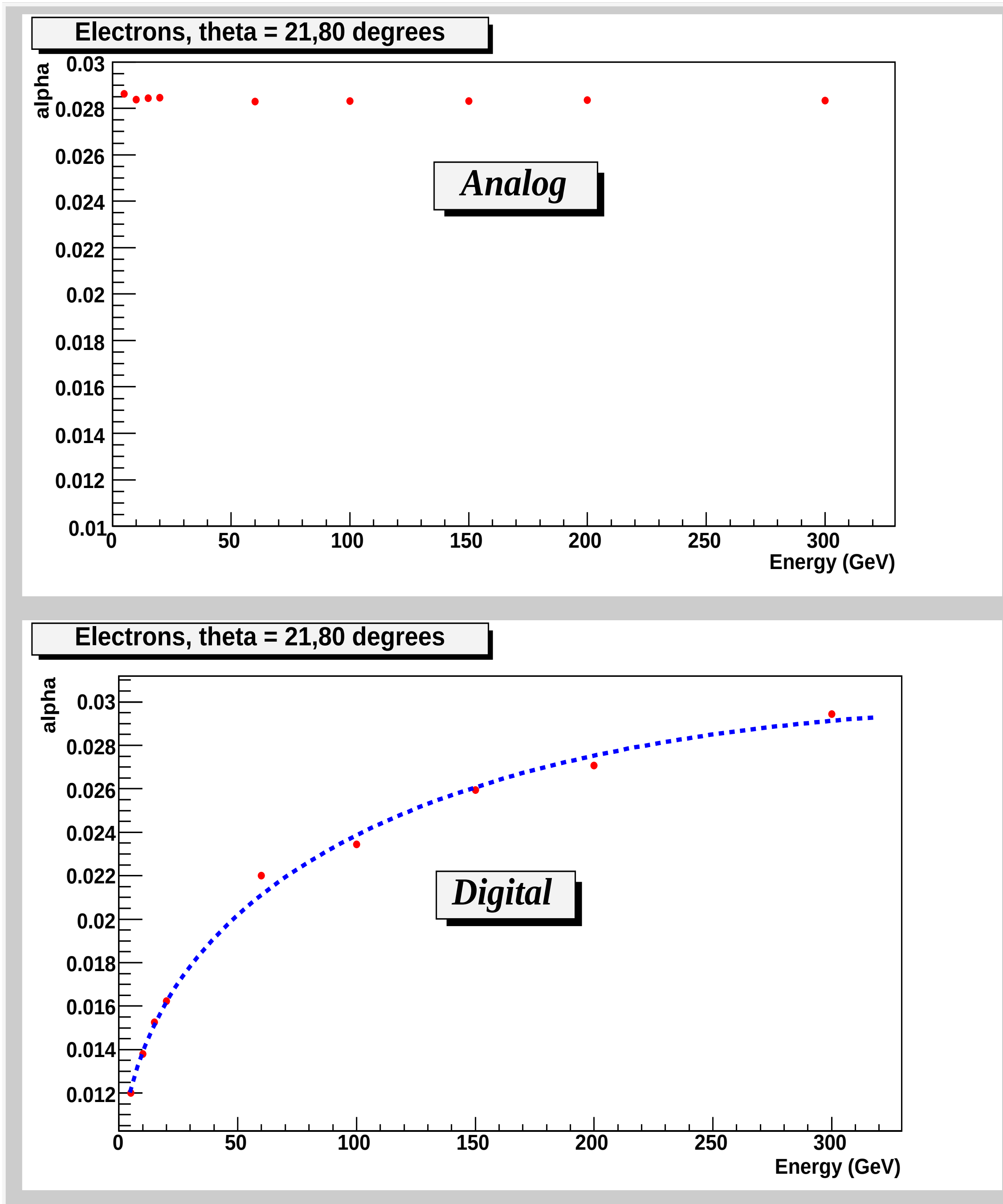

Figure 3: Evolution of α according to the energy for the analog and digital measurements.

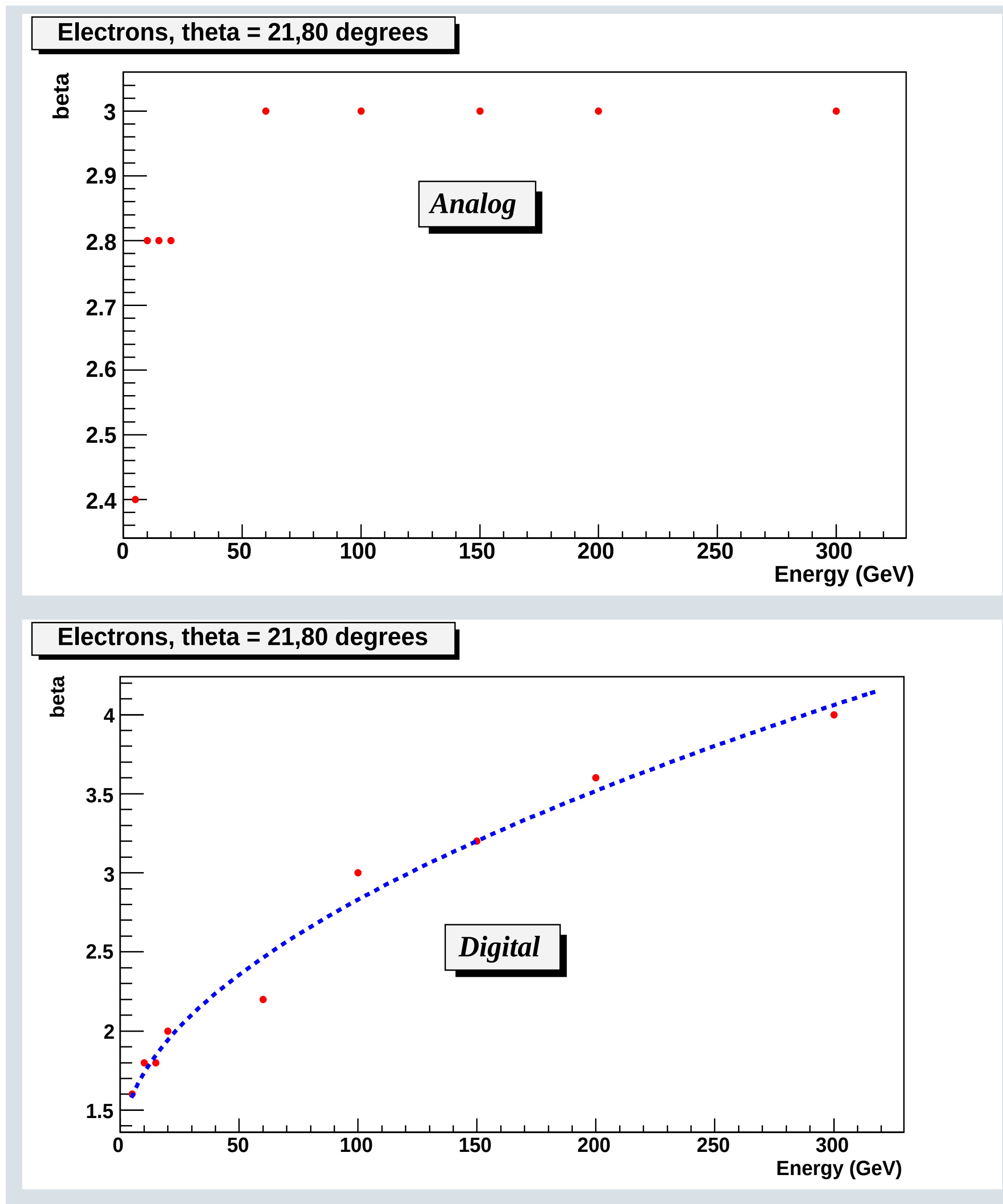

Figure 4: β evolution according to the energy for the analog and digital measurements.

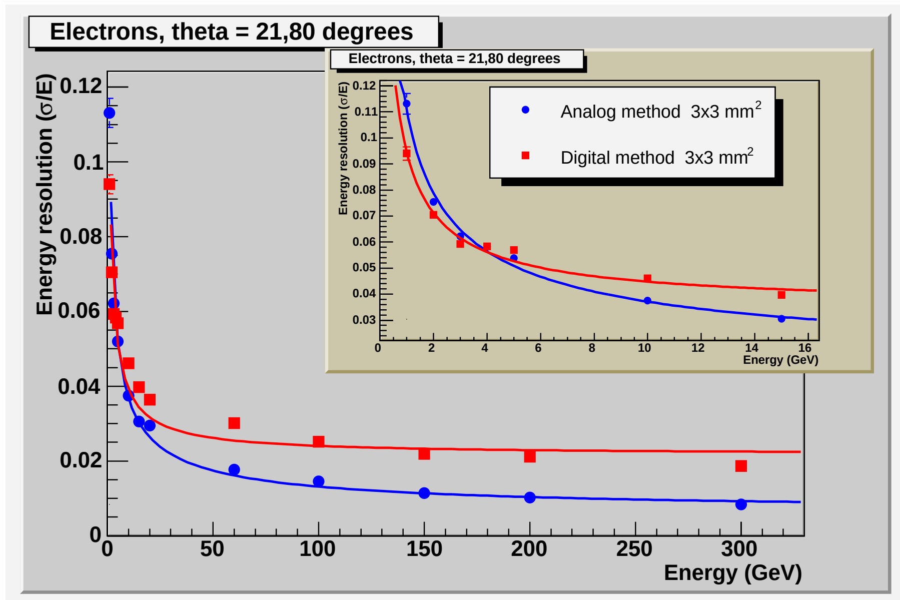

Figure 5: Energy resolution according to the energy E for analog and digital measurements.

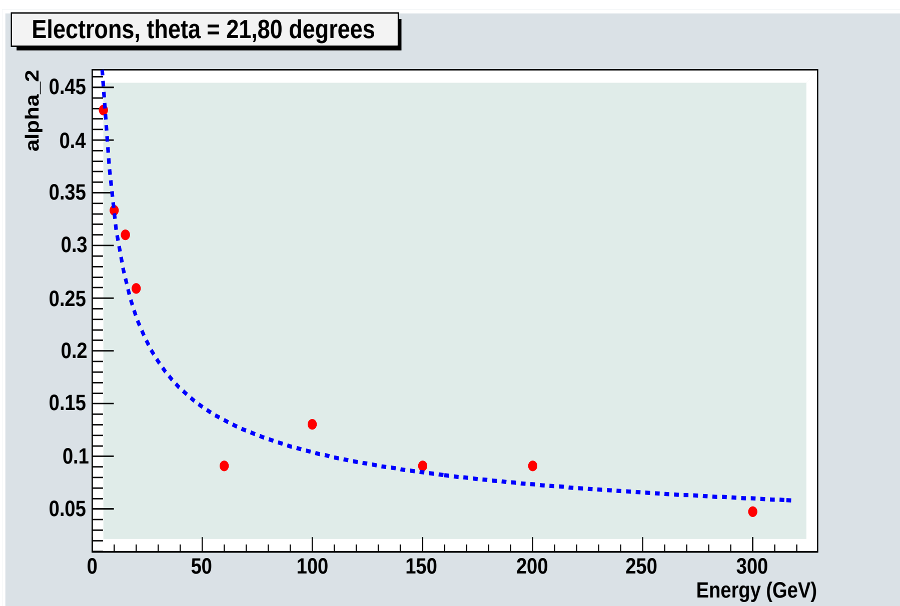

Figure 6: Evolution of the weight α_2 of the digital method according to the energy E.

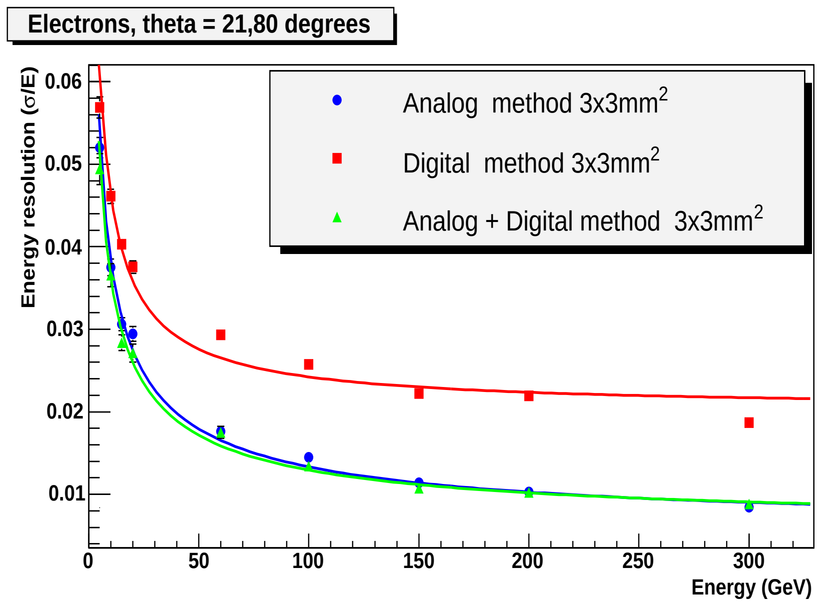

Figure 7: Energy resolution according to the energy E for analog, digital and analog-digital hybrid methods.

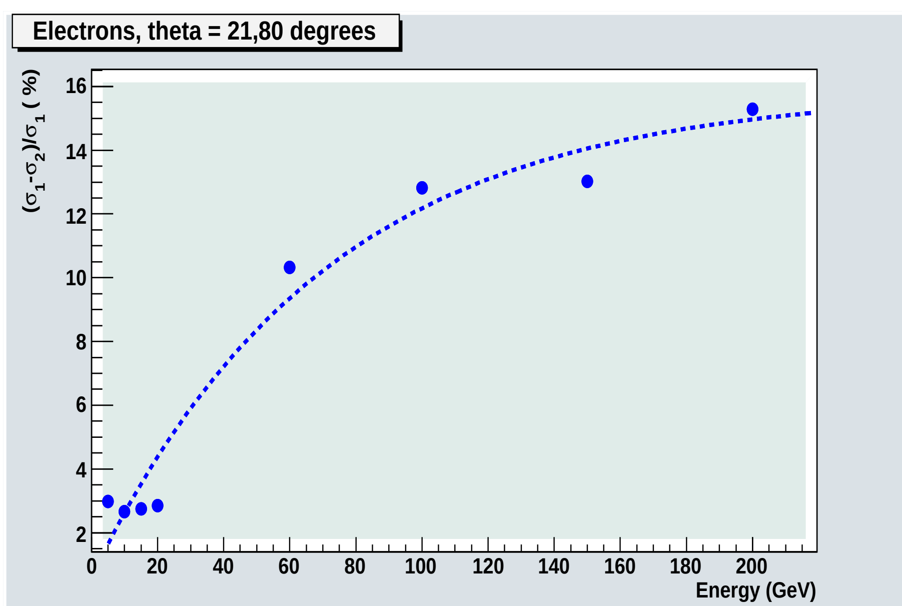

Figure 8: Energy resolution improvement between digital and multiweight digital methods.

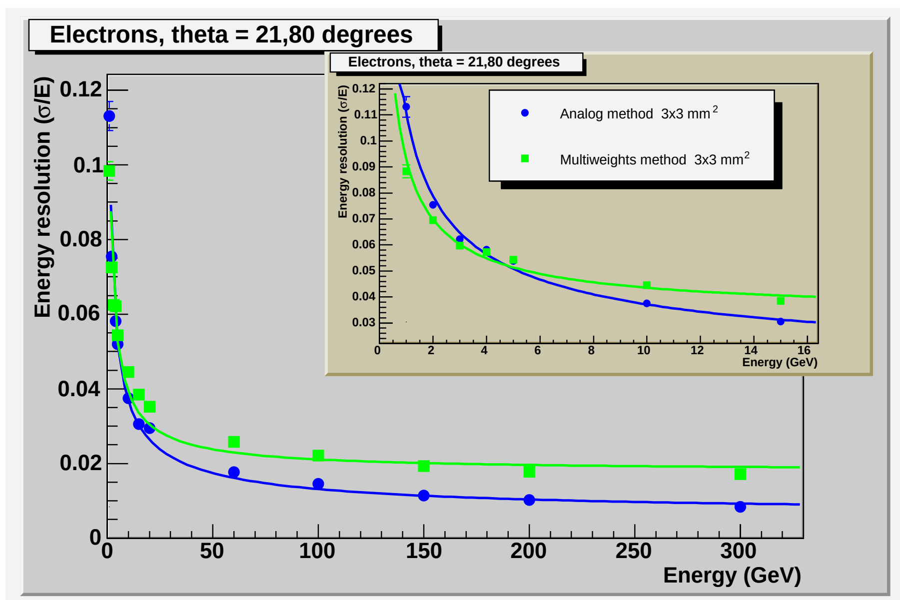

Figure 9: Energy resolution according to the energy E for analog and multiweight digital method.