V.Epshteyn (ITEP, Moscow) ATLAS-FCAL beam test Note 10, 2004-06-09
Last update: 2004-09-07, with P.Gorbunov (Univ. of Toronto and ITEP)

GEANT3 simulation of the FCAL performance and a comparison with TB'2003 results

In this note the FCAL characteristics measured in electron and pion beams in the 2003 tests are confronted with MC GEANT 3.21 simulations. A good agreement with electron beam data is achieved and used as a basis for a pilot MC study of the FCAL response to pions.

The simulation model includes:

- the beam particle absorption in the calorimeter, simulated with GEANT 3.21 (ATLAS version with ATLSIM extensions);
- a conversion of the energy absorbed in liquid argon into ion-electron pairs;
- a drift of electrons in liquid argon;
- a formation of the current signal in individual tubes;
- a formation of an output signal from the groups of tubes;
- the electronics noise (optionally, for electrons only);
- the amplifier-shaper;
- sampling of the shaped signal with the FADC.

In the case of a full simulation, the output data are formatted into a data stream similar to the Fcal'2003 raw data and the same analysis software is used to analyze real and simulated data. For the FEB signal reconstruction (fit) in each event, the waveform shapes from the FCAL electronics simulation are used. For convenience of the comparison of real and MC data, the transformation factor of the electronic channel is chosen so as to get the average signal amplitude of 1160 ADC counts for 100 GeV electrons − approximately the same as for real electrons.

MC samples

Electrons were simulated for the energies of 5, 10, 20, 30, 40, 60, 80, 160 and 320 GeV and pions − for 20, 40, 80, 160 and 320 GeV. The number of simulated events varied from ~4000 for lowest energy to ~600 for the highest energy.

The geometry and beam parameters

The FCAL 1, 2 and 3 modules were described in the GEANT 3.21 model as 45 cm deep blocks with a square cross-section of 50×50 cm², see Fig. 1. The auxiliary elements like the tubes and spacers were neglected. This simplification (compared to the standard ATLSIM geometry[1]) helped to speed-up the simulation, without any loss in the physics outcome − at least for particles hitting the area with a regular tube structure. That the influence of the auxiliary elements could be neglected, was shown in a separate study conducted before starting a mass MC production.

The beam impact point was uniformly spread over the $|X|\leq3.5$cm, $|Y|\leq3.5$cm. An additional data set was produced with a fixed impact point at X=Y=0 (the center of a rod), for electrons. The slope of the beam particles was, by a mistake, set to $\theta=4.3^{o}$ ($Pz=P0*\cos(\theta)$, $Px=P0*\sin(\theta)$, $Py=0$)

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[1] See, e.g., `http://atlas-php.web.cern.ch/atlas-php/NOVA`

− slightly greater than in the 2003 test beam (3^{0}). *The influence of the beam angle will have to be studied.*

No material in front of the calorimeters was simulated.

1. The results for electrons

- **GEANT (Atlsim) parameters**:

– Tracking: stemax=stmin=epsil=50 μm (actually, the results were practically stable below 400 μm);

– cutoff energy: 10 keV;

– HITS {name} x:0.001: y:0.001: z:0.1: tof:0.5E-9:(0, 1.E-7) eloss:0: .

- **Signal clustering.** As was discussed in earlier analysis notes [1], the energy of electron-induced events − both in real and MC data – was reconstructed by summing up the FCAL1 signals within a circular cluster area of the radius *r_core,* centered at the particle impact point[2]. From *r_core*=8 cm on, when a full containment is reached, the response and the resolution – both for data (with the noise subtracted) and MC (with the noise turned off) – do not depend on *r_core*. All the results below are quoted for *r_core* = 8 cm.

- **Sampling fraction** – a mean fraction of the energy deposited in the active liquid argon gaps – 1.44% (the same value was obtained in the earlier GEANT3 study – [2, Table 1]).

- **Current-unit calibration for the FCAL1** – the correspondence between the amplitude of the total current in the tubes and the incoming particle energy – 1.7 μA/GeV (for the ion-electron pair production energy of 25 eV/pair).

- **The response** depends linearly on the incoming particle energy. However, unlike with real data [1], there is no offset in the MC results. This can be related to the absence of a simulated dead material in front of the FCAL and to the way of processing of very small signals. *A further study is required.*

- **"Measured" energy distributions for MC** are shown in Fig. 1.1. As the electron energy increases, one observes an increasing deviation of these distributions from the Gaussian shape: the right tail gets longer and the left tail shorter. The same behavior is seen in the experimental data. What causes this effect? When analyzing the real data [1], we suggested that this could be related to the electronic noise. Since it was impossible to exclude the noise from data, we were adding *extra* noise by hand, which resulted in *decreasing* the distribution asymmetry. This indirectly supported our hypothesis on the randomizing effect of the noise.

  In MC we could turn the noise off entirely and see that without it, the deviation from the Gaussian shape persists at all energies, Fig. 1.2. Therefore, this effect is a property of the absorbed energy fluctuations. At low energies, when the noise contribution is greater or comparable with the absorbed energy fluctuations, the effect of the latter is masked out.

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[2] It is assumed that in the case of real data the impact point can be accurately measured with the beam trackers.

Table 1 Parameters a, b, c of the energy resolution formula, for electrons

№	condition	a, %	b, %(√GeV)	c, %(GeV)
1	Model, noise off, X=0, Y=0	1.08±0.13	20.3±0.2	-
2	Model, noise off, |X, Y|≤3.5cm, Efluct_only	3.92±0.11	21.6±0.4	-
3	Model, noise off, |X, Y|≤3.5cm	3.96±0.10	22.5±0.4	-
4	Model, noise on, |X, Y|≤3.5cm, Efluct _only	3.70±0.22	24.6±3.9	141±5.4
5	**Model, noise on, |X, Y|≤3.5cm**	**3.67±0.26**	**23.9±3.8**	**140±6.3**
6	Model, noise on, |X, Y|≤3.5cm, Efluct _only, E_Gaussian	3.92±0.08	21.2±1.3	140±3.3
7	Model, noise on, |X, Y|≤3.5cm, E_Gaussian	3.94±0.08	21.8±1.3	139±2.7
8	**Test 2003 data**	**3.76±0.06**	**24.5±0.8**	**145±1.6**

Notes:

- Efluct _only – only fluctuations of the energy absorbed in the active Lar gaps are taken into account. By default, the GEANT simulation is used, unless the "E_Gaussian" option is selected. The subsequent signal formation and digitization are not simulated.
- E_Gaussian – the energy deposited in the active Lar gaps is modelled by a Gaussian distribution $G(R(E), \sigma(E))$, where $R(E)$ and $\sigma(E)$ are the average response and the resolution computed with the "Efluct_only, noise off " options for the beam energy E. The purpose of this mode is explained in the text.
- noise on/off – the electronics noise is simulated (on) or not (off).

The simulated measured energy distribution for a fixed beam impact point X=Y=0, without noise (Fig. 1.3), is much closer to the Gaussian that for a smeared beam. The same plots also demonstrate the dependence on the impact point co-ordinates.[3] When the beam is smeared over the calorimeter area, the resulting energy distribution consists of individual partial distributions with different means and develops the observed shape distortion. Note, that the FCAL1 response averaged over the area |X, Y|≤3.5 cm is *greater* than the response for the fixed impact point X=Y=0.

We conclude that the main cause of the non-Gaussian shape of the measured energy distributions is the lateral structure of the calorimeter.

- **The energy resolution.** Fig. 1.4 shows a good agreement of the model with the experimental data. Let us take a closer look at the calorimeter resolution and the parameters ***a, b, c*** of the resolution curve $\frac{\sigma(E)}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}$ (Fig. 1.5 and Table 1). The parameters found from the full simulation and from the real data (lines 5 and 8 of the Table 1) agree within the statistical errors.

The constant term ***a*** is different from zero even if the particle hits the fixed point at the FCAL1 front face (for X=Y=0, ***a***≈1%). With |X, Y|≤3.5 cm, the constant term increases to ≈3.7%, for the reasons discussed earlier. For an additional illustration, see Fig. 1.6 showing a simulated response as function of the impact point X- and Y co-ordinates. The response is

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[3] This dependence, earlier studied in 1998 FCAL beam tests [2], is further illustrated below, at the discussion of the constant term of the energy resolution

modulated along Y and is flat in X. A similar behavior is observed in real data (see Figures 10, 11 of [1] and the explanations therein).

The stochastic term ***b*** slightly increases (from 20% to 22%, lines 1 and 3 of Table 1) when switching from a "pin" beam (X=Y=0) to a diffused beam |X, Y|≤3.5 cm − again, because of the dependence of the response on the impact point position. Fig. 1.5 shows that there is no energy domain where the stochastic term clearly dominates. Its influence is noticeable only in the narrow energy range of (30-60) GeV. At lower energies the resolution is dominated by the noise term, at higher energies − by the constant term. As a consequence, the estimation of the stochastic term from the resolution curve is not robust: it can be expected to be very sensitive to statistical uncertainties in σ/E determined within the full energy range.

Indeed, adding the electronic noise to the simulation model leads to a sharp increase of the error of ***b*** (lines 3 and 5 of Table 1). With such big errors it is hard to say anything on a possible influence of the electronic noise on value of this parameter. The GEANT statistics needs to be increased by an order of magnitude, which is currently impossible due to limited CPU resources.

However, if we wish to assess the effect of all factors beyond the energy absorption in the calorimeter and the noise – the electronics, digitization, signal shape reconstruction etc – a simplified MC model without GEANT, assuming a purely Gaussian absorbed energy spread, can be employed. In that case, we could easily multiply the statistics. We see (lines 6 and 7 of Table 1) that the effect, if any, is very small (a few percent of ***b*** value). We also note that, expectedly, ***a*** is not sensitive to the "post-noise" contributions.

The conclusions: for electrons, we have a fairly good agreement between predictions of the GEANT 3.21-based model and the behavior of the real FCAL. However, to reduce the errors of the predicted stochastic term, a sharp increase of the MC statistics is required. The origin of the observed FCAL response offset (in particular, the role of the material in the beam line) has to be separately studied.

2. The results for pions

- **GEANT (Atlsim) parameters**:
  - stemax=200μm, stmin=200μm, epsil=200μm, [4]
  - cutoff energy for electromagnetic processes was set to 10keV, for hadronic processes - 10MeV,
  - HITS {name} x:0.001: y:0.001: z:0.1: tof:0.5E-9:(0, 1.E-7) eloss:0:

- **Noise subtraction.** Practically at all energies of the 2003 tests, the noise dominates over other signal fluctuations. Accordingly, including the noise in the model would make it more difficult to estimate the constant and stochastic terms of the energy resolution. Therefore, the MC results for pions presented here are obtained with the noise turned off, while the experimental data points are given with the noise statistically subtracted.

- **The response**
  Like with the experimental data, to compute a response for a given event we selected a cylinder with the radius *r_core* centered at the particle impact point at the front face of FCAL1. Then we took signals from all the tubes in FCAL1, 2 and 3 whose centers fall inside this cylinder and summed them up according to the formula

$$FCAL = g1 \cdot FCAL1 + g2 \cdot FCAL2 + g3 \cdot FCAL3,$$

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[4] See some remarks about choosing these parameters below.

where *g1, g2* and *g3* were the equalization factors.

We tried the *r_core* values of 16, 20 and 25 cm and found that starting with 20 cm, the response and the resolution, both for data and MC, did not depend on *r_core.* All the results below are quoted for *r_core* = 20 cm.

Table 2 Equalization factors for FCAL1, 2 and 3

	g1	g2	g3
Efluct _only	1	1.5	1.116
Current amplitude in tubes	1	2.199	2.673
Total	1	**1.874**	2.021

Notes:

- Efluct _only –the same as in Table 1; the factors are, in essence, ratios of sampling fractions FCAL1/FCAL2 and FCAL1/FCAL2.
- Current amplitude in tubes – the amplitudes of the total current in the tubes.
- Total – the amplitude of the fitted total measured waveform (the same notion of the total signal amplitude, as applied to the experimental data, see [1]).

One way to inter-calibrate the FCAL modules is to equalize their response to electrons. Table 2 shows the MC equalization factors yielded at different stages of the simulation. Since the calibration of FCAL2 and 3 with electrons was not carried out in the 2003 tests, in the earlier beam data analysis [1] we evaluated *g2* and *g3* by optimizing the FCAL hadronic energy resolution. The values *g2=g3*=2 obtained in this way turned out to be close to the MC electron inter-calibration factors (Table 2, line "Total") [5]. See further remarks on the inter-calibration at the end of this Section. To be able to compare the experimental and simulated data, we applied the same values *g2=g3=2* both to MC and beam events.

ATLSIM provides interfaces to four generators for simulation of hadronic showers in matter: FLUKA, MICAP, GCALOR and GHEISHA.[6] The distributions of the FCAL response obtained with the first three generators are shown in Fig. 2.1[7] . Fig. 2.2 shows the corresponding simulated energy response and linearity plots, together with the fit with the function $R = b\_r \cdot (E - E_0)$. A nonlinearity of the FCAL response with FLUKA, MICAP and GCALOR does not exceed 1.5% at E>30 GeV. All three generators produce an offset E_0 of about 3 GeV, similar to the one observed in the 2003 beam data [1]. This offset appears because hadronic showers start fully developing only at the energies of a few GeV. However, the values of *b_r* obtained with different generators are different.

- **The FCAL resolution:** see Fig. 2.3.
  Unlike with electrons, the agreement between the model and the experiment is mediocre. In the energy range 40-200 GeV GCALOR and FLUKA curves are closest to the experimental points.

  The constant term ***a*** is (5-7)% in the models and ≈4.5% in the data. The stochastic term ***b*** is (80-100)% in the models and ≈108% in the data.

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[5] The same observation, made in the analysis of the 1998 test beam data by the ITEP group [3, p8 and the Appendix], was rated as a "coincidence by chance".

[6] http://atlas.web.cern.ch/Atlas/GROUPS/SOFTWARE/DOCUMENTS/ATLSIM/Manual/manual1.html - HADR

[7] GHEISHA results are not shown for reasons explained in the text below.

The results for GHEISHA were not shown in the above plots as the discrepancy with the data was very bad. For example, it predicted σ/E ≈ 35% at 80 GeV, while the experimentally found value is ≈13.5% (all values are quoted for **noise off**).

- **h/e ratio**
  Thus, the models with various generators predict the FCAL resolution for pions with the accuracy of (10-20)% in the energy range 40-200 GeV. However, the situation gets worse if we take a look at the h/e ratio. As Fig. 2.4 shows, none of the generators gives the h/e value matching the one observed in the 2003 tests. FLUKA is the closest to the data, while GCALOR gives h/e≈0.6 (by the way, GHEISHA gives h/e≈0.3!).

- **Remarks concerning equalization factors *g2* and *g3*.**
  As was mentioned above, the values *g2* and *g3* computed from the FCAL1,2,3 response to electrons and the ones obtained by optimizing the hadronic energy resolution match rather well. In order to further check the validity of the optimization method, we applied it to the simulated data, see Fig.2.5. It turned out that different generators predicted different optimal *g2* values. Only GCALOR gave the result close to the expected value *g2*=1.874 (Table 2), whereas FLUKA predicted *g2*≈1.4 and the corresponding σ/E ≈ 5.7%, instead of the expected ~9% with *g2*=2, at E=160 GeV (Fig. 2.3).

  What such a behavior is related with? Let us consider a few examples.
  - The simplest case: FCAL2 and 3 are identical to FCAL1 and the absorber material is copper. We expect *g2*≡1, and all generators predict the optimum at *g2*≈1, accordingly (Fig. 2.6).
  - FCAL1, 2 and 3 have their proper structures, but the absorber material is copper everywhere. The MC electron calibration gives *g2*≈1, and the optimal values are also close to 1 (Fig. 2.7).
  - Same as above, but the absorber is tungsten everywhere. The computed expected *g2* is ≈0.9, and the optimal values are about the same (Fig. 2.8).

  Thus, the optimal and the expected values diverge when the materials of FCAL1 and FCAL2,3 are different. The greatest divergence occurs with FLUKA, and only GCALOR gives *g2* close to the expected value.
  One can consider different concepts of the FCAL modules equalization, e.g. optimize the response linearity or use the requirement of h/e=1 as a constraint. This can be done in near future, as it does not involve re-running GEANT.

- **Remarks concerning GEANT 3.21 setting parameters.**
  As it was already said, all MC results for pions were obtained with stemax=stmin=epsil= 200µm. These parameters, affecting the tracking granularity in GEANT 3.21, should be tuned for each concrete application. Generally speaking, the criterion of a correct tuning is an independence of the solution on further increase of the granularity. Such a classical situation takes place for electrons. With hadrons, this is different, see Fig. 2.9A. At step values below 50 µm, we observed a variation of the computed response and the resolution and the appearance of "zero" events (Fig. 2.9B). The reason of this effect is not clear yet − most likely, it is due to GEANT memory overflow. From Figure 2.9 the value 200 µm was chosen as a common value for stemax, stmin and epsil.
  It will be necessary to investigate the influence of these parameters and the related anomalies in GEANT in more detail.

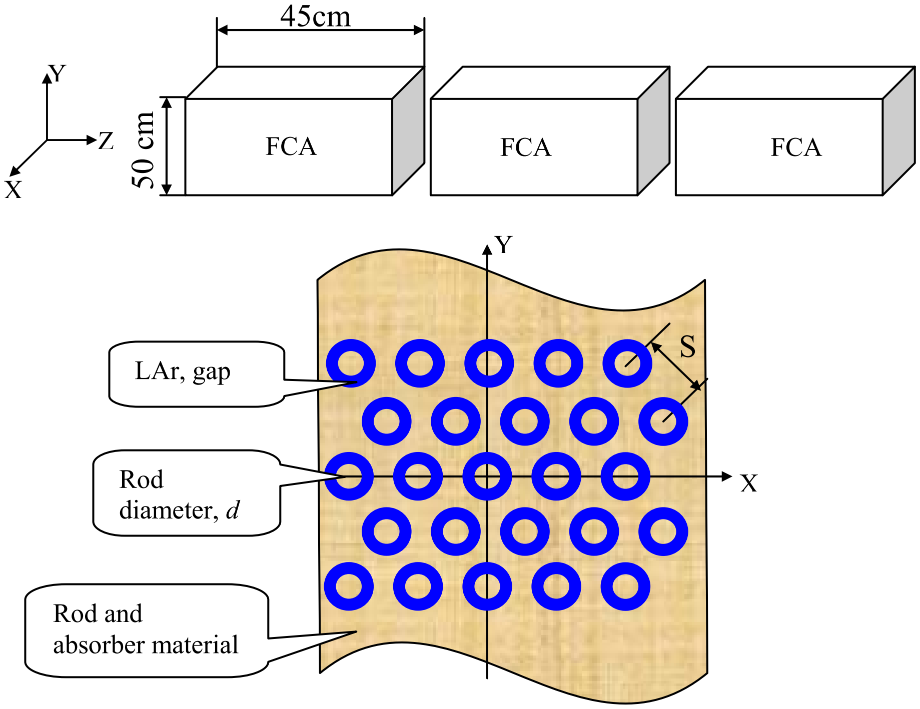
The conclusions for pions in the energy range 40-200 GeV:

- The energy resolutions obtained with GCALOR and FLUKA agree with the experimental data within 10%. The resolution by MICAP differs from the experiment by 25%.
- h/e ratio: both experiment and the simulations give the value of h/e<1. All generators yield the values that differ from the experimental one: FLUKA by 10%, MICAP by 25% and GCALOR by 30%.
- GHEISHA disagrees with the experiment way too much.
- The equalization factors *g2* and *g3* obtained by optimizing the experimental energy resolution are close to the ones coming from the simulated calibration of all FCAL modules by electrons. This property could be reproduced, to some extent, only with GCALOR.
- So, none of the hadronic shower generators provides a satisfactory description of all the aspects of the experimental data. At a first look, FLUKA seems to be the best in describing the response, the resolution and the h/e ratio. However, it predicts that the pion energy resolution of ~6% (Fig. 2.5) can be attained with g2≈1.4 for E=160 GeV, which is not confirmed by data.

References

1. V.Epshteyn, P.Shatalov and P.Gorbunov, *The analysis status report,* ATLAS-FCAL Internal Note 4, 2003-10-30 (http://cern.ch/atlas-fcaltb/Memos/Analysis/ITEP_note4); V.Epshteyn, P.Shatalov and P.Gorbunov, *The analysis status report,* ATLAS-FCAL Internal Note 6, 2004-02-06 (http://cern.ch/atlas-fcaltb/Memos/Analysis/ITEP_note6).
2. J.C.Armitage et al., *Electron Results for the ATLAS Electromagnetic Forward Calorimeter Module 0 Test Beam 1998*, ATLAS Internal Note, April 14, 2002
3. ITEP group, *Progress of FCAL modul-0 Test Beam data analysis,* FCAL internal note, 16-Nov-1998

Figures



	Absorber material	rod d, mm	LAr gap, mm	S, mm
FCAL1	copper	4.71	0.266	7.500
FCAL2	tungsten	4.93	0.375	8.179
FCAL3	tungsten	5.50	0.500	9.000

Figure 1: FCAL geometry model in GEANT.

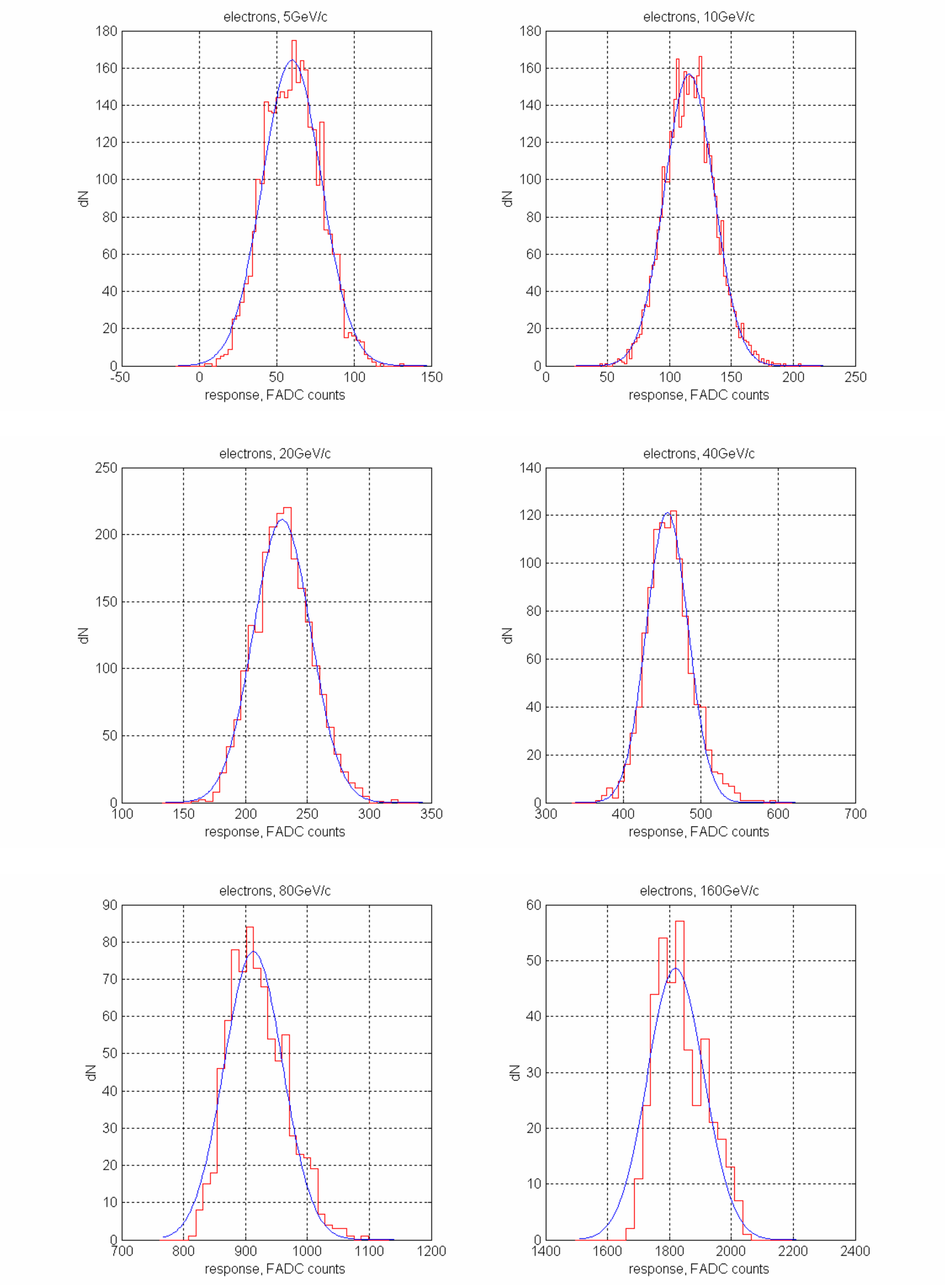


Figure 1.1: Distributions of the total signal in FCAL1: — model data, — Gaussian fit.

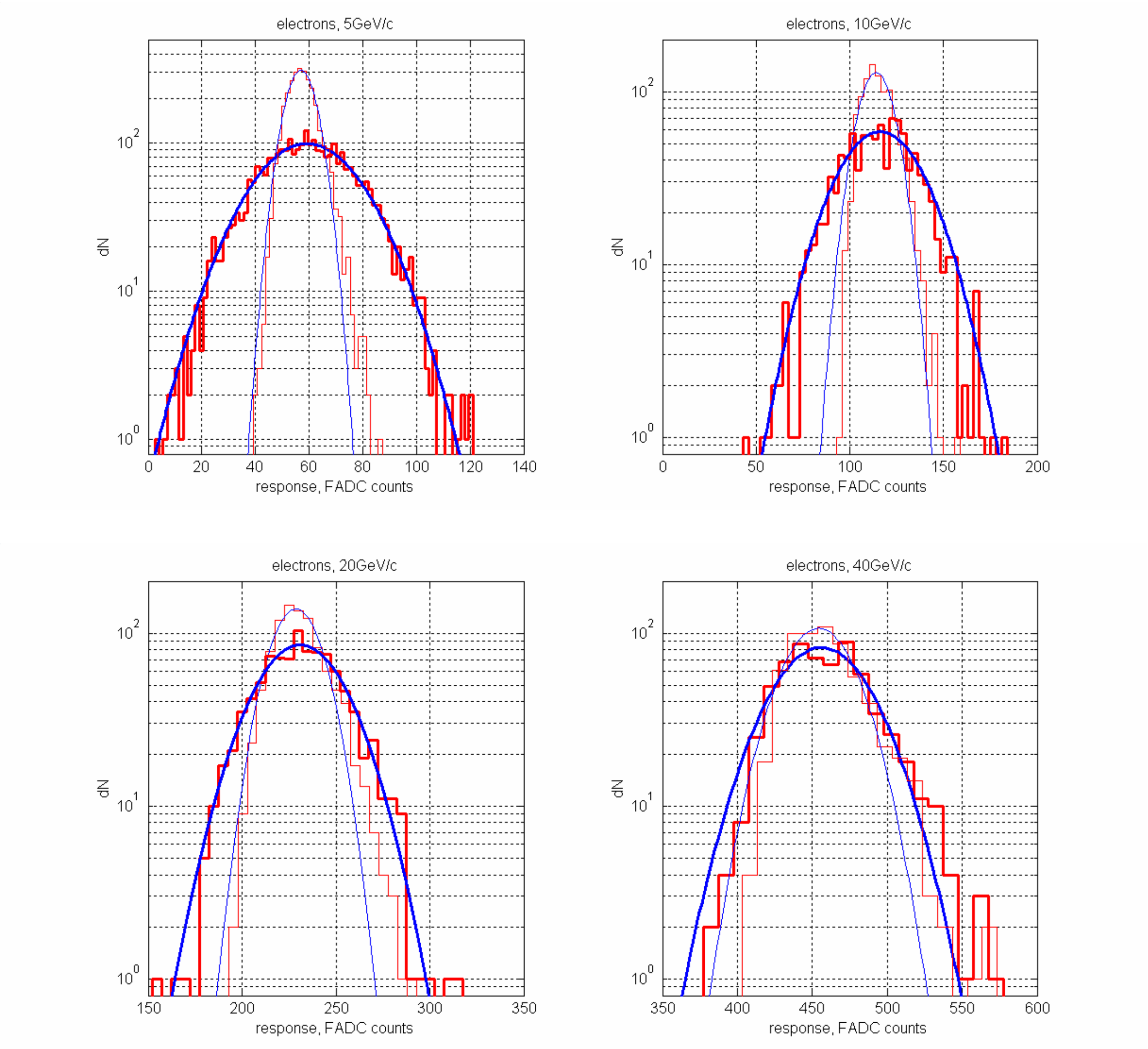


Figure 1.2: Distributions of the total signal from FCAL1: —— model data, —— Gaussian fit (thin lines: noise off; thick lines: noise on).

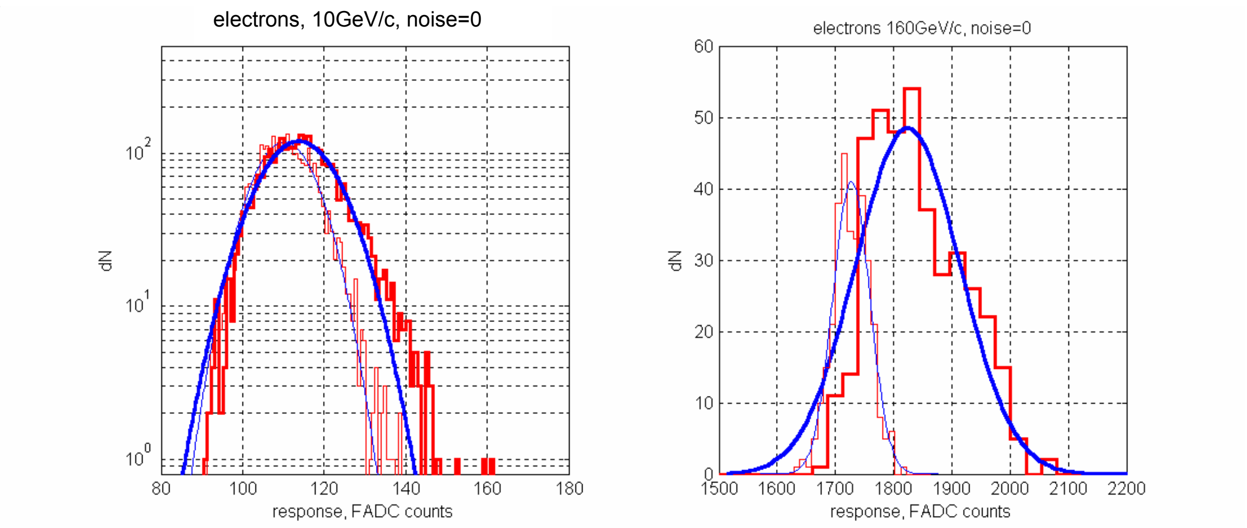


Figure 1.3: Distributions of the total signal from FCAL1, without noise: —— model data, —— Gaussian fit (thin lines: X=0, Y=0; thick lines: |X|≤3.5cm, |Y|≤3.5cm).

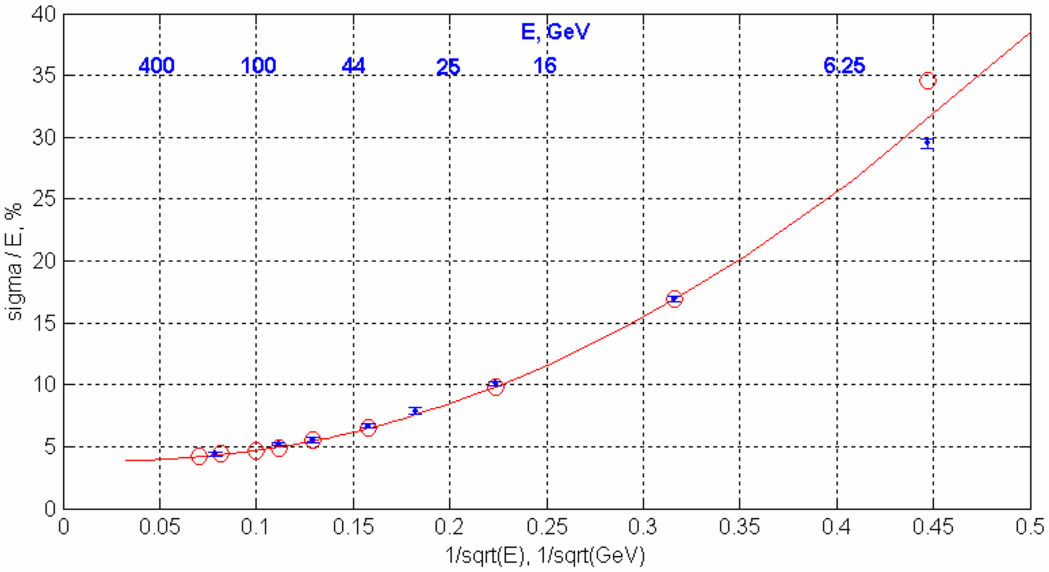


Figure 1.4: Energy dependence of the FCAL1 energy resolution on the energy
○ test 2003, ● MC model,

The line: fit of the data with the function $\frac{\sigma(E)}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}$

data 2003: a=(3.76±0.06)%, b=(24.5±0.84)%, c=(145.5±1.6)%
MC model: a=(3.67±0.26)%, b=(23.9±3.8)%, c=(140±6.3)%

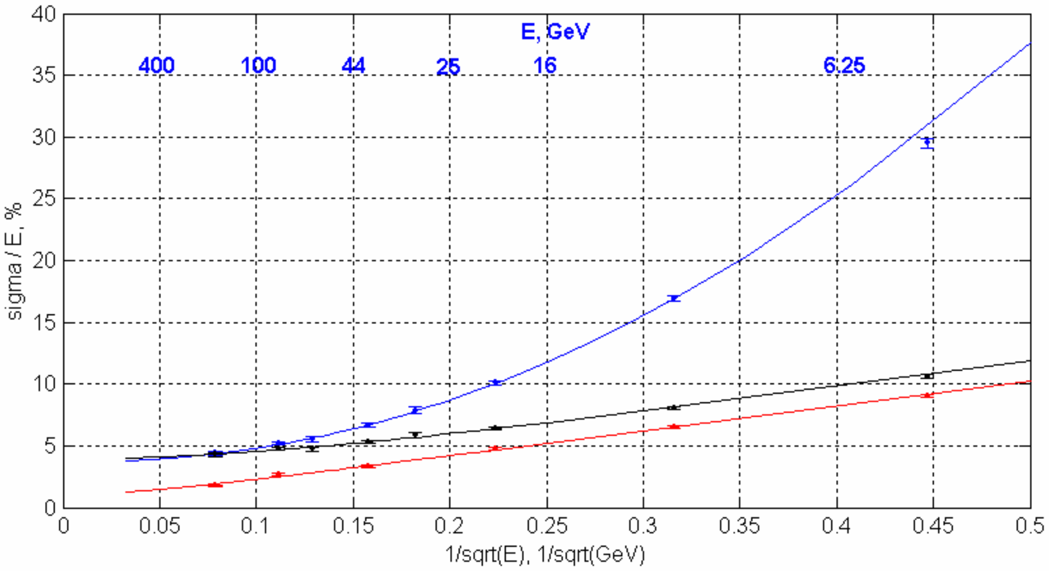


Figure 1.5: Energy dependence of the FCAL1 energy resolution on the energy (Monte-Carlo).

— (noise off, X=0 Y=0), — (noise off, |X, Y|≤3.5cm), — (noise on, |X, Y|≤3.5cm)

The lines: fit of the data with the function $\frac{\sigma(E)}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}$ (with the noise on), or

$\frac{\sigma(E)}{E} = a \oplus \frac{b}{\sqrt{E}}$ (with the noise off).

MC (noise off, X=0 Y=0):	a=(1.08±0.13)%,	b=(20.3±0.2)%	
MC (noise off, |X, Y|≤3.5cm):	a=(3.96±0.10)%,	b=(22.5±0.4)%	
MC(noise on, |X, Y|≤3.5cm):	a=(3.67±0.26)%,	b=(23.9±3.8)%,	c=(140±6.3)%

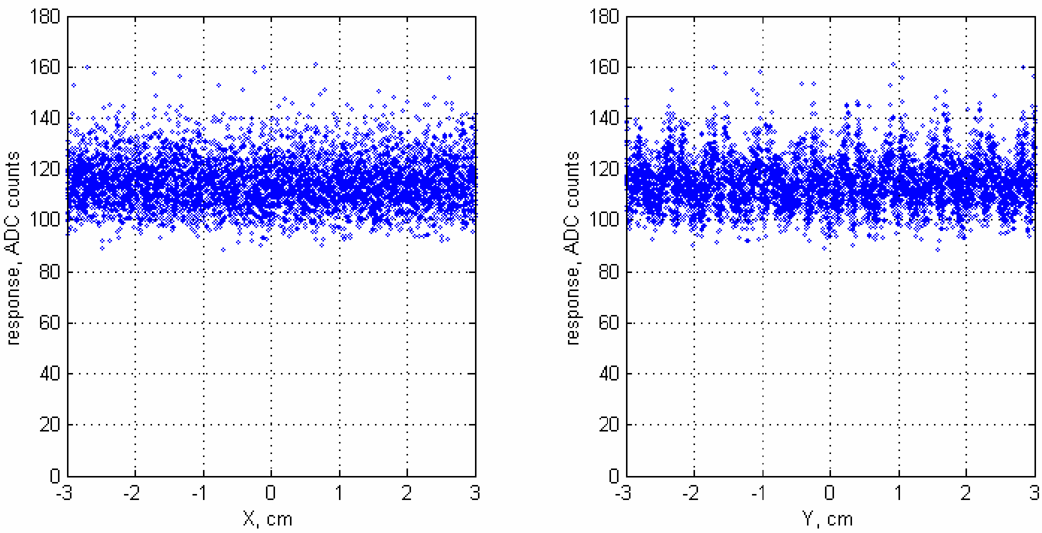


Figure 1.6: Simulated FCAL1 response vs. X and Y, 10 GeV/c, the model - noise off.

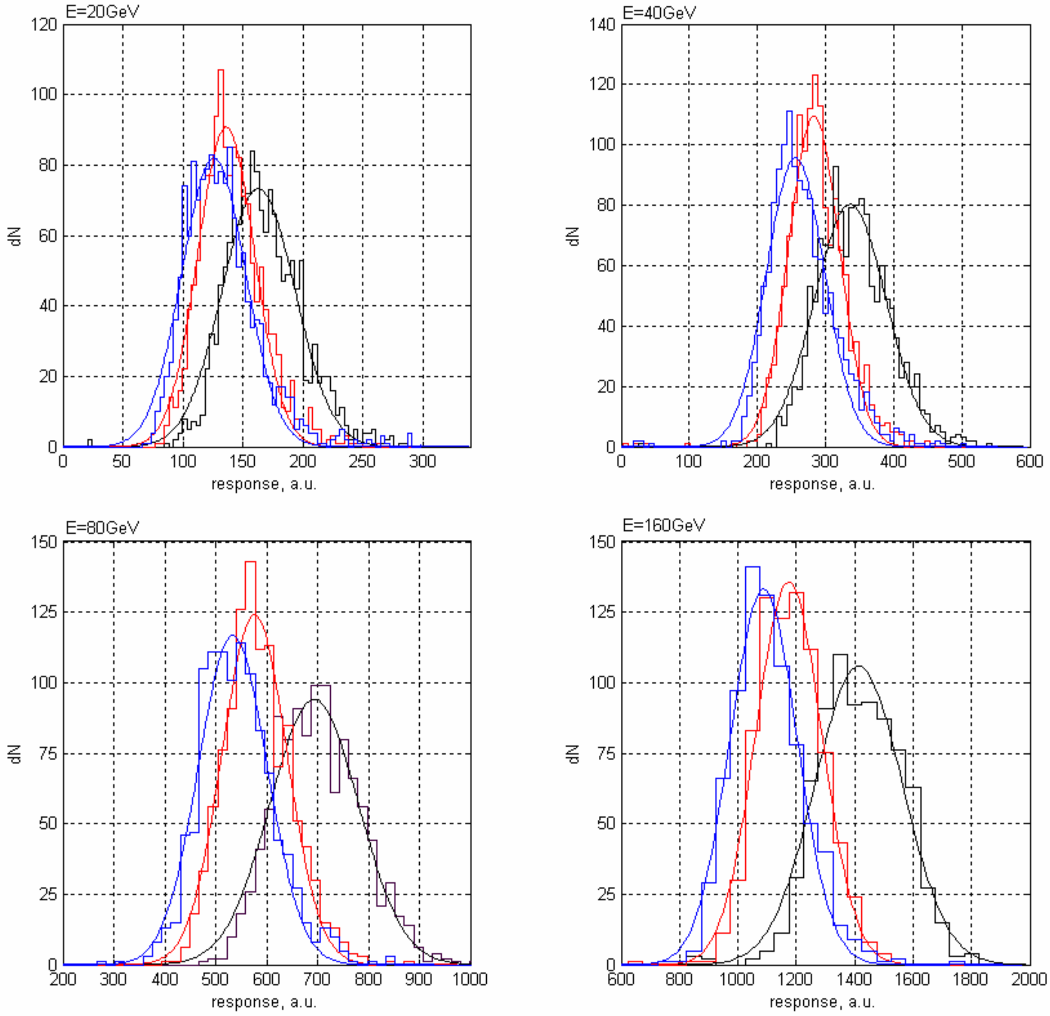


Figure 2.1: Examples of FCAL response distributions obtained with different GEANT generators (full signal simulation, noise off). The curves are Gaussian fits.
___GCALOR, ___MICAP, ___FLUKA.

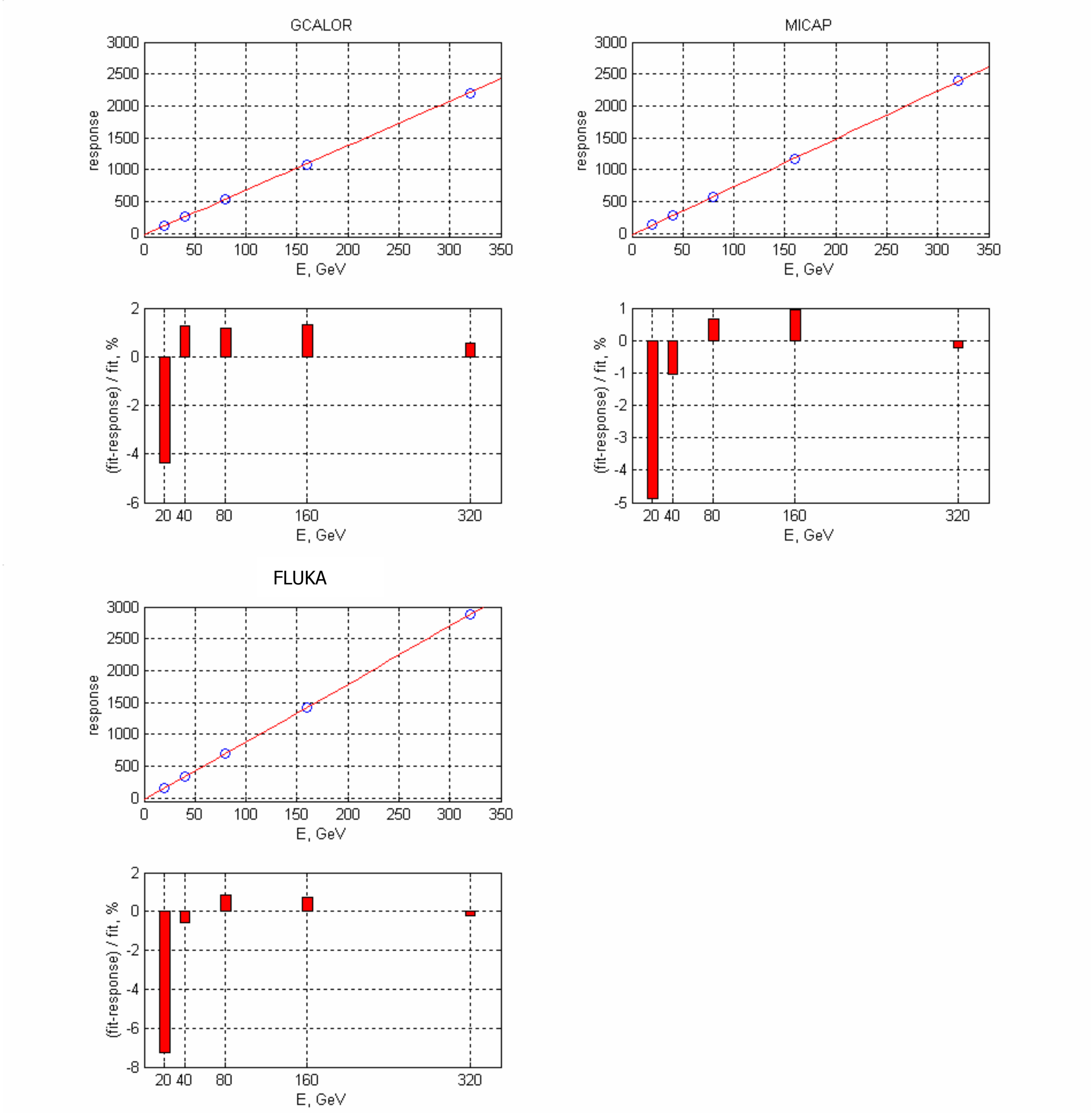


Figure 2.2: The dependence of the FCAL response and its non-linearity on the pion energy E for different generators (noise off). Solid lines show the fits with the function $R = b\_r \cdot (E - E_0)$.

Pion generator	E_0	b_r
GCALOR	2.74	6.984
MICAP	2.81	7.52
FLUKA	3.3	9.093
Beam data 2003	3.0	9.82

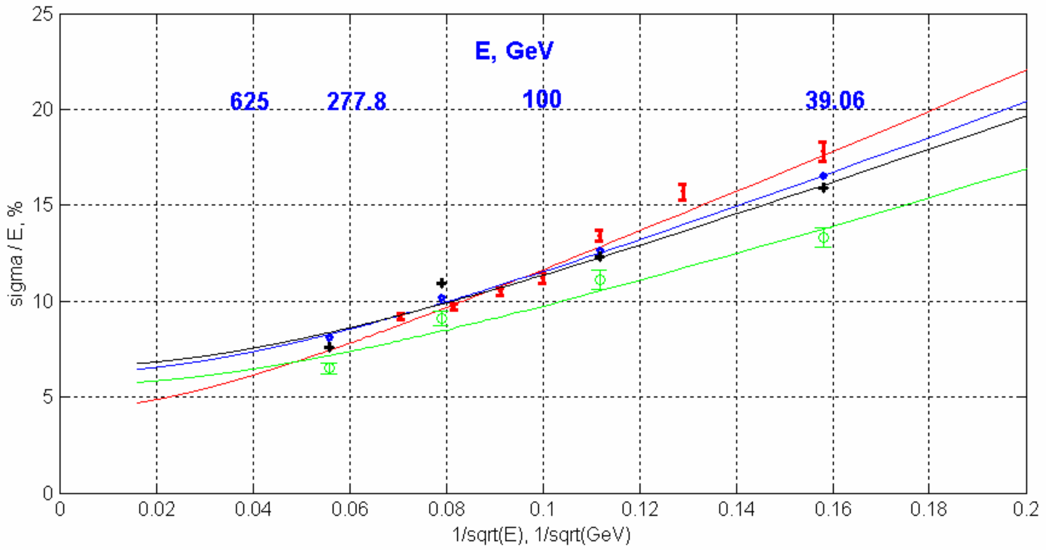


Figure 2.3: The pion energy resolution: ·· data 2003, •• GCALOR, oo MICAP, ++ FLUKA. The noise is subtracted in the experimental points; the simulated points correspond to the full model without the noise. In order not to overload the plot, the errors are shown only for experimental data and MICAP. The errors for other generators are similar. Solid lines show fits with the function $\frac{\sigma}{E} = a \oplus \frac{b}{\sqrt{E}}$, *[E]=GeV*

	a, %	b, %
data 2003	4.3±0.7	108.6±4.1
GCALOR	6.3±0.7	97.0±5.7
MICAP	5.6±0.5	79.6±4.1
FLUKA	6.6±0.9	92.6±6.4

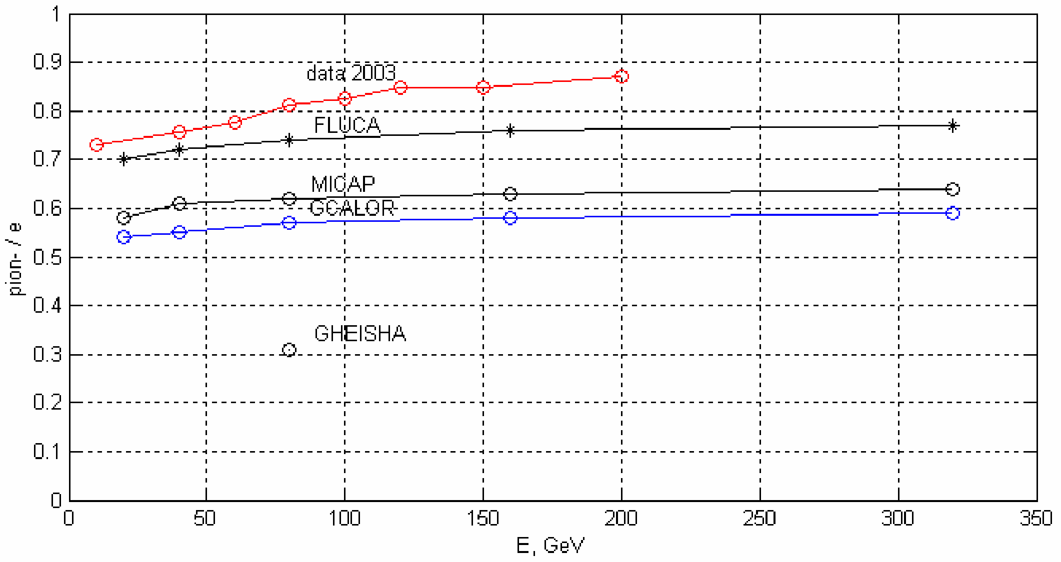


Figure 2.4: π^-/e ratio as function of the particle energy E, for the experiment and the MC, with g2=g3=2.

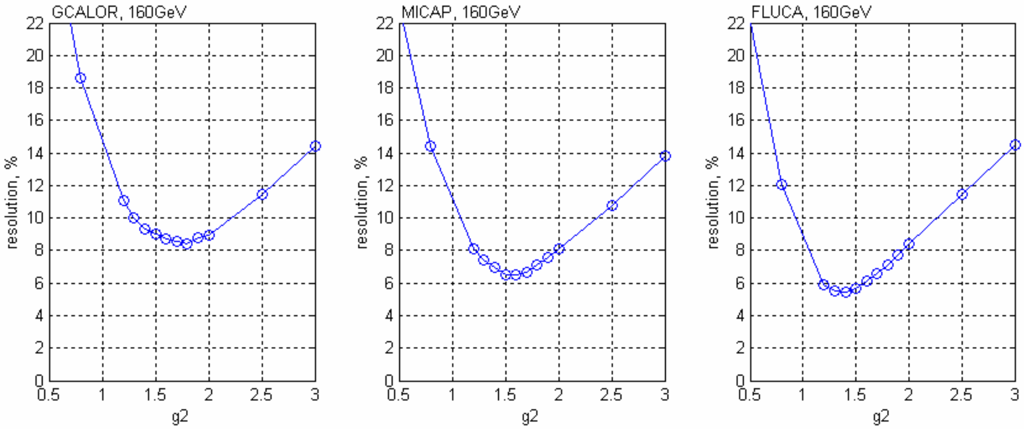


Figure 2.5: The influence of the factor *g2* on the FCAL hadronic energy resolution, for E=160 GeV (noise off). The expected value of *g2* is 1.87 (Table 2). Note that the value of *g3* here, as well as in Figures 2.6-2.8, is the one providing the best achievable resolution for each model; therefore, it may vary from plot to plot .

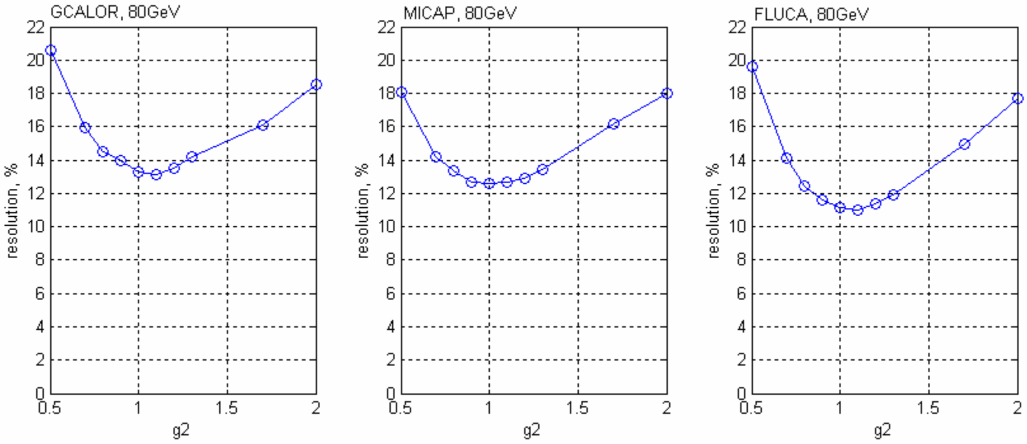


Figure 2.6: The influence of the factor *g2* on the FCAL hadronic energy resolution, for E=80 GeV (noise off). FCAL2 and 3 are artificially made identical to FCAL1. The expected value of *g2* is 1.

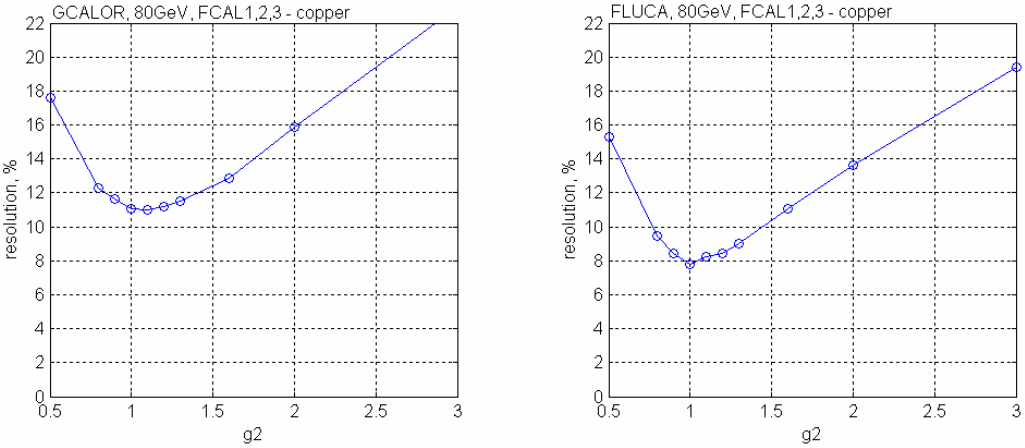


Figure 2.7: The influence of the factor *g2* on the FCAL hadronic energy resolution, for E=80 GeV (noise off). FCAL1, 2 and 3 have their proper structure but are all “made” of copper. The expected value of *g2* is 1.

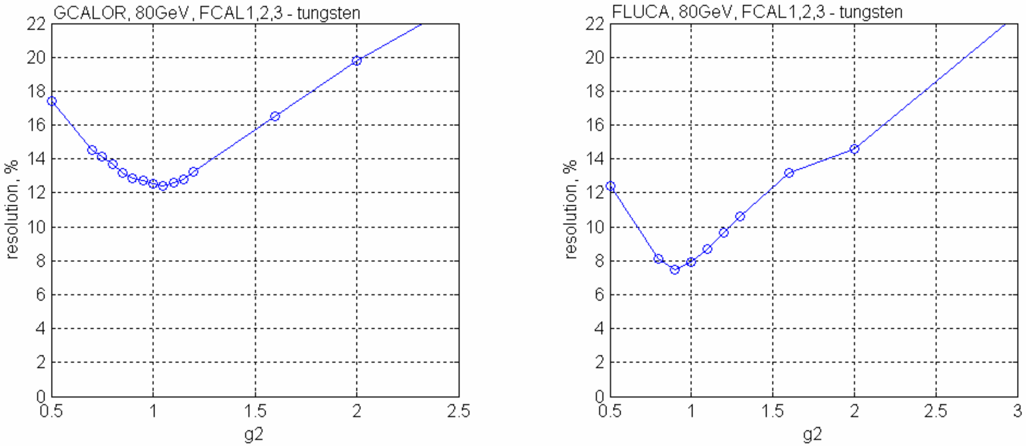


Figure 2.8: Same as Fig 2.7, with all FCAL modules “made” of tungsten. The expected value of *g2* is 0.9.

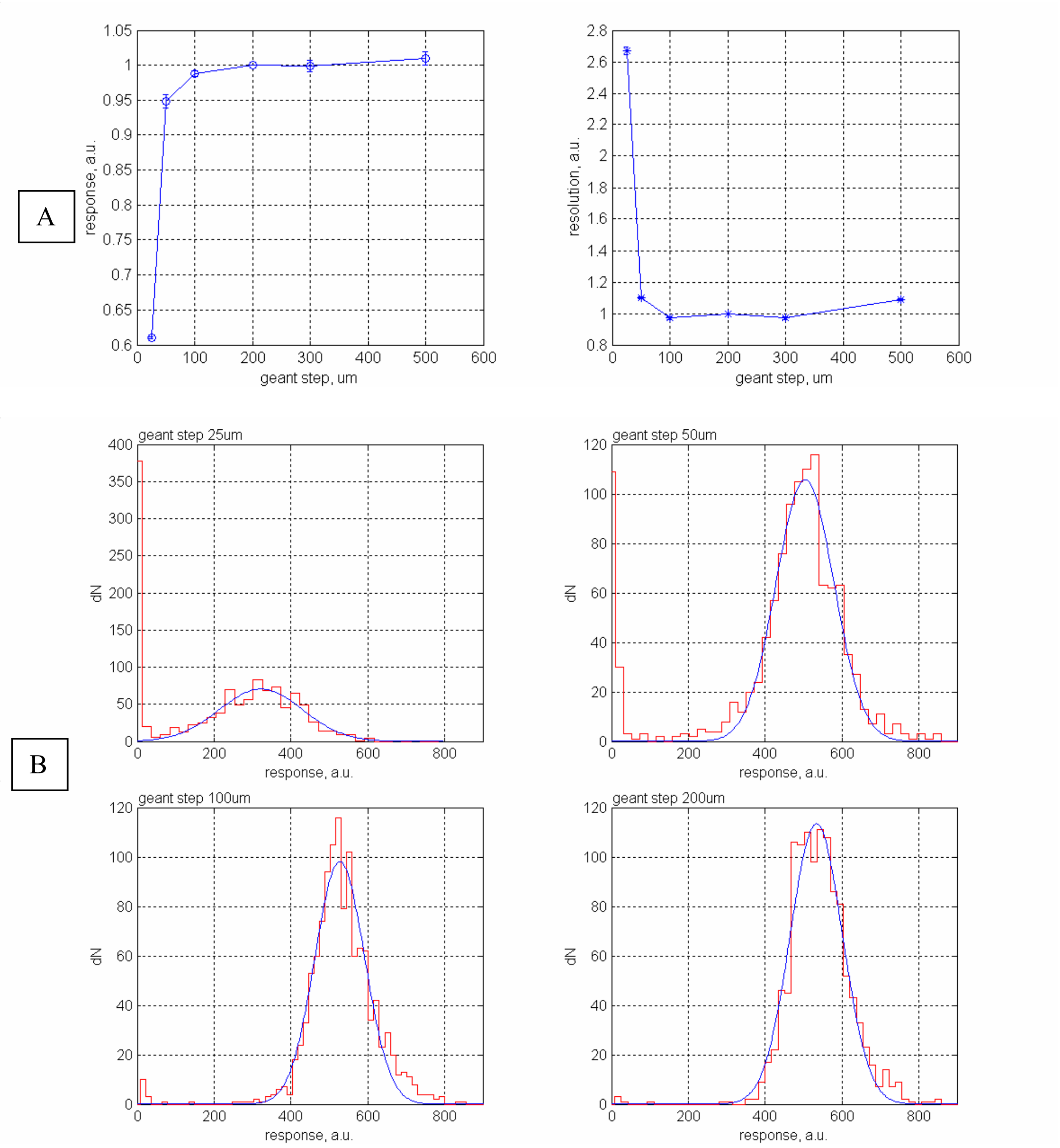


Figure 2.9: The influence of the value g*eant_step* on the simulated FCAL energy response and resolution (GCALOR, E=80 GeV), where *geant_step* is the common value of GEANT parameters *stemax, stmin* and *epsil.* A: the overall dependence; B: examples of the response distributions with different values of *geant_step.*