MC simulation of FCal 2003 electron beam tests with standalone LArG4 package

IIT 06.03.05, draft2

1 Introduction

Detailed analysis of the FCal performance during 2003 beam tests together with GEANT3/ATLSIM MC simulations was presented in [1]. It was demonstrated that the MC agrees rather well with the data for electrons. The contribution from non-physical sources to stochastic and constant terms of the energy resolution was found to be small.

The strategic aim of the present study is to compare the real FCal performance with the GEANT4-based MC and to predict its response at very high energies (around 1 TeV and larger) at which test-beams do not exist. In the current version of the note results obtained with the LArG4-standalone package are presented and comparison with [1] for "geant-only" simulations is given.

Since previous version dated 29.11.04, the following updates were made:

- Energy dependence of FCal1 response and resolution at different angles was studied in detail and complete results are presented;
- FCal1 response at very strong GEANT4 range cuts was investigated;
- EM shower profiles in the FCal were simulated;
- FCal2 and FCal3 responses to electrons were studied.

This note is organized as follows. In Section 2 there is a discussion about the range cut in GEANT4 as well as MC input is considered. The most important results of the simulation of the FCal1 response to electrons having an angle 2.98^0 are presented in Section 3. Section 4 is devoted to angular dependence of the FCal1 response. Shower profiles are considered in Section 5. Summary is given in Section 6. In addition, there are a few appendices with detailed tables. Simulated FCal1 average response and resolution at 3, 10 and 30μ range cuts in the energy range $5\div1000$ GeV are shown in Appendix 1. Appendix 2 contains full tables of FCal1 average response and resolution at eight values of the range cut between 3 and 700μ, at four angles from 1.3^0 to 4.3^0 and seven energies from 5 to 400 GeV. Very small values of range cuts, namely 0.5 and 1μ, are considered in Appendix 3. Complete tables with the results of two-parameter fits of energy dependence of the FCal1 resolution at different range cuts and angles are given in Appendix 4. Results of study of FCal2 and FCal3 response to electrons are presented in Appendix 5. Correctness of a *total* energy deposited in the FCal is checked in Appendix 6.

2 Input

2.1 Range cut in GEANT4

In the GEANT4 [2] there is only one parameter, so-called “range cut” (related to given medium) which affects the simulation procedure. In the ATLAS DC2 [3] it was chosen to be 30 microns based on studies performed for the ATLAS HEC [4].[1] In addition, it was observed [4, 6] that the average HEC response to electrons depends sizeably on the range cut in the region $5\div700\mu$. Moreover, it increases by $\sim$10% if we come to 1μ-cut, the same being also true both for barrel LAr and FCal cases [7]. There is still no explanation of such effect. So it was decided to try several settings of range cuts between 0.5 and 700μ with special attention to the region 3-30μ. Table 1 shows how low energy thresholds for photons, electrons and positrons in different media depend on the range cut in GEANT4.[2] It is seen that although for LAr 10μ range cut looks like sufficient (the equivalent energy cut for electrons is around 10 keV[3]), for materials like copper (FCal1 absorber) and tungsten (FCal2/3 absorber) $1\div3\mu$ range cut looks like more relevant.

ATLAS FCal geometry described in the LArG4-standalone package [8] was used. **No material in front of the FCal was simulated.** As pointed out in [9], in real test-beam setup the H6 “cryostat... has a 3mm thick inox cold vessel and a 2.5mm thick inox thin window in the warm vessel”. As this corresponds to $1/3X_0$, for simplicity we neglect here this additional material.[4] Beam spot size (square with 70×70 mm^2 size), its angle and position w.r.t. the FCal correspond to those used in the 2003 beam-tests [11].

cut, μ	*700*	*300*	*100*	*50*	*30*	*10*	*5*	*3*	*1*	*0.5*
LAr γ	5.1	3.4	2.0	1.4	1.1	1.0	1.0	1.0	1.0	1.0
LAr e^-	271	160	82	55	41	7.7	3.1	1.5	1.0	1.0
LAr e^+	265	156	81	54	40	7.6	3.1	1.5	1.0	1.0
FC1 γ	20.2	12.9	7.2	5.0	3.8	2.1	1.5	1.1	1.0	1.0
FC1 e^-	1000	521	243	158	115	60	40	15	4.0	1.5
FC1 e^+	953	496	237	154	113	59	40	15	3.9	1.4
FC2 γ	93	67	32	20	14	6.8	4.3	3.0	1.5	1.0
FC2 e^-	1521	745	335	210	152	77	52	38	8.0	3.3
FC2 e^+	1448	709	322	204	148	76	51	37	7.9	3.2

Table 1. GEANT4 range cuts vs energy cuts in different media related to the FCal.

2.2 Response and resolution at different positions at 5 GeV

Response and resolution can potentially depend on a position of the beam spot center on the front face of the FCal. We tried three positions.[5] The electron energy was taken as 5 GeV and the angle was 2.98^0. 400 events per range cut were generated. Mean values,

[1] Naively the value of the range cut should be small compared with the width of the LAr gap (266 microns) in the FCal1. However in earlier FCal studies it was taken to be equal to 700μ [5].

[2] This Table is compiled from standard GEANT4 output listings.

[3] 10 keV is a minimal possible energy cut in GEANT3.

[4] As was recently discovered by P.G. [10], in reality we had much more material, namely between 1.8 and 2.5 X_0. In addition, during the TB2003, there were special runs with extra absorber in front of the FCal needed to simulate conditions in the real ATLAS set-up.

[5] See Ref.[11] for details about positions.

rms's of the response functions as well as parameters of the related unrestricted gaussian fits are given in Table 2.

It is seen that the average response sizeably depends on the range cut resulting to a sampling fraction of 1.25-1.35.[6] Both response and resolution are stable w.r.t. the position. It is not a surprise as the beam spot size is much larger than the tube-to-tube spacing in the FCal1. So we take position 4 w/o vertical shift (let's call it "4Z") to study dependence of the response and the resolution vs energy and angle throughout this Note.

It should be mentioned that CPU time consumption depends strongly on the range cut if it is harder than 10μ, see Table 3. So some compromise between a quality and a speed of simulation should be found provided we need high statistics MC samples.

Position	*Range cut*	*700 mkm*	*300 mkm*	*100 mkm*	*50 mkm*	*30 mkm*	*10 mkm*	*5 mkm*
4H	Mean	.0613	.0633	.0643	.0652	.0659	.0633	.0620
	rms	.0097	.0094	.0096	.0095	.0089	.0086	.0084
	gauss	.0614(6)	.0623(5)	.0633(4)	.647(5)	.649(5)	.629(5)	.615(4)
	σ	.0092(4)	.0089(4)	.0083(3)	.0093(4)	.0080(4)	.0075(3)	.0079(4)
4L	Mean	.0613	.0623	.0633	.0649	.0660	.0638	.0621
	rms	.0092	.0090	.0091	.0088	.0087	.0085	.0078
	gauss	.0603(5)	.0618(5)	.0624(5)	.643(5)	.656(5)	.628(4)	.615(4)
	σ	.0086(5)	.0080(4)	.0089(5)	.0086(4)	.0080(4)	.0076(4)	.0077(3)
4Z	Mean	.0618	.0629	.0639	.0658	.0668	.0629	.0623
	rms	.0094	.0100	.0089	.0091	.0086	.0077	.0078
	gauss	.0608(4)	.0625(5)	.0638(5)	.652(5)	.665(4)	.626(4)	.622(4)
	σ	.0083(3)	.0095(5)	.0086(4)	.0089(5)	.0077(3)	.0072(3)	.0075(3)

Table 2. FCal response to 5 GeV electrons at 2.98^0 for three different positions of beam spot.

cut, μ	*700*	*300*	*100*	*50*	*30*	*10*	*5*	*3*	*1*	*0.5*
Speed	.512	.554	.567	.579	.600	.742	.833	1.98	3.88	10.2

Table 3. CPU time consumption per GeV per event (in NCU).[7]

3 Response vs energy at 2.98^0

3.1 Response shape and linearity of the average response

Events with electrons at 2.98^0 were generated at different energies and range cut settings (Table 4).

[6] In GEANT3 simulations [12] with 10 keV energy cut the sampling fraction is found to be 1.26.

[7] NCU is an abbreviation of so-called "New CERN Unit". Roughly speaking, 1 NCU corresponds to one second on a typical 400 MHz PC processor.

E, GeV / cut, μ	*700*	*300*	*100*	*50*	*30*	*10*	*5*	*3*	*1*	*0.5*
5	400	400	400	400	2500	2500	400	2500	400	400
10	400	400	400	400	2500	2500	400	2500	400	400
20	400	400	400	400	2500	2500	400	2500	400	400
40	400	400	400	400	2500	2500	400	1200	400	400
60	400	400	400	400	2500	2500	400	1200	–	–
80	400	400	400	400	2500	2500	400	1200	–	–
100	400	400	400	400	2500	2500	400	1200	–	–
120	400	400	400	400	2500	2500	400	1200	–	–
193	400	400	400	400	2500	2500	400	1200	400	400
400	400	400	400	400	400	400	400	400	400	–
1000	400	400	400	400	400	400	400	400	–	–

Table 4. Simulated MC statistics at different energies and range cuts.

Responses of the FCal to 10, 40, 193 and 1000 GeV electrons at 3 and 30μ range cuts are shown in Figs.1-4[8]. As in GEANT3 [1], distributions have slightly asymmetric shapes closed to gaussians in the central ($\pm 2\sigma$) region but small right tails are present. As pointed out in [1], it can be due to non-uniformity of the lateral FCal structure. Probably for the same reason the calorimeter response with energy shows $\sim$1% non-linearity (Fig. 5). The offset in the linearity is compatible with zero as should be (Fig.6).[9]

3.2 Resolution vs energy

We tried to parameterize energy dependence of the energy resolution using conventional function $\sigma/E = \sqrt{a^2/E + b^2}$. Results of fits are shown in Table 5.

	30 mkm	*10 mkm*	*3 mkm*
a	.272	.242	.233
Δa	.004	.004	.003
b	.0486	.0509	.0453
Δb	.0005	.0005	.0006

Table 5. Stochastic and constant terms of the simulated FCal electron energy resolution at 2.98^0.

It is seen that both stochastic and constart terms become somewhat smaller with tightening the range cut. Very good agreement between relative energy resolution obtained with LArG4 (at 3μ range cut) and GEANT3 simulations (10 keV energy cut) [12] is demonstrated in Fig.7. However, there is $\approx$10% discrepancy with the real data [1] both at low and high energies (Fig.8). Possible reason of better energy resolution in the MC at low energies can be due to possible underestimation of the noise contribution in the data. Indeed, the measured noise obtained with pedestal events by the "SPICE fit" [1, 10] is about 1.33 GeV while the noise term obtained from the 3-parameter fit is 10% larger [1].

[8] We call energy deposition in LAr obtained with the LArG4 package as "FCal response" throughout this note. Results at another range cuts with detailed comments are given in Appendices 1 and 3.

[9] Formally, with a fit in the energy region 5÷1000 GeV, the offset is turned out to be around 0.1 GeV, a fit quality being bad. However, the average simulated FCal response to 0.1 GeV electrons is 0.0013 GeV, in agreement with expectations for zero offset case.

The nature of better energy resolution in the data at high energies is probably presence of ≈2 X_0 material [10] in front of FCal which was not yet simulated. It is expected to be done within ATHENA [15] framework.

Details can be found in Appendix 4.

4 Response and resolution vs angle

In the ATLAS set-up, the FCal covers the range between η =3.0 and η =4.9 [13] which corresponds to angular interval $0.8^0 \div 5.7^0$. Previous studies with SPACAL-type calorimeters [14] showed the degradation of electron energy resolution at very small angles. So it was natural to study this effect in the FCal both in the TB2003 data and in the GEANT4-based MC. A few values of angles were tried, see Table 6. Note that at the position 1 (angle 0.88^0) a lateral shower leakage in the MC is found to be very large or incoming electron even doesn't hit the FCal.

TB position	*Radial distance, mm*	*Angle, degrees*	η	Comment
1	72	0.88	4.87	Lateral leakage
2	102	1.25	4.52	
3	132	1.61	4.27	
4L/H	246	2.98	3.65	FCal "center"
–	355	4.3	3.28	MC only

Table 6. Correspondence between the TB position and electron impact angle. Second column shows the distance between an average electron impact point and the axis of the FCal cylinder.

We also simulated FCal response at 4.3^0 which was also tried in the related test-beam studies with FCal1 module 0 [5]. For each angle, 400 events at 5, 10, 20, 40, 60, 193 and 400 GeV were generated. G4 range cuts between 3 and 700μ were tried. Simulated responses at angles 4.3^0, 1.61^0 and 1.25^0 to 5, 20, 60 and 400 GeV electrons are shown in Figs.9-12. It is seen that the shapes of the distributions become more and more asymmetric (right non-gaussian tails) and their widths increase with decreasing the angle. Details are given in Appendices 2 and 4.

5 EM shower profiles

EM shower profiles in FCal1 were simulated. To obtain them an information of energy deposition in LAr at each GEANT4 step (G4Step) was used.

Lateral shower profiles for 5 GeV electrons at 3, 30 and 300μ range cuts are plotted in Fig.13. There is tiny difference between these profiles at very small radii, R. 90% containment is reached at R=2.3 cm which roughly corresponds to Moliere radius of the FCal1.[10] At R=8 cm 99% of shower energy is deposited. Let's remind that this radius was used during data analysis [1]. Fig.14 demonstrates that the lateral profiles of 10 and 193 GeV electrons are the same as should be.

Longitudinal shower profiles for 10, 60 and 193 GeV electrons are plotted in Fig.15. As expected, showers become longer at higher energies. The positions of the shower maxima

[10] For LAr and Cu, Moliere radii are 1.5cm and 9.4cm respectively [16].

are roughly in agreement with [16]. Only a small fraction of energy is deposited in the FCal2.

6 Summary

Results of LArG4 simulations of FCal performance are the following:

1. Responses to electrons at 2.98^0 in the energy range 5÷1000 GeV have shapes closed to gaussian although with small right tails;

2. The average response is linear with energy within 1%. The offset is compatible with zero;

3. Constant term of the energy resolution at θ $=2.98^0$ is predicted to be between 4.5% and 5.1% depending on the GEANT4 range cut (3÷30 μ); in agreement with GEANT3/ATLSIM simulations [12];

4. Stochastic term of the energy resolution is expected to be between 23% and 27%, again in agreement with [12];

5. There is significant degradation of electron energy resolution at small angles;

6. Longitudinal and lateral shower profiles are reasonable which validates the MC.

Further studies will be performed with ATHENA-based version of LArG4.

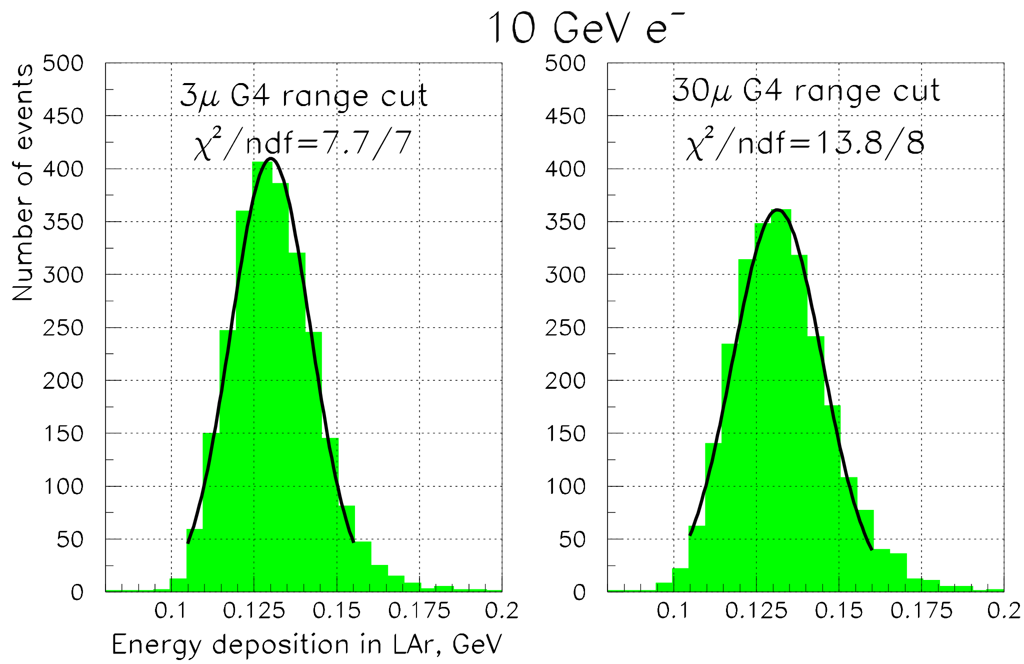

Figure 1: Simulated FCal response to 10 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed gaussian fit restricted within 2σ range around the maximum (solid black line)

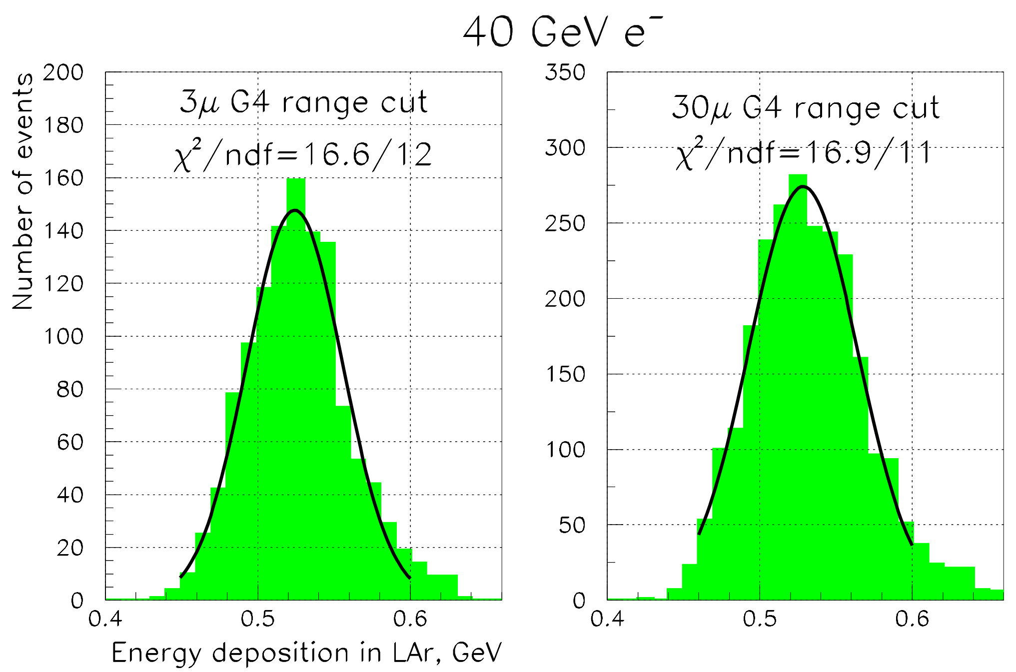

Figure 2: Simulated FCal response to 40 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed gaussian fit restricted within 2σ range around the maximum (solid black line)

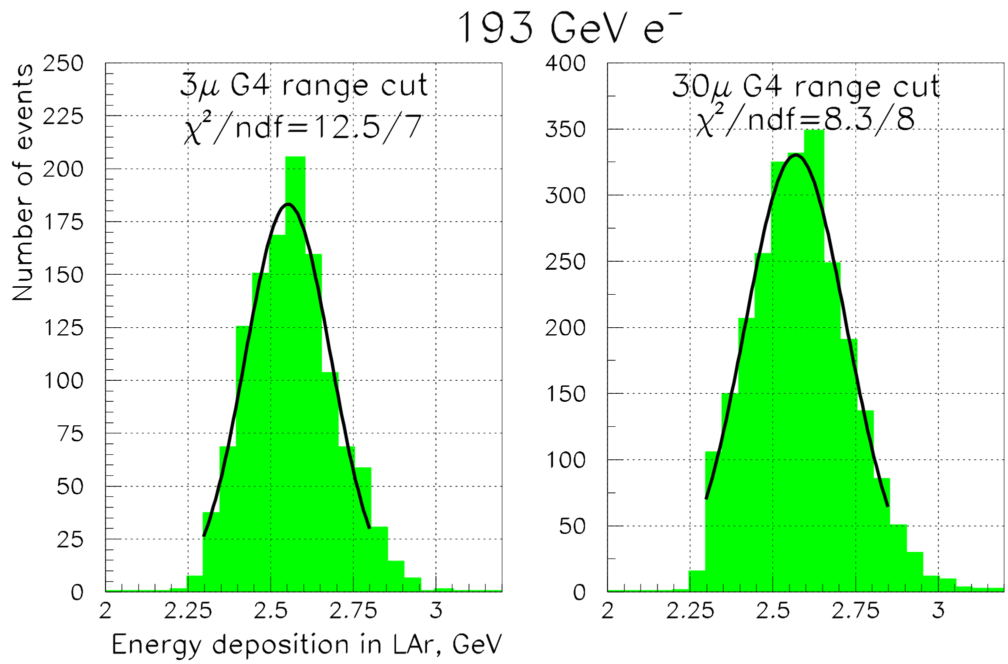

Figure 3: Simulated FCal response to 193 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed gaussian fit restricted within 2σ range around the maximum (solid black line)

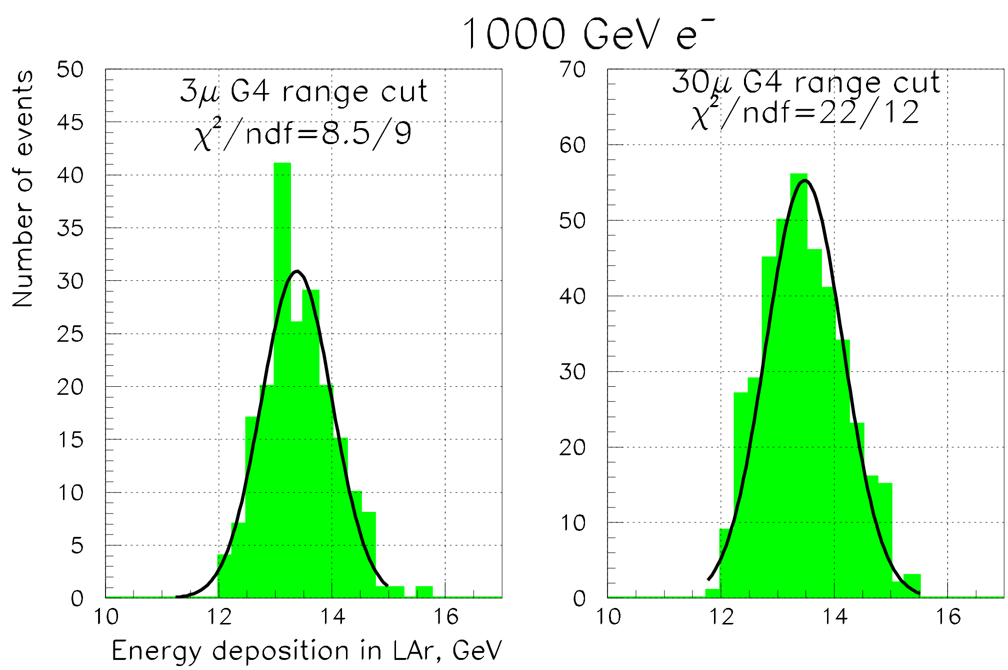

Figure 4: Simulated FCal response to 1000 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed gaussian fit restricted within 2σ range around the maximum (solid black line)

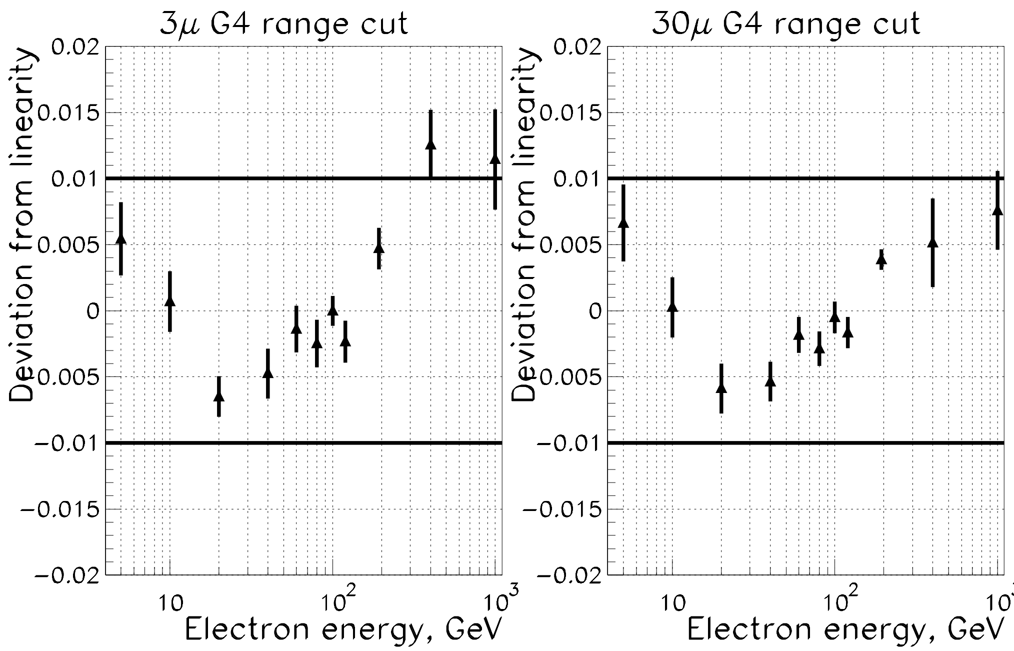

Figure 5: Simulated deviation from linearity of the FCal average response to electrons.

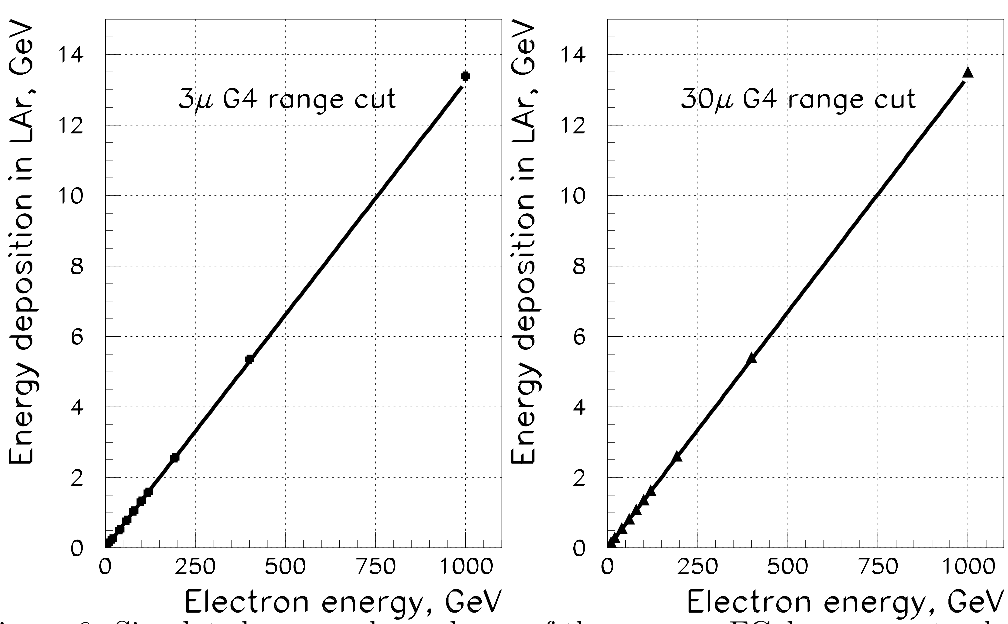

Figure 6: Simulated energy dependence of the average FCal response to electrons

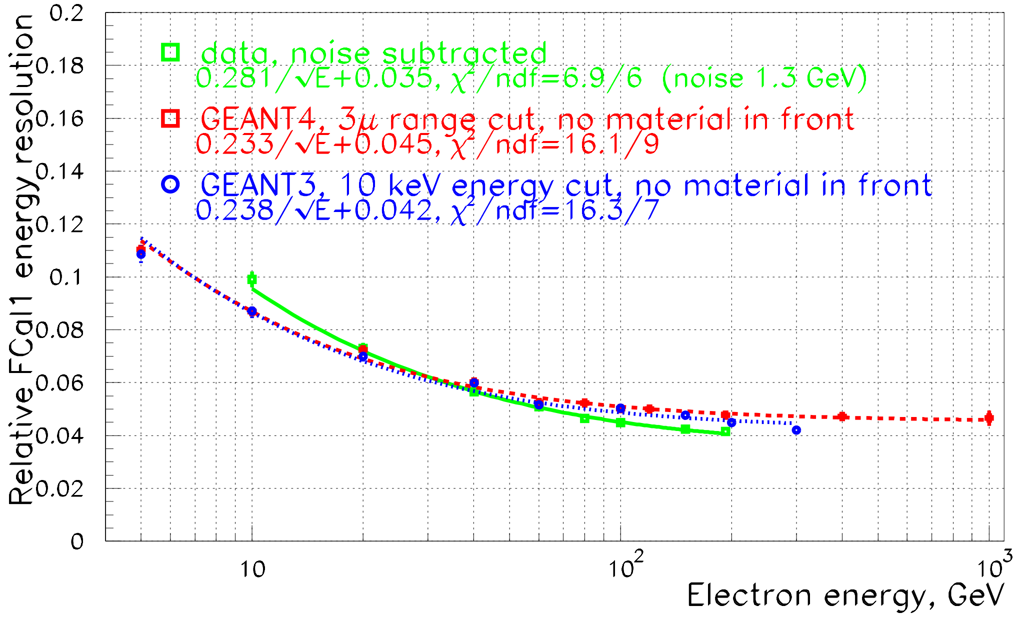

Figure 7: Energy dependence of the FCal relative energy resolution together with two parameter fit superimposed. Green colour is for real data [1] after noise subtraction, red colour is for LArG4 MC and blue colour is for GEANT3 MC [12].

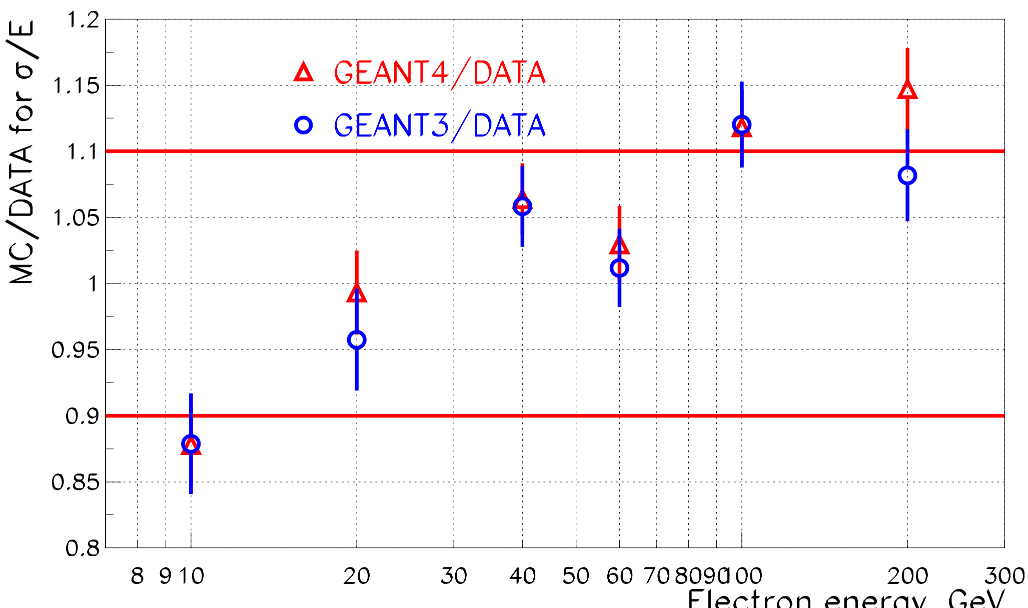

Figure 8: MC/DATA ratio for the relative energy resolution. Red triangles are for LArG4 MC and blue circles for GEANT3 MC [12].

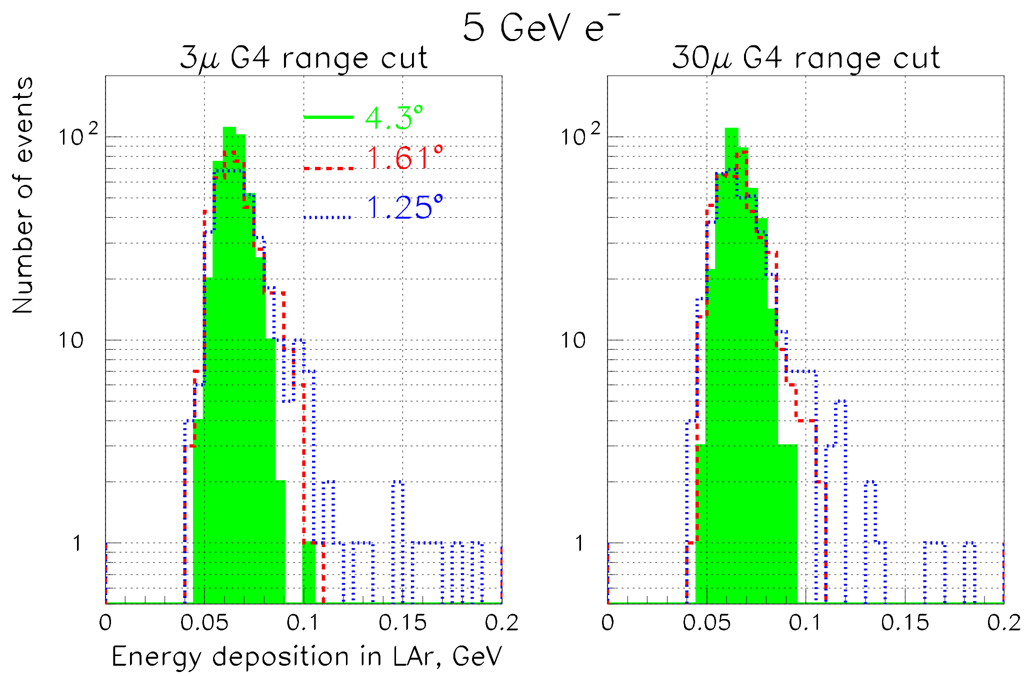

Figure 9: Simulated FCal response to 5 GeV electrons at different angles. Solid green histograms are for 4.3^0, dashed red histograms are for 1.61^0 and blue dotted histograms are for 1.25^0.

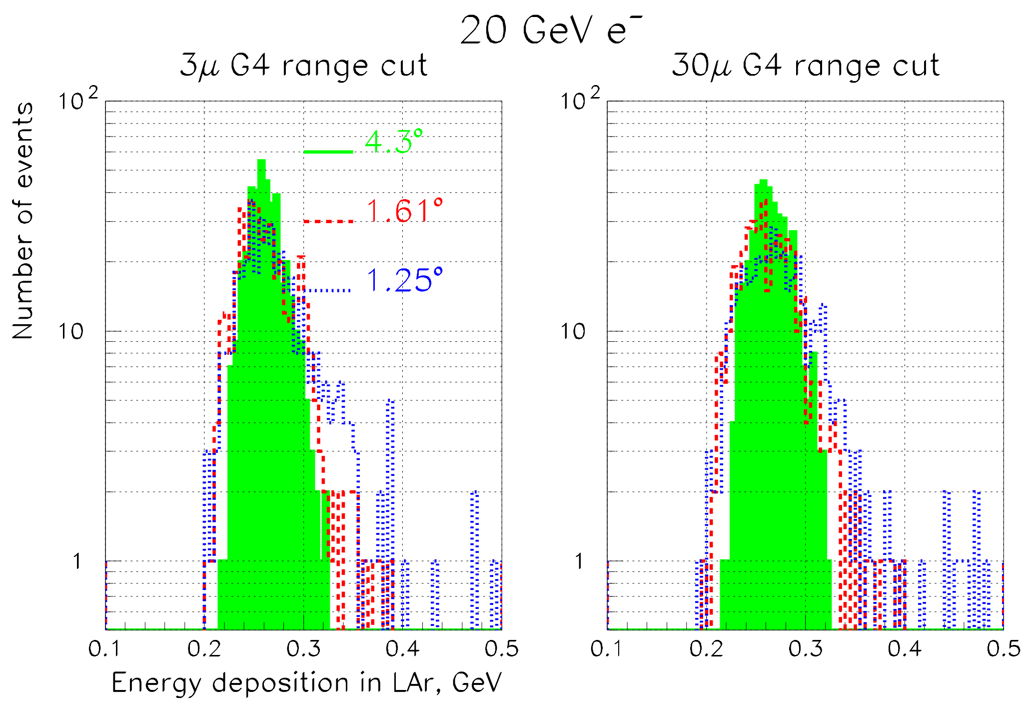

Figure 10: Simulated FCal response to 20 GeV electrons at different angles. Solid green histograms are for 4.3^0, dashed red histograms are for 1.61^0 and blue dotted histograms are for 1.25^0.

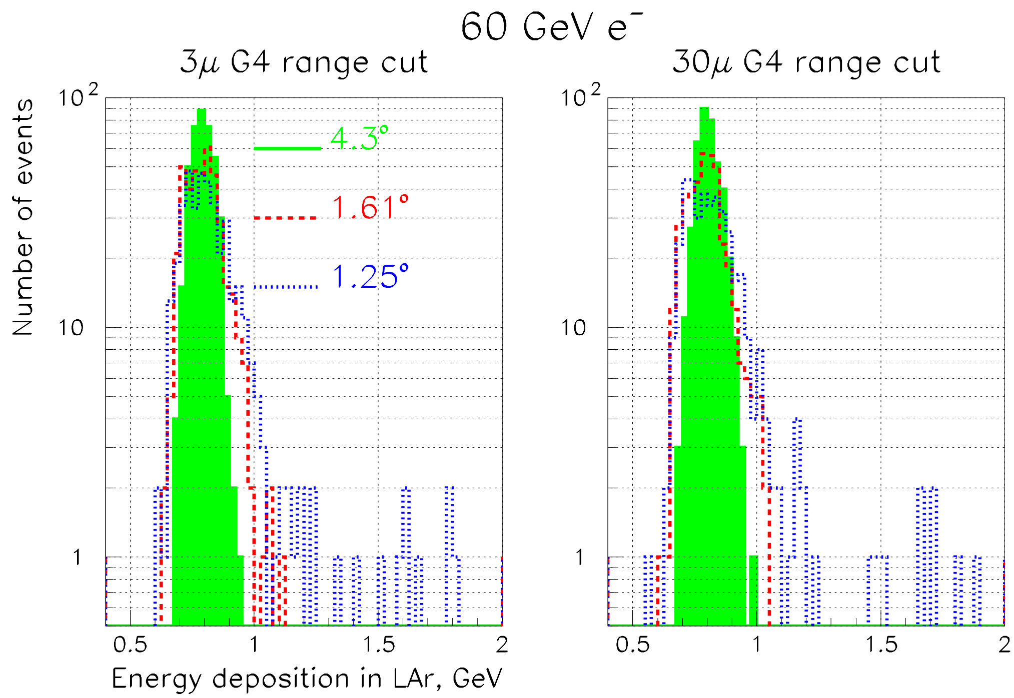

Figure 11: Simulated FCal response to 60 GeV electrons at different angles. Solid green histograms are for 4.3^0, dashed red histograms are for 1.61^0 and blue dotted histograms are for 1.25^0.

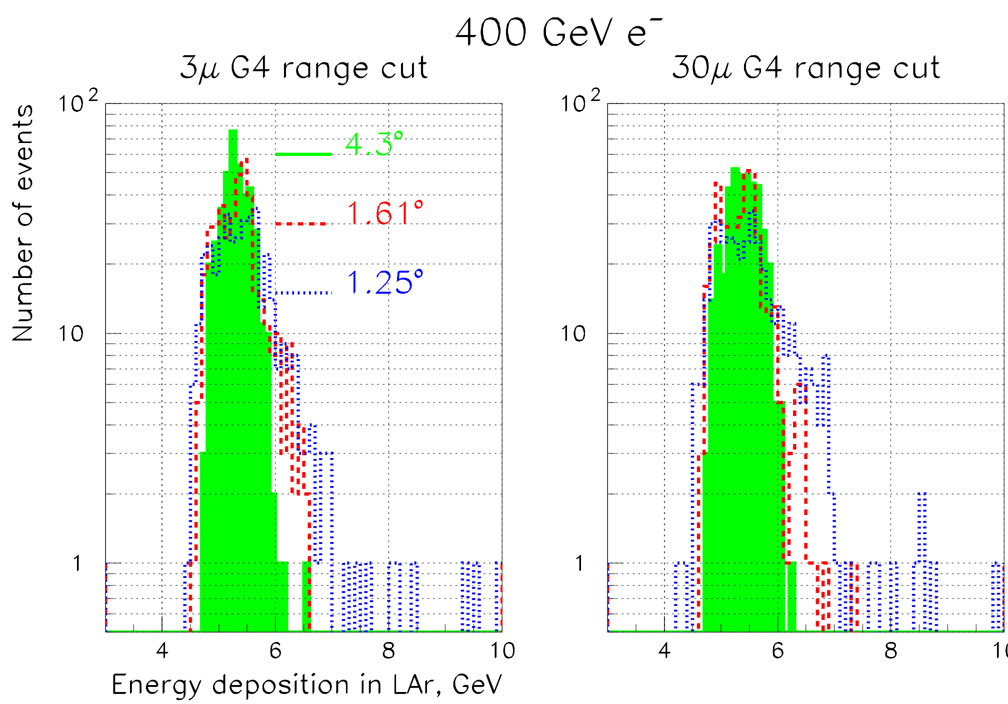

Figure 12: Simulated FCal response to 400 GeV electrons at different angles. Solid green histograms are for 4.3^0, dashed red histograms are for 1.61^0 and blue dotted histograms are for 1.25^0.

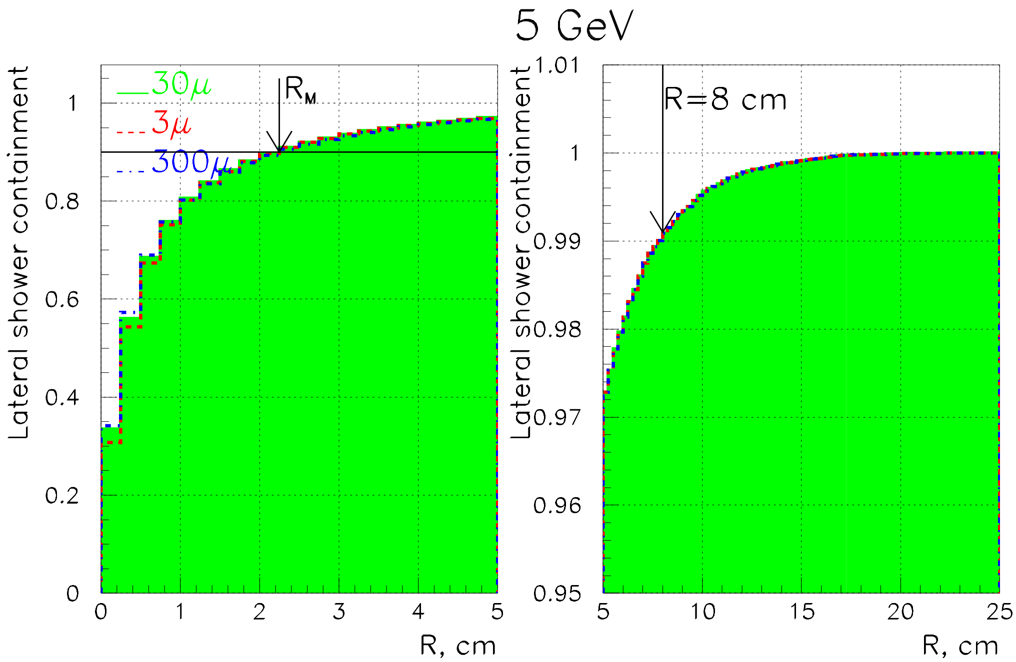

Figure 13: Simulated lateral shower profiles for 5 GeV electrons at 2.98^0. Solid green histograms are for 30μ range cut, dashed blue histograms are for 300μ and red dotted histograms are for 3μ.

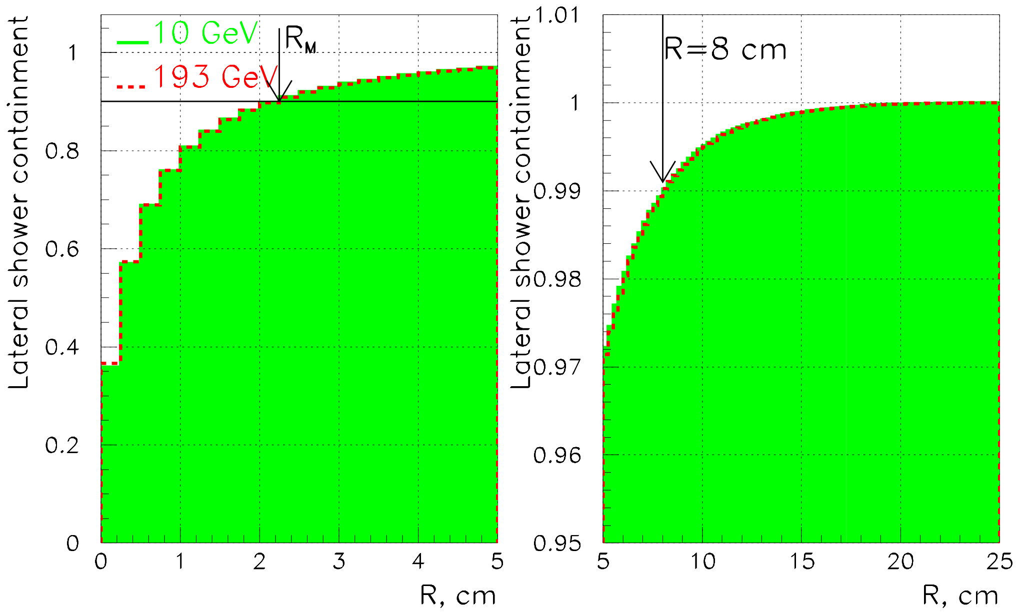

Figure 14: Simulated lateral shower profiles for electrons at 2.98^0. Range cut was 30μ. Solid green histograms are for 10 GeV, dashed red histograms are for 193 GeV.

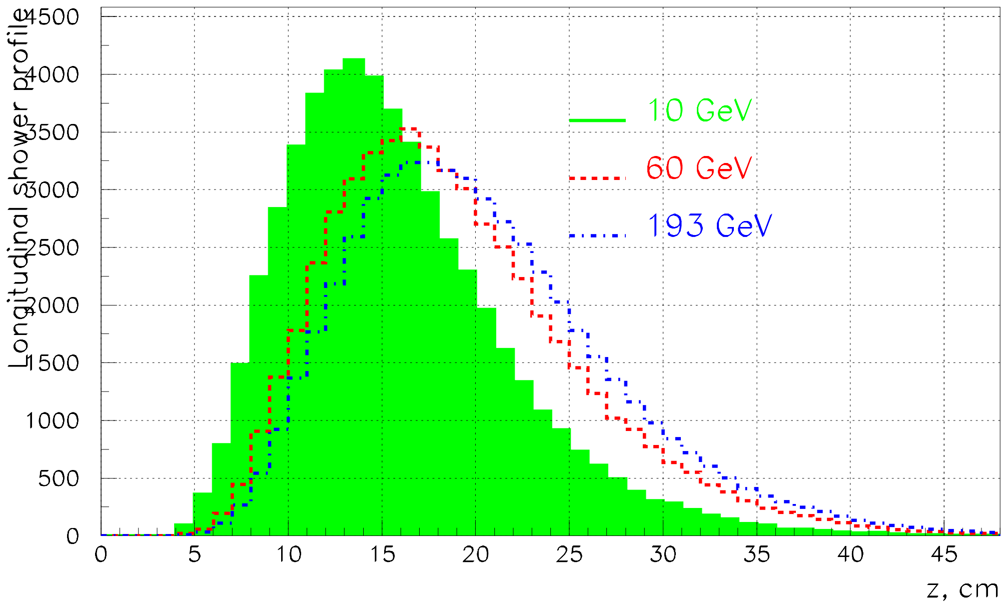

Figure 15: Simulated longitudinal shower profiles for electrons at 2.98^0. Range cut was 30μ. Solid green histograms are for 10 GeV, dashed blue histograms are for 60 GeV and red dotted histograms are for 193 GeV.

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7 Appendix 1. Simulated average response and resolution of FCal to electrons at 2.98^0

Average FCal response was calculated by the following three ways:

- the mean value of the distribution;
- the average value of unrestricted gaussian fit;
- the average value of restricted gaussian fit within $\pm 2\sigma$ around the maximum.

These three methods were used also to estimate an average energy resolution. Results are shown in Table A1. Let us note the following:

1. For the average response, three methods are mostly in 0.5% agreement (although not always within errors), the only exception is 5 GeV point;
2. The average response at 10μ cut is smaller than at 3 and 30μ by 5% irrespective of energy;
3. For the relative energy resolution, two gaussian methods give more or less compatible results, except at 193 GeV with 30μ range cut;
4. Relative energy resolution obtained with the first method is typically differed by a few % from the gaussian one. So the systematic error of estimated sampling and constant terms is not large;
5. Relative energy resolution slightly improves with tightening the range cut.

   It is interesting to note that the simulated average response of the FCal at 1 TeV and the result of extrapolation through the MC points in the region 10–200 GeV differs only by about 1%.

Energy		*30 mkm*	*10 mkm*	*3 mkm*
5 GeV	Mean	.06621(18)	.06304(17)	.06563(16)
	rms	.0090	.0083	.0082
	rms/mean	.1359	.1317	.1249
	gauss	.06580(19)	.06285(18)	.06511(18)
	σ	.00815(13)	.00721(11)	.00718(12)
	σ/gauss	.1239(20)	.1147(18)	.1103(18)
	gauss 2σ	.06490(20)	.06204(19)	.06454(17)
	σ	.00814(21)	.00781(20)	.00728(17)
	σ/gauss	.1254(32)	.1259(32)	.1128(26)
10 GeV	Mean	.1329(3)	.1261(3)	.1312(3)
	rms	.0144	.0132	.0127
	rms/gauss	.1084	.1047	.0968
	gauss	.1323(3)	.1256(3)	.1310(3)
	σ	.01351(22)	.01213(20)	.01138(16)
	σ/gauss	.1021(17)	.0975(22)	.0869(12)
	gauss 2σ	.1314(3)	.1248(3)	.1301(3)
	σ	.01357(31)	.01224(28)	.01204(26)
	σ/gauss	.1033(24)	.1016(29)	.0925(20)
20 GeV	Mean	.2653(4)	.2536(4)	.2626(4)
	rms	.0224	.0213	.0207
	rms/gauss	.084	.084	.079
	gauss	.2645(5)	.2530(4)	.2615(4)
	σ	.02207(40)	.02047(36)	.01895(32)
	σ/gauss	.0834(15)	.0809(14)	.0725(12)
	gauss 2σ	.2636(5)	.2523(5)	.2603(4)
	σ	.02138(47)	.02033(42)	.01899(41)
	σ/gauss	.0811(18)	.0806(17)	.0730(16)
40 GeV	Mean	.5326(8)	.5057(7)	.5267(10)
	rms	.0380	.0349	.0334
	rms/gauss	.0713	.0690	.0634
	gauss	.5308(8)	.5058(7)	.5253(10)
	σ	.03520(57)	.03181(49)	.03164(76)
	σ/gauss	.0663(11)	.0629(10)	.0602(14)
	gauss 2σ	.5284(8)	.5037(7)	.5242(10)
	σ	.03562(85)	.03314(67)	.03148(89)
	σ/gauss	.0674(16)	.0658(13)	.0601(17)

Energy		*30 mkm*	*10 mkm*	*3 mkm*
60 GeV	Mean	.801(1)	.765(1)	.793(1)
	rms	.0514	.0486	.0464
	rms/gauss	.0642	.0635	.0585
	gauss	.7998(11)	.7635(10)	.7913(14)
	σ	.0479(8)	.0461(7)	.0415(10)
	σ/gauss	.0599(10)	.0604(9)	.0524(13)
	gauss 2σ	.7958(12)	.7611(11)	.7888(14)
	σ	.0487(12)	.0470(10)	.0429(14)
	σ/gauss	.0612(15)	.0618(13)	.0544(18)
80 GeV	Mean	1.068(1)	1.015(1)	1.054(1)
	rms	.0667	.0601	.0605
	rms/gauss	.0625	.0592	.0574
	gauss	1.0658(14)	1.0139(12)	1.0544(19)
	σ	.0615(10)	.0557(8)	.0552(12)
	σ/gauss	.0577(9)	.0549(8)	.0524(11)
	gauss 2σ	1.0601(15)	1.0109(13)	1.0494(19)
	σ	.0631(16)	.0570(11)	.0592(18)
	σ/gauss	.0595(15)	.0564(11)	.0564(17)
100 GeV	Mean	1.335(2)	1.271(1)	1.323(2)
	rms	.0792	.0721	.0734
	rms/gauss	.0593	.0567	.0555
	gauss	1.3358(16)	1.2700(15)	1.3216(15)
	σ	.0761(12)	.0705(11)	.0664(15)
	σ/gauss	.0570(9)	.0549(9)	.0502(11)
	gauss 2σ	1.3281(20)	1.2669(16)	1.3171(23)
	σ	.0807(21)	.0709(16)	.0706(21)
	σ/gauss	.0608(16)	.0560(13)	.0536(16)
120 GeV	Mean	1.603(2)	1.527(2)	1.584(2)
	rms	.0915	.0880	.0816
	rms/gauss	.0571	.0576	.0515
	gauss	1.6014(19)	1.5261(18)	1.5825(25)
	σ	.0850(14)	.0868(14)	.0790(19)
	σ/gauss	.0531(9)	.0569(9)	.0499(12)
	gauss 2σ	1.5952(20)	1.5230(21)	1.5792(26)
	σ	.0879(20)	.0902(21)	.0809(24)
	σ/gauss	.0551(13)	.0592(14)	.0512(15)

Energy		*30 mkm*	*10 mkm*	*3 mkm*
193 GeV	Mean	2.584(3)	2.461(3)	2.564(4)
	rms	.1468	.1329	.1282
	rms/gauss	.0568	.0540	.0500
	gauss	2.5908(20)	2.4515(32)	2.5644(40)
	σ	.1313(18)	.1397(33)	.1221(27)
	σ/gauss	.0507(7)	.0570(16)	.0476(11)
	gauss 2σ	2.5692(38)	2.4490(32)	2.5528(45)
	σ	.1544(43)	.1310(36)	.1297(48)
	σ/gauss	.0601(17)	.0535(15)	.0472(19)
400 GeV	Mean	5.40	5.12	5.35
	rms	.282	.271	.265
	rms/gauss	.0522	.0529	.0495
	gauss	5.378(18)	5.131(16)	5.357(14)
	σ	.313(19)	.251(11)	.253(9)
	σ/gauss	.0582(35)	.0489(21)	.0472(17)
1000 GeV	Mean	13.38	12.92	13.42
	rms	.720	.715	.265
	rms/gauss	.0538	.0553	.0466
	gauss	13.48(4)	12.86(16)	13.38(5)
	σ	.739(36)	.681(25)	.623(39)
	σ/gauss	.0548(27)	.0530(19)	.0466(29)

Table A1 Simulated with LArG4 FCal1 response to electrons having angle 2.98^0

8 Appendix 2. Simulated average response and resolution of FCal to electrons at different angles

Energy and angular dependence of the simulated FCal1 response and resolution is demonstrated in Tables A2.1-2.4. The average response is stable vs angle in the region $1.61 \div 4.3^0$. However it becomes 5% higher at 1.25^0 due to long right tails. From the other hand, the mean value of the gaussian fit does not changed. Deviation from linearity is typically 1% (Fig.16). The r.m.s. widths of the spectra are almost two times larger than the gaussian σ's at 1.25^0. At 1.61^0 this difference is much smaller, being $\approx$20%. It is usually less than 10% at 2.98^0 and disappears at 4.3^0. The gaussian σ's themselves increase with decreasing the angle, especially below 3^0. This effect is more pronounced at high energies although it is also not small at 5 GeV. Note that the difference between gaussian resolutions at 2.98^0 and 4.3^0 is about 10%.

	700	*300*	*100*	*50*	*30*	*10*	*5*	*3*
					5 GeV			
M	.061	.062	.064	.066	.066	.063	.061	.065
R	.0093	.0085	.0087	.0083	.0080	.0078	.0075	.0071
4.3 G	.0607(5)	.0618(4)	.0640(4)	.0653(4)	.0656(5)	.0626(4)	.0609(4)	.0648(4)
σ	.0091(4)	.0081(4)	.0081(3)	.0077(4)	.0076(3)	.0076(3)	.0066(3)	.0069(3)
M	.0613	.0633	.0643	.0652	.0662	.0630	.0620	.0656
R	.0097	.0094	.0096	.0095	.0090	.0083	.0084	.0082
3.0 G	.0614(6)	.0623(5)	.0633(4)	.0647(5)	.0658(2)	.0629(2)	.0615(4)	.0651(2)
σ	.0092(4)	.0089(4)	.0083(3)	.0093(4)	.0081(1)	.0072(1)	.0079(4)	.0072(1)
M	.061	.063	.065	.065	.067	.064	.062	.067
R	.0117	.0125	.0110	.0108	.0116	.0108	.0099	.0113
1.6 G	.0601(8)	.0615(7)	.0633(5)	.0647(6)	.0660(7)	.0623(6)	.0613(5)	.0651(6)
σ	.0091(5)	.0105(5)	.0095(4)	.0093(4)	.0096(4)	.0083(5)	.0085(4)	.0092(5)
M	.068	.067	.068	.070	.072	.069	.069	.072
R	.0282	.0226	.0246	.0228	.0276	.0266	.0306	.0292
1.3 G	.0615(8)	.0626(7)	.0643(8)	.0651(8)	.0658(7)	.0639(7)	.0626(6)	.0661(6)
σ	.0132(9)	.0125(8)	.0121(7)	.0105(6)	.0114(6)	.0109(6)	.0098(4)	.0098(5)
					10 GeV			
M	.124	.124	.130	.132	.132	.126	.124	.130
R	.0133	.0135	.0138	.0134	.0134	.0120	.0111	.0110
4.3 G	.124(1)	.124(1)	.129(1)	.130(1)	.132(1)	.125(1)	.124(1)	.130(1)
σ	.0126(5)	.0127(6)	.0126(6)	.0123(7)	.0134(6)	.0111(4)	.0104(3)	.0109(5)
M	.123	.126	.128	.131	.133	.126	.124	.131
R	.0146	.0139	.0144	.0147	.0144	.0132	.0129	.0131
3.0 G	.123(1)	.125(1)	.127(1)	.130(1)	.1323(3)	.1256(3)	.124(1)	.1310(3)
σ	.0140(7)	.0125(5)	.0137(6)	.0131(6)	.0135(2)	.0121(2)	.0107(4)	.0114(2)
M	.123	.124	.129	.131	.133	.128	.123	.131
R	.0202	.0190	.0193	.0189	.0178	.0191	.0153	.0173
1.6 G	.1181(15)	.1214(10)	.1266(10)	.1283(10)	.1303(9)	.1238(9)	.1220(8)	.1287(8)
σ	.0203(12)	.0178(11)	.0181(9)	.0178(9)	.0147(7)	.0160(10)	.0145(7)	.0141(7)
M	.131	.134	.135	.139	.139	.135	.133	.140
R	.0379	.0360	.0296	.0341	.0310	.0367	.0364	.0369
1.3 G	.1222(11)	.1252(15)	.1311(12)	.1342(12)	.1351(14)	.1275(11)	.1247(11)	.1322(13)
σ	.0180(11)	.0204(13)	.0182(9)	.0208(10)	.0177(10)	.0169(10)	.0160(9)	.0177(11)

Table A2.1 Simulated with LArG4 FCal1 response to 5 and 10 GeV electrons at different angles. Abbreviations “M”, “R” and “G” stand for mean response, its r.m.s. and for an average value of gaussian respectively. Value of angle (in degrees) is indicated before the “G”.

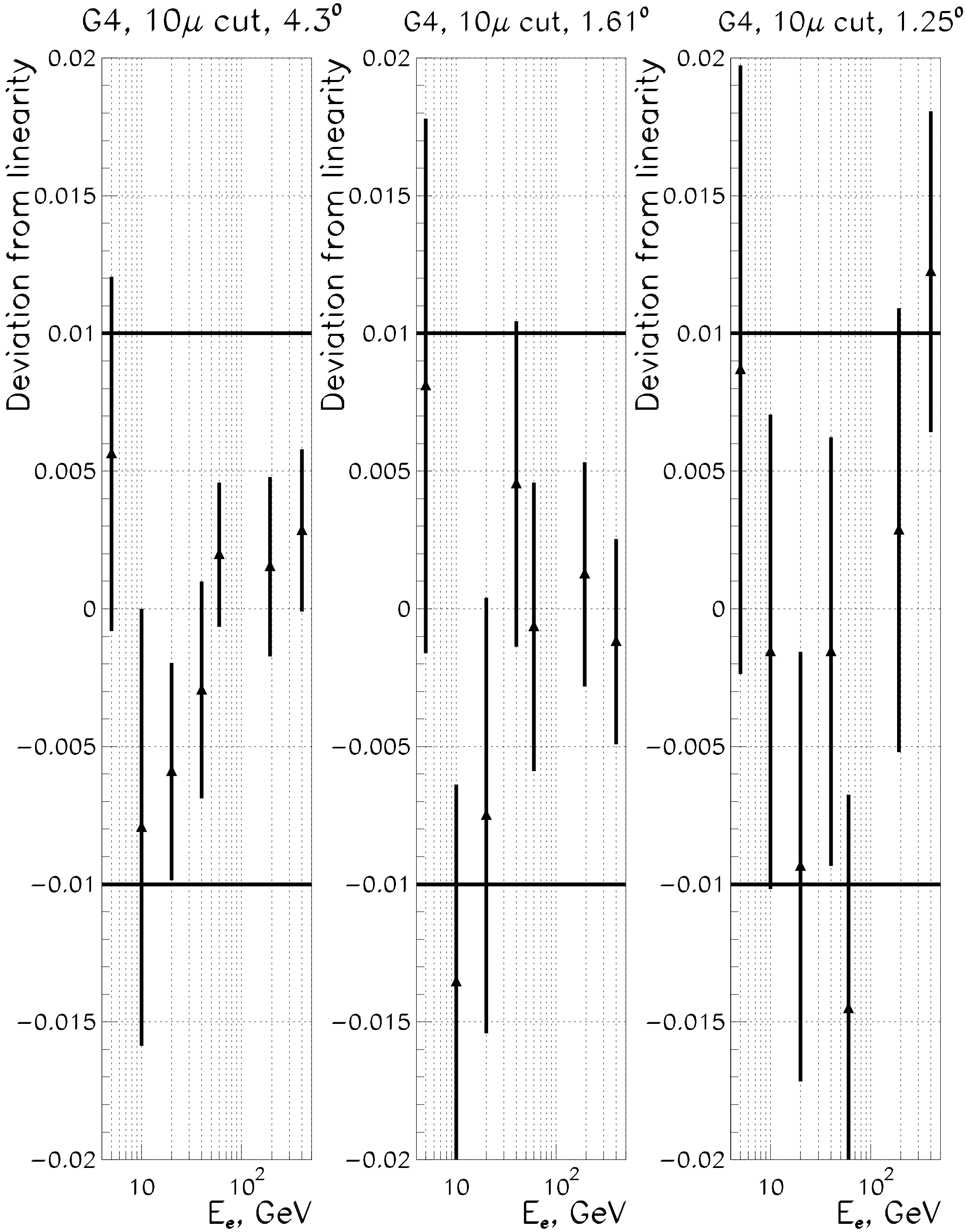

Figure 16: Simulated deviation from linearity of the FCal average response to electrons at different angles.

	700	*300*	*100*	*50*	*30*	*10*	*5*	*3*
					20 GeV			
M	.248	.252	.258	.262	.265	.253	.250	.262
R	.0202	.0211	.0218	.0196	.0193	.0198	.0170	.0181
4.3 G	.247(1)	.252(1)	.258(1)	.262(1)	.265(1)	.252(1)	.250(1)	.261(1)
σ	.0198(8)	.0203(11)	.0213(9)	.0186(7)	.0202(7)	.0197(8)	.0183(8)	.0165(8)
M	.247	.251	.260	.263	.2653	.2537	.248	.2626
R	.0229	.0237	.0265	.0230	.0223	.0212	.0206	.0205
3.0 G	.246(1)	.251(1)	.260(1)	.262(1)	.2647(5)	.2532(4)	.245(1)	.2616(4)
σ	.0215(10)	.0230(10)	.0227(10)	.0193(9)	.0216(4)	.0196(3)	.0174(8)	.0187(3)
M	.245	.253	.259	.264	.264	.253	.249	.264
R	.0331	.0334	.0325	.0329	.0310	.0297	.0289	.0298
1.6 G	.240(2)	.251(2)	.253(2)	.260(2)	.260(2)	.251(2)	.246(2)	.261(2)
σ	.0321(17)	.0297(14)	.0301(18)	.0315(16)	.0269(13)	.0260(12)	.0251(13)	.0257(13)
M	.264	.268	.266	.276	.285	.271	.266	.280
R	.064	.064	.052	.061	.068	.075	.073	.066
1.3 G	.247(2)	.254(2)	.257(2)	.262(2)	.269(2)	.254(2)	.251(2)	.265(2)
σ	.0357(22)	.0378(23)	.0353(19)	.0296(16)	.0325(16)	.0320(15)	.0287(17)	.0283(19)
					40 GeV			
M	.493	.503	.513	.528	.531	.507	.501	.526
R	.0343	.0351	.0334	.0355	.0337	.0328	.0309	.0310
4.3 G	.491(2)	.503(2)	.513(2)	.527(2)	.529(2)	.507(2)	.499(2)	.526(2)
σ	.0332(17)	.0347(14)	.0330(12)	.0342(13)	.0312(12)	.0331(11)	.0331(15)	.0311(12)
M	.496	.505	.522	.525	.5327	.5068	.502	.5270
R	.0401	.0393	.0403	.0357	.0384	.0353	.0354	.0338
3.0 G	.493(2)	.504(2)	.523(2)	.523(2)	.5317(8)	.5060(8)	.500(2)	.5259(10)
σ	.0375(18)	.0373(15)	.0374(15)	.0359(16)	.0338(5)	.0316(5)	.0340(18)	.0317(7)
M	.485	.497	.513	.524	.529	.506	.498	.531
R	.056	.055	.055	.052	.052	.049	.046	.052
1.6 G	.467(6)	.486(3)	.510(3)	.520(2)	.524(2)	.510(3)	.494(3)	.529(3)
σ	.063(5)	.0486(25)	.0481(20)	.0467(20)	.0468(21)	.0435(18)	.439(24)	.0469(22)
Mean	.524	.549	.549	.545	.556	.537	.520	.547
R	.121	.134	.111	.105	.092	.115	.088	.106
1.3 G	.490(4)	.518(4)	.527(4)	.529(4)	.540(4)	.513(4)	.509(4)	.529(3)
σ	.0719(46)	.0647(33)	.0617(30)	.0595(27)	.0577(27)	.0603(35)	.0522(25)	.0523(24)

Table A2.2 Simulated with LArG4 FCal1 response to 20 and 40 GeV electrons

	700	*300*	*100*	*50*	*30*	*10*	*5*	*3*
					60 GeV			
M	.741	.758	.777	.791	.806	.766	.750	.792
R	.050	.049	.048	.048	.048	.044	.044	.043
4.3 G	.741(2)	.757(2)	.776(2)	.789(3)	.805(3)	.765(2)	.750(2)	.791(2)
σ	.0481(18)	.0454(21)	.0466(22)	.0482(24)	.0477(21)	.0434(18)	.0439(18)	.0429(15)
M	.738	.760	.776	.793	.8012	.7644	.748	.7935
R	.053	.055	.050	.050	.0521	.0490	.044	.0465
3.0 G	.738(3)	.758(3)	.771(3)	.791(3)	.7999(11)	.7644(10)	.748(2)	.7909(14)
σ	.0488(18)	.0537(21)	.0491(22)	.0471(21)	.0479(7)	.0458(7)	.0414(16)	.0435(12)
M	.741	.760	.775	.794	.796	.768	.747	.795
R	.077	.080	.075	.075	.077	.073	.070	.073
1.6 G	.727(4)	.753(4)	.772(4)	.793(4)	.793(4)	.762(4)	.741(3)	.793(4)
σ	.0686(46)	.0685(30)	.0667(26)	.0711(31)	.0656(26)	.0653(30)	.0609(25)	.0673(30)
M	.779	.800	.811	.848	.840	.807	.799	.837
R	.185	.202	.144	.202	.176	.197	.164	.173
1.3 G	.739(5)	.756(6)	.789(5)	.812(6)	.816(5)	.760(6)	.769(5)	.804(6)
σ	.084(5)	.092(5)	.080(3)	.094(5)	.083(3)	.099(6)	.086(5)	.082(4)
					193 GeV			
M	2.39	2.44	2.52	2.55	2.58	2.46	2.42	2.55
R	.146	.134	.145	.136	.140	.130	.130	.131
4.3 G	2.397(8)	2.441(8)	2.510(8)	2.550(8)	2.570(8)	2.463(8)	2.416(7)	2.541(7)
σ	.141(5)	.141(6)	.145(6)	.140(7)	.141(6)	.134(7)	.125(5)	.130(5)
M	2.41	2.45	2.52	2.57	2.585	2.461	2.42	2.564
R	.147	.148	.140	.150	.149	.133	.125	.1282
3.0 G	2.41(1)	2.44(1)	2.52(1)	2.56(1)	2.591(2)	2.459(3)	2.42(1)	2.564(4)
σ	.141(6)	.146(7)	.139(6)	.153(8)	.131(2)	.126(2)	.126(6)	.122(4)
M	2.39	2.43	2.51	2.56	2.58	2.46	2.42	2.55
R	.207	.206	.221	.208	.211	.188	.200	.187
1.6 G	2.37(1)	2.42(1)	2.49(1)	2.54(1)	2.56(1)	2.46(1)	2.40(1)	2.54(1)
σ	.183(9)	.202(9)	.185(8)	.186(9)	.180(8)	.169(7)	.181(9)	.158(7)
M	2.51	2.55	2.62	2.63	2.75	2.56	2.55	2.68
R	.369	.433	.464	.452	.534	.382	.480	.446
1.3 G	2.45(2)	2.50(2)	2.54(2)	2.59(2)	2.61(2)	2.49(2)	2.45(1)	2.59(1)
σ	.269(15)	.255(18)	.270(15)	.250(14)	.258(14)	.211(9)	.215(10)	.200(10)

Table A2.3 Simulated with LArG4 FCal1 response to 60 and 193 GeV electrons

	700	*300*	*100*	*50*	*30*	*10*	*5*	*3*
					400 GeV			
M	4.97	5.07	5.21	5.30	5.40	5.11	5.04	5.31
R	.275	.274	.272	.274	.284	.265	.270	.263
4.3 G	4.976(15)	5.080(15)	5.204(17)	5.300(16)	5.397(16)	5.113(15)	5.041(14)	5.303(14)
σ	.272(12)	.265(12)	.284(14)	.283(13)	.288(12)	.278(13)	.258(10)	.255(10)
M	5.00	5.10	5.26	5.32	5.40	5.12	5.07	5.35
R	.306	.273	.304	.294	.282	.271	.258	.265
3.0 G	4.988(16)	5.098(16)	5.230(18)	5.302(18)	5.378(18)	5.131(16)	5.063(15)	5.356(14)
σ	.299(13)	.285(16)	.319(16)	.307(17)	.313(19)	.250(11)	.263(13)	.252(9)
M	4.97	5.07	5.19	5.30	5.37	5.09	5.03	
R	.418	.398	.404	.421	.399	.373	.365	
1.6 G	4.918(21)	5.065(21)	5.158(18)	5.242(21)	5.323(22)	5.088(19)	4.994(16)	5.303(20)
σ	.382(18)	.334(16)	.317(13)	.354(18)	.358(18)	.331(13)	.280(11)	.329(15)
M	5.15	5.35	5.55	5.57	5.61	5.36	5.22	5.54
R	.782	.933	.955	.953	.892	.671	.873	.853
1.3 G	5.00(3)	5.14(3)	5.30(3)	5.37(3)	5.41(3)	5.21(3)	5.04(3)	5.39(3)
σ	.469(26)	.471(25)	.408(19)	.474(24)	.493(26)	.464(25)	.471(29)	.451(22)

Table A2.4 Simulated with LArG4 FCal1 response to 400 GeV electrons

9 Appendix 3. FCal1 response at very strong range cuts

As seen from Table 1, to reach minimal possible 1 keV equivalent energy cut for electrons in FCal absorbers, copper and tungsten, we need to use 1 or even 0.5μ range cuts in GEANT4. 400 events at 5, 10, 20, 40, 60, 193 and 400 GeV were generated. The impact angle was 2.98^0. Typical response distributions are shown in Fig.17 and Fig.18. Details are presented in Table A3.1. It is clearly seen that the average response at 1μ (0.5μ) is 10% (15%) higher than at 3μ, irrespective of initial electron energy. The reason of such increase is unclear. From the other hand, the relative energy resolution is not changed significantly with the range cut in the region $0.5 \div 3\mu$. So taking into account that CPU time consumption dramatically increases when we come from 3μ to 1μ cut and especially to 0.5μ, it was decided not to continue related MC simulations.

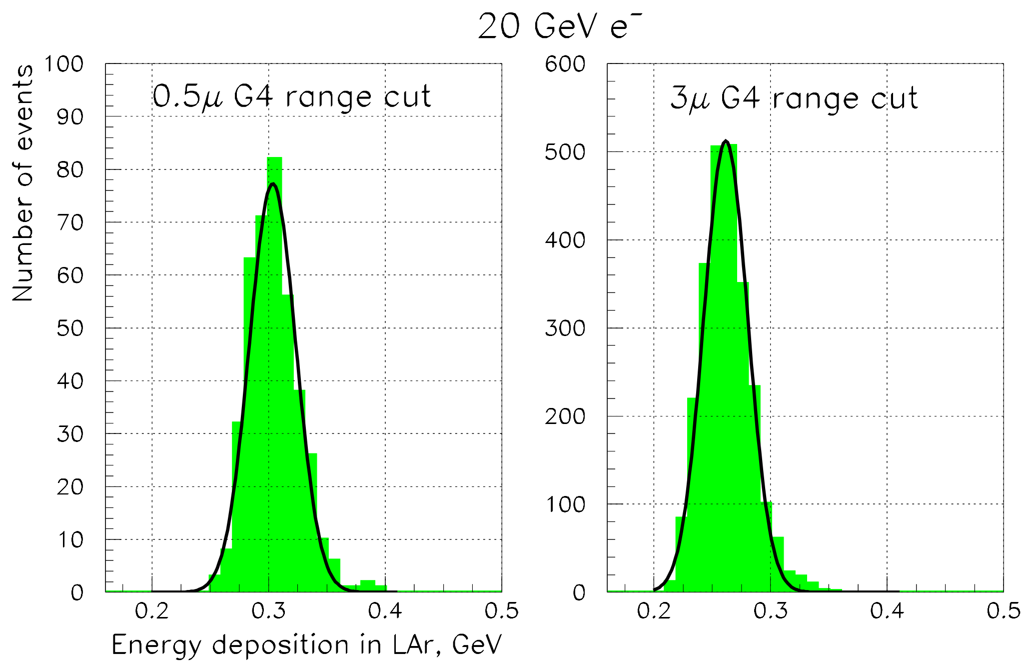

Figure 17: Simulated FCal response to 20 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestriced gaussian fit (solid black lines)

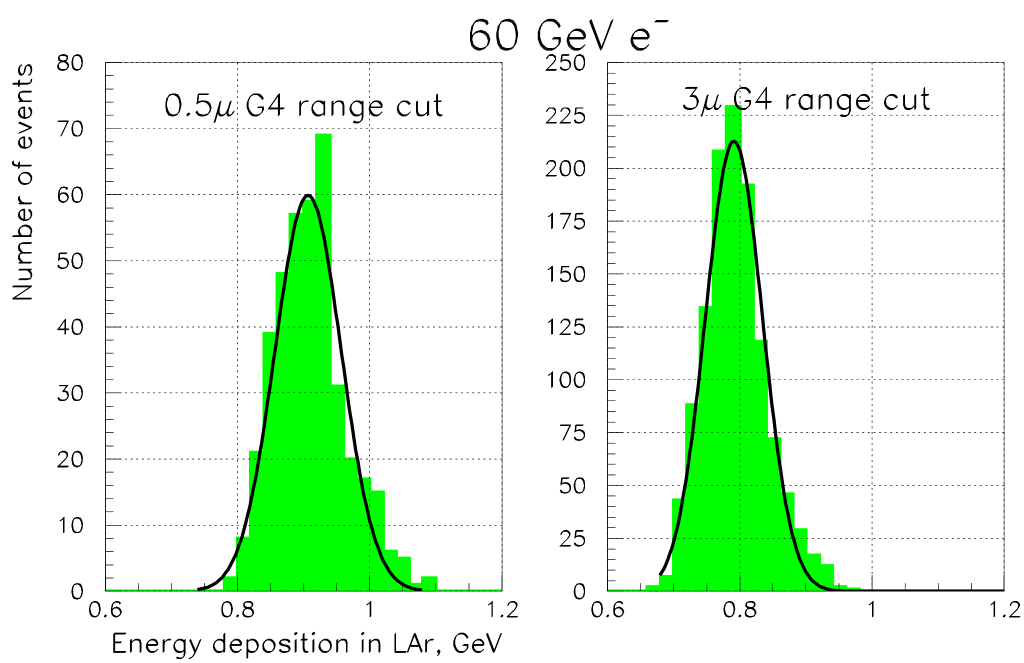

Figure 18: Simulated FCal response to 60 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestricted gaussian fit (solid black lines)

Energy		*0.5 mkm*	*1 mkm*	*3 mkm*
5 GeV	Mean	.0760	.0716	.06563(16)
	rms	.0093	.0084	.0082
	rms/mean	.122	.117	.1249
	gauss	.0752(4)	.0712(5)	.06511(18)
	σ	.0079(3)	.0083(4)	.00718(12)
	σ/gauss	.105(4)	.117(6)	.1103(18)
10 GeV	Mean	.150	.143	.1312(3)
	rms	.0130	.0135	.0127
	rms/gauss	.087	.094	.0968
	gauss	.1494(7)	.1417(8)	.1310(3)
	σ	.118(5)	.0142(9)	.01138(16)
	σ/gauss	.079(4)	.100(6)	.0869(12)
20 GeV	Mean	.305	.288	.2626(4)
	rms	.0216	.0207	.0207
	rms/gauss	.071	.072	.079
	gauss	.303(1)	.287(1)	.2615(4)
	σ	.0198(9)	.0191(7)	.01895(32)
	σ/gauss	.065(3)	.066(3)	.0725(12)
40 GeV	Mean	.604	.578	.5267(10)
	rms	.0362	.0366	.0334
	rms/gauss	.060	.061	.0634
	gauss	.602(2)	.574(2)	.5253(10)
	σ	.0366(17)	.0359(18)	.03164(76)
	σ/gauss	.063(3)	.061(3)	.0602(14)
60 GeV	Mean	.911	.872	.793(1)
	rms	.0543	.0524	.0464
	rms/gauss	.060	.060	.0585
	gauss	.904(3)	.869(2)	.7913(14)
	σ	.0470(22)	.0473(18)	.0415(10)
	σ/gauss	.052(2)	.054(2)	.0524(13)
193 GeV	Mean	2.94	2.81	2.564(4)
	rms	.127	.127	.1282
	rms/gauss	.043	.045	.0500
	gauss	2.92(1)	2.81(1)	2.5644(40)
	σ	.140(18)	.117(5)	.1221(27)
	σ/gauss	.048(5)	.042(2)	.0476(11)
400 GeV	Mean	–	5.82	5.35
	rms	–	.266	.265
	rms/gauss	–	.046	.0495
	gauss	–	5.80(2)	5.357(14)
	σ	–	.284(26)	.253(9)
	σ/gauss	–	.049(4)	.0472(17)

Table A3.1 Simulated FCal1 average response and energy resolution to electrons at very strong range cuts.

10 Appendix 4. Resolution vs energy at different angles.

Stochastic and constant terms of the simulated FCal energy resolution to electrons at different angles and GEANT4 range cuts are shown in Table A4.1. In some cases fit quality by the function $\sigma/E = \sqrt{a^2/E + b^2}$ is not good.

Stochastic term. At any angle it decreases with tightening the range cut in GEANT4, the difference between 700 and 3μ being ≈25%. The stochastic term is more stable below 50μ. At given range cut the stochastic term is the best at 4.3^0, becomes 10% larger at 2.98^0 and ≈40% larger at 1.61^0. There is no increasing of the stochastic term at very small angles.

Constant term. At fixed angle, the constant term slightly decreases at stronger range cuts. The uncertainty in the choice of the range cut transforms into the systematic error which is approximately equal to 10%. At cuts below 30–50μ the constant term becomes more stable. At fixed range cut it does not changed above 2.98^0. At 1.61^0 it is 30% larger and at 1.25^0 it doubles reaching a value 8–10%.

	700	*300*	*100*	*50*	*30*	*10*	*5*	*3*	*1*	*0.5*
					4.3^0					
a	.286	.274	.259	.234	.243	.241	.217	.211		
Δa	.010	.011	.010	.011	.009	.009	.008	.009		
b	.0532	.0518	.0527	.0522	.0508	.0516	.0509	.0474		
Δb	.0015	.0016	.0016	.0017	.0015	.0016	.0013	.0012		
χ^2	5.7/5	2.7/5	3.9/5	2.0/5	10.4/5	5.3/5	4.8/5	2.4/5		
					2.98^0					
a	.309	.286	.277	.272	.272	.242	.239	.233	.254	.209
Δa	.012	.011	.010	.011	.004	.004	.010	.003	.010	.010
b	.0554	.0573	.0550	.0527	.0486	.0509	.0489	.0453	.0407	.0466
Δb	.0017	.0019	.0017	.0019	.0005	.0005	.0016	.0006	.0017	.0024
χ^2	2.4/5	7.6/5	7.7/5	11.7/5	52.6/9	59.1/9	9.1/5	16.1/9	13.7/5	2.6/4
					1.61^0					
a	.365	.383	.349	.321	.297	.311	.315	.305		
Δa	.018	.016	.013	.014	.013	.016	.013	.014		
b	.0781	.0722	.0670	.0723	.0696	.0668	.0620	.0632		
Δb	.0027	.0024	.0020	.0023	.0021	.0019	.0019	.0020		
χ^2	47.4/5	17.8/5	35.3/5	28.6/5	8.0/5	17.4/5	36/5	20.9/5		
					1.25^0					
a	.409	.428	.390	.331	.320	.345	.289	.298		
Δa	.027	.026	.019	.021	.020	.020	.017	.018		
b	.101	.0977	.0860	.0843	.0930	.0896	.0913	.0827		
Δb	.004	.0037	.0028	.0030	.0028	.0029	.0029	.0025		
χ^2	16.3/5	9.2/5	28.2/5	14.9/5	2.0/5	27.1/5	6.5/5	12.3/5		

Table A4.1 Stochastic and constant terms of simulated FCal1 energy resolution to electrons at different angles as well as quality of the fit.

11 Appendix 5. FCal2 and FCal3 response to electrons

Although FCal2 and FCal3 will be used as hadronic calorimeters in ATLAS, it is a good idea to have a look at their responses to electrons. The reasons are the following:

1. With electrons, one can define intercalibration coefficients between three FCal sections. As there are no related data available, we plan to use the MC for this purpose;

2. In some (although rather rare) cases, EM component of hadronic showers (π^0) can be non-negligible in the FCal2 or even in FCal3. So with electrons we may get an idea what's its response to such events.

3. MC simulation of electron response is a good cross-check of the software.

Simulations were performed for 10 and 100 GeV electrons at 3 and 30μ range cuts. As seen from Fig.19-22, response has non-gaussian shape with significant right tails. Due to coarse granularity of the hadronic FCal modules, the widths of the distributions are much larger than for the FCal1 especially at 100 GeV. The sampling fractions obtained for FCal1, FCal2 and FCal3 are 1.33%, 0.64% and 0.86% respectively.[11] at 30μ range cut.

12 Appendix 6. Total energy deposition in the FCal

Although for physics studies one needs energy deposition in an active medium, i.e. LAr, for cross-checks it is helpful to know the total energy deposition, E_{tot}.

Distributions on E_{tot} are centered at values which are less than 0.1% lower than the nominal electron energy. The r.m.s's of the distributions are in the range 3÷30 MeV depending on the energy. Left tails are non-gaussian but not very long. In particular, for 120 GeV run at 30μ range cut, with 2500 events, 119.78 GeV$\leq E_{tot} \leq$119.95 GeV.

[11] The average values of the distributions are used to obtain these numbers.

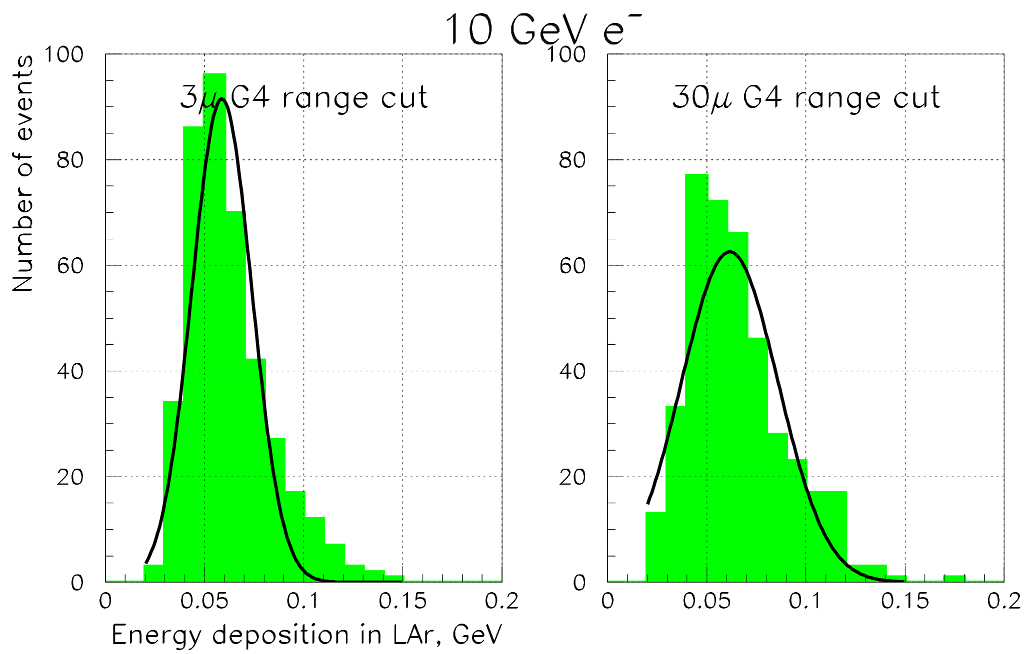

Figure 19: Simulated FCal2 response to 10 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestriced gaussian fit (solid black lines)

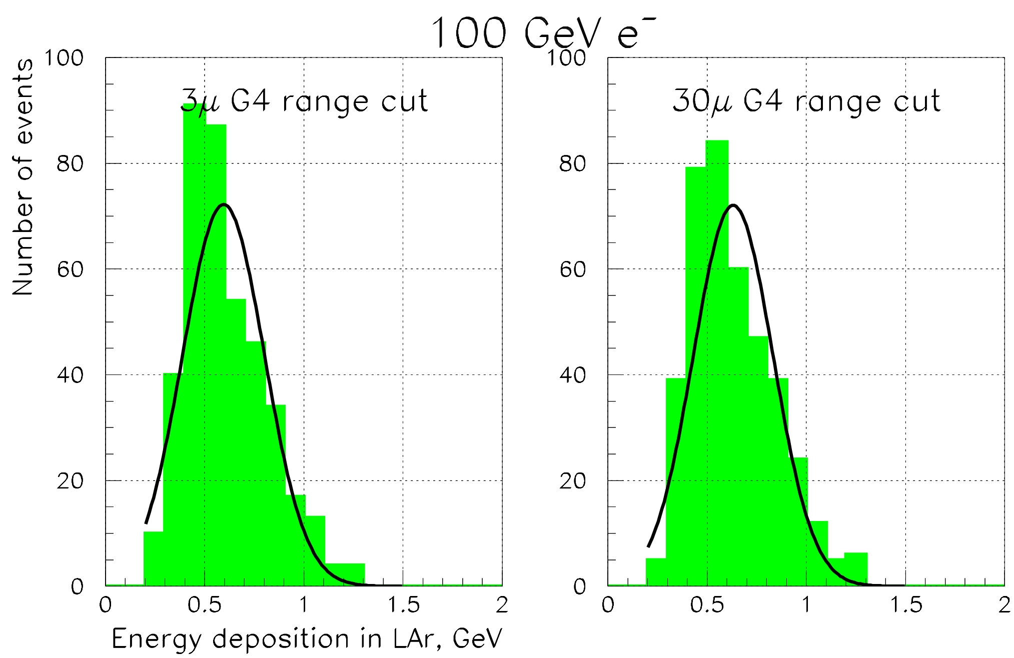

Figure 20: Simulated FCal2 response to 100 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestricted gaussian fit (solid black lines)

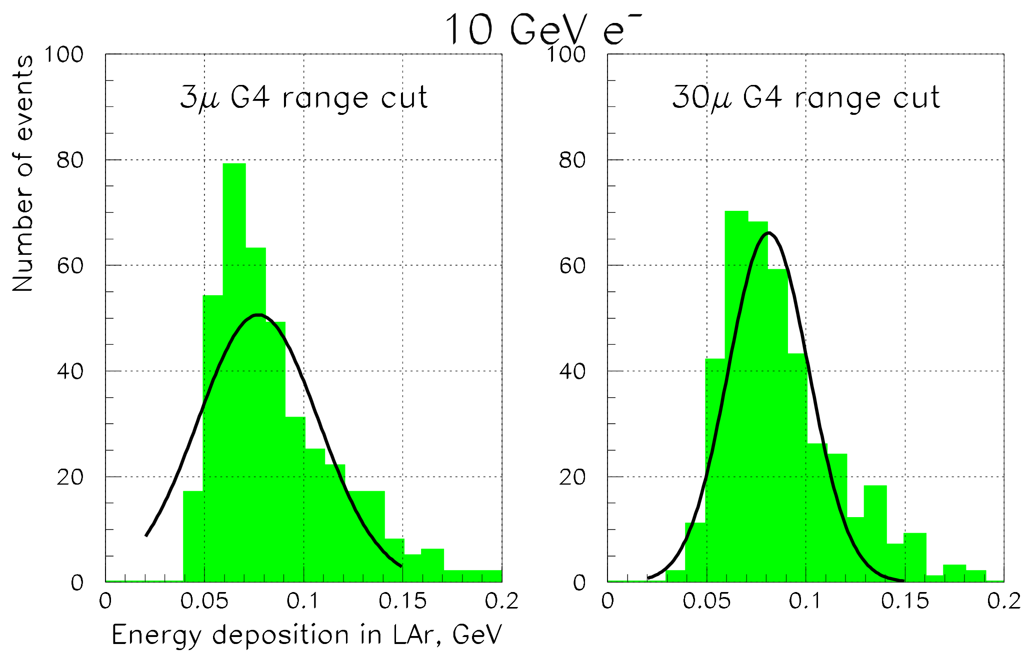

Figure 21: Simulated FCal3 response to 10 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestriced gaussian fit (solid black lines)

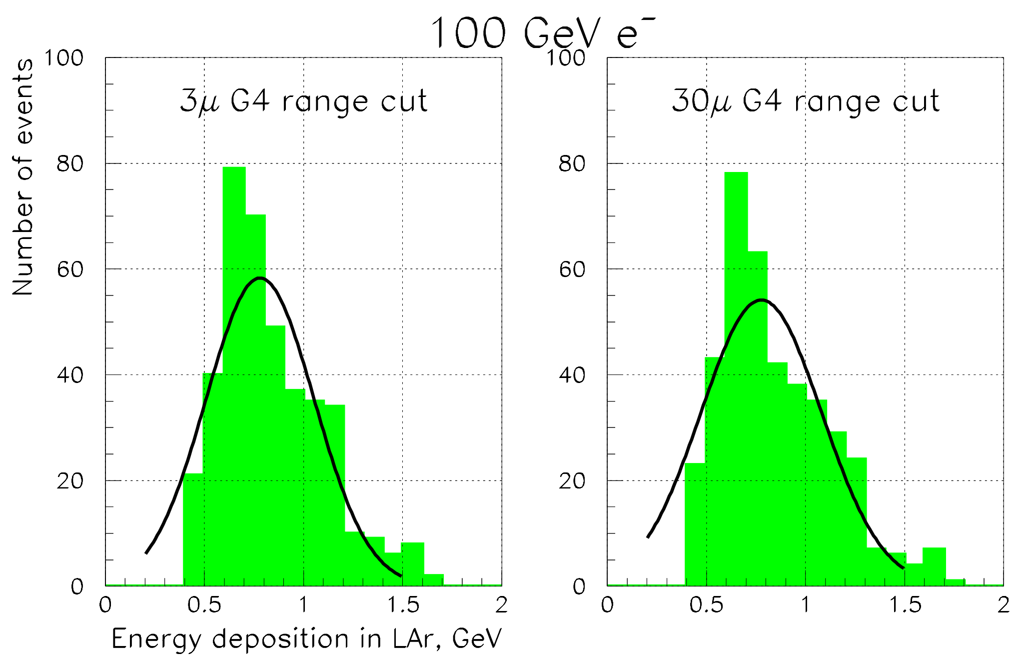

Figure 22: Simulated FCal3 response to 100 GeV electrons having impact angle 2.98^0 (solid green histograms) with superimposed unrestricted gaussian fit (solid black lines)