Angular dependence of FCal response to electrons and pions

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1 Introduction

Forward calorimeter in ATLAS (FCal) is intended for measurement of energy of hadronic jets having small polar angles and for missing-E_t vector determination together with other calorimeters. In particular, such jets accompany production of Higgs boson via vector bozon fusion mechanism. Recently it was shown that detection of forward going jets helps to increase significantly discovery potential not only for heavy Higgs boson [1] but also for intermediate mass Higgs boson [2]. Accurate missing-E_t determination is essential for many physics tasks, in particular, for SUSY searches using E_t^{miss}+multijet signature [1]. So the role of the FCal in possible discoveries of new particles is essential and its performance should be studied in detail. Note that good accuracy of **energy scale** determination is even more important than to have reasonable energy resolution.

In 2003, the complete FCal was exposed to electron and pion beams of CERN SPS. The first detailed analysis of the test-beam results together with GEANT3/ATLSIM MC simulations was presented in [3]. 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. For pions, it was shown that "none of the hadronic generators provides satisfactory description of all the aspects of the experimental data", namely, energy resolution and h/e ratio. However, that analysis was based only on runs where electron and pion impact angles were fixed to 2.98^0 while in real ATLAS experiment, the FCal covers range $0.8^0 \leq \theta \leq 4.7^0$. In addition, investigation described in [3] was not performed inside standard ATHENA framework.

The ATHENA-based software for FCal 2003 test-beam analysis was recently developed and first physics results were shown [4]. This software was modified and used for the study of the FCal shower profiles and baricenter/p_t-reconstruction, see [5].[1]

MC events were generated using official ATHENA-based software, release 10.0.1. At first, G4 [6] simulation (version 7.0) was performed and standard files (*.pool.root*) with *hits* was created.[2] At the next step these events were passed through the latest version of *LArG4Analysis* package with modifications described in [5]. The same clustering method and cluster sizes were used in the analysis of real data and MC.

[1]In the analysis considered below the clustering method *LArFCalTBRadialDigitCluster* is used. For electrons (pions), the cluster size R_{clus} was chosen as 80 mm (160 mm) respectively. Tile amplitude was calculated using the so-called *parabola fit* method. Only events passed S1 S2 S3 *mūon* trigger were selected. BPC's were used for multiple track rejection. All cuts were deduced from Ref.[5].

[2]Note that serious bug in one of MCS G4 routines is corrected only in version 8.0! This bug affects seriously average calorimeter response (sampling fraction) to electrons and, possibly, also energy resolution [7].

2 Response and resolution for electrons and pions

2.1 Initial conditions

During test-beam 2003, angular dependence of FCal response to electrons and pions was studied only for 200 GeV particles (more precisely, beam energy was 193.7 GeV for electrons). Tests were performed at five "positions" as seen from Table 1. It should be noted that the average distance between test-beam impact point[3] at the front face of the FCal1 and its edge was only about 4 cm for 1.25^0 so one would expect significant lateral shower leakage even for electrons in the position 2 and especially in the position 1.

Pos.	*R, mm*	*H, mm*	*Angle, degrees*	η range
1	37-107	-35 +35	0.88	4.47-5.53
2	67-137	-35 +35	1.25	4.22-4.94
3	97-167	-35 +35	1.61	4.02-4.57
4L	211-281	-75 -5	2.98	3.50-3.79
4H	211-281	+5 +75	2.98	3.50-3.79
5	315-385	-35 +35	4.30	3.19-3.39

Table 1. Test-beam conditions at different positions. R is radial distance between center of the FCal cylinder (it is situated at θ=0) and the beam impact point on the front face of the FCal1, L is vertical distance from this point to horizontal axis of the cylinder. Position 5 was considered only in the MC.[4] η is calculated as $\log(\tan(R/9330))$, 9330 mm being the double-distance between the FCal front face and the beam collision point at the LHC.

Table 2 contains short information about related runs extracted from the official run summaries [9]. Part of this statistics was processed through the analysis program.

[3] Let's remind that beam spot was a square with size 7x7 cm^2.

[4] It was tried in the 1998' beam tests of the FCal module0 [8].

Beam	*Pos.*	*First run*	*Last run*	*Events*	*Page in [11]*	*Material*	*Comments*
π^-	1	1852	1868	204000	117	Al block	–
e^-	1	1869	1877	108000	118	Al block	Pb target in beam?
e^-	2	1880	1889	120000	119	–	Pb target in beam?
π^-	2	1915	1918	48000	121	–	–
π^-	2	1923	1938	192000	122	–	–
π^-	3	1939	1973	420000	123	–	–
e^-	3	1974	1984	132000	123	–	Pb target in beam?
π^-	1	1985	2005	252000	126	Al block	–
π^-	2	2007	2011	60000	127	–	–
π^-	2	2012	2021	120000	128	–	–
e^-	1	2402	2418	204000	169	Al block	Air target + absorber
e^-	2	2419	2435	204000	171	–	Air target + absorber
e^-	3	2436	2437	22320	171	–	Air target + absorber
e^-	3	2948	2965	216000	251	–	–
π^-	1	3139	3155	204000	272	Al block	CEDAR π 200 GeV
π^-	2	3156	3172	204000	275	–	CEDAR π 200 GeV
π^-	3	3173	3189	204000	278	–	CEDAR π 200 GeV
e^-	4L	3224	3233	120000	283	–	–
e^-	4H	2967	2985	228000	251	poly angled	–
π^-	4L	2284	2313	360000	156	–	Pb target 6mm
π^-	4H	3043	3059	204000	262	Poly angled	–

Table 2. Run summaries for 200 GeV electrons and pions extracted from [9]. Al block and "poly angled" mentioned above represent aluminium with 3cm thickness and polyethylene with 1m length along the beam respectively. They imitate vacuum ion pump and a neutron backsplash shield ("LAr plug", [10]) in real ATLAS setup. Complete information can be found in the logbook [11].

200 GeV point was tried for electrons also in the MC. It was checked that results obtained with the ATHENA and with the standalone version of GEANT4 [12] are compatible.[5]

In real ATLAS conditions there is some amount of passive material, in particular aluminium from the end-cap cryostat, in front of the FCal. This (η-dependent) amount was estimated with the help of so-called "geantino-scan" of the forward region with the MC. To do this, the original C++ code [14] was a bit modified. Results are shown in Table 3. It is seen that at 2.98^0 we have more than $3X_0$ of material while at other angles the thickness is less than $1X_0$, consisting mostly of the aluminium end-cap cryostat walls. In contrast, in the test-beam setup one had approximately $2.7X_0$ of passive material in front of the FCal irrespective of angle [15]. Unfortunately, detailed geometry of the test-beam setup was not yet fully incorporated into ATHENA framework [16] so DATA/MC comparison described below can be biased.

[5]Please, compare Table A1.2 "no material" from the current memo with Table A1, point 193 GeV in Ref.[12].

				ATLAS setup					
η	3.3-3.4	3.4-3.5	3.5-3.7	3.7-3.9	3.9-4.1	4.1-4.3	4.3-4.5	4.5-4.7	4.7-4.9
$N(X_0)$	7.6	4.0	3.5	1.9	0.9	0.8	0.7	0.7	0.8
					All material				
Pos.	-	-	4	-	-	3	-	2	1
$N(X_0)$	-	-	3.1	-	-	0.9	-	0.9	1.4
					Only cryostat				
Pos.	-	-	4	-	-	3	-	2	1
$N(X_0)$	-	-	0.5	-	-	0.4	-	0.3	0.3

Table 3. Simulated amount of passive material (in X_0) in front of the FCal vs η and for four test-beam positionsin real ATLAS setup. To roughly simulate the effect of the TB cryostat alone, z_{vert} was chosen to be 4500 mm (see column "only cryostat" for results).

Another problem is absence of any traces of 1m-long polyethylene in the geometry description of the standard ATLAS MC. It corresponds to "a neutron backsplash shield" and usually called as "LAr plug" [10]. This problem is under investigation [17].

For pions, simulation was performed for 5, 25, 50, 100, 200, 400, 800 and 1600 GeV at five positions listed in Table 1.

Range cut was chosen to be 30μ both for electrons and pions.[6] **Passive material in front of the FCal was not included in most of the simulations.**[7].

2.2 Electrons at 200 GeV

About 20% events from each group of electron runs listed in Table 1 were processed. It turned out that presense of additional passive material in front of the FCal (like air target and absorber), does not significantly affect average response. However, results for 4H and 4L positions are found to be different, see details in Appendix 1. The average response (energy resolution) in the 4L position is found to be 0.4% (10%) smaller than in the 4H position respectively. This is due to presence of the 1m piece of polyethylene which imitates "LAr plug" in the ATLAS setup.[8] However, let's remind that this "LAr plug" is (occasionally?) absent in the ATLAS MC (to be clarified). As this study focuses on angular dependence of the FCal response, it was decided not to consider 4H position in future.

Response to electrons at four test-beam positions mentioned above is shown in Fig.1.[9] Right part of the distributions has a shape close to gaussian irrespective on the angle. In contrast, there are left non-gaussian tails which are more pronounced at small angles. At 2.98^0 and 1.61^0 low (very low) amplitudes are known due to residual pion (muon) contamination respectively. At 1.25^0 and especially at 0.88^0, the contribution from events with large lateral shower leakage to the left tails should be important. Indeed, the tails are strongly suppressed provided we select only particles from that half-part of the beam

[6] See discussion about a choice of the range cut in [13]. Starting from G4 version 8.0, range cut dependence should be at the percent level both for average response and resolution.

[7] Usually vertex was drawn directly on the FCal front face. Note that in real life fraction of events in which pion has a muonic decay before reaching the FCal front face is $\approx 0.08/E$ (E in GeV).

[8] Note, that test-beam particles traverse, in average, less than half-meter of this piece.

[9] Let us note that at 200 GeV electron energy resolution due to noise alone is $\leq 1\%$ and can be neglected, see [3].

spot (let's call it as **"left"**) which is opposite to the FCal inner edge. Unfortunately, it is hard or even impossible to extract more details about the lateral shower leakage from the test-beam data. Maybe information from the "tail catcher" will help.

Simulated distributions for 200 GeV electrons at different angles are demonstrated in Fig.2. In contrast to the test-beam data, non-gaussian tails towards right direction are clearly seen (except 2.98^0). They are likely due to well-known "channeling" effect in the SPACAL-type calorimeters. These tails are not seen in the data as significant amount of passive material was placed in front of the FCal. This fact is not taken into account in the MC histograms shown in this Figure. Left tails due to lateral shower leakage are clearly seen at 1.25^0 and especially at 0.88^0. Potentially it is possible to accurately calculate this leakage using so-called "calibration hits".

Summarizing, the average FCal response is reduced by 8% with decreasing the angle from 2.98^0 to 0.88^0 due to lateral shower leakage. It should be taken into account in the FCal calibrations for real ATLAS conditions. This effect is well described by the MC simulations (Fig.3, top plot). Energy resolution deteriorates almost twice in the same angular interval . However, MC predicts more rapid degradation of the energy resolution below 1.61^0 (Fig.3, bottom plot). This discrepancy is due to absence of the upstream material in the simulations. For the same reasons, one can see right non-gaussian tails in the MC distributions while they are absent in the data.[10]

Let's look how passive material in front of the FCal affects both its average response and resolution at different angles (see Fig.4 and Appendix 1.). Remind, that we used real ATLAS geometry/materials which are different from those in the test-beam setup, see Section 2.1. The average response at 2.98^0 is reduced by 6% mostly due to aluminium walls of the end-cap cryostat which particles cross at small angle. There is no effect at other angles as amount of material in front of the FCal1 is much smaller (see Table 3). Energy resolution at 0.88^0 slightly improves while at 2.98^0 it becomes a bit worse.

Complete information about the simulated FCal response and resolution to 200 GeV electrons at different angles and energies is given in Appendix 1.

2.3 Pions at 200 GeV

About 10% events from each group of pion runs listed in Table 1 were processed. Main parameters of the response distributions are presented in Appendix 2.1. It was observed that both response and resolution in different group of runs taken in position 3 are quite different while for positions 1 and 2 it is not a case. The reason of this effect is unclear.

FCal response to 200 GeV pions in the test-beam data is demonstrated in Fig.5. As in the case of electrons, right parts of the spectra are better described by gaussians than left parts. However, non-gaussian tails towards large amplitudes are seen at any angle. Left tails at 2.98^0 and 1.61^0 are due to contaminating muons which result to (angular-independent) fraction of events with very low amplitudes. At smaller angles, there is angular-dependent contribution from lateral shower leakage . As in the case of electrons, left tails are strongly suppressed (especially at 0.88^0) when we select only events from the **left** part of the beam spot.

[10] Remind that in the test-beam setup about $2.7X_0$ of material was situated in front of the FCal1 **irrespective of the beam impact angle**, see Ref.[15]. For this reason, one would expect that angular dependence of the average FCal1 response is not affected by this material and results obtained with the MC are unbiased in this respect. However, it is not true for the energy resolution.

Fig.6 shows FCal response to 200 GeV pions at different angles simulated with the MC. Response shape is gaussian around the maximum, however, non-gaussian tails towards large amplitudes are seen as in the data. Left tails at 2.98^0 and 1.61^0 are not large while at 1.25^0 and especially at 0.88^0 they are significant. Their origin is lateral shower leakage. Indeed, selection of events from **left** part of the beam spot helps to suppress them. To prove strictly that low amplitudes are due to this effect one needs to analyse so-called *calibration hits* in the MC.

Presense of passive material in front of the FCal results to long left tails in the distributions, see Fig.7. They are possibly due to pion scattering before reaching the calorimeter. Remind that we collect hits inside limited radius, namely 16 cm. Average gaussian response and resolution are not significantly affected. The only exception is a case of 2.98^0[11] where the response is reduced by 4% and the resolution deteriorates from 8% to 10%. The last number is in agreement with 11% resolution obtained for the data after noise subtraction (Table A2.3).

Summarizing, the average FCal response is reduced by ≈13% with decreasing the angle from 2.98^0 to 0.88^0 likely due to lateral shower leakage (Fig.8, top plot). MC slightly overestimates this effect (Fig.8, top plot) predicting ≈15%. Energy resolution deteriorates by a factor of 1.7 in the same angular interval, in rough agreement with the MC (Fig.8, bottom plot).

Complete information about the simulated FCal response and resolution to 200 GeV pions at different angles and energies is given in Appendix 2.

2.4 Pions at different energies and angles in the MC

In the test-beam data energy dependence of the FCal response to pions was studied only in the range 5-200 GeV and at fixed angle 2.98^0. Moreover, presense of large noise introduces complications in the analysis. However, in real ATLAS conditions, interesting objects like jets from Higgs production via vector boson fusion have energies ∼TeV and wide angular range. With the validated MC, one can investigate the performance at any energies and angles.[12] As lateral shower leakage at 0.88^0 is observed to be too large, there are no reasons to study the FCal performance at this angle. Instead, we add a point at 4.3^0 which is not far from the FCal-endcap boundary.

Simulated FCal responses at 25, 100 and 800 GeV at different angles are shown in Fig.9-11. Let's remind that passive material in front of the FCal was NOT simulated here. Distributions have gaussian shape in the narrow region around the maximum. Left tails at 4.3^0 and 1.25^0 are likely due to lateral shower leakage into the endcap and into the beam tube respectively.

MC predicts a few % non-linearity of the FCal response to pions with energy (above 25 GeV) irrespective of beam impact angle, see Fig.12. The situation can be improved if one excludes 25 GeV point from the fit. It is not a surprise as e/π ratio becomes (almost) constant at sufficiently high energies. The offset is large, positive and depends on angle, being in the range 1.5÷2.2 GeV. It is reduced by a factor of 3 provided 5 GeV point is also included into the fit. Variation of average response with angle does not depend on energy as shown in Fig.13. FCal energy resolution varies with angle especially at high energies

[11] It is not a surprise as material thickness is significant at this position.

[12] Detailed data/MC comparisons for electrons and pions at 2.98^0 were made. Results can be found in Ref.[3], Ref.[4] and Ref.[5]. One can see that MC roughly describes FCal performance.

(Fig.14 and 15). The best constant term is achieved at 2.98^0, being $(6.1\pm0.2)\%$ while at 1.25^0 it increases to $(11.5\pm0.3)\%$ due to lateral shower leakage. The angular dependence of stochastic term of the FCal energy resolution is weaker.

Complete information about the simulated FCal response and resolution at different angles and energies is given in Appendix 2.

2.5 What should be clarified bf FCal community

- FCal performance in 4L vs 4H positions (both for electrons and pions);
- Difference in FCal responses in different runs in position 3 for pions;
- Difference in passive material thicknesses in real ATLAS (MC) and TB setup;
- Absense of 1m-long polyethylene in ATLAS detector description for the MC;
- FCal performance in G4.8.0 MC (sampling fraction and energy resolution). I'll try to perform simple comparison of G4.8.0 vs G4.7.0 for electrons.

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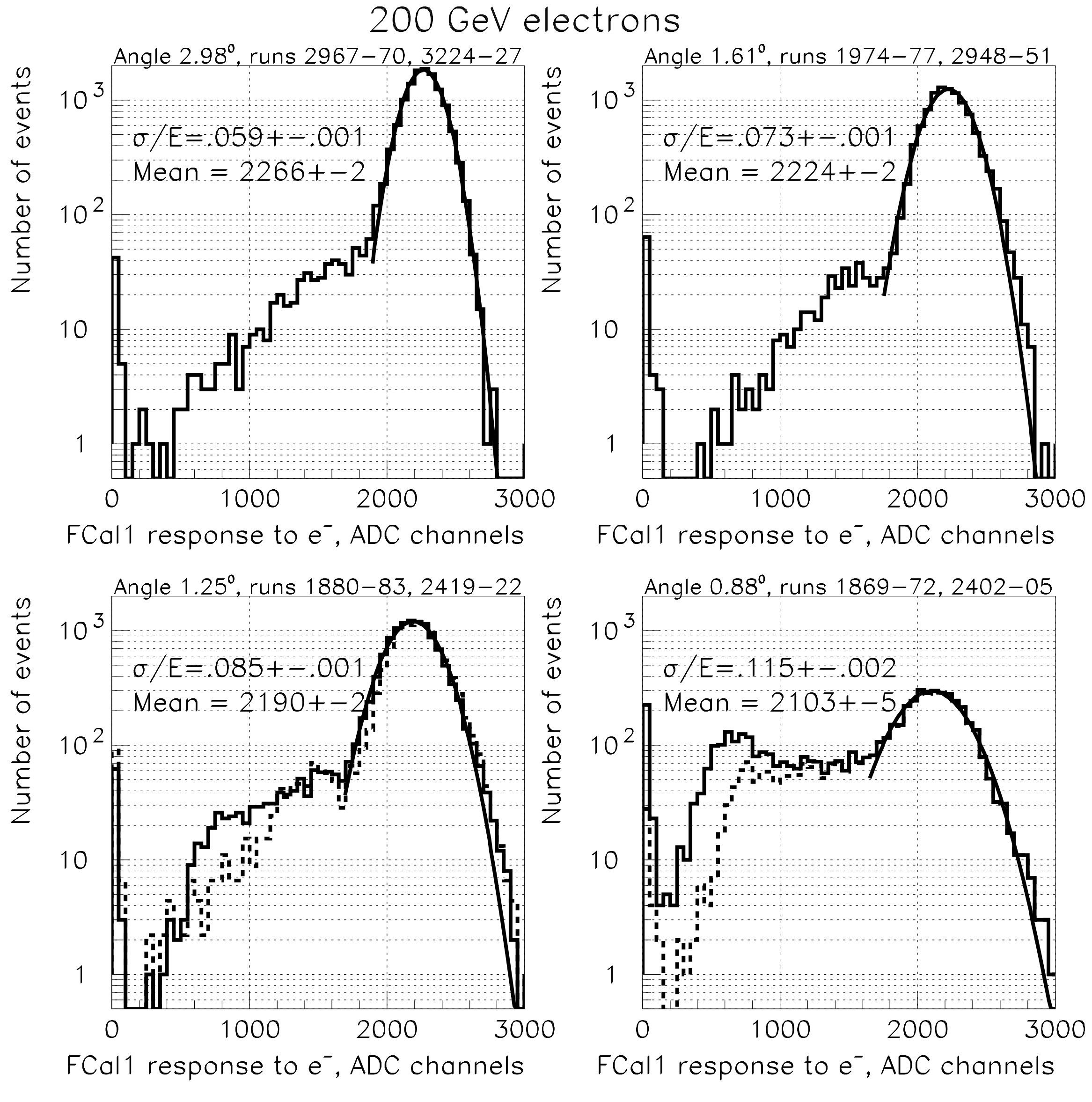

Figure 1: FCal response to 200 GeV test-beam electrons (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms are for events from the **"left"** part of the beam spot, see text.

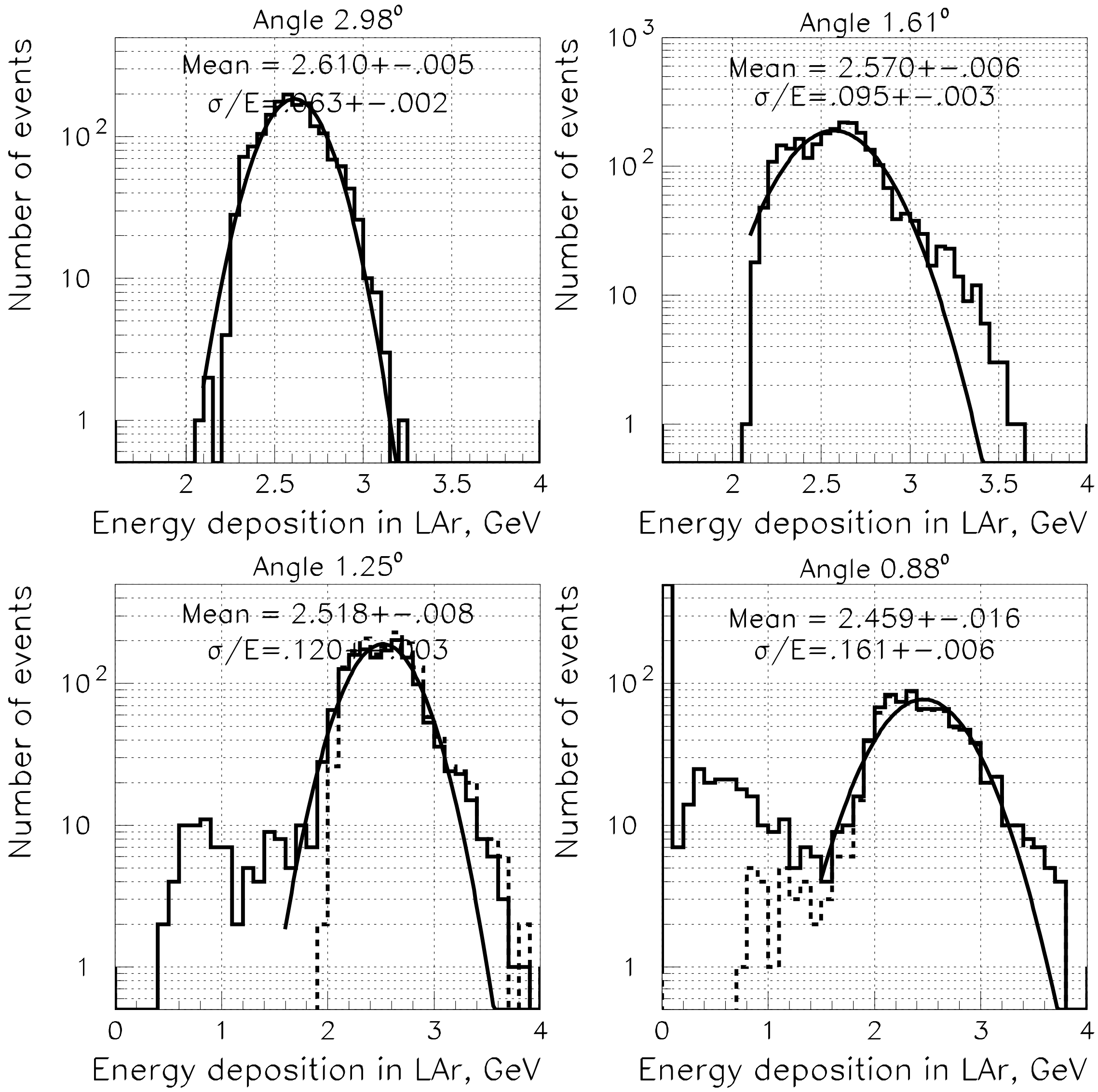

Figure 2: FCal response to 200 GeV electrons in the MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms are for events from the **"left"** part of the beam spot, see text. Passive material in front of the FCal **was NOT simulated.**

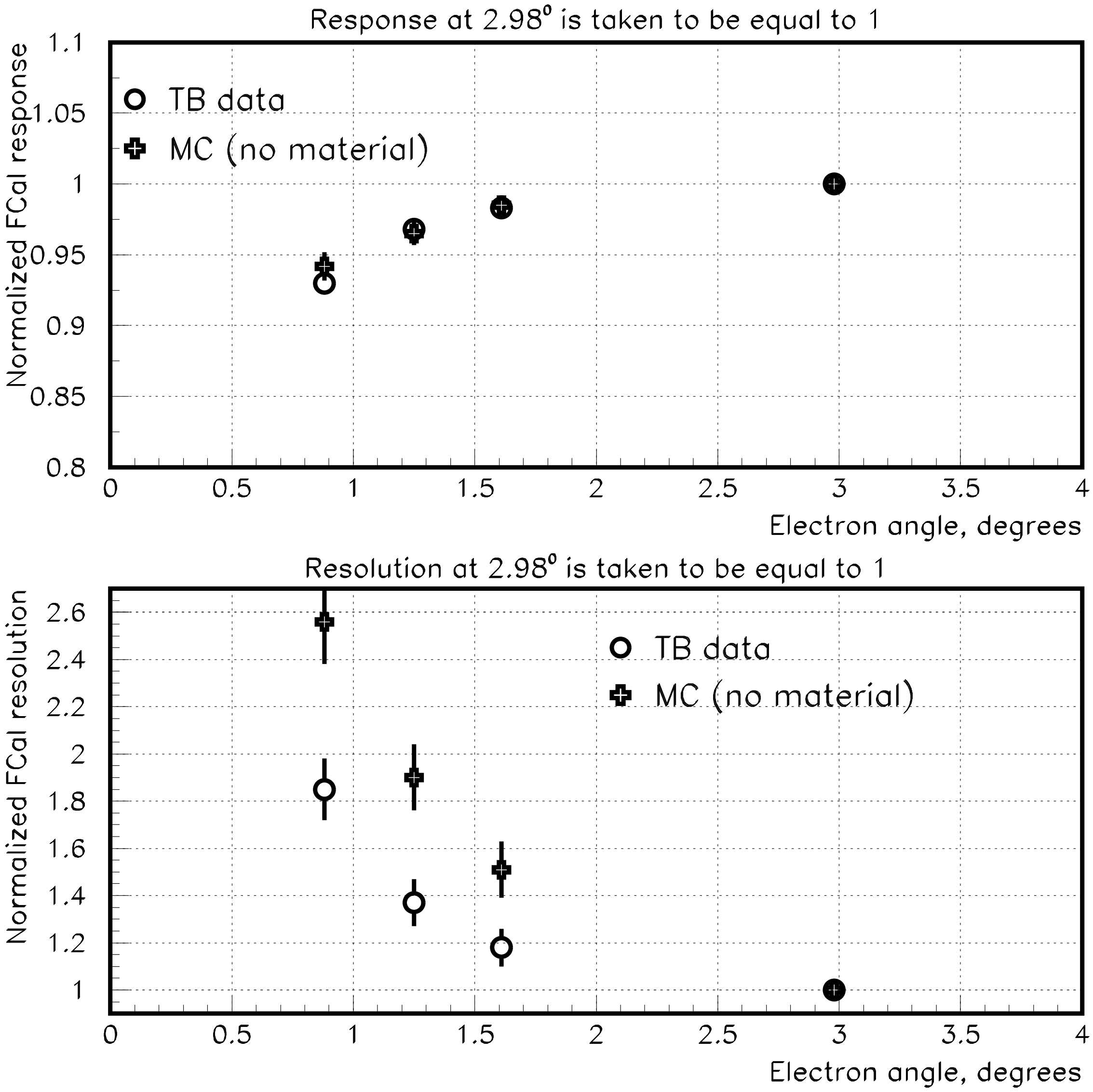

Figure 3: Angular dependence of the FCal response (top plot) and energy resolution (bottom plot) for electrons at 200 GeV. The response and resolution at 2.98^0 is taken to be 1. Systematic error of the average response (energy resolution) is taken to be 0.5% (5%) respectively, see Appendix 1.3. Passive material in front of the FCal **was NOT simulated.**

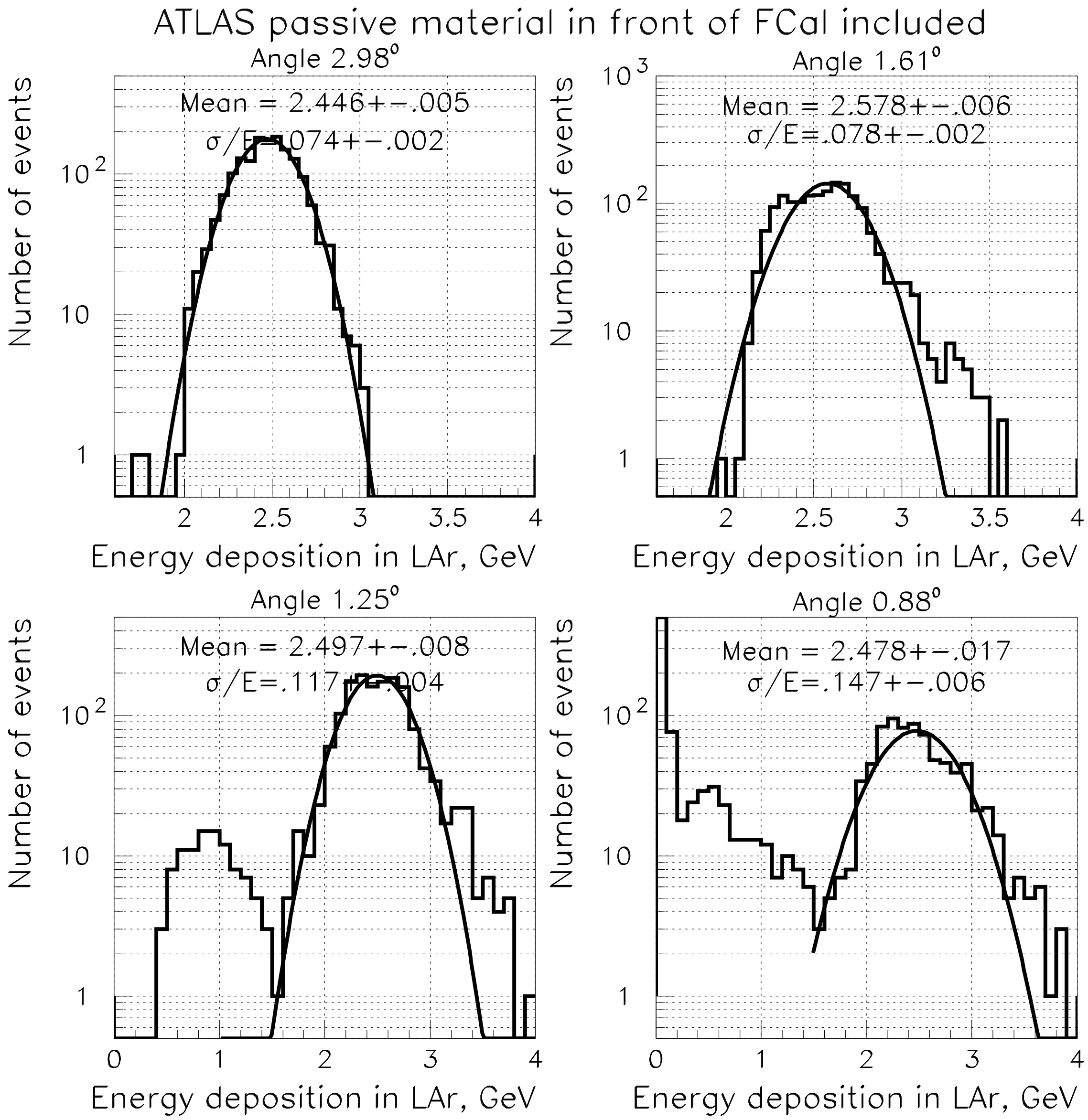

Figure 4: FCal response to 200 GeV electrons in the MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Passive material in front of the FCal in real ATLAS setup **was simulated.**

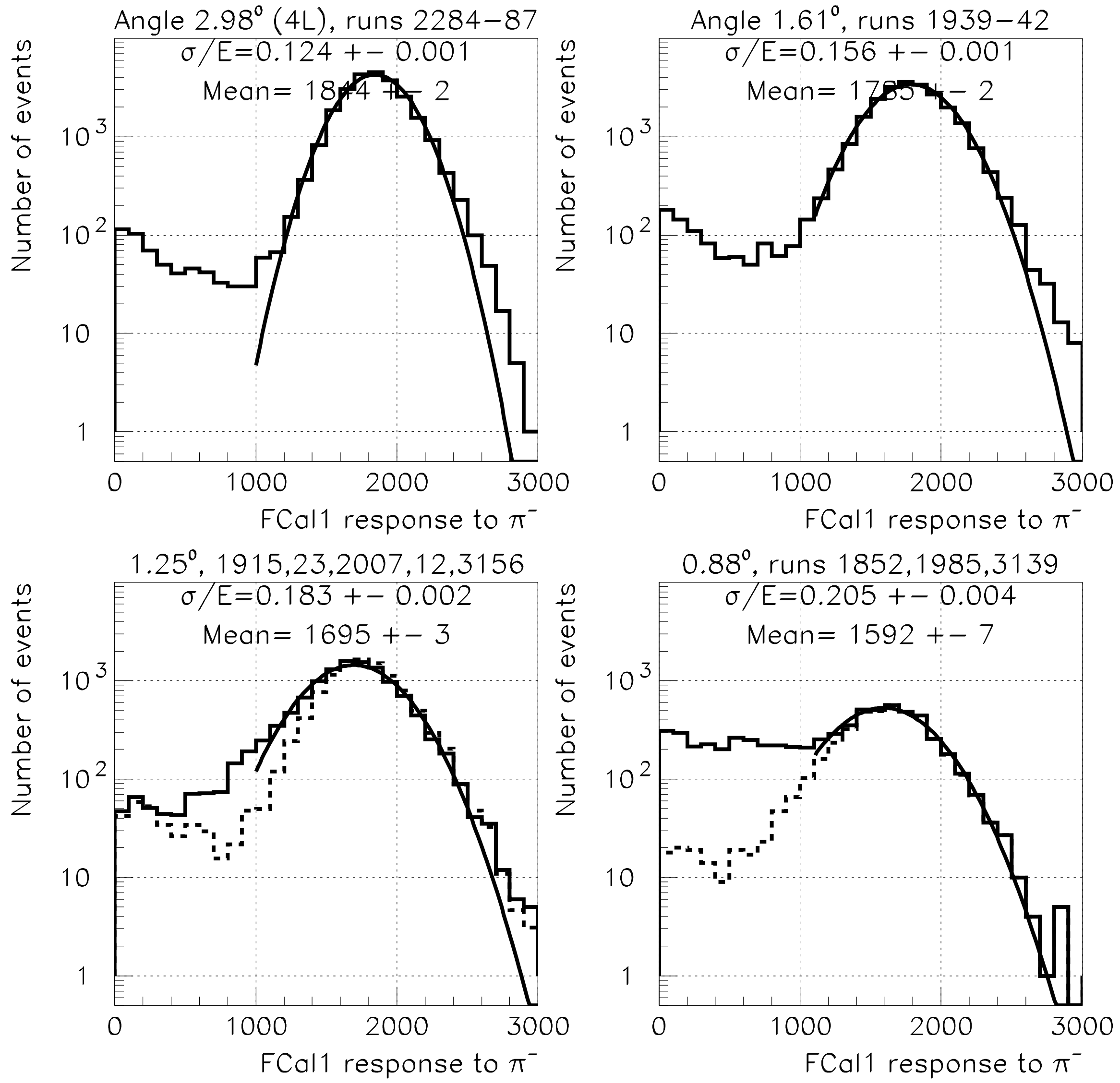

Figure 5: FCal response to 200 GeV test-beam pions (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms are for events from the **"left"** part of the beam spot, see text.

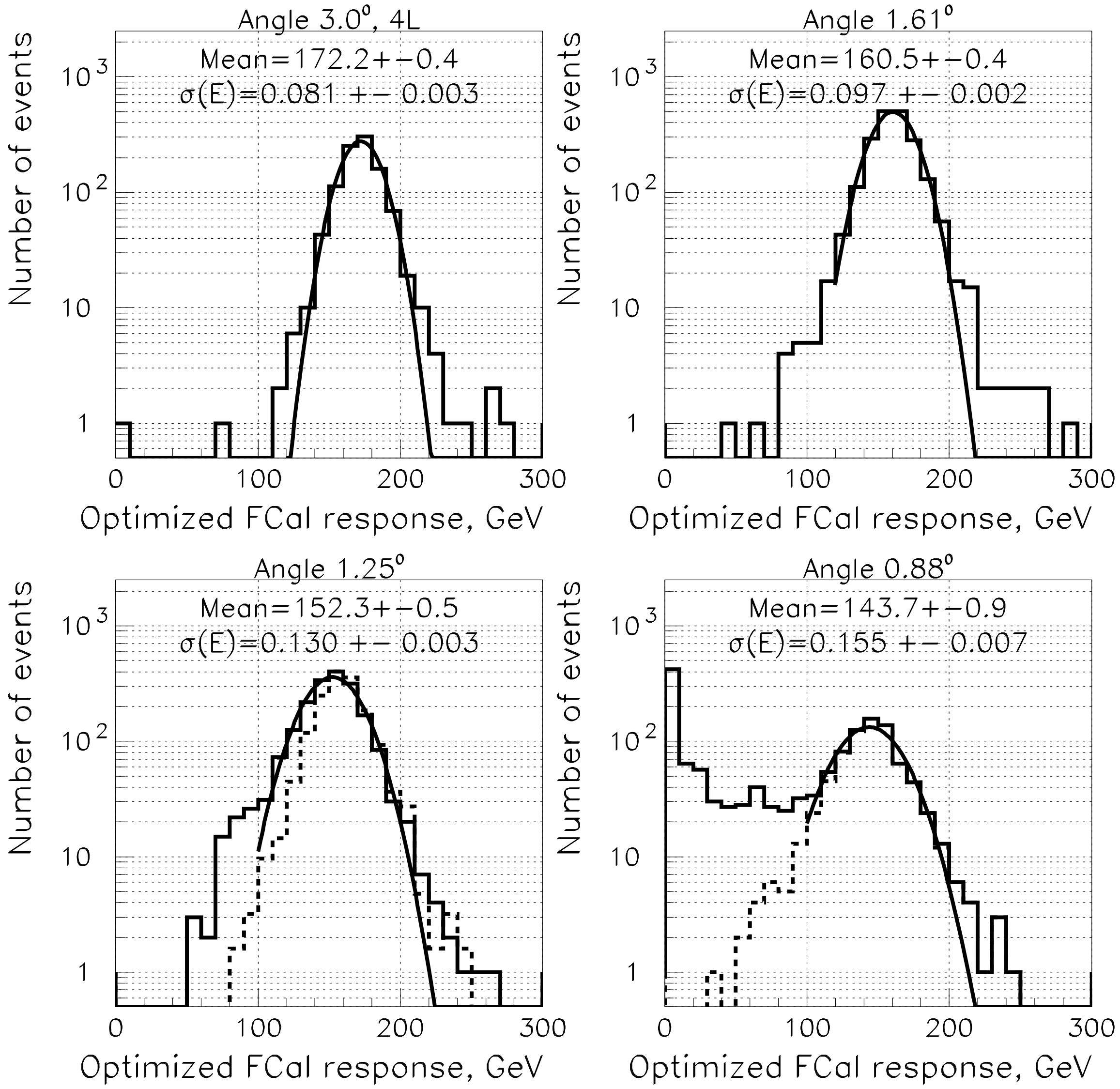

Figure 6: FCal response to 200 GeV pions in the MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms are for events from the **"left"** part of the beam spot, see text. Passive material in front of the FCal was NOT simulated.

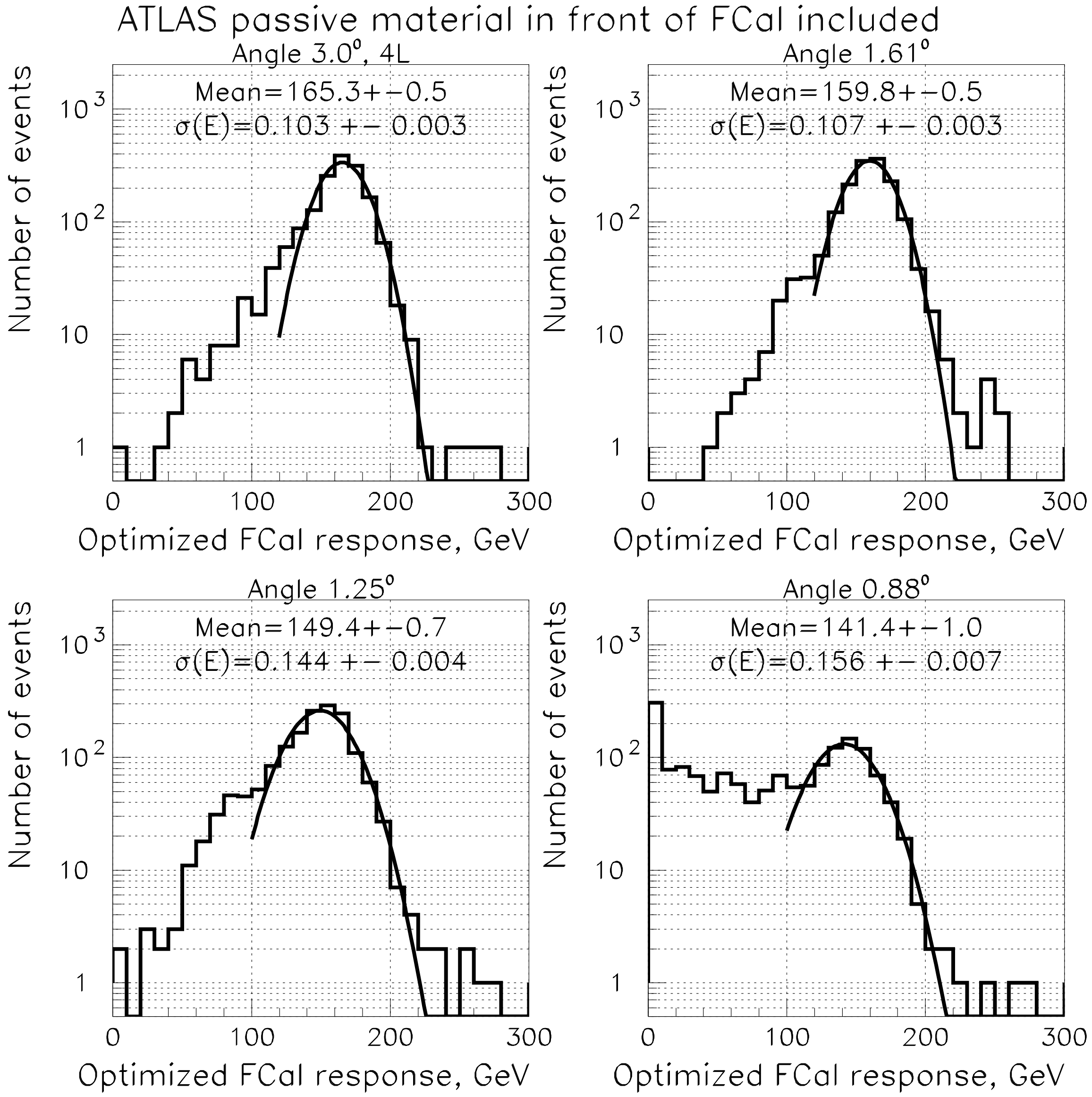

Figure 7: FCal response to 200 GeV pions in the MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Passive material in front of the FCal **was simulated.**

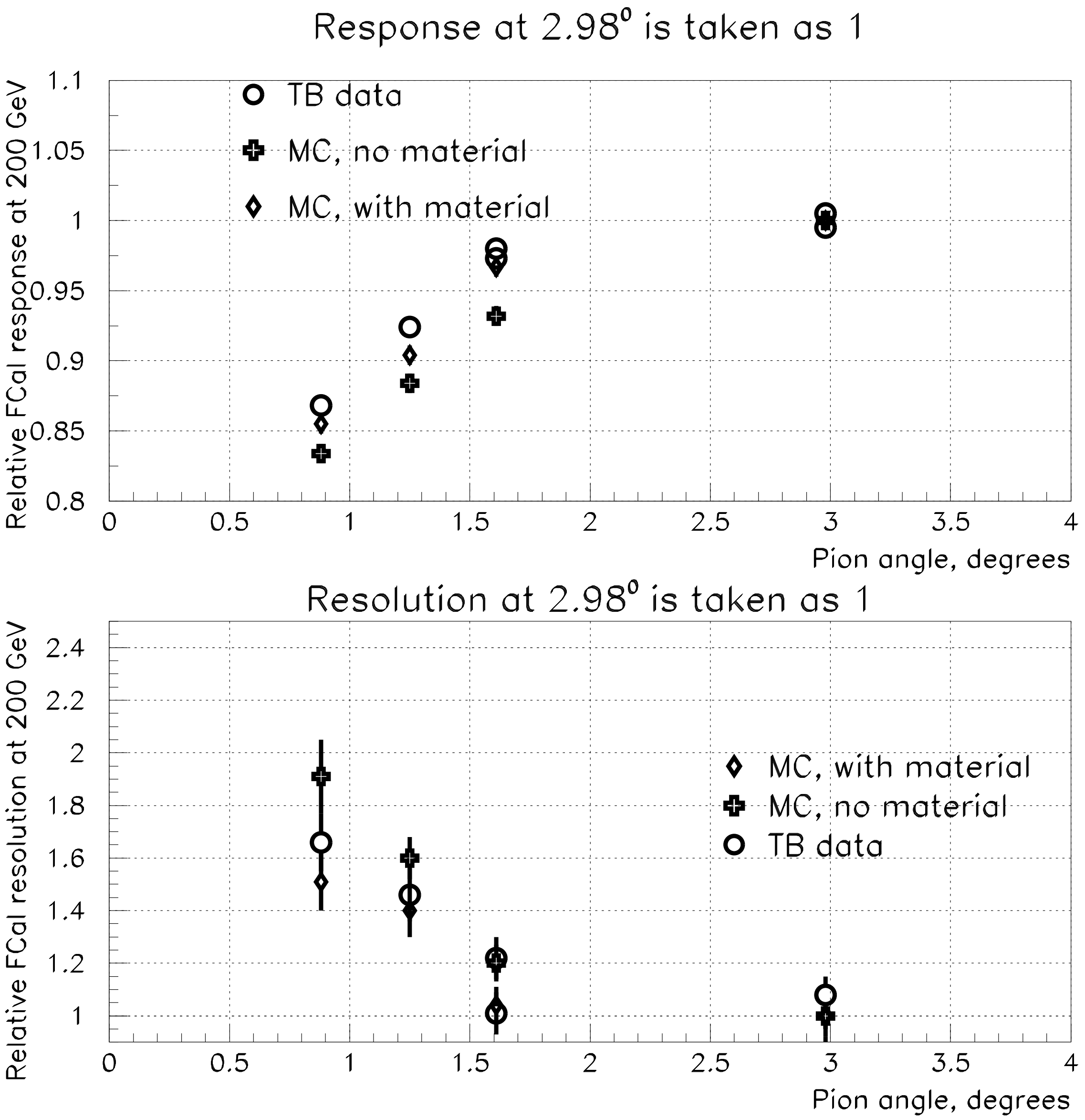

Figure 8: Angular dependence of the averaged gaussian response and energy resolution to pions in the MC. The response and resolution at 2.98^0 are taken to be equal to 1.

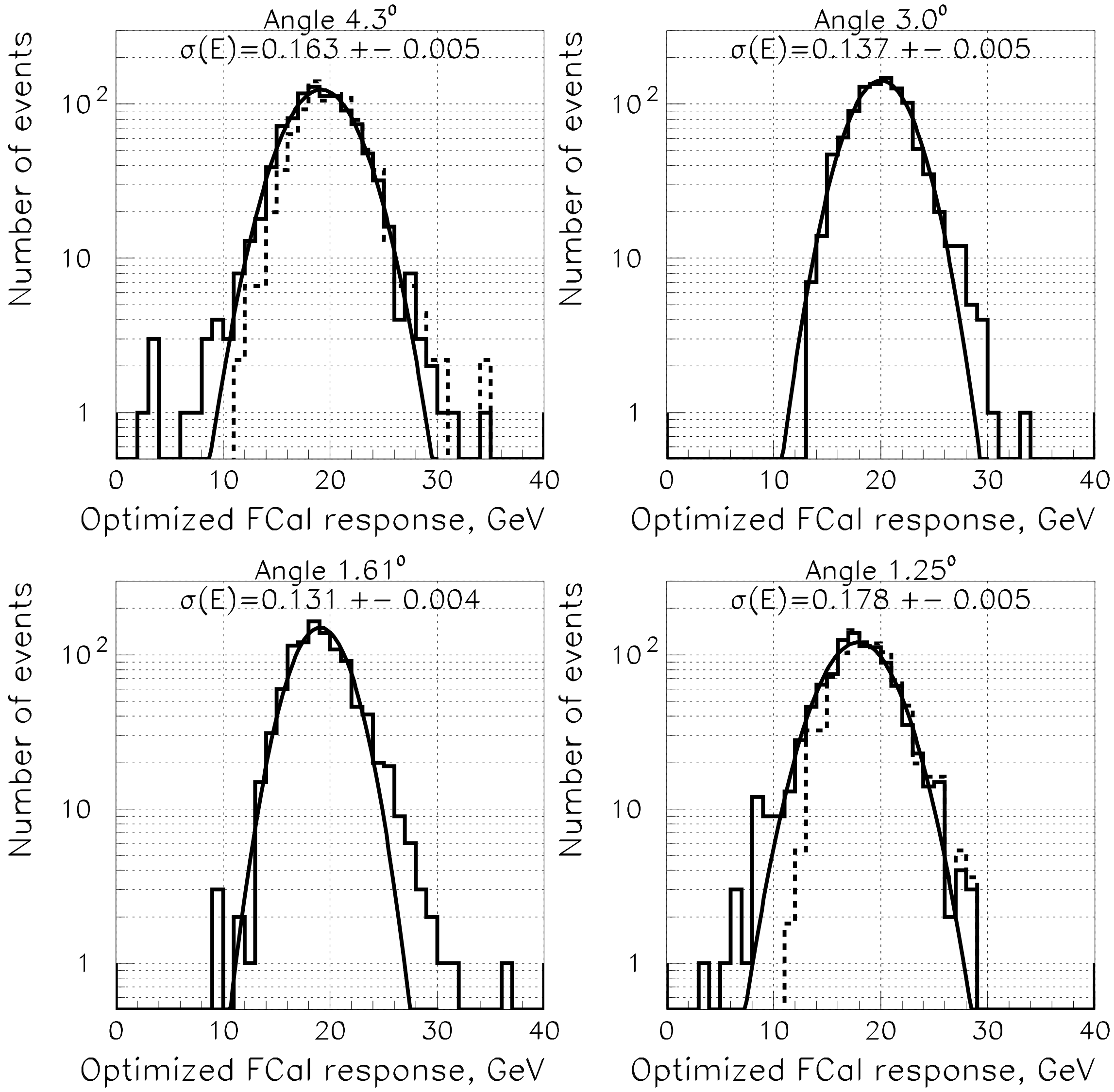

Figure 9: FCal response to 25 GeV pions in MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms at 4.3^0 (1.25^0) are for events from the **"right"** (**"left"**) part of the beam spot, respectively. Passive material in front of the FCal was NOT simulated.

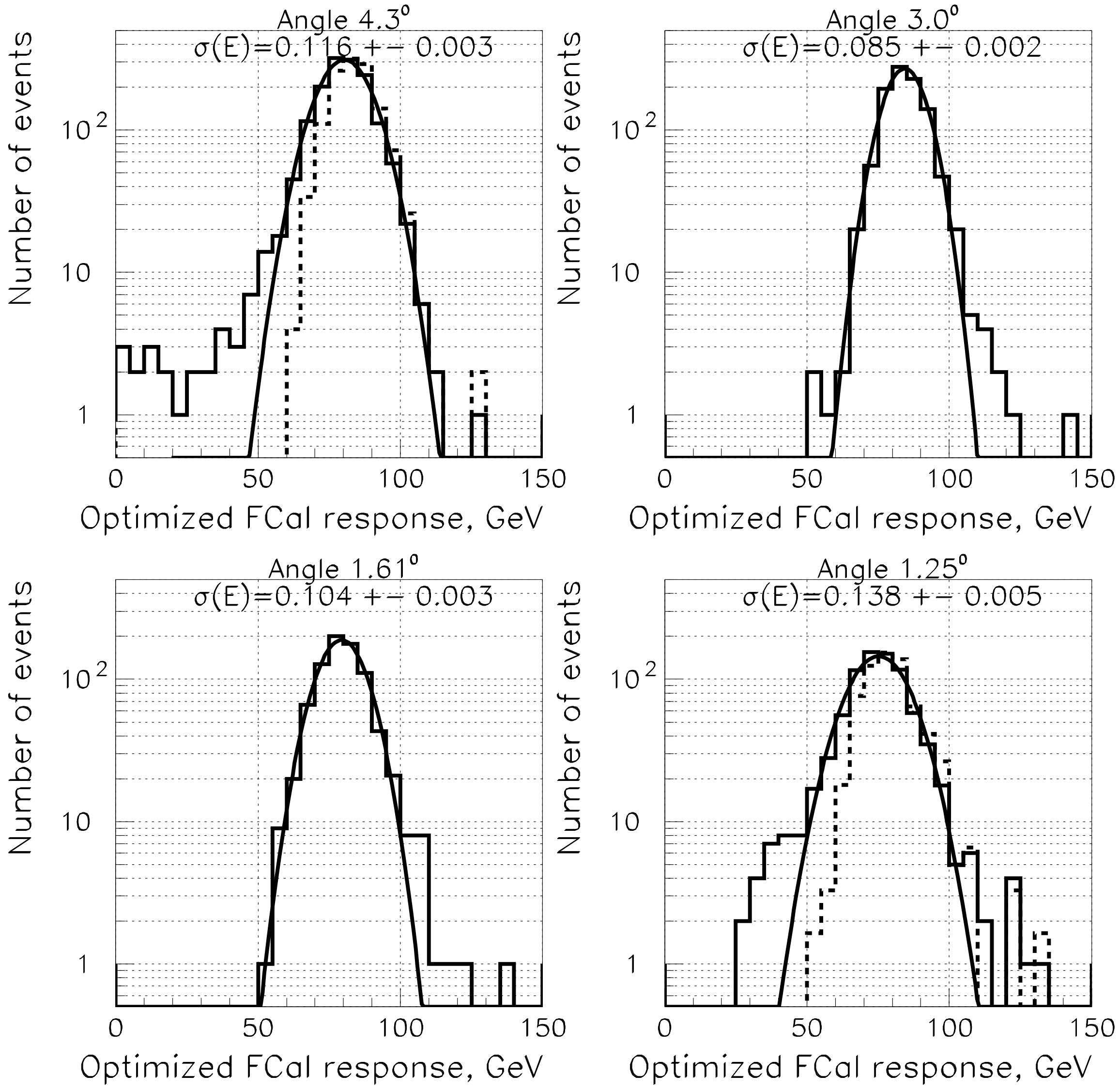

Figure 10: FCal response to 100 GeV pions in MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms at 4.3^0 (1.25^0) are for events from the **"right"** (**"left"**) part of the beam spot, respectively. Passive material in front of the FCal was NOT simulated.

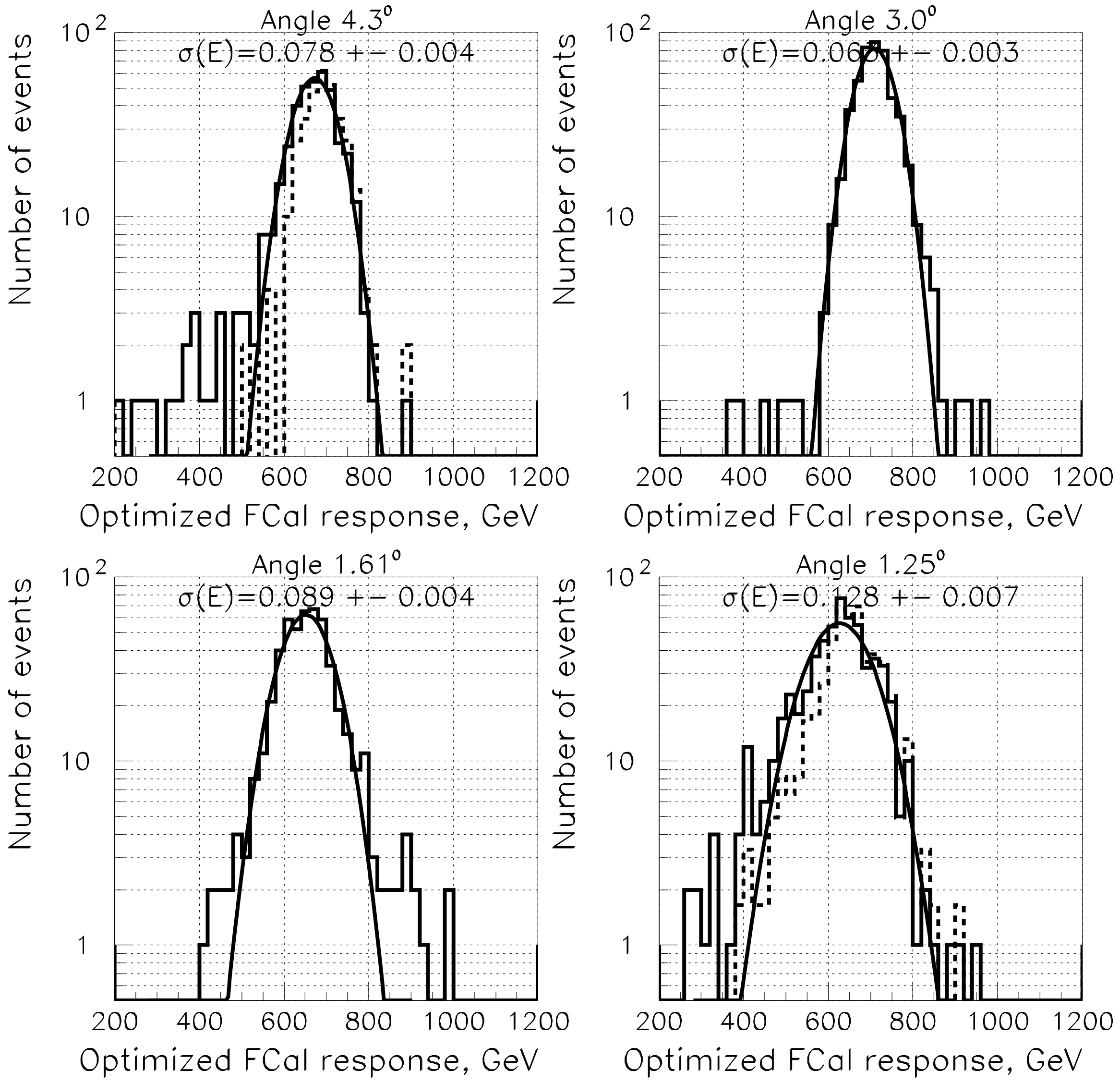

Figure 11: FCal response to 800 GeV pions in MC (solid histograms) with superimposed restricted gaussian fits (solid curves). Dashed normalized histograms at 4.3^0 (1.25^0) are for events from the **"right"** (**"left"**) part of the beam spot, respectively. Passive material in front of the FCal was NOT simulated.

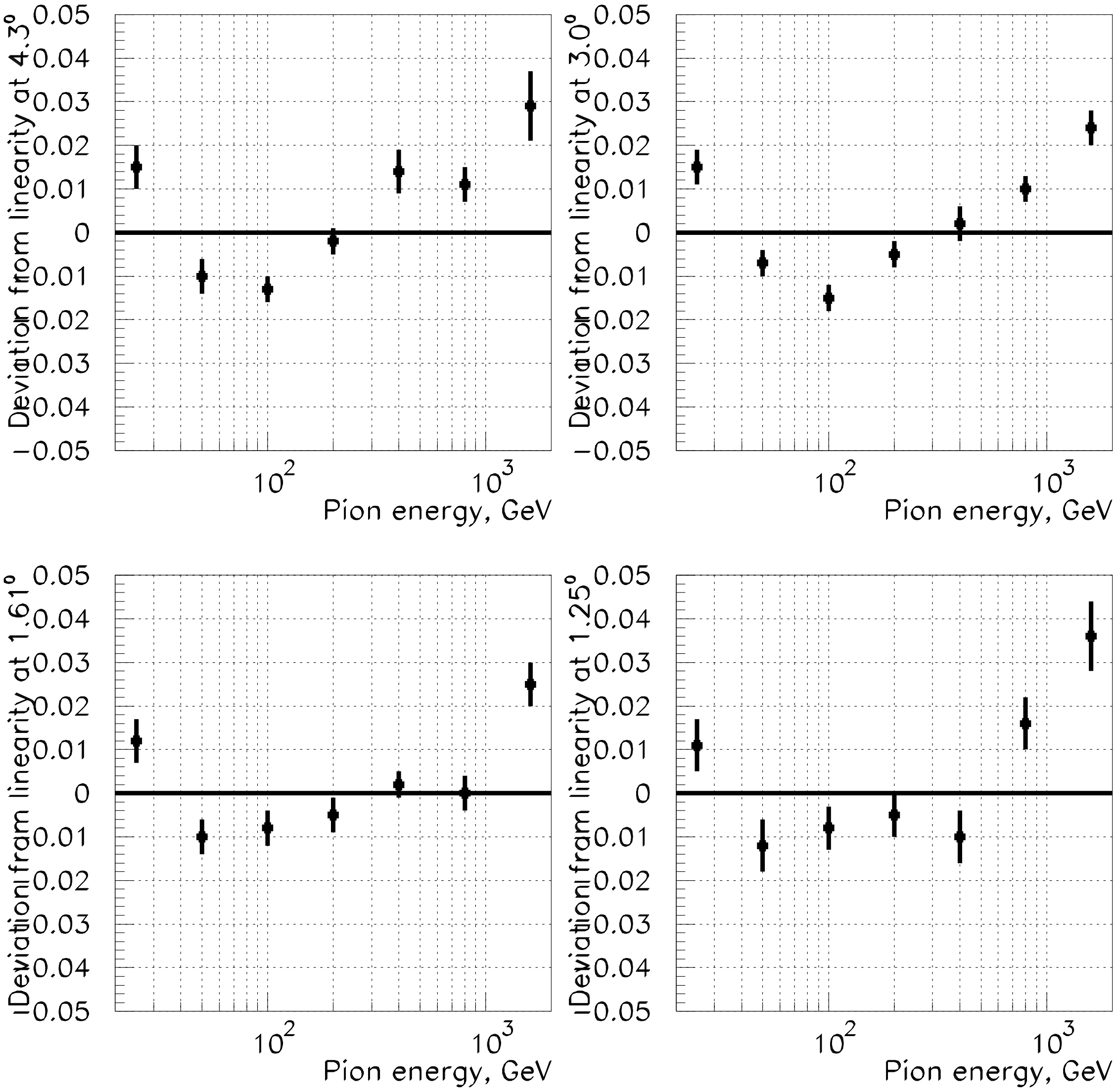

Figure 12: Deviation from linearity of the simulated FCal response to pions vs energy at different angles. Passive material in front of the FCal was NOT simulated.

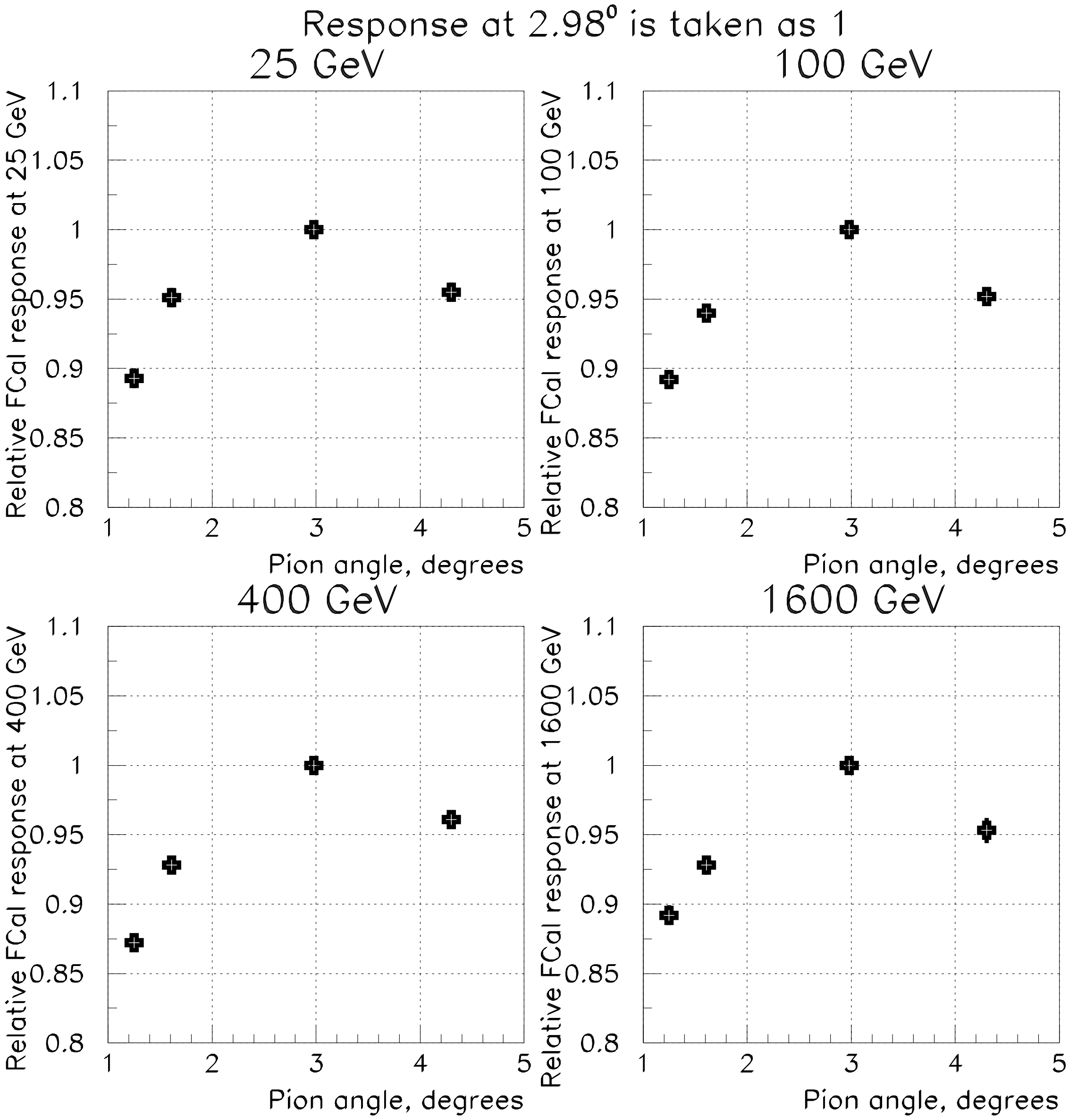

Figure 13: Angular dependence of the simulated FCal response to pions. The response at 2.98^0 is taken to be equal to 1. Passive material in front of the FCal was NOT simulated.

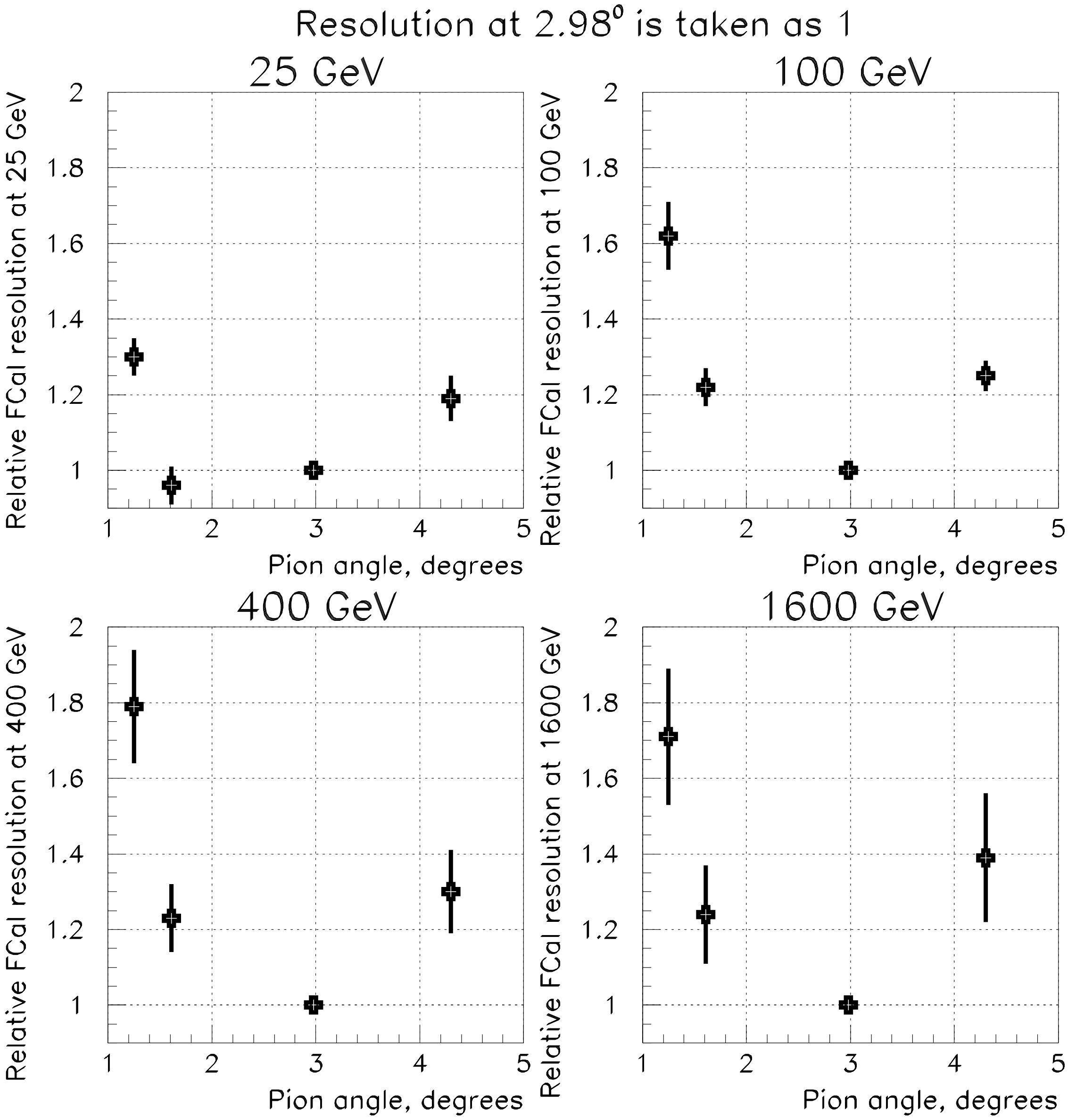

Figure 14: Angular dependence of the FCal resolution to pions in MC. The resolution at 2.98^0 is taken to be equal to 1. Passive material in front of the FCal was NOT simulated.

	4.3^0	*3.0*^{0}	*1.61*^{0}	*1.25*^{0}
		All		
A	-.794	-.801	-.638	-.674
ΔA	.017	.016	.017	.017
B	.8211	.8657	.8063	.7639
ΔB	.0014	.0012	.0013	.0017
χ^2/NDF	171/6	305/6	113/6	119/6
a	.579	.536	.533	.650
Δa	.010	.007	.009	.016
b	.0949	.0668	.0850	.1174
Δb	.0019	.0015	.0017	.0026
χ^2/NDF	47.2/5	22.5/6	6.69/6	11.5/6
		W/o 5 GeV		
A	-1.99	-2.22	-1.53	-1.67
ΔA	.011	.010	.011	.012
B	.8341	.8790	.8146	.7754
ΔB	.0019	.0015	.0016	.0022
χ^2/NDF	58/5	90/5	39/5	47/5
a	.737	.623	.515	.698
Δa	.027	.021	.025	.035
b	.0856	.0612	.0859	.1148
Δb	.0026	.0021	.0020	.0031
χ^2/NDF	15.6/5	5.52/5	6.14/5	9.3/5

Table 3. Linearity, stochastic and constant terms of simulated FCal1 energy resolution to pions at different angles as well as quality of the fit. The top part is for all points included while in the bottom one 5 GeV point is excluded.

3 Appendix 1. Details about FCal response to electrons

Position	N_{ev}	*Mean*	*r.m.s*	$Mean_{gauss}$	σ_{gauss}	χ^2/NDF	σ/E	tail, %
				200 GeV				
4H	5498	2211	270	2270(2)	127.5(1.4)	27.8/14	.056(1)	3.9%
4L	7329	2234	241	2262(2)	139.4(1.3)	21.9/15	.062(1)	5.4%
3	10617	2185	285	2224(2)	161.8(1.4)	128/20	.073(1)	3.9%
2	12210	2122	341	2190(2)	186.8(1.6)	93/22	.085(1)	7.0%
1	6079	1623	699	2103(5)	241(4)	44.8/24	.115(2)	40%

Table A1.1 FCal1 response to 200 GeV electrons in real data. Column tail$_{left}$ contains fraction of events with amplitude outside the fit region. To suppress the background from contaminating pions and muons negative amplitude in the FCal2 ($afc2 \leq 0$) was required[13].

[13] Negative amplitudes are possible due to noise.

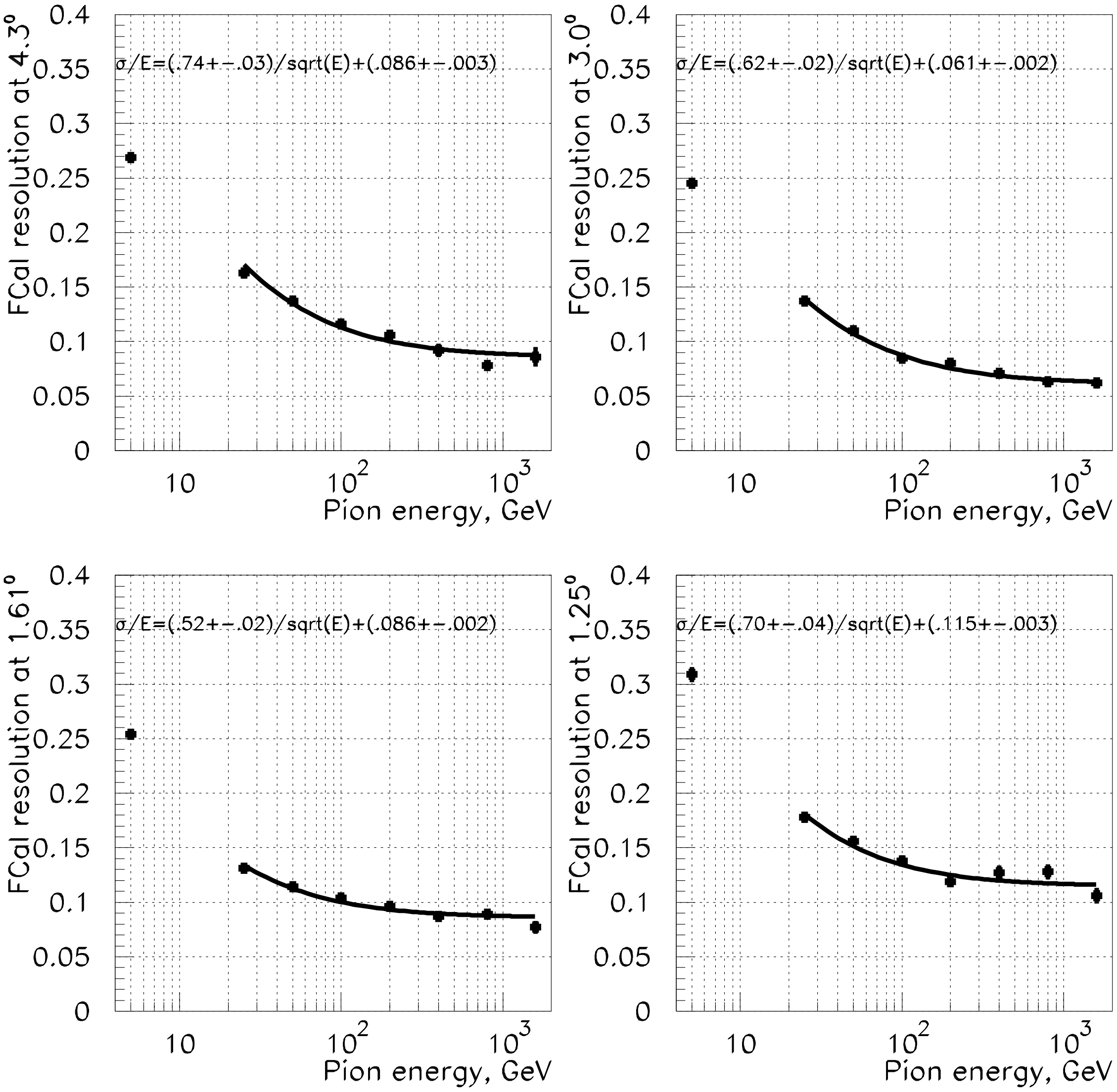

Figure 15: Angular dependence of stochastic and constant term of energy resolution to pions in the MC. Passive material in front of the FCal was NOT simulated.

Position	N_{ev}	*Mean*	*r.m.s*	$Mean_{gauss}$	σ_{gauss}	χ^2/NDF	σ/E	tail, %
				No material				
4	1600	2.607	.173	2.610(5)	.167(3)	61.4/18	.063(2)	0%
3	2447	2.598	.258	2.570(6)	.244(6)	189/28	.095(3)	0%??
2	1600	2.468	.441	2.518(8)	.303(7)	82/20	.120(3)	4%
1	1600	1.357	1.195	2.459(16)	.397(14)	49.7/20	.161(6)	50%
				ATLAS material				
4H	1600	2.446	.194	2.452(5)	.183(4)	34.2/26	.075(2)	-
4L	1600	2.442	.197	2.446(5)	.180(4)	41.5/27	.074(2)	-
3	1600	2.579	.241	2.578(6)	.200(4)	161/28	.078(2)	-
2	1600	2.424	.508	2.497(8)	.292(7)	129/26	.117(4)	-
1	1600	1.335	1.191	2.478(17)	.364(14)	77.6/21	.147(6)	-
				ATLAS cryo only				
4H	1600	2.607	.172	2.615(4)	.162(3)	60.7/19	.062(1)	-
4L	1600	2.608	.173	2.611(5)	.160(3)	73.3/21	.061(1)	-
3	1000	2.583	.249	2.575(7)	.205(5)	125/28	.080(2)	-
2	1600	2.427	.527	2.512(9)	.314(7)	97.0/22	.125(4)	-
1	1600	1.308	1.119	2.470(16)	.404(14)	55.6/22	.164(6)	-

Table A1.2 FCal1 response to 200 GeV electrons in the MC. Column $tail_{left}$ contains fraction of events with amplitude outside the fit region. Note that in accordance with [15] the amount of material in the test-beam in front of the FCal in positions 1, 2 and 3 was larger than expected in real ATLAS conditions.

Pos.	$Mean_{gauss}$	σ/E	$Mean_{gauss}$	σ/E	$Mean_{gauss}$	σ/E	$Mean_{gauss}$	σ/E
				200 GeV				
4L	2266(2)	.0594(4)	2266(2)	.0595(5)	2268(1)	.0573(5)	2256(6)	.064(2)
3	2220(3)	.072(1)	2227(2)	.073(1)	2222(2)	.074(1)	2227(7)	.075(2)
2	2182(3)	.086(1)	2194(2)	.086(1)	2191(2)	.085(1)	2190(4)	.084(2)
1	2099(7)	.114(3)	2111(3)	.115(2)	2117(6)	.109(2)	2091(8)	.123(4)

Table A1.3 FCal1 average response (even columns) and energy resolution (odd columns) to 200 GeV electrons in real data at different selection criteria: columns 2-3 are for $afc2 \leq 0$ *and* $afc3 \leq 0$ cut, columns 4-5 are for $afc2 \leq 0.03afc1$ *and* $afc3 \leq 0.03afc1$ cut; at narrower fit region (bins 34-60 in Fig.1, columns 6-7) and at 1.5 times larger bin size (40 bins in histograms in Fig.1 instead of 60, columns 8-9).

Both for data and MC, gaussian fit was performed in the region where contribution from shower leakage and from (in the case of data) contaminating pions and muons is minimal. The boundaries between more or less gaussian and non-gaussian parts of the spectra are clearly seen by eye in the plots. Systematic error in the average response and resolution was roughly estimated for the data by varying selection criteria to reduce a background, by changing bin width and fit region. Details are shown in Table A1.3. For the average response systematic error is turned out to be less than 0.5%. For the energy resolution it does not exceed 5%.

4 Appendix 2. Details about FCal response to pions

Position	N_{ev}	*Mean*	*r.m.s*	$Mean_{gauss}$	σ_{gauss}	χ^2/NDF	σ/E	σ/E_{corr}
				200 GeV				
4H	20971	1773	373	1825(2)	256.0(1.6)	170/16	.140(1)	.128(1)
4L	25449	1814	322	1844(2)	228.2(1.3)	295/16	.124(1)	.110(1)
3	24606	1738	383	1785(2)	277.6(1.5)	241/19	.156(1)	.145(1)
3'	22857	1774	317	1798(2)	239.0(1.4)	423/19	.133(1)	.120(1)
2	12118	1634	406	1695(3)	311(3)	139/17	.183(2)	.174(2)
1	6958	1202	624	1592(7)	327(6)	43.9/15	.205(4)	.197(4)

Table A2.1 FCal1 response to 200 GeV pions in the data. Column σ/E_{corr} contains relative energy resolution after subtraction of noise term in quadrature, see text.

Position	N_{gen}	*Mean*	*r.m.s*	$Mean_{gauss}$	σ_{gauss}	χ^2/NDF	σ/E
				200 GeV			
4H	717	172.2	15.8	171.3(5)	12.5(4)	17.2/13	.073(2)
4L	1000	172.4	17.3	172.2(4)	13.9(4)	29.3/12	.081(3)
3	2000	160.7	18.8	160.5(4)	15.5(3)	47.9/13	.097(2)
2	1888	150.6	24.1	152.3(5)	19.8(4)	37.0/14	.130(3)
1	1500	85.0	66.1	143.7(9)	22.3(10)	26.6/12	.155(7)
				ATLAS material			
4L	1600	160.4	25.2	165.3(5)	17.1(5)	61.9/12	.103(3)
3	1600	157.1	22.9	159.8(5)	17.1(4)	21.4/11	.107(3)
2	1600	143.0	30.7	149.4(7)	21.5(6)	48.1/14	.144(4)
1	1600	84.3	60.3	141.4(10)	22.0(9)	20.1/13	.156(7)

Table A2.2 FCal response to pions at 200 GeV in the MC.

$Position$	N_{gen}	$Mean$	$r.m.s$	$Mean_{gauss}$	σ_{gauss}	χ^2/NDF	σ/E
				5 GeV			
5	4000	3.40	1.02	3.333(15)	.897(13)	90.9/23	.269(4)
4	5000	3.64	1.02	3.558(14)	.870(11)	169/23	.245(3)
3	4000	3.48	1.00	3.412(15)	.867(12)	125/23	.254(4)
2	2500	3.24	1.11	3.179(21)	.982(20)	71.1/21	.309(7)
				25 GeV			
5	1000	19.10	3.52	19.15(10)	3.13(8)	21.3/21	.163(5)
4	1000	20.20	2.89	20.05(9)	2.75(8)	22.4/14	.137(5)
3	1000	19.21	2.98	19.07(10)	2.49(7)	63.0/17	.131(4)
2	1000	17.80	3.50	17.90(10)	3.18(9)	36.3/21	.178(5)
				50 GeV			
5	1000	39.10	6.19	39.31(17)	5.38(15)	21.2/21	.137(4)
4	1000	41.55	5.14	41.41(16)	4.56(12)	37.0/14	.110(3)
3	1000	38.96	4.90	38.84(15)	4.44(11)	25.8/17	.114(3)
2	1000	36.38	6.53	36.64(20)	5.72(16)	34.8/21	.156(5)
				100 GeV			
5	1000	79.3	12.0	80.36(25)	9.34(22)	37.7/17	.116(3)
4	1000	84.6	5.14	84.36(24)	7.21(19)	25.5/13	.085(2)
3	1000	79.9	9.26	79.32(30)	8.24(26)	20.0/13	.104(3)
2	800	74.8	12.95	75.22(38)	10.40(38)	43.4/18	.138(5)
				200 GeV			
5	1000	161.6	25.5	164.5(6)	17.44(54)	39.1/20	.106(4)
4	800	173.1	15.2	172.7(5)	13.80(48)	40.3/19	.080(3)
3	800	162.5	19.3	160.7(6)	15.44(51)	57.3/23	.096(3)
2	800	150.4	22.8	152.5(7)	18.13(66)	28.6/18	.119(4)
				400 GeV			
5	400	329.2	40.5	336.4(17)	30.9(1.9)	29.7/21	.092(6)
4	500	351.2	30.7	350.0(13)	24.7(1.2)	14.9/13	.071(4)
3	800	327.0	35.6	324.7(10)	28.1(1.0)	23.9/17	.087(3)
2	600	304.0	51.2	305.1(18)	38.6(2.1)	28.6/18	.127(7)
				800 GeV			
5	400	657.7	83.5	672.6(2.9)	52.7(2.5)	25.7/21	.078(4)
4	500	709.6	58.1	708.1(2.3)	44.9(2.1)	11.0/14	.063(3)
3	500	656.6	76.1	650.6(2.8)	58.0(2.6)	21.5/17	.089(4)
2	600	619.6	95.4	628.0(3.8)	80.4(4.0)	54.6/22	.128(7)
				1600 GeV			
5	250	1351	132.8	1370(11)	118(12)	39.7/14	.086(9)
4	300	1439	102.8	1438(6)	88.8(5.7)	20.0/11	.062(5)
3	250	1331	124.6	1335(7)	102.3(8.0)	18.3/13	.077(6)
2	300	1212	175.8	1283(9)	136(9)	28.0/20	.106(7)

Table A2.3 FCal response to pions with different energies in the MC (no material).