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Effect of the Tile calorimeter thickness in the ATLAS Barrel calorimeter performance

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Abstract

We report on the study of the effect of the Tile calorimeter thickness in the ATLAS Barrel calorimeter performance. The reduction of the Tile Calorimeter depth by 20 cm would have severe consequences on the hadron calorimeter performance and would increase the punchtrough probability in the muon chambers placed behind the calorimeter. Cost savings are also analysed.

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1 Introduction

The downscoping task force in the ATLAS collaboration has proposed two main changes to the Tile calorimeter design:

a) a reduction of the longitudinal dimension of the barrel and extended barrels by 800 mm (half length of the barrel shortened by 400 mm),

b) a reduction of the radial dimension by 200 mm corresponding to a reduction in depth of about one interaction length ($\sim 1\ \lambda$), (outer radius reduced from 4230 to 4030 mm).

Point a) has many implications on the integration of the Tile detector inside the overall calorimetry and in the general ATLAS framework. In terms of η coverage such a change would enlarge the internal gap and would reduce the "good" hadronic calorimeter detection region. In addition, it might also cause holes in the λ coverage. The space between the Barrel-EB (crack region) would be located around $0.6 < \eta < 1.1$ instead of $0.7 < \eta < 1.2$. This might from the technological point of view not be a big difficulty. In all our drawings the girder would just be shortened and for the barrel 17 submodules instead of 19 would be used. In this way a reduction of about 7% in the cost of the steel and a saving of about 760 PMTS (7.6%) could be obtained corresponding to a total gain of $\sim$ 780 KCHF. For point a) the necessary changes could be reabsorbed in the foreseen schedule, even for module0, which is already under construction, without wasting resources and manpower. In view of a possible gain in cost this point will be persued further to understand the consequences and hopefully advantages for the overall ATLAS detector.

Point b), however, has very severe implications to the Tile calorimeter with the following two main consequences:

- It will definitely and permanently downgrade the performance of the hadron calorimeter in the barrel region by changing the TILECAL performances as given in the TP on many aspects. As shown later, longitudinal leakage will dominate the calorimeter performances and will increase the punchthrough rates for the muon system drastically.
- It will jeopardize the work done up to now and will change our milestones for the future. The module0, which is already under construction, will just become an academic exercise. Another module0 will have to be rebuilt, with the consequence of a substantial waste of money and effort. The optics (different organization of the longitudinal samplings) and also the mechanics have to be redesigned completely. This will give a delay of at least 1 year.

Even if the second point will not be considered as important in the overall ATLAS environment, the first point should be taken seriously. Nevertheless, it should be pointed out that in the TILECAL community the money comes from many different instituts which are responsable to their funding agencies for the way their contribution is spend; also, most of these institutes will not be able to provide additional money once their contribution has been spend.

In the following chapters the subtantial deterioration of the Tile calorimeter performances due to a shortening in depth of 200 mm will be discussed and its consequences will be demonstrated.

2 Preliminary Studies on Test Beam Data

Before presenting preliminary results obtained with data from test beams a few arguments should be made clear:

- The "calorimeter depth reduction" has already been done once, about 2 years ago. The final outcome of this exercise was a general agreement on the necessity for a hadron calorimeter which should have a total depth of 11 λ, of which 10 λ should be of active material. It was felt that this was the minimum requirement in order not to have the performances of the calorimeter be dominated by longitudinal leakage. At that time the design of the ATLAS calorimetry had even 12 λ in total. Now (TP design) the calorimetry (TILECAL and LAr combined) has only 10.6 λ in total (including 1 λ for the support structure) at $\eta = 0$, which reduces to 9.6 λ of active material. As a consequence, the present hadron calorimeter design has already been compromised in performance and in cost.
- Studies for the SSC (Ref [1]) based on the di-jet mass resolution have shown that the resulution is limited by fragmentation fluctuations and by E_T^{miss} from missing neutrinos and not so much by fluctuations from leakage. If these criteria are extrapolated to the LHC, the maximum accessible di-jet mass goes from 10 TeV at SSC down to 6.3 GeV at the LHC and the characteristic single particle energy to be measured in a hadron calorimeter with full containment goes from 1150 GeV at the SSC down to 725 GeV at the LHC. Using a parametrized shower shape curve to describe a hadronic shower at the SSC and extrapolated to the LHC a need for for $\sim 9.7\ \lambda$ at the LHC can be made. This leads to the conclusion that the TP design of the calorimeter thickness is just adequate and agrees well with this independent estimate.
- From the above study it was concluded that one needs a minimum of 10 λ of active material at $\eta = 0$. It is general believed that around 10 λ of active material one enters a performance region which flattens out, whereas below this value the calorimeter performance shows a steeply falling behaviour. Test beam results of a calorimeter prototype which has only 8.8 λ of active material in stand-alone and of

10.1 λ in TILECAL-LAr combined mode at $\eta = 0$ show (see below) that already a limit in performances is reached.

- The simple argument that 1 λ reduction in depth is harmless is too simple and therefore incorrect: in particular, the consequences of the proposal of the descoping task force in reducing the depth of the calorimetry to only 8.6 λ of active material at $\eta = 0$ should rather be studied with great care.

In the following we present a preliminary analysis taken with the actual calorimeter prototype which has a depth of 8.8 λ in the TILECAL stand-alone and of 10.1 λ in TILECAL-LAr combined mode at $\eta = 0$. This analysis has been performed in view of simulating the proposed reduction in depth (to 8.6 λ of active material) of the Tile calorimeter as realistic as possible using real data. Pions at different incident beam energies have been shot into the calorimeter at a polar angle $\theta = 20^o$ in the stand-alone and of $\theta = 11.3^o$ in the TILECAL-LAr combined mode. The calorimeter depth has been corrected for this incident angle leading to an effective depth of 9.3 λ in the TILECAL stand-alone and of 10.3 λ in TILECAL-LAr combined mode. These effective depths are referred to in the following as "standard calorimeter" depth.

To study the performances of the Tile calorimeter in its stand-alone mode the proposed reduction of 1 λ has been simulated by keeping all events leaving only one mip in the first sampling (therefore selecting preferentially late hadronic showers). Application of this method would be equivalent to a reduction of the calorimeter depth by 1.5 λ, leading to a calorimeter of an effective depth of 7.8 λ referred to as "descoped calorimeter" which allows as close as possible the study of the proposed reduction in depth using existing hardware equipment and real data. In addition, the performances have been compared to an "ideal" calorimeter of "infinite" depth by removing all events leaking into a muon wall behind the Tile calorimeter, reffered to in the following as "no leakage". From these studies the following very important conclusions can be drawn:

a) The energy resolution of the Tile calorimeter is worsened in general. As an example, at 300 GeV the resolution σ_E/E increases from 5.0% to 6.4%; this deterioration can mostly be explained by a substantial increase of the constant term (an additional 2.9% has to be taken into account to the intrinsic value of 3%, which added in quadrature, gives $\sim$ 4%. This value is well outside the specs of the initial ATLAS milestones. The results of the analysis described above are shown in Fig. 1, Fig. 2 and Fig. 3. In Fig. 1 the energy distribution for 300 GeV pions at an incident polar angle of $\theta = 20^o$ is displayed. The energy resolution obtained from a Gaussian fit within $\pm$ 2 σ and the percentage of events in the tails below 3 σ are shown for events wich have no longitudinal leakage ("no leakage"), events traversing 9.3 λ

("standard calorimeter") and events which traverse 7.8 λ ("descoped calorimeter"). The plots on the left side of the Figure refer to the standard calibration and the plots on the right side are obtained after a recalibration of the last calorimeter sampling using different weighting factors (1.25*S4), see below. Fig. 2 shows the energy resolution as a function of the weighting factor (using a full fit region) for the three calorimeter configurations. Fig. 3 shows their resolution as a function of $1/\sqrt{E}$.

b) The low energy tails below three sigma of the energy resolution increase from 1% to 2.3% at 50 GeV and from 2.7% to 5.6% at 300 GeV (see Fig. 1 and Fig. 10), which means an increase of more than a factor of two. This should be compared to an "ideal" calorimeter of infinite depth which shows tails of only 0.4% at 300 GeV. To recover the loss in resolution the energy resolution has been reevaluted by giving an extra weighting factor to the last sampling of the Tile calorimeter by a factor of 1.25 times the deposited energy in this sampling. In fact, the energy resolution can be reduced with different weighting factors to 5.3% which is close to the value of the "standard" calorimeter. However, the low energy tails are not reduced at all and, what is even worse in this case, also high energy tails of 0.9% pop up (see Fig. 1 and Fig. 10). These low and high energy tails will have strong impacts on the jet energy reconstruction,with the consequence of worsening the di-jet mass resolution and the E_T^{miss} reconstruction.

c) The effect on non-linearity has not yet been estimated.

d) The punchthrough probability for pions as measured from test beam data (Ref [4]) increases by about a factor of 1.8, see Fig. 4. This Figure shows the expected punchthrough probability of pions for the stand-alone (full curve) the TILECAL-LAr combined mode (dashed curve), the TP design (dotted curve) and downscoped design (dash-dotted curve). The support structures have been included in the λ values for all cases. The punchthrough probability for jets will also increase by about a factor of two, from 4% at 50 GeV to 80% at 1 TeV, compared to 1.5% at 50 GeV and 44% at 1 TeV for the TP hadron calorimeter design as shown in Fig. 5. In addition, the average energy loss increases from 0.7% at 200 GeV to about 2.2% at 1 TeV compared to 0.01% at 200 GeV and 0.6% at 1 TeV for the TP hadron calorimeter design (see Fig. 6).

e) The overall screening effect of the calorimeter for neutrons and gammas for the muon system has not yet been evaluated for this change of radial dimensions.

In the same spririt and in a similar way, the TILECAL-LAr combined test beam data have also been reanalyzed. The "standard situation" is compared to a case in which the energy is reconstructed by ignoring the energy fraction measured in the 4th hadronic compartment ("descoped calorimeter"). This is equivalent to the removal of about 3 λ (60 cm) from the Tile calorimeter prototype, giving a total calorimeter of effective depth of 7.3 λ (em + hadronic). Figure 7 shows the energy distribution for pions at 50, 100, 150, 200 and 300 GeV nominal beam energy. The beam energy has been first reconstructed by summing up the energy deposition in the LAr and all four hadronic samplings in depth ("standard calorimeter"). Figure 8 shows the same distributions for the "descoped calorimeter", where in this case the energy has been reconstructed by ignoring the energy deposition in the last (4th) hadronic compartment (longitudinal). The significant increase of the tails is already clearly visible for pions at 100 GeV. Below three sigma of the energy resolution the tail amounts to 1.4% at 300 GeV for the "standard calorimeter" and to 7.4% for the "descoped calorimeter" (effective depth of 7.3 λ). That means an increase of a factor of 5. The energy resolution as a function of $1/\sqrt{E}$ has also been investigated, as shown in Figure 9. These results from the combined test confirm in general the conclusions obtained with the stand-alone test beam data.

- All the informations about a possible downscoping or staging scenario, from both the stand-alone and the combined test beam data, have been merged to give the plot of Figure 10. It shows the increase of the percentage of events in the tail of the energy distributions for different calorimeter depth configurations. Results are shown for 50 and 300 GeV pions, as well as for 300 GeV pions after having re-calibrated the hadronic samplings in the stand-alone data. One can see that the re-calibration procedure doesn't help much in recovering the tails.

3 Impact on Physics

The physics implications of the degraded calorimeter performance would be, f.ex.:

- The **dijet mass resolution** for high E_T (over 1 TeV) objects will be worsened. This effect has been studied in an ATLAS note in the past [2]. A detailed study by our SSC colleagues performed earlier shows the λ dependence of the di-jet mass (Ref [1]). Below 10 λ the calorimeter depth affects the di-jet mass resolution and the signal significance. Differently from the ATLAS note, in the SSC study non-Gaussian tails have been taken into account and have been judged important in reducing the efficiency for a signal. Fig. 5 of Ref. [1] in the same study shows the dependence on the number of λ of the containment for different di-jet masses. In conclusion, one gets a rough estimate that 10 to 11 λ of active material is required to be little sensitive to non-Gaussian tails. A preliminary analysis of the test beam data simulating as close as possible the downscoping scenario show that non-Gaussian tails are already produced at medium energies (> 100 GeV). Therefore, the di-jet mass resolution will also be affected in the intermediate mass region, with particular implication to the sensitivity of reconstructing f.ex. the top quark mass from its decay $t \to bW$ and $W \to jj$, the search for the charged Higgs via the process $t \to bH^{\pm}$ and $H^{\pm} \to cs$ and also the search for the heavy Higgs mass in its decay mode via $H \to WW \to jjl\nu$.

- From the substantial increase of non-Gaussian tails in the energy reconstruction, problems in the missing E_T reconstruction can be expected as well.

  - The Z+jet background will dominate the Higgs $\to$ ZZ $\to$ $ll\nu\overline{\nu}$ channel in the heavy Higgs mass region, which therefore will be very difficult to isolate. Ref. [3] indicates that a 1-2% amount of tails in the resolution is already dangerous. With a smaller percentage of tails the estimated constribution of the Z+jet BG is already of the order of the irreducible BG. There we might compromize that channel at all. To repeat this study in detail for the new configuration it will be work of several months. This work should be done before adopting a reduced λ coverage.

  - Searches for SUSY particles, such as squarks and gluinos, will be affected by an increase of the tails in the energy resolution faking E_T^{miss}, due to the reduced radial depth of the hadron calorimeter. In particular, the study on the SUSY Higgs $A^0 \to \tau\tau$ have shown that the invariant mass resolution depends strongly on the E_T^{miss} resolution.

  - Other channels giving raise to large E_T^{miss}, like W boson pair production could also be in question. Again several studies have shown that to match the natural leakage for jets due to prompt neutrinos and muons, one needs a minimum of 10 λ. SSC studies have shown that to match neutrinos leakage even 12 λ of radial coverage would be needed (see Fig. 12 of Ref. [1]).

- We know from past studies that an uncorrected non-linearity and an increase of the constant term will affect our discovery potential for compositness from high E_T jets. However, it is very difficult to make statements at the moment: work is in progress.

In conclusion, a downscoping of the calorimeter following suggestion b) will do a lot of harm to the Tile calorimeter performances with severe implications on the physics outcome. In addition, due to the much higher punchthrough rate the muon system will also be affected.

4 Cost Issues

Here are some considerations on the CORE numbers for the staging and downscoping scenario.

- **staging:**

  Two different approaches have been considered:

  1) leaving out all PMT-blocks of the last sampling, #3, in the initial phase.
  2) leaving out every second PMT of the last and before last samplings, #2 and #3. From the CORE cost we can estimate the cost of a complete PMT block to about 410 CHF. For the moment we should not consider reducing FERMI readout and HV, because that would complicate too much the recovery and the trigger organization.

  Approaches one and two would allow the following cost reduction

  - sampling 3 out : 1850 PMTs = 760 KCHF
  - 50% of sampling 2 and 3 out : 2820 PMTs = 1170 KCHF

- **downscoping:**

  If suggestion a) of the downscoping task force is considered, namely the reduction of the barrel by 800 mm in longitudinal dimensions, the total saving in core will amount to 780 KCHF, coming from.

  - 14 % saving on the laminated steel = 150 KCHF
  - 14 % on barrel girder = 130 KCHF
  - 14 % on some optical items(like fibers) = 40 KCHF
  - 760 channels at 600 CHF each = 460 KCHF.

References

[1] D. Green et al., Depth requirements in SSC calorimeters, FERMILAB-FN-570.

[2] A. Henriques and L. Poggioli, Detection of the Z' boson in the jet decay mode Z'→jj, ATLAS note PHYS-10

[3] M. Bosman and M. Nessi, Study of Z + jets background to H→ZZ→ll$\nu\bar{\nu}$ signal using full simulation of ATLAS calorimetry, ATLAS note PHYS-50

[4] T. Davidek et al., Measurement of pion showers longitudinal leakage in the TILECAL prototype, ATLAS note TILECAL-64

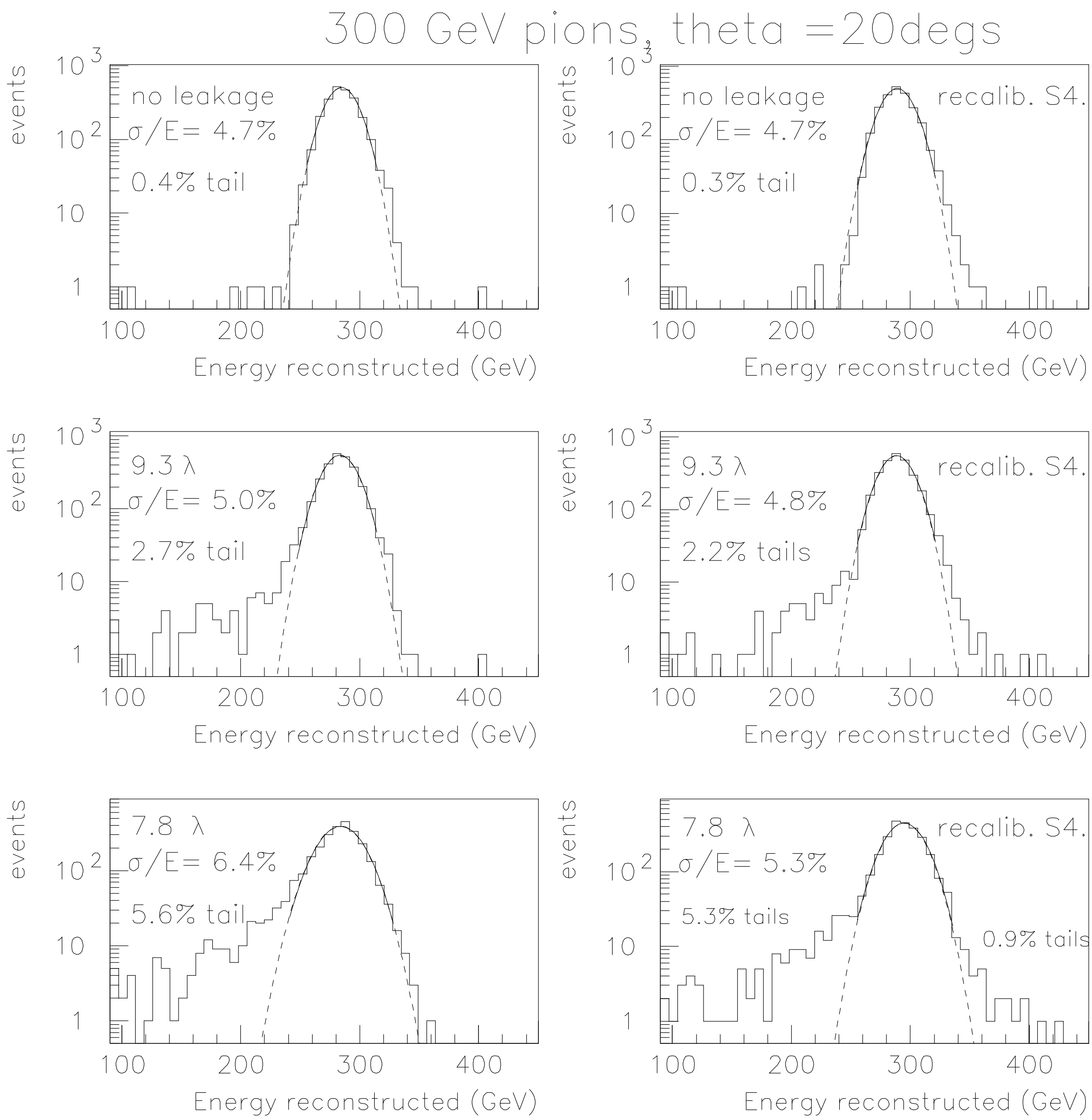

Figure 1: The energy distribution for 300 GeV pions at incident polar angle $\theta = 20^o$. The energy resolution obtained from a Gaussian fit within $\pm$ 2 σ and the percentage of events in the tails below 3 σ are shown for events wich have no longitudinal leakage, events traversing 9.3 λ and events which traverse 7.8 λ. The plots on the left side refer to the standard calibration and the plots on the right side are obtained after a recalibration of the last calorimeter sampling using different weighting factors (1.25*S4).

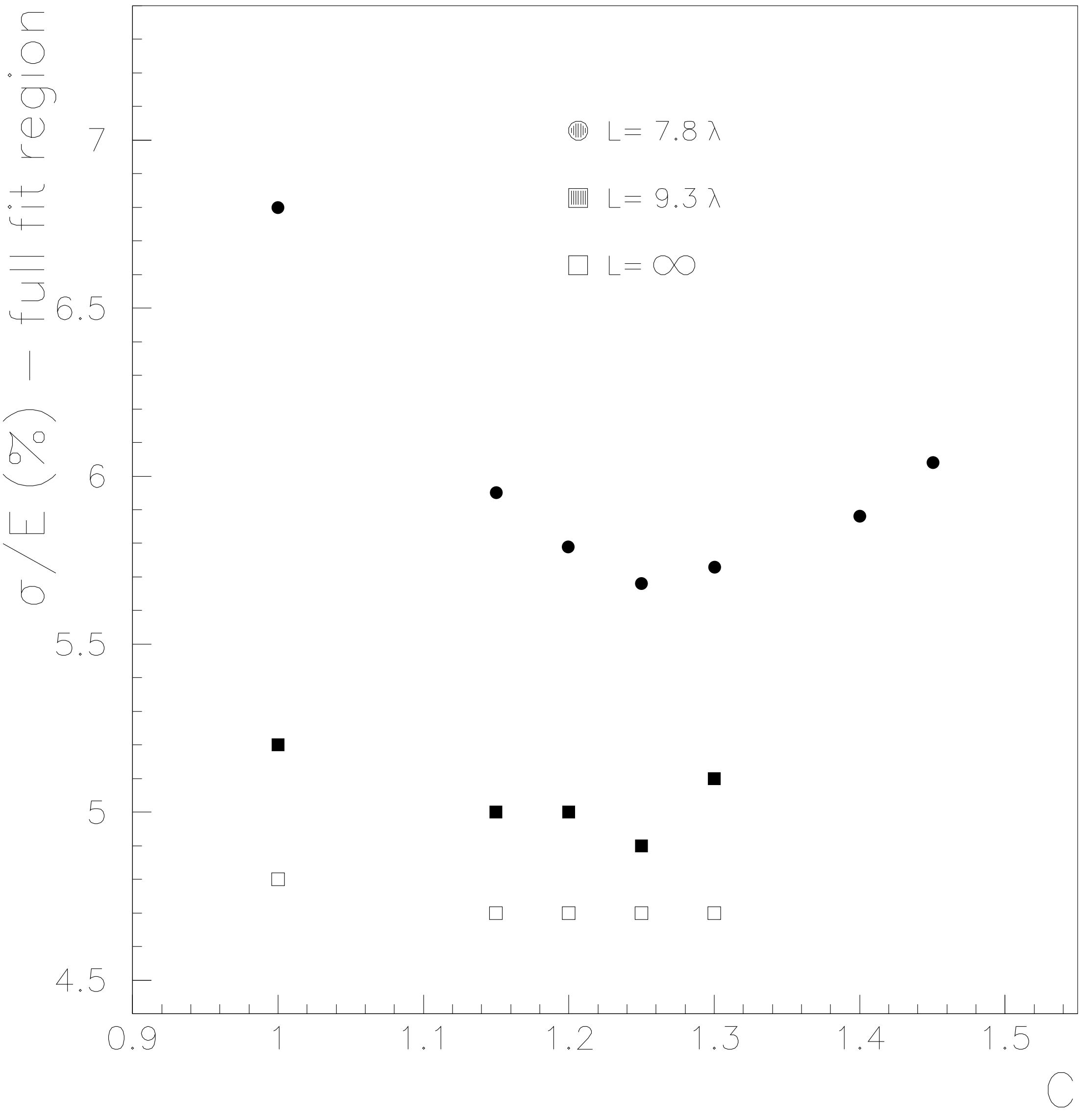

Figure 2: The energy resolution obtained with a full region Gaussian fit as a function of the extra weigthing calibration C in last sampling for 300 GeV pions at incident polar angle $\theta = 20^o$.

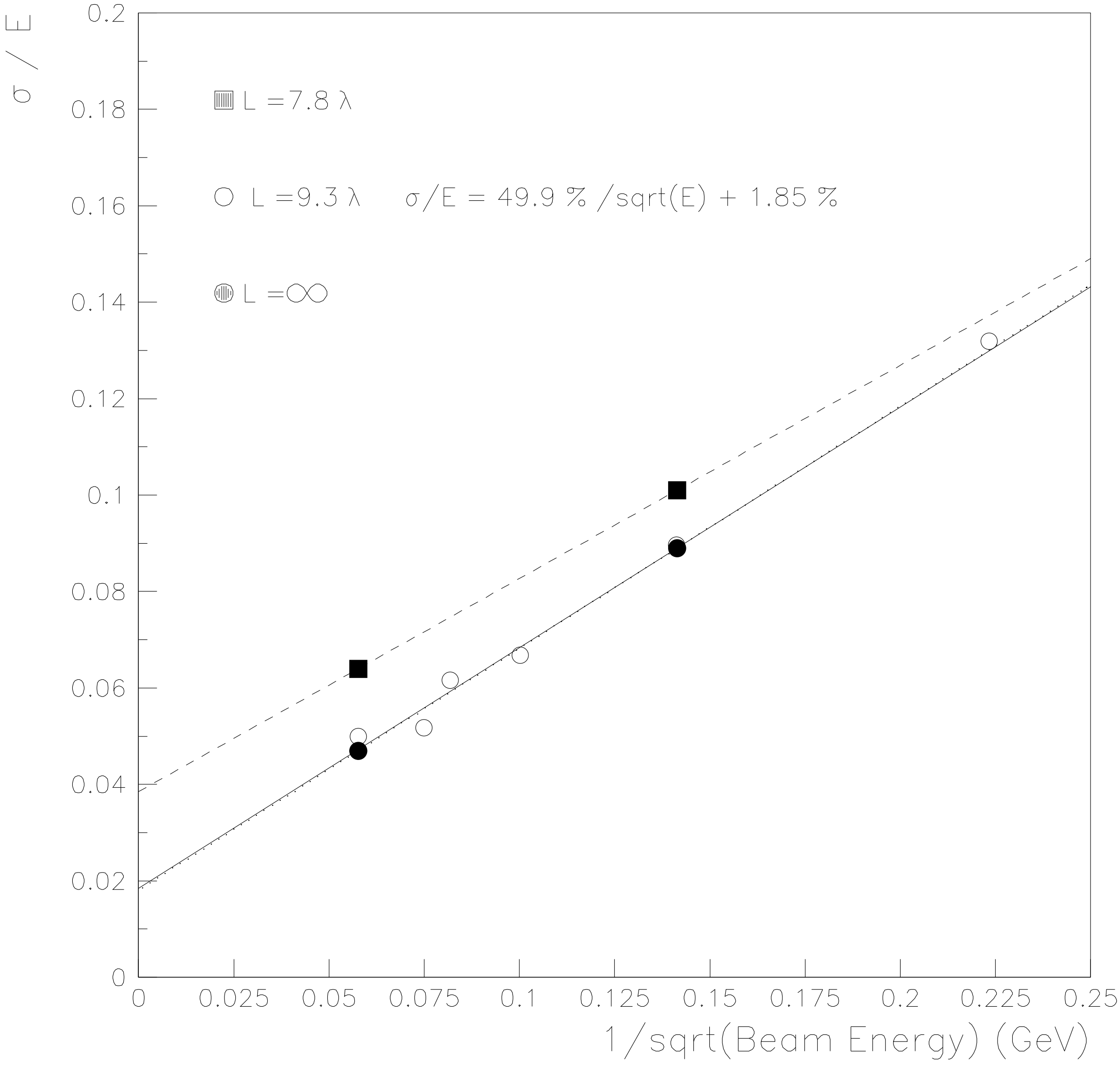

Figure 3: The energy resolution as a function of $1/\sqrt{E}$ for pions at incident polar angle $\theta = 20^o$.

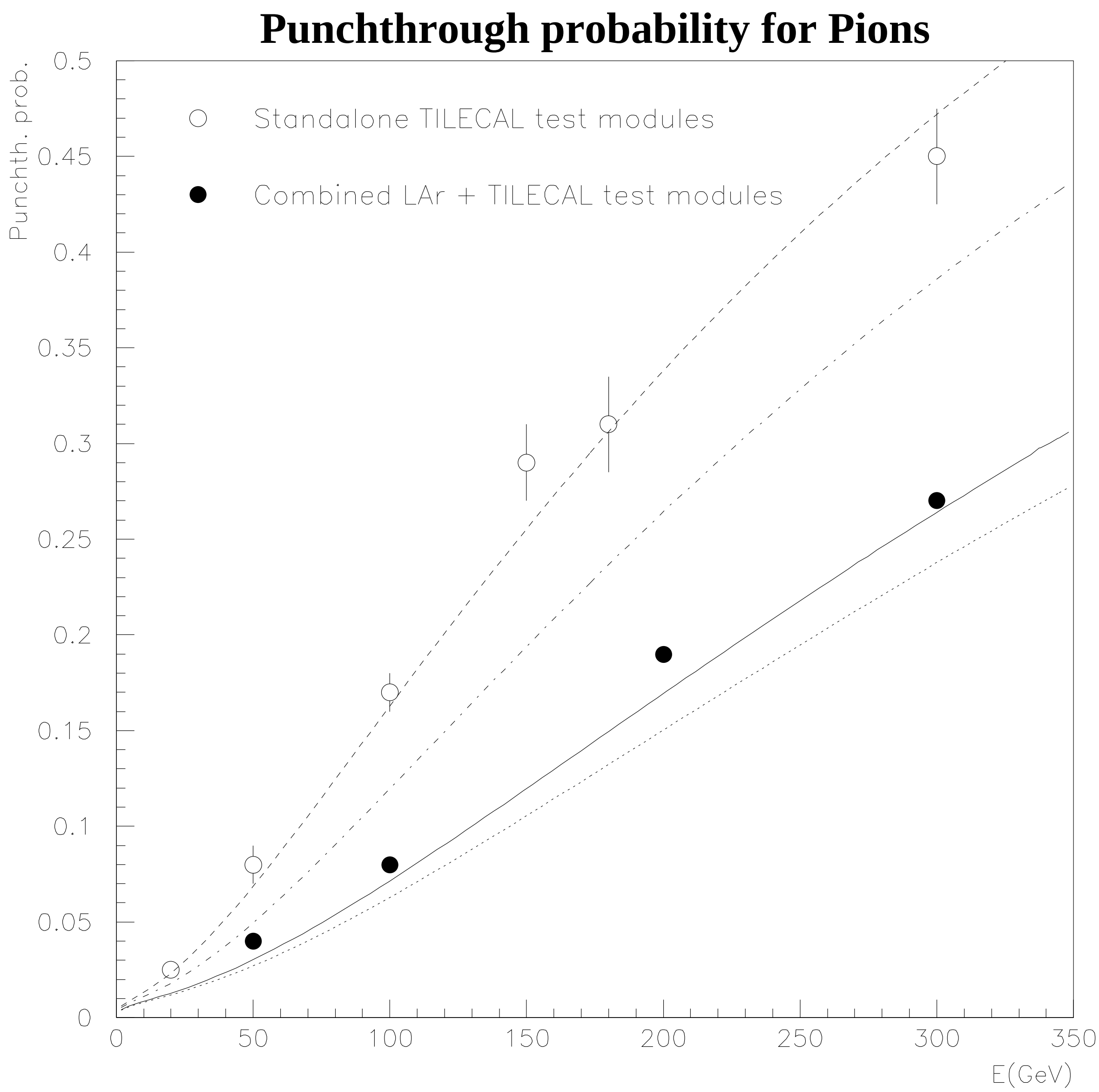

Figure 4: Expected punchtrough probability for pions traversing different calorimeter depths for the stand-alone, 9.2 λ (dashed curve), the TILECAL-LAr combined mode, 10.2 λ (full curve), the TP design, 10.6 λ (dotted curve), and downscoped design, 9.6 λ (dash-dotted curve), including in all cases the support structures.

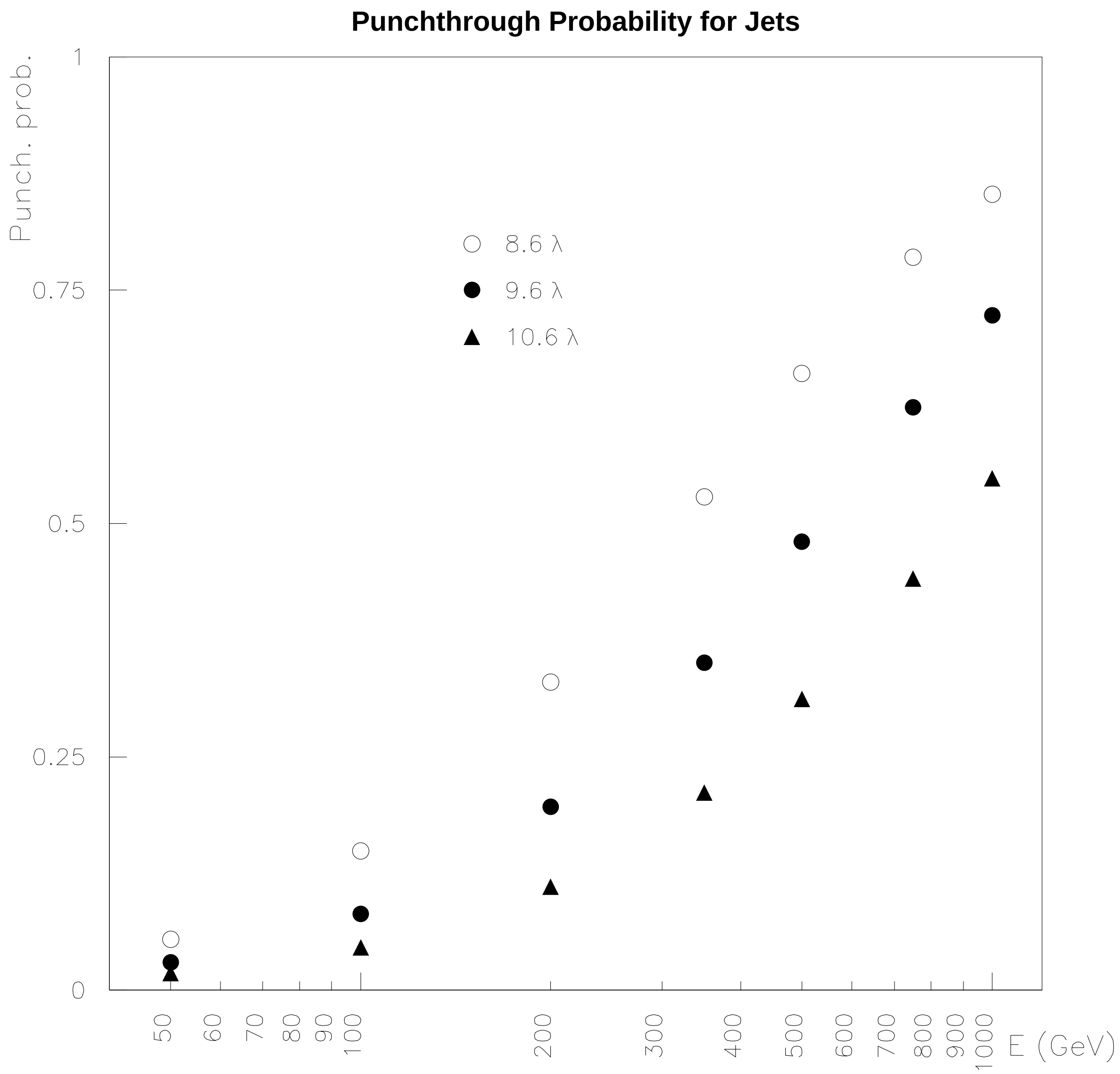

Figure 5: Expected punchtrough probability for jets traversing different calorimeter depths.

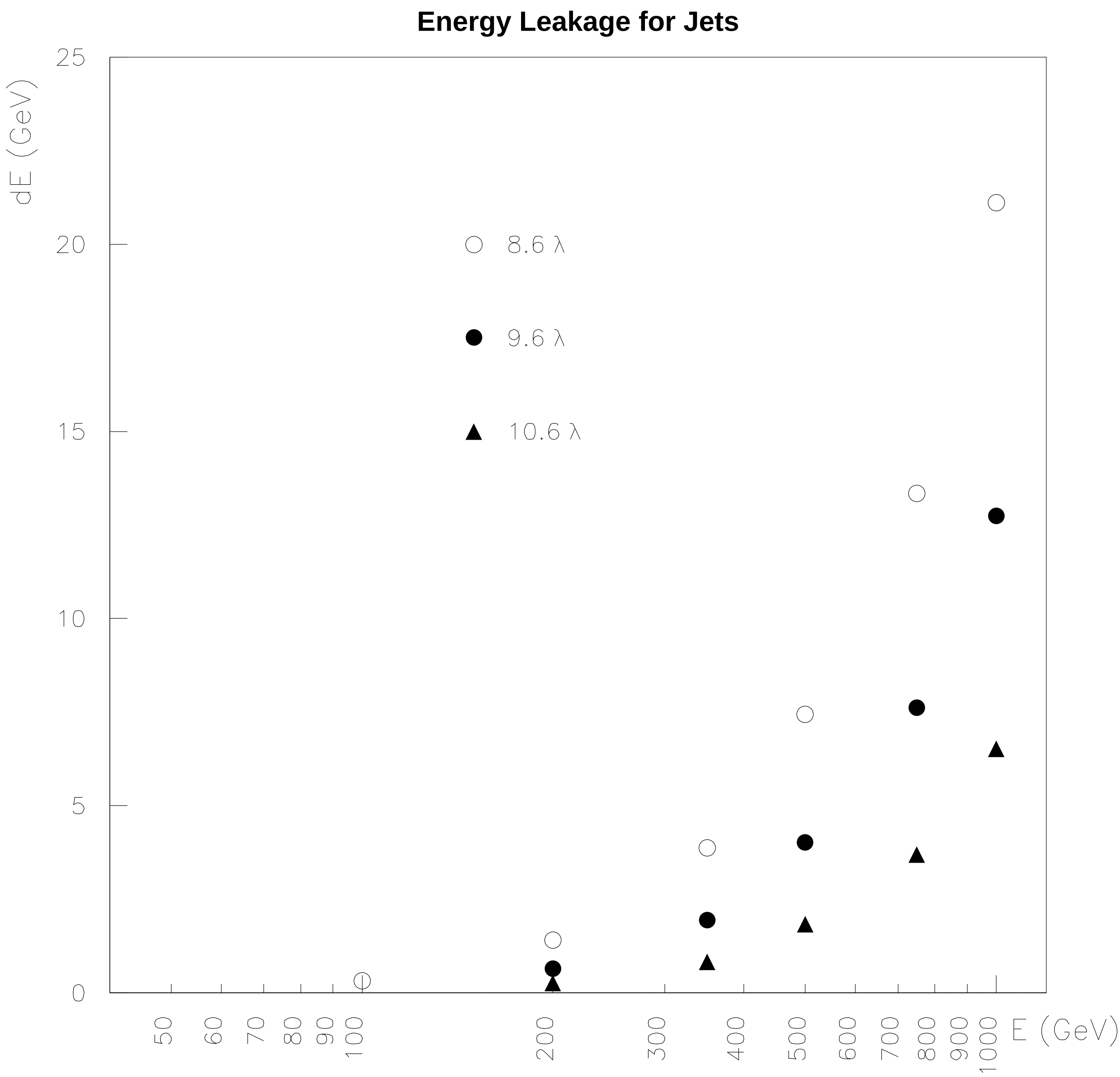

Figure 6: Energy leakage for jets as a function of the jet energy for different calorimeter depths.

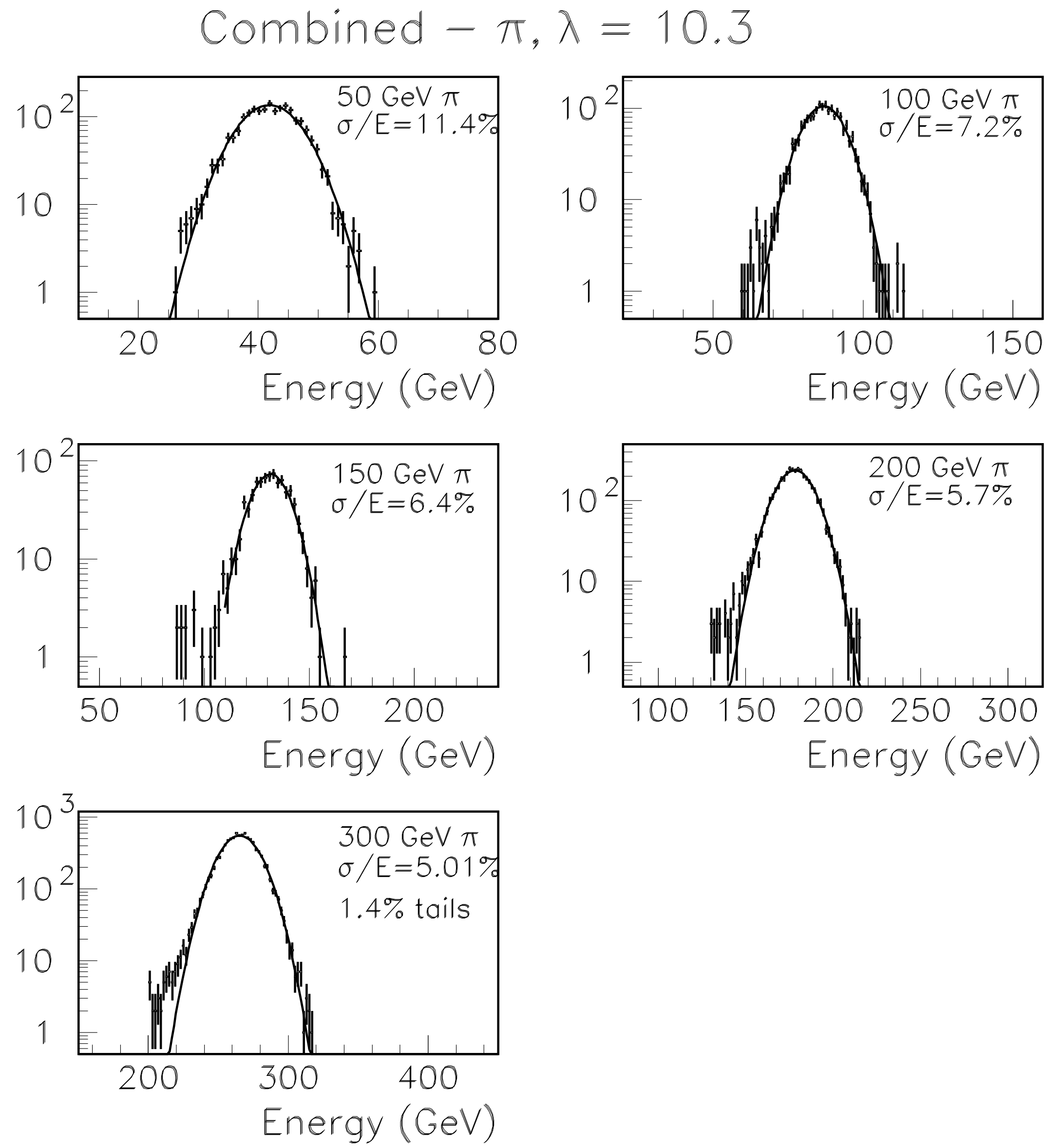

Figure 7: Energy distribution for pions at various energies (TILECAL+LAr combined test beam). The total energy has been calculated by summing up the energy depostion in the LAr and all four hadronic longitudinal samplings.

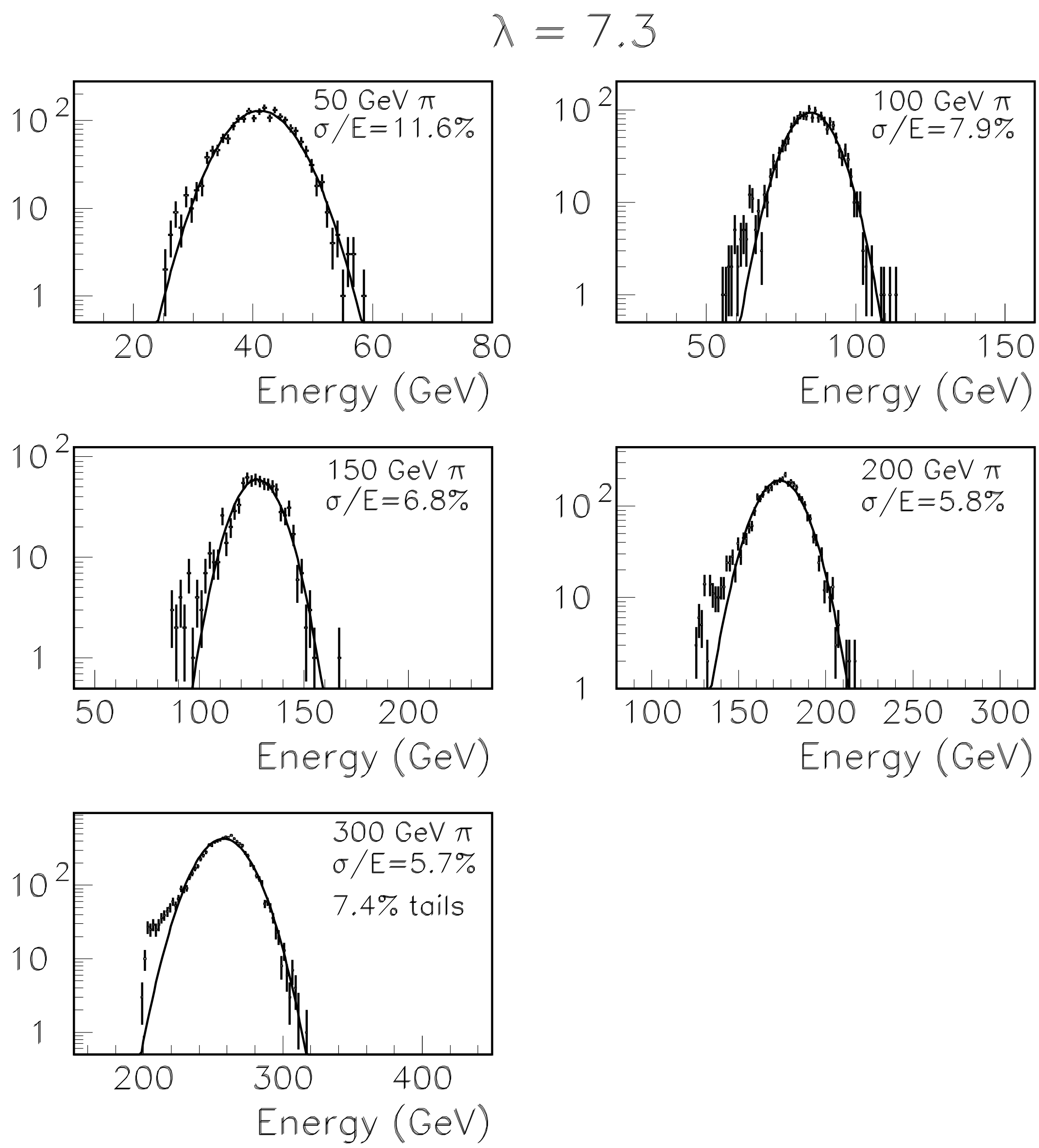

Figure 8: Energy distribution for pions at various energies (TILECAL+LAr combined test beam). The total energy has been calculated by summing up the LAr and only the first three hadronic longitudinal samplings.

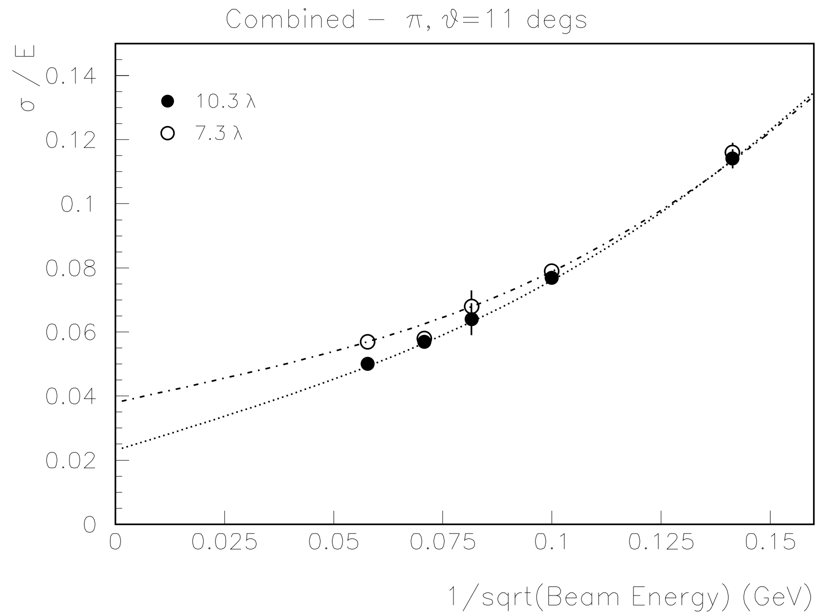

Figure 9: Energy resolution for the case where all the hadronic longitudinal samplings are taken into account (black dots), and where instead only the first three are used (white dots).

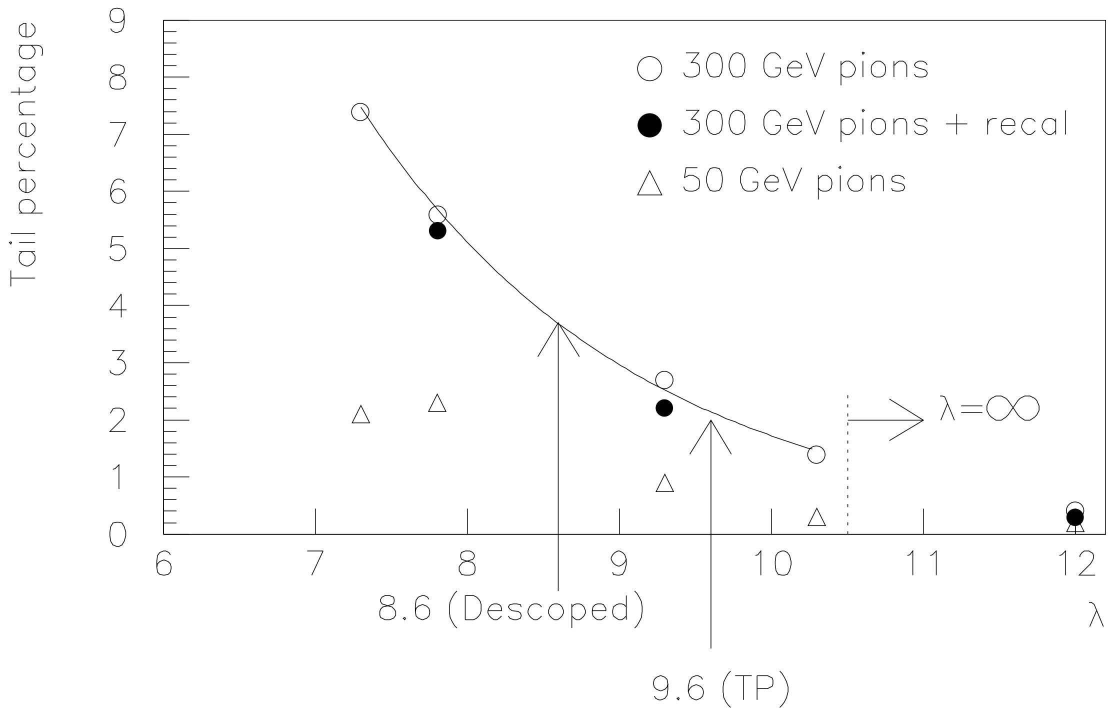

Figure 10: Percentage of events in the low energy tail (below 3 σ) for different calorimeter depth configuration. Results are shown for 50 and 300 GeV pions, as well as for 300 GeV pions after re-calibration of the hadronic samplings.