Study of ATLAS Tile Calorimeter Energy Resolution, Linearity and Sampling Fraction at Electromagnetic Scale

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Abstract

Tests of the combined electromagnetic liquid argon (LAr) and the hadronic Tile calorimeter modules of the future ATLAS experiment were carried out, using pion beams of energy 10-350 GeV. The main purpose of the combined setup was to demonstrate that the choice of a hybrid calorimeter (Liquid Argon electromagnetic Calorimeter and Tile Hadronic Calorimeter) will allows one to reconstruct the energy of incident hadrons with resolution and linearity within the goals of ATLAS.

Study of the energy resolution and linearity in TileCal for π mesons beams at energies of 20 ÷ 350 GeV at η=0.25 using ATLAS combined testbeam 2004 have been carried out. The reconstructed energy was defined in 3 different ways: as the sum of the energy in all Tile barrel samplings; as the sum of energy deposited in TileCal cells and using topological clusters method. The energy resolutions obtained was about $\sigma/E = 51.0\%/\sqrt{E\,[GeV]} \oplus 5.7\%$. *The obtained values of reconstructed energies, resolutions and linearities for π- mesons for all 3 issues are generally good, is reasonable agreement between them and between prototypes and CTB2004 in "standalone mode".*

The study of Monte-Carlo electromagnetic response versus pseudorapidity for 20 GeV energy electrons has been carried out. Electron response in TileCal showed that an electron response fluctuation strongly depends on pseudo-rapidity. Reasonable agreement between our MC results with CTB2004 experimental data and MC simulation within Geant 4.7.0 is observed.

Introduction

The Large Hadron Collider (LHC) at CERN promises a major step forward in the understanding of the fundamental nature of matter. The LHC is a proton-proton collider with 14 TeV center of mass energy and design luminosity of 10^{34} $cm^{-2}s^{-1}$, designed and constructing to explore the electroweak symmetry breaking mechanisms up to TeV energies. The LHC opens a new frontier in particle physics due to its higher collisions energy and luminosity compared to the existing accelerators. The ATLAS experiment is a general-purpose detector for the LHC. The major remit of the ATLAS experiment is the exploration of the TeV mass scale where ground breaking discoveries are expected. In the focus are the investigation of the Electroweak Symmetry Breaking (ESB), the search for the Higgs boson linked to ESB and as well as the search for Physics beyond the Standard Model.

The design of the ATLAS detector has now been finished, and its construction and installation have been completed [1]. An extensive test beam programm was undertaken. The ATLAS will have a great physics discovery potential. To perform the researches successfully, ATLAS needs to have very good electromagnetic and hadronic calorimeters for the identification of electrons, pions, photons and hadronic jets and for measurement of missing transverse energy. Calorimeters will play crucial role at LHC. Accurate measurement of energy and direction of particle coming from propon-proton collisions by calorimeter system is required to reconstruction events of prime interest of ATLAS. The Tile hadronic calorometer is the one of subdetectors of ATLAS.

An optimization and a final determination of electro-magnetic energy scale and a study of different characteristics (energy resolution and linearity) of Tile Calorimeter and its calibration before the running of the ATLAS detector and obtaining the real experimental data are very important tasks. Hadronic calibration of the calorimeter is very crucial aspect in studying of physical processes with hadronic jets production. The goal of the hadronic calibration is to provide improved methods and estimations of their parameters for an impact hadron energy reconstruction in the calorimeter. The way to solve this problem is a detailed Monte-Carlo (MC) study of the calorimeter response dependence on the impact hadron energy and pseudo-rapidity and comparing MC results with experimental test data

The Tile Hadronic Calorimeter

ATLAS (**A** **T**oroidal **L**HC **A**paratur**S**) [2-3] is one of the two general purpose detectors built at the LHC. It is designed to exploit the full discovery potential offered by the collider. Having 46 m length and 26 m height it is one of the largest and most elaborate particle physics detectors ever built at colliders (Fig.1). Its main parts are the Inner Detector, surrounded by a superconducting solenoid, the Calorimeters and the Muon Spectrometer with large superconducting air-core toroid magnets. The weight of the detector is 7000 tone.

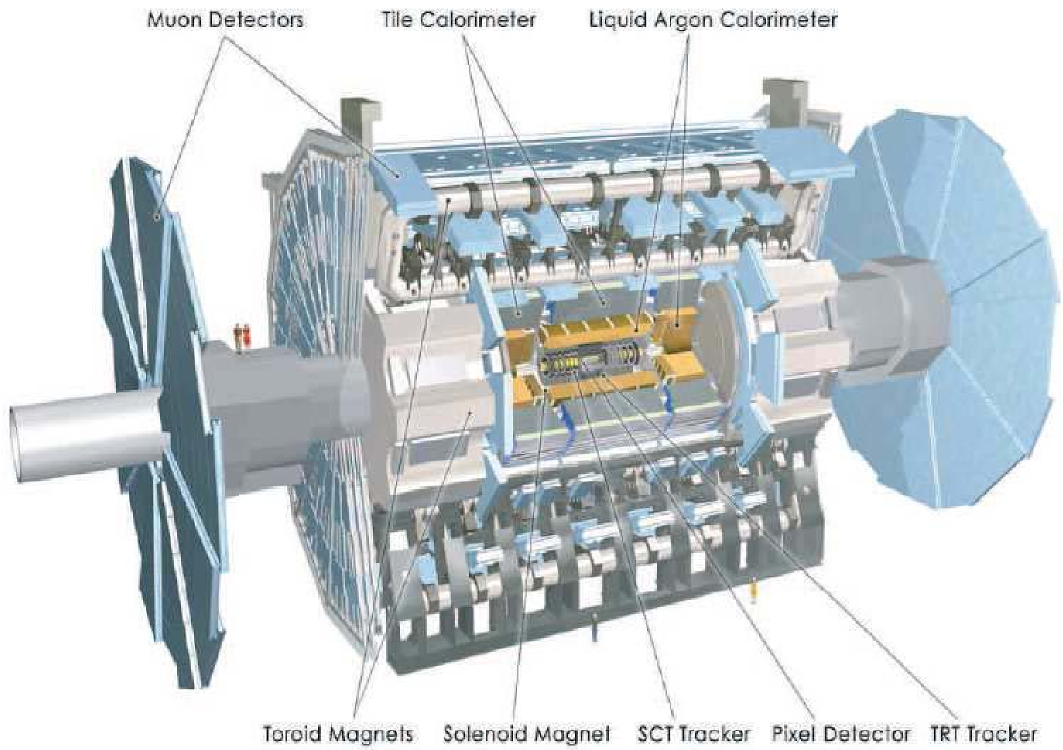

Figure 1: The ATLAS detector. The diameter and barrel toroid lengths are both 26 m and the overall length is 46 m.

The calorimeter system consists of an electromagnetic (EM) calorimeter [4] covering the pseudorapidity region $|\eta| < 3.2$, a hadronic barrel calorimeter covering $|\eta| < 1.7$, hadronic end-cap calorimeters covering $1.5 < |\eta| < 3.2$ and forward calorimeters covering $3.1 < |\eta| < 4.9$. The layout of ATLAS calorimeter system is shown in Fig. 2.

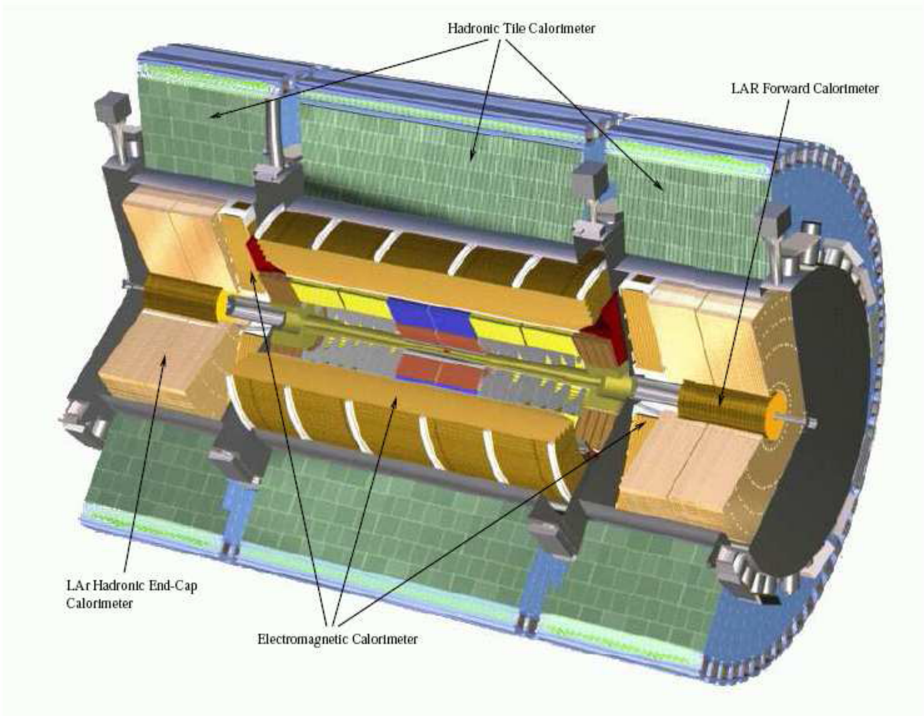

Figure 2: Schematic view of the ATLAS Calorimeter System.

The main function of the Tile Calorimeter is to measure the energy of the jets produced in the proton-proton interaction and, with the addition of the end-cap and forward calorimeters, to provide a good E_T^{miss} measurement. Achieving this at the LHC is not so straightforward. The large center of mass energy (14 TeV) requires good performance over extremely large dynamic range extending from a few GeV up to several TeV. To resolve events over a background of ~ 21 minimum bias events per bunch crossing a fast detector response with fine granularity is required. High radiation resistance is needed to cope with the high particle fluxes expected at the design luminosity over a period of 10 year of operation.

The Tile Hadronic Calorimeter is a sampling device made out of steel as the absorber material and scintillating plates (tiles) read out by wavelength shifting (WLS) fibers as the active medium [5]. The new feature of its design is the orientation of scintillating tiles which are placed in planes perpendicular to the colliding beams and are staggered in depth [6]. The Tile Calorimeter consists of a cylindrical structure with inner radius of 2.28 m and an outer radius of 4.23 m. It is subdivided into a 5.64 m long central barrel along the beam axis and two 2.91 m extended barrels. Each cylinder is built of 64 independent wedges (modules) along the azimuthal direction. Between the barrel and extended barrel parts there is a gap of about 0.6 m, which is needed for the Inner Detector and the Liquid Argon cables, electronics and services. The gap region is instrumented with special modules called Intermediate Tile Calorimeter made of iron scintillator sandwiches and with thin scintillator counters where the free space is limited. These devices allow partially recover the energy lost in the crack regions of the detector. The barrel covers pseudorapidity region $-1.0 < \eta < 1.0$, and extended barrels cover the region $0.8 < |\eta| < 1.7$.

The scintillating tiles lie in the r-φ plane and span the width of the module in the φ direction.WLS fibers running radially collect the light from the tiles along their two open edges. The principle of the TileCal design is shown in Fig. 3. Readout cells are defined by grouping together a set of fibers into a photomultiplier (PMT), to obtain a three dimensional segmentation. Radially, the calorimeter is divided into three layers (samplings), 1.5, 4.1 and 1.8 nuclear interaction lengths (λ) thick at $\eta = 0$, having total depth of 7.4 λ. In the first two layers the $\Delta\eta \times \Delta\varphi$

segmentation is 0.1 × 0.1 and it is 0.2 × 0.1 in the last layer. The iron to scintillator ratio is 4.7 : 1 by volume.

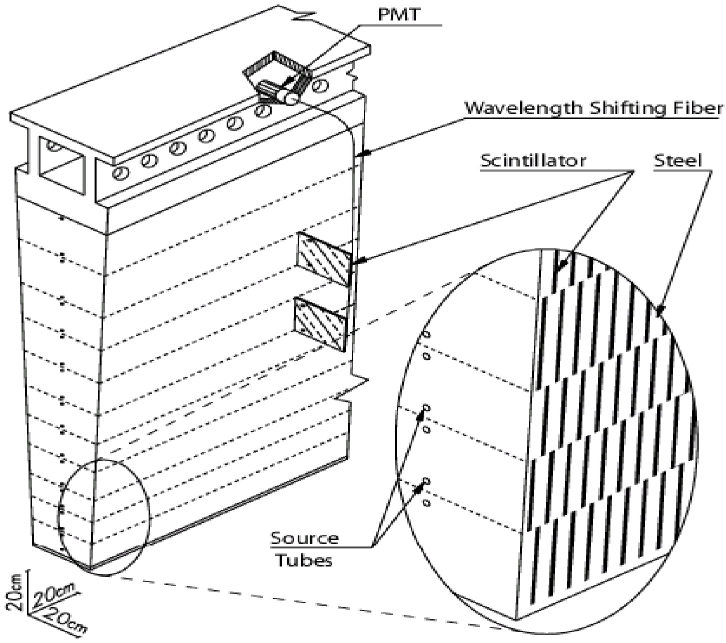

Figure 3: The principle of the Tile Calorimeter design.

Test Beam Experimental Setup and Event Selection

Analysis of combined test beam data and investigation of Tile calorimeter electromagnetic energy scale, hadronic calibration, energy resolution and linearity are very important before starting ATLAS experiment and obtaining an experimental data. Before 2004 tests of the combined electromagnetic liquid argon (LAr) and the hadronic Tile calorimeter prototypes of the future ATLAS experiment were carried out, using pion beams of energy 10-350 GeV. The main purpose of the combined test was to demonstrate that the choice of a hybrid calorimeter (Liquid Argon electromagnetic Calorimeter + Tile hadronic Calorimeter) would allow one to reconstruct the energy of incident hadrons with resolution and linearity within the goals of ATLAS**.**

During the ATLAS combined test beam 2004 a full slice of the ATLAS detector was tested. This test provided a unique opportunity to evaluate the individual sub-detector performances, and also to exploit the full power of the ATLAS detector for detailed particle identification and measurement and to understand better the detector performance in a realistic combined data taking. The electromagnetic calorimeter module (LAr) was housed inside a cryostat filled with liquid argon. For the hadron tile calorimeter (TileCal) 3-barrel modules, and 3 Extended Barrel (EB) models were used**.** Sketch of the Atlas combined electromagnetic liquid argon and the hadronic Tile calorimeters 2004 test beam setup is presented on Fig.4

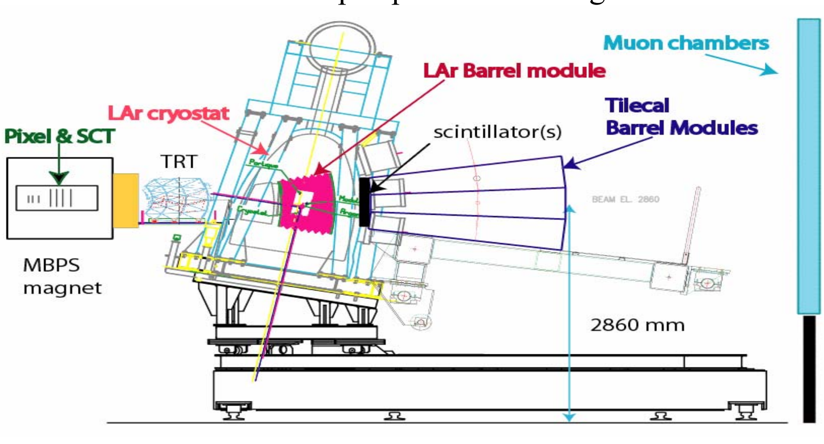

Fig.4. Sketch of the Atlas combined electromagnetic liquid argon and the hadronic Tile calorimeters 2004 test beam setup.

The pions of the following energies were analyzed: 20, 50, 100, 150, 180, 200, 250, 320, 350 GeV. The barrel runs were taken during different run conditions. The runs at energies of 200 and 250 GeV were taken during the combined calorimeter run period. The runs at energies of 20, 50, 100, 320, and 350 GeV were from the fully combined run period (including all the detectors). At 150 and 180 GeV data were taken during both periods. The experimental data are recorded as Ntuples. We have analyzed (Tiles group) about 700 000 events at pseudorapidity η =0.25 for pions energies from 20 to 350 GeV. The data (ntuples) were taken from CASTOR – an implementation of a Managed Storage system, developed at CERN:
/castor/cern.ch/grid/atlas/datafiles/ctb/realdata/11.0.41.v1/;
/castor/cern.ch/grid/atlas/datafiles/ctb/realdata/12.0.5.v6/;
/castor/cern.ch/grid/atlas/datafiles/ctb/realdata/12.0.5.v7/.

The data were reconstructed within the ATLAS software framework Athena releases 11.0.41 and 12.0.5.

The data have been analyzed by the C++ based data analysis package ROOT. Program of data analysis algorithm have been written by us.

Physics events were selected by requiring, Trig=1 (the trigger type was defined as 1=physics, 2=laser, 4=pedestal, 8=charge injection). Good physics events were selected, i.e. particles that are well collimated and not have undergone any interactions in the beam line before reaching the calorimeters. This was done using the beam line scintillates, S1 (sADC-S1 variable in TB/tree branch of topples), S2 (sADC-S2mDown, sADC-S2mUp variables in TB/tree branch), S3 (sADC-S3mLeft, sADC-S3mRight variables in TB/tree branch) and SMH (sADC-muHalo variable TB/tree branch), and four beam chambers BC-1, BC0, BC1 and BC2 on the high energy line**.** Measurements were performed in the H8 beam line at the SPS (Super Proton Synchrotron) at CERN**.** A 400 GeV proton beam was extracted from the SPS accelerator and directed onto the primary beryllium target. The typical intensity of the proton beam was 10^{12} particles per burst. The secondary beam had energies from 10 to 350 GeV and was directed onto the secondary filter target allowing increasing the electron or pion fraction of the beam by inserting different materials with different thickness into the beam line. A number of quadrupole and dipole magnets, as well as collimators were used to focus and bend the beam and to select correct momentum. The beam lines were instrumented in a standard fashion with one threshold Cherenkov counter used for π/e separation, delay-line wire beam chambers, and scintillators to define a trigger. The scintillators defined a beam spot of around 2-3 cm. Schematic outline of the beam line instrumentation is presented on Fig.5

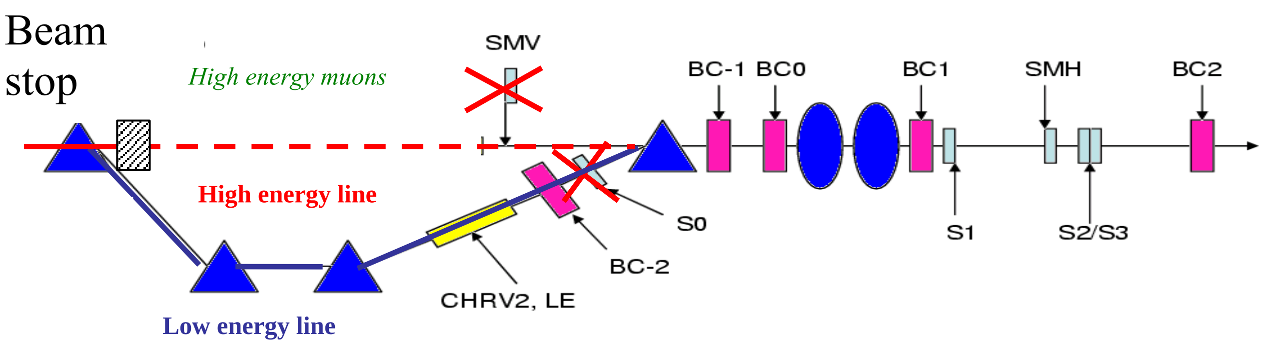

Fig.5: Schematic outline of the beam line instrumentation

The beam chamber cuts used were simple rectangular cuts on the x and y coordinate of each beam chamber (In TileRec/h1000 branch: XchN1, YchN1 -- BC-1; Xcha0, Ycha0 - BC0; Xcha1, Ycha1 - BC1; Xcha2, Ycha2 --BC2). These cuts have been obtained from 2 dimensional distributions of beam BC0, BC1, BC2 and BC-1 chambers x and y coordinates on the energy deposited in TileCal.

The cuts on the beam scintillators used for the Tile barrel runs were as follows: S1 < 900, S2 < 900, S3 < 900, SMH<900 ADC counts. The cuts on the cryostat scintillator was: SC < 300 ADC. The muons in the runs were removed using cut SMT> 500 ADC counts.

Energy Reconstruction

The energy of pions was reconstructed in 3 different ways:

1. The energy was defined as the sum of energy deposited in TileCal barrel samplings. For LAr samplings was applied cut $E < \mu_{fit} +2 \times \sigma_{fit}$ (LAr energy smp cut). In each layer of the LAr calorimeter we looked at the muon signal. This signal has been fitted with a Gaussian (μ_{fit} and σ_{fit}). Then the fit parameters have been used to define a threshold below which pions are considered as mips (minimal ionization particles).
2. The energy was reconstructed as the sum of energy deposited in TileCal cells with E^{Tile} cell > 50 MeV. For LAr cells was applied cut E^{LAr} cell < 5 MeV (LAr energy cell cut).
3. The energy was reconstructed as the sum of energy deposited in TileCal using topological clustering algorithm. The basic idea of the topological clustering method is to group cells in clusters based on their neighbour relations and on the significance of their energy contents. The following cuts were applied: For LAr topo clusters was applied cut: $E < \mu_{fit} +2 \times \sigma_{fit}$ (LAr energy topo cluster cut). $E \leq 0.8$ GeV, for variable cl_ecluster_topo (cluster energy from TB/tree branch of Ntuples) was applied cut: cl_ecluster_topo $\geq$ 10 GeV.

The energy reconstruction for π- mesons beams at energy 320 GeV is presented on Fig. 6 before applying any cuts.

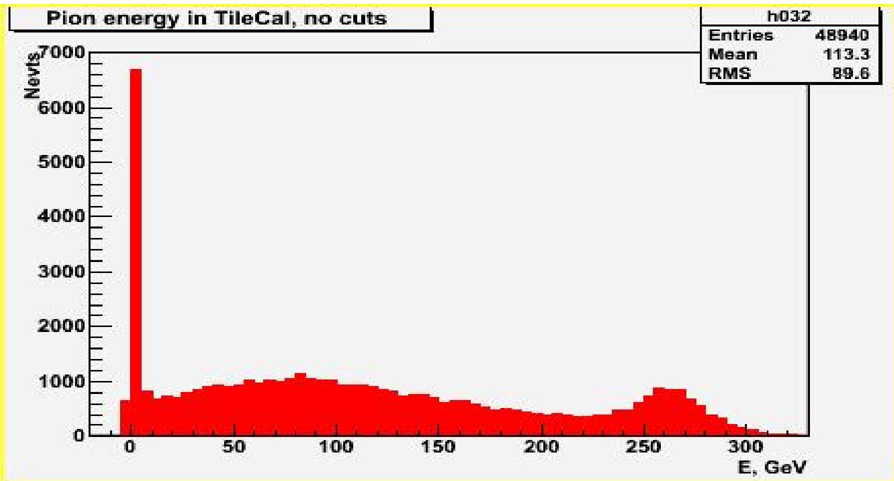

Fig.6: Example of the pion energy distribution for π- mesons beams at energy of 320 GeV before applying cuts.

The energy reconstruction for π- mesons beams at energy 320 GEC is presented on Fig. 7 after applying LAr energy topo cluster cut ($E \leq 0.8$ GeV).

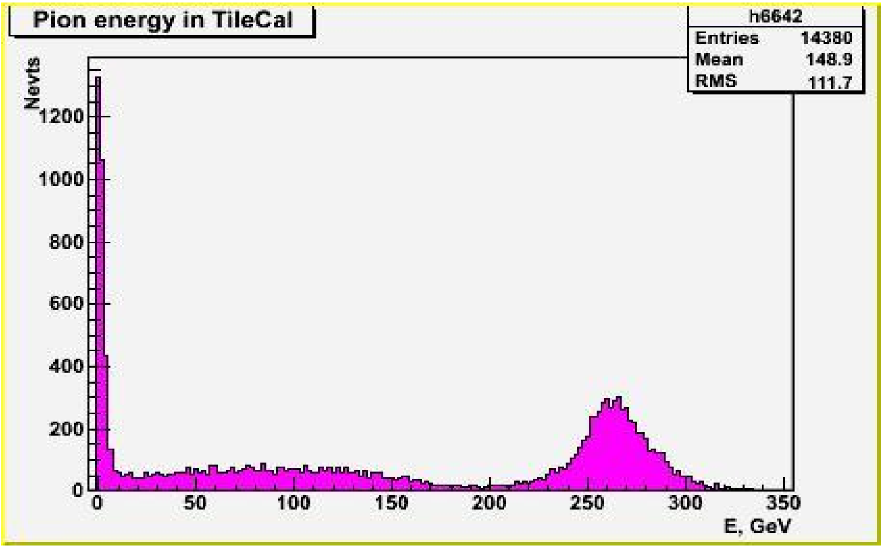

Fig. 7. Example of the pion energy distribution for π- mesons beams at energy of 320 GeV after applying LAr energy topo cluster cut (E ≤ 0.8 GeV).

The energy reconstruction for π- mesons beams at energy 320 GeV is presented on Fig. 8 after applying two cuts: LAr energy topo cluster cut (E ≤ 0.8 GeV) and Tile energy topo cluster cut E ≥ 10 GeV.

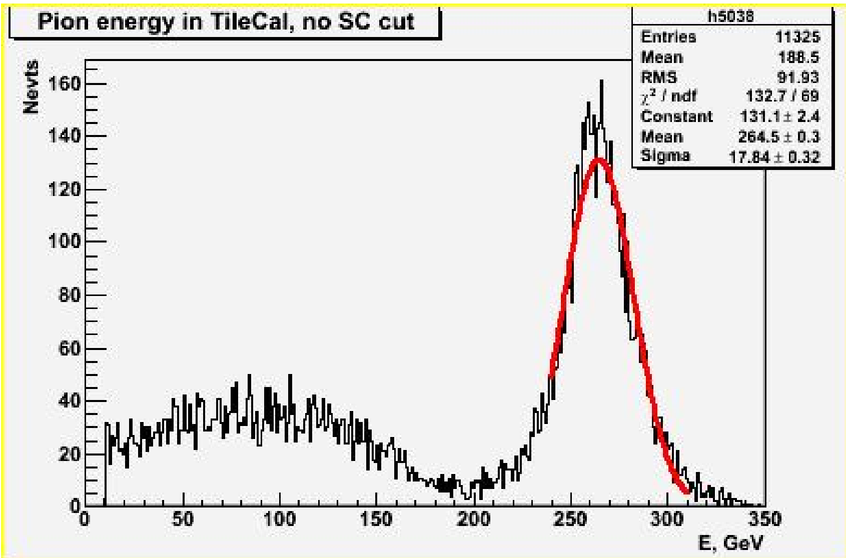

Fig. 8. Example of the pion energy distribution for π- mesons beams at energy of 320 GeV after applying two cuts: LAr energy topo cluster cut (E ≤ 0.8 GeV) and Tile energy topo cluster cut E ≥ 10 GeV.

It has been studied the dependence of the cut applied on the SC - cryostat scintillator on the energy reconstruction for π- mesons beams. The energy reconstruction for π- mesons beams at energy 320 GeV is presented on Fig. 8 after applying two cuts: SC < 300 ADC and : LAr energy topo cluster cut (E ≤ 0.8 GeV).

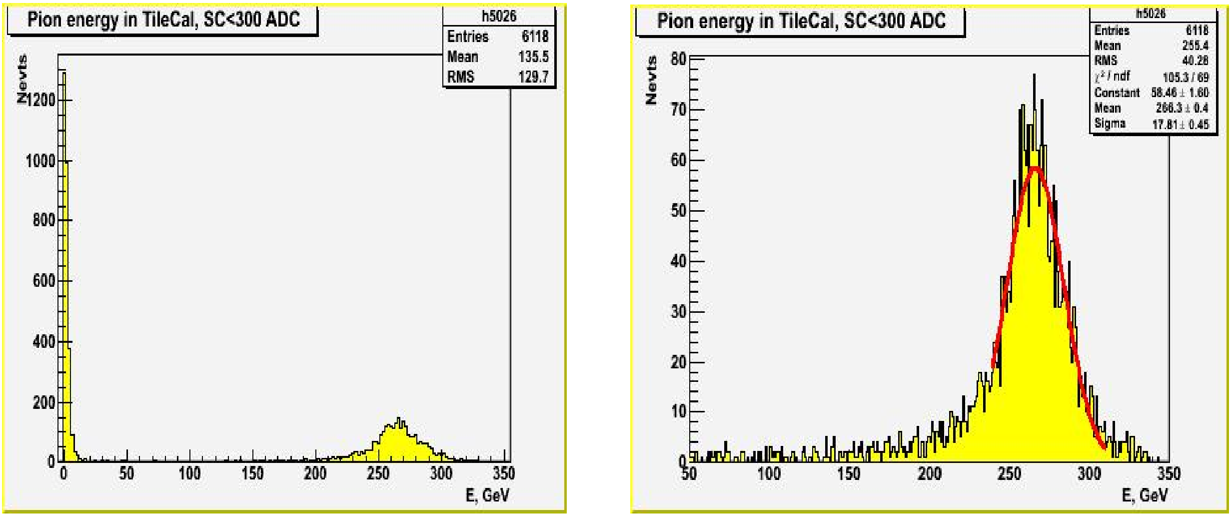

Fig. 9. Example of the pion energy distribution for π- mesons beams at energy of 320 GeV after applying two cuts SC < 300 ADC and : LAr energy topo cluster cut ($E \leq 0.8$ GeV).

The energy reconstruction for π- mesons beams at energy 320 GeV is presented on Fig. 10 after applying cuts: LAr energy topo cluster cut, cl_ecluster_topo ≥ 10 GeVcut, cuts on the beam scintillators (S1,SMH,S1,S2,S3,SC,SM); cuts on beam chambers (BC-1, BC0, BC1, BC2).

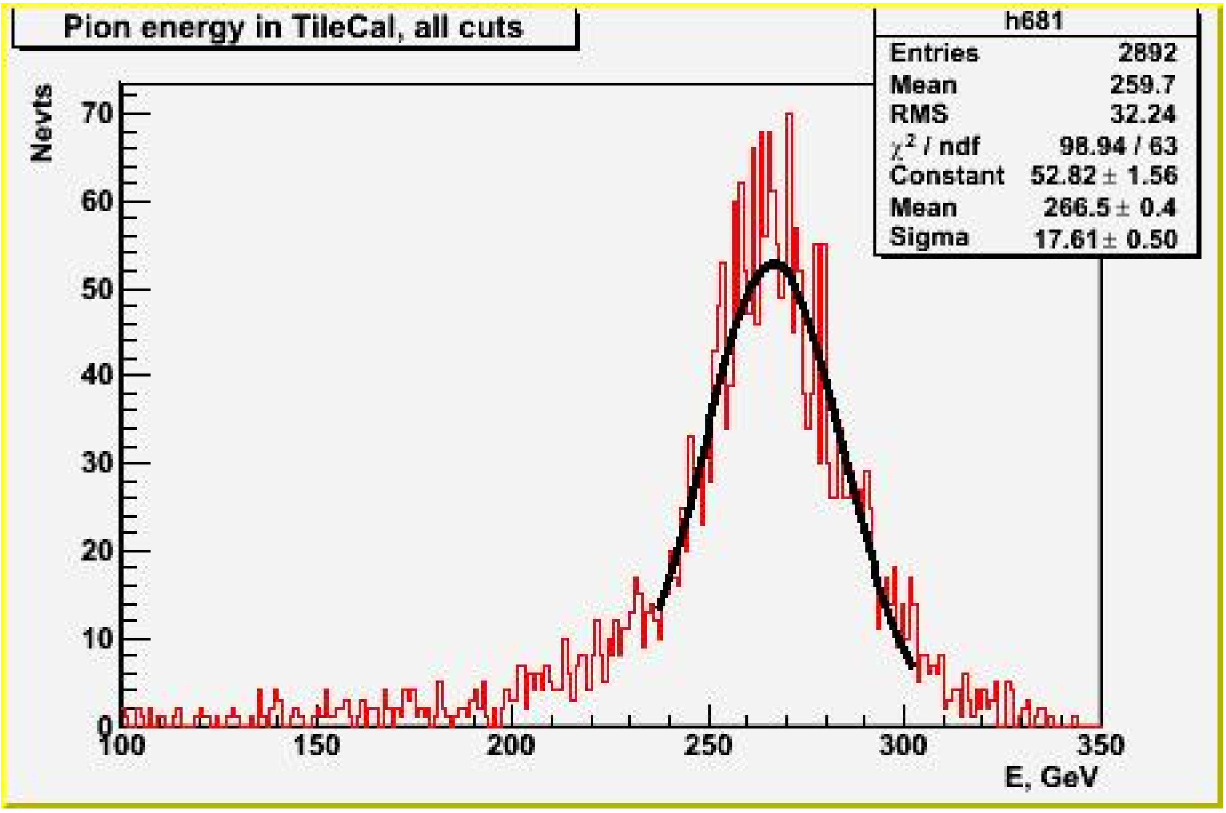

Fig.10. Example of the pion energy distribution and the for π- mesons beams at energy of 320 GeV after applying all cuts.

Energy resolution

The resolution is given by the measured spread of the energy divided by the energy (σ/μ). The energy distributions after applying all above mentioned cuts were fitted with a Gaussian, ± 2σ from the mean, and the resolution was calculated for each energy. The resolutions were fitted as a function of energy to the standard expression:

$$\sigma/E = a/\sqrt{E} \oplus b \qquad (1)$$

where a represents the statistical fluctuation in the shower development, b is a constant term which Is dominated by the different response to em and hadronis shower components, but also reflects uncertainties in the energy measurement due to mis-calibration, cracks, longitudinal leakage, etc.

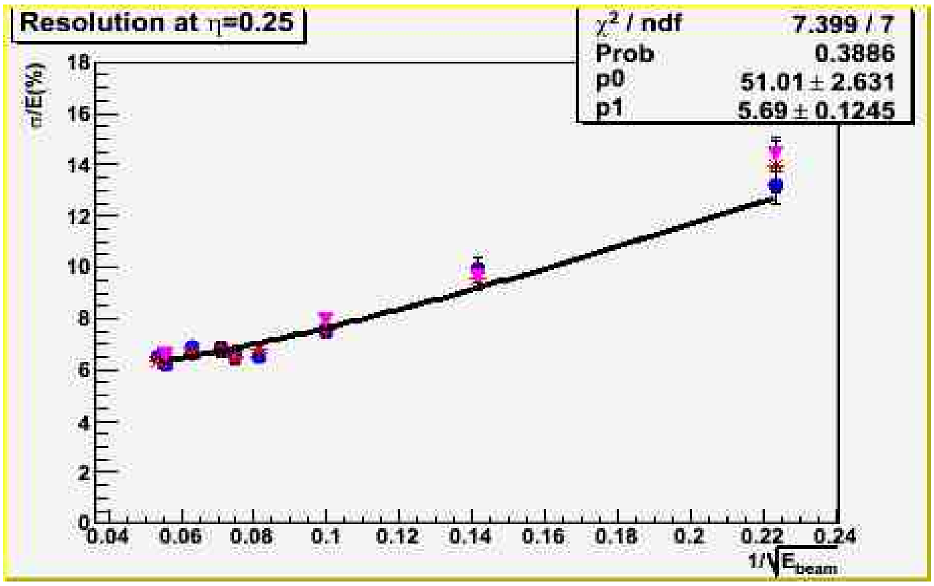

Fig.11. Energy resolution by topo clusters. On fig are presented results for topological clustering method. rings – data produced by Athena release 11.0.41, stars - data produced by Athena release 12.0.5 and triangles - 12.0.5v6,v7

The energy resolutions obtained are:

1. $\sigma/E = 50.4\%/\sqrt{E}$ [GeV] $\oplus$ 5.8% Topological clustering method – Athena release 11.0.41
2. $\sigma/E = 51.0\%/\sqrt{E}$ [GeV] $\oplus$ 5.7% Topological clustering method - Athena release 12.0.5

3. $\sigma/E = 53.5\%/\sqrt{E}$ [GeV] $\oplus$ 6.1% TileCal samplings – Athena release 11.0.41

4. $\sigma/E = 52.3\%/\sqrt{E}$ [GeV] $\oplus$ 6.0% TileCal samplings – Athena release 12.0.5
5. $\sigma/E = 52.9\%/\sqrt{E}$[GeV] $\oplus$ 5.9% TileCal cells – Athena release 11.0.41

The obtained values of reconstructed energy and resolutions for π- mesons beams at energies of 20 ÷ 350 GeV at η=0.25 obtained by means of above mentioned 3 different ways (as the sum of the energy in all Tile barrel samplings, as the sum of energy deposited in TileCal cells and using topological clusters) coincide, are generally good, is reasonable agreement between them and with older values [7]. In [7] ATL-TILECAL-PUB-2005-008 (V.Giangiobbe, P.Johansson, K.Jon-And, C.Santoni) it have been obtained for energy resolution at η=0.25 $\sigma/E = 51.2\%/\sqrt{E}$ [GeV] $\oplus$ 5.8%, which coincides with our results.

The Tile calorimeter is a non-compensating calorimeter which means that the response, h, to the deposited hadronic energy is lower than the response, *e*, for an electromagnetic shower (*e/h* >1). A hadron penetrating into a calorimeter will produce a shower with both a hadronic and an electromagnetic component. The electromagnetic part of the shower comes from π^0 production, which increases slowly with the incident hadron energy. From this point of view it is important to study the linearity E_{rec} / E_{beam} of the calorimeters. The event selection was the same as for the resolution.

The dependence of the linearity (obtained by topo clusters) on the beam energy is presented on Fig.29

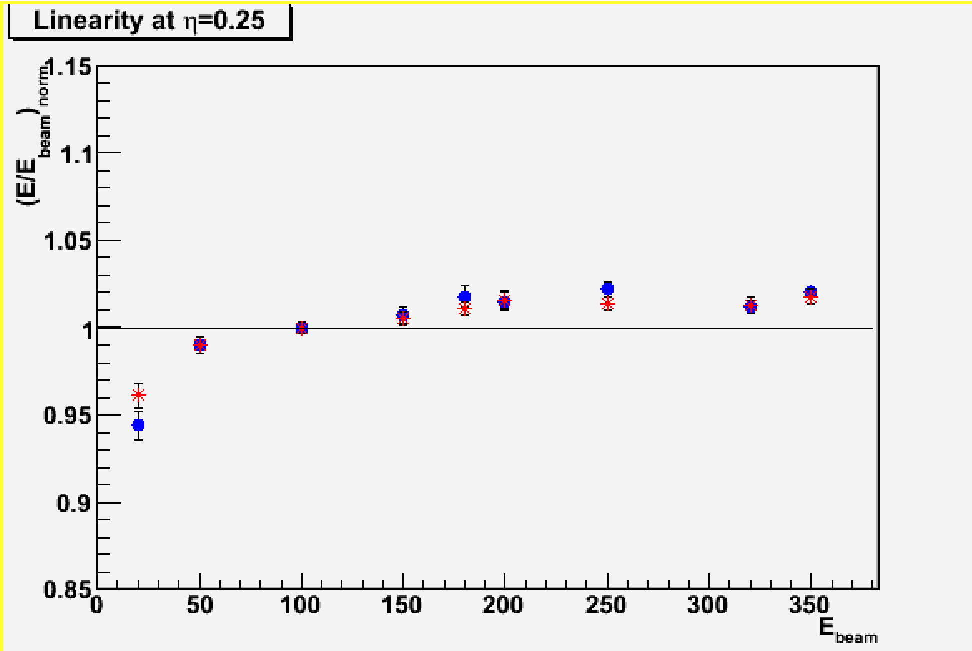

Fig. 12. The dependence of the linearity E_{rec} / E_{beam} on beam energy obtained by topological clustering method: rings – data produced by Athena release 11.0.41 and stars - data produced by Athena release 12.0.5

The obtained value of pion linearity for all 3 issues are generally good, is reasonable good agreement between them and between prototypes and CTB2004 in "standalone mode".

EM calibration constants versus pseudorapidity

However, in the ATLAS detector, an electromagnetic liquid argon (LAr) calorimeter is placed in front of TileCal. The LAr calorimeter will absorb most of the EM showers, while TileCal measures mainly hadronic showers.

If a 100 GeV particle crosses 45 cm of the Tile calorimeter from the front face it corresponds to 18 radiation lengths or 2.2 nuclear interaction lengths. The amount of the deposited energy is equal to 95% for the electromagnetic shower and only 50% for the hadronic shower [8].

In a calorimeter only some part of hadron shower energy is responsible for the formation of calorimeter response. This is the energy deposited in the sensitive parts of calorimeter cells. We will also call it a visible energy or energy in the electromagnetic scale (EM-scale). The response of calorimeter modules to electron beams is defined as the ratio of the charge collected in analyzed cells of the calorimeter module to the electron beam energy. The TileCal EM scale constants are obtained from an analysis of the TileCal response to electron test beams with energies of electrons 20, 50, 100 and 180 GeV impinging the cells in the first sampling of TileCal modules at the angle $\theta = \pm 20^0$. The mean value of the EM scale constant is 1.050 ± 0.003 pC/GeV and RMS=(2.4± 0.1)%.

The obtained calibration constants have been included in the TileCal calibration database and will be used for the energy calibration of the ATLAS Tile hadronic calorimeter.

As particles enter calorimeter modules under all possible angles, the dependence of EM scale calibration constant on θ was studied.

The following sources of data were used: real data from 20 GeV TileCal electron runs and Monte Carlo (MC) simulation of 20 GeV electrons, 20, 50, 100, 180 GeV pion runs in GEANT 4.8.3 QGSP+Bertini (including the new scattering model). The covered range of θ is $0 - 90^0$ for simulation and 3 - 90^0 for data. We have analyzed the ntuples produced for Monte Carlo TileCal standalone simulation (3 barrel modules). For the simulation and digitization Athena 13.0.30 release was used. In the digitization step of MC simulation the Calibration Hits algorithm was used. Details of single pion simulation in ATLAS are: Geant 4.83 and Physics List – QGSP_BERT. The ntuples have been produced for electrons $\eta = 0.0 \div 0.65$ ($\theta = 0 \div 46$ deg), the step $\Delta\eta = 0.01$ and for pions at $\eta = 0.0 \div 0.48$ ($\theta = 0 \div 27$ deg), the step $\Delta\eta = 0.02$. Number of MC events at each η point is 5000 events.

We used Geant4 based MC simulation with Calibration Hits to calculate TSF. TSF is the average ratio of total deposited energy in the cells over the energy deposited in scintillators [9]

$$TSF = E^{vis}_{cells} / E^{vis}_{scint} \qquad (2)$$

where, E^{vis}_{cells} - energy deposited in TileCall cells, E^{vis}_{scint} - energy deposited only in sensitive parts of cells (scintillators). Calibration Hits give a direct access to different components of total energy loss in the TileCal cells: E_{EM} – electromagnetic (chit_em variable in the ntuples), E_{NonEM} - non-electromagnetic (chit_nonem variable in the ntuples). Both together are a visible energy $E^{vis} = E_{EM} + E_{NonEM}$.

We calculated also 1/TSF:

$$1/TSF = E^{vis}_{scint} / E^{vis}_{cells} \qquad (3)$$

From the plots of TSF versus Z impact point (mm) we have get profile histograms and these profile distributions have been described by the formula:

$$TSF = TSF_{mean} + A_{TSF} \cdot \sin(kz + \varphi) \qquad (4)$$

where A_{TSF} is the variation of amplitude of energy deposited in scintillators; $k = 2\pi/\text{period}$ [mm^{-1}], φ – phase.

Fig. 13 shows an example of local 1/TSF variation as a function of Z –impact point fitted with the formula (4)

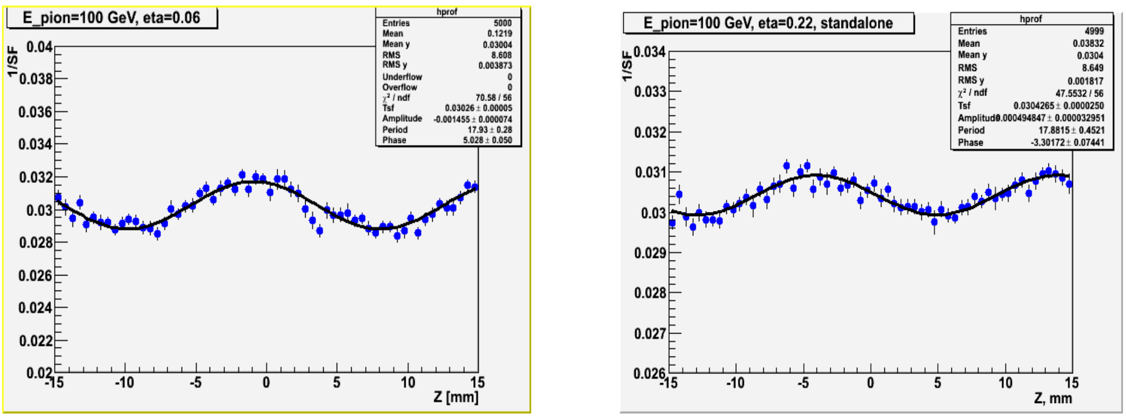

Fig.13. 1/Sampling Fraction versus Z of 100 GeV pions at at $\eta = 0.06$ and $\eta = 0.22$

Fig.14 represents the dependence of EM calibration constants on θ with 20 GeV electron runs. Various TileCal experimental data (open squares) and GEANT 4.8.3 QGSP+Bertini (small black full circles) and GEANT 4.8.0 QGSP_GN with 1 mm Range Cut (large blue full circles) simulation results are shown. The EM scale calibration increases with the incident angle θ in the range of 10% between $\theta = 0^0$ and $\theta = 90^0$. The ratio signals measured at $\theta = 90^0$ and $\theta = 20^0$ is 1.06 in experimental data, while in the simulation it is 1.02. The higher value of this ratio observed in the data can be qualitatively explained by the fact, that the response of tile center, hit by beams at θ =

90^0, is 3.5 % higher then the tile response averaged over its surface. In the case of runs with $\theta < 90^0$ the beam hits are distributed over a large area of tile surface, so a decrease of the signal response with respect to the $\theta = 90^0$ beams is expected. The tile non-uniformity is not simulated in Monte-Carlo.

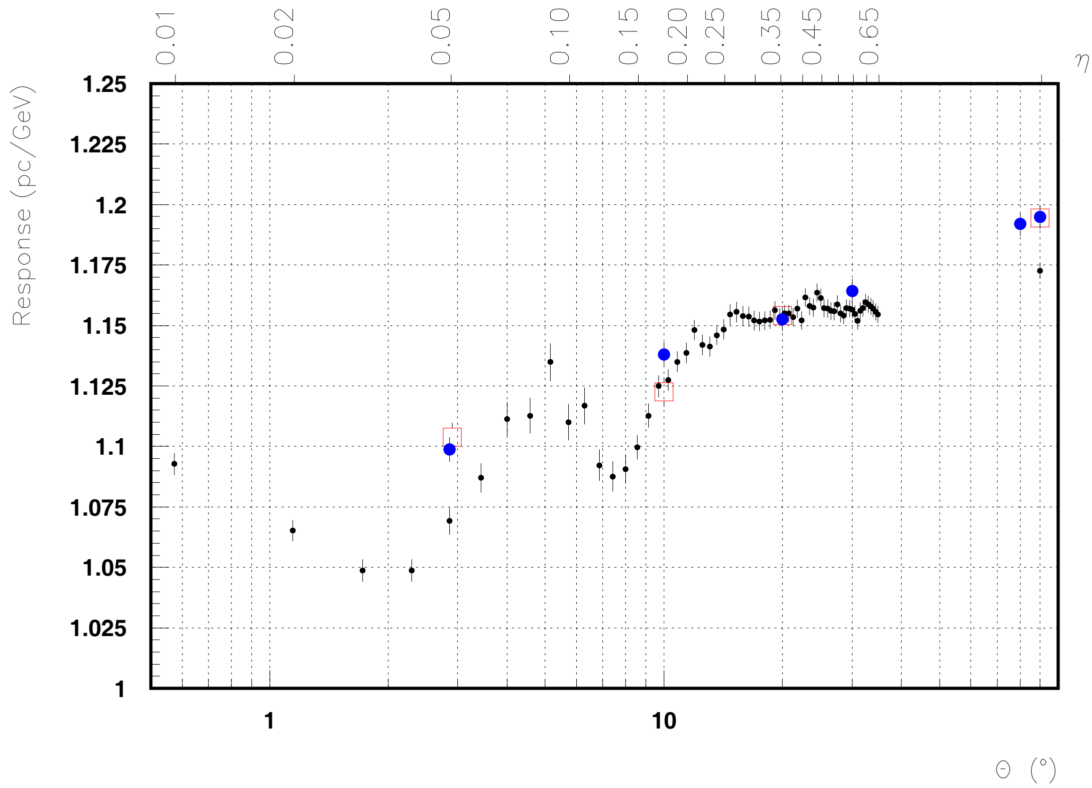

Fig.14. The dependence of EM calibration constants on θ with 20 GeV electron runs. Various TileCal experimental data (open squares), GEANT 4.8.3 QGSP+Bertini (small black full circles) and GEANT 4.8.0 QGSP_GN with 1 mm Range Cut (large blue full circles) simulation results are presented.

The angular dependence of TileCal response to hadronic showers was also studied for pions. Fig. 15 presents dependence of response on Θ for MC simulation pions at 180 GeV.

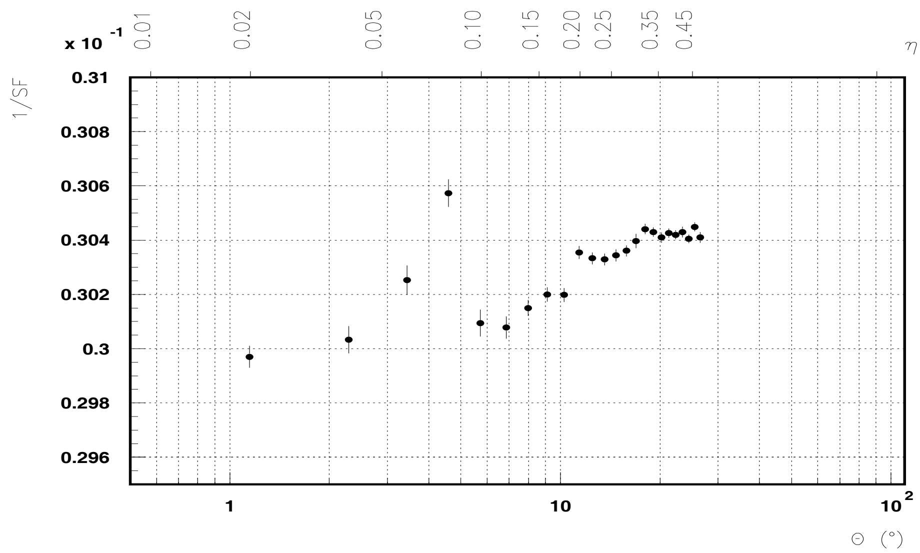

Fig.15. Example of the TileCal response to 180 GeV pions (GEANT 4.8.3 QGSP+Bertini simulation results) as a function of θ and pseudorapidity.

MC simulation predicts a small angular dependence of the response. For pseudorapidities $\eta >$ 0.2 the response changes by less than 0.5 %.

We conclude that the angular EM scale dependence in TileCal can be neglected in the ATLAS setup.

Conclusions

The pion energy reconstruction by the 3 different methods is performed. The energy was defined as: the sum of energy deposited in TileCal barrel samplings; as the sum of energy deposited in TileCal cells with E^{Tile} cell > 50 MeV and as the sum of energy deposited in TileCal using topological clustering algorithm. The obtained values of reconstructed energies, resolutions and linearities for π- mesons beams at energies of 20 ÷ 350 GeV at $\eta=0.25$ for all 3 issues are generally good, is reasonable agreement between them and between prototypes and CTB2004 in "standalone mode**"**.

Electron response in TileCal showed that an electron response fluctuation strongly depends on pseudo-rapidity. Reasonable agreement between our MC results with CTB2004 experimental data and MC simulation G4.7.0 is observed

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