A Layer Correlation Technique for Pion Energy Calibration at the 2004 ATLAS Combined Beam Test

Karl-Johan Grahn

Physics Department, Royal Institute of Technology (KTH), Stockholm, Sweden

on behalf of

The ATLAS Liquid Argon Calorimeter Group

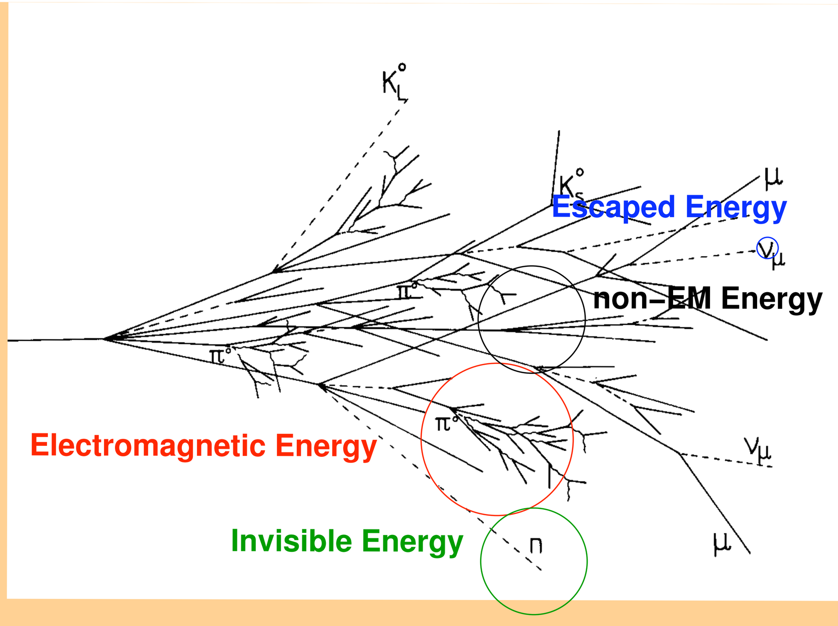
KTH Engineering Sciences

A new method for calibrating the hadron response of a segmented calorimeter is developed and applied to beam test data. It is based on a principal component analysis of the calorimeter layer energy depositions, exploiting longitudinal shower development information to improve the measured energy resolution. The calibration corrections were calculated with simulated Geant4 Monte Carlo events and used to reconstruct the energy of pions impinging on the ATLAS calorimeters during the 2004 Barrel Combined Beam Test at the CERN H8 area. For pion beams with energies between 20 and 180 GeV, the particle energy is reconstructed within 3% and the energy resolution is improved by about 20% compared to the response at the electromagnetic scale.

Hadronic calorimetry

In general, the response of a calorimeter to hadrons will be lower than for particles which only interact electromagnetically, such as electrons and photons. This is due to energy lost in the hadronic shower in forms not measurable as an ionization signal, i.e. nuclear break-up, spallation, and excitation, energy deposits arriving out of the sensitive time window (such as delayed photons), soft neutrons, and particles escaping the detector. The average relative size of the electromagnetic shower component increases with energy, giving rise to a non-linear calorimeter response. Moreover, hadronic showers are characterized by large event-by-event fluctuations, degrading the measured energy resolution.

Longitudinal information on the development of the shower should be sensitive to the size of its hadronic content.

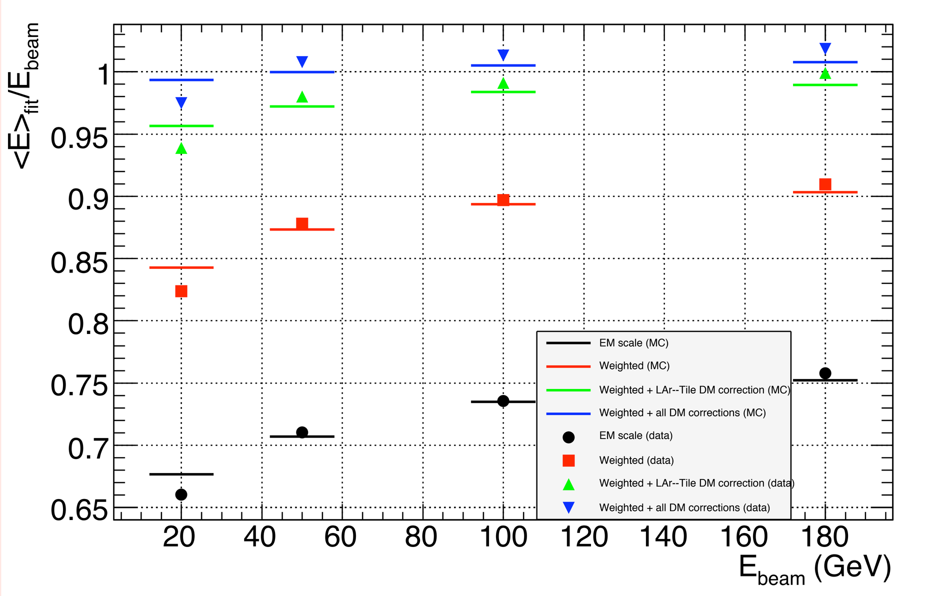


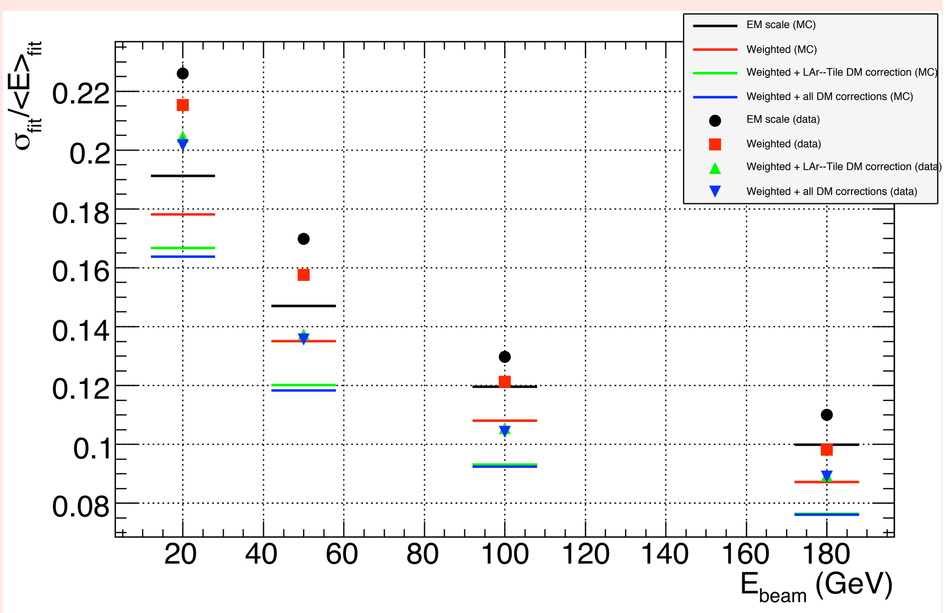
Results

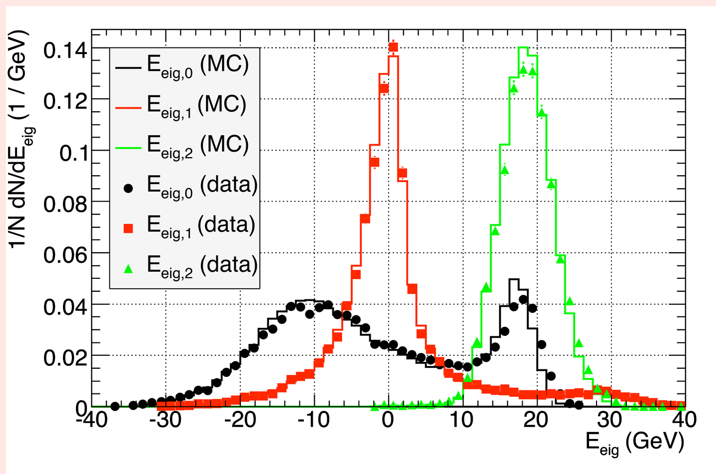
The linearity and relative resolution are shown in the two plots to the right (2-sigma Gaussian fit). After all corrections, the linearity is recovered within 2% for beam energies above 50 GeV (3% for 20 GeV). The relative resolution improvement in data (simulation) is about 17% to 22% (17% to 29%). The relative resolution is smaller in Monte Carlo simulation than in data: the discrepancies, at each correction stage, vary between 6% and 24% depending on the energy. However, the ratio of data to Monte Carlo simulation is unchanged within 1% (7%) for linearity (resolution) after the corrections are applied.

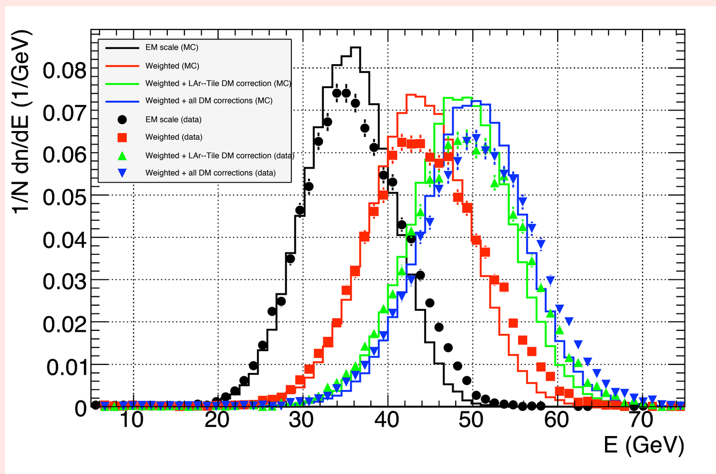
The left plot below shows the distribution of the first three eigenvector components for data and Monte Carlo simulation, with a beam of 50 GeV pions. Good agreement is obtained between data and simulation.

The shapes of the energy distributions for data and Monte Carlo simulation for 50 GeV pions are compared in the right plot below. The distribution in the Monte Carlo simulation is narrower and less skewed than in the data. This is seen already at the electromagnetic scale. The effect is even larger at 20 GeV but less pronounced at higher energies.









Method

The calibration consists of compensation weights and dead material corrections. The latter (see below) have an inherent dependence on the beam energy. This dependence is removed by employing an iteration scheme, where at each step the final estimated energy of the former step is used, until the returned value is stable.

All corrections are extracted from a Geant4.7 Monte Carlo simulation, which gives access to both the true deposited energy in the detector material and a simulation of the signal read out from the calorimeters. The latter is calibrated at the electromagnetic scale, i.e. giving the correct deposited energy for electrons and photons. Corrections are calculated using a Monte Carlo sample containing a scan of pion energies, from 15 to 230 GeV.

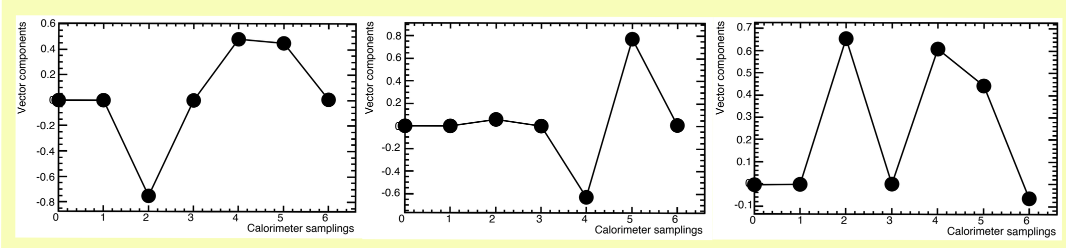
Eigenvectors of the covariance matrix

The covariance matrix between reconstructed energies in the seven calorimeter layers (four in LAr and three in Tile) is calculated as

$$\mathrm{Cov}(M,L) = \langle E_M^{\mathrm{rec}} E_L^{\mathrm{rec}} \rangle - \langle E_M^{\mathrm{rec}} \rangle \langle E_L^{\mathrm{rec}} \rangle .$$

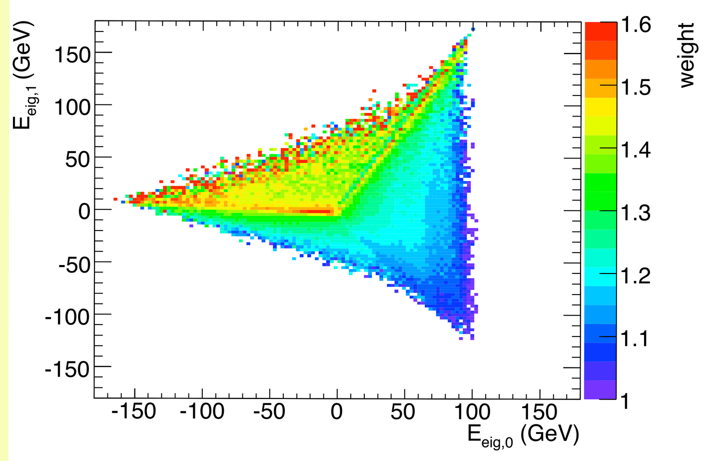
The coordinates representing an event in the seven-dimensional vector space of calorimeter layer energy deposits can now be expressed in a new basis of eigenvectors of the covariance matrix. The projections along the first few eigenvectors contain most of the event-by-event fluctuations and are used as input to the calibration.

The plots below show the first three eigenvectors of the covariance matrix in the basis of the original calorimeter layers. The first one is essentially a difference between the Tile and LAr calorimeters, the second one a difference within the Tile calorimeter and the third one a sum of both calorimeters. The rest of the eigenvectors contain individual calorimeter layers.



Compensation weights

The compensation weights account for the non-compensation of the calorimeters. They are two-dimensional 128x128-bin lookup tables and are functions of the projections along the first two eigenvectors. Bi-linear interpolation is performed between the bins.



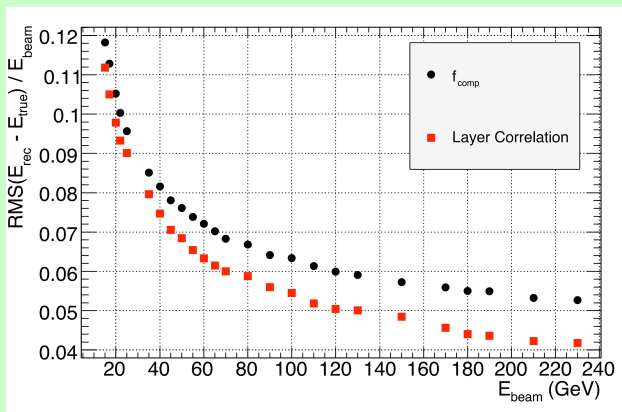
There is one weight table for each calorimeter layer, three for LAr and three for Tile. Shown above is the one for the first Tile layer. The LAr presampler is not weighted. The total reconstructed energy is the sum of the weighted energies in each calorimeter layer.

$$E_L^{\mathrm{weighted}} = w_L E_L^{\mathrm{rec}}$$
$$E_{\mathrm{tot}}^{\mathrm{weighted}} = \sum_L E_L^{\mathrm{weighted}}$$

Method validation

Compensation

The calibration is here applied to a sample statistically independent of the one used for extracting the compensation weights and dead material corrections.



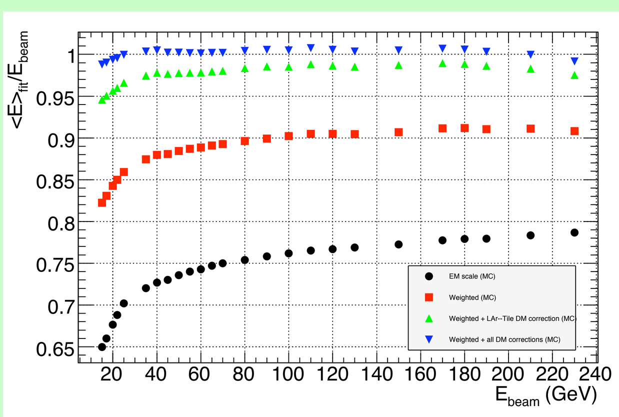
The reconstructed energy after applying compensation weights is compared to the true total deposited energy as given by the Monte Carlo simulation. The event-by-event

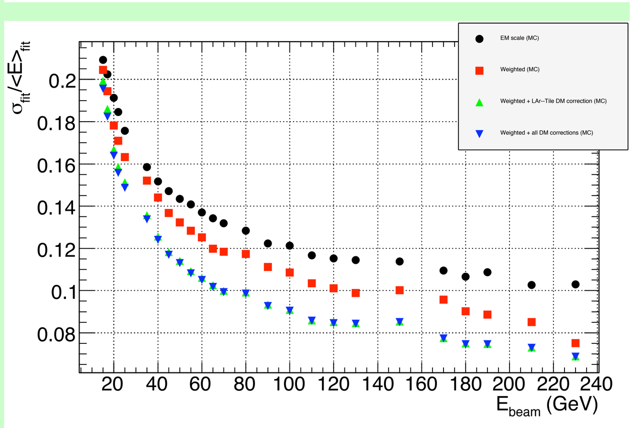
$$E_{\mathrm{tot}}^{\mathrm{weighted}} - E_{\mathrm{tot}}^{\mathrm{true}}(\mathrm{calo})$$

difference is considered. The bias in the energy reconstruction is defined as the average value of this difference and the resolution is obtained by calculating its standard deviation. The performance of the layer correlation technique is compared to a simple calibration scheme where each event in the sample is weighted with a single factor (f_{comp}) calculated to give the total deposited energy back on average for each beam energy.

Linearity and resolution

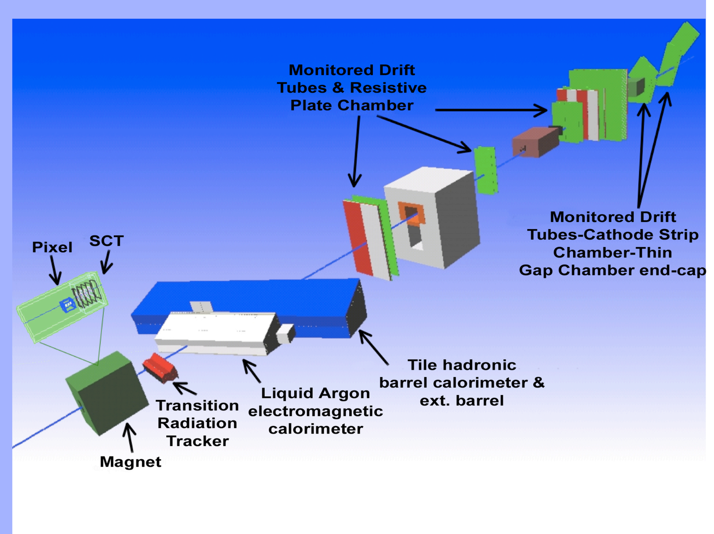
The performance for the fully corrected energy reconstruction is assessed in terms of linearity with respect to the beam energy and relative resolution (2-sigma Gaussian fit). Linearity and resolution are shown after successively applying the corrections. Linearity goes from a strongly non-linear response at the electromagnetic scale, to a flat response within 1% with all corrections applied. The compensation weights give a better improvement of the linearity at high energies, while the dead material effects play a more significant role at low energies. At high beam energies (above 100 GeV) the contribution of the compensation weights to the improvement in energy resolution has the same magnitude as that of the LAr–Tile dead material corrections, while at lower beam energies dead material corrections dominate.





ATLAS Combined Beam Test

ATLAS is one of the general-purpose physics experiments at the CERN Large Hadron Collider (LHC). Physics goals include searching for the Higgs boson and looking for phenomena beyond the standard model of particle physics, such as supersymmetry.



In the central barrel region, the ATLAS calorimeters consist of the lead–liquid argon (LAr) electromagnetic calorimeter and the steel–scintillator Tile hadronic calorimeter. Both are intrinsically non-compensating, meaning they have a non-linear response for hadronically interacting particles.

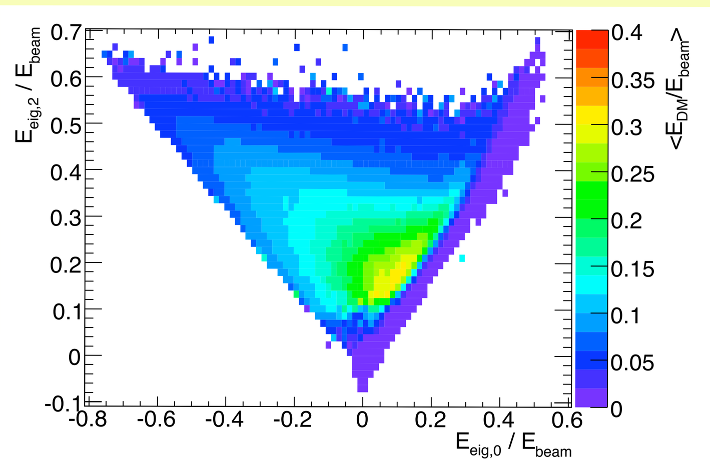
The 2004 Combined Beam Test included a full slice of the ATLAS Barrel region, including the inner tracker with the pixel detector, the silicon strip semiconductor tracker (SCT), the transition radiation tracker (TRT), the liquid argon and Tile calorimeters and the muon tracker. In addition, special beam-line detectors were installed to monitor the beam position and reject background events. Those include beam chambers monitoring the beam position and trigger scintillators.

Events are selected by requiring signals in a trigger scintillator, beam chambers and the inner detector compatible with one particle passing close to the nominal beam line. The TRT is used to reject positrons by making a cut on the detected transition radiation.

The proton contamination of the beam must be taken into account, since the calorimeter response for pions and protons is different. The fraction of protons in the beam was measured using the differing probabilities of pions and protons to emit transition radiation in the TRT. It ranges from 0% at beam energy of 20 GeV to 76% at 180 GeV.

Dead material

Dead material corresponds to parts of the experiment where there is no calorimeter read-out. This is mainly the back LAr cryostat wall. There pion showers are often fully developed, giving rise to large energy loss.



Projections along the first and third eigenvectors are used. In the lookup-table both the eigenvector projections and the dead material losses themselves are scaled with the true beam energy. Just as for the compensation weights, the tables are two-dimensional with 128x128 bins.

In addition, there is also dead material before the LAr calorimeter (e.g. the inner detector) and leakage beyond the Tile calorimeter. These losses are small in comparison (a few GeVs) and a simple parameterization as a function of beam energy was used.