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Comparison of Monte Carlo simulations based on Geant4 and Fluka to the TileCal test beam data

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Summary. — We present a study of the signal produced by charged pions of energies ranging between 20 and 350 GeV in modules of ATLAS Tile Calorimeter. The results from test beam data are compared to the predictions of different Monte Carlo simulations (Geant4 and Fluka). The goal is to assess in a quantitative way how well different Monte Carlo codes can reproduce the distribution of visible energy in the calorimeter and the details of the hadronic shower.

PACS `24.10.Lx` – Monte Carlo simulations (including hadron and parton cascades and string breaking models).
PACS `29.40.Vj` – Calorimeters.

Monte Carlo simulation of detector hardware is increasingly important and many aspects of modern experiments demand a reliable software simulation.

This work was developed to validate the official simulation chosen by the ATLAS Collaboration (Geant4) against the data acquired during the test beam of ATLAS hadronic calorimeter and to compare Geant4 predictions to those of a completely different software simulation (the Fluka package).

1. – Experimental set-up

TileCal, the ATLAS Hadron Tile Calorimeter, is an iron-scintillator sampling calorimeter [1]. It is divided into one Barrel and two Extended Barrel cylindrical partitions. Each sections is formed by 64 modules, with each module in “pseudo-projective” towers (0.1×0.1 in $\Delta\eta \times \Delta\phi$) and in three longitudinal sections. This segmentation is obtained connecting groups of scintillating tiles to the same readout PMTs.

During the TileCal stand alone test beam a stack of several modules was exposed to beams of varying composition and energies ranging between 20 and 350 GeV.

The Module 0 reference prototype was placed at the bottom of the stack, the middle layer was a production barrel module and on the top there were two extended barrel modules (see fig. 1). Further details on the experimental set-up can be found in [2].

(*) For the TileCal Collaboration.

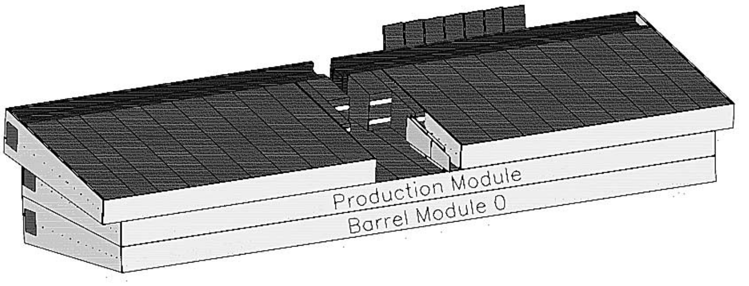

Fig. 1. – The TileCal stand alone test beam set-up.

On the beam line, upstream of the calorimeter, there was a threshold Cherenkov counter to assist particle identification, two wire chambers to monitor the beam position and divergence and three trigger scintillators.

Typically, the H8 beam is a mixture of hadrons, muons and electrons. A small muon contamination is present in the particle beam at all energy points. Since muons pass through TileCal without being stopped we identify them by requiring the energy measured in the calorimeter to be lower than a threshold.

To identify electrons in the beam we use the Cherenkov counter at low energy. For energies larger than 20 GeV we use a combination of two adimensional variables to separate electrons from hadrons:

$$C_{\text{long}} = \sum_{c \in \text{ sample } 1,2} \frac{E_c}{E_{\text{beam}}}\,, \qquad C_{\text{tot}} = \frac{1}{\left(\sum_c E_c^{\alpha}\right)} \sqrt{\sum_c \frac{\left(E_c^{\alpha} - \sum_c E_c^{\alpha}/N_{\text{cell}}\right)^2}{N_{\text{cell}}}}\,.$$

C_{long} is the fraction of energy released in the first two samples of TileCal and C_{tot} is related to the size of the shower in the detector.

The distribution in the C_{long}-C_{tot} plane is projected on the axis of maximum separation C_2 [3].

The bias induced by the calorimetric selection is estimated by Monte Carlo simulations and a correction is applied on data.

Table I summarizes the beam composition at all the energy points. Electrons are rejected using the Cherenkov counter at 20 GeV while a calorimetric selection is used at 50 and 100 GeV. At 50 GeV protons are separated from pions using the Cherenkov detector, for the 100 and 180 GeV beams the expected proton fraction of the beam has been taken from [4], a 10% uncertainty is assumed on these figures to take systematic effects into account. The 20 and 350 GeV beams have negative polarity and the antiproton contamination is negligible.

Table I. – *Summary of the beam composition after selection at each energy point.*

Nominal Energy	20 GeV	50 GeV	100 GeV	180 GeV	350 GeV
e^+ or e^-	$3 \pm 1\%$	$0.28 \pm 0.10\%$	$0.07 \pm 0.05\%$	$< 0.1\%$	$< 0.1\%$
(anti)proton	$< 0.1\%$	$5 \pm 2\%$	$64 \pm 10\%$	$74 \pm 10\%$	$< 0.1\%$

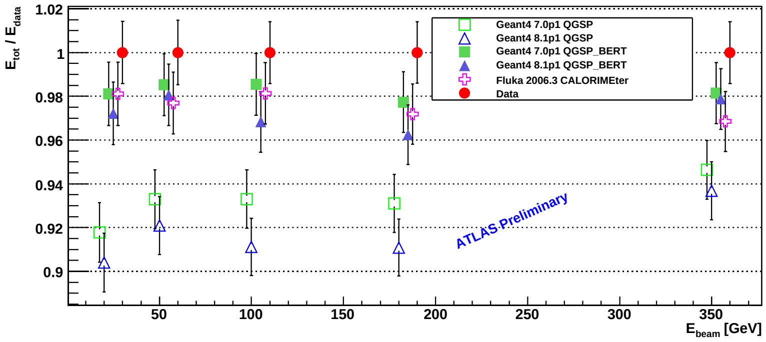

Fig. 2. – Visible energy in TileCal.

2. – The Monte Carlo simulations

For Geant4 we tested the releases `Geant4-07-p01` and `Geant4-08-01-p01`, we also used two different physics lists: `QGSP` and `QGSP_BERT` [5]. The version of Fluka used in the test is `Fluka-2006.3` with the `CALORIMEter` configuration card [6, 7]. In all cases Birk's law was enabled.

The beam is simulated reproducing the characteristics of the real beam profile. The primary particle and the generated secondaries are tracked through the detector.

In Geant4 the details of the processes simulated are described in the physics list. `QGSP` (that uses the Quark-Gluon String model for hadronic interactions) and `QGSP_BERT` (like `QGSP`, but uses the Bertini Intra-Nuclear Cascade below 10 GeV).

Fluka hadronic interactions are based on resonance production and decay below a few GeV, and on the Dual Parton model above. Both modules include a form of Generalized Intra-Nuclear Cascade.

Geant4 and Fluka simulations share the same geometry description (through the FLUGG interface for Fluka), and the output of Fluka is produced with a similar format as for Geant4, so that the same digitization code is used for both simulations.

3. – Validation results

The electromagnetic scale for the Monte Carlo simulations is set using a sample of 20 GeV electrons. Fiducial volume is ±0.15 in ϕ (the 3 layers of the stack) and ±0.35 in η around the beam direction (from $\eta = -0.7$ to $\eta = 0$). The exact beam composition is reproduced in the Monte Carlo samples.

Figure 2 shows the ratio between experimental data and the Monte Carlo prediction for the mean value of the energy released in TileCal by the hadron beam. The mean is extracted with a 2 sigma Gaussian fit of the energy distribution. Both Geant4 with the `QGSP_BERT` physics list and Fluka are compatible with the measurements.

In fig. 3 we compare against the experimental measurement the simulations prediction for the fraction of the total energy released in each longitudinal sample of the Tile calorimeter. The first section (S1), of about 1.4 interaction length, samples the beginning of the shower development; the second (S2) is the longest section (4λ) and contains the bulk of the hadronic shower; the last sample (S3, 2λ) measures the energy in the tail of the shower.

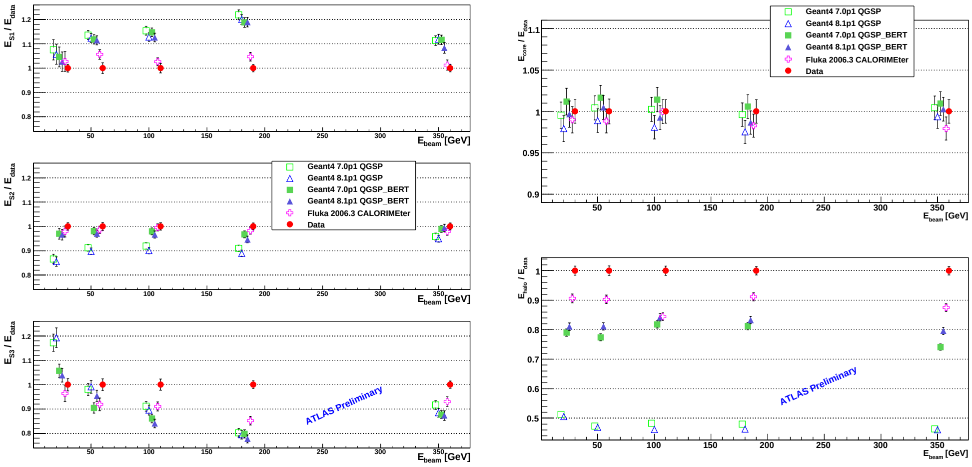

Fig. 3. – Ratio of simulation prediction over data for the energy released in the three longitudinal sections of TileCal (left) and in the volumes containing the core and halo of the hadronic shower (right).

Both Geant4 `QGSP_BERT` and Fluka reproduce the bulk of the energy release in the second section; the showers produced by Geant4 starts too early, releasing more energy than expected in the first section. For energies larger than 50 GeV the predicted energy release in the last section is always lower than observed.

To investigate the lateral profile of the hadronic shower in TileCal we define two variables, E_{core} is the energy released in the projective tower hit by the beam (0.1×0.1 in $\Delta\eta \times \Delta\phi$) and E_{halo} the energy in the volume around that tower.

The ratio between data and Monte Carlo prediction for these variables is shown in fig. 3, the energy released in the core of the shower is well described by all simulations while the energy in the halo is always underestimated, with Geant4 `QGSP` being the worst (50% below the experimental data) and Fluka being the closer to the data (about 10% below).

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