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Validation of Geant4 and Fluka Hadronic Physics with Pixel Test-Beam Data

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Abstract

In this note we present an update of the validation of Geant4 hadronic physics against the ATLAS pixel 2001 test-beam data. Furthermore, we also report the comparison with Fluka simulation, using the same Geant4 geometry, navigation and digitization.

1 Introduction

Hadronic physics is notoriously a very broad and difficult field, mainly because the underlying theory, Quantum Chromodynamics (QCD), cannot produce predictions for observables whose dominant energy range is outside the perturbative high-energy regime. The only current viable approach, in these cases, is to use approximated models, whose validity is often restricted to particular incident particles, target material types, and interaction energies. By using a proper set of these models it is often possible to cover different regions of interest.
In Geant4 [1] a large set of hadronic models are available, and the user can choose and combine them according to her/his needs, in terms of application, precision, and computing time. To ease such a choice, a certain number of "educated guess" Physics Lists, each being a complete and consistent collection of different models, are provided according to use cases. The goal of this note is to report about tests of some of these Geant4 Physics Lists (LHEP, QGSC, QGSP: see [2] for more information) and of Fluka [3] using a pixel tracker apparatus, which provides complementary information with respect to the more traditional calorimeter test-beam data. In the latter case, in fact, the observables are the convolution of many complex processes and interactions, whereas in the former case one can study single hadronic interactions in a clean and simple environment.

The ATLAS pixel test-beam we are considering was done in August 2001, and we refer to [4] for all the details of the setup and the analysis. Below we will provide a summary of the main steps.

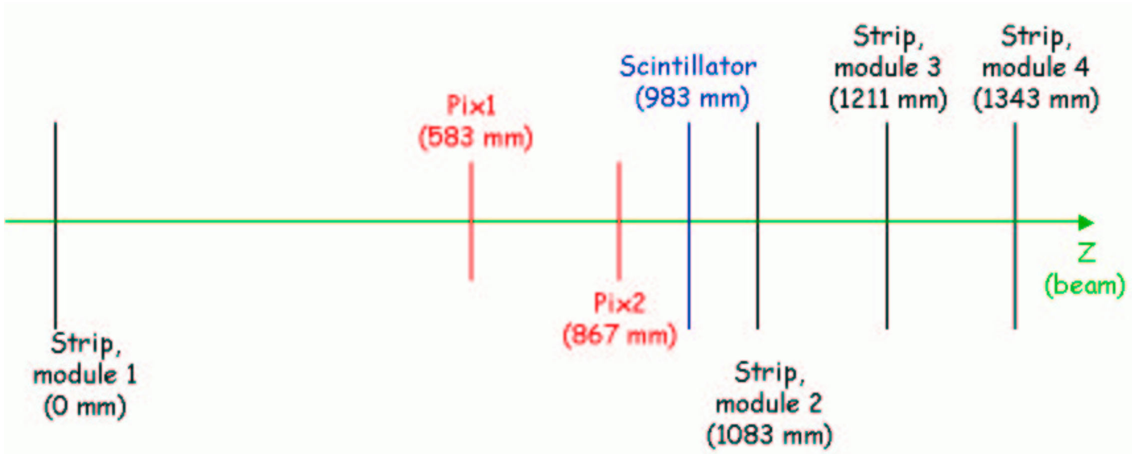

Figure 1: Pixel test-beam setup.

2 Pixel test-beam setup and analysis

A test-beam with $180\,GeV/c$ positive pions on silicon sensors of the ATLAS Pixel tracker detector has been made at CERN in 2001 [4] [5]. The setup is presented in Figure 1. It consists of a telescope of four microstrip planes (each double sided), two pixel detector planes (to test two different chips), and a scintillator counter. The microstrip planes have a pitch of $50\,\mu m$ in both sides, and a thickness of $300\,\mu m$. The pixel detectors have $50\,\mu m$ pitch in one dimension, $400\,\mu m$ in the other, and a thickness of $280\,\mu m$. Figure 2 shows a single pixel detector in detail, and an example of a simulated hadronic interaction happening in the sensor (as for the events we would like to select in order to study these interactions).

In a run dedicated to the study of hadronic interactions, the trigger required an energy deposition in the scintillator corresponding to at least three minimum-ionising particles. A total of about 800 000 interaction events were collected. Only those events in which at least three clusters have been reconstructed in each of the three downstream microstrip planes (in both sides) are further considered in the analysis. Before analysing the real data, a precise alignment of the telescope planes was performed using two beam trigger runs, taken just before and just after the interaction trigger run. Furthermore, the pixel detectors were individually calibrated, i.e. the energy deposited (in terms of the number of electron-hole pairs that have been created) was evaluated from the Time-over-Threshold read-out, using pulse injection and radioactive sources. It is important to note that this calibration procedure involves energy releases equivalent to about one minimum-ionising particle, whereas in the case of hadronic interactions the energy deposited can be equivalent to several hundred minimum-ionising particles. Therefore, in the study of hadronic interactions, we had to extrapolate the calibration into a region far away from where it was performed, which entails uncertainties on the absolute energy scale. Hence, only observables not

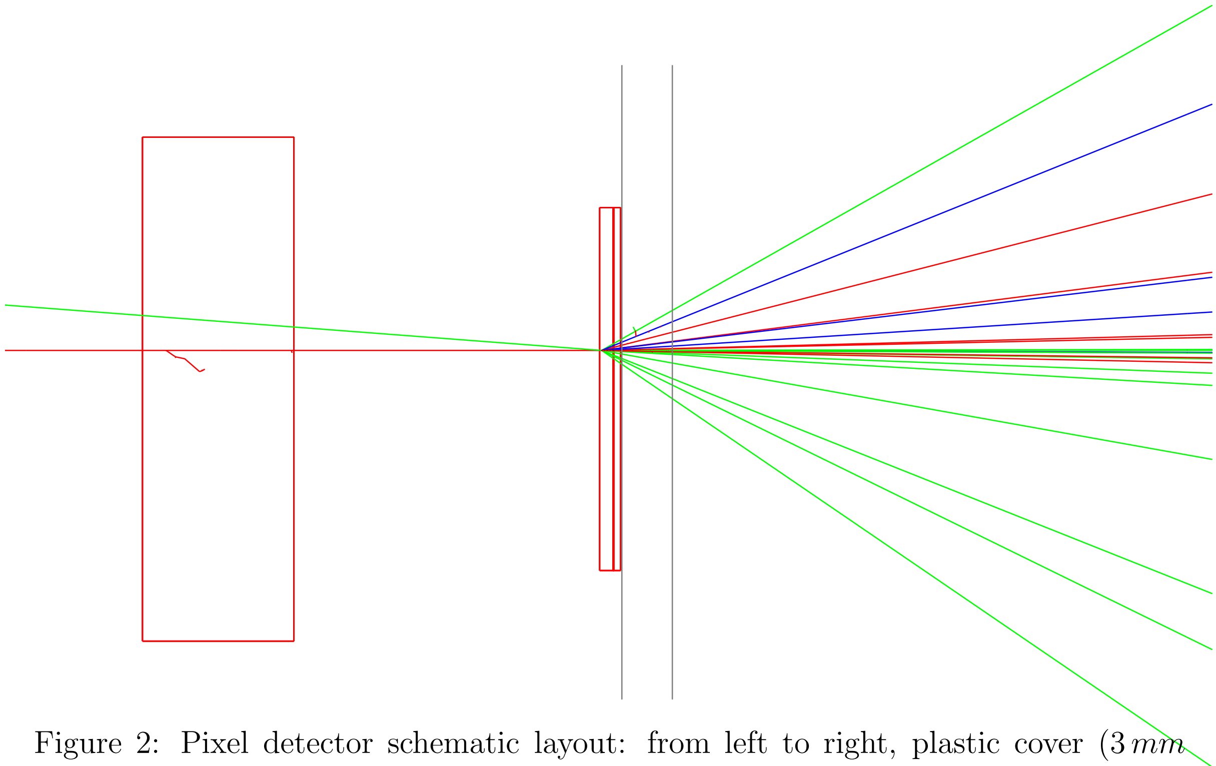

Figure 2: Pixel detector schematic layout: from left to right, plastic cover ($3\,mm$ thick), silicon sensor ($280\,\mu m$ thick), front end read-out chip ($150\,\mu m$ thick), printed circuit board ($1\,mm$ thick). A simulated hadronic interaction in the sensor is shown.

directly dependent on the absolute energy should be considered when comparing with simulation results.

The analysis procedure consists of four steps:

1. Tracks are reconstructed in the three microstrip planes downstream of the pixel planes.

2. The interaction vertex is reconstructed. A better vertex resolution is observed if the interaction happens in the second pixel plane, because of the larger geometrical acceptance, limited by the last downstream microstrip plane. Therefore only interactions in this plane are further considered.

3. The pixel cluster closest in the transverse plane to the interaction vertex is selected, and it is further considered only if it satisfies a requirement aimed at selecting only those interactions which happen in the pixel sensor, rather than in the plastic cover or the read-out chip or the printed circuit board (see Figure 2). A pixel cluster is defined as a contiguous set of pixels whose signal is above a given threshold (3500 electrons). The reconstructed vertex is required to be close enough ($\pm 4\,mm$) to the center of the pixel sensor, taking into account the vertex resolution (about $2\,mm$ in the Pixel2 plane) along the beam direction. A large energy deposition is required in the pixel detector, because for an inelastic nuclear interaction in the sensor we expect a large local energy deposit from

heavy nuclear fragments of very short range. More precisely, the "normalized cluster charge", Eloss/Ndig, i.e. the ratio between the total charge of the cluster and the number of pixels of that cluster must be greater than a certain threshold, which has been decided by selecting events happening in the plastic cover (by requiring that the reconstructed vertex is between $-15\,mm$ and $-5\,mm$ with respect to the center of the pixel sensor). As shown in Figure 3, the various simulations agree very well with each other, but not with the data: this is presumably caused by calibration and saturation effects. We did not correct for the shift between data and simulation, but we used different threshold values for the cut on Eloss/Ndig: 100,000 electrons for the data, and 56,000 electrons for the simulation.

4. The cluster properties of such selected interaction clusters are finally compared to the simulation (see Section 5).

3 Geant4 simulation

We have used Geant4 6.01, on Linux RH 7.3 with g++ 3.2, with CLHEP 1.8.0.0 . The versions of the Physics Lists that have been considered are the following:

- LHEP 3.7
- QGSP 2.8
- QGSC 2.9

The range cut has been set to $10\,\mu m$, which is approximately the detector resolution of the pixels and the telescope microstrips, given the fact that the smallest dimension of the pixels and the microstrip pitch are $50\,\mu m$. This range cut corresponds to an energy cut in Silicon of about $30\,keV$ for electrons and positrons.
Although the beam is nominally made of π^+, it turned out that the real composition is quite different: $67\,\%$ protons, $29\,\%$ π^+, and $4\,\%$ K^+. We have generated 10 million events (each having an incoming particle of $180\,GeV/c$ momentum) for each Physics List, with the correct proportion of protons, pions and kaons.
The spread of the momentum around the nominal value is quite small (of the order of few GeV/c) and its effect is negligible.
For the beam spot spread, we use a flat smearing of $\pm 1\,mm$, in both transverse directions, with respect to the nominal beam axis.
The beam is shot upstream the telescope plane 1, as in the real situation.
The scintillator plane is described in the simulation, but it includes neither quenching effects nor the trigger efficiency.
The digitization of the pixel is simulated with great detail, taking into account the charge diffusion, cross-talk and noise. The latter is negligible.

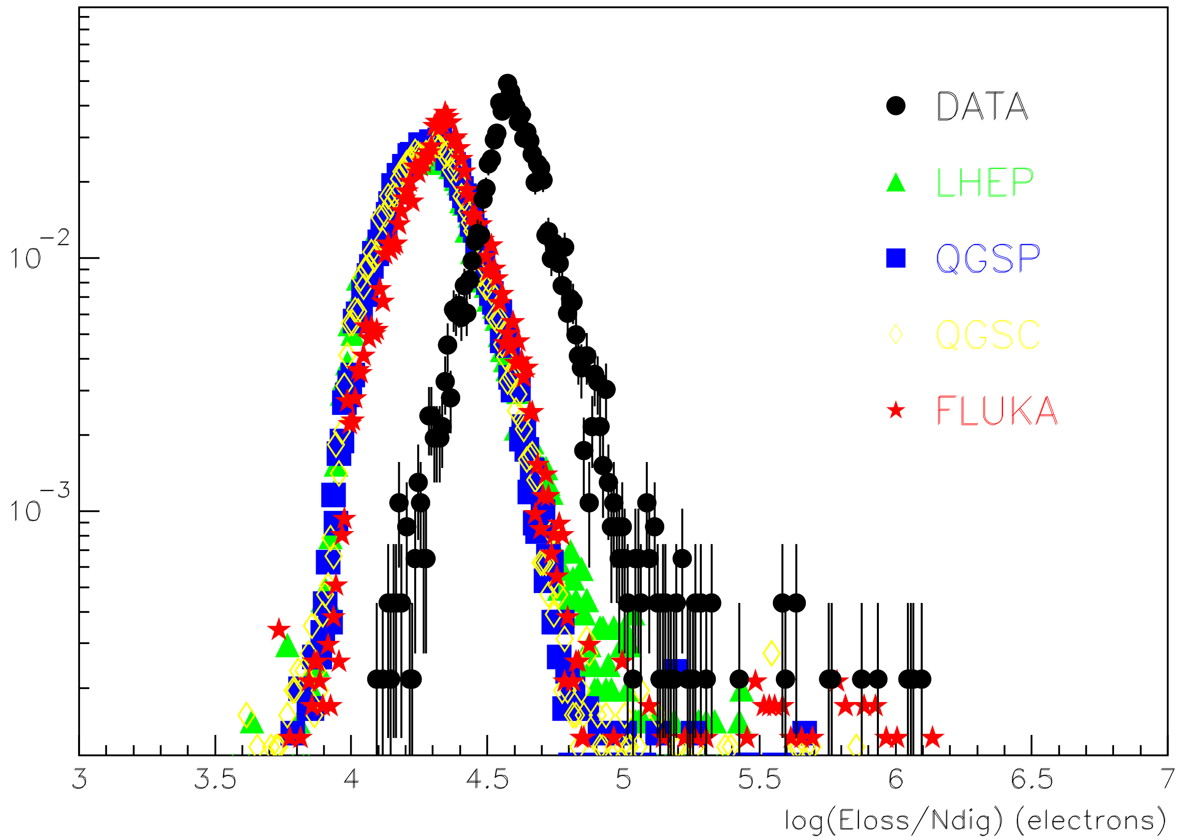

Figure 3: Released energy in the pixel sensor normalised to the number of digits in the cluster for events originating in the plastic cover.

The clustering of pixel hits is done after the simulation, in the reconstruction, and it works as the readout system of the real data: only the pixels with charge above a certain threshold, 3500 electrons, are considered, and neighbour pixels (i.e. pixels differing in row and column by no more than one) are clustered together.
For the telescope planes, the microstrip hits are not fully digitized in the simulation, but, more simply, we group together all hits separated by less than $100\,\mu m$ (the two-track resolution of the microstrip detector), and then, during the recostruction, we smear the cluster position with a $\sigma = 10\,\mu m$ gaussian distribution, which corresponds to the detector resolution.

4 Fluka simulation

We have used the latest Fluka official public release, Fluka2003 (December 2003).
The main cut, i.e. the transportation cut for electrons, positrons and gammas, is set to $10\,keV$. The same value has been used also for the delta-ray threshold. The transportation cut for muons, hadrons, and nuclear fragments is $100\,keV$. The bremsstrahlung and pair-production thresholds for muons and hadrons are set to $300\,keV$.
We have used FLUGG in order to read directly the Geant4 geometry. FLUGG is an interface which allows the Geant4 navigation to be used while the physics and transportation are driven by Fluka. More details on how to use FLUGG can be found in the Appendix.
The other nontrivial part of the simulation that we wanted to reuse from Geant4 is the pixel hit digitization. To do so we have written an interface that, at the end of each event, converts the hits information stored in a Fluka common block into Geant4-like hits, and then calls the Geant4 digitization.
We used the same beam composition and beam divergence as in Geant4. The same number of events, 10 million, have been generated also with Fluka.

5 Results

Because of the calibration uncertainty, the following observables, which should not be directly affected by it, have been selected:

- number of reconstructed tracks, Figure 4;
- η (pseudorapiditity) distribution of the reconstructed tracks, Figure 5;
- ratio between the maximum charge in a single pixel and the total charge of the cluster, Figure 6;
- cluster size (number of pixels in the cluster), Figure 7;

- distance of the farthest pixel of the cluster from the cluster barycenter, Figure 8.

For completeness, we also show the cluster charge distribution, Figure 9, and the maximum charge in a single pixel, Figure 10, although they are directly affected by the calibration problem.

In the plots, we show the statistical error bars only for the real data, because those of the simulation are more than a factor of two smaller. In fact, the number of events, after all cuts, is the following:

- real data : 474 events;
- Geant4 LHEP : 1873 events;
- Geant4 QGSP : 2866 events;
- Geant4 QGSC : 2944 events;
- Fluka : 3187 events.

The comparisons are shown after normalizing to the same number of events. The upper plots are in linear scale, and the lower ones in logarithmic scale.

We have verified that the distributions remain essentially unchanged when varying within reasonable limits: the beam spot, the noise level, the zero-suppression threshold used for the pixel clustering, the cut on Eloss/Ndig, the minimum number of required tracks.

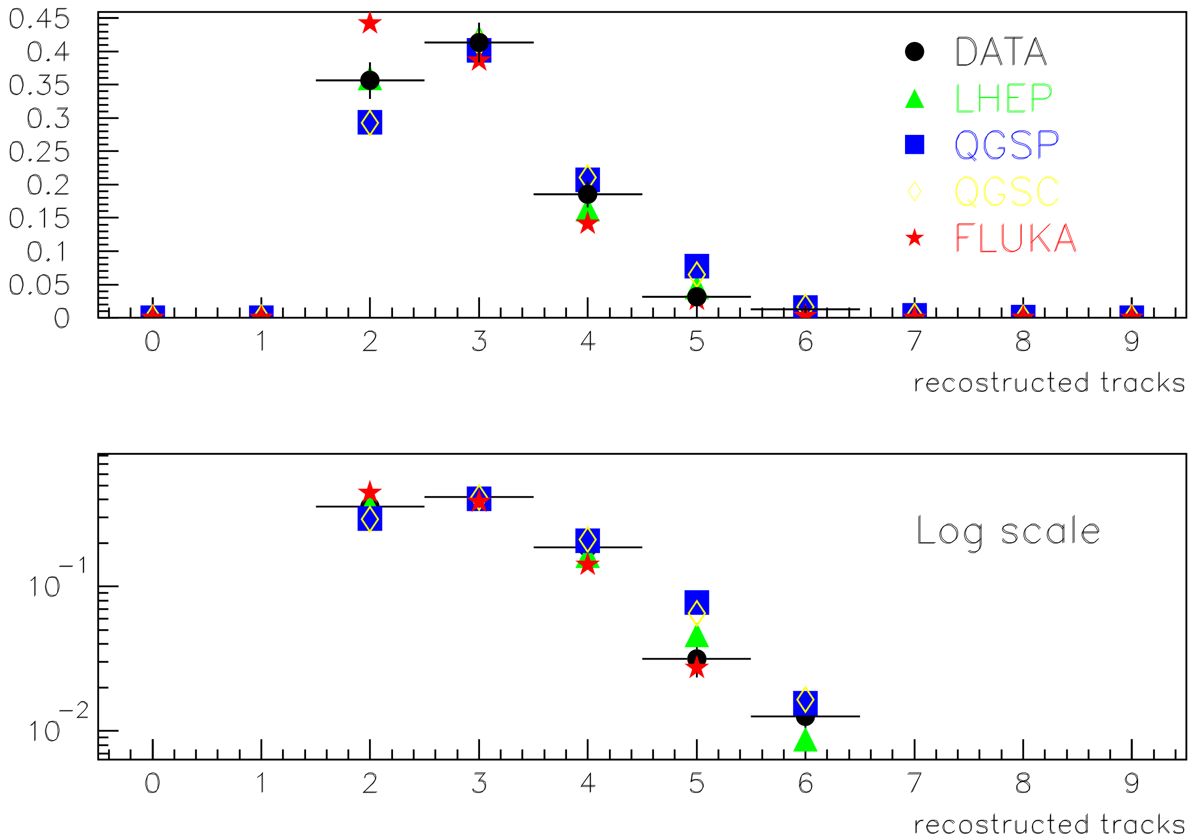

Figure 4: Number of reconstructed tracks.

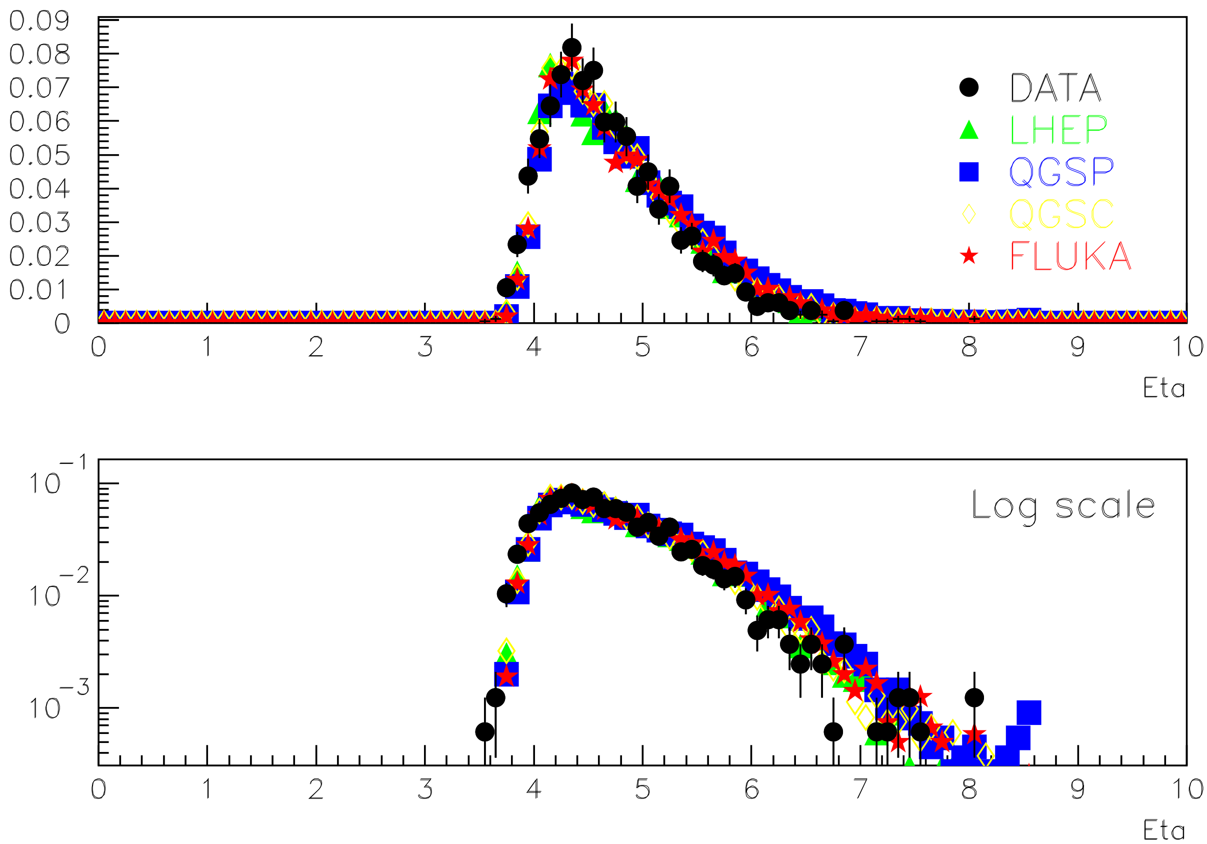

Figure 5: Pseudorapidity of the reconstructed tracks.

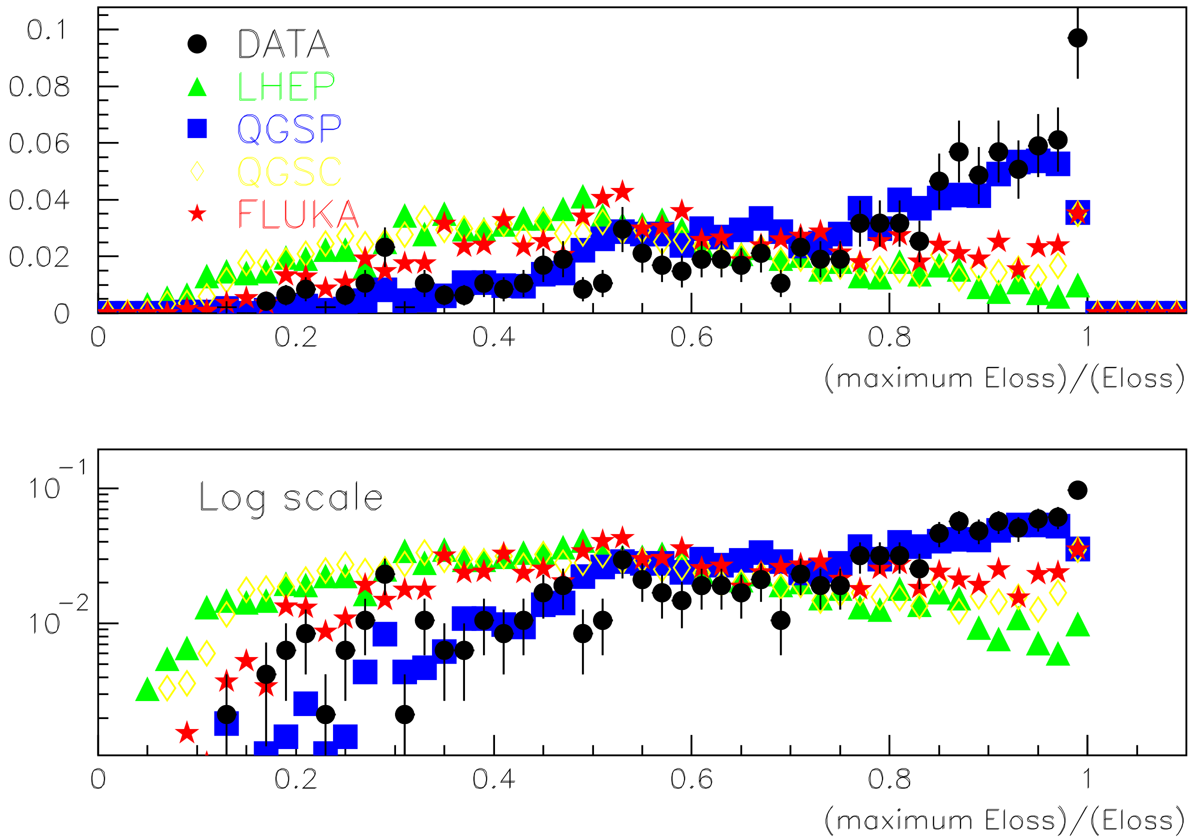

Figure 6: Maximum energy in a single pixel of the cluster divided by the total cluster energy.

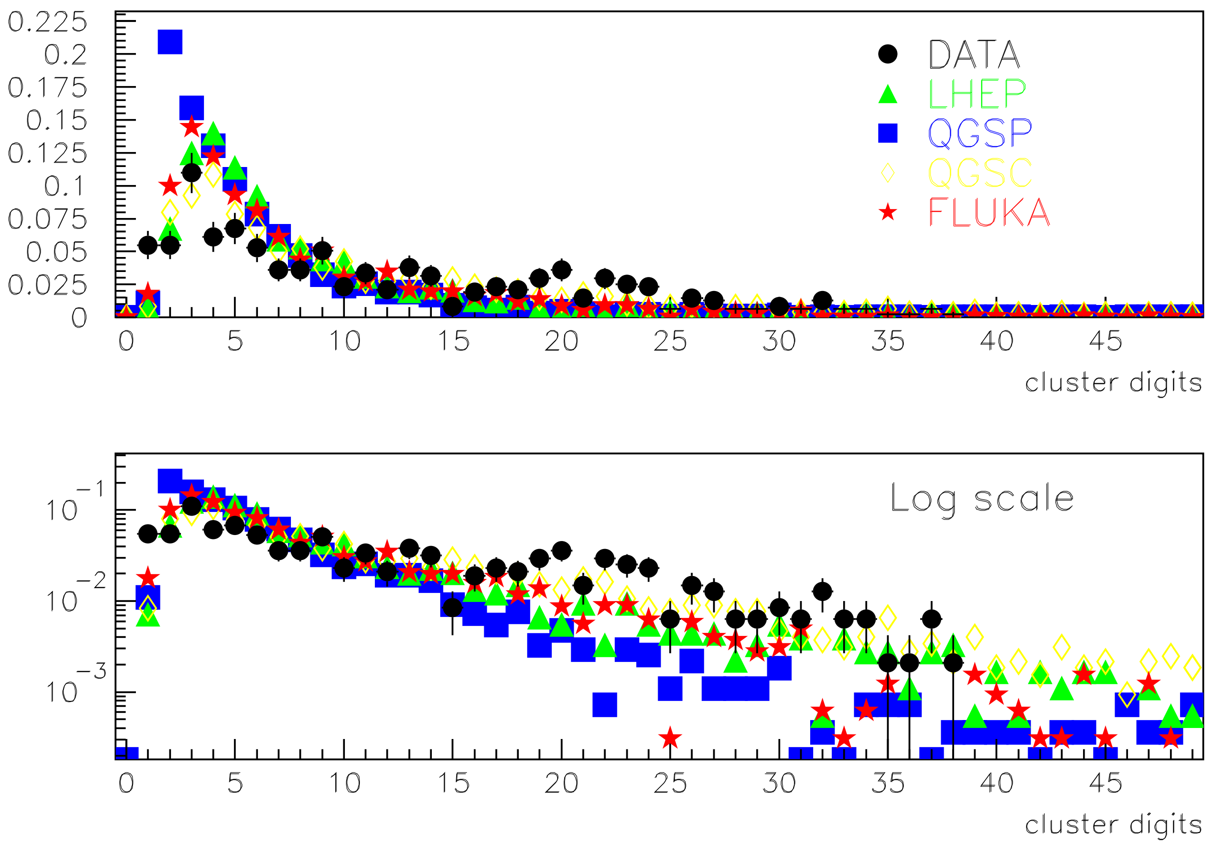

Figure 7: Number of pixels in the cluster (cluster size).

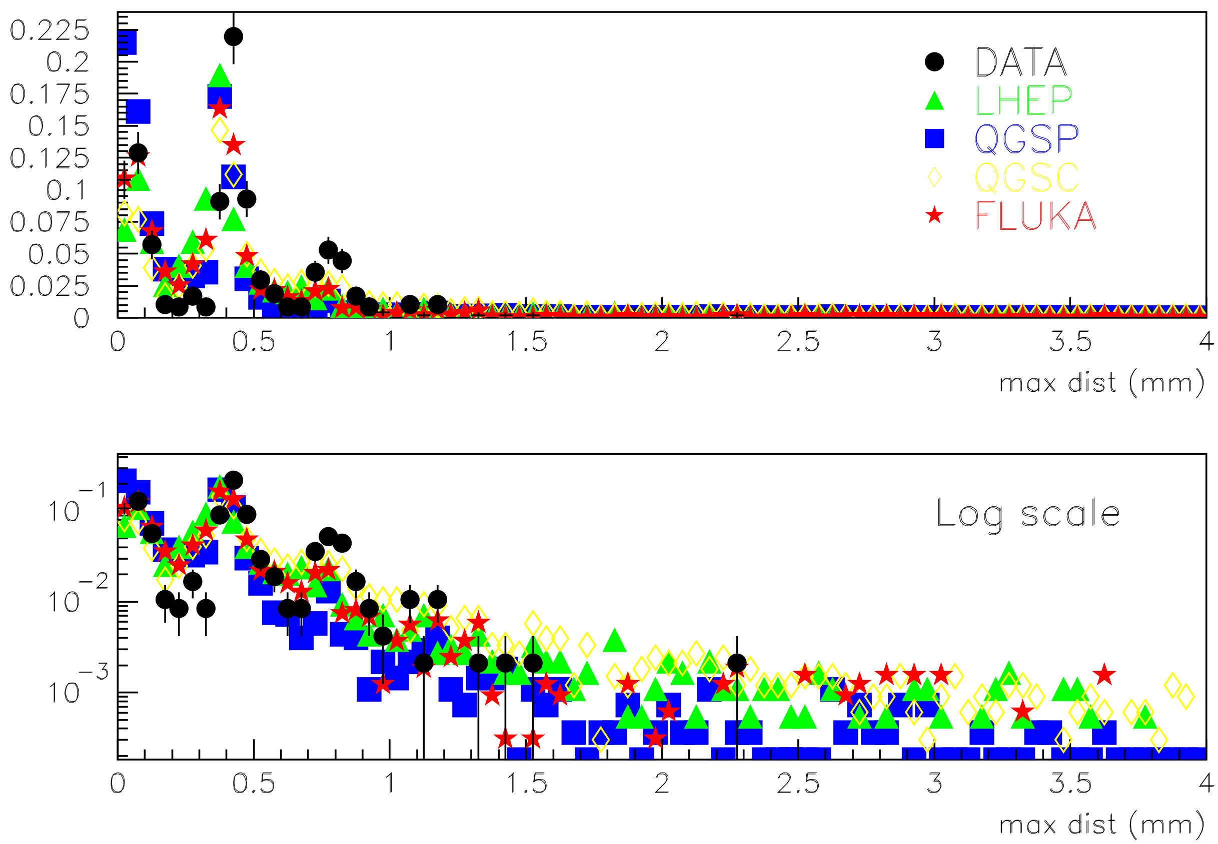

Figure 8: Distance of the farthest pixel of the cluster from the cluster barycenter.

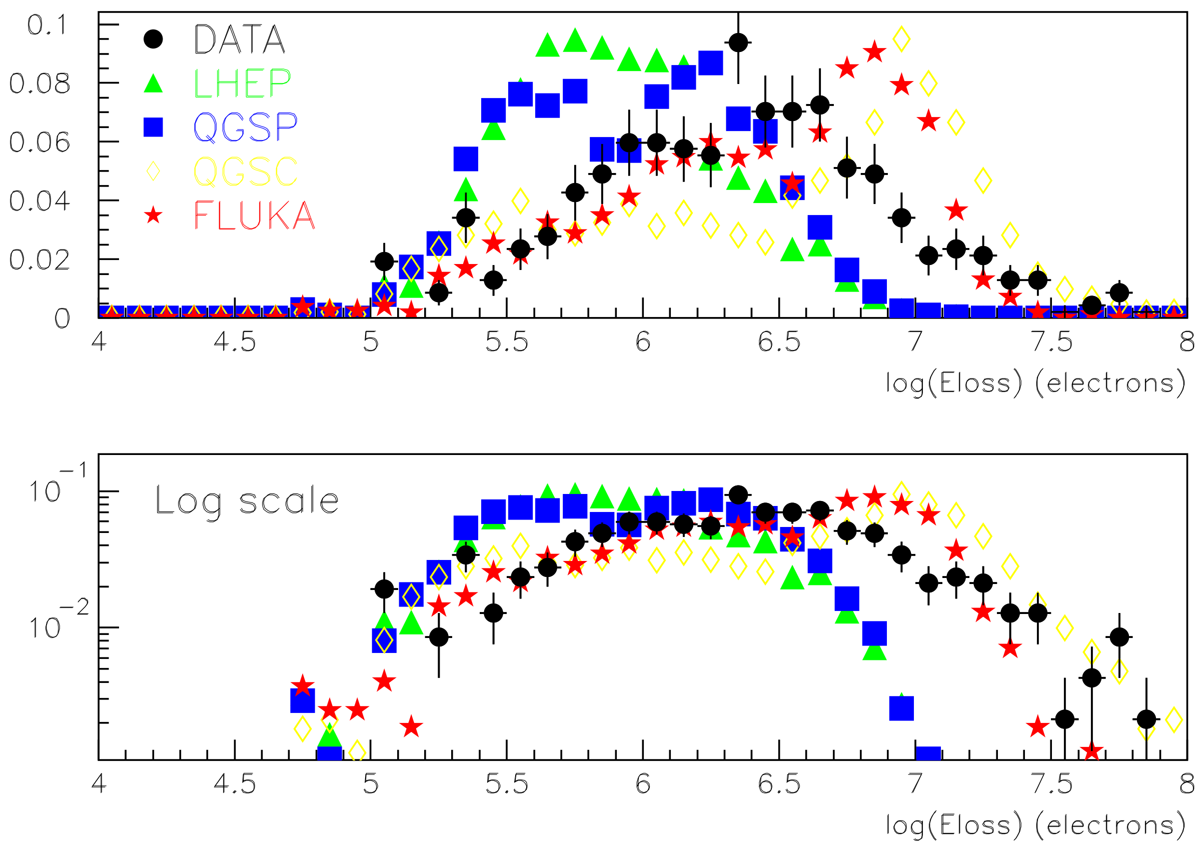

Figure 9: Total charge of the cluster.

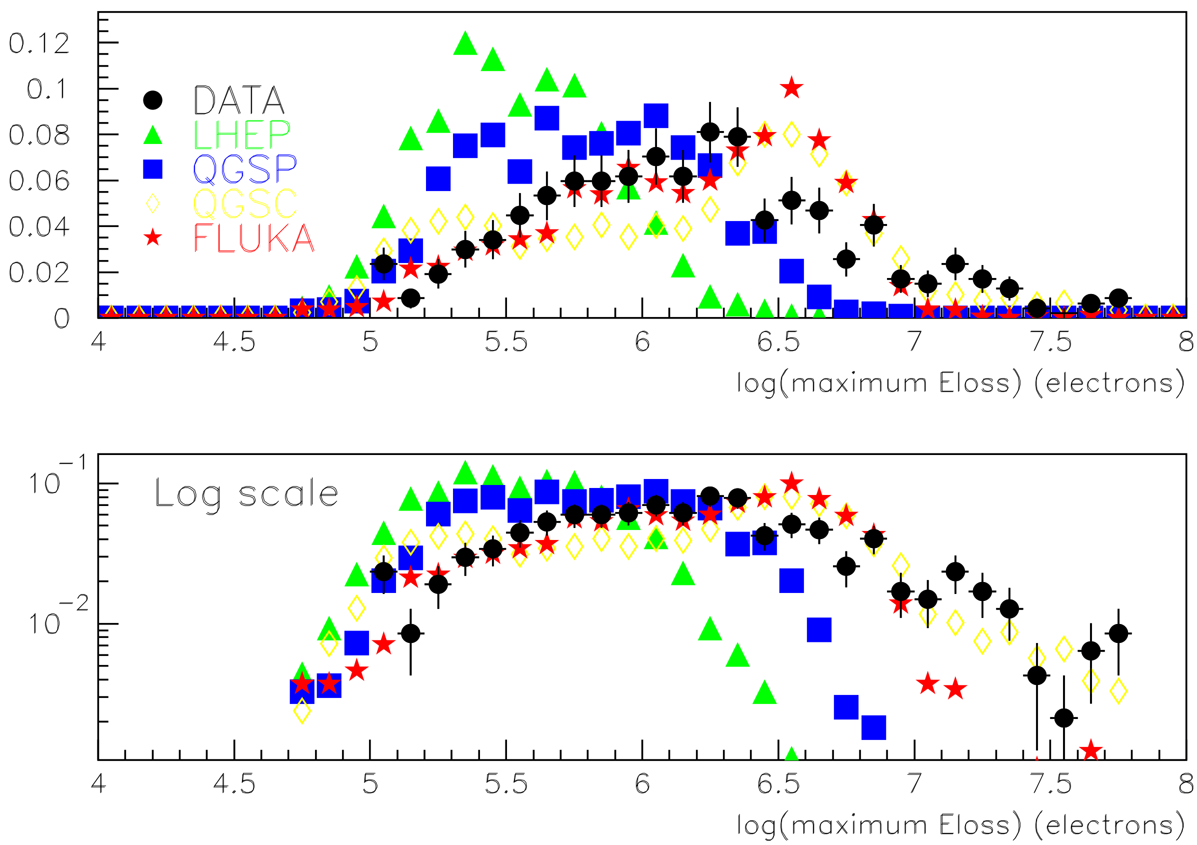

Figure 10: Maximum charge in a single pixel of the cluster.

6 Conclusion

The energy calibration problem affects directly some cluster distributions (Eloss, Emax). Other distributions, especially the number of reconstructed tracks, the pseudorapidity of these tracks, the cluster size, the distance of the farthest hit, should be less affected by this problem. These distributions are quite stable with respect to various changes tried in the simulation or analysis. Given these considerations, we can conclude that:

- Fluka and Geant4 offer a more or less similar description of the ATLAS pixel test-beam data.
- The overall level of agreement between simulation and data is reasonably good, although not excellent for some observables.
- LHEP describes very well the number of reconstructed tracks; QGSP describes well the ratio between the maximum charge in a single pixel of the cluster and the total cluster charge; Fluka describes better the cluster spatial extension.
- QGSC seems to be closer to Fluka than to the other Geant4 Physics Lists.
- There are some features of the data (e.g. the two bumps in the cluster size distribution at 3 and around 20; the peak around 1 in the ratio of the maximum charge in a single pixel of the cluster over the total cluster charge) which are not reproduced by any model.
  Mikhail Kossov is trying a new, indipendent analysis of this test-beam data to understand these features. Another note will report his findings.

Acknowledgment

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7 Appendix: how to use FLUGG

FLUGG is an interface between the transportation and physics of Fluka and the Geant4 Navigation. In practice, this means that if one has already a Geant4 geometry description of a setup, and wants to try Fluka, the simplest way is to use FLUGG.

To run FLUGG, the following steps are required:

- download Fluka and FLUGG from http://www.fluka.org

- setup the following environmental variables:
  FLUGGINSTALL = directory path where you have installed FLUGG
  FLUPRO = directory path where you have installed Fluka
  G4SYSTEM = platform you are using. e.g. Linux-g++
  G4LIB_BUILD_SHARED = yes
  CLHEP_BASE_DIR = directory path where CLHEP is installed, e.g. /afs/cern.ch/sw/lhcxx/specific/redhat73/gcc-3.2/CLHEP/1.8.0.0
  Add to LD_LIBRARY_PATH the libraries of FLUGG and CLHEP.

- build FLUGG (type: gmake);

- create the application: keep only the pure geometrical part of the Geant4 setup (no sensitive detectors, no hits, no digitization);

- write the name of the application in the GNUmakefile, and the name of the geometry class (i.e. MyDetectorConstruction.hh) in the main program;

- run Fluka a first time for initialization, using a standard Fluka input, e.g. my-input.inp, with the GEOEND card immediately after the GEOBEGIN without MATERIAL and ASSIGNMAT cards with a STOP card after the GEOEND card. For instance:
  ```
  TITLE
  My example
  DEFAULTS                                NEW-DEFA
  BEAM      -50.                           PROTON
  BEAMPOS 0.0       0.0       -50.0
  GEOBEGIN                                COMBINAT
  GEOEND
  STOP
  ```
  this produces in output Fluka cards for the materials;

- paste the Fluka cards for the materials in the final Fluka input file, and prepare the standard PEMF file; finally run Fluka in the standard way.

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