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THE TRANSITION FROM GEANT3 TO GEANT4

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Abstract

In the last two years the High Energy Physics (*HEP*) community has completed the transition from simulation programs based on Geant3 to the new Geant4 framework. The status of the current understanding and the comparison with test beam data is presented, outlining a possible strategy for the continuation of the effort.

1 Introduction

The realization of simulation programs for the soon-to-come LHC experiments presents huge problems, due to the complexity of the apparata and to the high multiplicity events which will contaminate the trigger event.

In this review, I try and sketch the evolution of such simulation programs from the Fortran Geant3 [1)] framework, to the new C++ Geant4 [2)] framework. The current status of physics validation is then presented.

2 From Geant3 to Geant4

The previous HEP experiments, *e.g.* the LEP ones, had simulation programs based on Geant3, a Fortran framework for the simulation of the interactions of particles with matter, developped starting from 1982 for the OPAL [3] experiment.

The success of the LEP physics program for precision measurements, where the availability of a detailed Monte Carlo simulation is unavoidable, shows that the Geant3 framework could fulfill to the expectations.

In 1993 a parallel project started to port the Geant3 code to C++; at the same time, any further development of Geant3 was stopped to focus the efforts on the new product.

The transition from Fortran to C++ was needed since C++ was already understood as the language for the LHC experiments; moreover, recent techniques of computer science were claiming an easier control of the code base and an easier release sequence.

3 About Physics Validation

The complete validation of the Geant4 framework by the experiments is a long and complex process. It involves

- validation of the components (geometry building, beam simulation, interface to generators, interface to databases);
- validation of physics (hadronic physics, elecromagnetic physics);
- validation of performance (C++ is known to be slower than Fortran, and possibly more prone to crashes).

The first type of validation is more interesting for Computer Scientists, having not much to do with physics itself. The second point is the core of the problem and is covered in details in the next sections. The third one is again not really linked to physics, but is utterly important when massive productions have to be carried out.

4 Physics Validation

A physics validation program must be based on the comparison of Geant4 simulations with real data. A comparison Geant3 vs Geant4 does not have much sense here, since, at least in principle, Geant4 should be superior to Geant3 *a priori*, since it incorporates 10 years of further studies.

A comparison with data, on the other hand, is much more complicated from the practical point of view. Test beam data, for example, is often taken with non final detectors and electronics, and in unstable situations (beam, environment ...). Any attempt to extract valuable information about the underline physics must address and simulate this problems before drawing any conclusion.

Then, when can be a physics validation program considered accomplished? Various definitions could be used, but one seems natural: a physics simulation can be considered adeguate if any systematic errors introduced by residual discrepancies in a benchmark analysis (after proper calibration) is not the dominant one on the total error.

4.1 Hadronic Physics

In Geant4 a single hadronic model valid for all processes and energies is not available; instead, a collection of models is present, which cover a wide range of use cases.

Moreover, various models can be available for the same energy range. Differences can be in the modelling, either based on theoretical arguments or fits to existing data, in speed and in accuracy. While in principle the user is entitled to *build* the hadronic model combining model with different validity range, in practice a group of experts (*Hadronic Physics Working Group*) has provided *Physics Lists* for general use and validity from thermal neutrons to HEP applications. These are:

- LHEP: *Data Driven Low-High Energy Parameterization.* It is a low/high energy parameterization of the available data, and describes in a fairly accurate way the final states, while neglecting intermediate states like resonances. It is, to a large extent, a porting in C++ of the existing hadronic model of Geant3.

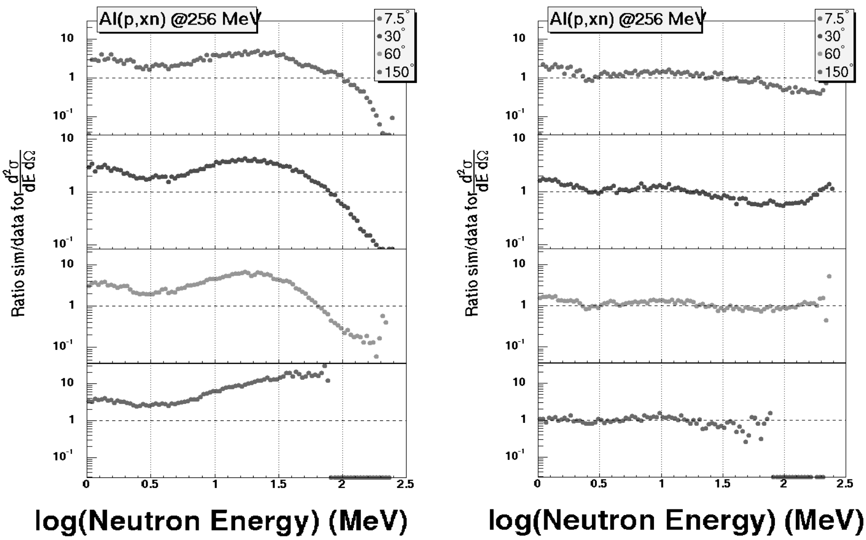

Figure 1: Differential cross section of neutrons out of proton(256 MeV)-Al. Left: using LHEP hadronic model; right: QGSP model.

- QGSP: a theory-driven model, based on the *Quark Gluon String Model* with Bertini/Binary cascade under 3 GeV.

Validation has been carried out using these two models, with data from low energy experiments from nuclear physics and test beams of LHC (up to 200 GeV); higher energy data will be available during the commissioning of the LHC accelerator.

Low-Energy Hadronic Physics The ALICE Collaboration [4] has studied Los Alamos data about proton (up to 800 MeV) scattering on fixed targets, looking at the produced neutrons at different energy and angle. Figure 1 shows one example of such distributions. The conclusion by ALICE states that the LHEP model is not able to describe the experimental data, while the QGSP model is adequate, giving an agreement between data and Monte Carlo Simulation within 20% everywhere, and better in most cases.

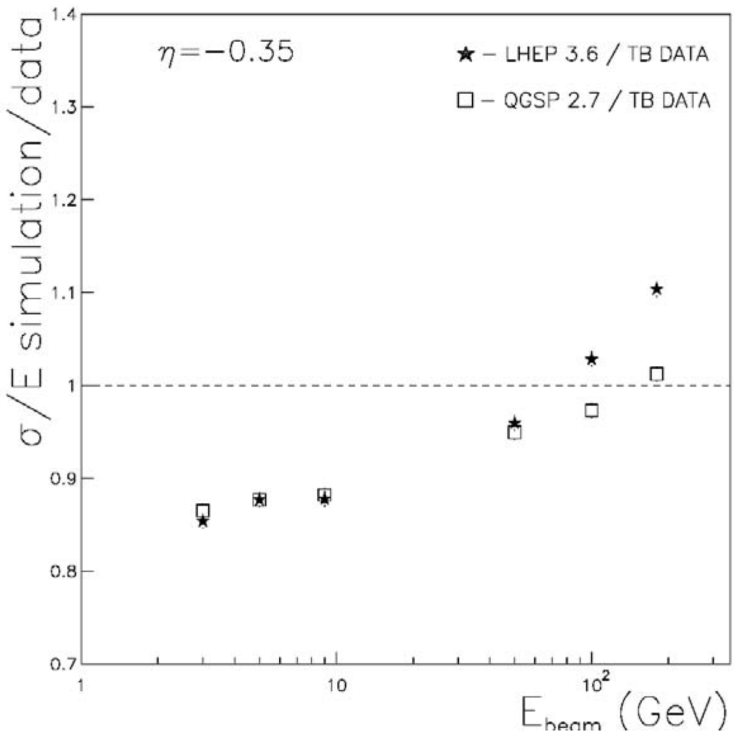

Figure 2: Energy resolution simulation/data for pions on ATLAS TileCal.

High-Energy Hadronic Physics Data is available from ATLAS [5] and CMS [6] LHC test beams (SPS Collider), and studies the response of the hadronic and electromagnetic calorimeters for electrons, muons and pions in the energy range 1-200 GeV. Quantities under study are

- reconstructed energy: linearity and resolution;
- e/π energy response separation;
- shower profiles.

Figures 2,3 shows the energy resolution from the ATLAS TileCal calorimeter; while neither LHEP nor QGSP agree at the percent level, QGSP is able to give a description within less than 5%.

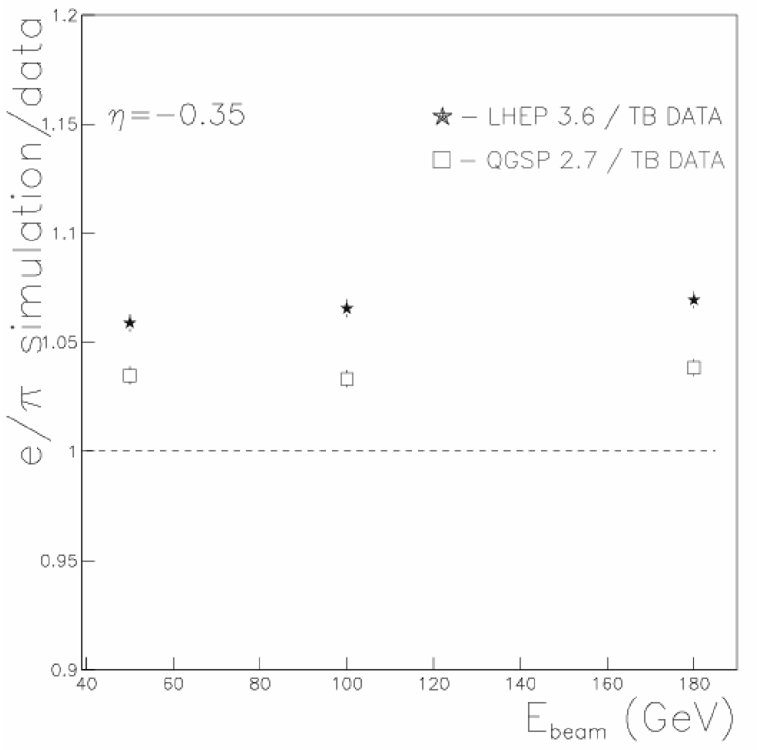

Figure 3: Relative response to pions and electron, simulation/data.

Figure 4 shows shower profiles from the ATLAS HEC calorimeter. Only in one case the Geant3 simulation seems in better agreement with data.

Figure 5 shows shower profiles from the CMS HCAL calorimeter; again the conclusions are not straightforward, but Geant4 smulations are in each case quite in agreement with data.

While conclusions are not always easy to draw, the general trend is that when data is compared with Geant3 and Geant4, Geant4 shows a better agreement with both the Physics Lists. Moreover,the complex theory-driven QGSP is generally better than the simple parameterization offered by LHEP.

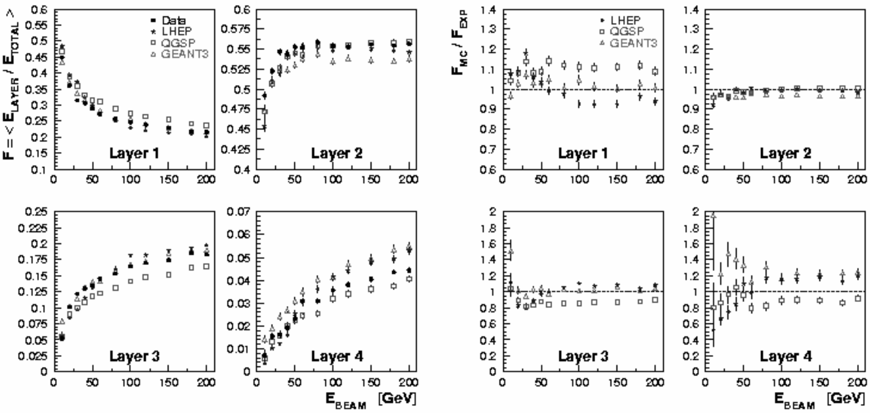

Figure 4: Longitudinal shower shapes in 4 HEC layers. Left: distributions as a function of pion energy; right: simulation/data.

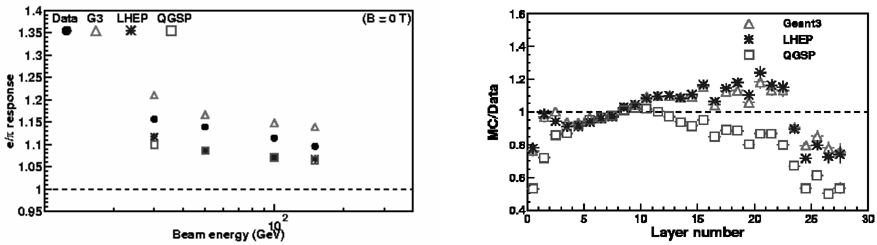

Figure 5: Left: e/π response in the CMS HCAL. Right: longitudinal shower evolution, simulation/data.

4.2 Hadronic Physics in Thin Layers

A correct modelling of the hadronic physics is at the base of calorimetry simulations, but can be important also in the simulation of thin detectors, like silicon tracking devices. The response of such detectors is mainly due to Em interactions, but the rare ($O(10^{-3})$ occurrence of hadronic interactions can generate problems. In fact, the energy deposition of these is in the MeV range, at least

10 times more then the corrisponding Em one, and can generate saturations in the front end electronics. On the other hand, these can be valuable in studying hadronic interactions: with detectors less than 1 mm thick, an hypothesis of single interaction can be used.

ATLAS, in a test beam with pixel detectors, has selected events with pions colliding in a detector, which generate at least three tracks downstream. In such a trigger condition, kinematic distributions such as the number of tracks coming out of the layer, the relative height of the hit pixels (shape of the cluster) and the angular distributions of such tracks are compared to the simulation of the setup.

Also in this case, the Geant4 based simulation is able to reproduce the data within a few percent.

4.3 Em Physics

The electromagnetic physics simulation is an easier task, since the model is well known and understood since long. In fact, Geant4 provides virtually no options for the model, apart from the choice of the precision level.

On thin layers, like tracking devices, the level of accuracy must be such has to correctly reproduce the elementary interaction up to very small energies: in pixel detectors, the expected resolution in of the order of 10 μm, which is comparable to the range in silicon of 30 keV electrons. Delta ray emission must be allowed and correctly simulated up to this level. CMS has shown with recent test beams that resolutions, cluster shapes and energy deposits are well in agreement with the simulations (see Figure 6).

In Em calorimeters, on the other hand, the hadronic showers must be correctly simulated from the pile-up scale (100 MeV) to the energy of the jets (TeV scale). Quantities which need to be checked in the simulation are energy, linearity and resolution, but also shower shapes, needed to separate electrons from jets, and position resolutions, used to identify the correct primary interaction vertex.

CMS has compared test beam data with electrons 20-180 GeV in ECAL to the simulation, comparing confimenement and resolutions to the Geant4 simulation. The agreement is considered satisfactory. Figure 7 shows the agreement data/simulation for what concerns confinement, while Figure 8 shows the resolution in energy.

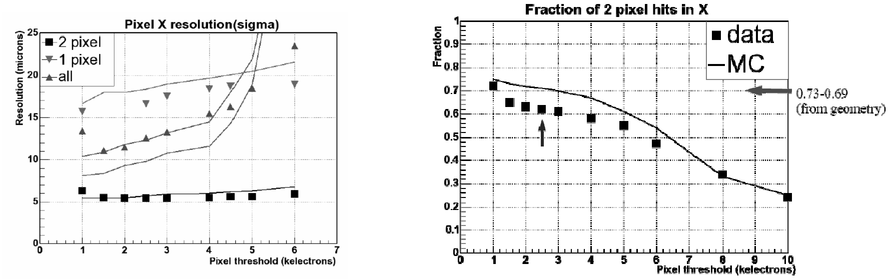

Figure 6: Left: resolution in X coordinate in a CMS pixel detector; right: fraction of hits with 2 pixels as a function of the pixel threshold.

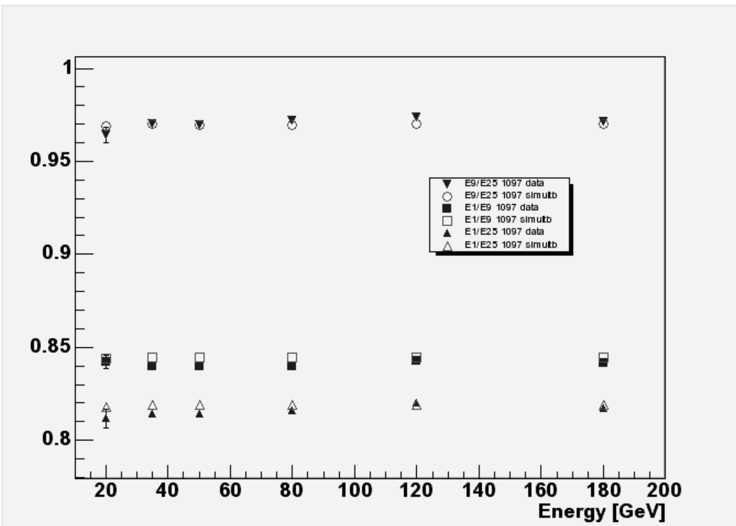

Figure 7: Confinement in a CMS ECAL crystal matrix.

5 Conclusions

By now, the LHC experiments have all switched to simulation programs based on the Geant4 framework. While the initial validation seems successful, more

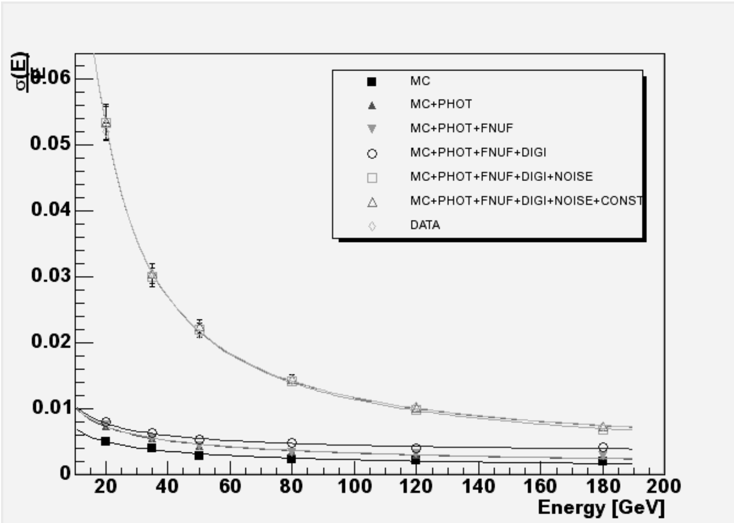

Figure 8: Energy resolution as a function of beam energy.

data is needed to prepare the simulation by the start of the LHC program. A critical eye must be kept when comparing simulations and test beam data, since for a correct understanding a very accurate understanding and simulation of the electronic and beam conditions are unavoidable.

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