ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Genova

INFN/AE-04/02
14 Aprile 2004

PRECISION VALIDATION OF GEANT4 ELECTROMAGNETIC PHYSICS

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Abstract

The Geant4 toolkit provides an ample set of physics models for electromagnetic interactions. Results from a series of detailed tests with respect to well established reference data sources and experiments are presented, focusing on the precision validation of cross sections and angular distributions of various alternative physics models available in Geant4. Such precision tests are especially relevant for critical applications of simulation models, such as tracking detectors, calorimetry, neutrino and other astroparticle experiments, medical physics.

PACS:11.30.Er; 13.20.Eb; 13.20Jf; 29.40.Gx; 29.40.Vj

Published by ***SIS–Pubblicazioni***
Laboratori Nazionali di Frascati

1 Introduction

Geant4 is an object-oriented toolkit for simulating the passage of particles through matter [1]. Accurate and comprehensive simulations of complex detectors are nowadays necessary for a large number of scientific applications, ranging from elementary particle physics to space science and medical physics. At the heart of the Geant4 system is a wide set of complementary, and sometimes alternative, physics models which describe the basic interaction of particles with matter. In order to have reliable simulations, the physics content of the toolkit must be as solid and accurate as possible. It is hence of paramount importance to validate all the models by comparing them with well-established experimental data. For this reason, a project is in progress in the Geant4 Collaboration for a systematic and quantitative validation of the Geant4 electromagnetic physics.

2 Geant4 electromagnetic physics

The Geant4 electromagnetic package handles the electromagnetic interactions of leptons, gamma rays, optical photons, hadrons and ions: it includes, in particular, multiple scattering, bremsstrahlung, ionisation, positron annihilation, photoelectric effect, Compton and Rayleigh scattering, gamma conversion, synchrotron and transition radiation, Čerenkov effect, refraction, reflection, absorption, scintillation, fluorescence x-rays and Auger electrons generation. The Geant4 electromagnetic package provides both high-energy physics models (from 1 keV up to 100 TeV), that are fundamental for accelerator and cosmic rays experiments, and specific low-energy models (down to 250 eV), that include, for instance, atomic effects and are hence appropriate for space science, medical applications and astroparticle physics experiments. Moreover, two alternative and independent models are presently available for all the processes included in the low-energy subpackage: a complete set of dedicated and original low-energy electromagnetic models has been in fact obtained by the re-engineering of the Penelope Monte Carlo code [2,3] in Geant4[1]. This flexibility in the extension and in the implementation of new models is the direct result of the use of OO-technology, as all processes do obey to the same abstract interfaces.
Since the detection in many HEP experiments is mainly based on Čerenkov effect and on scintillation, the Geant4 electromagnetic package also includes processes for the description of optical photons, like absorption, refraction and reflection. Moreover, it also provides specific models for the simulation of high energy muons (up to 1000 PeV), which is relevant for ultra-high energy and cosmic rays physics.

[1] The photons processes have been released in the 5.2 version of Geant4, while the positron-electron ones will be in the next 6.0.

3 The validation of Geant4 physics

A systematic and extensive validation of the physics content is fundamental in Geant4. A complete and reliable validation of the electromagnetic processes requires to test:

1. microscopic quantities of the various elementary processes, as cross sections, angular/energy distributions, attenuation coefficients, stopping powers, CSDA ranges, etc.;

2. macroscopic quantities coming from use cases, i.e. from the simulation of complete experimental set-ups.

At each of the two testing levels, the results of the Geant4 simulations are compared with established and authoritative reference data (wherever they exist), taken from open and recognized references (NIST, ICRU, Livermore) or from publications on refereed journals (preferably from different sources or experiments). The search and the collection of suitable reference data to compare to is one of the most important steps of the validation process.

3.1 Microscopic analysis

The analysis of several microscopic quantities for the validation of the individual physics models has been performed in a systematic way for many processes (see. [4]) and in a wide range of absorber materials. Fig. 1 and 2 show, for instance, the mass attenuation coefficient vs. energy for gamma rays in aluminum in the energy range 1 keV – 100 MeV. The results coming from the simulations with the Geant4 Standard, Low-Energy and Penelope photon models have been compared with reference data taken from NIST [5]; the agreement of distributions has also been quantitatively evaluated using χ^2-based statistical tests.
Similarly, Fig 3 shows the angular distribution of transmitted 15.7 MeV electrons through a thin gold slab (18.66 mg/cm^2), obtained by the Geant4 simulations, superimposed with the corresponding reference data from Hanson *et al.*, Phys. Rev. 84, 634 (1951).
An extensive set of results (both plots and goodness-of-fit values) is available for many physics models in Geant4, involving electrons, positrons, gamma rays, fluorescence x-rays, Auger electrons, protons and ions. Different microscopic quantities (attenuation coefficient, stopping power, CSDA range, transmission/backscattering coefficient, fluorescence and ionisation spectra) have been systematically tested for a wide range of materials. This huge amount of work, which is heavily CPU-demanding and time-consuming, requires a flexible automatic system, both for the submission of the simulation jobs and for the comparison with reference data.

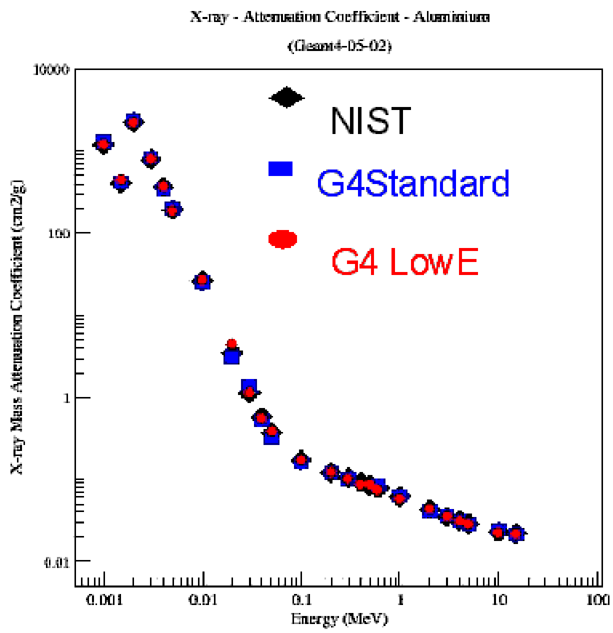

Figure 1: Mass attenuation coefficient vs. energy for γ rays in aluminum calculated from the Geant4 simulations with the Standard and Low-Energy photon models, superimposed with reference data taken from NIST. A χ^2 statistical test has been used to quantify the agreement of the simulated and the experimental distributions: the p-values are 0.08 for reference data vs. Geant4 simulation with Standard photon models (χ^2=23.3 and ν=15) and 0.87 for reference data vs. Geant4 simulation with Low-Energy models (χ^2=13.3 and ν=20).

3.2 Macroscopic analysis

The validation at the macroscopic level is a test of the complete detector set-up, based on the comparison with experimental data. The realistic and accurate simulation of a complex experiment requires the detailed knowledge of the detector, so macroscopic validation tests must be carried on in a close collaboration of Geant4 developers and research groups of different domains. It is certainly of great importance to take into account experiments and detectors referring to different scientific communities (accelerator physics, astroparticle physics, space science, medical physics), in order to verify the reliability and suitability of the Geant4 models in different energy ranges and experimental areas.

Geant4 has been used to simulate the electron response in the ATLAS calorimeter (see Fig. 4, courtesy of P. Loch) and the results have been compared with the corresponding test-beam data. It turns out (see Fig. 5, courtesy of P. Loch) that Geant4 can simulate very well (much better than the old Geant3 code) the average electron signal as a function of incident energy in all ATLAS calorimeters; moreover, the signal fluctuations in the elec-

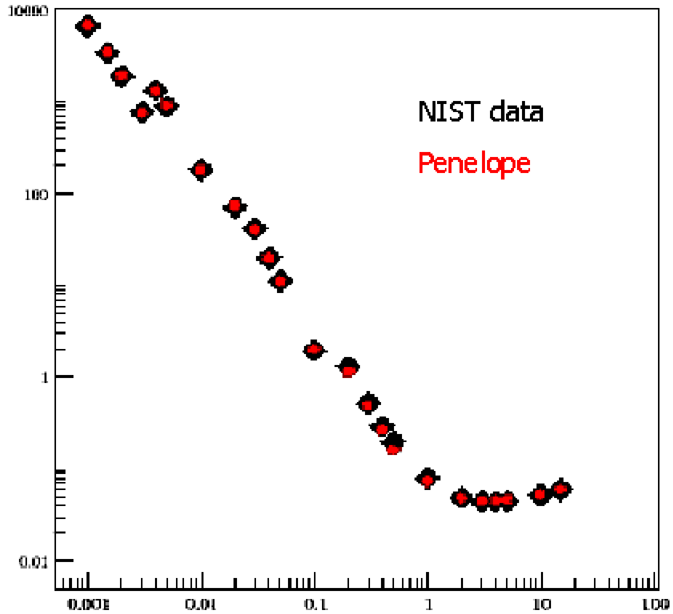

Figure 2: Mass attenuation coefficient vs. energy for γ rays in aluminum calculated from the Geant4 simulations with Penelope photon models [3], superimposed with the same reference data as in Fig. 1. The p-value coming from the χ^2 comparison of reference data and Geant4 simulation is 0.63 (χ^2=19.3 and ν=22).

tromagnetic barrel are also corrected reproduced. The agreement of Geant4 simulations with test-beam data in the accelerator physics domain has also been verified, for instance, for the ATLAS liquid argon calorimeter (courtesy of P. Mendez Lorenzo) and for the CMS electromagnetic calorimeter (courtesy of P. Arce).
A further macroscopic validation test of Geant4, in a completely different energy domain, has been performed taking as reference the experimental data from the proton beam line at Laboratori Nazionali del Sud, Sicily, which is used for medical therapy of eye cancer. The Geant4 simulation has been able to reproduce very precisely the position of the proton Bragg peaks (see Fig. 6) measured at various energies; the agreement has also been quantitatively verified using both the Kolmogorov-Smirnov and the χ^2 statistical tests [6]. These are just examples of macroscopic validations of experimental set-ups but more tests are available form Geant4 Collaboration [8].

4 Conclusion

Geant4 electromagnetic package encompasses an ample set of physics models, specialised for particle type, energy range and detector applications. It is continuously subject to

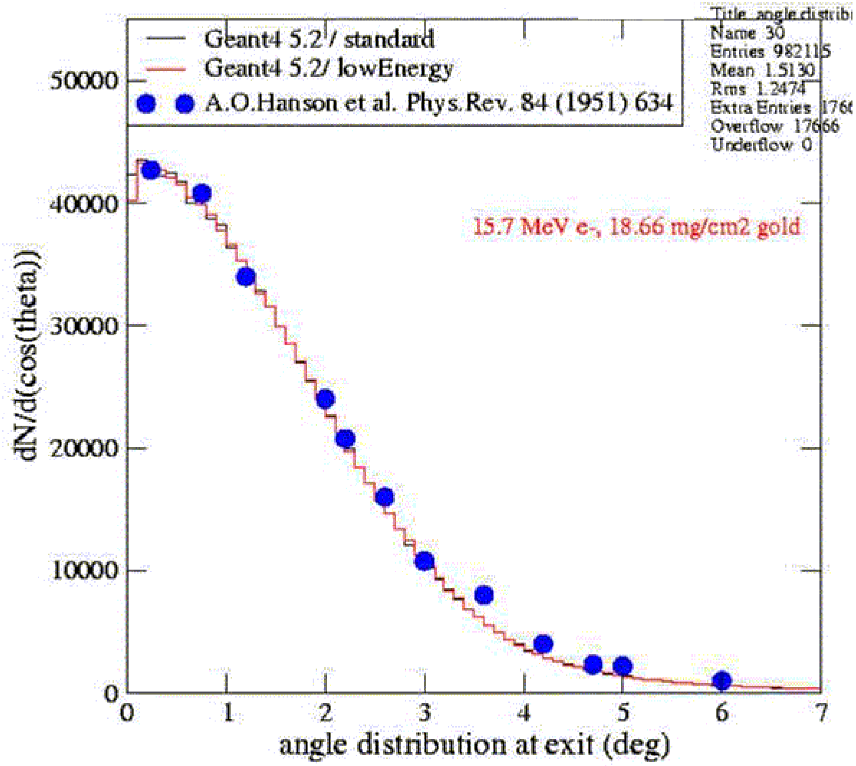

Figure 3: Angular distribution of electrons with energy 15.7 MeV transmitted through a gold slab of thickness 18.66 mg/cm^2. The distributions coming from the Geant4 simulations with the Standard and Low-Energy electron models are superimposed with the experimental reference data taken from Hanson *et al.*, Phys. Rev. 84, 634 (1951).

a rigorous testing and to a systematic validation process, both at the microscopic and macroscopic level, in order to completely monitor the physics performances and to ensure a highly-reliable simulation toolkit. This is a major effort, involving many people, sites and collaborating groups, that triggered the development of a new general toolkit for statistical analysis and a system for test automation.

An extensive set of results (plots and quantitative goodness-of-fit values) is presently available from the microscopic tests of basic physics distributions (see [7]). Moreover, many significant contributions to the validation of Geant4 electromagnetic physics at the macroscopic level come from test beams and user application in the experiments, from different domains of the physics research.

A new project has been recently launched for a Geant4 Physics Book, with the main aim to provide a solid and comprehensive reference on all the physics models included in Geant4, focusing in particular on their validation.

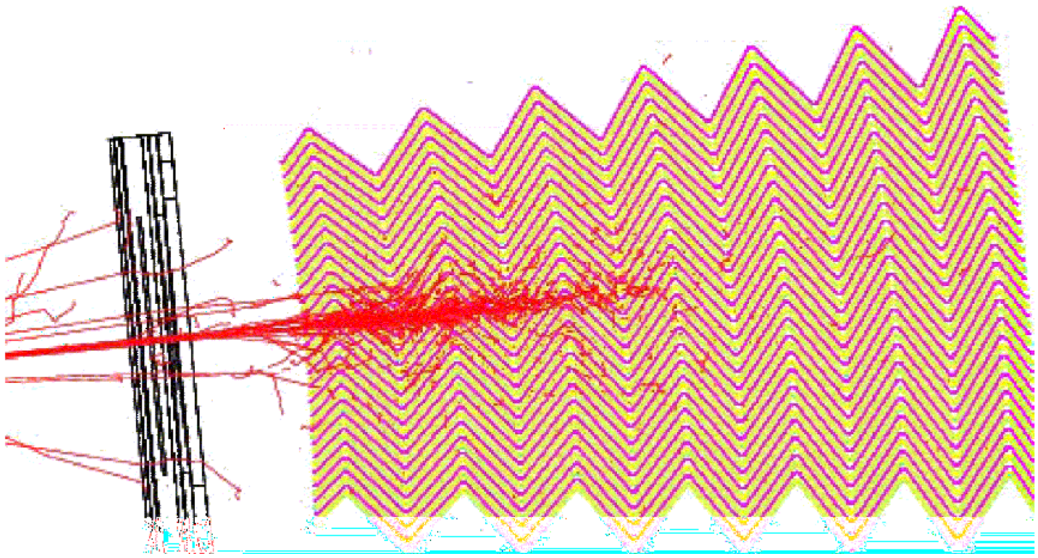

Figure 4: Simulation of the electromagnetic shower produced by a 10 GeV electron in the ATLAS electromagnetic barrel accordion calorimeter (courtesy of P. Loch.)

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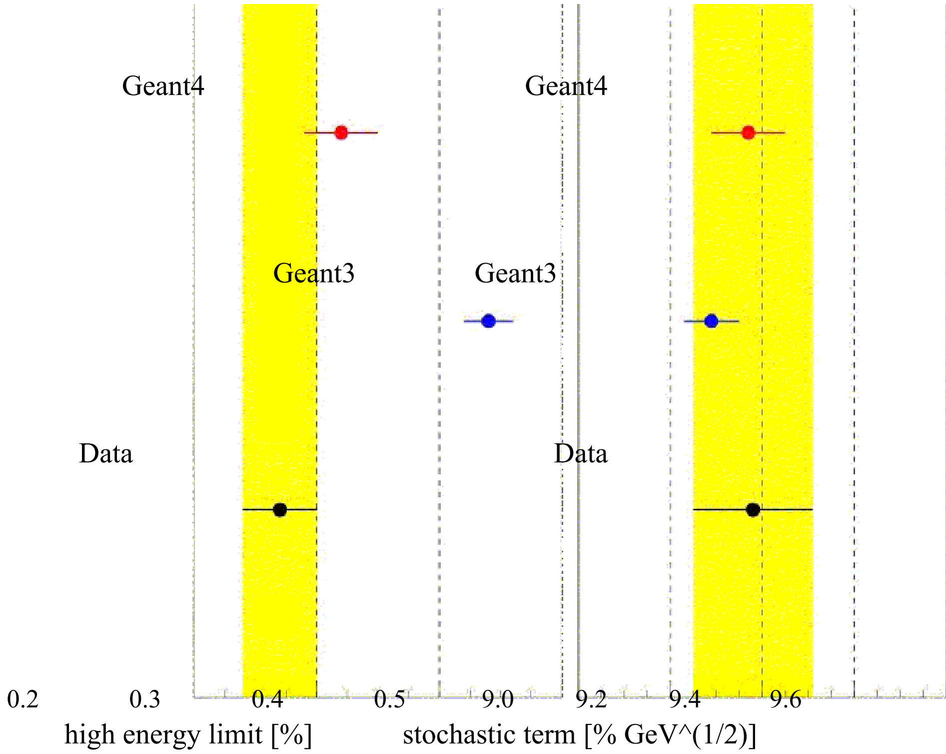

Figure 5: Electron energy resolution in the ATLAS electromagnetic calorimeter. The results obtained with the Geant4 and Geant3 Monte Carlo simulations are compared with the experimental data from test-beam (courtesy of P. Loch).

[8] http://geant4.web.cern.ch/geant4.

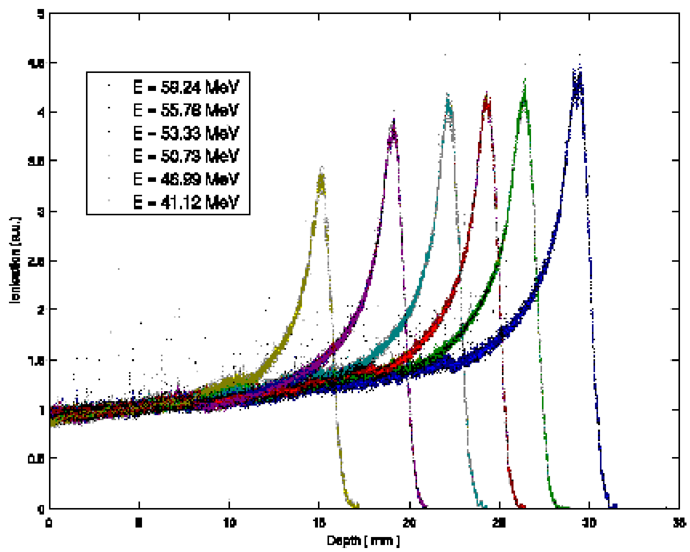

Figure 6: Depth position of the proton Bragg peaks at different energies. Experimental data from the Proton Beam Line at Laboratori Nazionali del Sud, Italy. Details can be found in ref. [6].