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# Geant4 electromagnetic physics for the LHC and other HEP applications

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**Abstract.** An overview of the electromagnetic physics (EM) models available in the Geant4 toolkit is presented. Recent improvements are focused on the performance of detector simulation results from large MC production exercises at the LHC. Significant efforts were spent for high statistics validation of EM physics. The work on consolidation of Geant4 EM physics was achieved providing common interfaces for EM standard (HEP oriented) and EM low-energy models (other application domains). It allows the combination of ultra-relativistic, relativistic and low-energy models for any Geant4 EM processes. With such a combination both precision and CPU performance are achieved for the simulation of EM interactions in a wide energy range. Due to this migration of EM low-energy models to the common interface additional capabilities become available. Selected validation results are presented in this contribution.

## 1. Introduction

Geant4 is a toolkit for the simulation of the passage of particles through matter [1]. It is the basis for most detector simulations in the HEP domain. Geant4 is the main simulation engine for ATLAS, CMS and LHCb experiments. It is also used in medical and astro-particle physics applications.

The electromagnetic physics packages are responsible for the description of interactions of electrons and photons, electromagnetic interactions of muons, hadrons and ions. This also includes X-ray processes and processes with optical photons. The combination of different models allows to cover the energy range from the eV to TeV scale. In the past years substantial effort has been put into the validation and improvement of the Geant4 toolkit. In this paper, we describe the developments in the area of electromagnetic physics models included in the 9.3 (December 2009) and 9.4 (December 2010) Geant4 toolkit releases.

**Table 1.** Initialization times of Geant4 EM physics for a simplified setup with 289 materials.

| Geant4 version | amd 32-bit | amd 64 bit |
|---|---|---|
| G4 9.2 | 147 s | 179 s |
| G4 9.3 | 51 s | 56 s |

## 2. Recent developments in the EM packages

### *2.1. Performance and infrastructure*

Since Geant4 release 9.3 the standard and the low-energy EM package use a common software interface [2]. This has a number of benefits. Most noticeably it is now possible to combine models valid in different energy regions. Thus it is possible to use the Geant4 EM physics at the eV and PeV scale in one user application. Models may be activated only in certain detector regions, in order to keep CPU performance under control.

All EM models take now advantage of the common infrastructure. One example is the spline interpolation in physics tables. This allowed to reduce the number of interpolation points to 70 for the default energy interval 1 keV to 10 TeV, which reduced the memory footprint corresponding to EM physics tables by 20%. At the same time the interpolation uncertainties could be reduced from the few percent level below a per mill. A number of builder classes are provided for the construction of physics lists, which take advantage of these capabilities.

Additional improvements include a revised converter of cuts in range for secondary particles to production energy thresholds and improvements in the physics vector classes. In combination with some improved standard EM initialization routines, this resulted in a significant improvement of start-up time for application with many materials (e.g. LHC experiments). A comparison for a simple test setup with 289 materials is given in table 1.

### *2.2. Validation Framework*

Validation and verification is an important task for the Geant4 EM physics group [3]. It includes comparisons of Geant4 performance and physics output with previous Geant4 versions, and also comparison with experimental data or theory prediction.

A number of tests are run on a regular basis by the Geant4 system testing team (STT). These are low-statistics tests which require little CPU time. High-statistics tests are run by individual Geant4 developers utilizing CPU farms, or the large computing grid. A dedicated validation framework has been developed and is now used for most tests. It allows semi-automatic running of test jobs for any intermediate Geant4 version (so called reference tag). The results are generated by a number of helper scripts, which also create the corresponding comparison plots. A web interface provides an easy access to the results. An overview of this system is given in figure 1.

### *2.3. Bremsstrahlung and pair production*

Recently improved models for electron bremsstrahlung and pair production for high-energies have been included into the Geant4 framework [4].

The relativistic bremsstrahlung model is available since Geant4 version 9.2. It is based on the well-known Bethe-Heitler formula with corrections, which include density and the Landau-Pomeranchuk-Migdal (LPM) effect. It assumes complete screening and is a valid approximation for electron energies above 1 GeV. A consistent combination of density and LPM effect was developed using the prescription by Ter-Mikaelian [5]. With this improvement a good agreement

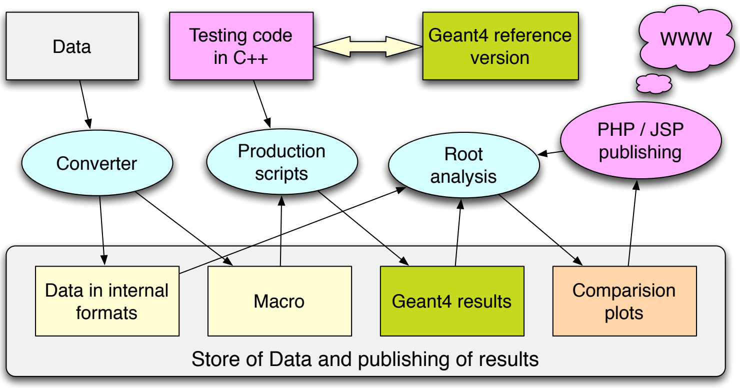


**Figure 1.** Validation framework overview.

of Geant4 simulation with data from dedicated test beam experiments at SLAC and CERN could be achieved [6, 7].

Since Geant4 version 9.3, also a relativistic pair production model is available, which includes the LPM effect. Depending on the material the LPM effect in pair production becomes visible above 1–10 TeV beam energy.

### *2.4. Multiple scattering models*

Multiple scattering (MSC) is one of the areas where much effort was put into improvements in the past years, as described in ref. [8]. Urban MSC [9] is the standard MSC model in Geant4 which is used in most HEP applications. The *Urban93* MSC model was introduced and validated within Geant4 release 9.3 and made default in Geant4 release 9.4. With this model simulation results for low Z materials have improved.

In general the accuracy of the Urban model is of the order of a few percent, sufficient for most HEP applications. In addition a number of alternative MSC models have recently been implemented in Geant4, which aim at a higher precision: *Goudsmit-Saunderson*, *single scattering*, and *Wentzel-VI*.

The *Goudsmit-Saunderson* is a purely theory based model [10]. First results are promising but at a cost of increased CPU time. It can only be used for electrons and positrons at the moment.

In addition a *single scattering* [8] model has been introduced, which is based on the Wentzel scattering function [11]. It provides a physics benchmark for all MSC models, but good physics modeling comes at a high cost in terms of CPU time. For low density media it provides an alternative to the MSC models.

Recently the *Wentzel-VI* model has been introduced [8]. This model is based on a combination of single scattering and multiple scattering models, where the large scattering angle is derived using the *single scattering* model and small angles by a modified multiple scattering approach. The focus of this model is to provide precise simulations of muons and hadrons as well as nuclear recoil in hard high-energy collisions. First results are promising. The model is now default for muons in Geant4 release 9.4. Figure 2 shows a simulated angular distribution of muons with data from a fixed-target experiment [12].

### *2.5. Fluctuation model*

The model for sampling of the fluctuations of energy loss is based on ref. [13]. It was recently improved to become applicable to very thin layers or low density materials. The revised model

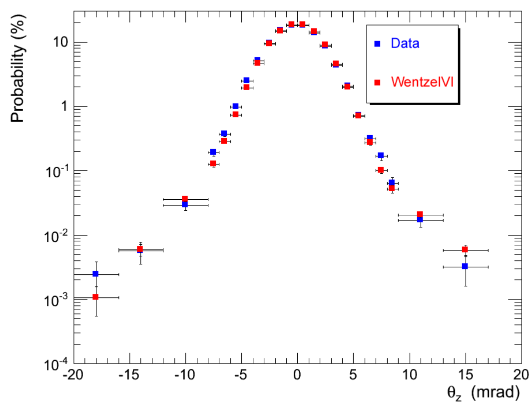


**Figure 2.** Muon scattering angular distribution for 7.3 Gev/c muon on a copper target (1 radiation length thick) [12] in comparison with the Wentzel-VI MSC model.

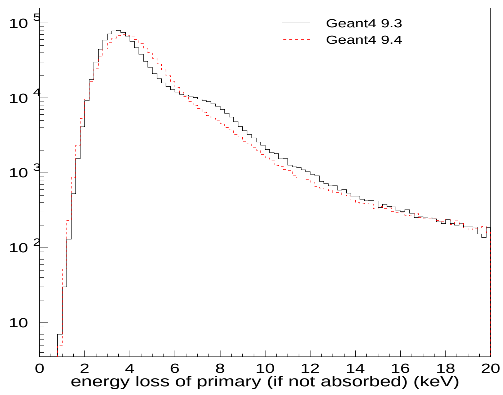


**Figure 3.** Energy loss distribution of 500 MeV electron in 15 mm argon +10% $CO_2$ gas mixture illustrating the change in the fluctuation model between release 9.3 and 9.4.

is also less dependent on step limitations, e.g. cuts in range for secondary particles, compared to previous versions. It was included in Geant4 release 9.4. A comparison between old and new model is given in figure 3.

## 3. Validation results

One of the goals of a detailed Monte Carlo simulation of HEP experiments is to derive a realistic response in all sensitive detector components. For LHC type detectors a huge number of particles produced in the beam-beam interaction will travel through the detector. In interactions with active and passive detector material many low-energy secondary particles are produced (e-, photons, e+, and other particles). The important EM physics processes are ionization, bremsstrahlung, Compton scattering, pair production, the photo-electric effect and multiple scattering. Validation is needed for all particle types and for the complete energy range from 1 keV to a few TeV. In the past years a variety of tests have been improved or added to the EM validation suite, some of which are described below.

### *3.1. Backscattering of electrons*

A validation test for electron MSC compares backscattering data from ref. [14] with different Geant4 MSC models. The energy ranges from 100 keV to 1 MeV. Target materials include beryllium, carbon, aluminum, titanium an molybdenum. Two scenarios have been investigated: The incident electron beam perpendicular to the target surface, or tilted by 60°. All considered MSC models give a reasonable description of the data. Also the Urban MSC model with improved parameters (Skin 3, $f_g$=2.5, $f_r$=0.01) gives good results. Two examples are given in figure 4.

### *3.2. Multiple scattering of muons and hadrons*

A validation test dedicated to the comparison of MSC models has been added to the validation suite.

A test of muon scattering uses data from a fixed-target experiment at the IHEP accelerator [12]. It compares scattering angles of outgoing muons from a copper target (one radiation length thick) from incoming muon momentum of 7.3 and 11.7 GeV/c. The results can be

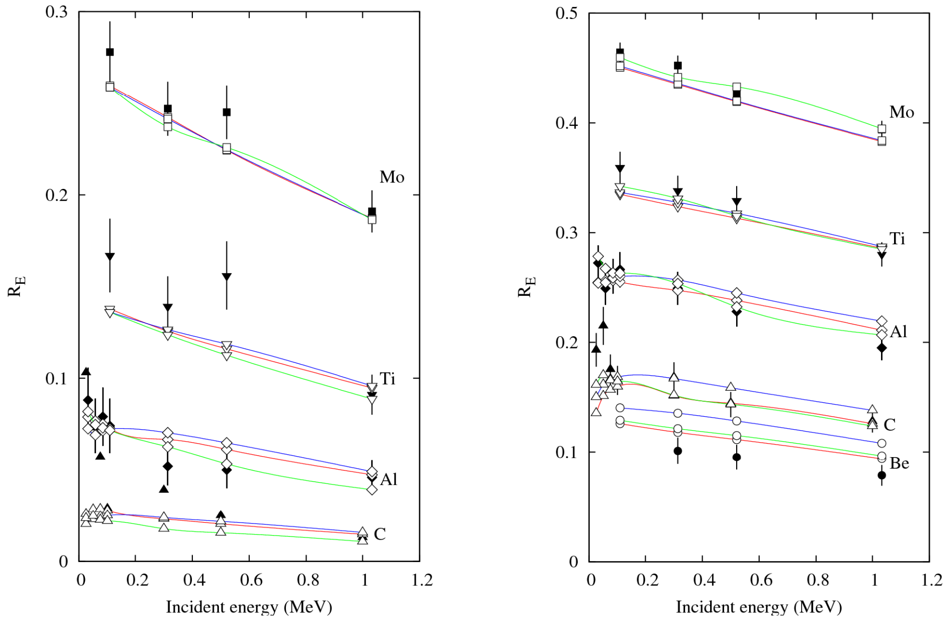


**Figure 4.** Ratio of backscattering electrons from different targets and energies. The left plot is for an incident beam perpendicular to target surface, the right plot for an inclination of 60°. Black points are data from ref. [14], the colored lines with open symbols correspond to Geant4 simulation results for original Urban model – *Urban92* (blue), revised Urban model – *Urban93* (red) and Goudsmit-Saunderson (green).

compared with simulations using different Geant4 MSC models. An example plot is given in figure 2.

In addition MSC for hadrons (pions, kaons, protons and anti-protons) is investigated using data from a Fermilab fixed-target experiment [15]. Various targets from Hydrogen to Lead are considered in an energy range from 50–200 GeV/c. The Geant4 MSC models are compared with data and with Moliere theory.

### *3.3. Energy deposition in thin Si layer*

The energy loss spectra for hadrons passing through thin layers of silicon are studied in a dedicated validation test, sensitive to details of the Geant4 fluctuation model. Simulation results are compared with data from a review by Bichsel [16], where the energy loss distributions are characterized by the most probable value and the full width at half maximum. Target thickness of 300 $\mu$m and 1565$\mu$m are considered. Figure 5 shows a comparison of the most probable value with experimental data for different particle types and energies.

### *3.4. LHC type calorimeter response*

In addition to validation tests dedicated to selected physics processes, a number of tests compare the overall performance and stability of typical Geant4 calorimeter applications. For example the Atlas EM calorimeter is represented by a simplified calorimeter consisting of a 50-layer stack of 2.3 mm Lead and 5.7 mm liquid Argon layers. Visible energy and resolution for 10 GeV electrons are determined for various cut values and different physics lists. In general results are very stable. With Geant4 version 9.4 a 0.5% increased response is observed, while the relative resolution is not changed. Similar tests exist for simplified crystal calorimeter (CMS type), lead scintillator calorimeter (LHCb), and iron scintillator calorimeter (Atlas).

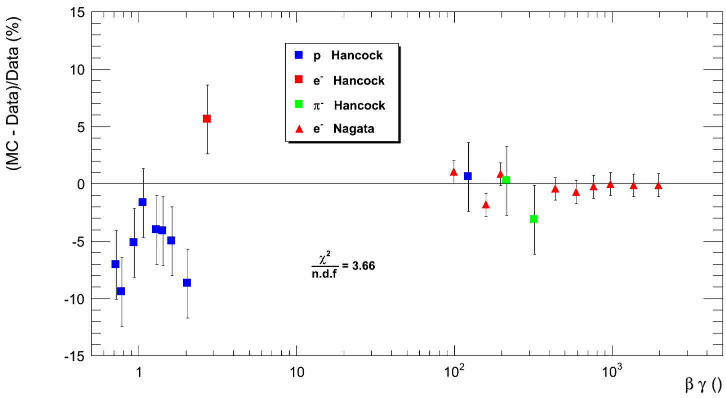


**Figure 5.** Geant4 vs. data [16] comparison of most probable energy deposition in thin layers of silicon (thickness 300 $\mu$m – Hancock; 1565 $\mu$m – Nagata). Difference is given in per cent.

## Summary

The Geant4 toolkit is used in detector simulation applications by most LHC experiments. In order to further improve physics description and guarantee reliable results, the simulation results are continuously validated against previous Geant4 versions and against experimental data or theory predictions.

For the electromagnetic packages, the validation suite has been extended to include tests for electron backscattering, multiple scattering of muons, and energy deposition in thin layers of silicon for various particle types. Recent developments of multiple scattering models and the fluctuation model led to visible improvements in the physics performance. Relativistic models for bremsstrahlung and pair production now consistently treat the LPM effect, and yield a good description of dedicated experimental data. The impact of all these developments on the simulated response of a LHC type calorimeter to EM showers amounts to about 0.5%.

## Acknowledgments

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