Overview and new developments in Geant4 electromagnetic physics

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OVERVIEW AND NEW DEVELOPMENTS IN GEANT4 ELECTROMAGNETIC PHYSICS

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Abstract

We summarize the recent developments and the current status of the Geant4 standard package of electromagnetic physics (G4StEm). The package provides simulation of electromagnetic (EM) interactions of leptons and hadrons in the energy range from 1 keV to 10 PeV. It also includes the simulation of optical photons production and interaction. Thus, a complete simulation can be performed using G4StEm, starting from the beam all the way to the final detector response.

STANDARD PACKAGE

The Geant4 toolkit [1] provides general Monte Carlo simulation of particle transport and interaction with media. EM interactions contribute at all energies for any particle type. A precise description of this physics is the purpose of G4StEm. The package arose naturally from many years of experience gained in Geant3 [2]. It includes precise descriptions of ionization, bremsstrahlung, gamma conversion, and other charged particles and gamma interactions with media. A sub-package for simulation of optical photons emissions and transport is also part of G4StEm.

G4StEm is focused on the simulation of high energy physics (HEP) experiments. The greatest number of events is produced in BaBar experiments [3]. However, it is well applicable to space, medicine, and other studies. G4StEm is continually under development in order to increase precision and performance of its components. The major recent improvements are the following:

- Introduction of production thresholds per region.
- Physics models improvements.
- Design iteration for G4StEm.

Key aspects and some results of these developments will be discussed below.

PRODUCTION CUTS PER REGION

In the Geant4 release 5.1 a design iteration across the toolkit has been done in order to provide the possibility to have different cuts for different sub-detectors. In G4StEm all interfaces use now a G4MaterialCutsCouple object, which includes information both on material and on production thresholds for gamma, electrons, and positrons. These production thresholds are unique for each G4Region – a summary object associated with some part of the geometry setup.

PHYSICS MODEL IMPROVEMENTS

Multiple Scattering Model

Geant4's multiple scattering model (MSM) [4] is based on Lewis theory [5]. It samples the scattering angle and the lateral displacement of a particle after each step. It is applicable for small and big steps taking into account scattering both on atomic electrons and nuclei. Since MSM is important to many applications, it must be compared with the data for different energies (Figs.1-3). We also compared results with the Highland formula [6], which is used widely in HEP.

The results of comparisons show that the new Geant4 model is closer to data than the Geant3 model based on Moliere's approach. The recent upgrades of the model decrease the dependency of the results on step size of a particle in the simulation.

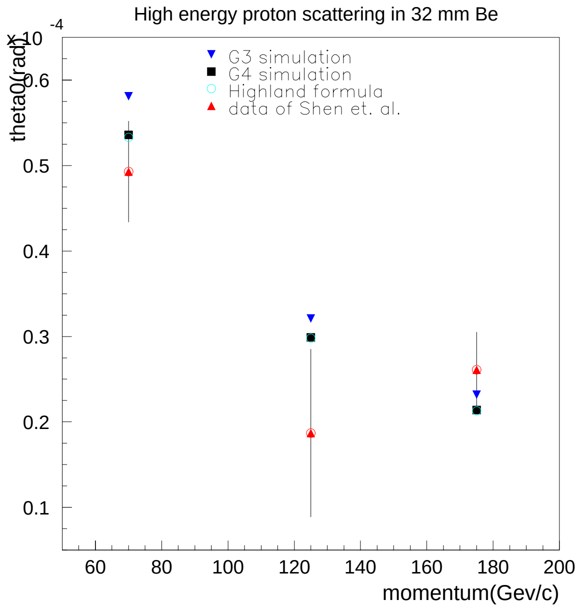

Figure 1: Multiple scattering for high energy protons.

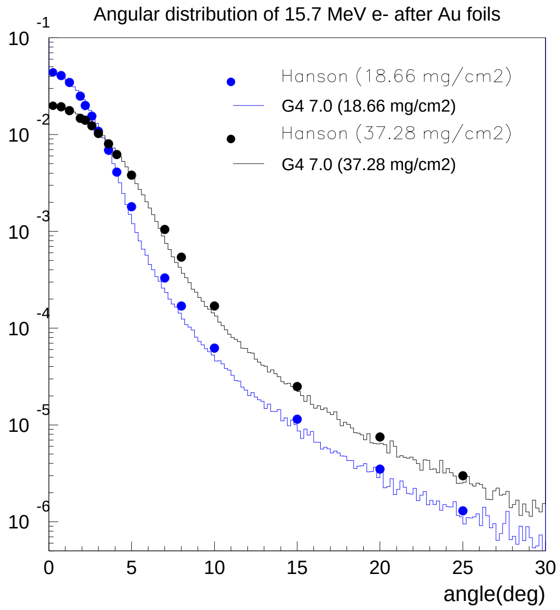

Figure 2: Multiple scattering for electrons.

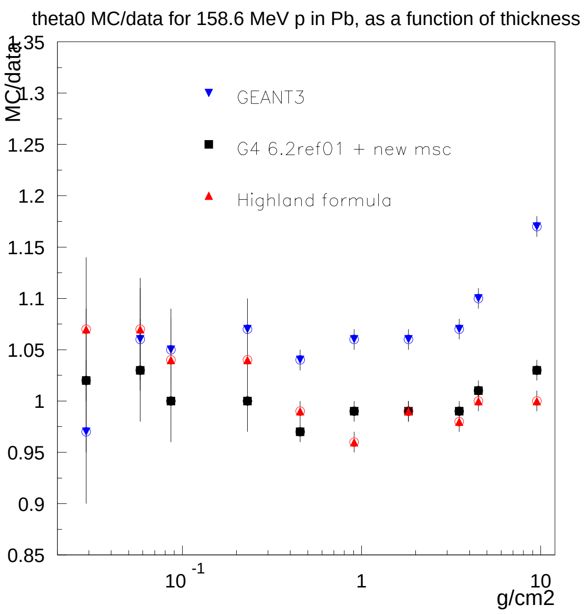

Figure 3: Multiple scattering for protons.

Photo Absorption Ionization Model (PAI)

Geant4's PAI [7] provides for a detailed simulation of ionization. Since the Geant4 release 6.0 it can be defined per G4Region. With the release 6.2 two variants are distributed: G4PAIModel and G4PAIModelWithPhoton, which provide also a sampling of energy transfer to media excitations. The predictions of all available models for the signal of a gaseous chamber (Fig.4) well describe the data. However, PAI has a major advantage – it can work with any production threshold, even zero. Thus, it can be used for detailed simulation of complicated gaseous detectors including transition radiation detectors [8].

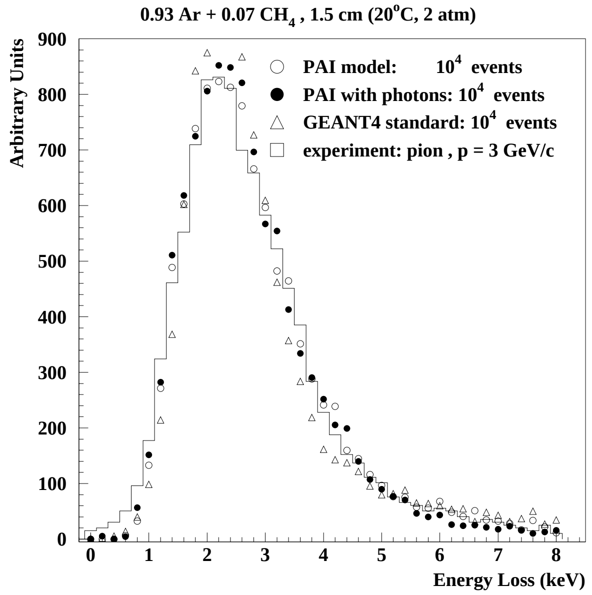

Figure 4: Geant4 simulation of gaseous detector.

Muon Energy Loss

Muon energy losses are simulated as the sum of contributions of the following processes (Fig.5): ionization, bremsstrahlung, e^+e^- pair production. Nuclear interactions are simulated as a discrete process without a contribution to continuous energy loss.

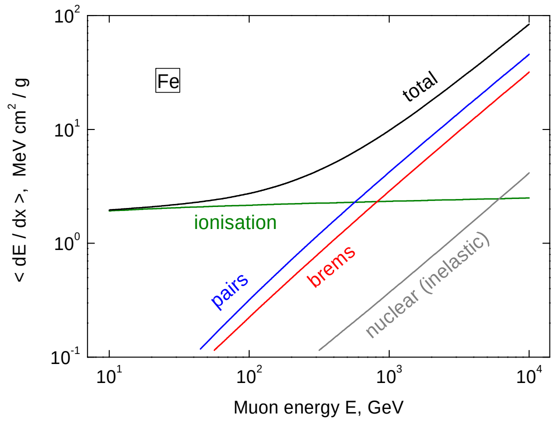

Figure 5: Average muon energy loss in iron.

Three models are used for the ionization process at different muon kinetic energies: ICRU49 parameterisation below 0.2 MeV [9], Bethe-Bloch model, and Bethe-Bloch model with radiative corrections above 1 GeV [10].

The e^+e^- pair production process was also reviewed. As a result, the precision of sampling the differential cross section improved to better than 5% over the full energy region of the model [11]. The initialization time was also reduced significantly.

Ion Interactions in G4StEm

We implemented a new ion ionization process. The process should be instantiated for a G4GenericIon and is used for simulation of ionization of all nuclear fragments produced during simulation. The model if based on a scaling relation for ionization of heavy particles and the effective charge approach [12]. During tracking of an ion in a media, the effective charge is recalculated after each step and this value is used both for transportation in a field and for sampling the scattering angle. MSM is instantiated once for a G4GenericIon and in run time all calculations for any ion are performed on the fly.

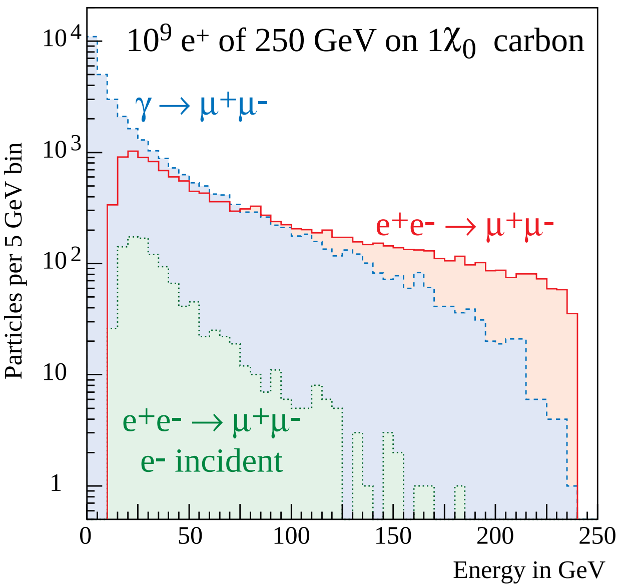

Figure 6: Geant4 simulation of muon pair production.

High Energy Processes

A set of high energy processes is being developed as a part of G4StEm. The following new processes are available:

$$\gamma \rightarrow \mu^+\mu^- \quad (\sigma \sim Z^2),$$

$$e^+ \rightarrow \mu^+\mu^- \quad (\sigma \sim Z),$$

$$e^+ \rightarrow \pi^+\pi^- \quad (\sigma \sim Z).$$

The first process is due to gamma-atom interactions [13], while other two are annihilation processes of positrons with electrons of the media [14, 15]. The cross sections of these processes are small (Fig.6). However, they can produce a significant background for linear collider experiments and the LHC search for rare events.

Optical Photons Transport

The process of 'wave-length-shifting' (WLS) has been added to the list of optical photon processes. This makes it possible to simulate scintillation detectors with WLS-fiber read-out. As well, the scintillation process has been made more complex allowing for both a slow and a fast component with different emission spectra.

DESIGN ITERATION

For many years G4StEm has been used in different applications. In the meantime it was also extensively upgraded with the side effect that architecture problems accumulated. In order to provide better bases for further extensions and to improve performance of the package a complete design iteration has been done.

Requirements to New Design

On account that the package is used intensively in various productions the strong requirements arise:

- user interface must be unchanged;
- physics must be unchanged or improved;
- physics models decouple from routine management;
- remove pieces of repeated software;
- reduce number of static objects;
- decouple ionization and bremsstrahlung;
- provide for the possibility to combine in one process models for different energy ranges;
- allow for the possibility to define a model per G4Region;
- allow for the possibility to use different models of straggling for different particles;
- provide an integral method for sampling of interaction length.

Implementation Details

The key to the implementation are three interfaces: G4VEnergyLossProcess, G4VEmProcess, and G4VMultipleScattering. These generic processes perform all common calculations for the concrete process. The processes are kept but their functions were completely changed. In the new design they are responsible for defining a set of models and perform the initialization. Physics models are realised via a G4EmModel generic interface. The advantage of this design is that to create a new model only the physics needs to be implemented and all management will be performed by generic classes.

The only static object in the package is the singleton G4EnergyLossManager which is responsible for registration, de-registration of processes, external access to processes, and for organisation of physics tables.

The migration was done in small increments with about 15 tests after each step. For backward compatibility all processes from the release 5.2 are kept as an alternative together with the updated processes in releases 6.0 and later.

Performance of G4StEm

One of the main results of the redesign of G4EmSt is the performance improvement. According to estimates of production coordinators of CMS and HARP, the size of EM tables has been reduced by roughly a factor two. The initialisation time is reduced by a factor two as well. The run time required for simulation of one event is also at least 10% less. This number strongly depends on production threshold and geometry. In Fig.7 this dependency is demonstrated for a liquid argon sampling calorimeter similar to ATLAS HEC. The physics quality of the results is also improved. For the same sampling calorimeter the results obtained with the release 6.2 are in better agreement with the test beam data (Fig.8).

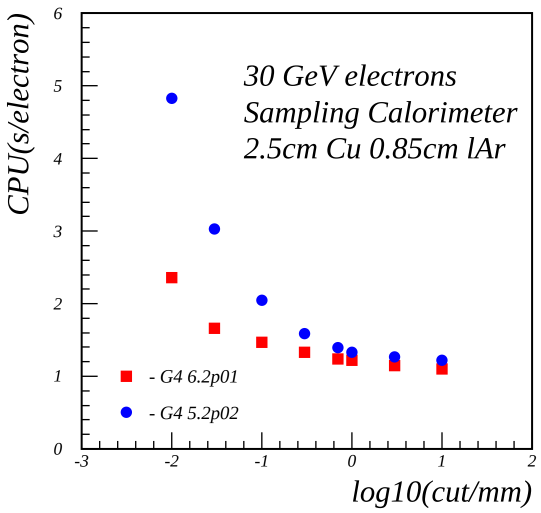

Figure 7: CPU for 2.4 GHz 512 KB PC Linux.

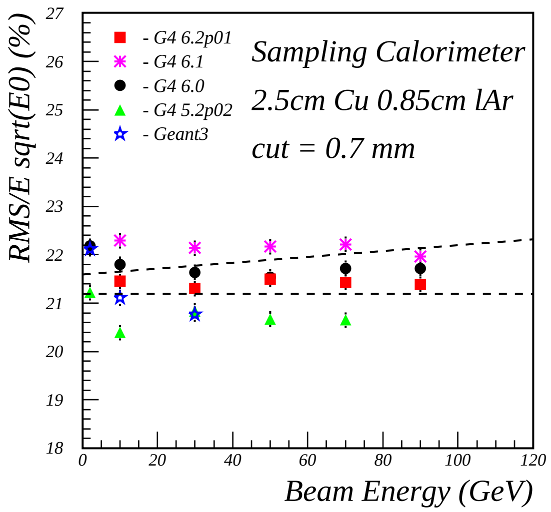

Figure 8: Energy resolution: dashed line -1σ road of data.

PHYSICS LISTS FOR EM USE-CASES

To make it easy for the user to combine an optimal combination of physics models a new package was released with Geant4 6.2, "electromagnetic_lists". It includes a number of builders for QED, muon, hadron, and high energy processes. A steering class G4EmOptions defines the energy scale of the application, verbosity level, and other details of EM processes. The methods of compilation of PhysicsList are demonstrated in extended EM examples. Remarkably, the dependence of results shown in Fig.8 on a release is significantly less if the best combination of processes is used.

ACCEPTANCE SUITE

To insure stability of the simulation results for long-term production for LHC detectors and other applications, a testing suite for G4StEm is under development. Currently, the testing suite is based on extended electromagnetic examples distributed with Geant4. These examples cover all major aspects of EM physics. The following three levels of tests are suggested:

- check of cross sections and stopping powers;
- check of average energy depositions, resolutions, scattering angle;
- comparisons of test distributions with control ones.

For the first type of tests a new class G4EmCalculator was designed. It provides several methods to access cross sections and stopping powers. The second type of tests is realised as part of EM examples. The last level of testing is under discussion.

CONCLUSIONS

In conclusion, we emphasize that G4EmSt has been redesigned and as a result the performance has been improved and various new developments were accelerated.

ACKNOWLEDGEMENTS

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