The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
Chattanooga, Tennessee, April 17–21, 2005, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2005)

GEANT4 "STANDARD" ELECTROMAGNETIC PHYSICS PACKAGE

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ABSTRACT

The status of Geant4 "Standard" electromagnetic package is presented. The package provides simulation of electromagnetic 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 interactions. Thus, a complete simulation can be performed with the package, starting from the beam all the way to the final detector response.

Key Words: Geant4, simulation, multiple scattering, ionization

1 INTRODUCTION

The Geant4 toolkit [1] provides general Monte Carlo simulation of particle transport and interaction with media. Electromagnetic (EM) interactions contribute at all energies for any particle type. A precise description of this physics is the purpose of the Standard Electromagnetic Package (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 emission and transport is also part of G4StEm.

G4StEm is focused on the simulation of high energy physics (HEP) experiments [3−5]. A very large number of events has been produced for the BaBar experiment [6]. It is well applicable to space, medicine, and other studies. Being intensively used for production in HEP G4StEm is continually under development in order to increase precision and performance of its components. The major recent improvements in the package are two design iterations. A number of physical models have been revised and new models have been added. The key aspects and some results of these developments will be discussed below.

2 DESIGN ITERATIONS

2.1 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 or other geometrical regions [7]. For that a new class G4Region was introduced. It is an object associated with some part of the geometry. The production cuts are unique for each G4Region. In G4StEm in many cases a G4MaterialCutsCouple object is used now instead of G4Material. This object includes information both on material and on production cuts. The design iteration was performed according to requirements established by LHC experiments and is used already in LHC detector simulations.

2.2 Model approach

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 significant design iteration has been done.

Taking into account the fact that the package is already used intensively in various productions, the following requirements have to be met:

1. user interface must be unchanged;
2. physics must be unchanged or improved;
3. decouple physics models from routine management;
4. decouple ionization and bremsstrahlung;
5. provide for the possibility to combine in a process several models for different energy ranges;
6. allow for the possibility to define a model specific to G4Region;
7. allow for the possibility to use different models of straggling for different particles;
8. provide an integral method [8] for sampling of interaction length;
9. remove pieces of repeated software;
10. reduce number of static objects.

The key to the revised design of the model variant of EM processes are three abstract classes: G4VEnergyLossProcess, G4VEmProcess, and G4VMultipleScattering. These classes perform common calculations for a concrete process. EM physics process classes retain but their private methods have been completely changed. In the new design, they are responsible for defining of a set of models and perform the initialization. Physics models are realized via a G4EmModel abstract interface, which requires implementation of the cross section calculation, of the restricted energy loss calculation, of the final state generation, and of few other methods. All management methods are implemented inside classes mentioned above.

The one static object in the package is the singleton G4EnergyLossManager, which is responsible for registration, de-registration of processes, external access to processes, and for the organization of the physics tables. The new utility class G4EmOptions provides steering of all EM processes. Another new utility, the G4EmCalculator, provides interface to physics tables and on-fly calculation of energy loss, cross sections, and mean free path values.

The migration was done for the Geant4 release 6.0. To provide continuity and extra safety in the transition period the physics processes classes from the release 5.2 are renamed and kept as an alternative together with the updated processes.

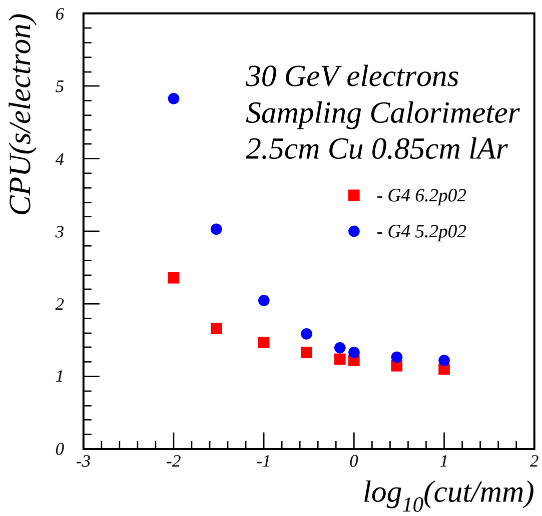

Figure 1. CPU for 2.4 GHz 512 kB PC Linux as a function of cut in range. The same value of the cut is used for gamma, electrons, and positrons.

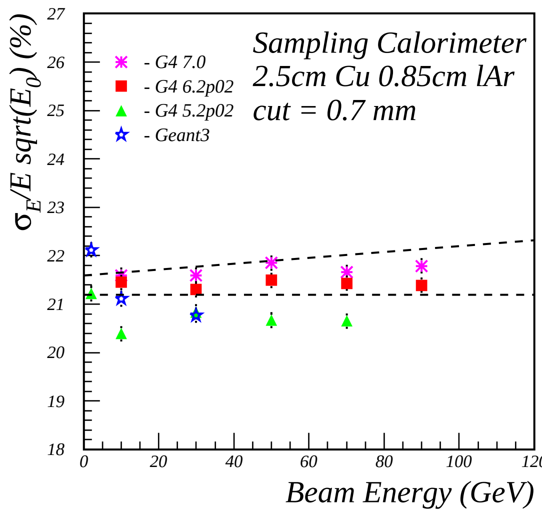

Figure 2. Energy resolution in the sampling calorimeter a a function of beam energy: dashed lines show 1σ road of the data [4].

2.3 Results of Redesign

The first benefit of the redesign of G4StEm is the performance improvements. The size of EM tables has been reduced by roughly a factor two. The initialization 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.1 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 releases 6.2 and 7.0 are in better agreement with the test beam data (Fig.2). It is the effect of the integral method of the sampling of EM showers.

2.4 Developments Triggered by Redesign

We implemented a new ion ionization process G4ionIonisation. The process should be instantiated for the particle type G4GenericIon and is used for simulation of ionization of all nuclear fragments produced during simulation. The model is based on a scaling relation for ionization of heavy particles and the effective charge approach [9]. 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.

Currently it is also possible to define different EM physics models for each G4Region. For example, Photo Absorption Ionization Model (PAI) [10] provides for a detailed simulation of ionization. This simulation can be very time consuming and may be only practical if it is restricted to specific detector regions. With the release 6.2 two variants are distributed: G4PAIModel and G4PAIPhotonModel. Currently, the first model is recommended for the use in production. The second one provides a sampling of energy transfer to knock-on electrons or also to photons. It is still under development and can be used only as a prototype. The predictions of all available models for the signal of a gaseous chamber (Fig.3, 4) well describe the data [11, 12]. 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 [13].

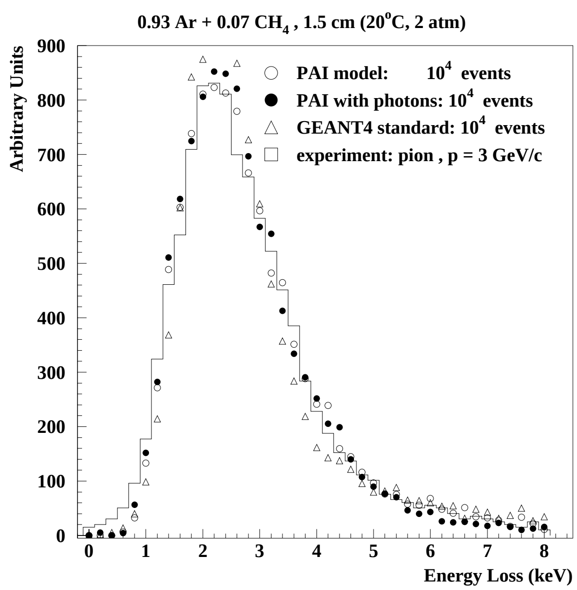

Figure 3. Geant4 simulation of the drift chamber filled with Ar/CH_4: histogram – data [11], points – simulation.

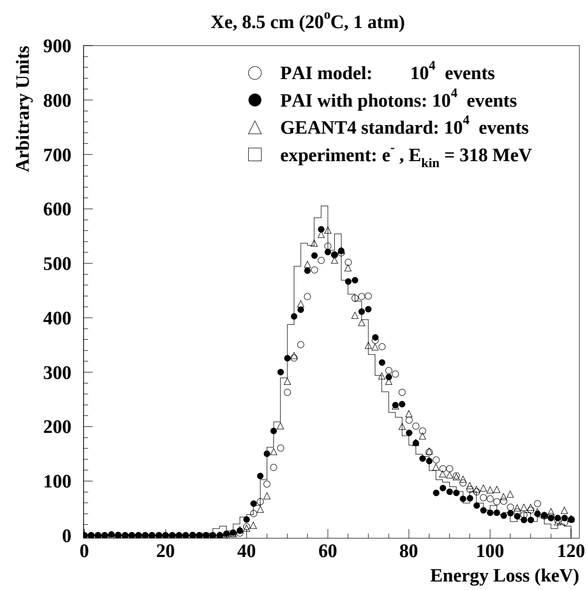

Figure 4. Geant4 simulation of the drift chamber filled by Xe: histogram – data [12], points – simulation.

3 PHYSICS MODEL IMPROVEMENTS

3.1 Multiple Scattering Model

Geant4's multiple scattering model [14] is based on Lewis theory [15]. 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 on both atomic electrons and nuclei. For ions, the multiple scattering process is instantiated once for the G4GenericIon and in run time all calculations for any ion are performed on the fly. The model was evaluated for recent releases in order to provide more stable simulation and less step dependence of simulation results.

Since multiple scattering is important to many applications the benchmark of comparisons is created. 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. Some results of the Monte Carlo simulation, of the Highland formula [16] predictions, and the data [17-19] are shown in Figs.5-8.

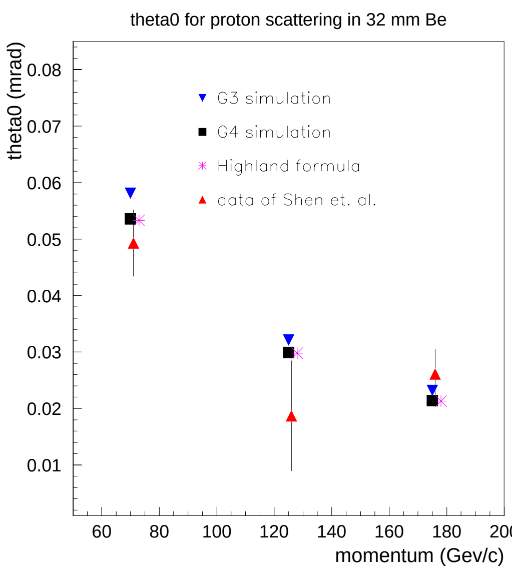

Figure 5. Multiple scattering for high energy protons in beryllium: simulations, Highland formula predictions, and the data [17].

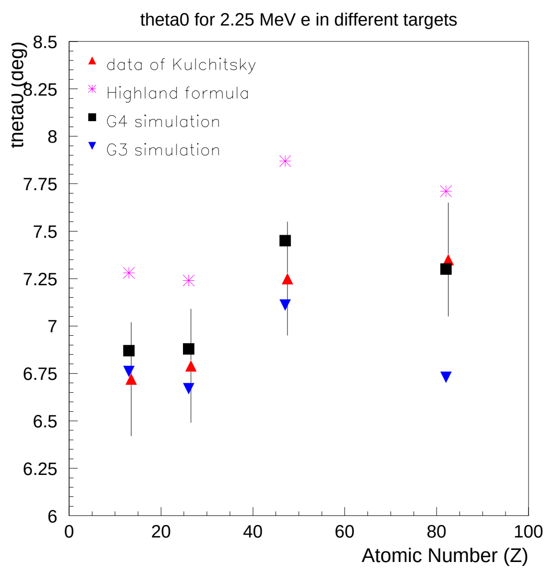

Figure 6. Multiple scattering for low energy electrons in different targets: simulations, Highland formula predictions, and the data [18].

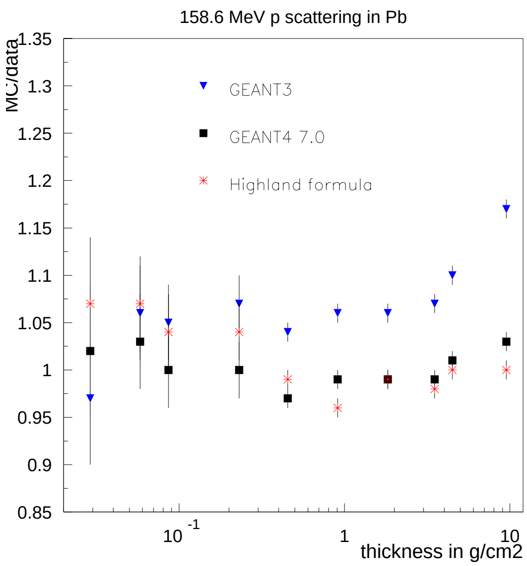

Figure 7. Multiple scattering of 158.6 MeV protons in thin lead foil as a function of the thickness. Simulation angle is divided by the data angle [19].

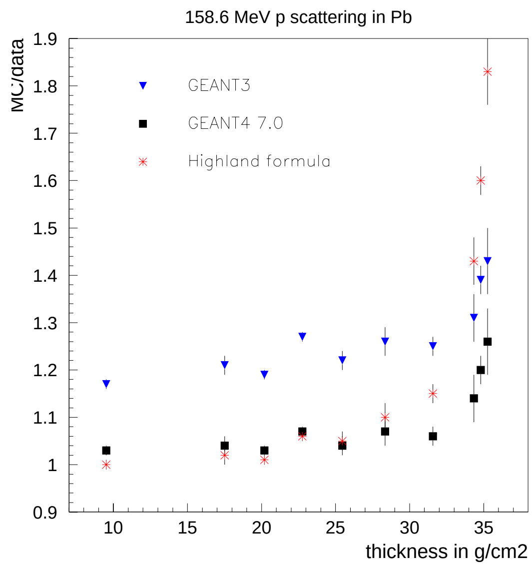

Figure 8. Multiple scattering of 158.6 MeV protons in thick lead foil as a function of the thickness. Simulation angle is divided by the data angle [19].

3.2 Muon Interactions

There are four basic processes of muon interaction that determine muon energy loss and generation of secondary showers in matter: ionization (including production of high-energy knock-on electrons, or δ-rays), direct production of electron-positron pairs, bremsstrahlung, and inelastic muon interaction with nuclei. Since the main contribution to the latter is given by low-Q^2 region which is usually described in terms of nuclear absorption of virtual photons, it is often called "photonuclear" muon interaction.

The dependence of macroscopic differential cross sections σ(E,ε) of these four processes in iron for two values of muon energy on the relative energy transfer v = ε/E is shown in Fig. 9. E is the muon energy and ε is the energy transfer. For convenient representation, the cross sections in the plot are multiplied by ε. The relative importance of a given process depends on the muon energy, atomic number Z and atomic weight A of the material. At moderate muon energy practically in the whole region the main interaction process is the production of knock-on electrons (in iron, E < 100 GeV). At high energies, the relation between the cross sections of different processes is drastically changed. For example, for E = 10 TeV in a wide range of energy transfer direct electron pair production dominates, for v = 10^{-4}– 10^{-2} its cross section being by 1-2 orders of magnitude greater than that of other interaction processes and the relative contribution of the knock-on electron production becomes negligibly small.

Cross sections of muon bremsstrahlung, electron pair production by muons, and of inelastic muon interaction with nuclei nearly scale with the relative energy transfer:

$$\varepsilon\sigma(E,\varepsilon) = v\sigma(E,v) \approx f(v).$$

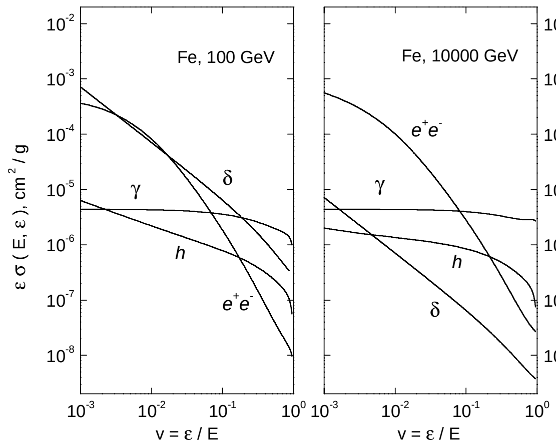

Figure 9. Differential cross section for muon interaction processes in iron.

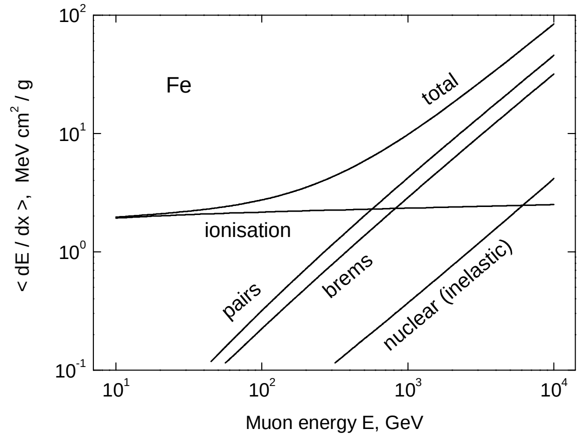

Figure 10. Average energy loss of muons in iron.

Hence, the average muon energy loss related to these processes increases almost linearly with muon energy (Fig. 10). By analogy with the electrons, the combined contribution of these three processes to the total muon energy loss is often called "radiation loss". However, it should be noted that (unlike for electrons) the bremsstrahlung process is strongly suppressed because of a large muon mass. Contrary, direct electron pair production and photonuclear interaction play an important role (contribution of pair production is even higher than that of bremsstrahlung). Similar to electrons, muon critical energy E_{cr} may be defined as the value at which the average ionization and radiation energy losses are equal [20]; for iron, $E_{cr} \approx 340$ GeV.

Muon energy losses are simulated as the sum of contributions of the mentioned processes: ionization, bremsstrahlung, and e^+e^- pair production. Nuclear interactions are simulated as a discrete process without a contribution to continuous energy loss. Three models are used for the ionization process at different muon kinetic energies:

1. $E < 0.2$ MeV, ICRU49 parameterization [21];
2. 0.2 MeV $< E < 1$ GeV, Bethe-Bloch model;
3. 1 GeV $< E$, Bethe-Bloch model with radiative corrections above 1 GeV [22].

The e^+e^- pair production process was also revised. As a result, the precision of sampling the differential cross section improved to better than 5% over the full energy region of the model [23]. The initialization time was also reduced significantly.

3.3 Optical Processes

The process of 'wave-length-shifting' (WLS) has been added to the list of optical photon processes [24]. 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.

4 RARE HIGH ENERGY PROCESSES

A set of high-energy processes is being developed inside the Geant4 Standard Electromagnetic Package. The cross sections of these processes are relatively small. However, these processes may provide a serious background for high energy experiments.

One of the new processes is gamma conversion to muon pair in electric field of a nucleus. The cross section is proportional to Z^2. There is also a weaker logarithmic dependence on Z and A. The details of theory and implementation are described in [25]. Because of this process, muon pairs can be produced by high energy photons in dense materials of LHC detectors or in beam elements of a linear collider.

The annihilation of positrons with atomic electrons into muon pairs [26] requires a minimum energy of the positron of

$$E_{th} = 2m_\mu^2/m_e - m_e = 43.69 \text{ GeV}.$$

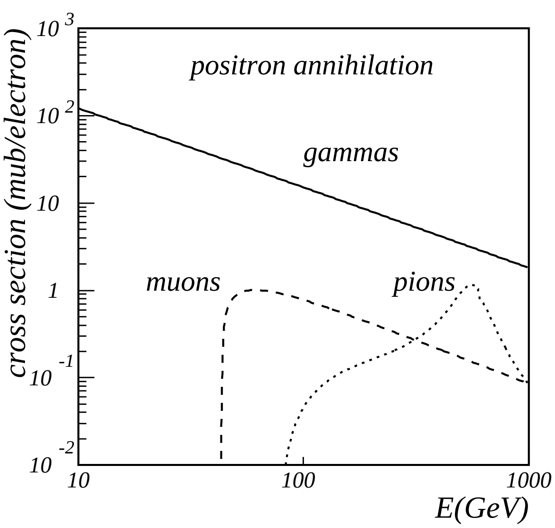

Figure 11. Cross sections per media electron of positron annihilation.

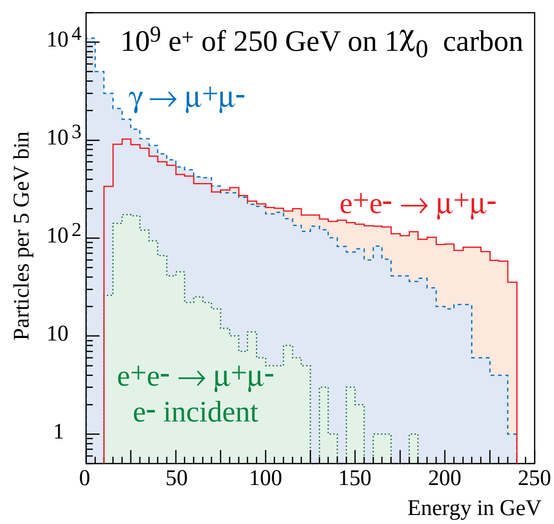

Figure 12. Muon energy spectrum in the beam pipe of 250 GeV linear collider. After a carbon collimator of one radiation length thick.

The motion of media electrons is negligible, so formulas for cross section of electron-positron annihilation are applicable to this process in the kinematical condition of positron annihilation with resting electron. In contrast to the scaling with Z^2 for the photon conversion in the field of the nucleus, we are dealing here with the interaction with atomic electrons, which scales with Z. Its cross section is small compared to the two-gamma annihilation (Fig. 11). However, this reaction may be a source of background for different HEP experiments.

Electron-positron annihilation to hadrons has been studied for many years in e^+e^- colliders over a large range of energies and the cross sections involved are well known. A first implementation of positron annihilation to hadrons is now available in Geant4. The threshold for the process is

$$E_{th} = 2m_\pi^2/m_e - m_e = 70.35 \text{ GeV}.$$

In the first Geant4 implementation of hadron production by positron, only pion pair production is simulated. The validity range of the model is limited to 1 TeV. For these energies the following reaction dominates:

$$e^+e^- \rightarrow \gamma\rho \rightarrow \pi^+\pi^-\gamma,$$

where γ is a radiative photon, which is emitted by initial electron or positron. This radiative correction is essential, because it significantly modifies the resonance shape of the ρ-meson (Fig.11). Details of the theory used are described in [27], in which the main terms and the leading α^2 corrections for this reaction are taken into account.

5 BACKGROUND IN LINEAR COLLIDERS

Muon production in high energy electromagnetic showers can be a major source of background for high energy linear colliders. From initially 10^{10} particles in the beam, a fraction of 10^{-3} may hit collimators and produce thousands of muons which could travel over several kilometers through the vacuum chamber and reach the detector region. A good simulation is essential for the design of the collimation system, the final focus region and the detectors.

Several stages of collimation inside a linac will be necessary. High Z-materials like lead or tungsten would easily be destroyed under primary beam impact. For the first stage of collimation, relatively thin spoilers made of carbon are considered. For carbon ($Z = 6$), the muon production by gamma conversion and positron annihilation will be comparable (Fig. 12). The positron annihilation is the dominant source of high energy muons, close to the positron energy. For an electron beam, positron annihilation only plays a minor role as a secondary process in the electromagnetic cascade in the production of lower energy muons.

The process of positron annihilation to hadrons provides hadron background in the beam pipe. It also increases the number of background muons because of pion decay.

6 USER SUPPORT

To ensure stability of the simulation results for long-term production for LHC detectors and other applications, an extended testing suite for G4StEm is under development. The following three levels of tests are suggested:

1. check of cross sections and stopping powers;
2. check of average energy depositions, resolutions, scattering angle;
3. 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 or to calculate cross sections, stopping powers, and ranges. The second type and the third level of tests are based on extended EM examples distributed with Geant4. These fourteen examples cover major aspects of EM physics.

7 CONCLUSIONS

In conclusion, we emphasize that G4StEm has been redesigned and as a result the performance has been improved and various new developments have been accelerated. The CPU performance of the simulation with low production thresholds was upgraded significantly. The initialization time is reduced and the size of the tables calculated during initialization is reduced as well. The multiple scattering model have been improved significantly. Two new PAI models are available for simulation of gaseous detectors and thin solid absorbers. The improvements in testing and user support are in progress.

8 ACKNOWLEDGEMENTS

We thank John Apostolakis for valuable comments. We are also grateful for many Geant4 collaborators and users for discussions and testing.

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