PROCEEDINGS of
CHEF 2013

Simulation of Showers with Geant4

Andrea Dotti*
SLAC National Accelerator Laboratory, Stanford, California 94309, USA
E-mail: adotti@slac.stanford.edu

On behalf of

the Geant4 Hadronic and Electromagnetic Working Groups

The simulation of electromagnetic and hadronic showers plays an essential role for both the design of detectors and the analysis of data in high-energy physics experiments. Electrons, gammas, taus and jets are important physics objects that require an accurate shower simulation. For the accurate simulation of electromagnetic showers, the challenge is to match the high precision of modern electromagnetic calorimeters. For the simulation of hadronic showers, the main difficulty comes from the inapplicability of perturbative quantum-chromodynamics (pQCD) and therefore the need to rely only on approximate, hadronic models. In addition, experimental effects like non-compensation and leakage play an important role. Since these last aspects are detector specific, we will concentrate on general and common features of the simulation of electromagnetic and hadronic showers in Geant4 . The focus will be on high-energy physics calorimeters at present and future colliders. Many improvements of Geant4 physics models have been driven by the need to improve the agreement with calorimeter test-beam data on shower observables (energy response, energy resolution, longitudinal and lateral shower profiles). The tuning and validation of each model relies exclusively on thin-target published data, whereas thick-target data are used only at the end to check the overall quality of the simulation of showers.

Calorimetry for High Energy Frontiers - CHEF 2013,
April 22-25, 2013
Paris, France

*Speaker.

1. Introduction

Geant4 is a toolkit for Monte Carlo simulation of the transportation and interaction of particles in matter [1, 2]. It can be used in a wide variety of applications including high energy physics, space and medical science. The toolkit is the de-facto standard for the simulation of high energy physics experiments: all LHC experiments use Geant4 to study in detail the expected detector performances. Three of them regularly use Geant4 to produce the large-scale simulated datasets to study the performance, calibration and tuning of the detector; and to develop the analysis algorithms used on real data.

One of the most challenging aspects of detector simulation for high-energy physics is the precise description of jets and isolated electrons and gammas. Jets are composite objects formed by a set of collimated particles (both in space and momentum): mainly photons (from neutral pion decays), charged pions and nucleons.

At current and future high energy physics experiments all calorimeters are segmented, at least in two main sections: an electromagnetic calorimeter, optimized to measure the energy of electrons and gammas; and a hadronic calorimeter, optimized to contain and measure hadron showers. Different materials and read-out technologies are used in different regions of the experimental apparatus and often the calorimeters are sub-divided in towers and cells. This segmentation can be exploited to improve the energy measurements (for example with the weighting techniques used by the ATLAS experiment); or even to distinguish the sub-structure of jets in terms of its content (energy flow techniques, used by the CMS experiment). Future calorimeters designed for the International Linear Collider (ILC) will benefit from very high granularity to observe shower sub-structure. It is clear that a precise description of the dimensions of showers (in particular the showers induced by high energy hadrons) is an important aspect for analyses based on these techniques to reduce the systematic error due to imprecise shower descriptions.

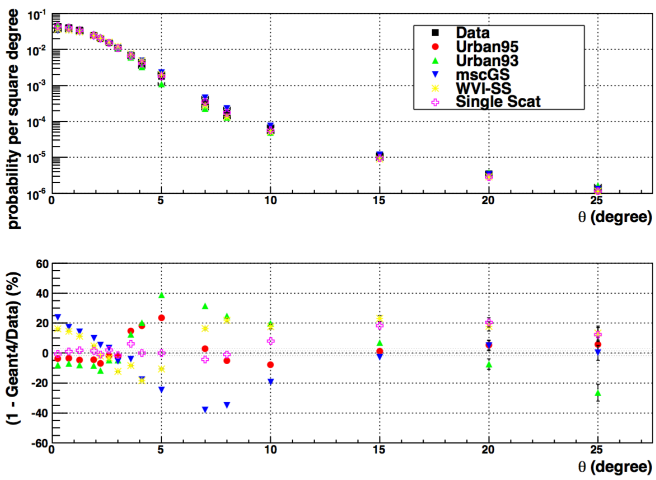

Figure 1: Comparison of predictions for different Geant4 multiple-scattering algorithms with experimental data [3] for 15.7 MeV electrons scattering off 9.68μm Gold foil: angular distribution (top); Monte Carlo over data (bottom). *Urban 95* model and the *single scattering* model provide overall better agreement with the data.

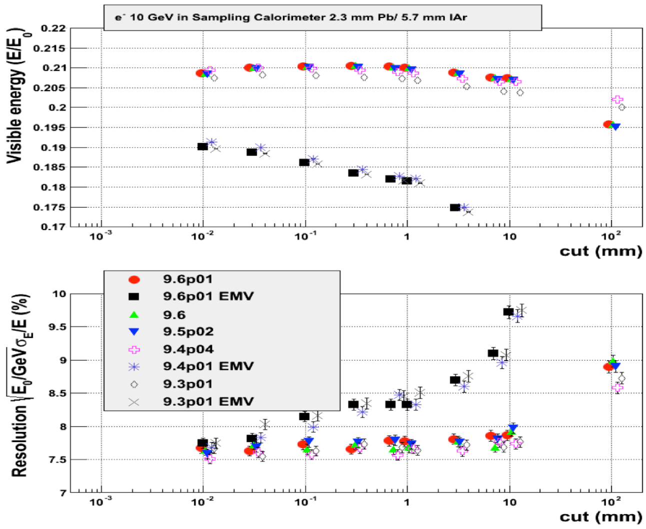

Figure 2: Visible energy and resolution for a 10 GeV electron response in a simplified sampling calorimeter with 2.3 mm Lead and 5.7 mm liquid Argon as a function of the production cut range for different Geant4 versions. With the exception of the fast EM physics (EMV), all versions of Geant4 yield stable responses over a wide range of cut parameters.

2. Electromagnetic showers

The Geant4 *standard electromagnetic* physics sub-packages [4, 5, 6, 7] are important components of the toolkit. Stability and accuracy of the simulation results for large scale simulation production are major requirements for Geant4 .

Significant efforts have been made to improve the simulation of EM shower shapes in order to describe the details of H$\rightarrow\gamma\gamma$ signal [8, 9] and other reactions. The Bremsstrahlung process and the simulation of multiple scattering were reviewed and improved, having been identified as key components in defining EM shower shapes. Calorimeters are particularly sensitive to the simulation of electron and gamma transport in MeV energy region. Therefore a significant validation and benchmarking are being carried out for medium and low-energy electrons and gamma. For these validation studies experimental data are used as well as a comparison with other Geant4 models of low- energy EM, the sub-packages Livermore and Penelope, which have been recently adapted to a common interface with the Standard EM sub-packages [10].

The process of multiple scattering (MSC) of charged particles is a key component of Monte Carlo transport codes. At high energy it defines the deviation of charged particles from ideal tracks, limiting the spatial resolution of detectors. The scattering of low-energy electrons defines the energy flow via volume boundaries. This affects the sharing of energy between absorbers to sensitive elements directly affecting shower shapes. The Geant4 toolkit offers several models for the simulation of multiple scattering [11]. The production model is developed by L.Urban and it is used in Geant4 by default. Because of high sensitivity of simulation results on MSC model for high statistics Monte Carlo production for LHC experiments, any modification of the Urban model algorithm is provided in a separate C++ class. This approach allows to configure backward compatible physics lists with new versions of Geant4 . In particular, *G4UrbanMscModel95* provides better agreement with the scattering data [3] for electrons (Figure 1) than the previous version of the model *G4UrbanMscModel93*. With the exclusion of the data points around 5 degrees and the very far tail the agreement with experimental data is at the level of few percent. The list of upgrades introduced in this model include:

- New tuning of tail of scattering function;
- Added sampling of correlations between scattering angle and lateral displacement for a step;
- Added sampling of end of step position along particle direction.

A comprehensive description of recent improvements of Geant4 EM module can be found in [12]. The general agreement of Geant4 predictions with experimental data collected at LHC is better than percent [13]: Geant4 predictions for response and resolution are stable since several versions of Geant4 as it can be seen from Figure 2 where the response (top) and resolution (bottom) is compared for different options and versions as a function of the production cut[1].

3. Hadronic showers

There is no theory for the interaction of hadrons with matter valid for all energies and particle species. A *physics list* is a collection of models covering the full energy range for a given application. For high energy physics experiments, and in particular for calorimeters, we encourage the use of physics lists based on theory-driven or phenomenological models. Both QGSP_BERT and FTFP_BERT physics lists use an intra-nuclear cascade model at low energy (the Geant4 implementation of the Bertini cascade code [14, 15]) and a quark-gluon string model at high energy (the well-known Fritiof model [16, 17] for FTFP_BERT and the Geant4 quark-gluon-string model for QGSP_BERT). The differences between the two physics lists are mainly on the energy ranges where the models are applied (for a detailed description of the effect of transition between models see [18]). To increase the quality of physics simulations of hadronic showers three main components are needed: a string models at high energies, a cascade model at intermediate energies (from few hundred MeV up to about 10 GeV) and an evaporation and pre-equilibrium model at low energies (below few hundreds MeV). For the three energy ranges we recommend the use of Fritiof, Bertini and *G4Precompound*.

The comparison with LHC test-beam data has shown that a fundamental ingredient to improve the description of the lateral development of showers is the use of an intermediate- and low-energy models that can describe the cascading of hadrons in nuclear matter and the subsequent de-excitation of the wounded nucleus. The longitudinal development of hadron showers mainly depends on the hadronic interactions at higher energies in the forward direction: quasi-elastic scattering and diffraction.

While for response the agreement between simulation and data for hadron-induced showers is at the level of a few percent, shower shapes and resolution are less precisely described and show an

[1]To simulate precisely calorimeter response it is important to choose a production cut such that physics results do not depend on the cut itself: a too large cut can significantly speed-up simulations but could degrade the physics performances.

agreement at a level of 10-20%. Figures 3 show the comparison between the predictions of Geant4 simulations with test-beam data collected by the ATLAS Collaboration [19, 20]. The response to pion beams is shown, as a function of the particle energy, for different versions of Geant4 (left). On the right-side plot similar results are shown comparing, for the latest Geant4 version, the predictions of two different physics lists: QGSP_BERT and FTFP_BERT . Variants of both with high precision neutron description (HP) are also shown. While the Fritiof based physics list show a smoother behavior at intermediate energies [18] and should be preferred over QGS ones, the precise and CPU-time consuming high precision model does not modify this observable (it should be noted [21] that the high precision neutron description plays instead an important role in other calorimetric observables: time structure of the showers and lateral development in neutron rich materials and these extensions should be considered if these are important observables).

A comparison between test-beam data and Monte Carlo calculations for the lateral (left) and longitudinal (right) dimensions of hadronic showers [22] are shown in Figures 4 as a function of the beam energy for different versions of Geant4 simulations. For detailed descriptions of recent developments and validations for these model see [15, 17].

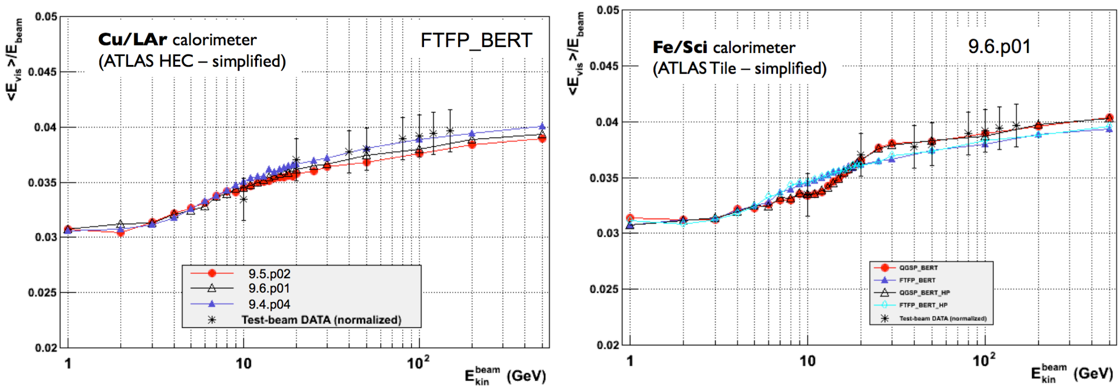

Figure 3: Response to pion beams: (*left*) comparison of recent Geant4 version with test-beam data; and (*right*) comparison between different physics lists.

4. Conclusions

In the past years significant efforts have been put to further improve the quality of Geant4 simulations in view of the LHC data taking. These efforts have led to the Monte Carlo productions that contributed to the Higgs Boson discovery in 2012. Even if the quality of the simulations obtained with Geant4 is satisfactory for current luminosity and energy of LHC, increase in the current generation of experiment performances and the optimal design of a future detector at ILC call for a further refinement of Geant4 simulations.

Calorimetric observables for electrons and gammas are simulated with a precision of better than a percent, at the same time high precision LHC data show that some additional work is needed to improve the lateral shower shape description. A review and validation of all relevant processes (in particular Bremsstrahlung) is under way. Multiple scattering is the challenging process for all Monte Carlo simulation codes. In the past years significant progresses have been achieved with

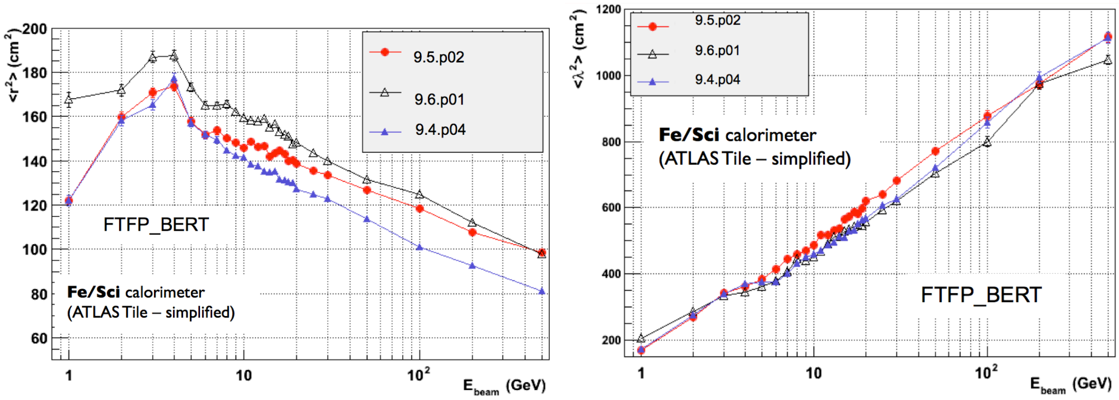

Figure 4: (*left*) Lateral and longitudinal (*right*) pion showers dimensions. Results comparing different Geant4 versions.

several new algorithms and tunings made available. A continuous effort is put in place to validate these models.

For hadrons current precision is about 10%: Fritiof and Bertini models, coupled with de-excitation and evaporation model, are the current best combination to simultaneously describe thin and thick (test-beam) data. Response is described within few percent, while shower shapes need additional attention to improve the current level of agreement (about 10-20%). The focus of the Geant4 developers is concentrated on the description of neutron related process (capture) and further tuning of Bertini cascade parameters, this will refine the description of the lateral dimension of showers. In addition the ongoing tuning of Fritiof model at high energy will better describe the longitudinal description of shower.

References

[1] S. Agostinelli et al. Geant4—a simulation toolkit. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250 – 303, 2003.

[2] J. Allison et al. Geant4 developments and applications. *Nuclear Science, IEEE Transactions on*, 53(1):270–278, 2006.

[3] A. O. Hanson et al. Measurement of multiple scattering of 15.7-MeV electrons. *Phys. Rev.*, 84:634–637, Nov 1951.

[4] A. G. Bogdanov et al. Geant4 simulation of production and interaction of muons. *Nuclear Science, IEEE Transactions on*, 53(2):513–519, 2006.

[5] J. Apostolakis et al. The performance of the Geant4 standard EM package for LHC and other applications. *Journal of Physics: Conference Series*, 119(3):032004, 2008.

[6] V. Ivanchenko et al. Recent progress of Geant4 electromagnetic physics and readiness for the LHC start. In *PoS (ACAT2008)*, page 108, 2008.

[7] A. Schälicke et al. Geant4 electromagnetic physics for the LHC and other HEP applications. *Journal of Physics: Conference Series*, 331(3):032029, 2011.

[8] ATLAS Collaboration. Observation of a new particle in the search for the standard model higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 716(1):1 – 29, 2012.

[9] CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716(1):30 – 61, 2012.

[10] V. Ivanchenko et al. Recent improvements in Geant4 electromagnetic physics models and interfaces. In *The Joint International Conference of the 7th Supercomputing in Nuclear Application and the 3rd Monte Carlo (SNA+MC 2010)*, 2011.

[11] V.N. Ivanchenko, O. Kadri, M. Maire, and L. Urban. Geant4 models for simulation of multiple scattering. *J.Phys.Conf.Ser.*, 219:032045, 2010.

[12] J. Allison. Geant4 electromagnetic physics for high statistic simulation of lhc experiments. *Journal of Physics: Conference Series*, 396(2):022013, 2012.

[13] E. Abat et al. Photon reconstruction in the ATLAS inner detector and liquid argon barrel calorimeter at the 2004 combined test beam. *Journal of Instrumentation*, 6(04):P04001, 2011.

[14] Geant4 Collaboration. Physics reference manual, available at: http://geant4.org.

[15] D. Wright. Improving the medium and low energy physics models in Geant4. In *In this proceedings*.

[16] B. Andersson et al. A model for low-pT hadronic reactions with generalizations to hadron-nucleus and nucleus-nucleus collisions hadronic reactions with generalizations to hadron-nucleus and nucleus-nucleus collisions. *Nuclear Physics B*, 281(1–2):289 – 309, 1987.

[17] V. Uzhinsky. The fritiof (FTF) model in Geant4. In *In this proceedings*.

[18] A. Ribon et al. Transition between hadronic models in Geant4. In *Nuclear Science Symposium Conference Record (NSS/MIC), 2009 IEEE*, pages 526–529, 2009.

[19] P. Adragna et al. Testbeam studies of production modules of the ATLAS tile calorimeter. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 606(3):362 – 394, 2009.

[20] A.E. Kiryunin et al. Geant4 physics evaluation with testbeam data of the ATLAS hadronic end-cap calorimeter. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 560(2):278 – 290, 2006.

[21] A. Dotti. Description of hadron-induced showers in calorimeters using the Geant4 simulation toolkit. In *Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2011 IEEE*, pages 2128–2134, 2011.

[22] A. Dotti et al. Recent improvements on the description of hadronic interactions in Geant4. *Journal of Physics: Conference Series*, 293(1):012022, 2011.