Journal of Physics: Conference Series **219** (2010) 032044 doi:10.1088/1742-6596/219/3/032044

Validation and verification of Geant4 standard electromagnetic physics

J Apostolakis[1], A Bagulya[5], S Elles[4], V N Ivanchenko[1,2,8], J Jacquemier[4], M Maire[4,6], T Toshito[3,7] and L Urban[6]
[1] CERN, 1211 Geneva, Switzerland
[2] Ecoanalytica, 199992 Moscow, Russia
[3]KEK, Tsukuba, Japan
[4] LAPP, 74941 Annecy-le-vieux, France
[5]Lebedev Physics Institute, 119991 Moscow, Russia
[6] Geant4 Associates International Ltd, United Kingdom

Abstract. The software tools developed for the validation and verification of the standard electromagnetic physics package of Geant4 are described. The validation is being performed versus experimental data and in regression to a previous version of Geant4. Examples of validation results are presented.

1. Introduction

The standard electromagnetic (EM) physics package of Geant4 [1-4] has been developed for simulation of particle transport in matter and high energy physics (HEP) detector response [5-9]. Geant4 is the main simulation engine for the ATLAS, CMS and LHCb experiments. The requirements to the precision and stability of Monte Carlo simulation for LHC experiments are well within 1%. In order to keep under control a long-standing quality of the EM package, software suites for its validation and verification have been developed. In this work we describe main approaches for the validation and the structure of validation software.

2. Validation of the Geant4 EM physics package

Geant4 EM package includes simulation of ionisation, bremsstrahlung, photo-electric effect, Compton scattering, multiple scattering and other processes [10]. The main goal of the detailed Monte Carlo simulation of HEP experiments is to provide a realistic response of various particle detectors. LHC applications deal with particle production at 10 TeV proton-proton collisions with high energy secondary particles registered by huge experimental apparatus consisting of many sub-detectors. Even if initial particles are high energy hadrons, the response of HEP calorimeters is sensitive to EM physics simulation at energies below than 1 MeV. Low-energy secondary particles (gamma, electrons, positrons and others) contribute to responses of majority of HEP detector systems providing as main signal and background. Thus, validation of the EM physics package for LHC applications should be done for all particle types and for the complete energy range from 1 keV to the maximum energy of the experiment. It is necessary to control energy loss, ranges, straggling, cross sections and other physics quantities. The validation sequence includes following types of tests:

[7] Current address NIRS, Chiba, Japan
[8] Corresponding author Vladimir.Ivantchenko@cern.ch

- developer unit tests and tests versus specific data;
- low and medium statistic tests with control on basic numbers;
- high statistic regression tests with comparison to data and to results of the previous version of Geant4;
- user validation.

The testing suite for the EM physics has been developed for many years [4, 10, 11]. It is mostly based on official Geant4 code examples distributed together with the toolkit. Thus, allowing any user to repeat validation performed by the Geant4 EM working group. Additionally few special tests are created for the validation of essential experiments or use-cases. The testing suite (Figure 1) includes a data-base of experimental data, a set of Geant4 applications and the additional software, which is needed to perform data conversion from a publication format to the testing suite format, storage of results, regression analysis and publishing of validation results in the web [10].

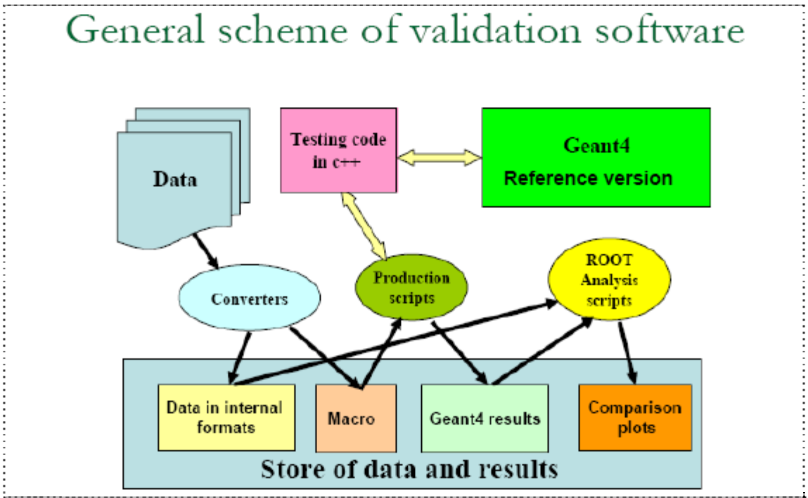

Figure 1. Geant4 EM physics validation.

3. Basic medium statistic tests of EM physics

The core part of the testing suite is a set of medium statistic tests (Table 1), which are run on regular basis by the Geant4 EM physics group after any modification of the EM package. The results are stored in the database for each Geant4 reference version. The same tests are executed by the Geant4 system testing team on all supported software platforms in nightly mode [12]. The selection of initial conditions of these tests was based on following requirements:

- all EM processes and models should be tested;
- all important use-cases should be tested;
- the reference output of physics quantities should be provided for all tests;
- required CPU is limited (< 15 minutes);
- statistical comparisons between simulation results and the data should be performed whenever it is possible;
- statistical comparisons with regression to the previous reference version of the software should be performed whenever it is possible.

The results is qualified as “accepted” if no warning or errors appears during execution and obtained results of all tests are in statistical agreement with the reference values within allowed deviations.

Table 1. Basic medium statistic tests

Test	Particle	Energy	Cut (mm)	Target	Purpose
TestEm0	e^-	500 keV 10 MeV	1	Ge Water	Cross sections
TestEm1	e^-	100 MeV	1 0.01	Al	Cross section
TestEm2	e^-	100 MeV	1 0.01	$PbWO_4$	Shower shape
TestEm3	e^-	100 MeV	1	Pb/lqAr	Sampling calorimeter
TestEm4	γ	100 MeV	1	C_6H_6	Gamma processes
TestEm5	π e^- μ^- μ^- p	5 GeV 15.7 MeV 96.2 MeV 100 GeV 174 GeV	0.007 0.01 0.01 1 1	Si Au Polyethylene Fe Al	Multiple scattering
TestEm6	γ e^+ pbar	100 TeV 1 TeV 1 GeV	1	Fe	Rare high energy processes
TestEm7	P ^{12}C K^+ ^4He ^4He	160 MeV 3.5 GeV 100 MeV 0.265 keV 100 MeV	1	Water Water Cu Vacuum Water	Ranges and Bragg peak for hadrons and ions
TestEm8	P	200 GeV	1	$Xe+CH_4+C_3H_8$	PAI ionisation model
TestEm9	e^-	1 GeV	0.3	CsI	Crystal calorimeter
TestEm10	e^-	2 GeV	1	$Xe+CO_2$ gas	Transition radiation
TestEm11	e^-	500 keV	1	Si	
TestEm12	e^-	4 MeV	0.001	Water	
TestEm13	γ e^-	100 keV 100 MeV	1	Water	
TestEm14	γ e^-	100 keV 100 MeV	1	Water	
TestEm15	e^-	5 MeV 100 keV	1	Water	
TestEm16	e^-	10 GeV	1	Vacuum	
TestEm17	μ^+ π^+ p	10 TeV	1	Fe	
TestEm18	e^-	10 MeV	1	Water	
GammaTherapy	e^-	50 MeV	0.1	Water, Be, W	
fanoCavity	γ	1.25 MeV	10^4	Water, water-vap	
fanoCavity2	e^-	1 MeV	10^4	Water, water-vap	
Pol01	γ	10 MeV	0.1	Fe	
Monopole	Monopole	100 GeV	0.7	Si	

Table 2. High statistic testing suite for EM physics.

Test	Particle	Energy	Setup	Target	Purpose
Sampling calorimeter	e^-	10 GeV 10-120 GeV	ATLAS barrel ATLAS HEC LHCb ZEUS	Pb/lquidAr Cu/liquidAr Pb/Scint. Pb/Scint.	Cut and energy dependences of calorimeter response and resolution
Crystal calorimeter	e^-	10 GeV	CMS ECAL	$PbWO_4$	Cut dependences of calorimeter response, resolution and transverse energy profile
Combined calorimeter	e^- γ hadrons	1-300 GeV	CMS ECAL + HCAL	$PbWO_4$, Fe, Cu, Scint.	Cut and energy dependences of calorimeter response, resolution and shower shape
Energy deposition profile	e^-	0.3-1.0 MeV	Semi-infinite media	Al, Mo, Ta, TaAl, AlAuAl	Low-energy electron transport
Fano theorem	γ e^-	1 MeV	Cavity filled by vapour gas	Water	Low-energy electron and gamma transport
Electron scattering	e^-	1-16 MeV	Thin targets	Al, Au	Multiple scattering
Muon scattering (MuScat data)	μ^+	96.2 MeV	Thin targets	liquidH, Li, Be, C, CH_2, Al, Fe	Multiple scattering
Bragg peak	p, ^4He, ^{12}C	100-400 MeV/A	Uniform media	Water	Ranges, straggling, scattering
High energy muon penetration	μ^+	100 GeV	Uniform media	Fe	Energy loss, straggling, scattering

4. High statistic tests of EM physics

The high statistic tests (Table 2) are executed for each public release of Geant4 or after any major modification of the EM package. Typically, two weeks of wall clock time are needed for the execution at CERN lxbatch and IN2P3 computer centre. The regular runs for validation of proton and ion physics for medical applications were performed also in KEK.

The high statistic tests are focused on the main HEP detectors, first of all on various HEP calorimeters. The reason is in usage of Monte Carlo simulation for calibration of LHC calorimeters, defining a scale of a calorimer response for hadronic showers. The requirements to the stability of these responses are very strict (down to 10^{-3}), because any change of EM scale of a calorimeter will require its recalibration for the data analysis, which is a very time consuming job. The resulting energy scale of the experiment depends on accuracy of the simulation, thus final results (like the mass of a possibly discovered new particle) are affected by the precision of the EM interaction simulation.

For the validation of the Geant4 EM package simplified structures of calorimeters are used, which are similar to real HEP calorimeters [4, 10]. As an example, in Figure 2 the simulation results are shown for the Lead/Scintillator calorimeter structure of LHCb-type. These results are used to control the stability of the EM simulation for different Geant4 versions and production cuts. The verification versus the data (Figure 3) is being performed for the classical Lead/Scintillator sampling calorimeter setups used in ZEUS test-beam studies [13, 14]. These two structures have sampling fractions different by a factor 2, calorimeter geometry and materials are taken from the publications. The results are obtained without any tuning of Geant4 simulation. They demonstrate stability between Geant4 versions and the precision versus the data.

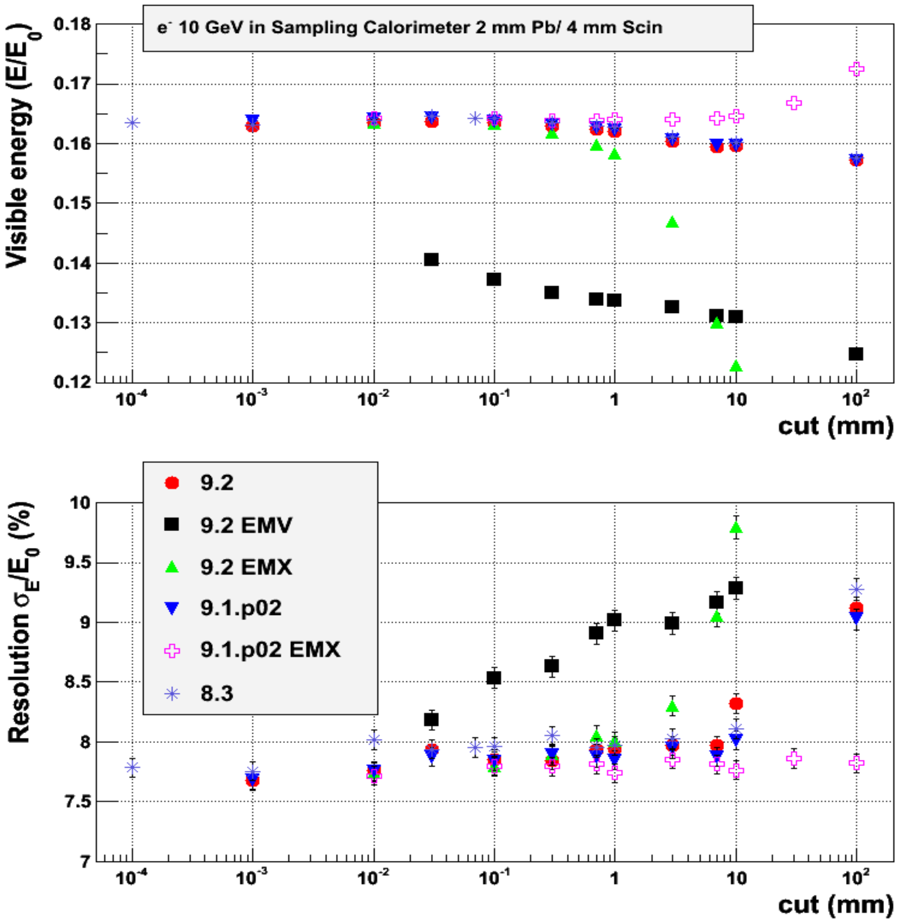

Figure 2. Geant4 simulation of the 10 GeV electron beam in the sampling calorimeter of LHCb-type as a function of production cuts in range: top plot – calorimeter response, bottom plot – calorimeter resolution. The comparison is performed between recent Geant4 releases used for LHC productions and for different configurations of EM physics in Physics Lists: default, EMV (simplified), EMX ("ApplyCuts" option).

As it was mentioned above, the accuracy of the low-energy electron transport directly affects the accuracy of the simulation of high energy calorimeters. Two special tests have been developed focusing on validation of low-energy electron transport:

- the energy deposition profile of MeV electron beams in extended media [15] versus Sandia calorimetric data;
- the test of the Fano theorem [16] - energy deposition in a cavity of a media filled by gas.

The results for low-energy electron transport are very sensitive to the accuracy of a multiple scattering model. One can see in Figures 2-3 that EMV Physics List provides biased results, because electron transport between high density material and low density material require more number of steps. The same conclusion can be made from Figure 4, where Geant4 simulation is compared with the Sandia data.

The accuracy of a multiple scattering model may affect the resolution of vertex and muon detectors. The dedicated tests for medium and high energy scattering results are also part of the validation suite.

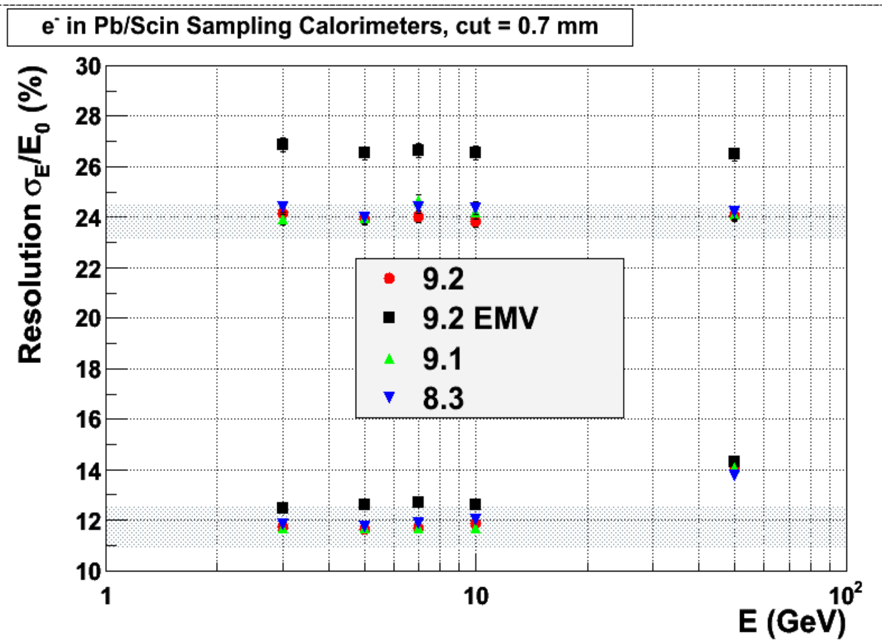

Figure 3. Geant4 simulation of the resolution of ZEUS calorimeter test-beam setups [13, 14] for electrons beams from 3 to 50 GeV. Hashed area – the data (± one standard deviation) for two types of sampling calorimeters: 5 mm Pb/5 mm scintillator and 12.5 mm Pb/2.5 mm scintillator. The comparison is performed between recent Geant4 releases used for LHC productions and different configurations of EM physics: default describing data well and EMV - fast simplified, which provides biased results. For the data point at 50 GeV in test-beam analysis events were selected with limited forward leakage, this selection was not applied in Geant4 analysis.

Large user communities perform their own validations of Geant4 software and make conclusions on the quality of the EM package. In particular, test-beam analyses for LHC experiments are reported on a regular basis (see for example [7-9]). The feedback is taken into account by the EM working group.

5. Conclusions

The validation suite for Geant4 EM physics has been established. The developed software allows performing regular validation in the development phase and intensive validation in the phase of Geant4 release. The practice of recent Geant4 releases demonstrates that LHC calorimeters and other detectors simulation results are stable and were predicted in advance by the EM working group. Changes and evolutions of the results are under control. As a rule, user feedback confirms predictions obtained with the EM testing suite. However, the suite is not covering all aspects of EM physics and some issues are reported by Geant4 users. Thus, further development of the suite is required and extensions are planned by Geant4 EM working group, first of all, by adding more experimental data and more use-cases for validation. The structure of the testing software allows easy additions.

Acknowledgements
This work has been supported in part RFBR grant 09-02-91065 and CNRS grant PICS-4865.

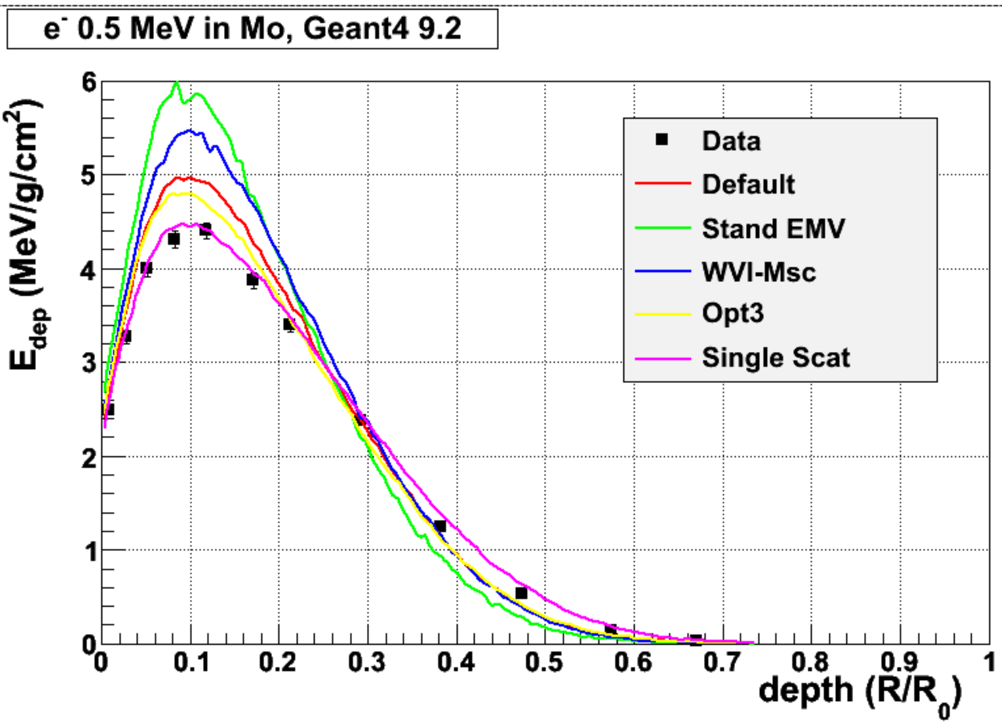

Figure 4. Geant4 simulation of the depth dose profile of 0.5 MeV electron beam in Molybdenum: points – Sandia data [17], curves – different Geant4 options for electron scattering. Single scattering model (magenta) reproduce the data, Option3 of EM physics (yellow) uses the most strong step limitation, fastest variant EMV (green) uses the most weak step limitation.

References

[1] Agostinelli S et al. 2003 *Nucl. Instr. Meth.* A **506** 250
[2] Allison J et al. 2006 *IEEE Trans. Nucl. Sci.* **53** 270
[3] Bogdanov A G, Burkhardt H, Ivanchenko V N, Kelner S A, Kokoulin R P, Maire M, Rybin A M and Urban L 2006 *IEEE Trans. Nucl. Sci.* **53** 513
[4] Apostolakis J, Bagulya A, Elles S, Ivanchenko V N, Kadri O, Maire M and Urban L 2008 *J. Phys. Conf. Ser.* **119** 032004
[5] Banerjee S 2008 *J. Phys. Conf. Ser.* **119** 032006
[6] Banerjee S et al. 2008 *J. Phys. Conf. Ser.* **119** 032007
[7] Barberio E et al. 2008 *J. Phys. Conf. Ser.* **119** 032008
[8] Cossutti F 2008 *J. Phys. Conf. Ser.* **119** 032015
[9] Cossutti F 2009 *J. Phys. Conf. Ser.* Talk at the CHEP'09 conference
[10] http://geant4.cern.ch/collaboration/working_groups/electromagnetic/index.shtml
[11] Ivanchenko V N and Ivantchenko A 2008 *J. Phys. Conf. Ser.* **119** 032026
[12] Diez Gonzalez V, Folger G and Roiser S 2009 *J. Phys. Conf. Ser.* Talk at the CHEP'09
[13] Bernardi E et al. 1987 *Nucl. Instr. Meth.* A **262** 229
[14] D'Agostini G et al. 1989 *Nucl. Instr. Meth.* A **274** 134
[15] Kadri O, Ivanchenko V N, Gharbi F and Trabelsi A 2007 *Nucl. Instr. Meth.* B **258** 381
[16] Elles S, Ivanchenko V N, Maire M and Urban L 2008 *J. Phys. Conf. Ser.* **102** 012009
[17] Lockwood G J et al. 1987 Calorimetric Measurement of Electron, Energy Deposition in Extended Media – Theory vs. Experiment, SANDIA REPORT SAND79-0414.UC-34a.