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Use Of Geant4 in CMS

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Abstract

GEANT4 is a detector simulation toolkit designed for the next generation of high energy physics experiments. It exploits advanced software engineering techniques and Object-Oriented technologies. A first use of GEANT4 has been made in the CMS Collaboration of the future LHC experiment at CERN, for the simulation of the highly complex detector structure. The detector construction is based on an external description of a mother-daughter volumes hierarchical logic. A graphical representation of CMS is shown, as well as some validation plots concerning the hadronic physics, based on the simulation of a hadronic calorimeter test-beam setup.

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1 Introduction

Since 1989 at CERN[1], the European Laboratory for Particle Physics, physicists have been testing the Standard Model of particle interactions using the Large Electron Positron collider (LEP). The very precise measurements obtained at LEP energies (between 80 GeV and close to 200 GeV) give evidence that new physics should be discovered at higher energy, giving some light on the still unanswered questions about the origin of mass and the disappearance of antimatter in our universe.

In 2005, LEP will be replaced by the LHC (Large Hadron Collider) in the existing tunnel of 27 km circumference. In a first stage, proton interactions will occur at an energy of 14 TeV and a luminosity of 10^{34} cm^{-2} s^{-1}, resulting in the creation of about 20000 particles per beam crossing, each 25^{th} nanosecond. In the second stage, heavy ion collisions will be produced. The LHC will be equipped with four major detectors: ATLAS, CMS, LHCb and Alice. The design of such detectors requires a detailed simulation of both the engineering aspects and the physics processes occuring inside the detector. The CMS Collaboration has started to use the recent Geant4 object-oriented simulation toolkit for this purpose.

2 The CMS detector

The Compact Muon Solenoid LHC detector[2], CMS, is being designed by a world-wide collaboration of about 1600 physicists and engineers. Its major physics goals are the discovery of the predicted Higgs boson and SUSY particles via the identification and the measurement of muons, photons and electrons with a precision better than one percent for 100 GeV particles. It is a complex compact detector equipped with a solenoid generating a 4 T magnetic field parallel to the beam axis. Centered on the interaction point, several cylindrical layers of tracking devices are installed around the beam-pipe, surrounded by an electromagnetic and a hadronic calorimeter, inside the solenoid. The external layer consists of the magnet flux return yoke, and the muon detection system. Devices similar to the ”barrel” ones, the ”forward” devices, are installed at both end-caps of the detector to assure a maximal hermeticity. The complete detector is a cylinder of 22 m length and 15 m diameter weighting 12500 tons.

The detector engineering studies and optimization require a detailed simulation of CMS as well as the determination of a trigger logic for data acquisition, the estimation of the potential for physics discoveries, and the interpretation of the experimental data recorded by the detector. Consequently, it is necessary to simulate in a reliable and precise way the detector geometry (several 100000 physical volumes of about 50 different shapes), the particle interactions in the detector materials (some 200 material types), and the electronic signals produced by the sensitive parts.

The CMS Collaboration has turned towards the object-orientation paradigm in order to handle more efficiently the complexity of the software. It is linked to the world-wide distribution of the developers, the long time scale (more than 20 years) and the large number of people involved in the software implementation which requires expertise in more and more specific domains.

Two object-oriented projects for the CMS data analysis have started. The simulation project OSCAR will use the Geant4 toolkit for the production of ”hit” objects (i.e. the determination of the impact time and position and of the amount of energy lost by particles in detector sensitive volumes). The reconstruction project ORCA, an independent software will compute the detector response as a function of the simulated hit values, and perform the reconstruction of the particle trajectories for simulated and experimental data.

3 The Geant4 toolkit

After four year of Research and Development phase involving more than one hundred physicists, engineers and computer scientists from about 40 institutes, the first public version of Geant4[3] (Geant4.0.0) was released in January 1999. It has been designed and implemented with object-oriented technologies using the C++ language, in order to meet the requirements of the LHC experiments. It is now a collaboration involving about ten High Energy Physics institutes and nuclear and medical research groups, in a joint-project with the European Space Agency. Geant4 is a complete toolkit for electromagnetic and hadronic physics in any material. It includes solid modeling, tracking of particles through matter handling field effects and volume boundaries, detector response,

[1] http://www.cern.ch/Public

[2] http://cmsinfo.cern.ch/Welcome.html

[3] http://wwwinfo.cern.ch/asd/geant/geant4.html

run and event management, object storage, visualization and graphic user interface, each domain being transparent and user extensible.

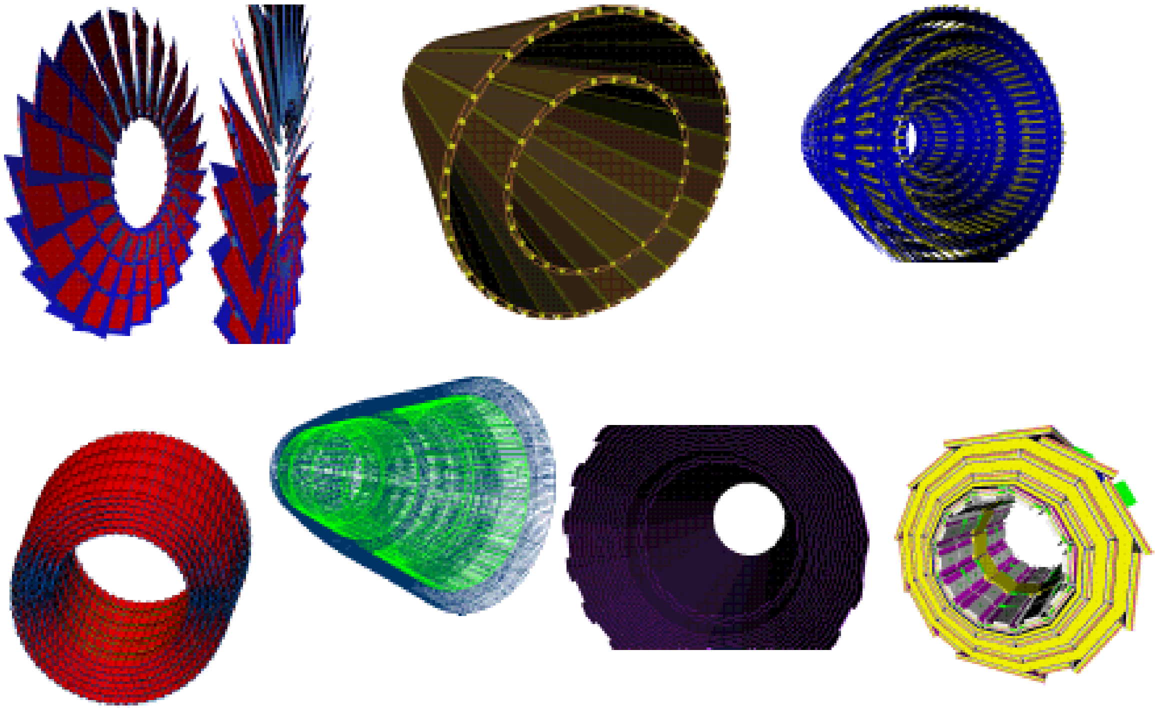

Figure 1: *Current status of the Geant4 simulation of the CMS detector sub-systems: from left to right: Forward Silicon Pixel, Barrel Silicon Pixel, Barrel Silicon Strip, Barrel MSGC, Barrel Hadronic Calorimeter, Barrel Hadronic Calorimeter, and Barrel Muon System*

4 CMS experience with Geant4

CMS has been using the Geant4 toolkit for about two years, providing feedback to the developers and prototyping CMS specific applications, namely the simulation of the full detector geometry and of a hadronic calorimeter test-beam setup. The muon physics simulation has also been partially tested.

4.1 The CMS geometry simulation with Geant4

The architecture of the code for the CMS geometry simulation reflects the physical architecture of the detector: the CMS detector volumes are constructed according to a mother-daughter hierarchy of which the complete CMS assembly is the top mother. The construction process is propagated from ”CMS” to its constituents: the Beam-Pipe, the Tracker, the Calorimeters, and the Muon System (each corresponding to one C++ class). Then, taking as an example the Tracker class, the construction methods are called for the Tracker constituents: the Barrel or Forward Silicon Pixel Detectors, Silicon Strip Detectors and MicroStrip Gas Chambers (Msgc). The actual details of the assembly (the volumes for services, support, cables, sensitive parts, electronics and cooling system) are located in the lowest level daughter classes, using factorization into layers and sub-structures. A Geant4 visualization of the CMS sub-system simulated so far is shown in figure 1.

For this first prototype, the access to the input data is de-coupled from the construction of the Geant4 geometry as far as the parameters (volume sizes and positions) are concerned. These parameters are read from external files by CMS specific classes (e.g. ”BarrelPixel”) inheriting from a ”CMSDetector” base class. The shape information is hard-coded at the level of the bottom-tree classes (e.g. the ”G4BarrelPixel” which inherits from ”BarrelPixel” and from a ”G4Able” interface) which produce the Geant4 logical, physical and sensitive volumes. The ”G4LogicalVolume” has shape, size, material, sensitivity and visualization attributes; the ”G4PhysicalVolume” is a logical volume positioned in its mother volume reference frame; the ”G4SensitiveVolume” is responsible for the production of hit objects.

CMS has developed a ”CMSMaterialFactory” for the instantiation of ”G4Material” objects needed for the construction of the CMS geometry, which reads material names and composition in an external file and allows the definition of a material by volume fractions of its element or material components, in addition to the Geant4 provided methods using weight fractions or atomic proportions.

Also a ”CMSRotationMatrixFactory” has been developed to extend the CLHEP based Geant4 matrices with a constructor specifying the polar and azimuthal angles of the axes of the new reference frame to be defined by the matrix.

A CMS magnetic field map description has been implemented in a CMS specific class which can be integrated inside the Geant4 field management system by a simple inheritance from the ”G4MagneticField” interface.

4.2 Muon physics with Geant4

Comparison between the Geant3.21 and the Geant4.0.0 simulations have been done regarding the muon physics: energy loss and transverse displacement due to multiple scattering have been investigated for low (10 GeV) and high (100 GeV) energy muons traversing a 100 cm iron block. As can be seen in figure 2, a good agreement between both simulations is observed at 10 GeV while, as expected, differences are found at higher energy: 100 GeV is the validity range limit of Geant3.21 where some processes and correction factors are missing. Geant4 uses up-to-date cross-section values. The results obtained with Geant4 by CMS will soon be compared with experimental data.

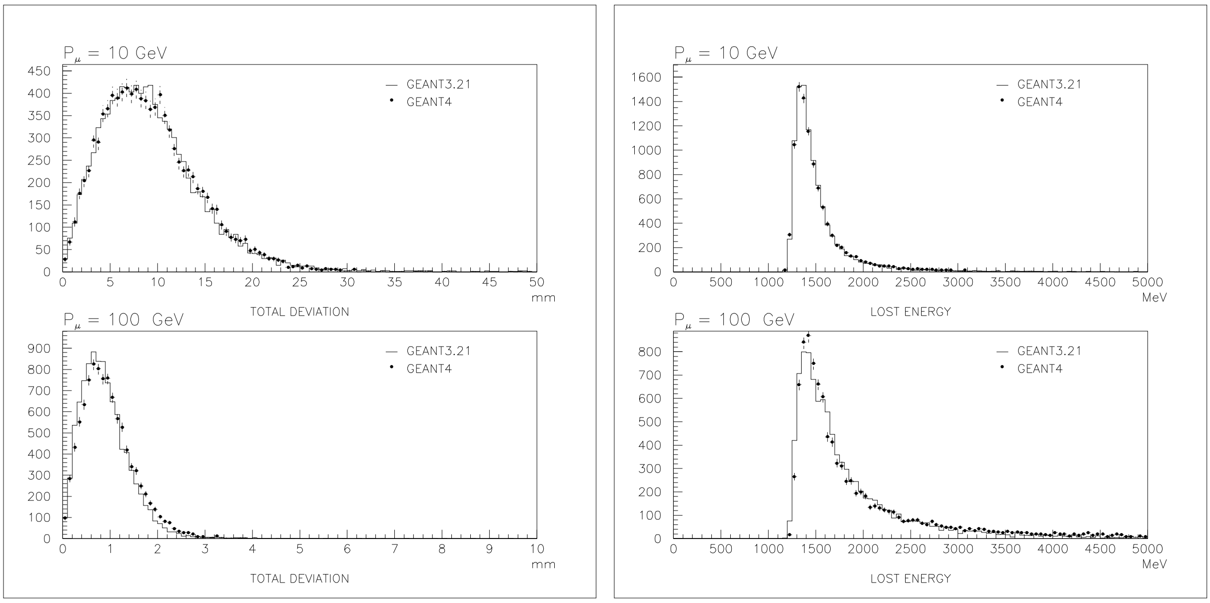

Figure 2: *Comparison of Geant3.21 and Geant4.0.0 simulation of muon interactions in a 100 cm iron block, for 10 GeV and 100 GeV muons.*

4.3 Hadron physics with Geant4

A CMS hadron calorimeter test-beam setup has been simulated with Geant4. It consists of a 64 cm $\times$ 64 cm $\times$ 152 cm block of copper layers of varying thicknesses interspersed with 7 mm thick scintillator layers. Simulated hadronic shower developments have been analyzed for pions of energy between 5 GeV and 300 GeV showing reasonable behaviour (see figure 3) and a good matching of the shower longitudinal profile with the test-beam data. Further comparisons need still to be done.

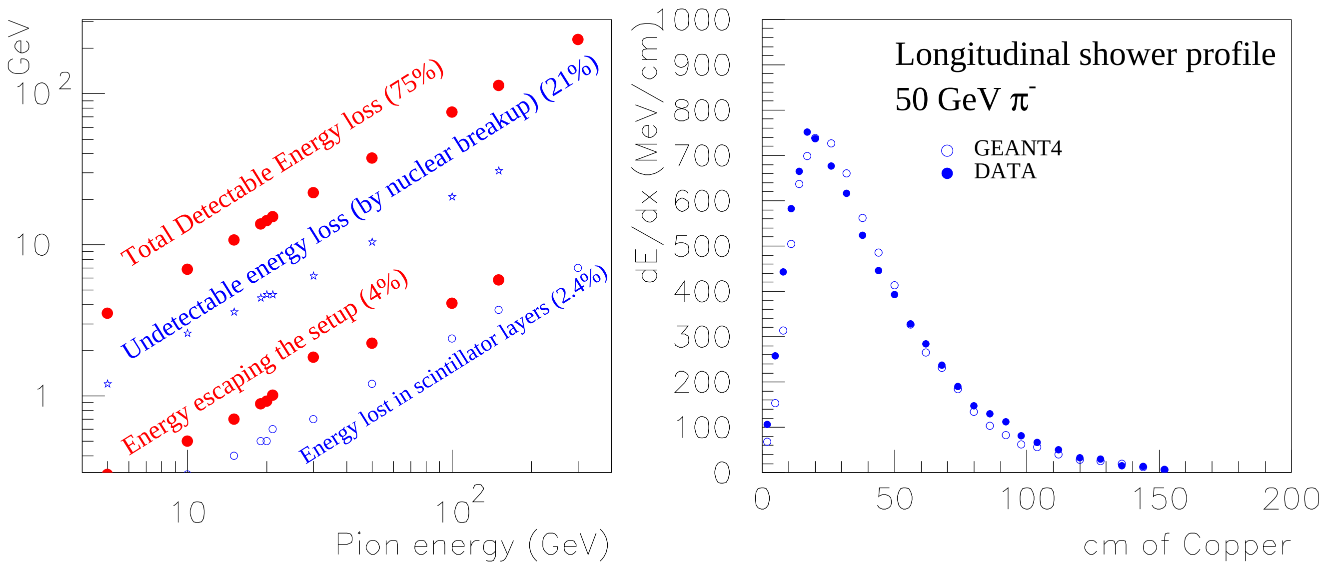

Figure 3: *Hadron physics Geant4 simulation in the CMS hadron calorimeter test-beam setup.*

5 Summary

CMS has close to two year experience with alpha, beta and the first public releases of the Geant4 toolkit, and with the object-oriented technologies in general. Results obtained so far are encourageing. Geant4 will be used for a full simulation of the CMS detector geometry and the tracking of the particles produced in LHC beam interactions. The validity of the physics processes simulated by Geant4 will continue to be tested on the basis of test-beam data.