Progress in Geant4 electromagnetic physics modeling and validation

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Abstract

The Geant4 electromagnetic (EM) physics sub-packages are key components of any simulation; in particular for the simulation of LHC experiments. A small variation of EM physics may affect prediction accuracy and CPU performance of large scale Monte Carlo simulations for HEP, medical physics, or space science.

In this work we report on recent improvements of the EM models and on new validations of EM physics of Geant4. Improvements were made in models of the photoelectric effect, Compton scattering, gamma conversion to electron and muon pairs, fluctuations of energy loss, multiple scattering, synchrotron radiation, and high energy positron annihilation. The results of these developments are included in the new Geant4 version 10.1 and in patches to previous versions 9.6 and 10.0 that are planned to be used for production for run-2 at LHC.

The Geant4 validation suite for EM physics has been extended and new validation results will be shown in this work. In particular, the effect of gamma-nuclear interactions on EM shower shape at LHC energies will be discussed.

EM sub-packages infrastructure upgrades

For the new Geant4 version 10.1 all EM Standard sub-packages have been fully adopted to multi-treading approach. Internal data tables for processes and models are shared between threads.

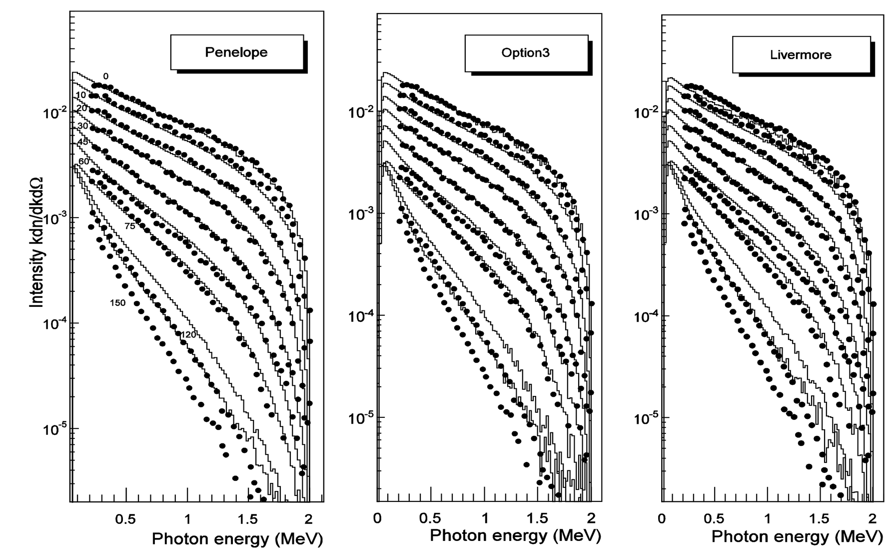
A new conception of EM parameters definition is introduced. EM parameters are subdivided on two groups:

1. *Static parameters shared between all EM processes;*
2. *Parameters defined per process/particle type.*

Parameters from the first group are kept inside *G4EmParameters* singleton class, can be modified via UI command or C++ interface, and is enabled during initialisation of a new run. Parameters from the second group may be defined during construction of EM physics in order to have optimal values per particle type.

EM physics constructors were updated:

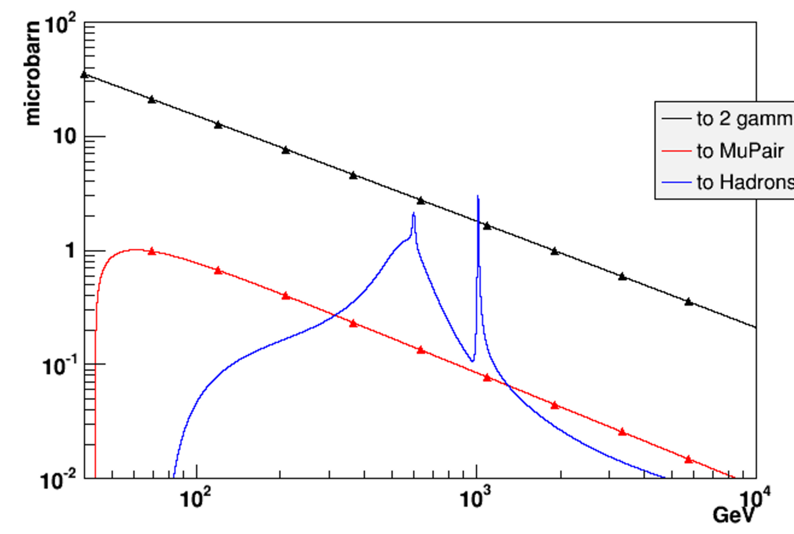
- *G4EmStandardPhysics_option4 – combined standard/lowenergy models*
- *G4EmStandardPhysicsSS – use single scattering instead of multiple scattering*
- *G4EmStandardPhysicsWVI – use WentzelVI multiple scattering model for e±*
- *G4EmLowEPPhysics – experimental physics for new lowenergy models*



Bremsstrahlung process defines high energy EM shower shape. At any shower energy, contribution of low-energy e± is significant. In the plot (*NIMB in press arXiv:1410.2002*), validation of double differential cross section of bremsstrahlung for 2 MeV e⁻ in Al target is presented versus data (*W.E. Dance et al., J. App. Phys. 39, 1967*). 10^9 events were simulated for each configuration, statistical analysis of results are done assuming data accuracy 20 %. The there physics lists are almost equivalent, with Penelope providing a slightly better agreement to the data.

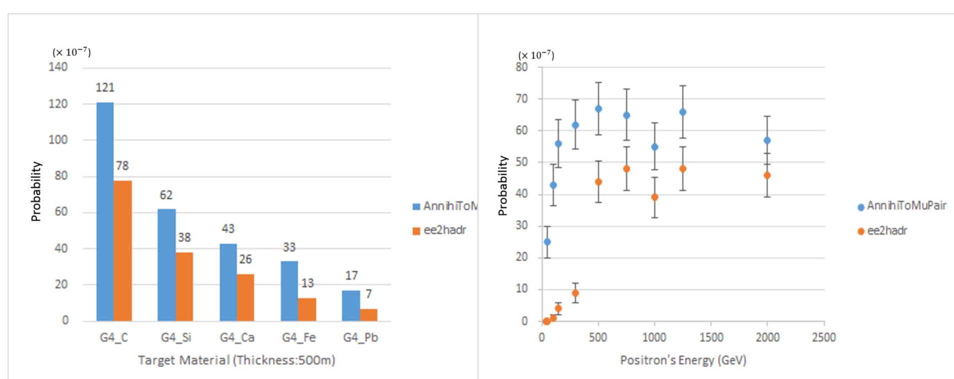
Rare positron annihilation processes

An incident positron usually annihilate with an electron of a medium into two photons. If the energy of positron becomes over a threshold, 43.69 GeV, positron may annihilate into muon pairs. Annihilations to hadrons, such as to (π^+, π^-), ($\pi^+.\pi^-$, π^0), (K^+, K^-), (K_L, K_S), (η, γ), (π^0, γ), may also happen, with higher energy than a threshold for each process. These rare processes are implemented inside Geant4 (*A. Bogdanov et al., IEEE Trans. Nucl. Sci. 53 (2):513-519, 2006*), were verified, and ready to use with Geant4 10.0.



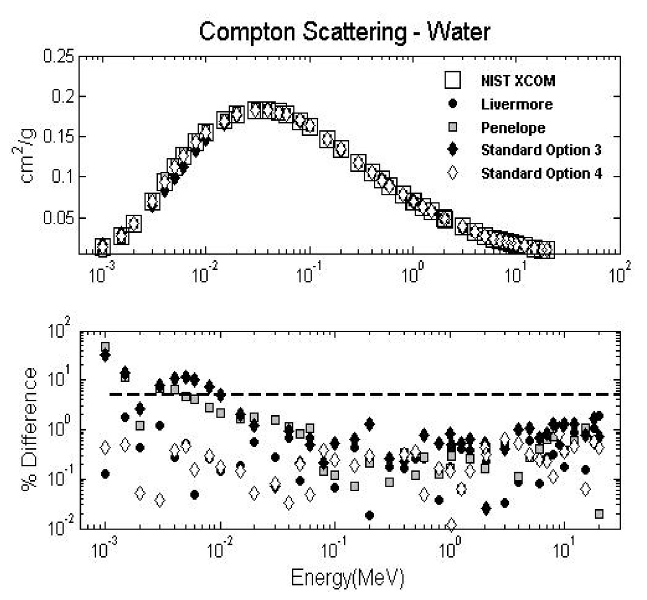
Geant4 cross sections are shown in the plot, points are theoretical computations.

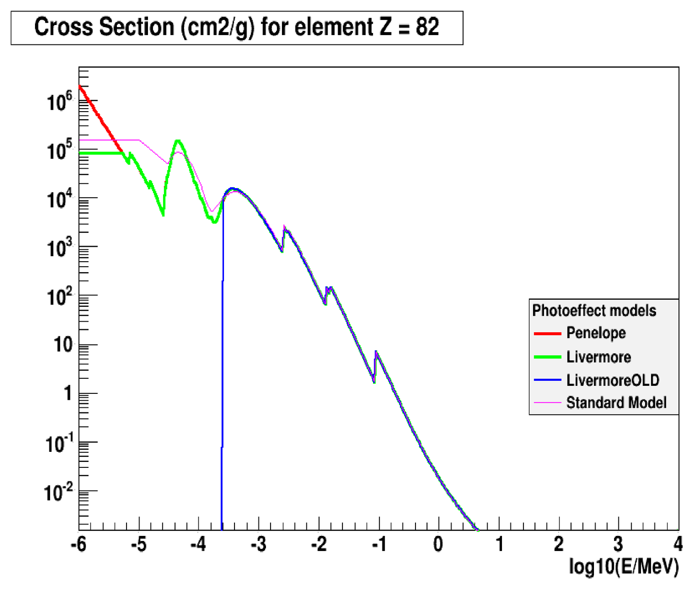
These processes provide a background to the interaction region of linear collider (*I. Agapov et al., Phys. Rev. ST Accel. Beams 12 (2009) 081001*). Also these processes may provide background at LHC search for new physics.



Figures show the probability of annihilation of positrons in uniform media to muon pairs (blue) and to hadrons (red). On the left plot probability is computed for 1 TeV positrons as a function of atomic number, on the right – as a function of energy for the Silicon target. The probability of these process decreases as atomic number Z increases. In relatively light material as Silicon the probability increases above reaction threshold until it reaches plateau on level ~10^{-5}. With high luminosity run at LHC such events may occur inside trackers.

Gamma processes: model updates and validation results





Main Geant4 gamma processes were revised and common approach was implemented for the Compton scattering and photo-electric effect:

- *Compton cross section is forced to be zero at low-energy model limit;*
- *Photoelectric-effect cross sections are const non-zero value below first ionisation potential or low-limit of model applicability;*
- *All gamma conversion cross section tables have more fine grid .*

This provides prompt absorption of very low-energy gamma produced by Geant4 hadronic models in LHC simulation for all EM Physics Lists.

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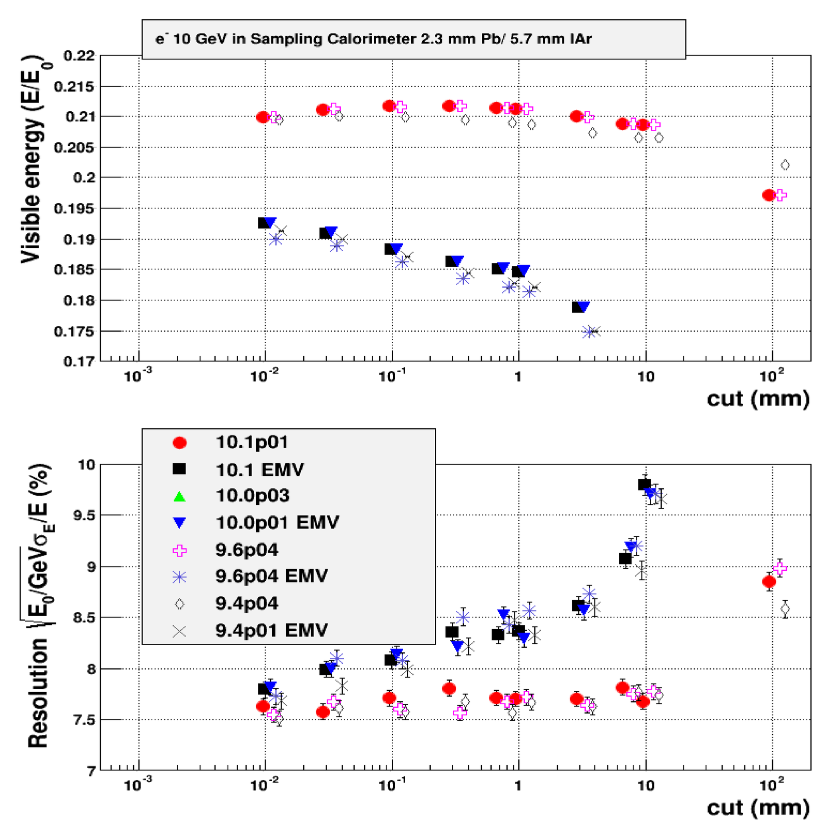
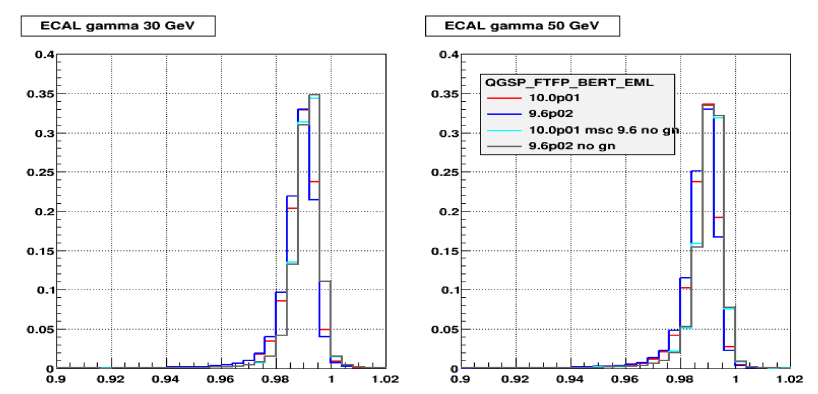
High energy calorimeters response

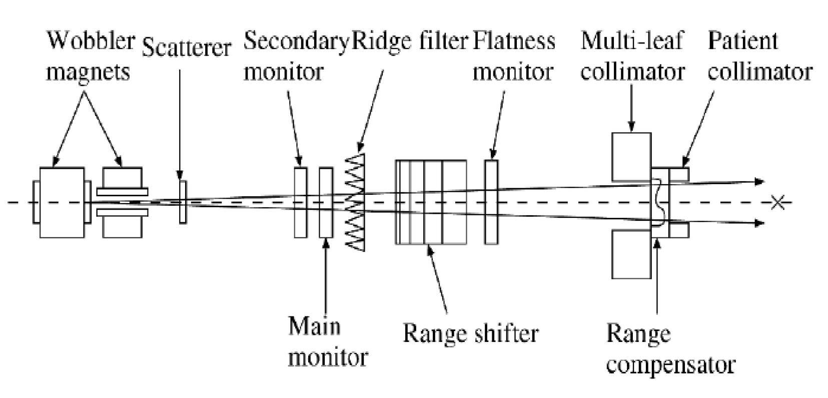


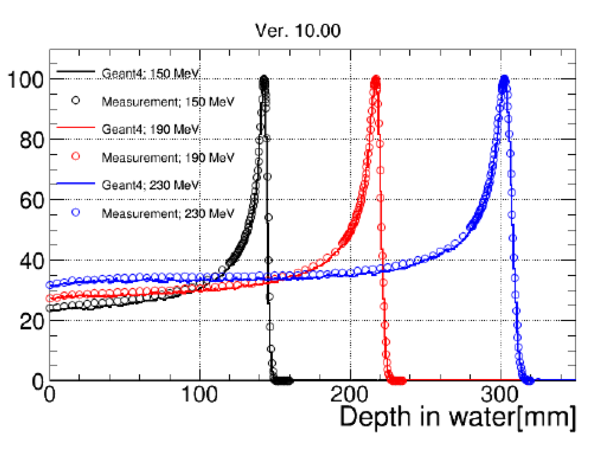
In the plot above response and resolution of simplified Pb/liquidAr (ATLAS-barrel type) sampling calorimeter as a function of cut in range for different Geant4 versions and EM Physics Lists. For the version 9.6p04 it is expected 0.2% increased response compare to the 9.4p04 version. No difference between 9.6, 10.0, and 10.1 is expected. Accurate stable response of sampling calorimeter can be obtained with the default configuration of EM physics. In the case of weak step limitation (EMV) both response and resolution are biased.

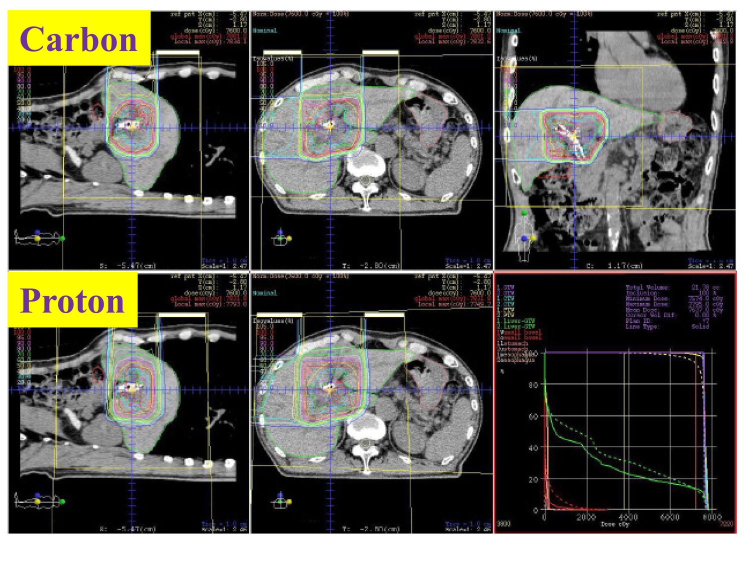


For CMS type crystal calorimeter an effect on EM shower from gamma-, electro- nuclear interactions was identified as a shift of peak energy deposition for 0.5%. In Geant4 10.0 these interactions are simulated with the Bertini cascade and neutron yield from gamma-nuclear interaction decreases compare to Geant4 9.6. This provides a shift of peak position of energy deposition for 0.2%.

Validations of simulation of medical proton beam



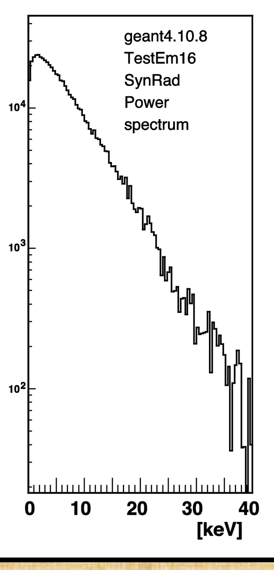




Methods of usage of proton and carbon beam for cancer treatment have been established in recent decade in Japan. HIBMC facility provides high quality beam allowing to measure of Bragg peak position in water with accuracy 0.1 mm.

Several Geant4 Physics Lists were tested. In all cases simulation predictions reproduce the range with precision better than 1 mm.

Future Circular Collider (FCC) Machine Detector Interface (MDI) Studies and Synchrotron radiation



Minimisation of synchrotron radiation to detectors is the major challenge of all FCC options – ee, eh, hh (pp and ion-ion). FCC for pp 2x50 TeV with 20 Tesla magnetic field will provide 3 MW in proton synchrotron radiation with $E_{critical}$ = 5.4 keV compatible to B-factories. Recent Geant4 version provides the G4SynchrotronRadiation process applicable to all types of charged particles.