Geant4 release 9.6+P01

Vladimir Ivanchenko, CERN

Michel Maire, IN2P3

Sebastien Incerti, IN2P3

on behalf of Geant4 electromagnetic working groups

ELECTROMAGNETIC PHYSICS
STANDARD CATEGORY

Content

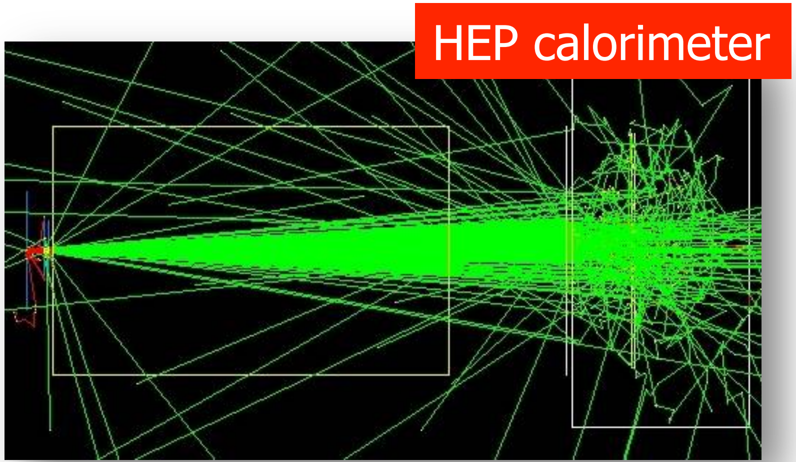
Located in $G4INSTALL/sources/processes/electromagnetic

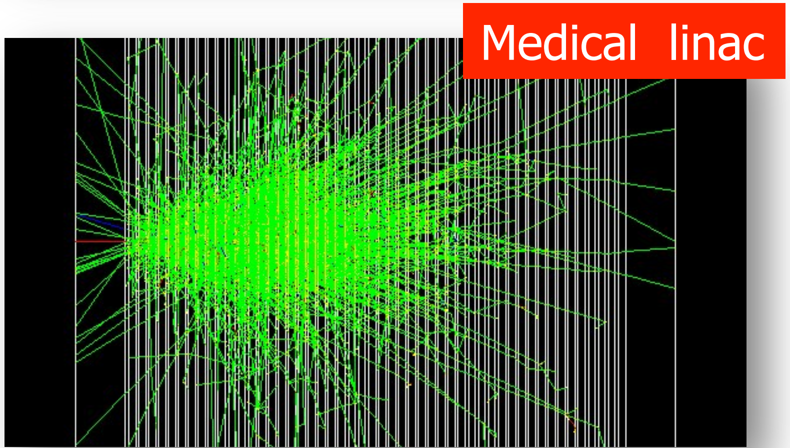
Geant4 EM packages

- Standard
  - γ, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- Muons
  - up to 1 PeV
  - energy loss propagator
- X-rays
  - X-ray and optical photon production proc.
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of polarized beams
- Optical
  - optical photon interactions
- Low-energy
  - Livermore library γ, e- from 250 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE code rewrite , γ, e- , e+ from 100 eV up to 1 GeV (2008 version)
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- Geant4-DNA
  - microdosimetry models for radiobiology (Geant4-DNA project) from eV to ~100 MeV
- Adjoint
  - New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation
- Utils
  - general EM interfaces

Gamma and electron transport

- Photon processes
  - γ conversion into e+e- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - *Gamma-nuclear interaction in hadronic sub-package*
- Electron and positron processes
  - Ionisation
  - Coulomb scattering
  - Bremsstrahlung
  - Positron annihilation
  - *Nuclear interaction in hadronic sub-package*
- Suitable for HEP & many other Geant4 applications with electron and gamma beams





Software design

- Since Geant4 9.3beta (June, 2009) the design is uniform for all EM packages
  - Allowing a coherent approach for high-energy and low-energy applications

- A physical interaction or process is described by a process class
  - Naming scheme : « G4ProcessName »
  - For example: G4ComptonScattering for photon Compton scattering
  - Assigned to Geant4 particle types
  - Inherits from G4VEmProcess base class

- A physical process can be simulated according to several models, each model being described by a model class
  - Naming scheme : « G4ModelNameProcessNameModel »
  - For example: G4LivermoreComptonModel
  - Models can be assigned to certain energy ranges and G4Regions
  - Inherit from G4VEmModel base class

- Model classes provide the computation of
  - Cross section and stopping power
  - Sample selection of atom in compound
  - Final state (kinematics, production of secondaries…)

How to invoke EM Physics in Geant4 ?

Physics lists

- A Physics list is the mandatory user class making the general interface between the physics the user needs and the Geant4 kernel
  - It should include the list of particles
  - The G4ProcessManager of each particle maintains a list of processes

- Geant4 provides several configurations of EM physics lists called constructors (G4VPhysicsConstructor) in the physics_lists library of Geant4

- These constructors can be included into a modular Physics list in a user application (G4VModularPhysicsList)

Geant4 9.6: EM Physics constructors for HEP

- List of particles for which EM physics processes are defined

γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\Sigma^{\pm}$, Ξ^{-}, Ω^{-}, anti($\Sigma^{\pm}$, Ξ^{-}, Ω^{-})

$\tau^{\pm}$, $B^{\pm}$, $D^{\pm}$, $D_s^{\pm}$, Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{+} , anti(Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{+})

d, t, He3, He4, GenericIon, anti(d, t, He3, He4)

Constructor	Components	Comments
G4EmStandardPhysics	Default (QGSP_BERT, FTFP_BERT…)	ATLAS and other HEP productions, other applications
G4EmStandardPhysics_option1	Fast due to simple step limitation, cuts used by photon processes (FTFP_BERT_EMV)	Similar to the one used by CMS, good for crystals, not good for sampling calorimeters
G4EmStandardPhysics_option2	Experimental: updated photon models and bremsstrahlung on top of Opt1	Similar to the one used by LHCb

Geant4 9.6: EM Physics constructors for space and medical applications

Constructor	Components	Comments
G4EmStandardPhysics_option3	Msc95 for prticle types, standard models when applicable	The most accurate standard
G4EmStandardPhysics_option4	WentzelVI at high energy, msc95 below 100 MeV, photon models from Livermore and Penelope, Livermore ionisation for e-	The most accurate EM physics
G4EmLivermore	Livermore models when applicable	Livermore
G4EmPenelope	Penelope models when applicable	Penelope
G4EmLivermorePolarized	Polarized models	
G4EmDNA	Example of DNA physics	
G4EmLowEPPhysics	Livermore models when applicable + MU Compton	

User interfaces and helper classes

- G4EmCalculator
  - easy access to cross sections and stopping powers (TestEm0)
- G4EmProcessOptions
  - C++ interface to EM options alternative to UI commands
- G4EmSaturation
  - Birks effect (recombination effects)
- G4ElectronIonPair
  - sampling of ionisation clusters in gaseous or silicon detectors
- G4EmConfigurator
  - add models per energy range and geometry region

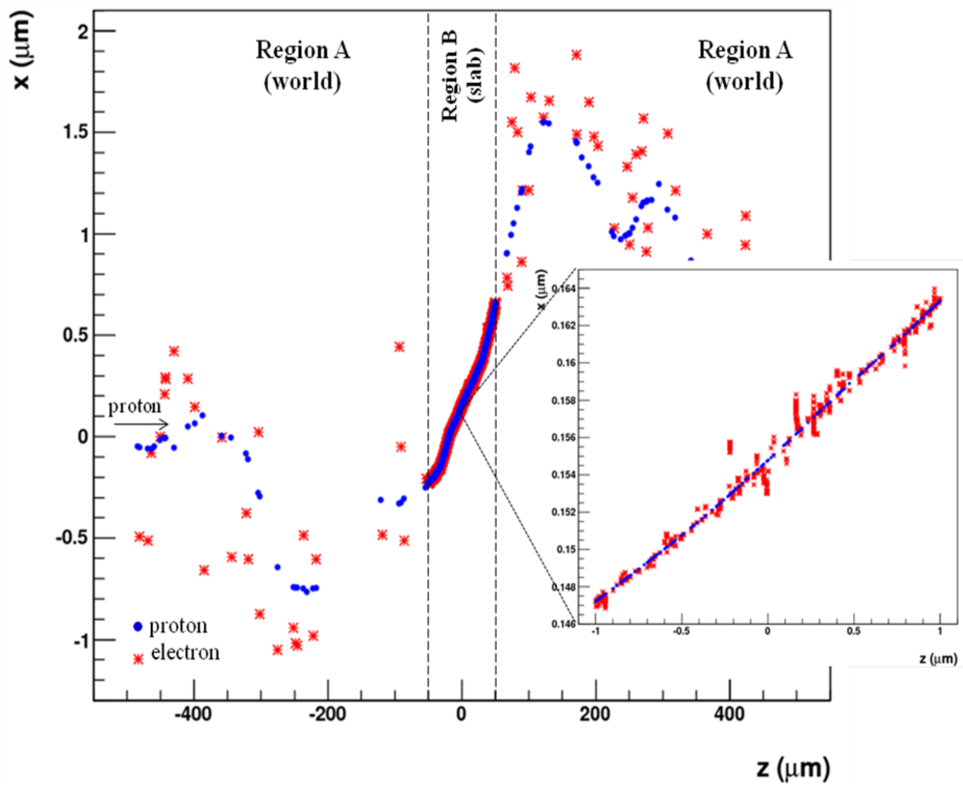
Example: G4EmStandardPhysics


```
G4PhysicsListHelper* ph = G4PhysicsListHelper::GetPhysicsListHelper();
G4String particleName = particle->GetParticleName();

   if ( particleName == "gamma"  ) {
     ph->RegisterPhysics(new G4PhotoElectricEffect, particle);
     ph->RegisterPhysics(new G4ComptonScattering, particle);
     ph->RegisterPhysics(new G4GammaConversion, particle);

   } else if ( particleName == "e+" ) {
      ph->RegisterPhysics(new G4eMultipleScattering, particle);
      ph->RegisterPhysics(new G4eIonisation, particle);
      ph->RegisterPhysics(new G4eBremsstrahlung, particle);
      ph->RegisterPhysics(new G4eplusAnnihilation, particle);
```

- G4PhysicsListHelper provides
  - Activation of a process AtRest, AlongStep, PostStep according to the process SubType
  - Process ordering for process manager

Specialized models per G4Region: example of Geant4-DNA physics

- Standard EM physics constructor as a base
- G4EmConfigurator is used to add Geant4-DNA models
- Geant4-DNA models are enabled only in the small G4Region for energy below 10 MeV
- CPU performance optimisation



Atomic de-excitation effects

- Atomic de-excitation initiated by other EM processes
  - Examples: photo-electric effect, ionisation by e- and ions (eg. PIXE)
  - Leave the atom in an excited state

- EADL data contain transition probabilities
  - radiative: fluorescence
  - non-radiative:
    - Auger e-: inital and final vacancies in different sub-shells
    - Coster-Kronig e-: identical sub-shells

- Atomic de-excitation simulation is now compatible with both Standard & Low Energy EM categories

- See more in the talk on Low Energy EM physics

How to extract Physics ?

- Possible to retrieve Physics quantities using a G4EmCalculator object
- Physics List should be initialized
- Example for retrieving the total cross section of a process with name procName, for particle and material matName

```
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;

G4Material* material =
  G4NistManager::Instance()->FindOrBuildMaterial(matName);

G4double density = material->GetDensity();

G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
    (energy,particle,procName,material)/density;

G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
```

- A good example: $G4INSTALL/examples/extended/electromagnetic/TestEm14.
  Look in particular at the RunAction.cc class

15

Details of selected standard models: Ionisation

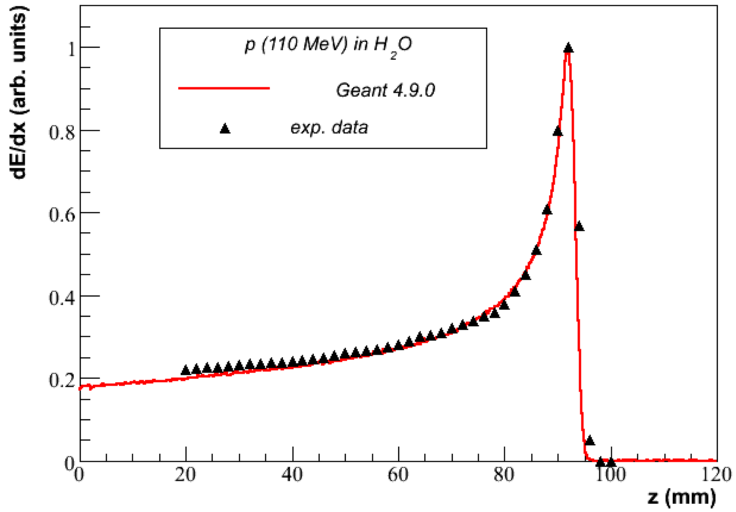
Hadron and ion ionisation

- Bethe-Bloch formula with corrections used for E>2 MeV

$$-\frac{dE}{dx}=4\pi N_e r_0^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I}-\frac{\beta^2}{2}\left(1-\frac{T_c}{T_{max}}\right)-\frac{C}{Z}+\frac{G-\delta-F}{2}+zL_1+z^2L_2\right)$$

  - C – shell correction
  - G – Mott correction
  - δ – density correction
  - F – finite size correction
  - L_1- Barkas correction
  - L_2- Bloch correction
  - Nuclear stopping
  - Ion effective charge

- Bragg peak parameterizations for E< 2 MeV
  - ICRU'49 and NIST databases

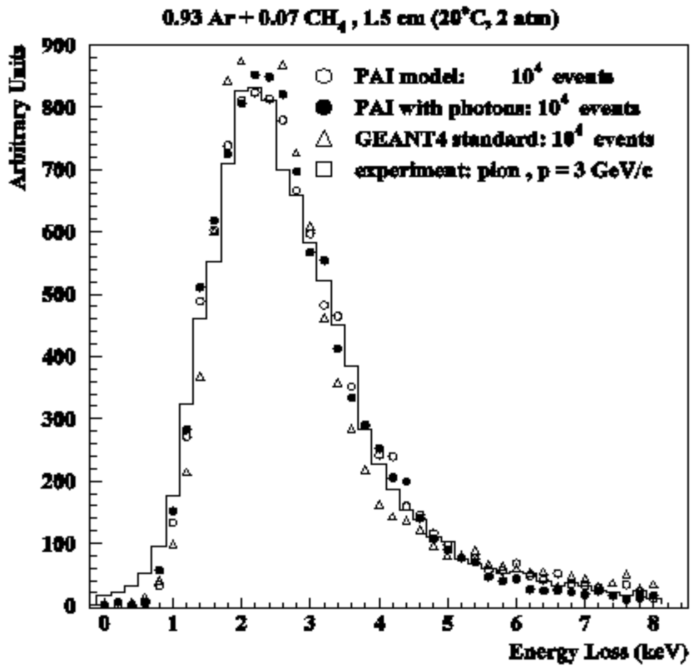


Simulation of a step of a charged particle

- The Bethe-Bloch formula (or low-energy parametrisation) provides value of mean energy loss
- Values of mean dE/dx, range and cross section of δ-electron production are pre-computed at initialisation stage of Geant4 and are stored in G4PhysicsTables
- Spline interpolation is used at run time for fast interpolation at each simulation step to get mean energy loss
- And sampling of energy loss fluctuation is performed
  - The interface to a fluctuation model G4VEmFluctuationModel
- The cross section of δ-electron production is used to sample production above the threshold T_{cut} at PostStep
- If de-excitation is active then fluorescence and Auger electron production is sampled AlongStep

Geant4 models of energy loss fluctuations

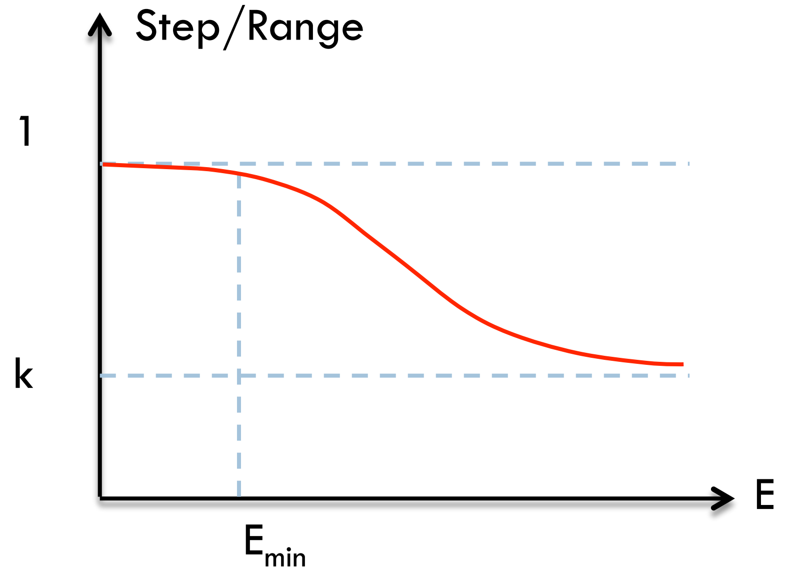
- Two models
- Urban model based on a simple model of particle-atom interaction
  - Atoms are assumed to have only two energy levels E_1 and E_2
  - Particle-atom interaction can be
    - an excitation of the atom with energy loss $E = E_1 - E_2$
    - an ionization with energy loss distribution $g(E) \sim 1/E^2$
- PAI model uses photo absorption cross section data
  - Energy transfers are sampled with production of secondary e^- or γ
  - Very slow model, should be applied for sensitive region of detector



Step limitation by ionisation process

- To guarantee precision of computation, step size should be limited
- Step limit S is defined by stepping function
- It takes into account particle range R and two parameters, k (dRoverRange) and ρ (finalRange)

/process/eLoss/StepFunction 0.1 50 um



$$S/R = k + \rho/R\cdot(1-k)\cdot(2-\rho/R)$$

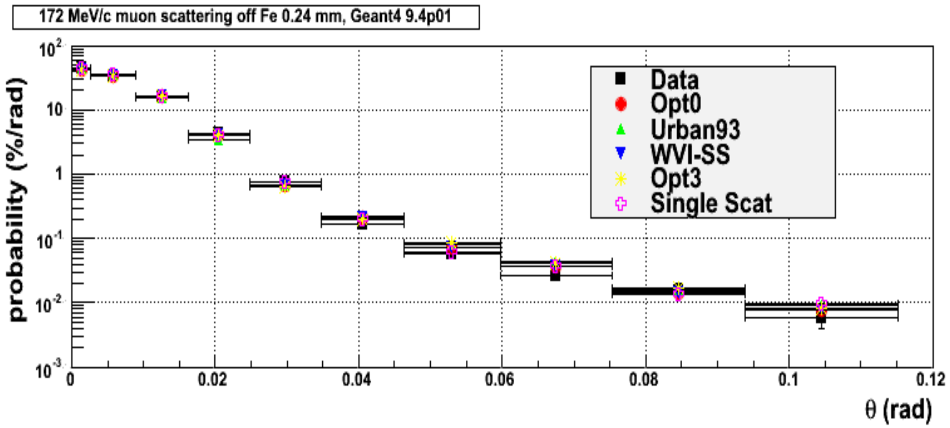
20

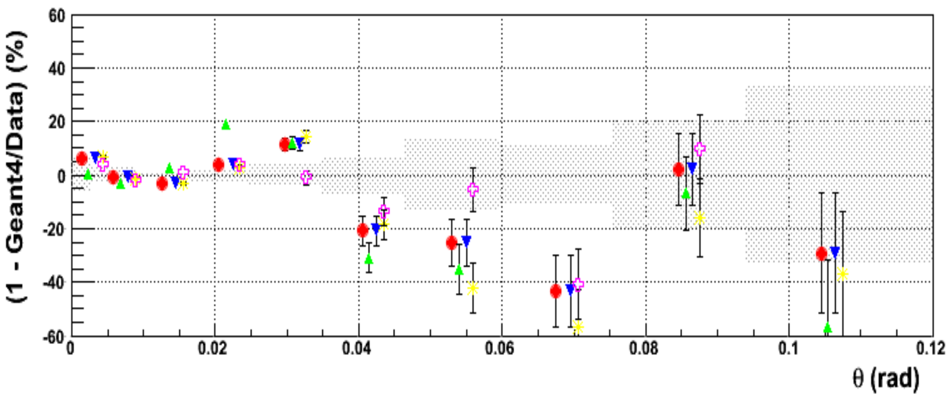
Details of selected standard models:

Multiple scattering

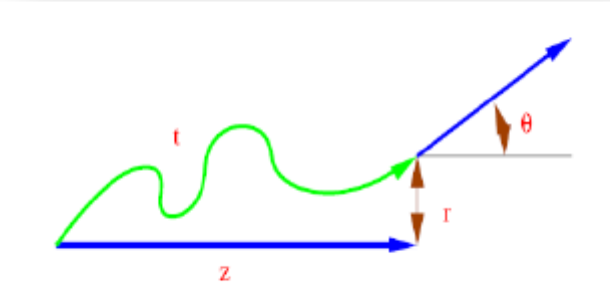
Multiple Coulomb Scattering (MSC)

- Charged particles traversing a finite thickness of matter suffer elastic Coulomb scattering
- The cumulative effect of these small angle scatterings is a net deflection from the original particle direction
- MSC implementation determine accuracy and CPU performance of simulation





MSC algorithm



- Legend
  - True path length : t
  - Longitudinal or geometrical displacement : z
  - Lateral displacement : r
  - Angular deflection : (θ, Φ)

- The algorithm performs several steps for the simulation of MSC which are essentially the same for many « condensed » simulations
  - The physics processes and the geometry select the step length;
    MSC performs the t ↔ z transformation only
  - The transport along the initial direction is not MSC's business
  - Sampling of scattering angle (θ , Φ)
  - Computing of lateral displacement and relocation of particle

MSC and single scattering models

Model	Particle type	Energy limit	Specifics and applicability
Urban (Urban 2006)	Any	-	Default model for electrons and positrons below 100 MeV, (Lewis 1950) approach, tuned to data, used for LHC production
Screened Nuclear Recoil (Mendenhall and Weller 2005)	p, ions	< 100 MeV/A	Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space app
Goudsmit-Saunderson (Kadri 2009)	e^{+}, e^{-}	< 1 GeV	Theory based cross sections (Goudsmit and Saunderson 1950). EPSEPA code developed by Penelope group, final state using EGSnrc method (Kawrakov et al. 1998), precise electron transport
Coulomb scattering (2008)	any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (2009)	any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e^{+}, e^{-}	-	Model based on Wentzel formula + relativistic effects + screening effects for projectile & target. From the work of P. G. Rancoita, C. Consolandi and V. Ivantchenko.

MSC classes

- Processes per particle type are available
  - G4eMultipleScattering for e+/e-
  - G4MuMultipleScattering for μ+/μ-
  - G4hMultipleScattering for hadrons and ions

- L. Urban models
  - G4UrbanMscModel93 : used for LHC production for backward compatibility
  - G4UrbanMscModel95 : used by default in G4eMultipleScattering
  - G4UrbanMscModel96 : the most recent tuning of the model
    - will be future default

- Alternative single and multiple scattering models are available to users
  - see extended examples…

Step limitation for charged particle transport

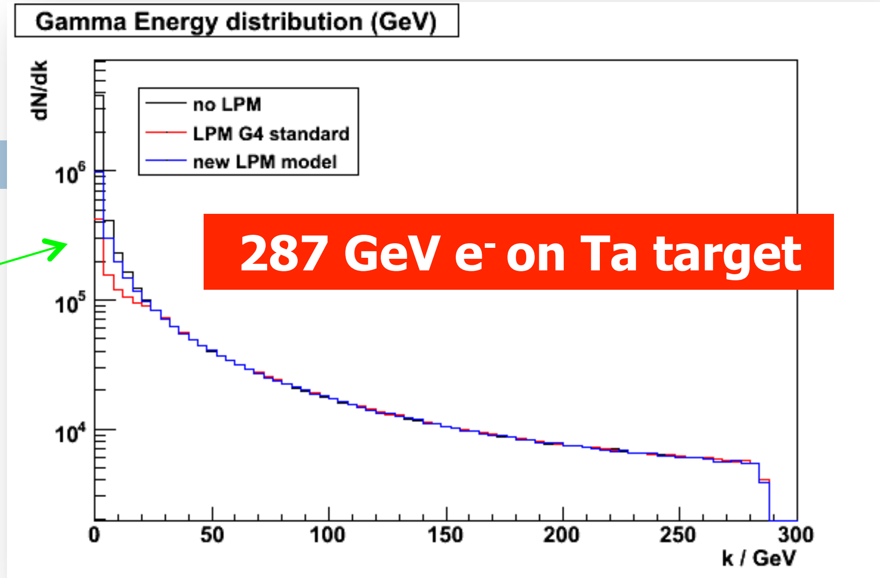
- Step size of a charged particle may be limited by several Geant4 processes
  - Ionisation
    - discussed in previous slide
  - Multiple scattering
    - strong step limitation near geometry boundary
      - 3 modes: Minimal, UseSafety, UseDistanceToBoundary
  - Delta-electron production and bremsstrahlung
    - cut dependent
  - User defined step limit
- Simulation results strongly depend on step limit method

26

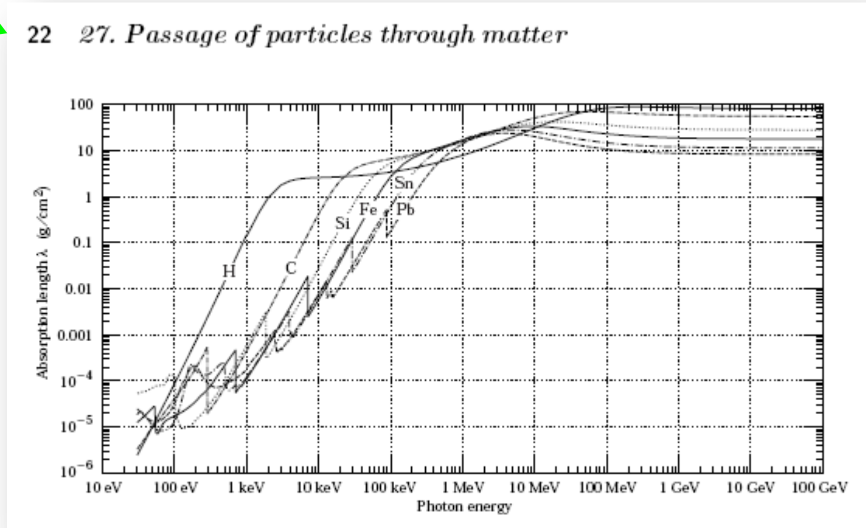
Geant4 cuts

Bremsstrahlung

- Bremsstrahlung spectrum grows at low energy as 1/k
  - k is the gamma energy



- Low energy gammas have very small absorption length



- Simulation of all low-energy gammas is non-efficient
- Cuts/production threshold are used in all Monte Carlo codes
- Gamma emission below production threshold is taken into account as a continuous energy loss
- Similar approach is used for the ionisation process where spectrum of delta-electrons is proportional to $1/T^2$

Cut and production thresholds for energy loss processes

- User defines a cut in range expressed in units of length

- Using this range, the Geant4 kernel computes production threshold T_{cut} for each material during initialization

- For a typical process (G4hIonisation, G4eIonisation, …), the production threshold T_{cut} subdivides the continuous and discrete parts of energy loss:
  - Mean rate of energy lost due to soft energy transfers

    $$\frac{dE(E,T_{cut})}{dx} = n_{at} \int_0^{T_{cut}} T \frac{d\sigma(Z,E,T)}{dT} dT$$

  - Total XS for discrete delta-electron production above T_{cut}

    $$\sigma(Z,E,T_{cut}) = \int_{T_{cut}}^{T_{\max}} \frac{d\sigma(Z,E,T)}{dT} dT$$

- At each step, the energy deposition is sampled by a fluctuation model using the computed mean energy loss

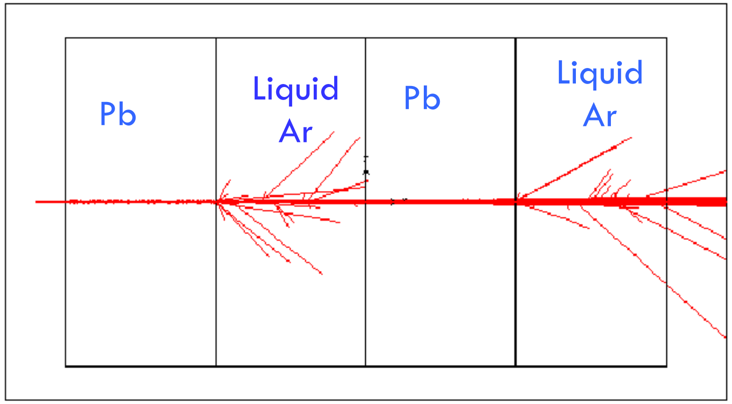
- Optionally, energy loss may be modified
  - for the generation of extra delta-electrons under the threshold when the track is in the vicinity of a geometrical boundary (sub-cutoff)
  - for the sampling of fluorescence and Auger–electrons emission

- 4-momentum balance is provided in all cases

Effect of production thresholds

500 MeV incident protons on EM Pb/LAr calorimeter

In Geant4



One sets the production threshold for delta rays as a unique range:

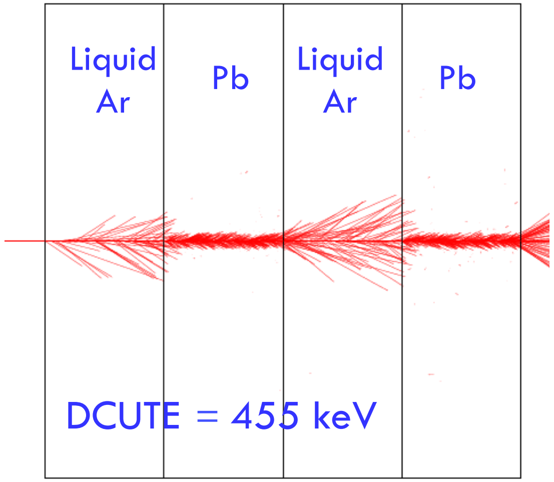
1.5 mm

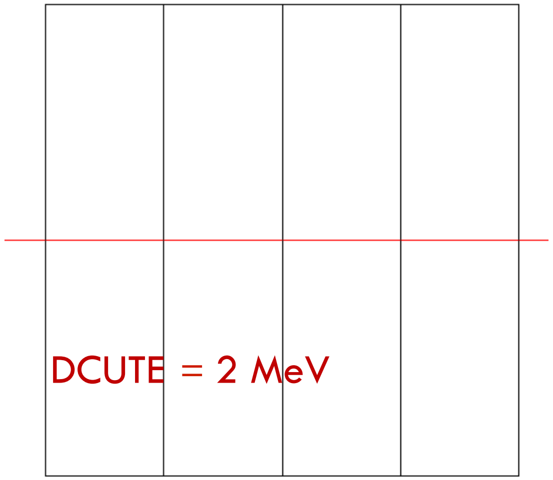
It is converted by Geant4 to energy

T_c = 455 keV electron energy in liquid Ar

T_c = 2 MeV electron energy in Pb

In Geant3





one has to set the cut for delta-rays (DCUTE) as an energy threshold

Either to the Liquid Argon value, thus producing many small unnecessary delta-rays in Pb,

Or to the Pb value, thus killing the delta-rays production everywhere

Which particles have cuts ?

- Since Geant4 9.3 cuts are defined for
  - Gamma
  - Electron
  - Positron
  - Proton

- Cut for proton is used for all hadrons and ions by elastic scattering processes

Which processes use cuts ?

- It is not mandatory to use cuts
- Energy thresholds for gamma are used in Bremsstrahlung
- Energy thresholds for electrons are used in ionisation and e+e- pair production processes
- Energy threshold for positrons is used in the e+e- pair production process
- Energy threshold for protons is used in processes of elastic scattering for hadrons and ions defining the threshold for kinetic energy of nuclear recoil
- Energy thresholds for gamma and electrons are used optionally in all discrete processes ("ApplyCuts" options)
  - Photoelectric effect, Compton, gamma conversion

Comments

- Range cut approach was established for simulation of energy deposition inside solid or liquid media
  - Sampling and crystal calorimeters
  - Silicon tracking
- For specific user application, it may be revised, for example, by defining different cuts in range for electron and gamma
  - Gaseous detectors
  - Muon system
- Tracking cuts may be also used (saving some CPU) for simulation of penetration via shielding or for simulation in non-sensitive part of the apparatus
  - Astrophysics applications
  - Nanodosimetry

How to define cut in range ?

- Use UI interface to geant4 kernel
  - /run/setCut 0.1 mm
  - /run/setCutForAGivenParticle e- 10 um

- Or implement a virtual method SetCuts() of G4VUserPhysicsList

- In Geant4 examples, several different implementations of cut definition in user code are shown
  - including user defined UI commands
  - $G4INSTALL/examples/extended/electromagnetic

Cuts per G4Region

- Uniform cut in range provides balanced simulation of particle transport in media with different density

- Requirements for precision in different parts of complex geometry may be very different
  - Micron precision in tracking devices
    VS millimeter precision in calorimeters
  - Unique value of the cut in range may be not effective and not practical

WHERE to find help ?

List of main Geant4 documents and tools

- User documents
  - Application Developers' Guide
  - Installation Guide
  - Toolkit Developer Guide
  - Examples
  - Physics Reference Manual

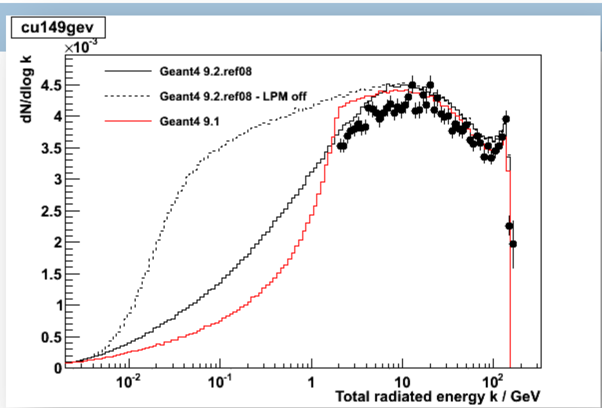
- User tools
  - Linux Crossed Reference (LXR) source code browser
  - HyperNews User Forum
  - Bug report system

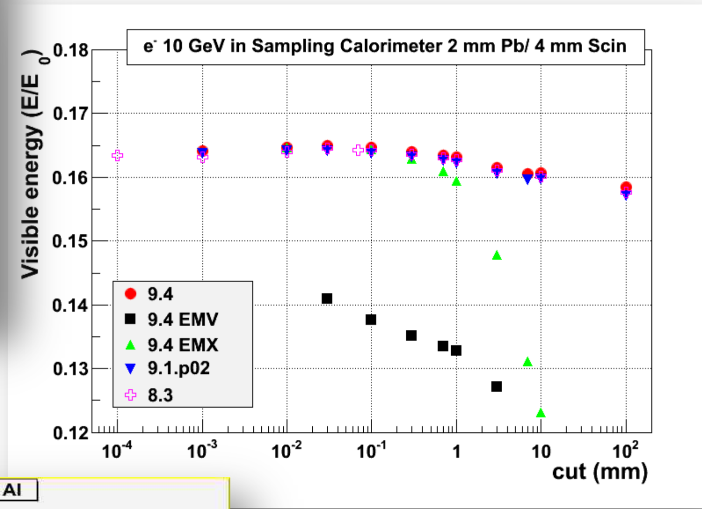
Suggestions

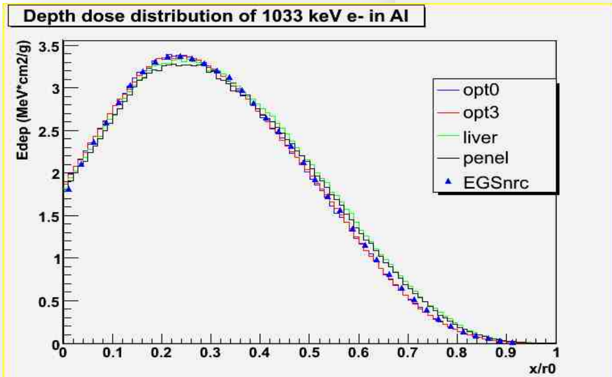
- The list of available EM processes and models is maintained by the EM working groups, see more in the EM web pages
  - http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml
- Geant4 extended and advanced examples show how to use EM processes and models
  - Located in $G4INSTALL/examples
- Visit the Geant4 HyperNews forum, section "electromagnetic processes" for discussion
- Use Geant4 bug report system for problems
- User feedback is always welcome

Validation repository

- A web-based verification tool has been developed for easy comparison of EM physics results obtained with different Geant4 version, and with measurements







https://geant4.cern.ch/collaboration/working_groups/electromagnetic/indexv.shtml

To learn more

$G4INSTALL/examples/extended/electromagnetic

Check basic quantities	
Total cross sections, mean free paths, SP …	TestEm0, Em13, Em14
Stopping power, particle range …	Em0, Em1, Em5, Em11, Em12
Final state : energy spectra, angular distributions	Em14
Energy loss fluctuations	Em18
Multiple Coulomb scattering	
as an isolated mechanism	Em15
as a result of particle transport	Em5
More global verifications	
Single layer: transmission, absorption, reflexion , atomic deexcitation, msc	Em5
Bragg curve, tallies	Em7
Depth dose distribution	Em11, Em12
Shower shapes, Moliere radius	Em2
Sampling calorimeters, energy flow	Em3
Crystal calorimeters	Em9
Other specialized programs	
High energy muon physics	Em17
Other rare, high energy processes	Em6
Synchrotron radiation	Em16
Transition radiation	Em8
Photo-absorption-ionization model	Em10

Refer to section on extended examples in App. User Guide.