Geant4 release 9.4

Electromagnetic Physics:
Geant4 EM Physics

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Electromagnetic Physics of Geant4

On behalf of the Geant4 Electromagnetic WGs

Outline

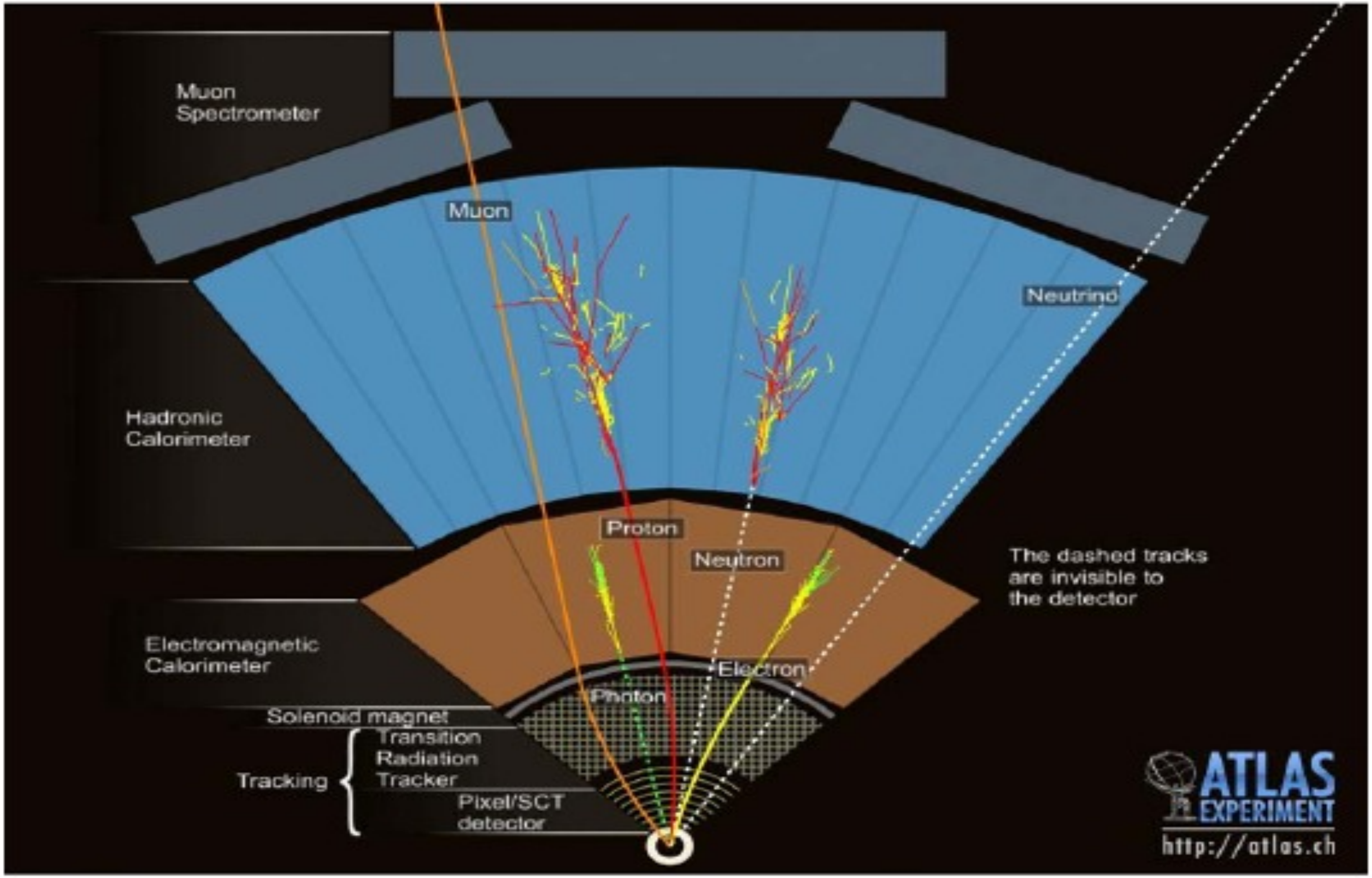
- Electromagnetic (EM) physics overview
  - Introduction
  - Structure of Geant4 EM sub-packages
  - Processes and models
  - MSC
- Geant4 cuts
  - Cut in range and energy thresholds
- How to invoke EM physics in Geant4
  - EM Physics lists
  - How to extract physics
  - How to find help

Electromagnetic (EM) physics overview

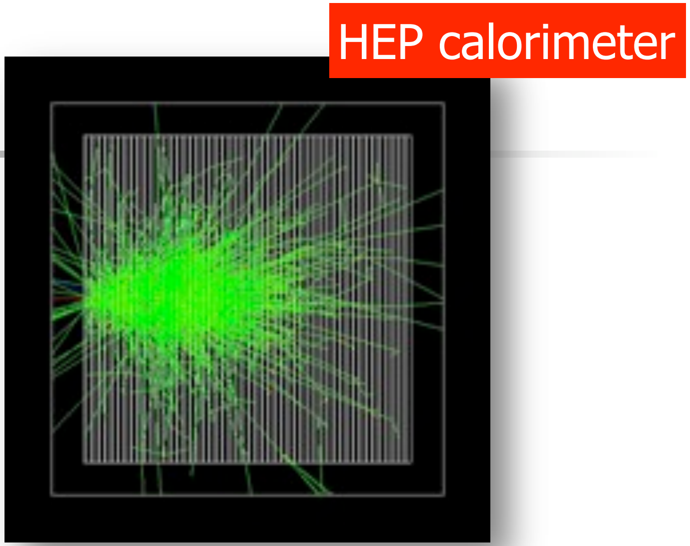
Geant4 Electromagnetic Physics

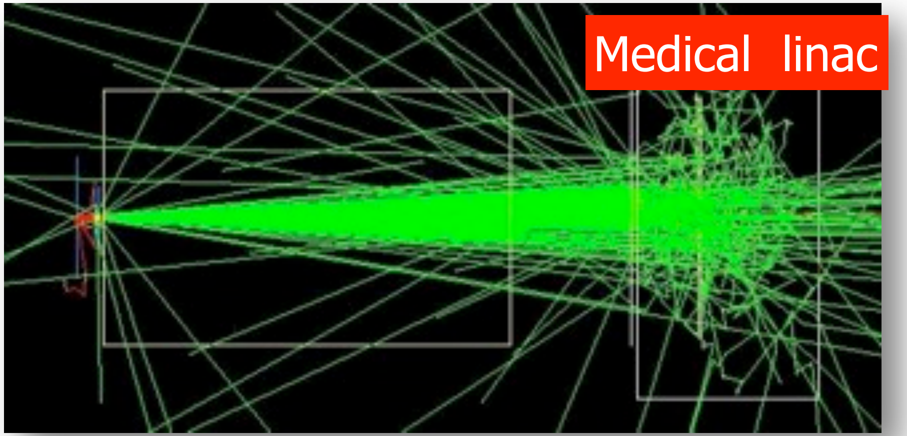
- Released with the 1st version of Geant4 with EM physics based on Geant3 experience (1998)
- Significant permanent development in many aspects of EM processes simulation since the beginning of Geant4 up to now
- Many years is used for large HEP experiments
  - BaBar, SLAC (since 2000)
  - LHC experiments: ATLAS, CMS and LHCb (since 2004)
- Many common requirements for HEP, space, medical and other applications
- A unique reference web page on Geant4 EM Physics
  - http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml
  - Includes a Web interface to validation repository

Geant4 simulation of ATLAS experiment at LHC, CERN



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 CHIPS
- Electron and positron processes
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - Nuclear interaction in hadronic sub-package CHIPS
  - Positron annihilation
- Suitable for HEP & many other Geant4 applications with electron and gamma beams

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 processes
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of polarised 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 250 eV up to 1 GeV (2001 version & 2008 version as beta)
  - hadrons and ions up to 1 GeV
  - microdosimetry models for radiobiology

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: G4Compton for photon Compton scattering
  - Assigned to Geant4 particle types
  - Inherit from G4VEmProcess base class

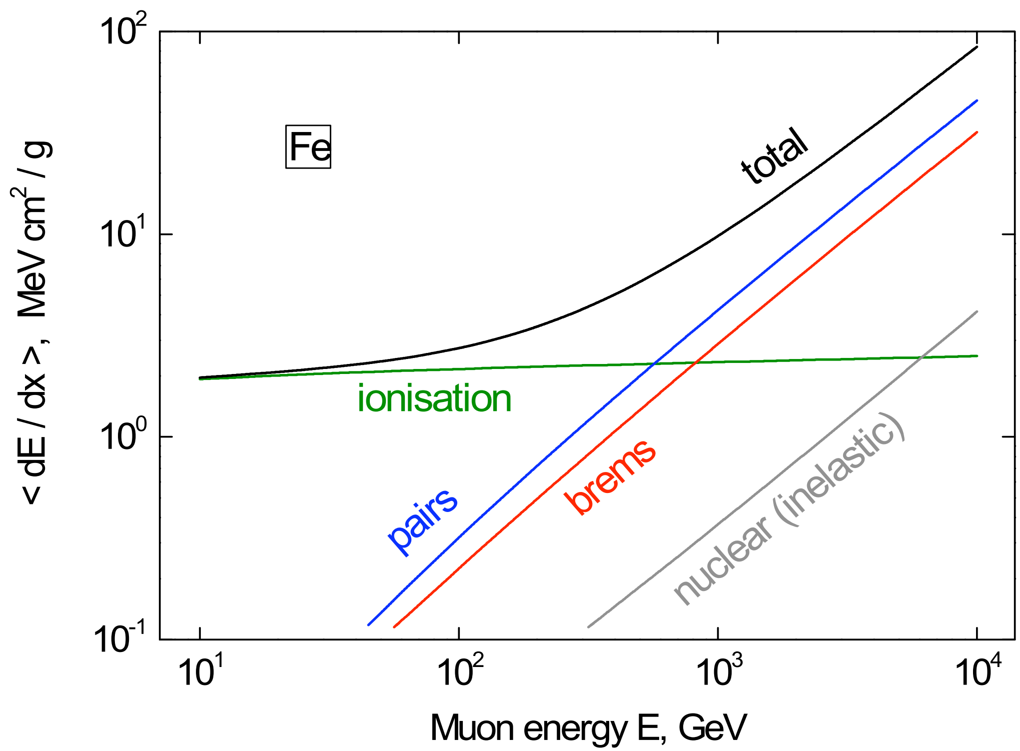
- A physical process can be simulated according to several models, each model being described by a model class
  - Naming scheme : « G4ModelNameProcessNameModel »
  - For example: G4LivermoreComptonModel
  - Models can be assigned to certain energy ranges and G4Regions
  - Inherit from G4VEmModel base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

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

Example : muon energy loss

- Continuous energy loss from processes
  - Ionisation
  - Production of e+e-
  - Bremsstrahlung
- Ionisation and delta-electron production
  - G4BetheBlochModel
- Below 200 keV – ICRU'49 parameterization of dE/dx
  - G4BraggIonModel
- Radiative corrections to ionization at E > 1 GeV
  - G4MuBetheBlochModel

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

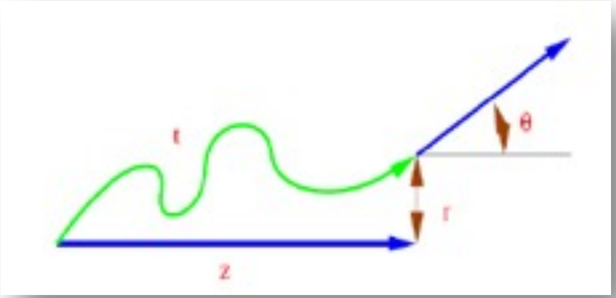


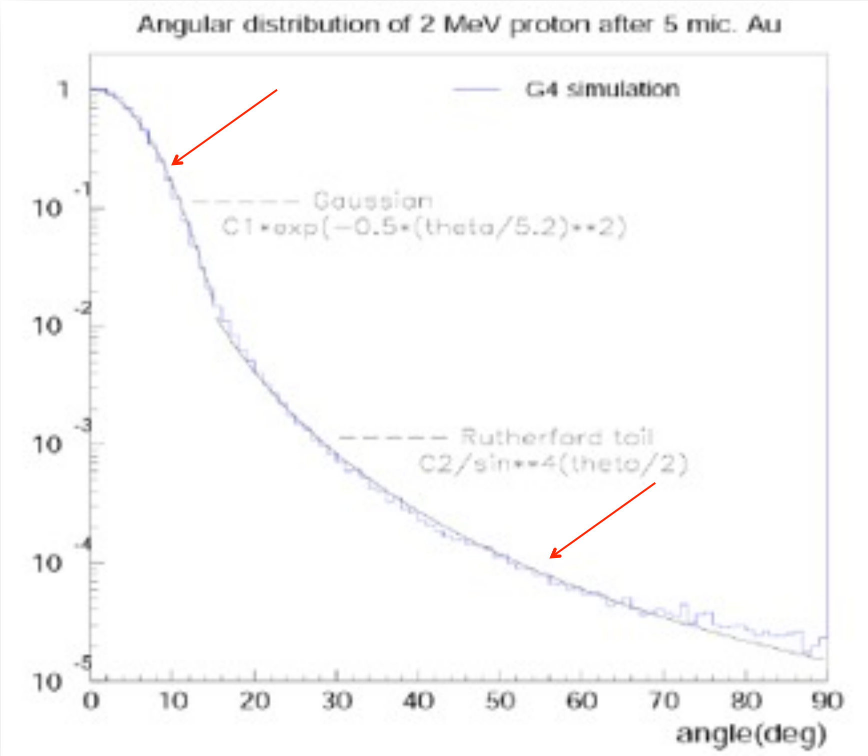
Muon stopping power precision ~2%

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.

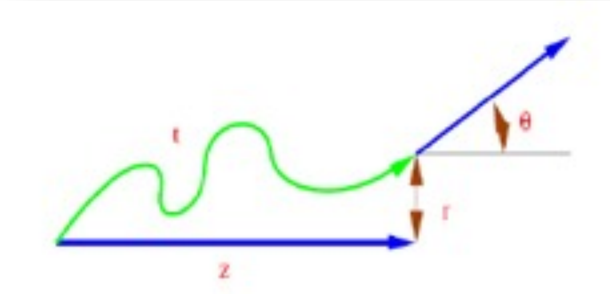




MSC models

Model	Particle type	Energy limit	Specifics and applicability
Urban (Urban 2006)	Any	-	Default model, (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),
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)	ions	-	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 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

Geant4 Urban MSC model

- The MSC model used in Geant4 is based on Lewis' MSC theory of transport of charged particles (1950)
- It uses phenomenological functions to determine the angular and spatial distributions after a simulation step
- The functions have been chosen in such a way as to give the same moments of the angular and spatial distributions as the Lewis theory

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 by default in G4eMultipleScattering
  - G4UrbanMscModel90 : used for muons in G4MuMultipleScattering, and for hadrons & ions in G4hMultipleScattering

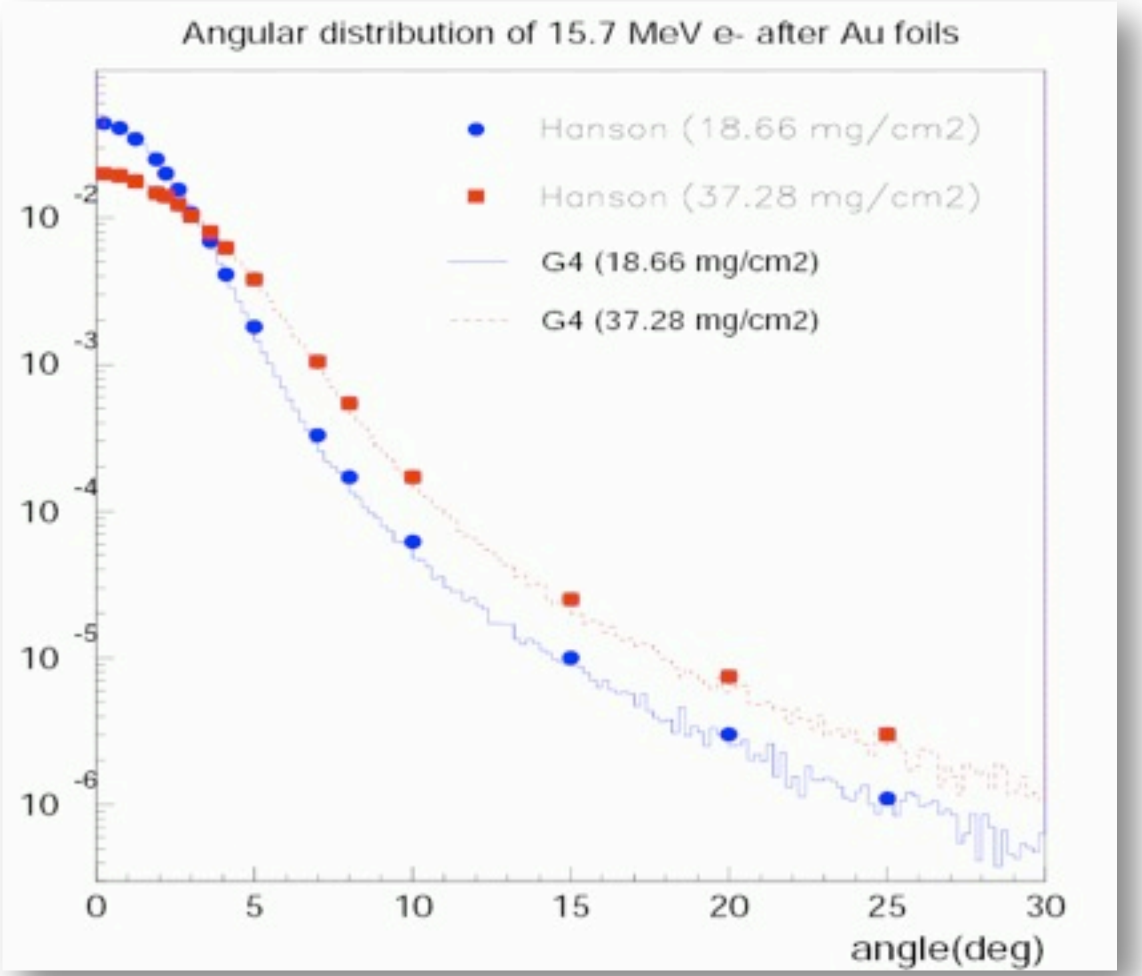
- Alternative single and multiple scattering models are available to users
  - see extended examples…

MSC in Physics Lists from G4 9.4

- Situation is changed significantly

EM Reference Physics list	e- / e+ G4eMultipleScattering	mu+ / mu- G4MuMultipleScattering	Hadrons, ions G4hMultipleScattering
G4EmStandardPhysics	G4UrbanMscModel93	G4WentelVIModel + G4CoulombScattering	G4UrbanMscModel90
G4EmStandardPhysics_option1	G4UrbanMscModel93	G4WentelVIModel+ G4CoulombScattering	G4UrbanMscModel90
G4EmStandardPhysics_option2	G4UrbanMscModel93	G4WentelVIModel+ G4CoulombScattering	G4WentelVIModel for pions, kaons, protons
G4EmStandardPhysics_option3	G4UrbanMscModel93	G4WentelVIModel+ G4CoulombScattering	G4UrbanMscModel90
G4EmLivermorePhysics	G4GoudsmithSaundersonMscModel	G4WentelVIModel+ G4CoulombScattering	G4UrbanMscModel90
G4EmLivermorePolarizedPhysics	G4GoudsmithSaundersonMscModel	G4WentelVIModel+ G4CoulombScattering	G4UrbanMscModel90
G4EmPenelopePhysics	G4GoudsmithSaundersonMscModel	G4WentelVIModel+ G4CoulombScattering	G4UrbanMscModel90

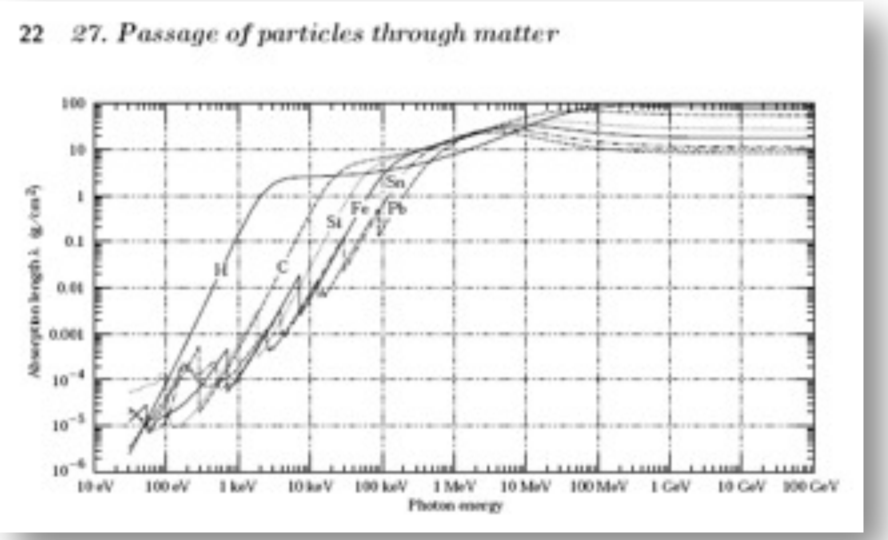
Example of MSC validation

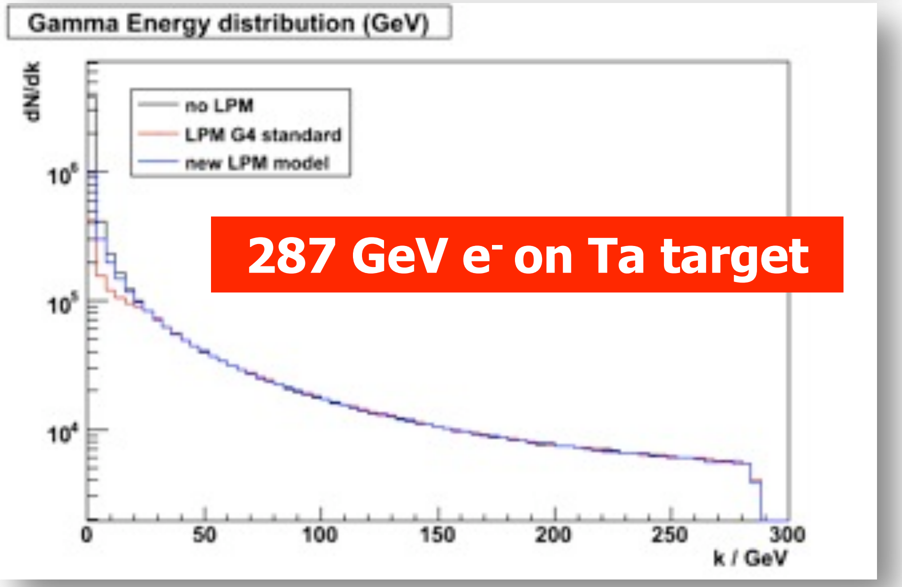


Geant4 cuts

Bremsstrahlung

- Bremsstrahlung spectrum grows to 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-effective
- Cuts/production threshold are used in all Monte Carlo codes
- Then, gamma emission below production threshold is taken into account as a continuous energy loss
- Similar approach is used for the ionisation process where spectrum is proportional to $1/T^2$





Geant4 cuts

- No tracking cuts by default

- Production threshold T_{cut} is defined by unique value cut in RANGE

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

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

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

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

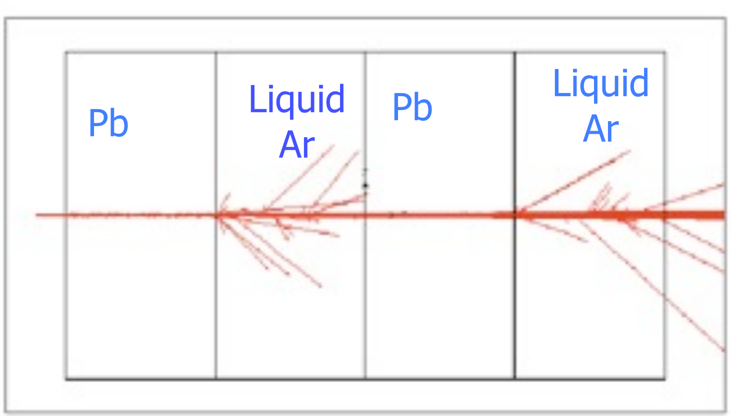
- Optionally, energy loss may be modified :
  - for the generation of extra δ-electrons under the threshold when the track is in the vicinity of a geometrical boundary (sub-cutoff)
  - for the sampling of fluorescence and Auger–electrons emission

- 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

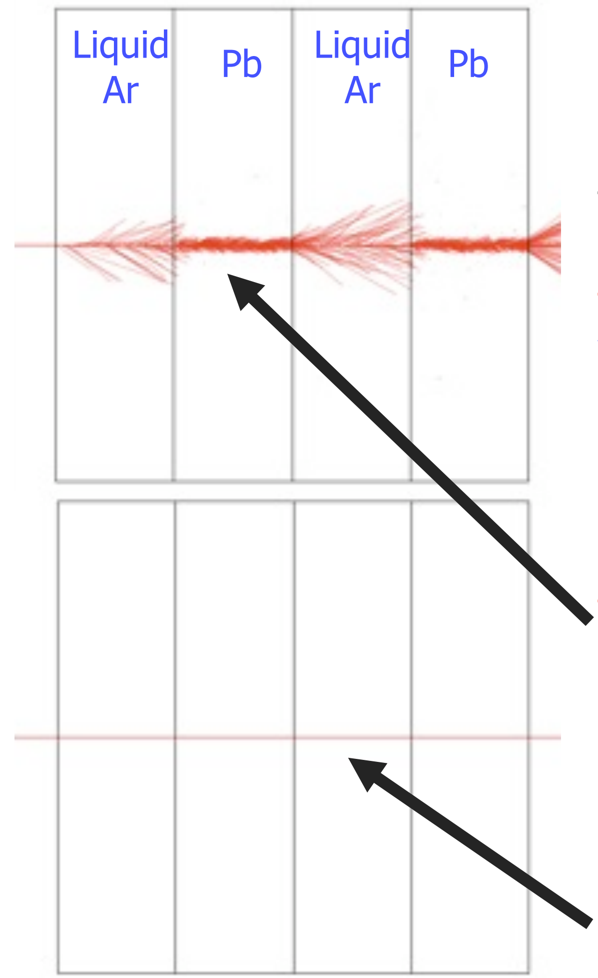
It is converted by Geant4 to energy:

T_c = 455 keV electron energy in liquid Ar

T_c = 2 MeV electron energy in Pb

In Geant3

DCUTE = 455 keV



DCUTE = 2 MeV

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 δ-rays in Pb,

or to the Pb value, thus killing the δ-rays production everywhere

Which processes 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 thresholds for gamma and electrons are used optionally ("ApplyCuts" options) in all discrete processes
  - Photoelectric effect, Compton, gamma conversion
- Energy threshold for protons are used in processes of elastic scattering for hadrons and ions defining the threshold for kinetic energy of nuclear recoil

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

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

- There are 3 ordered types of processes per particle which are active at different stages of the Geant4 tracking:
  - AtRest (annihilation, …)
  - AlongStep (ionisation, Bremsstrahlung, …)
  - PostStep (photo-electric, Compton, Cerenkov,….)

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

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

EM Physics constructors

- G4EmStandardPhysics – default
- G4EmStandardPhysics_option1 – HEP, fast but not precise
- G4EmStandardPhysics_option2 – experimental
- G4EmStandardPhysics_option3 – medical, space
- G4EmLivermorePhysics
- G4EmLivermorePolarizedPhysics
- G4EmPenelopePhysics
- G4EmDNAPhysics

Combined Physics:
- Standard > 1 GeV
- Low Energy < 1 GeV

- Located in $G4INSTALL/source/physics_list/builders
- Advantage of using of these classes
  - they are tested on a regular basis and are used for regular validation

Example: G4EmStandard Physics

Only PostStep

```
G4ProcessManager* pmanager

  if ( particleName == "gamma"  ) {
    pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
    pmanager->AddDiscreteProcess(new G4ComptonScattering);
    pmanager->AddDiscreteProcess(new G4GammaConversion);

  } else if ( particleName == "e+" ) {
    pmanager->AddProcess(new G4eMultipleScattering,  -1,  1, 1);
    pmanager->AddProcess(new G4eIonisation,          -1,  2, 2);
    pmanager->AddProcess(new G4eBremsstrahlung,      -1,  3, 3);
    pmanager->AddProcess(new G4eplusAnnihilation,     0, -1, 4);
```

AtRest AlongStep PostStep

3 stages

- Numbers are process order
  - G4Transportation is the 1st (order = 0) for AlongStep and PostStep
- "-1" means that the process is not active

Example: Penelope Physics

- Process class G4PhotoElectricEffect
- The default model is G4PEEffectModel
- There are alternative Livermore and Penelope models
- Example of combined EM Physics Lists
  - Penelope photo-electric below 1 GeV

```
…
G4double limit = 1.0*GeV;
If ( particleName == “gamma”  )
{
   G4PhotoElectricEffect* pef= new G4PhotoElectricEffect();
   G4PenelopePhotoElectricModel* aModel = new G4PenelopePhotoElectricModel();
   aModel->SetHighEnergyLimit(limit);
   pef->AddEmModel(0, aModel);              // 1st parameter - order
   pmanager->AddDiscreteProcess(pef);
…
```

How to extract Physics ?

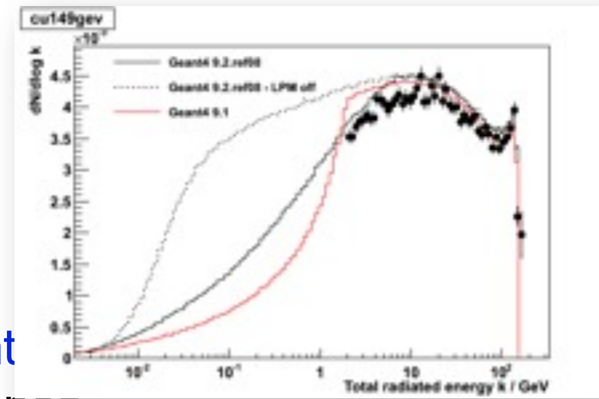
- Possible to retrieve Physics quantities using a G4EmCalculator object
- Physics List should be initialized
- Example for retrieving the total cross section of a process with name procName, for particle and material matName

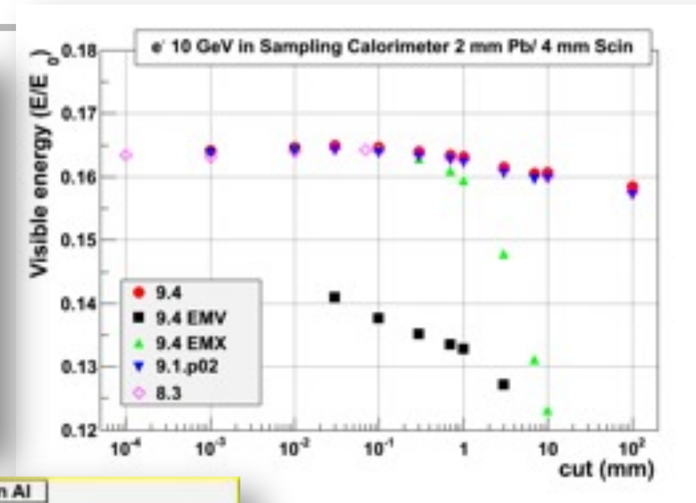
```
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;

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;
```

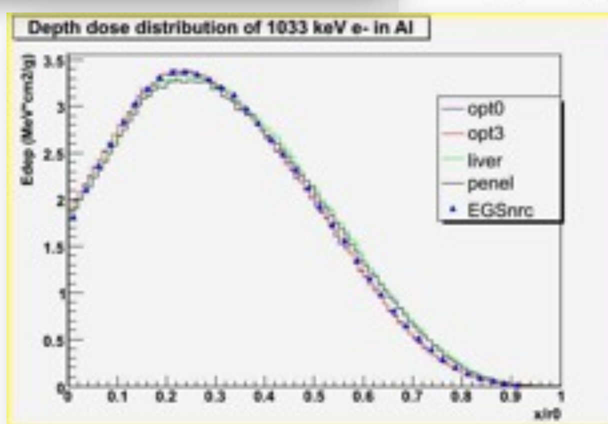
- A good example: $G4INSTALL/examples/extended/electromagnetic/TestEm14. Look in particular at the RunAction.cc class

Validation repository

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







http://www-zeuthen.desy.de/geant4/web/

To learn more:
$G4INSTALL/examples/extended/electromagnetic

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

Check basic quantities	
Total cross sections, mean free paths ...	TestEm0, Em13, Em14
Stopping power, particle range ...	Em0, Em1, Em5, Em11, Em12
Final state : energy spectra, angular distributions	Em14
Energy loss fluctuations, fluorescence	Em18
Multiple Coulomb scattering	
as an isolated mechanism	Em15
as a result of particle transport	Em5
More global verifications	
Single layer: transmission, absorption, reflexion	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

Suggestions

- The list of available EM processes and models is maintained by EM working groups in 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
  - In $G4INSTALL/examples
- User feedback is always welcome

Thank you