Electromagnetic Physics I

Standard EM package

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Outline

- Electromagnetic (EM) physics overview
  - Electromagnetic working group
  - Standard EM packages
- How to invoke EM physics in Geant4
  - EM Physics Lists
- Important sample processes
  - Compton scattering
  - ionization
  - multiple scattering
- Energy-range relation and stepping

Electromagnetic (EM) physics overview

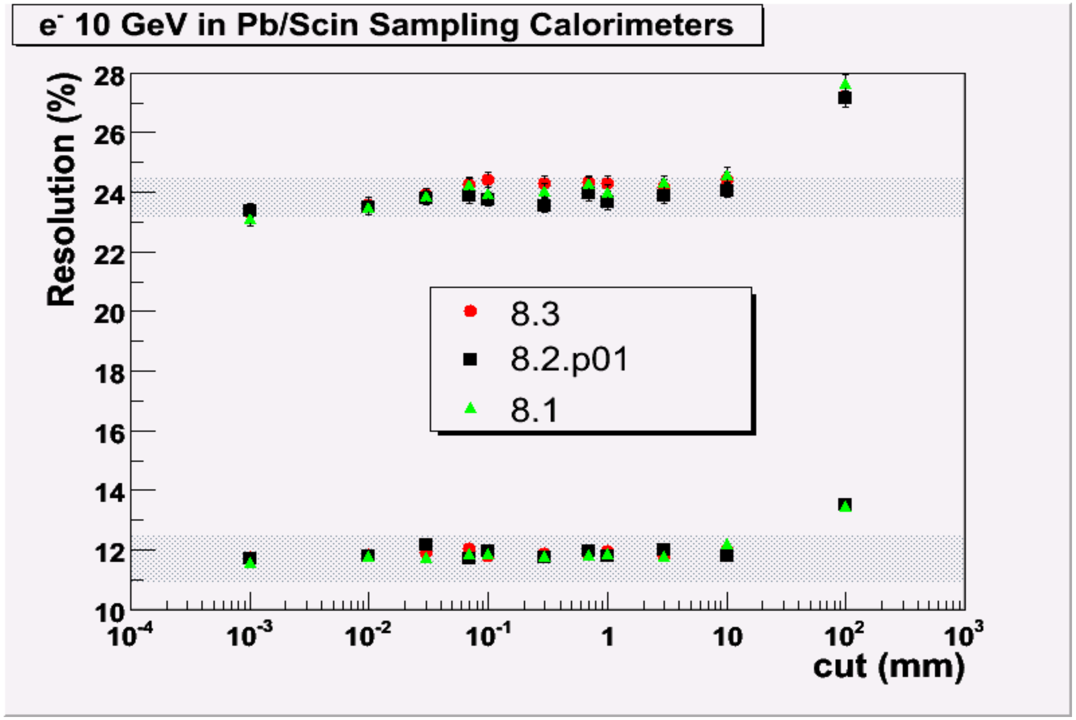
Electromagnetic physics working group

- Many years is used in production for BaBar and other HEP experiments
- Main focus today is LHC and other HEP experiments including ILC
- Many common requirements for HEP, space, medical and other applications
- Working group page:

http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml

Standard EM packages

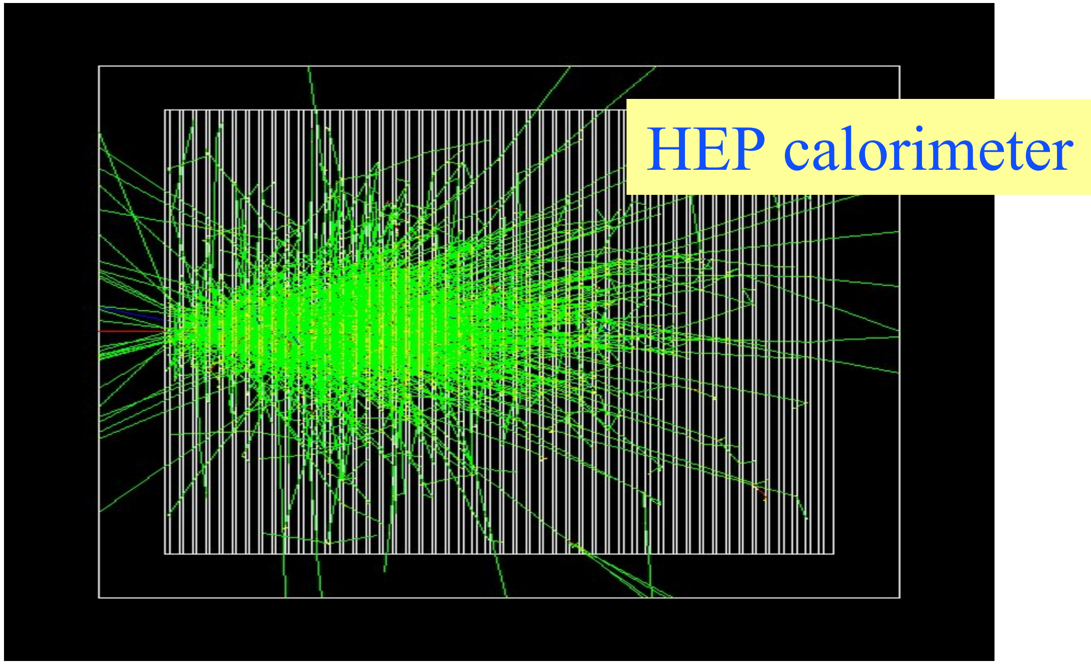
- ***Standard***
  - γ, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- ***Muons***
  - up to 1 PeV
  - Energy loss propagator
- ***Xrays***
  - X-ray and optical photon production processes
- ***Optical***
  - Optical photon interactions
- ***High-energy***
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- ***Polarisation***
  - New package for simulation of polarized beams

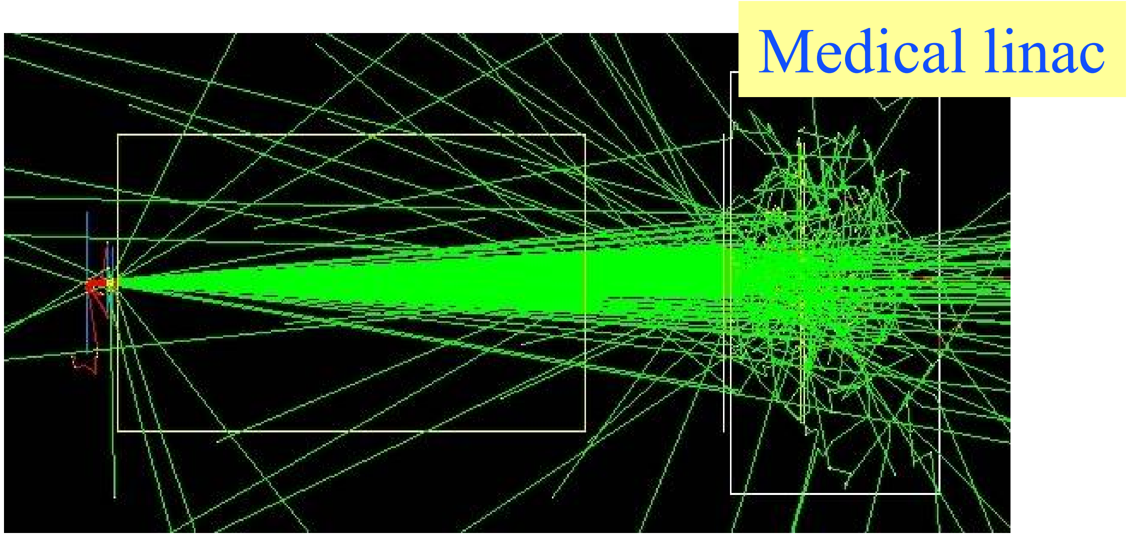


- ***Default Physics Lists***
- ***Two configurations:***
  - 5 mm Pb/5 mm Scintillator
  - 10 mm Pb/ 2.5 mm Scintillator
- ***Data*** from NIM A262 (1987) 229; NIM A274 (1989) 134

Gamma and Electron Transport

- Photon processes:
  - γ conversion into e^+e^- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering in low-energy package
  - 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
- Many Geant4 applications with electron and gamma beams

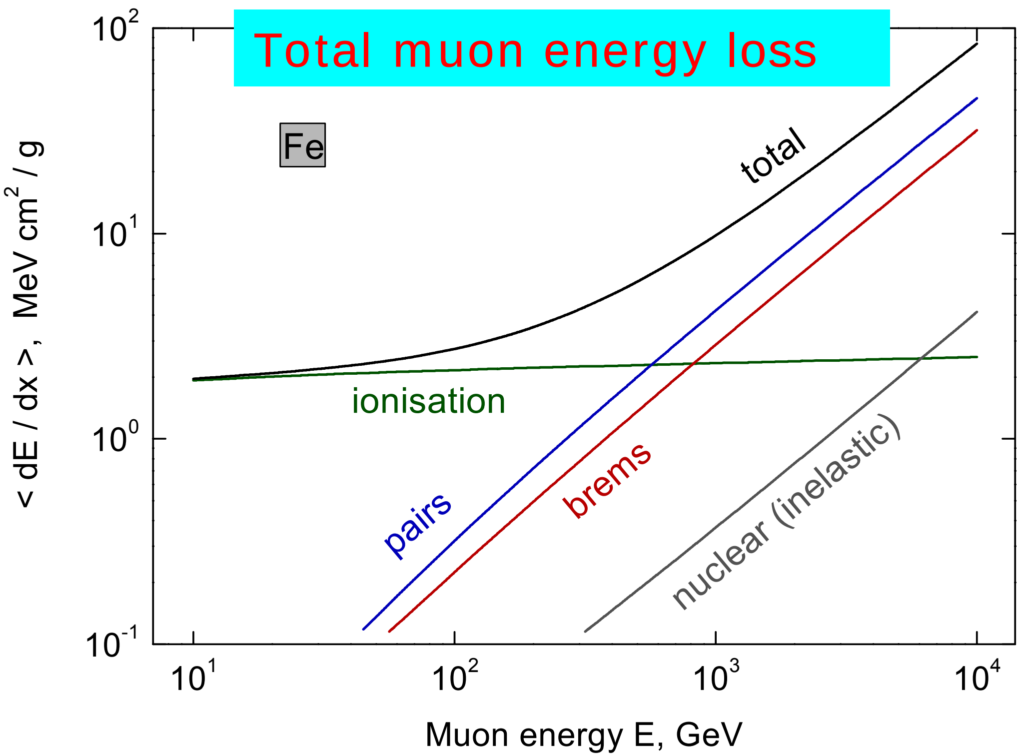


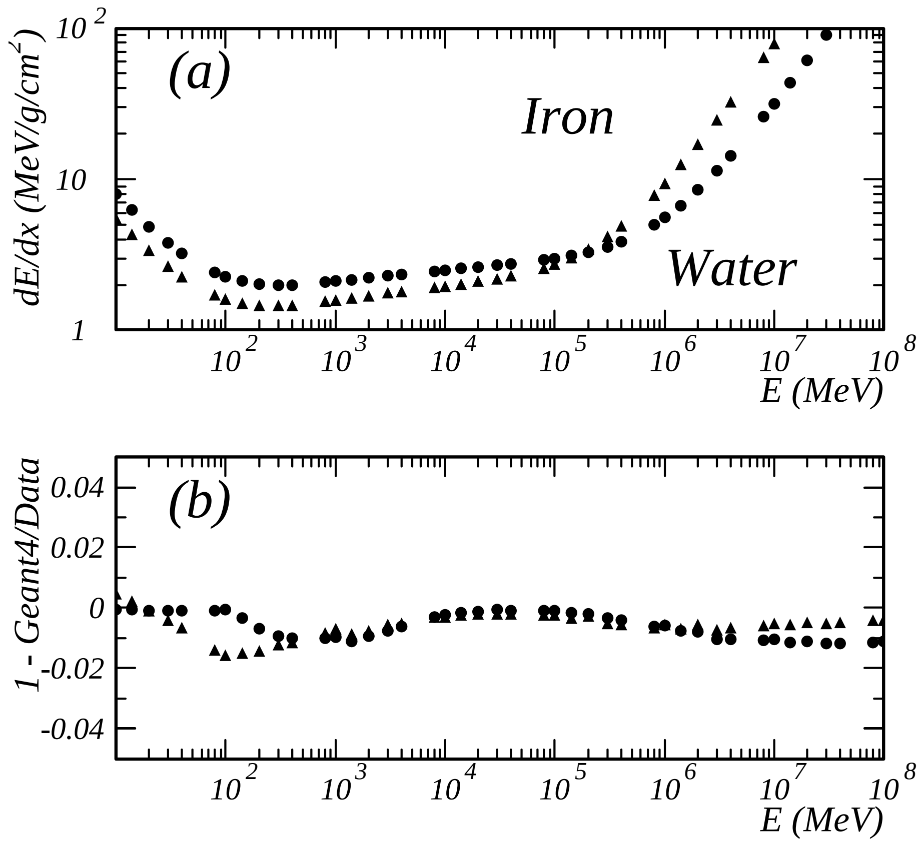


Muon EM Physics Simulation

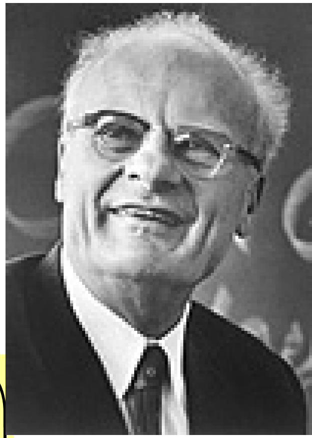
- Main processes:
  - Ionization
  - Bremsstrahlung
  - e^+e^- pair production
  - Muon-nuclear interactions in hadronic packages

Muon stopping power
Precision about 2%





Hadron and ion EM physics

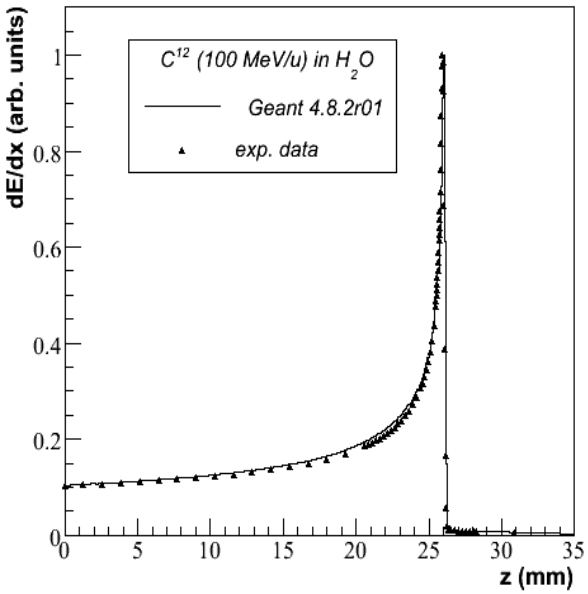


- Coulomb scattering
- Ionization
- Bethe-Bloch formula with corrections used for E>2 MeV

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

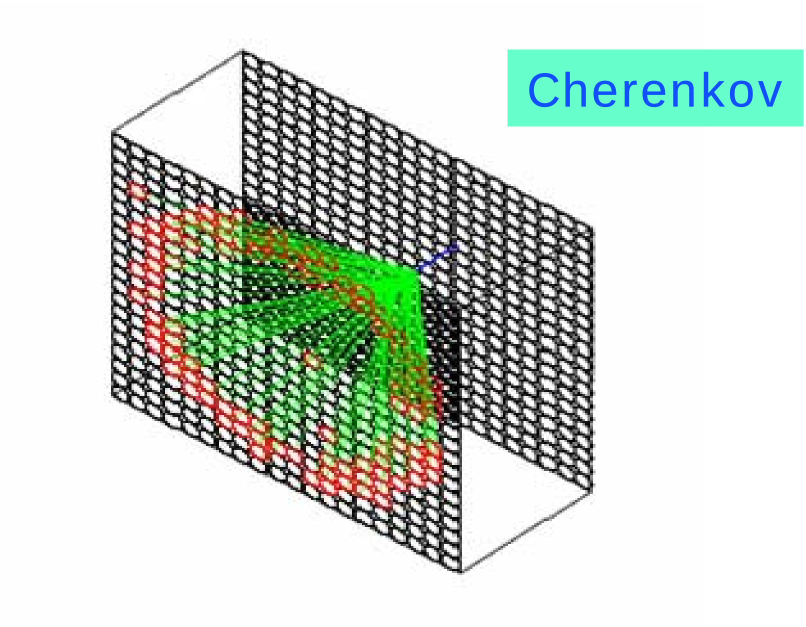
  - C – shell correction
  - G – Mott correction
  - δ – density correction
  - F – finite size correction
  - L_1- Barkas correction
  - L_2- Bloch correction
  - Nuclear stopping
  - Ion effective charge

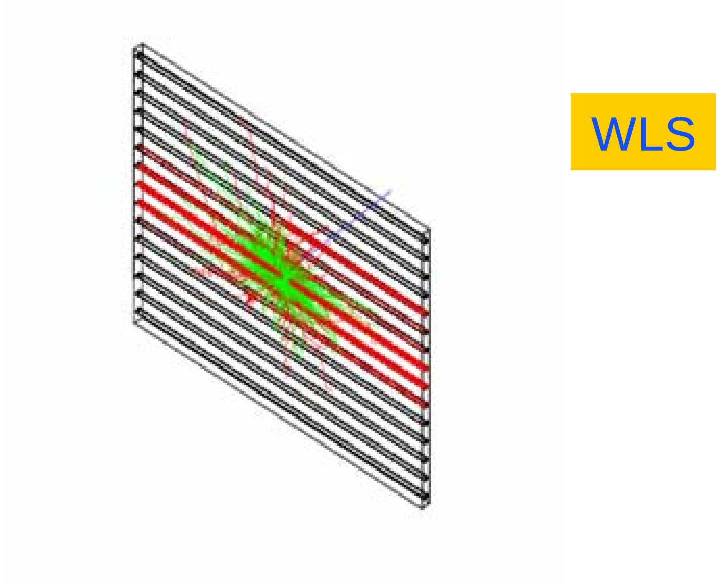
- Bragg peak parameterizations for E< 2 MeV
  - ICRU'49 and NIST databases



X-ray and optical photon simulation

- Standard packages:
  - Cherenkov radiation
  - Synchrotron radiation
  - Transition radiation
  - Scintillation
- Low-energy EM package:
  - Atomic relaxations – fluorescence and Auger transitions
- Optical
  - Reflection
  - Refraction
  - Absorption
  - Rayleigh scattering





How to invoke EM physics in Geant4

PhysicsList

For each type of particle the ProcessManager maintains a list of processes to be apply.

More precisely, there are 3 ordered lists of processes :

- AtRest action
- AlongStep action
- PostStep action

These lists are registered in the `UserPhysicsList` class.

example of PhysicsList

ordAtRestDoIt ordPostStepDoIt

```
if (particleName == "e-") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4eIonisation,        -1, 2,2);
pmanager->AddProcess(new G4eBremsstrahlung,    -1,-1,3);
}

else if (particleName == "e+") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4eIonisation,        -1, 2,2);
pmanager->AddProcess(new G4eBremsstrahlung,    -1,-1,3);
pmanager->AddProcess(new G4eplusAnnihilation,   0,-1,4);
}
```

ordAlongSteptDoIt

-1 - parameter to indicate InActive DoIt

```
if (particleName == "mu+" || particleName == "mu-") {
pmanager->AddProcess(new G4MultipleScattering, -1, 1,1);
pmanager->AddProcess(new G4MuIonisation,        -1, 2,2);
pmanager->AddProcess(new G4MuBremsstrahlung,    -1,-1,3);
pmanager->AddProcess(new G4MuPairProduction,    -1,-1,4);
}

if ((particle->GetPDGCharge() != 0.0) &&
(!particle->IsShortLived()) &&
(particle->GetParticleName() != "chargedgeantino")) {
pmanager->AddProcess(new G4MultipleScattering, -1,1,1);
pmanager->AddProcess(new G4hIonisation,         -1,2,2);
}
```

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

is a shortcut for :

```
pmanager->AddProcess(new G4PhotoElectricEffect, -1,-1,1);
pmanager->AddProcess(new G4ComptonScattering,   -1,-1,2);
pmanager->AddProcess(new G4GammaConversion,     -1,-1,3);
```

For processes which have only PostStepAction, the ordering is not important.

Recent updates of Physics Lists

- For positive ions

```
If (particleName == "alpha" || particleName == "He3" ||
   particleName == "GenericIon") {
      pmanager->AddProcess(new G4hMultipleScattering, -1,1,1);
      pmanager->AddProcess(new G4ionIonisation,        -1,2,2);
}
```

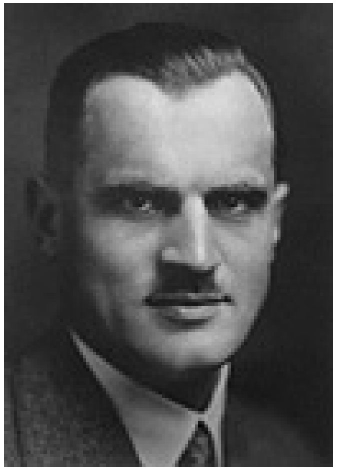
- Predefined builders $G4INSTALL/source/physics_lists/builders
  - G4EmStandardPhysics – default EM physics
  - G4EmStandardPhysics71 (G4EmStandardPhysics_option1 since g4 9.0)
    - Fast but less precise simulation
  - G4EmStandardPhysics72 (G4EmStandardPhysics_option2 since g4 9.0)
    - Sub-cutoff option enabled

Important sample processes

Compton scattering

The Compton effect describes the scattering off quasi-free atomic electrons :

$$\gamma + e \rightarrow \gamma' + e'$$



Each atomic electron acts as an independent cible; Compton effect is called incoherent scattering. Thus:

$$\text{cross section per atom} = Z \times \text{cross section per electron}$$

The inverse Compton scattering also exists: an energetic electron collides with a low energy photon which is blue-shifted to higher energy. This process is of importance in astrophysics.

Compton scattering is related to (e^+, e^-) annihilation by crossing symmetry.

energy spectrum

Under the same assumption,the unpolarized differential cross section per atom is given by the Klein-Nishina formula [Klein29] :

$$\frac{d\sigma}{dk'} = \frac{\pi\, r_e^2}{mc^2}\,\frac{Z}{\kappa^2}\left[\epsilon + \frac{1}{\epsilon} - \frac{2}{\kappa}\left(\frac{1-\epsilon}{\epsilon}\right) + \frac{1}{\kappa^2}\left(\frac{1-\epsilon}{\epsilon}\right)^2\right] \qquad (1)$$

where

k' energy of the scattered photon ; $\epsilon = k'/k$

r_e classical electron radius

κ k/mc^2

k is total electron energy

total cross section per atom

$$\sigma(k) = \int_{k'_{min}=k/(2\kappa+1)}^{k'_{max}=k} \frac{d\sigma}{dk'}\, dk'$$

$$\sigma(k) = 2\pi\, r_e^2\, Z \left[\left(\frac{\kappa^2 - 2\kappa - 2}{2\kappa^3} \right) \ln(2\kappa+1) + \frac{\kappa^3 + 9\kappa^2 + 8\kappa + 2}{4\kappa^4 + 4\kappa^3 + \kappa^2} \right]$$

limits

$k \to \infty :$ σ goes to 0 : $\sigma(k) \sim \pi\, r_e^2\, Z \dfrac{\ln 2\kappa}{\kappa}$

$k \to 0 :$ $\sigma \to \dfrac{8\pi}{3} r_e^2\, Z$ (classical Thomson cross section)

low energy limit

In fact, when $k \leq 100\ keV$ the binding energy of the atomic electron must be taken into account by a corrective factor to the Klein-Nishina cross section:

$$\frac{d\sigma}{dk'} = \left[\frac{d\sigma}{dk'}\right]_{KN} \times S(k, k')$$

See for instance [Cullen97] or [Salvat96] for derivation(s) and discussion of the *scattering function* S(k,k').

As a consequence, at very low energy, the total cross section goes to 0 like k^2. It also suppresses the forward scattering.

At X-rays energies the scattering function has little effect on the Klein-Nishina energy spectrum formula 1. In addition the Compton scattering is not the dominant process in this energy region.

total cross section per atom in GEANT4

The total cross section has been parametrized :

$$\sigma(Z,\kappa) = \left[P_1(Z)\,\frac{\log(1+2\kappa)}{\kappa} + \frac{P_2(Z)+P_3(Z)\kappa+P_4(Z)\kappa^2}{1+a\kappa+b\kappa^2+c\kappa^3}\right]$$

where:

$$\begin{aligned} \kappa &= k/mc^2 \\ P_i(Z) &= Z(d_i+e_iZ+f_iZ^2) \end{aligned}$$

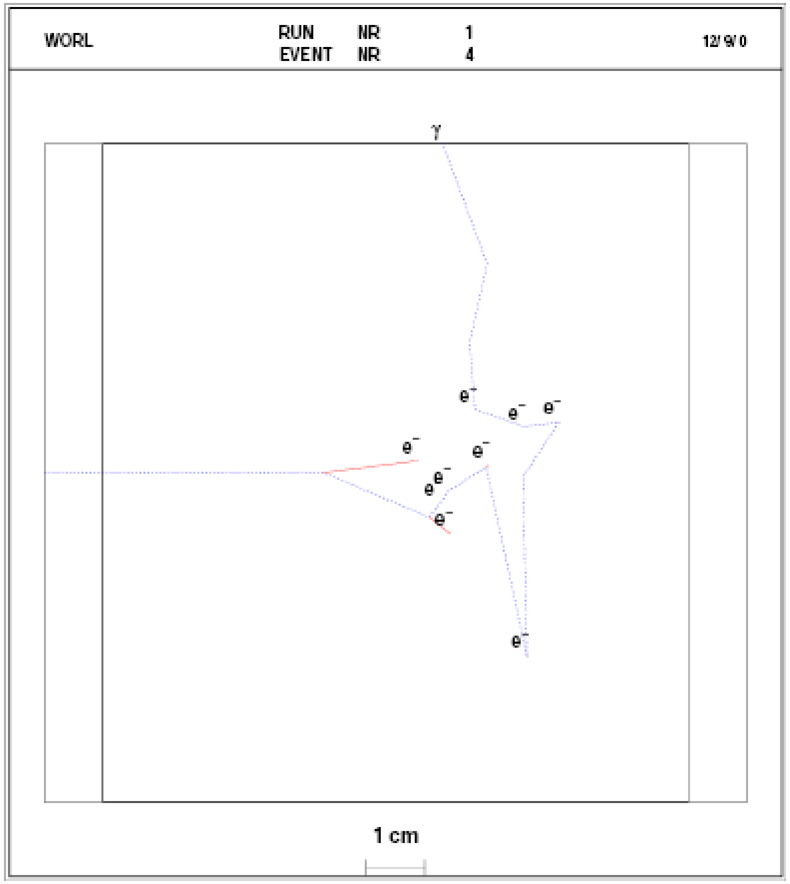
The fit was made over 511 data points chosen between:

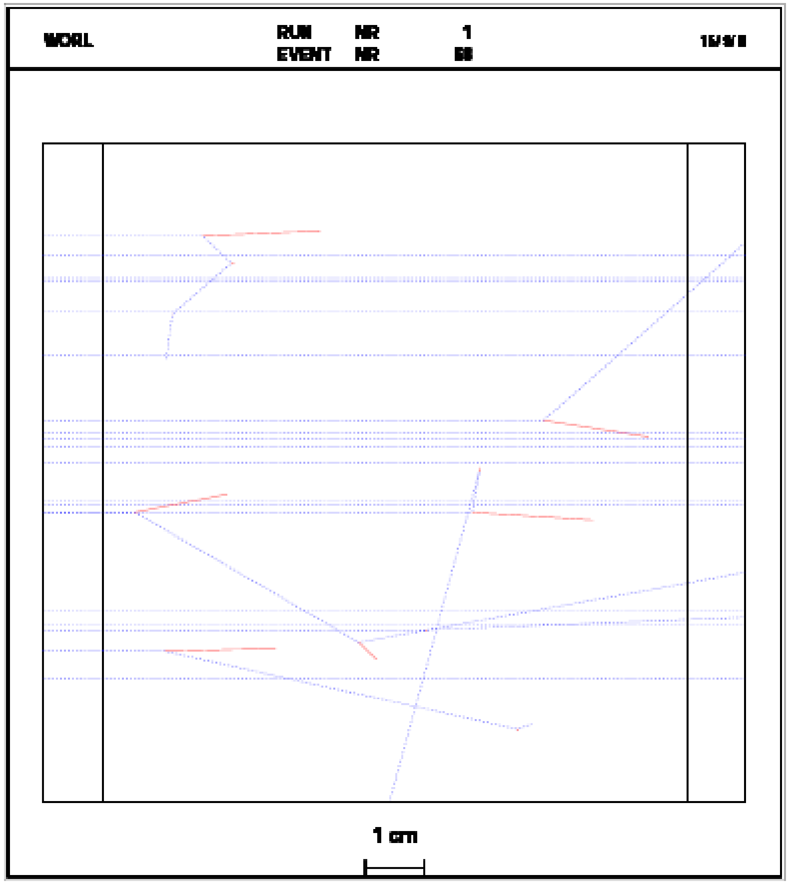
$$1 \le Z \le 100 \qquad ; \qquad k \in [10\ \mathrm{keV}, 100\ \mathrm{GeV}]$$

The accuracy of the fit is estimated to be:

$$\frac{\Delta\sigma}{\sigma} = \begin{cases} \approx 10\% & \text{for } k \quad \simeq 10\ \mathrm{keV} - 20\ \mathrm{keV} \\ \le 5-6\% & \text{for } k \quad > 20\ \mathrm{keV} \end{cases}$$

γ 10 MeV in 10 cm Aluminium: Compton scattering





γ e^-

Ionization

The basic mechanism is an inelastic collision of the moving charged particle with the atomic electrons of the material, ejecting off an electron from the atom :

$$\mu + atom \rightarrow \mu + atom^{+} + e^{-}$$

In each individual collision, the energy transfered to the electron is small. But the total number of collisions is large, and we can well define the average energy loss per (macroscopic) unit path length.

Mean energy loss and energetic δ-rays

$$\frac{d\sigma(Z,E,T)}{dT}$$

is the differential cross-section per atom for the ejection of an electron with kinetic energy T by an incident charged particle of total energy E moving in a material of density ρ.

One may wish to take into account separately the high-energy knock-on electrons produced above a given threshold T_{cut} (miss detection, explicit simulation ...).

$T_{cut} \gg I$ (mean excitation energy in the material).

$T_{cut} > 1$ keV in GEANT4

Below this threshold, the soft knock-on electrons are counted only as continuous energy lost by the incident particle.

Above it, they are explicitly generated. Those electrons must be excluded from the mean continuous energy loss count.

Mean energy loss

The mean rate of the energy lost by the incident particle due to the soft δ-rays is :

$$\frac{dE_{soft}(E, T_{cut})}{dx} = n_{at} \cdot \int_0^{T_{cut}} \frac{d\sigma(Z, E, T)}{dT} T \, dT \qquad (2)$$

n_{at} : nb of atoms per volume in the matter.

The total cross-section per atom for the ejection of an electron of energy $T > T_{cut}$ is :

$$\sigma(Z, E, T_{cut}) = \int_{T_{cut}}^{T_{max}} \frac{d\sigma(Z, E, T)}{dT} \, dT \qquad (3)$$

where T_{max} is the maximum energy transferable to the free electron.

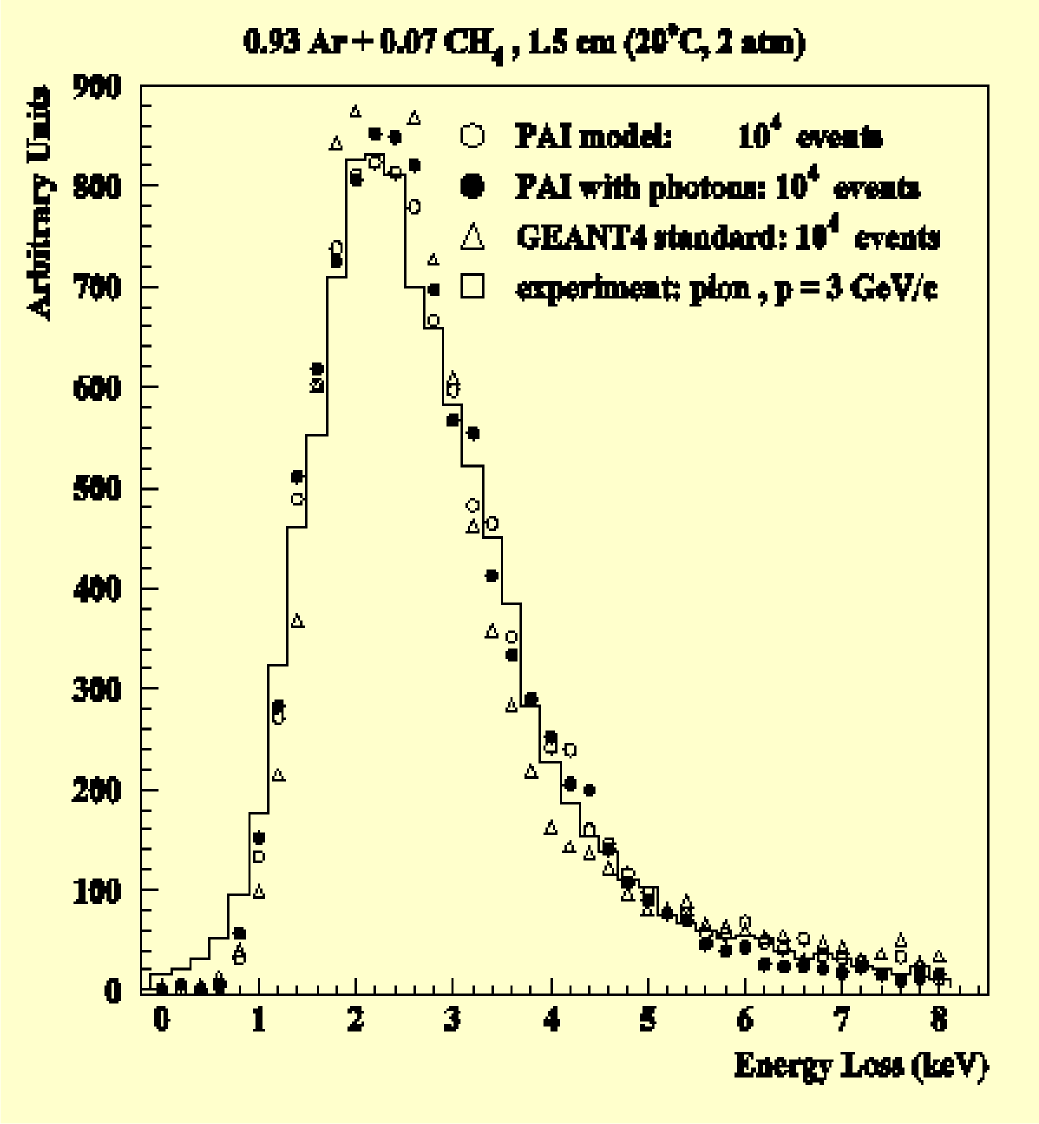
Fluctuations in energy loss

$\langle \Delta E \rangle = (dE/dx).\Delta x$ gives only the average energy loss by ionization. There are fluctuations. Depending of the amount of matter in Δx the distribution of ΔE can be strongly asymmetric ($\rightarrow$ the Landau tail).

The large fluctuations are due to a small number of collisions with large energy transfers.

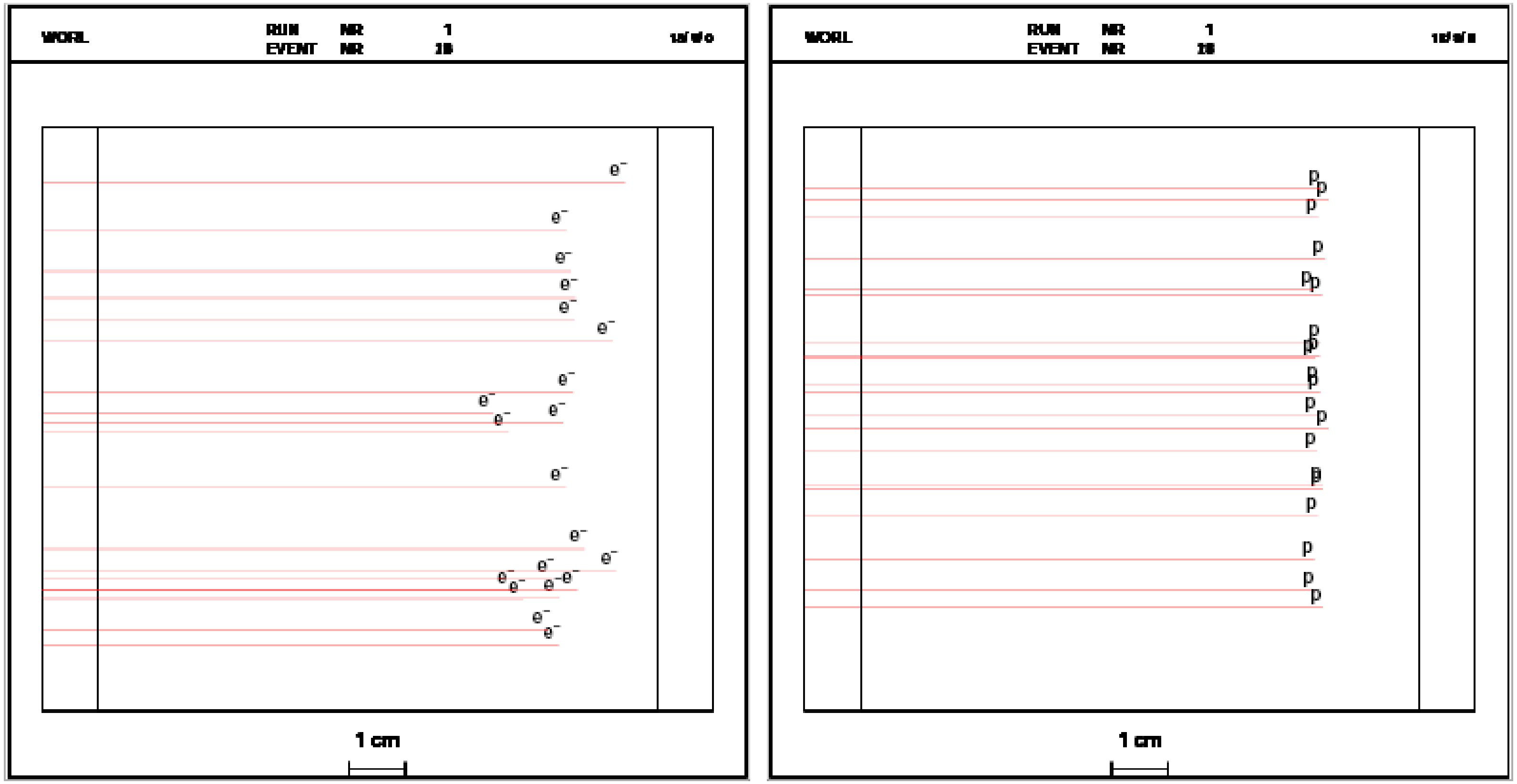
Geant4 models of energy loss fluctuations

- 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 data
  - All energy transfers are sampled with production of secondary e^- or γ
  - Very slow model, should be applied for sensitive region of detector



Fluctuations on ΔE lead to fluctuations on the actual range (straggling).

penetration of e^- (16 MeV) and proton (105 MeV) in 10 cm of water.



Sampling of δ-electrons for hadrons and ions

Energetic δ rays

The differential cross-section per atom for producing an electron of kinetic energy T, with $I \ll T_{cut} \leq T \leq T_{max}$, can be written :

$$\frac{d\sigma}{dT} = 2\pi r_e^2 mc^2 Z \frac{z_p^2}{\beta^2} \frac{1}{T^2} \left[1 - \beta^2 \frac{T}{T_{max}} + \frac{T^2}{2E^2} \right]$$

(the last term for spin 1/2 only).

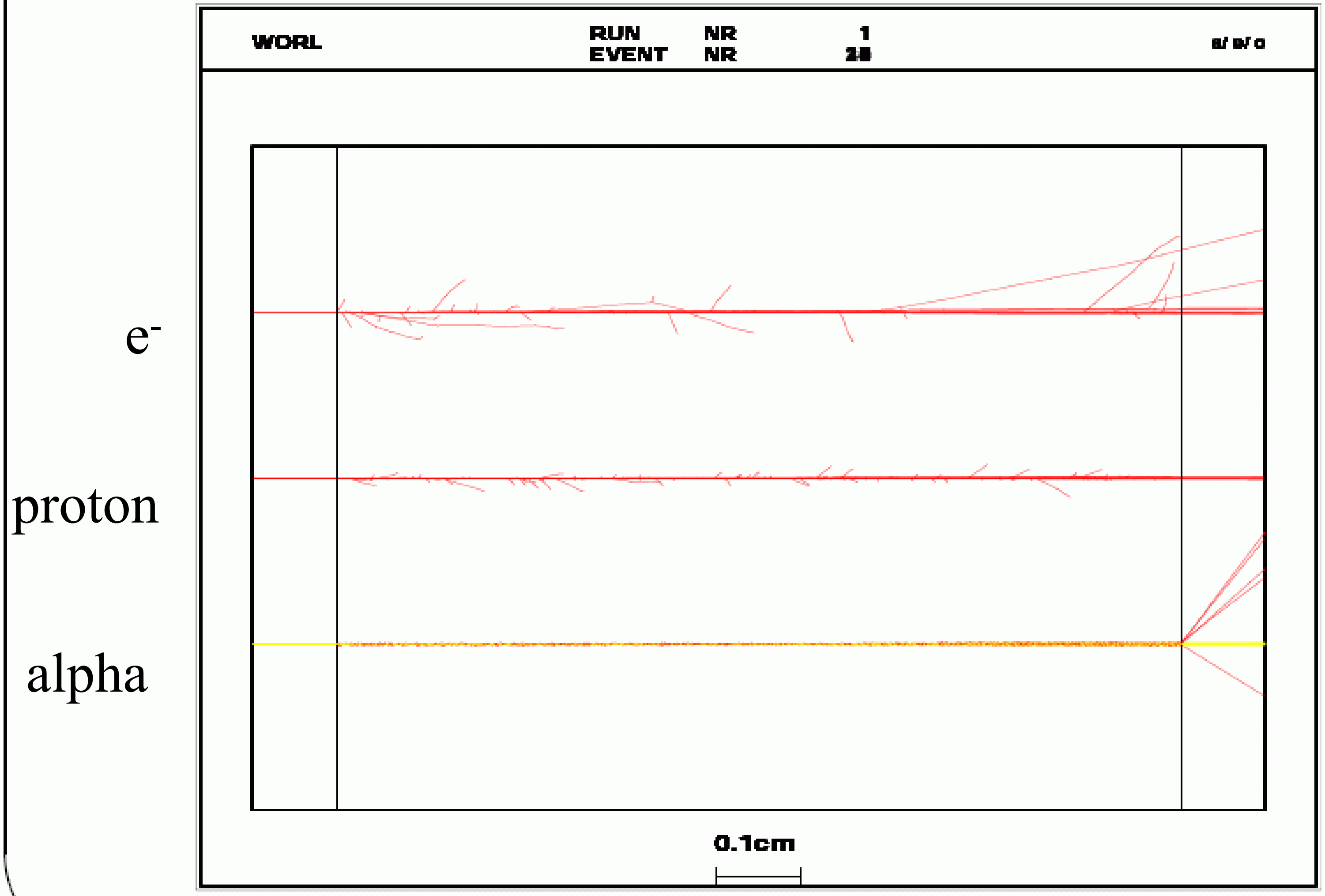
The integration (3) gives :

$$\sigma(Z, E, T_{cut}) = \frac{2\pi r_e^2 Z z_p^2}{\beta^2} \left[\left(\frac{1}{T_{cut}} - \frac{1}{T_{max}} \right) - \frac{\beta^2}{T_{max}} \ln \frac{T_{max}}{T_{cut}} + \frac{T_{max} - T_{cut}}{2E^2} \right]$$

(the last term for spin 1/2 only).

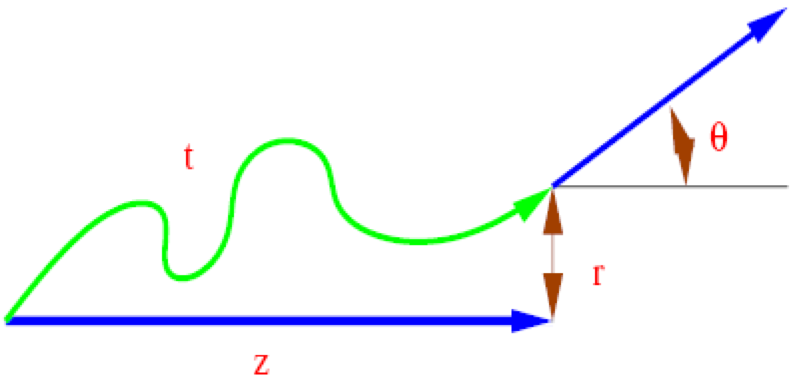
delta rays

200 MeV electrons, protons, alphas in 1 cm of Aluminium



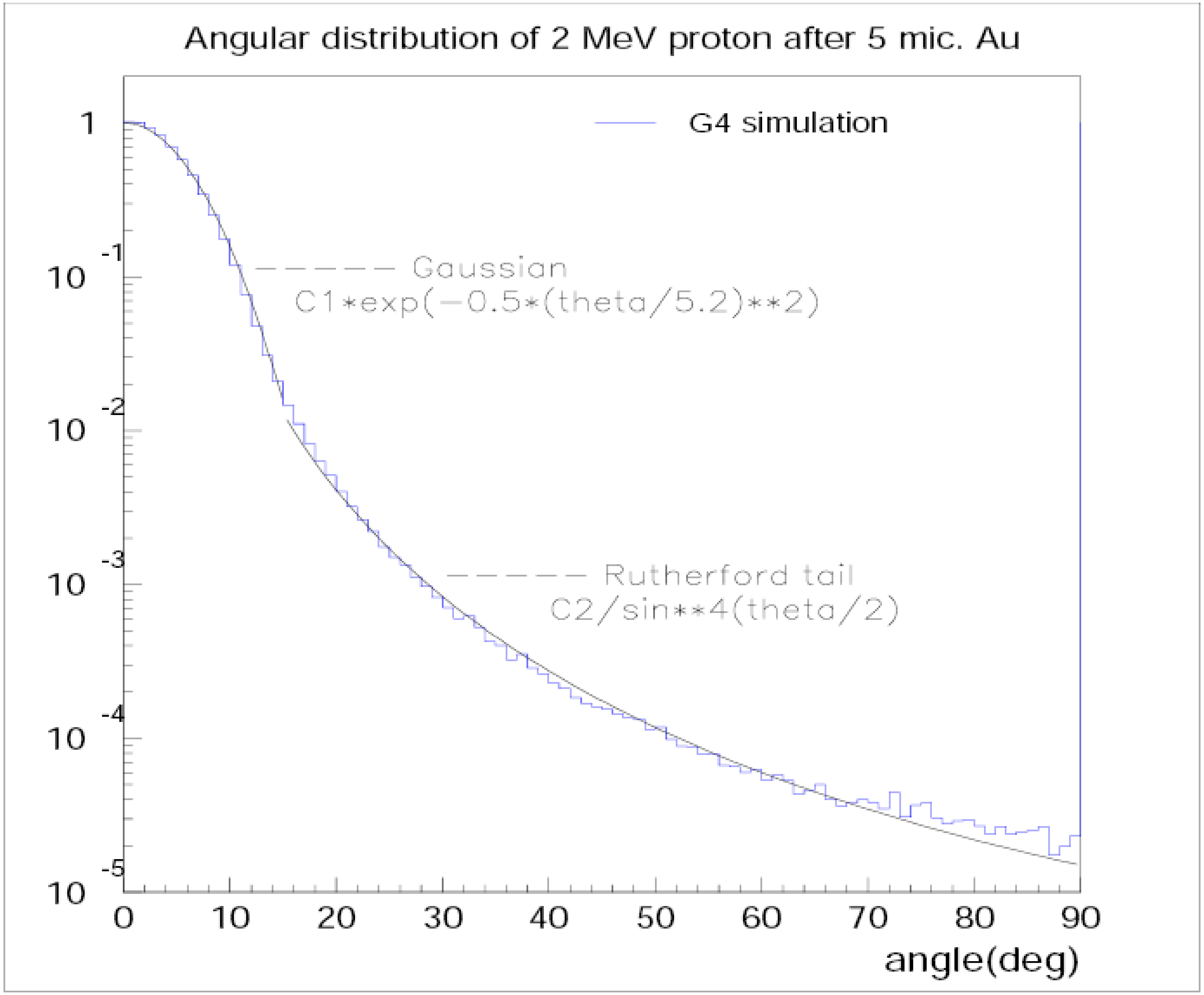
Multiple Coulomb scattering (MSC)

Charged particles traversing a finite thickness of matter suffer repeated elastic Coulomb scattering. The cumulative effect of these small angle scatterings is a net deflection from the original particle direction.



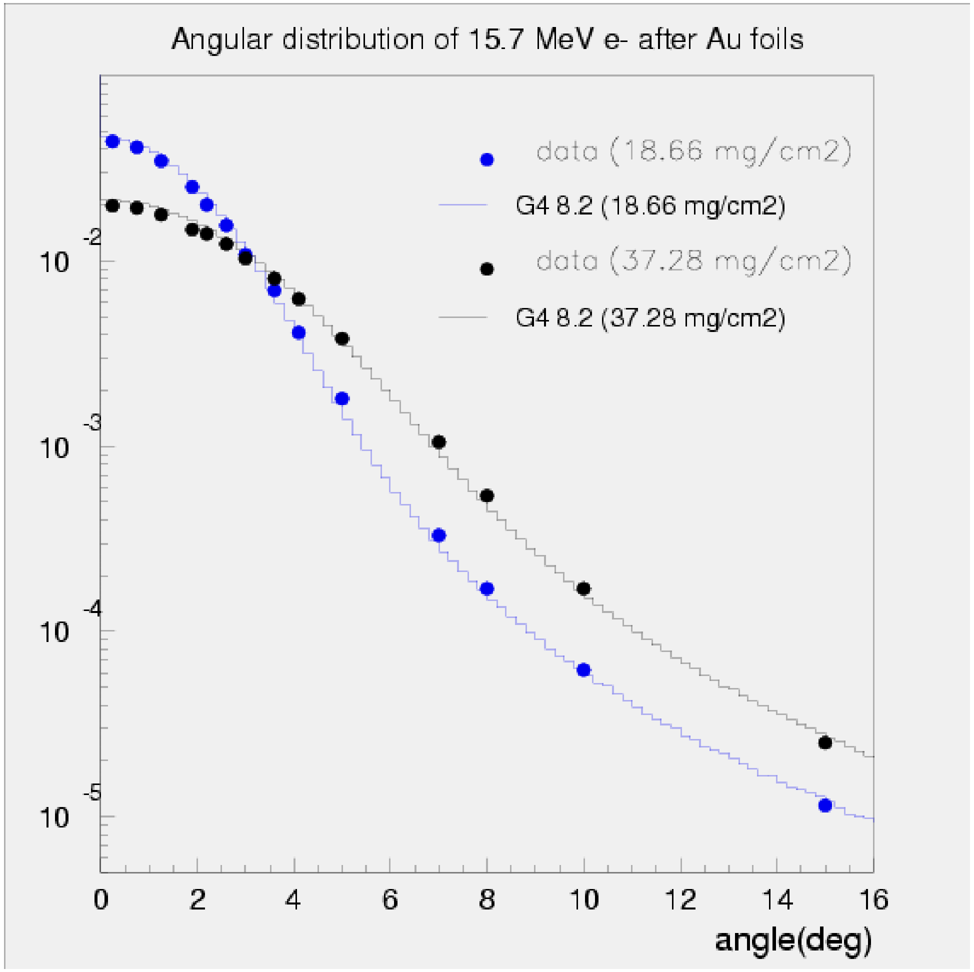
- longitudinal displacement z (or geometrical path length)
- lateral displacement r, Φ
- true (or corrected) path length t
- angular deflection θ, ϕ

Angular distribution



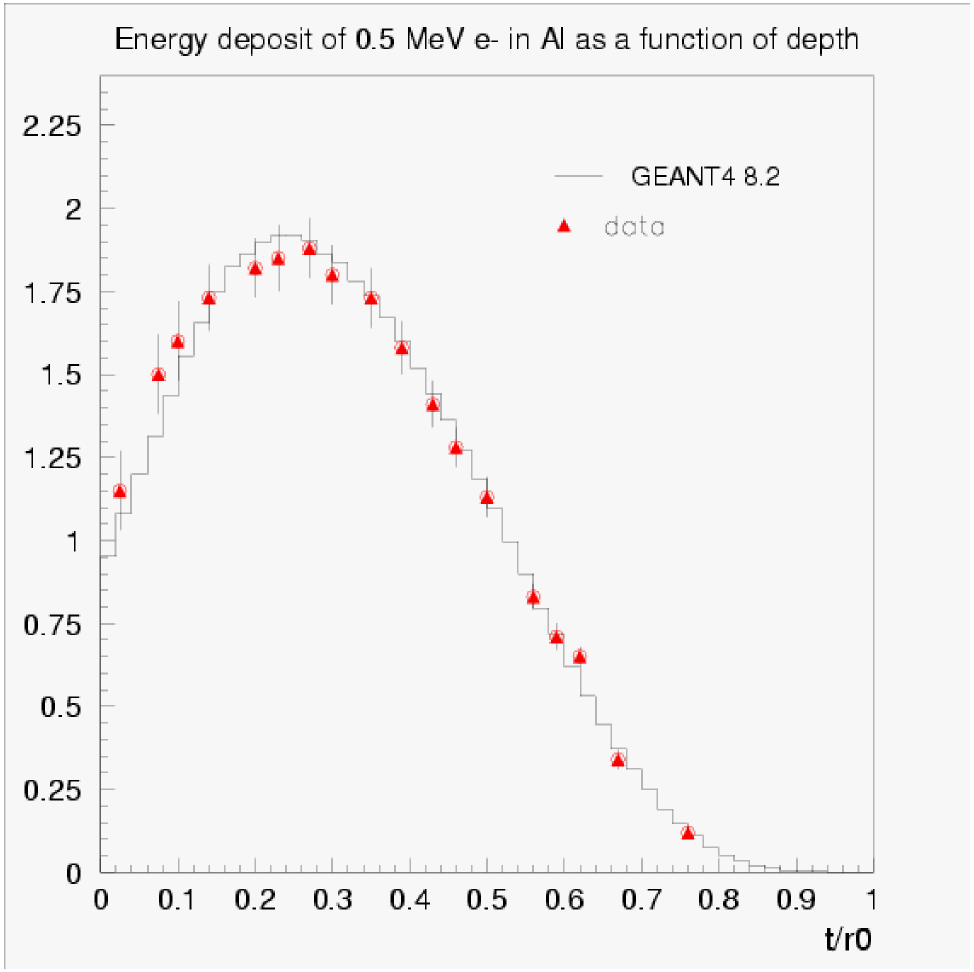
Geant4 Urban MSC model

- To get more complete information it is better to start with theory of Lewis which based on the transport equation of charged particles
- The Urban MSC model uses phenomenological functions to sample angular and spatial distributions after the simulation step
- The functions parameters are chosen to provide the same value of moments of the distribution as in Lewis theory
- See details in the Geant4 Physics Reference Manual and in EM web



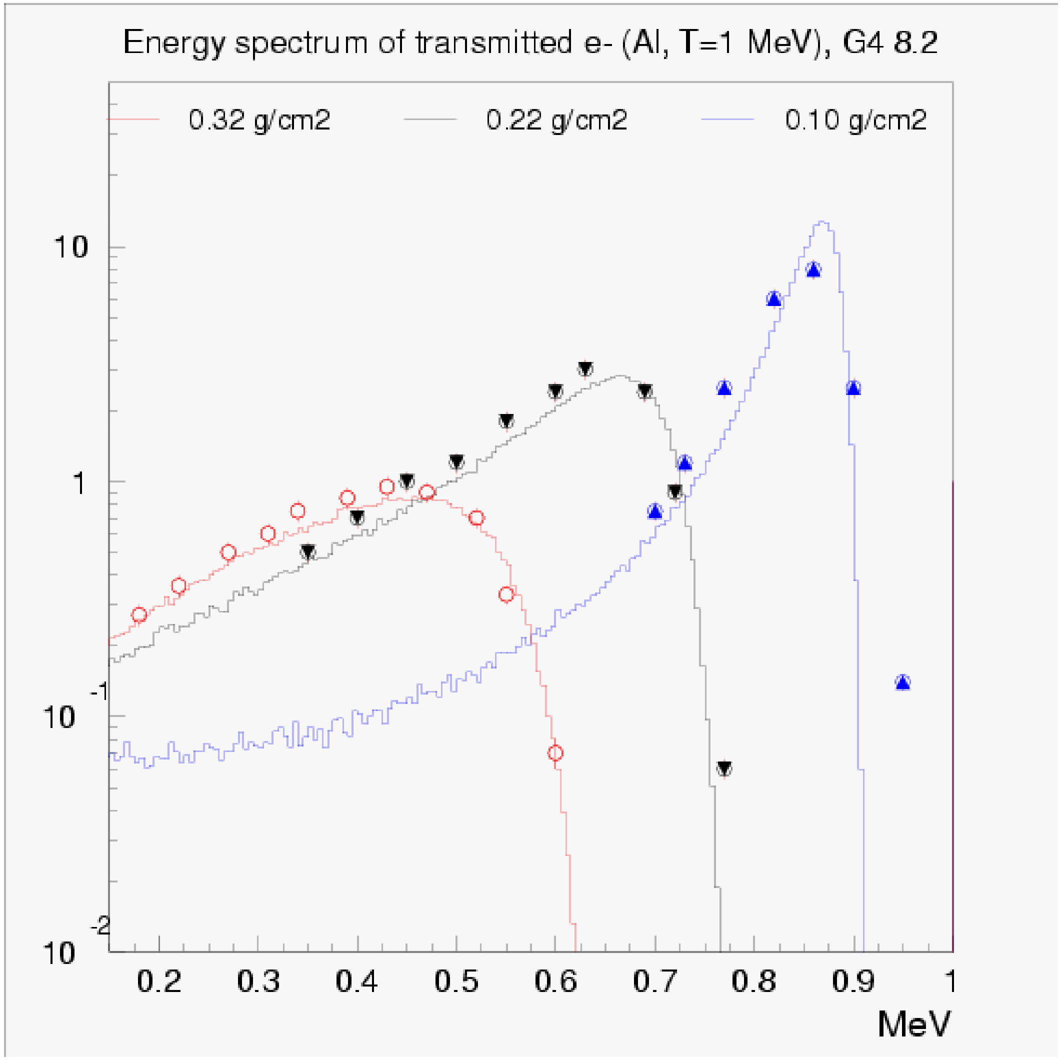
Step limitation from MSC : g4 7.1 → g4 8.3

- Step limit defined at first step and reevaluated after a boundary
  - applied only if range > safety
- StepLimit = F_R •max (range, λ)
  - λ is transport cross section
  - new default Range Factor F_R = 0.02 (instead of 0.2)
    - strong constraint only for low energy particles
- ensure that a track always goes few steps in any volume (at least 3)
- step limit min becomes material dependant, via λ :
  - StepLimitMin = max (0.04 λ, 5 nm)



Sampling of MSC : g4 7.1 → g4 8.3

- Reevaluate safety radius before to perform lateral displacement
  - d < safety (*safety is often underestimated*)
- Correlate final direction with lateral displacement
  - u·d = f (λ) taken from Lewis theory
- Angular distribution : both central part and tail slightly modified
- Single Coulomb scattering at boundaries
  - 1 very small step (~ λ elastic) before boundary crossing
  - apply approximate single Coulomb scattering in this step



Energy-range relation and stepping

Energy-Range relation

Mean total pathlength of a charged particle of kinetic energy E :

$$R(E) = \int_{\epsilon=0}^{\epsilon=E} \left[\frac{d\epsilon}{dx} \right]^{-1} d\epsilon$$

In GEANT4 the energy-range relation is extensively used :

- to control the stepping of charged particles
- to compute the energy loss of charged particles
- to control the production of secondaries (cut in range)

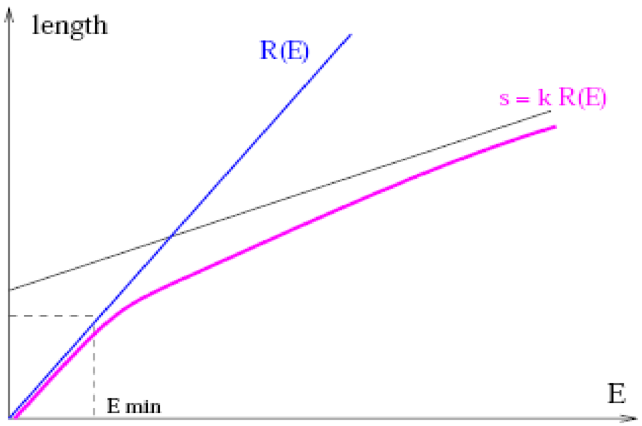
Step limitation by ionization processes

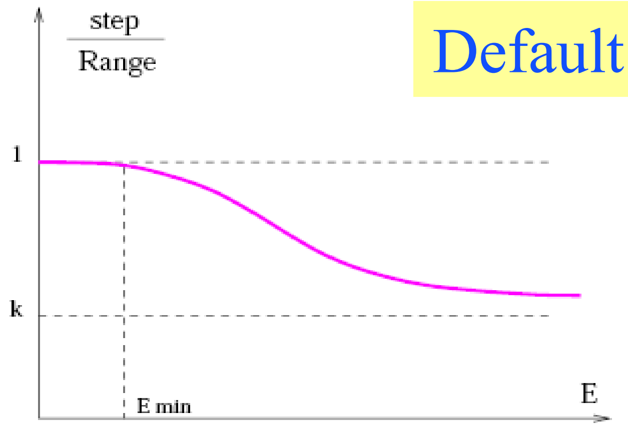
control the stepping of charged particles

The continuous energy loss imposes a limit on the stepsize.

The cross sections depend of the energy. The step size must be small enough so that the energy difference along the step is a small fraction of the particle energy.

This constraint must be relaxed when $E \to 0$: the allowed step smoothly approaches the stopping range of the particle.

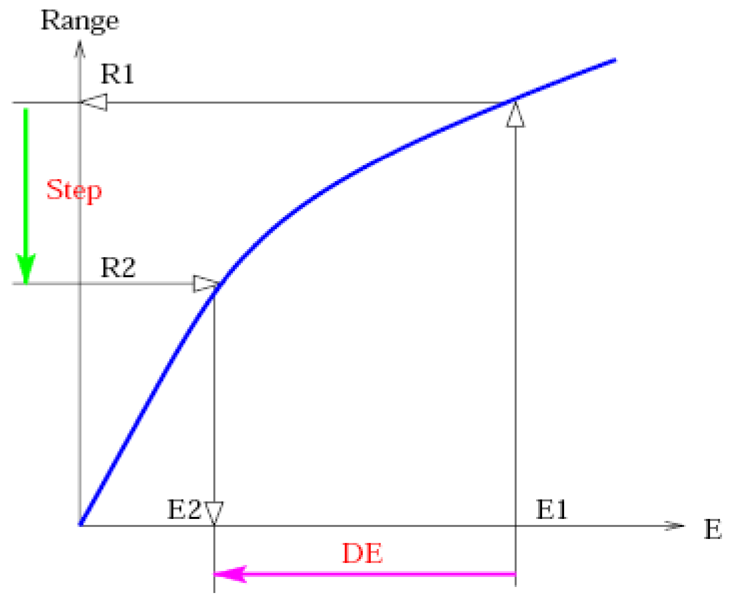




Default k = 0.2

compute the mean energy loss of charged particles

The computation of the mean energy loss on a given step is done from the Range and inverse Range tables.



This is more accurate than $\Delta E = (dE/dx) * \text{stepLength}$. if step is long

dEdx, Range and inverse Range tables are computed initialization phase of Geant4 using production thresholds (cuts) per detector region

Summary

- Standard EM physics processes are available for gammas and charged particles from 1 keV and up
- MSC process must be ordered next after transportation process in a Physics List
- EM processes are based on theoretical cross sections with corrections. During simulation, quantities are taken from tables calculated at initialization time
- Multiple scattering is handled by model functions which represent fits to Lewis transport theory results (not Moliere)
- Energy-range relation is used to compute energy loss, and to control step lengths and secondary production