Geant 4

Electromagnetic Physics

http://cern.ch/geant4

The full set of lecture notes of this Geant4 Course is available at
http://www.ge.infn.it/geant4/events/nss2003/geant4course.html

Geant 4

Standard Electromagnetic Physics

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LAPP

Standard electromagnetic physics in Geant4

The model assumptions are:

- The projectile has energy ≥ 1 keV
- Atomic electrons are quasi-free: their binding energy is neglected *(except for the photoelectric effect)*
- The atomic nucleus is free: the recoil momentum is neglected
- Matter is described as homogeneous, isotropic, amorphous

Compton scattering

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

$$\gamma + e \to \gamma' + e'$$

cross section per atom $= Z \times$ cross section per electron

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

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:

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

Geant 4

Standard Compton scattering 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:

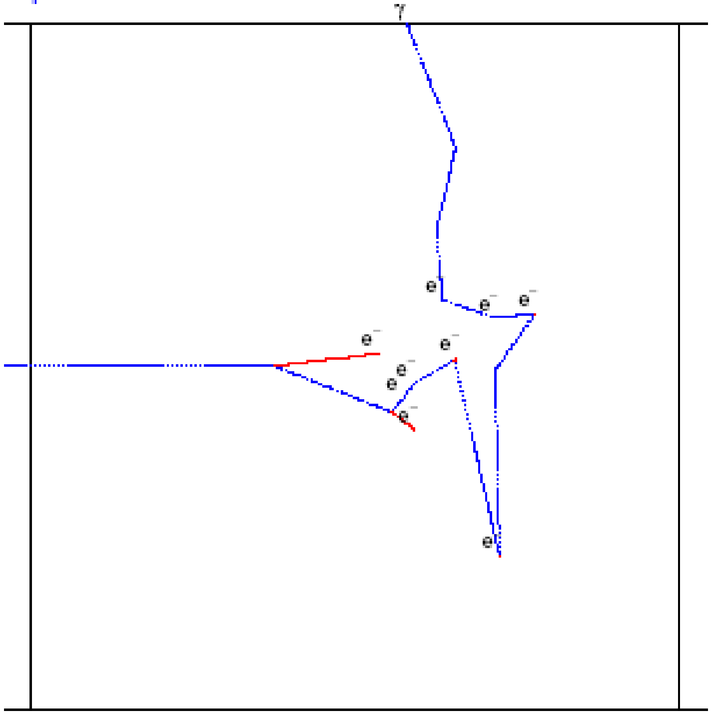
$$\begin{aligned} \kappa &= k/mc^2 \\ P_i(Z) &= Z(d_i + e_i Z + f_i Z^2) \end{aligned}$$

The fit was made over 511 data points chosen between:

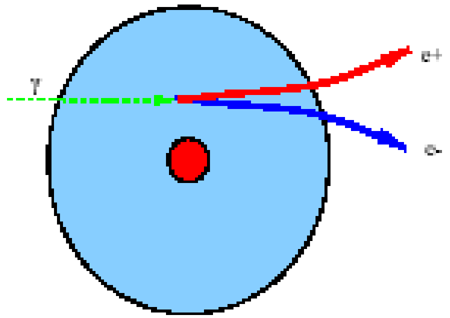
$$1 \le Z \le 100 \qquad ; \qquad k \in [10\ \mathrm{keV}, 100\ \mathrm{GeV}]$$

The accuracy of the fit is estimated to be:

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



γ conversion

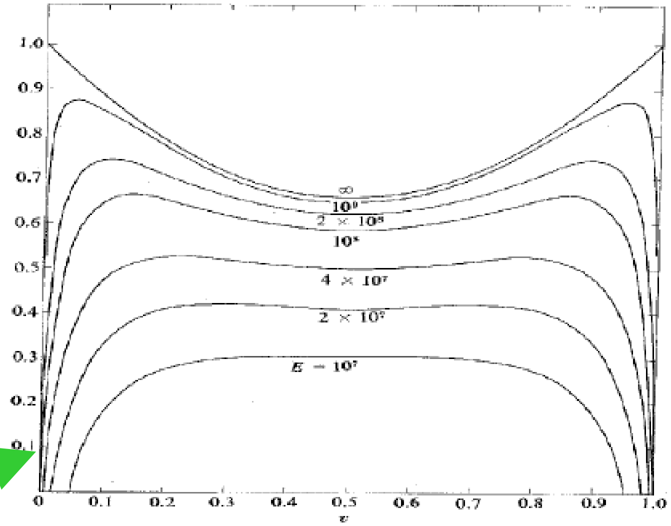


This is the transformation of a photon into an (e^+, e^-) pair in the Coulomb field of atoms (for momentum conservation).

To create the pair, the photon must have at least an energy of $2mc^2(1 + m/M_{rec})$.

The differential cross section is given by the Bethe-Heitler formula [Heitl57], corrected and extended for various effects:

- the screening of the field of the nucleus
- the pair creation in the field of atomic electrons
- the correction to the Born approximation
- the LPM suppression mechanism
- ...



The partition of the photon energy between e^+ and e^- is flat at low energy ($E_\gamma \leq 50\ MeV$) and increasingly asymmetric with energy. For $E_\gamma >\ TeV$ the LPM effect reinforces the asymmetry.

Standard total cross section per atom in Geant4

E_γ = incident gamma energy, and $X = \ln(E_\gamma / m_e c^2)$

The total cross-section has been parameterised as :

$$\sigma(Z, E_\gamma) = Z(Z+1)\left[F_1(X) + F_2(X)\,Z + \frac{F_3(X)}{Z}\right]$$

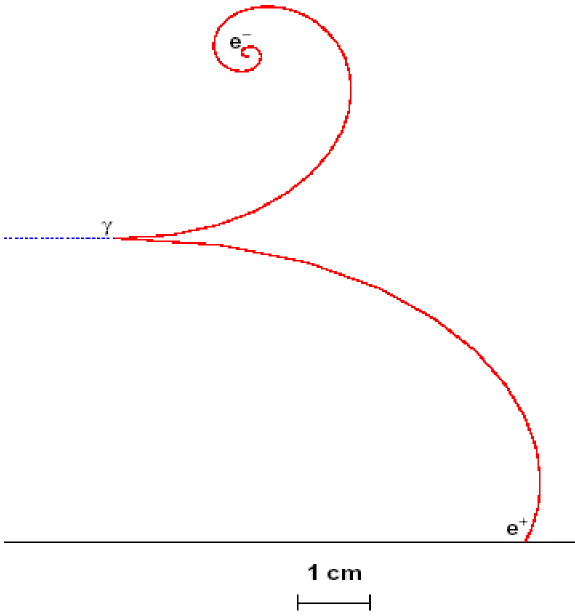
with :

$$\begin{aligned} F_1(X) &= a_0 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 + a_5 X^5 \\ F_2(X) &= b_0 + b_1 X + b_2 X^2 + b_3 X^3 + b_4 X^4 + b_5 X^5 \\ F_3(X) &= c_0 + c_1 X + c_2 X^2 + c_3 X^3 + c_4 X^4 + c_5 X^5 \end{aligned}$$

The parameters a_i, b_i, c_i were fitted to the data [hubb80].

This parameterisation describes the data in the range :

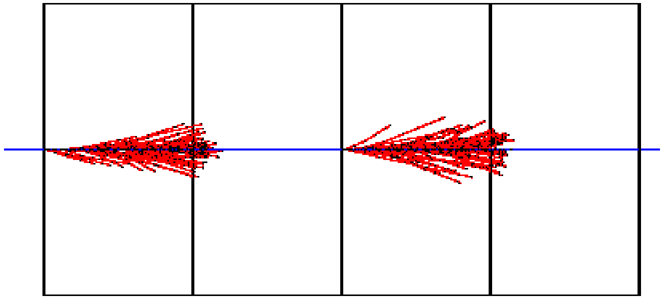
$$\left.\begin{array}{c} 1 \le Z \le 100 \\ E_\gamma \in [1.5\ \mathrm{MeV}, 100\ \mathrm{GeV}] \end{array}\right\} \frac{\Delta\,\sigma}{\sigma} \le 5\% \quad \text{with a mean value of} \approx 2.2\%$$



Ionisation

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 :

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



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 rate of energy loss

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

$$\frac{dE_{soft}(E,T_{cut})}{dx} = n_{at} \cdot \int_0^{T_{cut}} \frac{d\sigma(Z,E,T)}{dT} T\, dT \qquad (3)$$

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

The integration of 3 leads to the well known Bethe-Bloch truncated energy loss formula [PDG] :

$$\left.\frac{dE}{dx}\right]_{T<T_{cut}} = 2\pi r_e^2 mc^2 n_{el} \frac{(z_p)^2}{\beta^2} \times \left[\ln\left(\frac{2mc^2\beta^2\gamma^2 T_{up}}{I^2}\right) - \beta^2\left(1 + \frac{T_{up}}{T_{max}}\right) - \delta - \frac{2C_e}{Z}\right]$$

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.

The model in Geant4

Based on a very simple model of the particle-atom interaction.

The atoms are assumed to have only two energy levels E_1 and E_2.

The particle-atom interaction can be :

- an excitation with energy loss E_1 or E_2
- an ionization with energy loss distribution $g(E) \sim 1/E^2$.

Production of 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 :

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

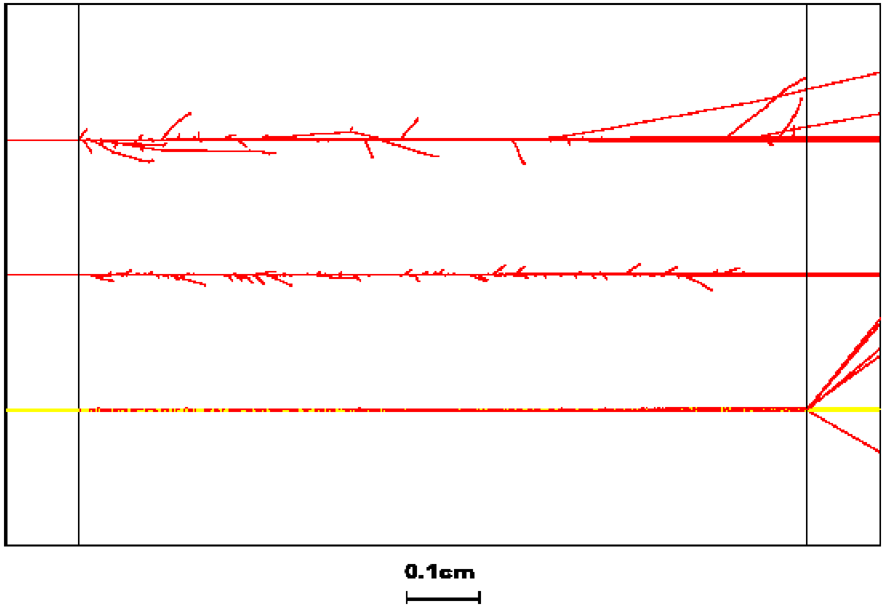
(the last term for spin 1/2 only).

The integration (4) 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).

2000 MeV electron, proton and α in Al

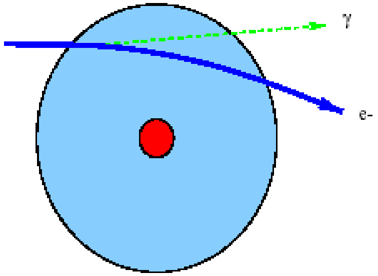


Bremsstrahlung

A fast moving charged particle is decelerated in the Coulomb field of atoms. A fraction of its kinetic energy is emitted in form of real photons.

The probability of this process is $\propto 1/M^2$ (M: masse of the particle) and $\propto Z^2$ (atomic number of the matter).

Above a few tens MeV, bremsstrahlung is the dominant process for e- and e+ in most materials. It becomes important for muons (and pions) at few hundred GeV.



Differential cross section

The differential cross section is given by the Bethe-Heitler formula [Heitl57], corrected and extended for various effects:

- the screening of the field of the nucleus
- the contribution to the brems from the atomic electrons
- the correction to the Born approximation
- the polarisation of the matter (dielectric suppression)
- the so-called LPM suppression mechanism
- ...

Emission of energetic photons and truncated energy loss rate

One may wish to take into account separately the high-energy photons emitted above a given threshold k_{cut} (miss detection, explicit simulation ...).

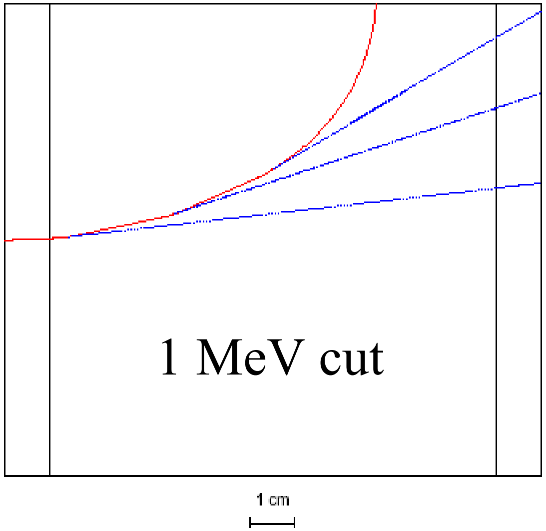
Those photons must be excluded from the mean energy loss count.

$$-\frac{dE}{dx}\Big]_{k<k_{cut}} = n_{at}\int_{k_{min}=0}^{k_{cut}} k\,\frac{d\sigma}{dk}\,dk \qquad (5)$$

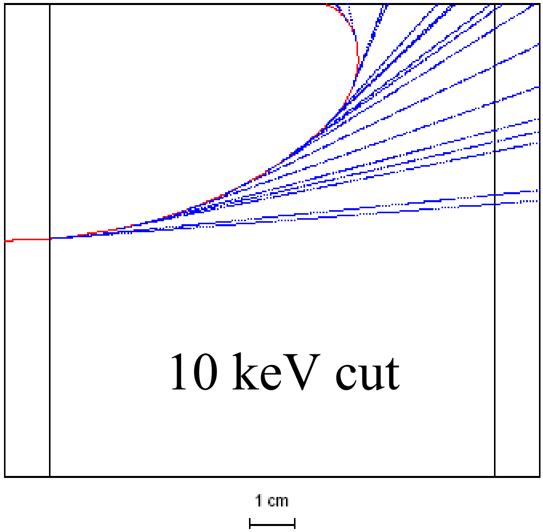
n_{at} is the number of atoms per volume.

Then, the truncated total cross-section for emitting 'hard' photons is:

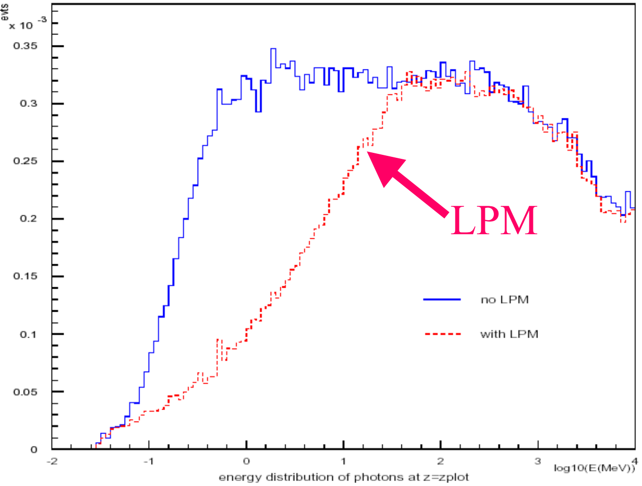
$$\sigma(E, k_{cut} \le k \le k_{max}) = \int_{k_{cut}}^{k_{max}\approx E} \frac{d\sigma}{dk}\,dk \qquad (6)$$



e^- 200 MeV in 10 cm Aluminium



LPM effect



10 GeV e- in Pb, γ spectrum

In the bremsstrahlung process the longitudinal momentum transfer from the nucleus to the electron can be very small. For $E \gg mc^2$ and $E \gg k$:

$$q_{long} \sim \frac{k(mc^2)^2}{2E(E-k)} \sim \frac{k}{2\gamma^2}$$

Thus, the uncertainty principle requires that the emission take place over a comparatively long distance :

$$f_v \sim \frac{2\hbar c\gamma^2}{k} \tag{7}$$

f_v is called the formation length for bremsstrahlung in vacuum. It is the distance of coherence, or the distance required for the electron and photon to separate enough to be considered as separate particles. If anything happens to the electron or photon while traversing this distance, the emission can be disrupted.

The electron can multiple scatter with the atoms of the medium while it is still in the formation zone. If the angle of multiple scattering, θ_{ms}, is greater than the typical emission angle of the emitted photon, $\theta_{br} = mc^2/E$, the emission is suppressed.

In the gaussian approximation : $\theta^2_{ms} = \frac{2\pi}{\alpha}\frac{1}{\gamma^2}\frac{f_v(k)}{X_0}$ where f_v is the formation length in vacuum, defined in equation 7.

Writing $\theta^2_{ms} > \theta^2_{br}$ show that suppression becomes signifiant for photon energies below a certain value, given by

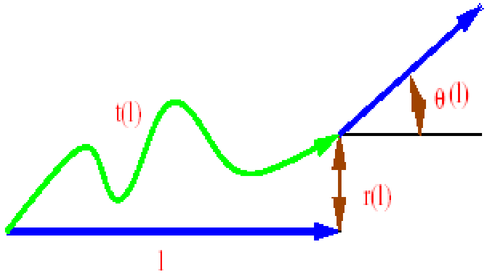
$$\frac{k}{E} < \frac{E}{E_{lpm}}$$

E_{lpm} is a characteristic energy of the effect :

$$E_{lpm} = \frac{\alpha^2}{4\pi}\frac{mc^2}{r_e}X_0 \sim (7.7\ TeV/cm) \times X_0\ (cm)$$

Multiple Coulomb scattering

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.



If the number of individual collisions is enough (> 20) the multiple Coulomb scattering angular distribution is gaussian at small angles and like Rutherford scattering at large angles.

The Molière theory reproduces rather well this distribution.

[Mol48, Bethe53]

Neither the Moliere theory nor the Gaussian approach of MSC give information about the spatial displacement of the particle, they give the scattering angle distribution only.

To get a more complete information it is better to start with theory of Lewis which based on the transport equation of charged particles ([Lewis50, Kawrakow98]).

Particle transport in Monte Carlo simulation

related quantities

- lateral displacement $r(l)$
- true (or corrected) path length $t(l)$
- projected angular deflection $\theta_{proj}(l)$

they are correlated random variables, for instance needed in Monte Carlo simulation.

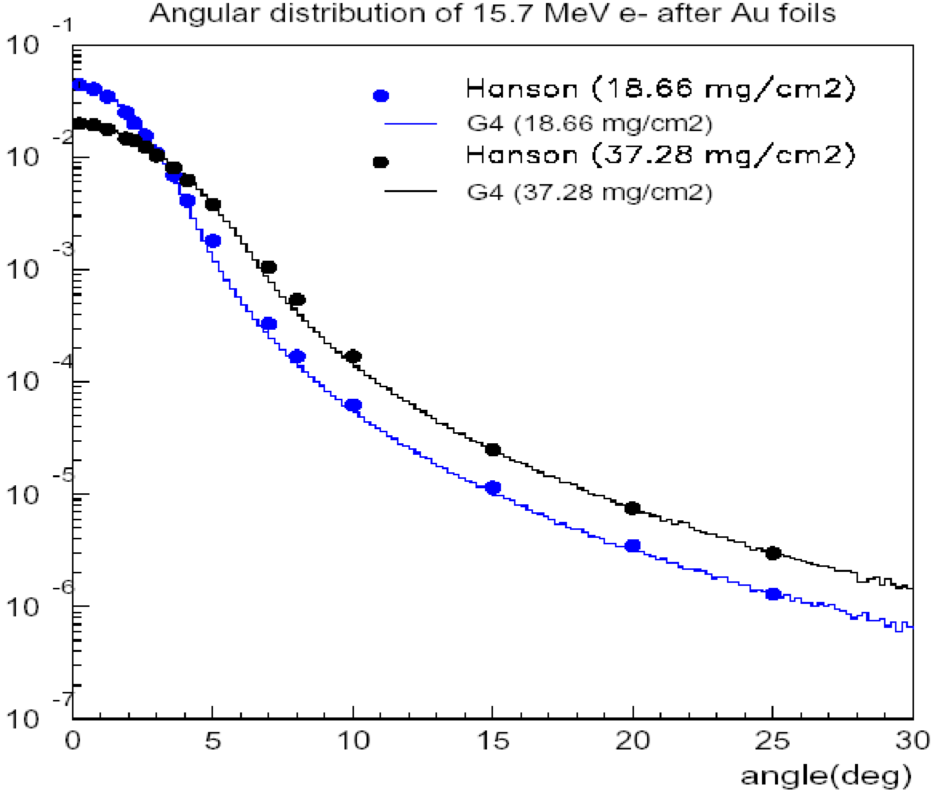
The practical solutions of the particle transport can be classified :

- detailed (microscopic) simulation : exact, but time consuming if the energy is not small. Used only for low energy particles.
- condensed simulation : simulates the global effects of the collisions during a macroscopic step, but uses approximations. EGS, GEANT3 - both use Moliere theory -, GEANT4
- mixed algorithms : "hard collisions" are simulated one by one + global effects of the "soft collisions". PENELOPE [Fer93].

Multiple scattering in Geant4

The MSC model used in GEANT4 uses the Lewis theory to simulate the transport of charged particles.

In this approach model functions are used to sample the spatial and angle distributions after a step, the theory gives constraints for these model functions :
the model functions should give the same moments of the distributions than the theory.



More details in Geant4 Physics Reference Manual

Cherenkov radiation

In a material with refractive index n, a charged particle emits photons if its velocity is greater than the local phase velocity of light.

The charged particle polarizes the atoms along its trajectory. These time dependent dipoles emit electromagnetic radiations.

If $v < c/n$ the dipole distribution is symmetric around the particle position, and the sum of all dipoles vanishes.

If $v > c/n$ the distribution is asymmetric and the total time dependent dipole is non nul, thus radiates.

The average number of photons produced per unit path length :

$$\frac{dN}{dx} = \frac{(\alpha z)^2}{r_e\, mc^2} \int_{\epsilon_{min}}^{\epsilon_{max}} d\epsilon \left(1 - \frac{1}{\beta^2 n^2(\epsilon)}\right)$$

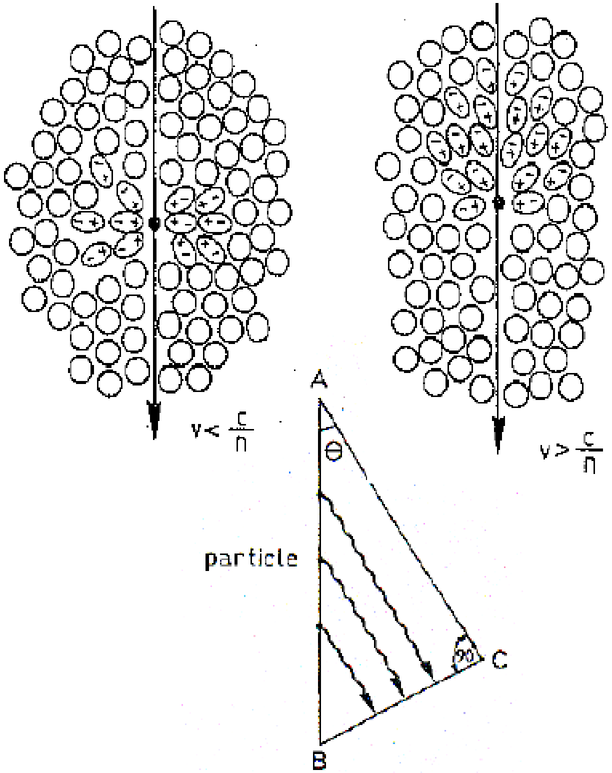
The number of photons produced per step is calculated from a Poissonian distribution with average value :

$$< n >= \text{StepLength}\ \frac{dN}{dx}$$

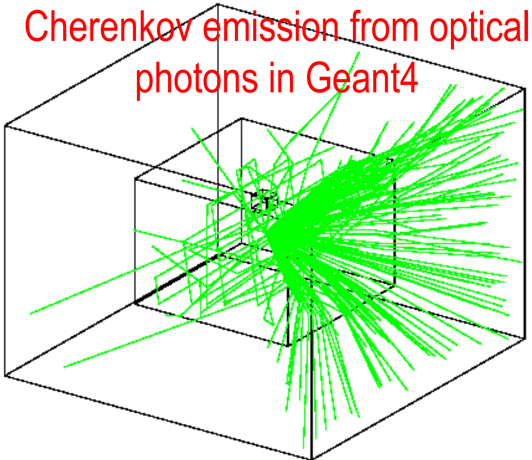
The generated photons are uniformly distribued along the track.

The energy distribution of the photon is sampled from the density function:

$$f(\epsilon) = \left[1 - \frac{1}{n^2(\epsilon)\beta^2}\right]$$



Cherenkov emission from optical photons in Geant4

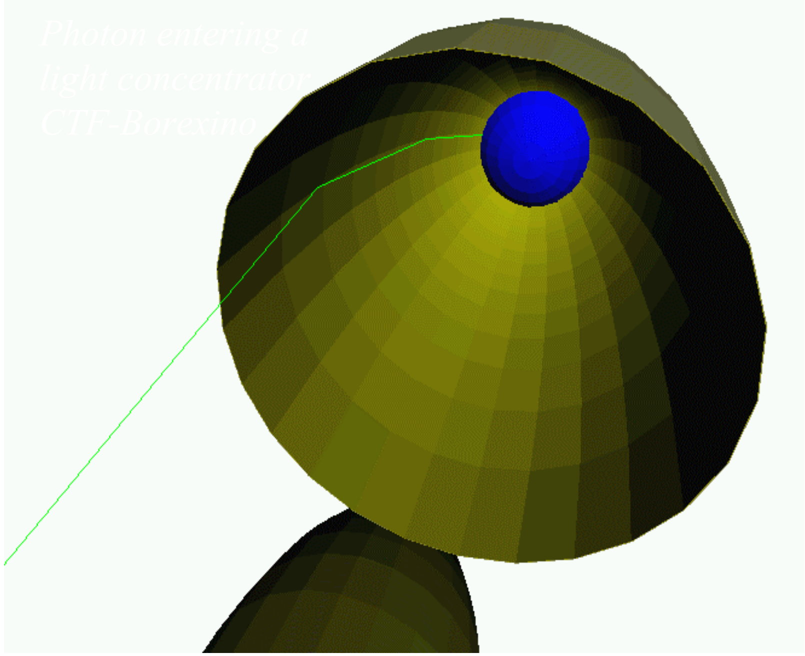


Optical photons

Production of optical photons in detectors is mainly due to Cherenkov effect and scintillation

Processes in Geant4:

- in-flight absorption
- Rayleigh scattering
- medium-boundary interactions (reflection, refraction)

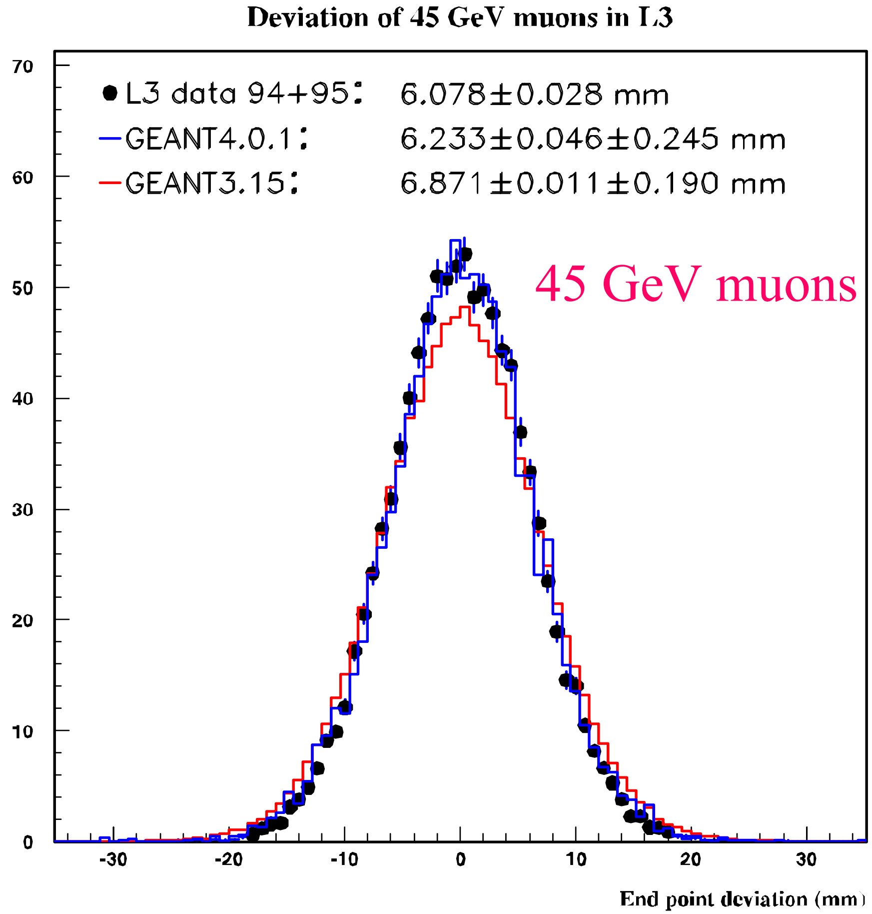


Photon entering a light concentrator CTF-Borexino

Muons

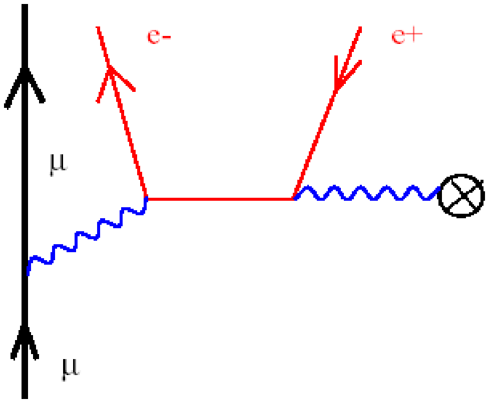
1 keV up to 1000 PeV scale

- *simulation of ultra-high energy and cosmic ray physics*
- High energy extensions based on theoretical models



Geant 4

Direct e+e- pair creation by muon



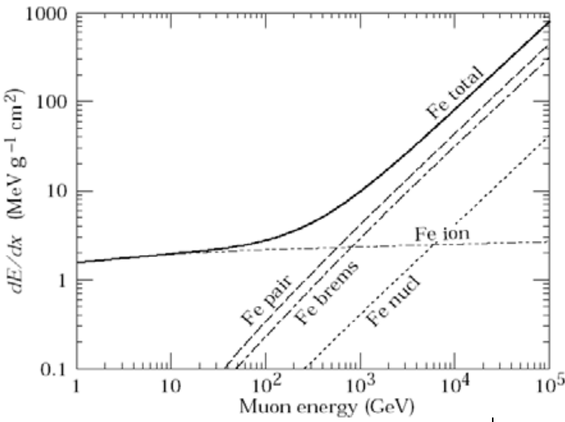
Creation of a (e^+, e^-) pair by virtual photon in the Coulomb field of the nucleus (for momentum conservation).

$$\mu + \text{nucleus} \longrightarrow \mu + e^+ + e^- + \text{nucleus}$$

It is one of the most important processes of muon interaction.

At TeV muon energies, pair creation cross section exceeds those of other muon interaction processes in a wide region of energy transfers :

$$100 \text{ MeV} \leq \epsilon \leq 0.1\ E_\mu$$



Average energy loss for pair production increases linearly with muon energy, and in TeV region this process contributes over 50 % to the total energy loss rate.

The differential cross section is given by Kokoulin et al. It includes :

- screening of the field of the nucleus
- correction for finite nuclear size
- contribution from the atomic electrons [Keln97]

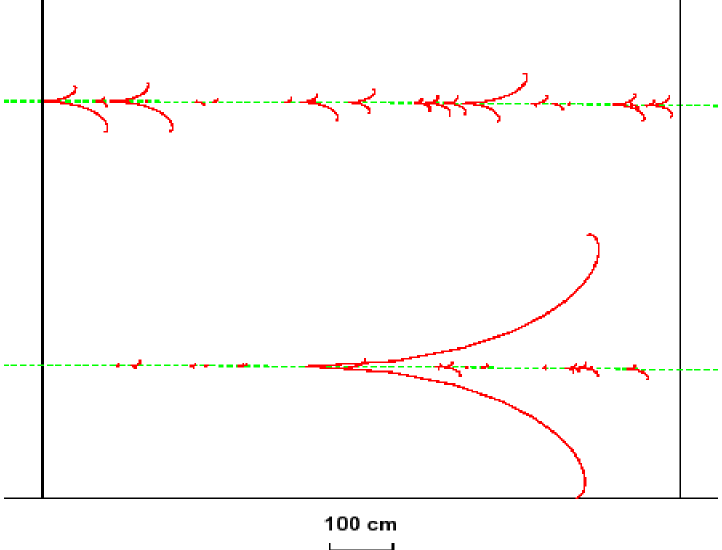
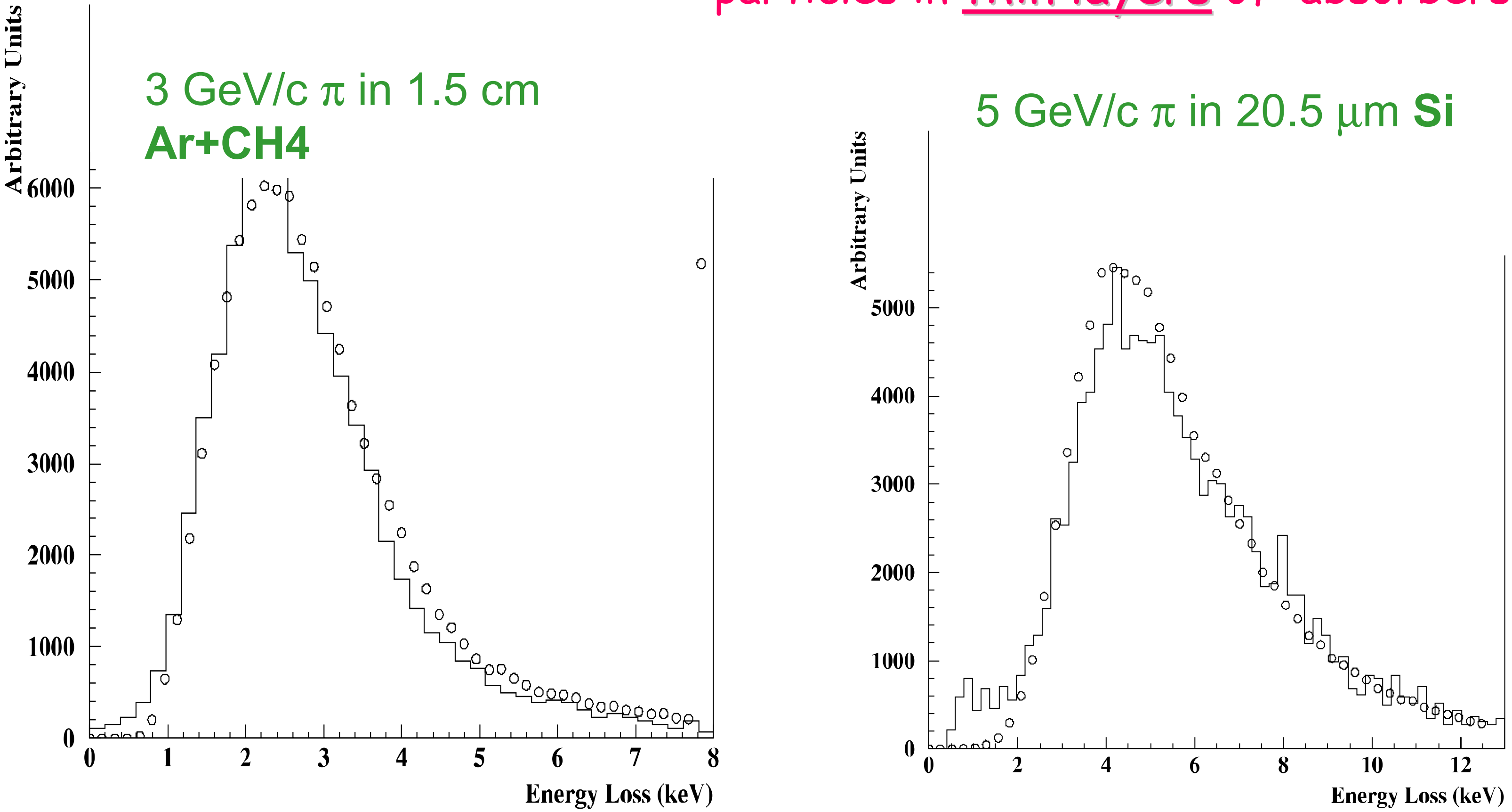


Photo Absorption Ionisation (PAI) Model

Ionisation energy loss produced by charged particles in thin layers of absorbers



Ionisation energy loss distribution produced by pions, PAI model

Geant 4

Low Energy Electromagnetic Physics

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on behalf of the Low Energy Electromagnetic Working Group

http://www.ge.infn.it/geant4/lowE/

What is

- A package in the Geant4 electromagnetic package
  - *geant4/source/processes/electromagnetic/lowenergy/*
- A set of processes extending the coverage of electromagnetic interactions in Geant4 down to “*low*” energy
  - 250 eV *(in principle even below this limit)/100* ev for electrons and photons
  - down to the approximately the ionisation potential of the interacting material for hadrons and ions
- A set of processes based on detailed models
  - shell structure of the atom
  - precise angular distributions
- Complementary to the “standard” electromagnetic package

Overview of physics

- Compton scattering
- Rayleigh scattering
- Photoelectric effect
- Pair production

- Bremsstrahlung
- Ionisation

- Polarised Compton

- + atomic relaxation
  - fluorescence
  - Auger effect

  following processes leaving a vacancy in an atom

in two “flavours” of models:

- based on the **Livermore Library**
- à la **Penelope**

- In progress
  - More precise angular distributions (Rayleigh, photoelectric, Bremsstrahlung etc.)
  - Polarised γ conversion, photoelectric

- Development plan
  - *Driven by user requirements*
  - *Schedule compatible with available resources*

Software Process

A rigorous approach to software engineering

- support of a better quality of the software
- especially relevant in the physics domain of Geant4-LowE EM
- several mission-critical applications (space, medical…)

Spiral approach A life-cycle model that is both iterative and incremental

Collaboration-wide Geant4 software process, tailored to the specific projects

Huge effort invested into SPI

- *started from level 1 (CMM)*
- *in very early stages: chaotic, left to heroic improvisation*

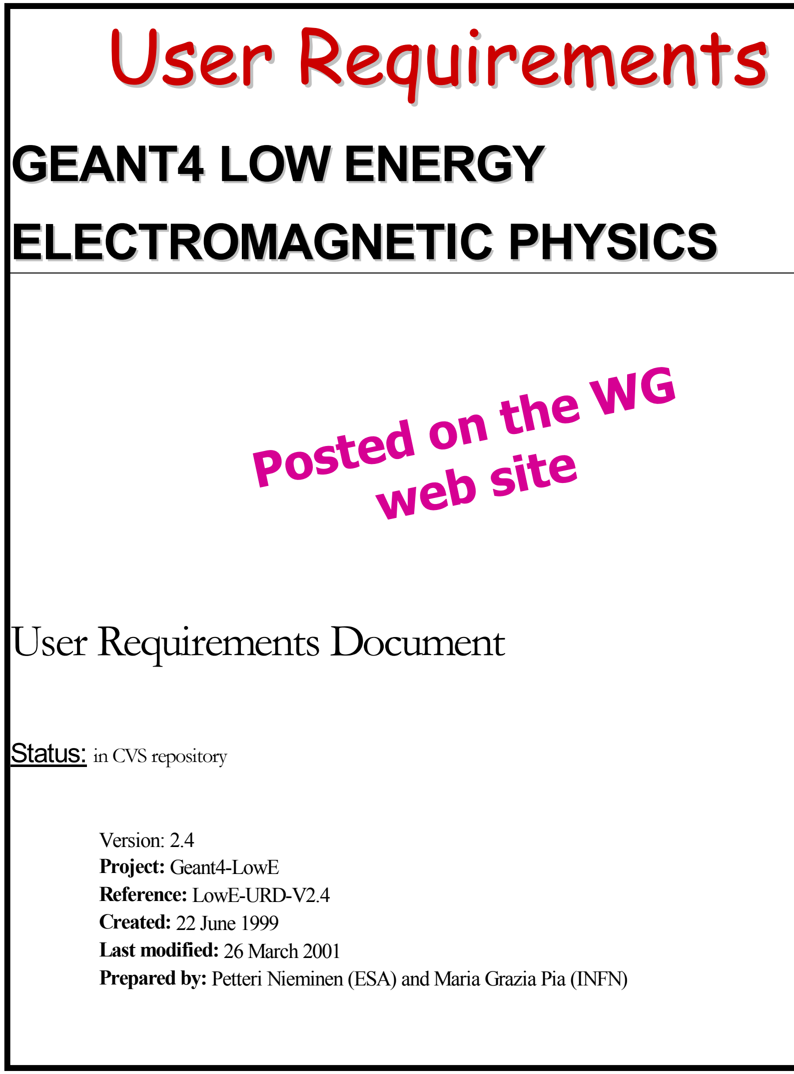
current → status

- *Public URD*
- *Full traceability through UR/OOD/implementation/test*
- *Testing suite and testing process*
- *Public documentation of procedures*
- *Defect analysis and prevention*
- *etc.…*

User requirements

Various methodologies adopted to **capture** URs

- **Elicitation through interviews and surveys**
  - *useful to ensure that UR are complete and there is wide agreement*
- **Joint workshops with user groups**
- **Use cases**
- **Analysis of existing Monte Carlo codes**
- **Study of past and current experiments**
- **Direct requests from users to WG coordinators**



User Requirements

GEANT4 LOW ENERGY

ELECTROMAGNETIC PHYSICS

Posted on the WG web site

User Requirements Document

Status: in CVS repository

Version: 2.4
Project: Geant4-LowE
Reference: LowE-URD-V2.4
Created: 22 June 1999
Last modified: 26 March 2001
Prepared by: Petteri Nieminen (ESA) and Maria Grazia Pia (INFN)

LowE processes based on Livermore Library

Photons and electrons

different approach w.r.t. Geant4 standard e.m. package

- Based on evaluated data libraries from LLNL:
  - EADL *(Evaluated Atomic Data Library)*
  - EEDL *(Evaluated Electrons Data Library)*
  - EPDL97 *(Evaluated Photons Data Library)*

  especially formatted for Geant4 distribution *(courtesy of D. Cullen, LLNL)*

- Validity range: 250 eV - 100 GeV
  - The processes can be used down to 100 eV, with degraded accuracy
  - In principle the validity range of the data libraries extends down to ~10 eV

- Elements Z=1 to Z=100
  - Atomic relaxation: Z > 5 *(transition data available in EADL)*

Calculation of cross sections

Interpolation from the data libraries:

$$\log(\sigma(E)) = \frac{\log(\sigma_1)\log(E_2/E) + \log(\sigma_2)\log(E/E_1)}{\log(E_2/E_1)}$$

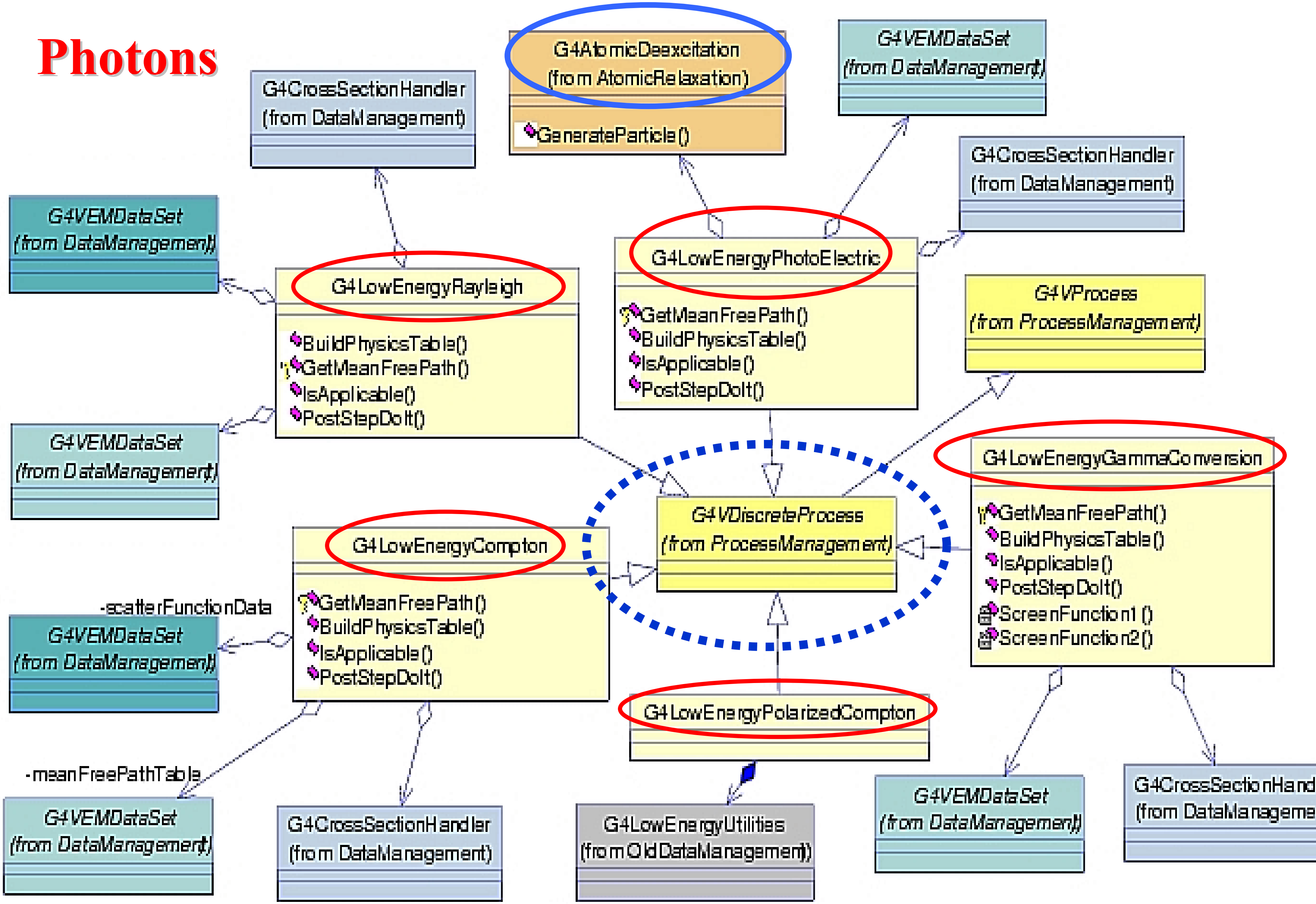
E_1 and E_2 are the lower and higher energy for which data (σ_1 and σ_2) are available

Mean free path for a process, at energy E:

$$\lambda = \frac{1}{\sum_i \sigma_i(E) \cdot n_i}$$

n_i = atomic density of the i^{th} element contributing to the material composition

Photons


G4AtomicDeexcitation
(from AtomicRelaxation)
GenerateParticle()
G4CrossSectionHandler
(from DataManagement)
G4VEMDataSet
(from DataManagement)
G4CrossSectionHandler
(from DataManagement)
G4VEMDataSet
(from DataManagement)
G4LowEnergyRayleigh
BuildPhysicsTable()
GetMeanFreePath()
IsApplicable()
PostStepDoIt()
G4LowEnergyPhotoElectric
GetMeanFreePath()
BuildPhysicsTable()
IsApplicable()
PostStepDoIt()
G4VProcess
(from ProcessManagement)
G4VEMDataSet
(from DataManagement)
G4LowEnergyGammaConversion
GetMeanFreePath()
BuildPhysicsTable()
IsApplicable()
PostStepDoIt()
ScreenFunction1()
ScreenFunction2()
G4VDiscreteProcess
(from ProcessManagement)
G4LowEnergyCompton
GetMeanFreePath()
BuildPhysicsTable()
IsApplicable()
PostStepDoIt()
-scatterFunctionData
G4VEMDataSet
(from DataManagement)
G4LowEnergyPolarizedCompton
-meanFreePathTable
G4VEMDataSet
(from DataManagement)
G4CrossSectionHandler
(from DataManagement)
G4LowEnergyUtilities
(from OldDataManagement)
G4VEMDataSet
(from DataManagement)
G4CrossSectionHand
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Compton scattering

Klein-Nishina cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} r_0^2 \frac{h\nu^2}{h\nu_0^2}\left[\frac{h\nu_0}{h\nu} + \frac{h\nu}{h\nu_0} - 2 + 4\cos^2\Theta\right]$$

- Energy distribution of the scattered photon according to the Klein-Nishina formula, multiplied by scattering functions *F(q)* from EPDL97 data library

- The effect of scattering function becomes significant at low energies
  - suppresses forward scattering

- Angular distribution of the scattered photon and the recoil electron also based on EPDL97

Rayleigh scattering

- Angular distribution: $F(E,q)=[1+\cos^2(q)]\cdot F^2(q)$
  - where F(q) is the energy-dependent form factor obtained from EPDL97

- Improved angular distribution released in 2002, further improvements foreseen

Photoelectric effect

- Cross section
  - Integrated cross section (over the shells) from EPDL + interpolation
  - Shell from which the electron is emitted selected according to the detailed cross sections of the EPDL library

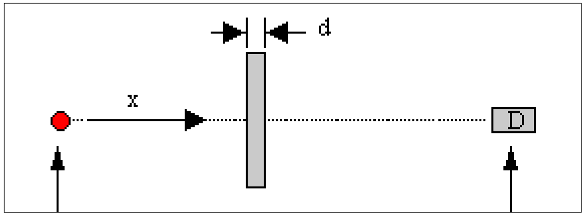
- Final state generation
  - Direction of emitted electron = direction of incident photon

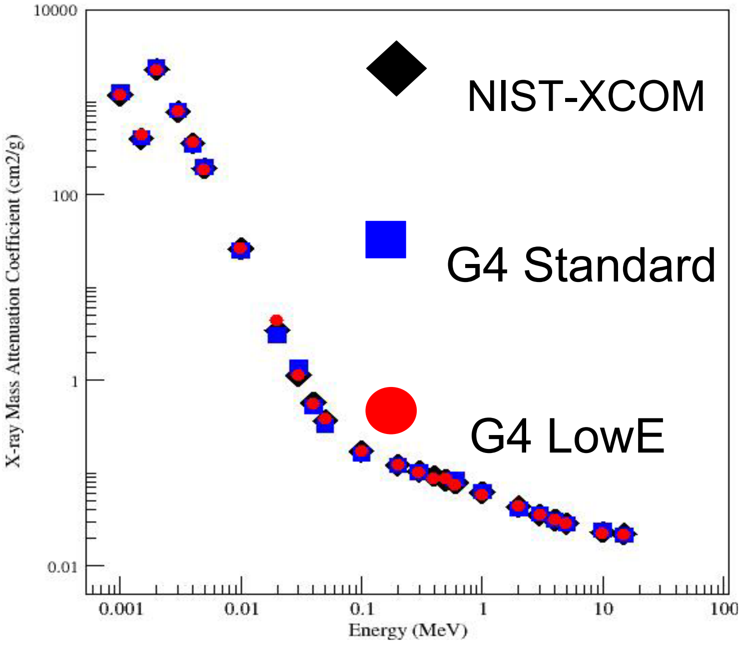
- Deexcitation via the atomic relaxation sub-process
  - Initial vacancy + following chain of vacancies created

γ conversion

- The secondary e^- and e^+ energies are sampled using Bethe-Heitler cross sections with Coulomb correction
- e^- and e^+ assumed to have symmetric angular distribution
- Energy and polar angle sampled w.r.t. the incoming photon using Tsai differential cross section
- Azimuthal angle generated isotropically
- Choice of which particle in the pair is e^- or e^+ is made randomly

Photons: mass attenuation coefficient

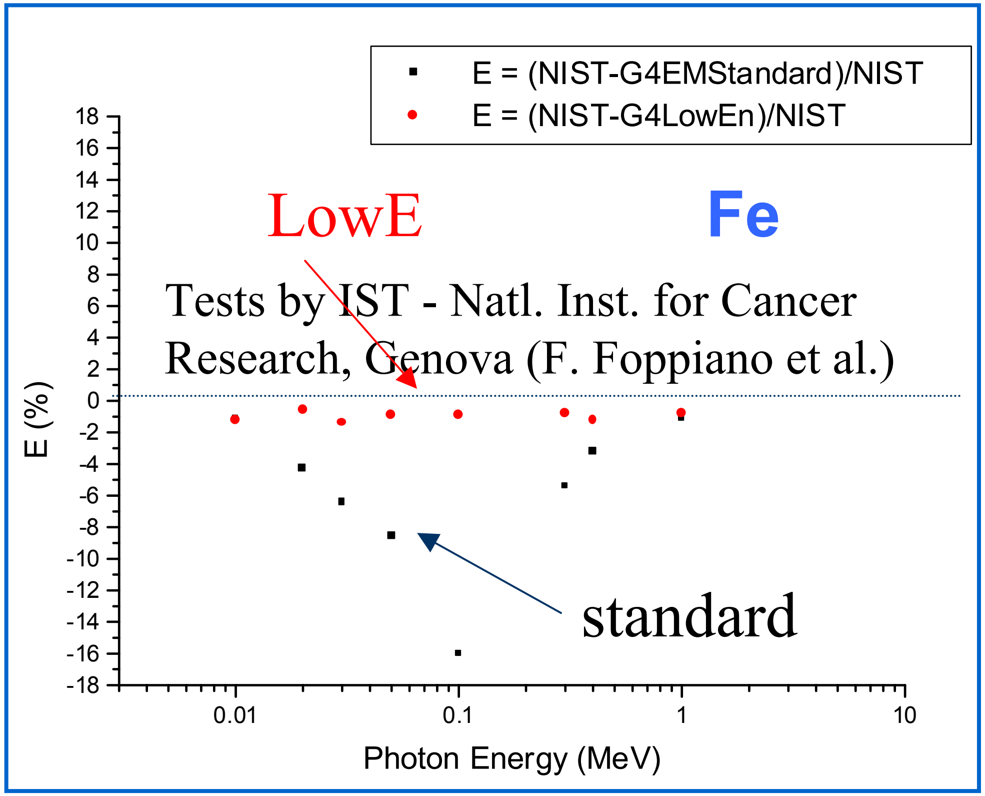




$\chi^2_{N\text{-}L}=13.1 - \nu=20 - p=0.87$

$\chi^2_{N\text{-}S}=23.2 - \nu=15 - p=0.08$

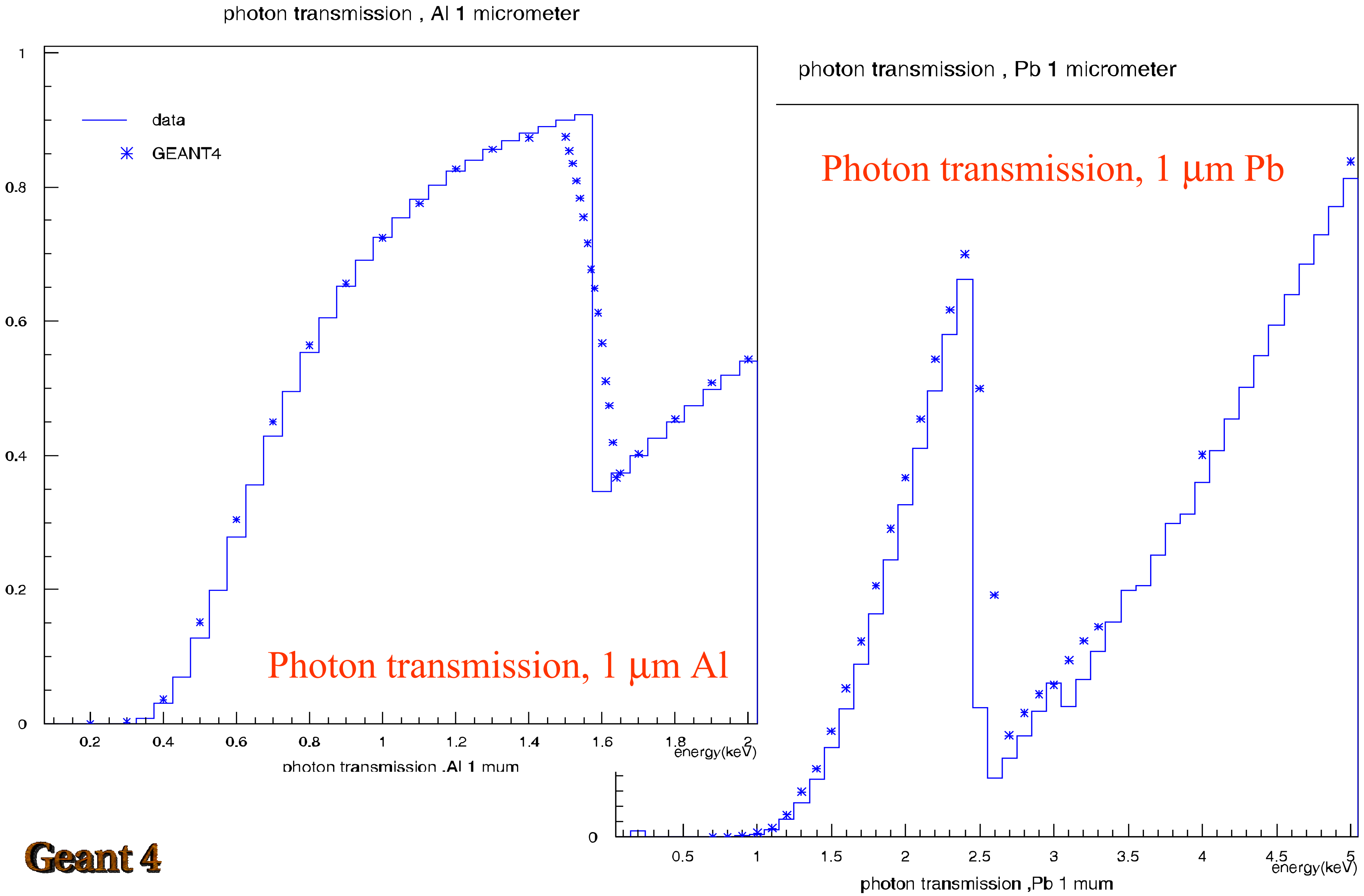
Comparison against NIST data



Tests by IST - Natl. Inst. for Cancer Research, Genova (F. Foppiano et al.)

LowE accuracy ~ 1%

Photons, evidence of shell effects



Photon transmission, 1 µm Al

Photon transmission, 1 µm Pb

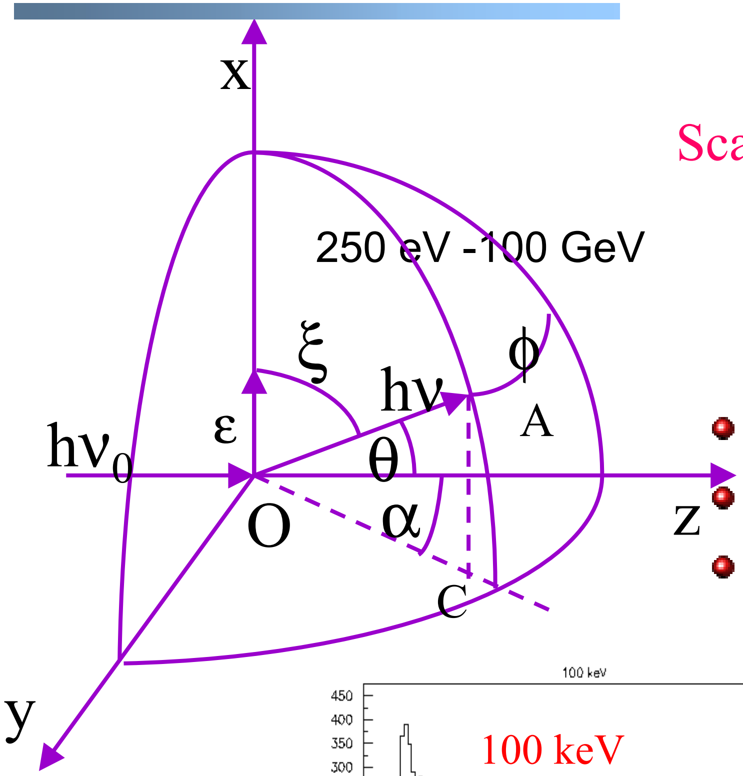
Polarisation

Cross section: $$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{h\nu^2}{h\nu_0^2}\left[\frac{h\nu_0}{h\nu} + \frac{h\nu}{h\nu_0} - 2\sin^2\theta\cos^2\phi\right]$$

$$\cos\xi = \sin\theta\cos\phi \Rightarrow \sin\xi = \sqrt{1-\sin^2\theta\cos^2\phi} = N$$

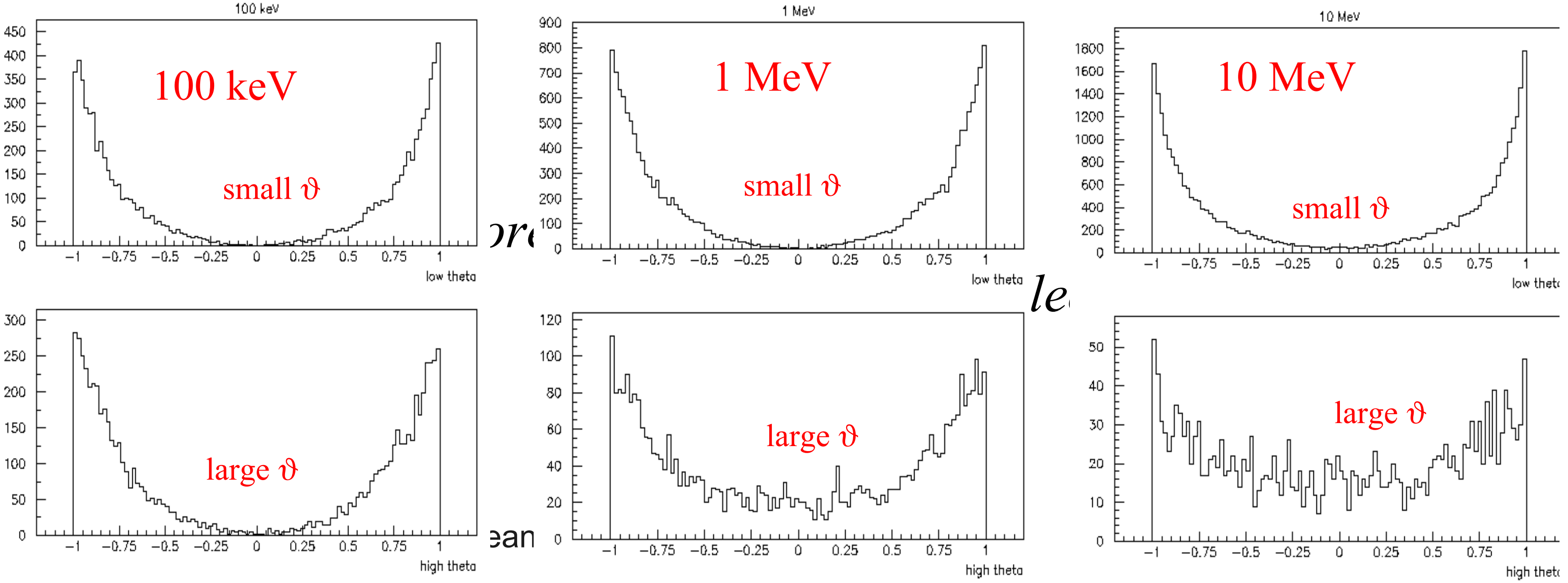
Scattered Photon Polarization $$\overline{\varepsilon'_\perp} = \frac{1}{N}\left(\cos\theta\,\hat{j} - \sin\theta\sin\phi\,\hat{k}\right)\sin\beta$$

$$\overline{\varepsilon'_\parallel} = \left(N\hat{i} - \frac{1}{N}\sin^2\theta\sin\phi\cos\phi\,\hat{j} - \frac{1}{N}\sin\theta\cos\theta\cos\phi\,\hat{k}\right)\cos\beta$$



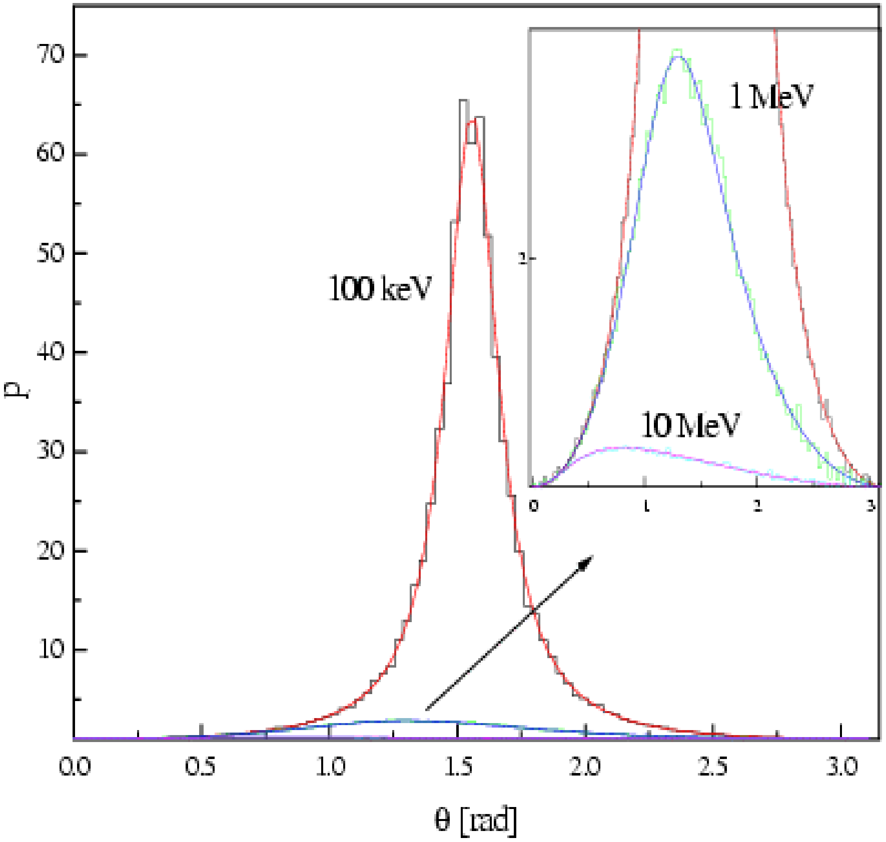
- θ Polar angle
- φ Azimuthal angle
- ε Polarization vector

Low Energy Polarised Compton

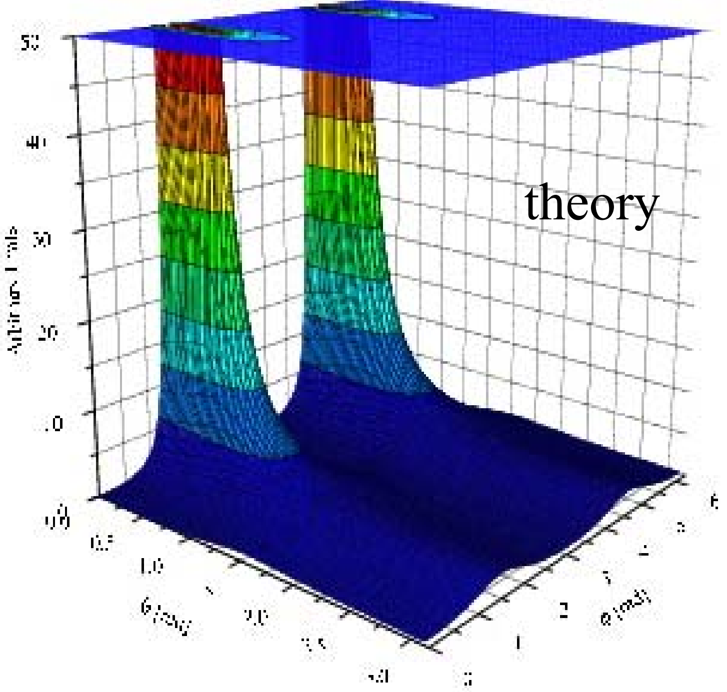


Geant 4

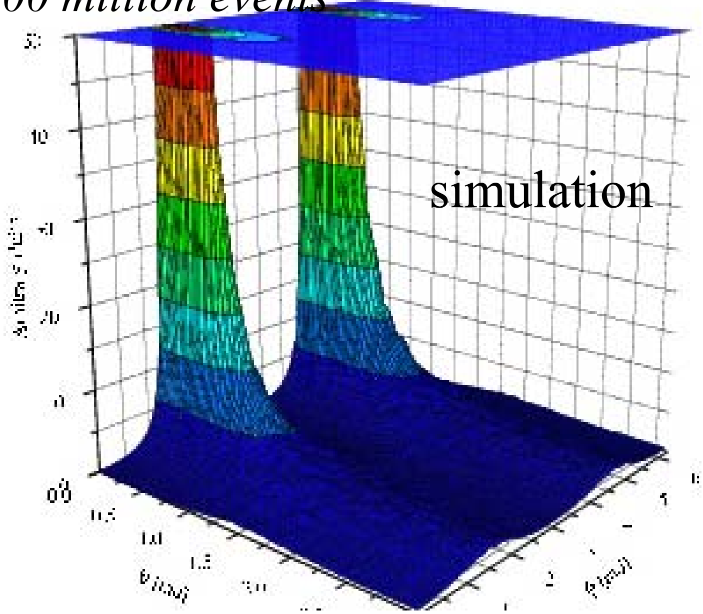
Polarisation



Polarisation of a non-polarised photon beam, simulation and theory



500 million events

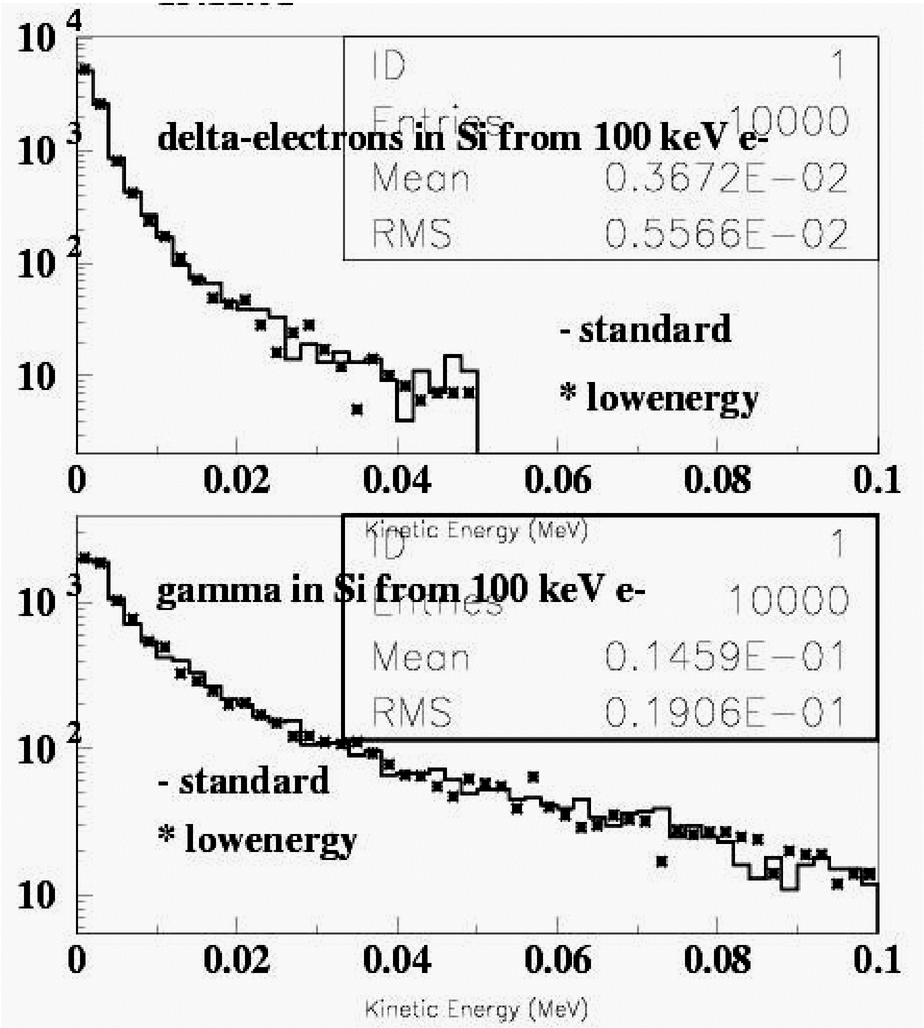


Ratio between intensity with perpendicular and parallel polarisation vector w.r.t. scattering plane, linearly polarised photons

Electron Bremsstrahlung

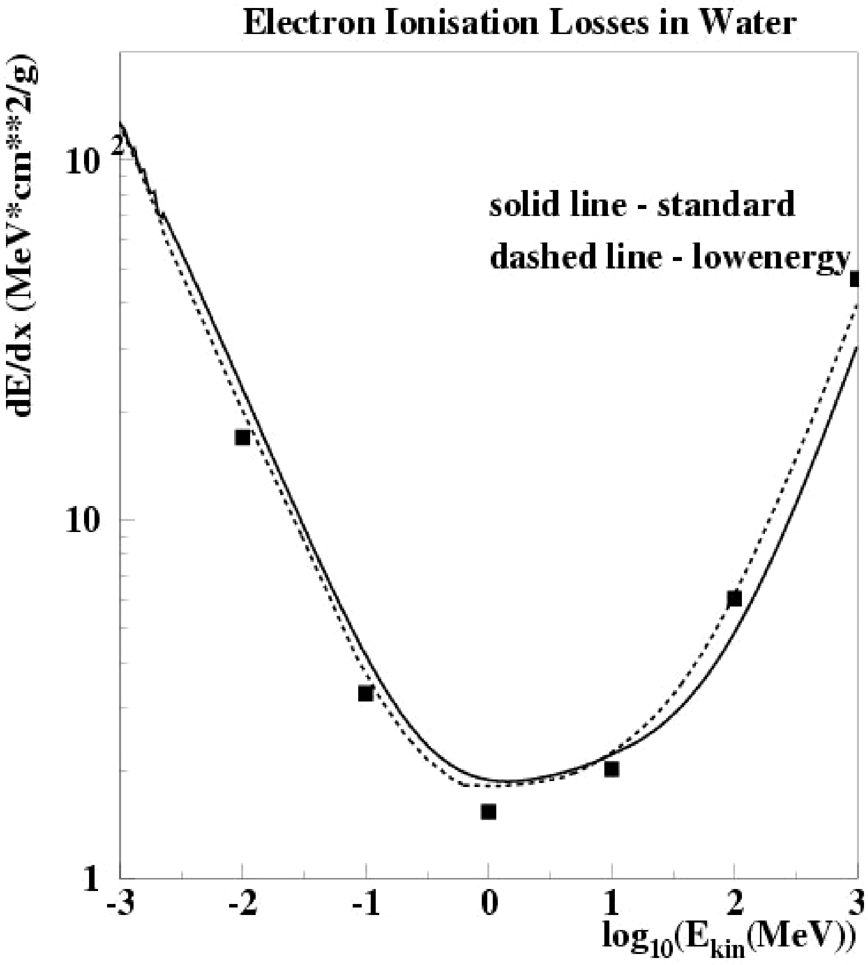
- Parameterisation of EEDL data
  - 16 parameters for each atom
  - At high energy the parameterisation reproduces the Bethe-Heitler formula
  - Precision is ~ 1.5 %

- Plans
  - Systematic verification over Z and energy



Electron ionisation

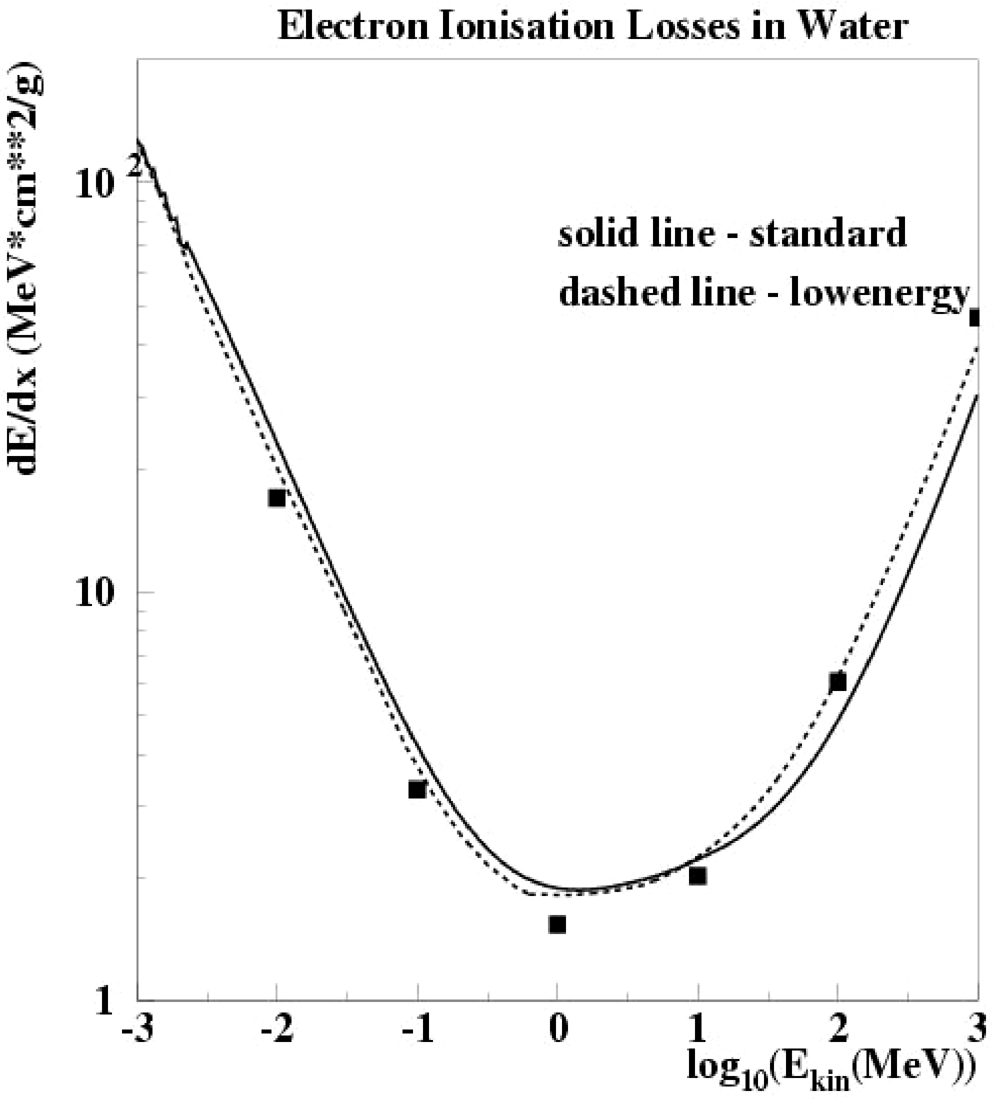
- Parameterisation based on 5 parameters for each shell
- Precision of parametrisation is better then 5% for 50 % of shells, less accurate for the remaining shells
- Work in progress to improve the parameterisation and the performance



Electron ionisation

- New parameterisations of EEDL data library recently released
  - precision is now better than 5 % for ~ 50% of the shells, poorer for the 50% left

- Plans
  - Systematic verification over shell, Z and energy
  - New Test & Analysis Project for automated verification *(all shells, 99 elements!)*



Electrons: range

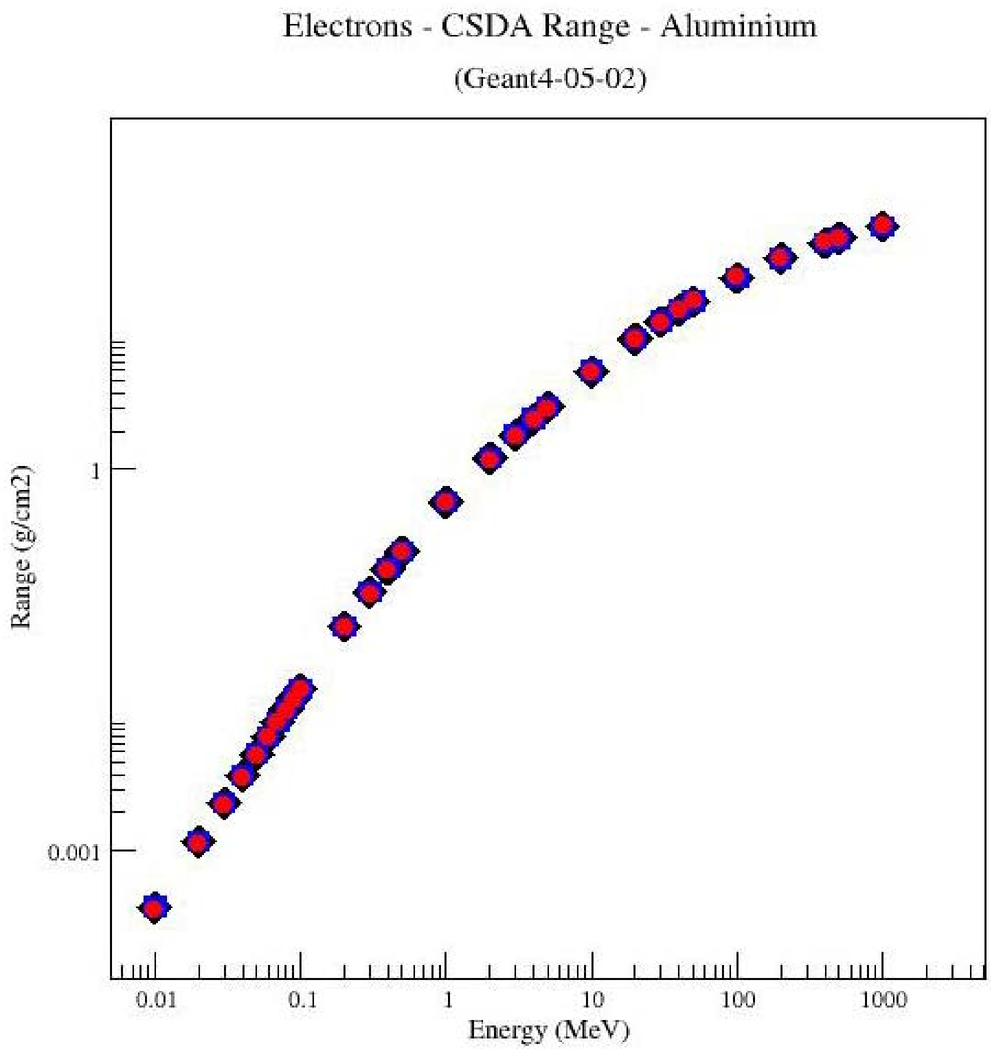
Range in various simple and composite materials

Compared to NIST database

◆ NIST-ESTAR

■ G4 Standard

● G4 LowE

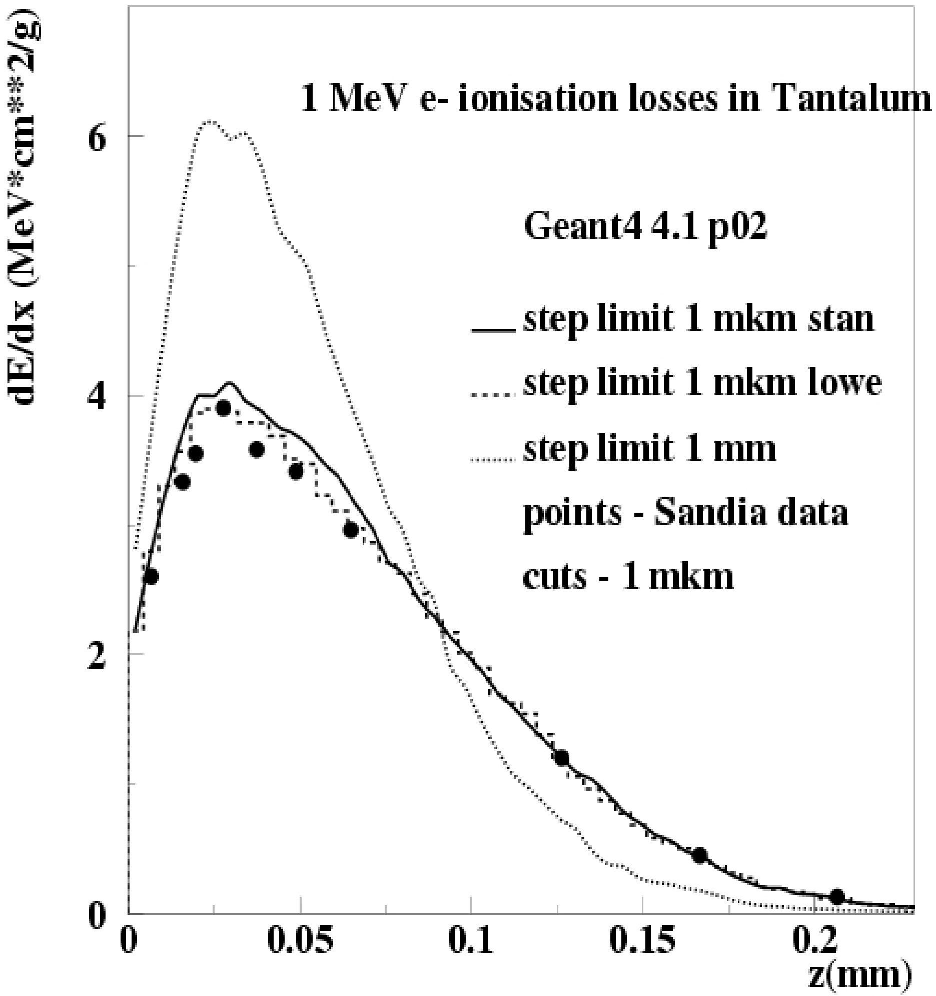


Electrons: dE/dx

Ionisation energy loss in various materials

Compared to Sandia database

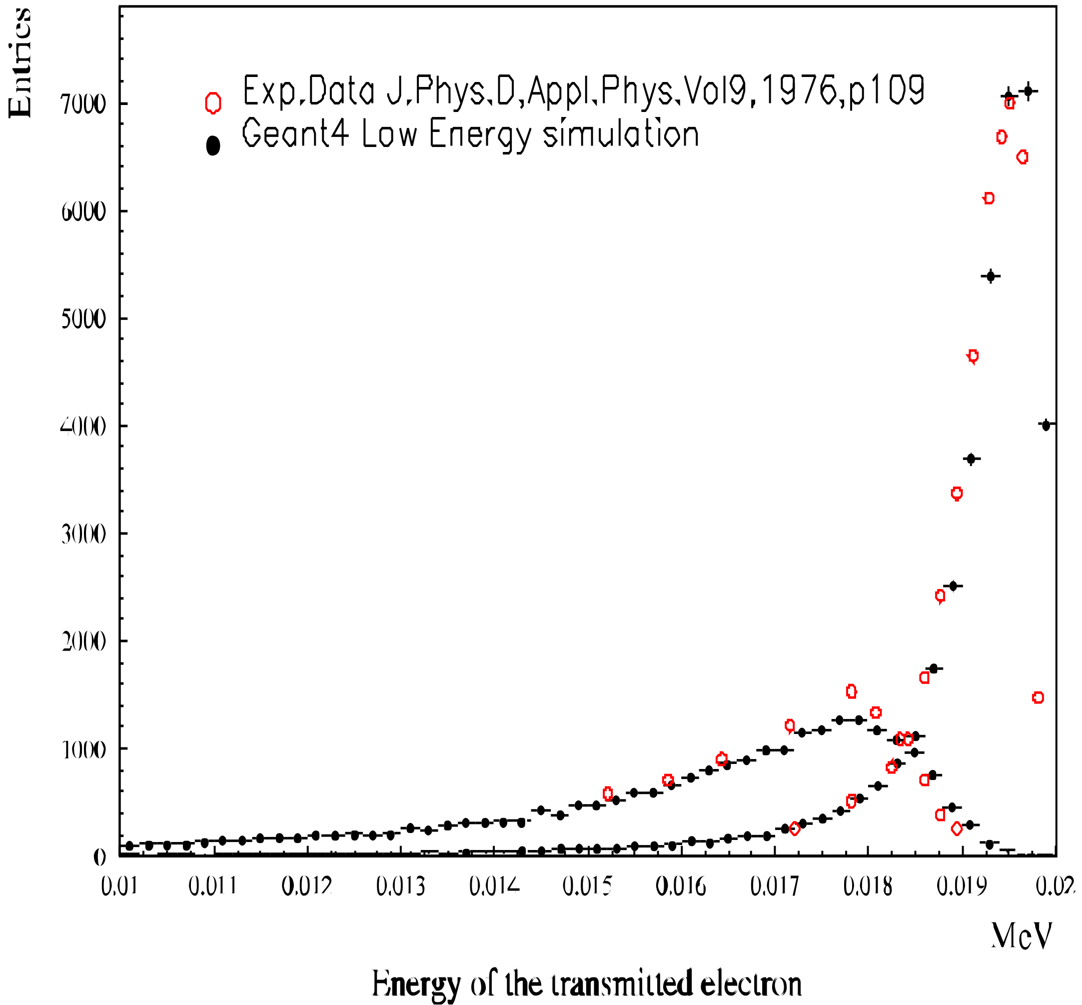
More systematic verification planned



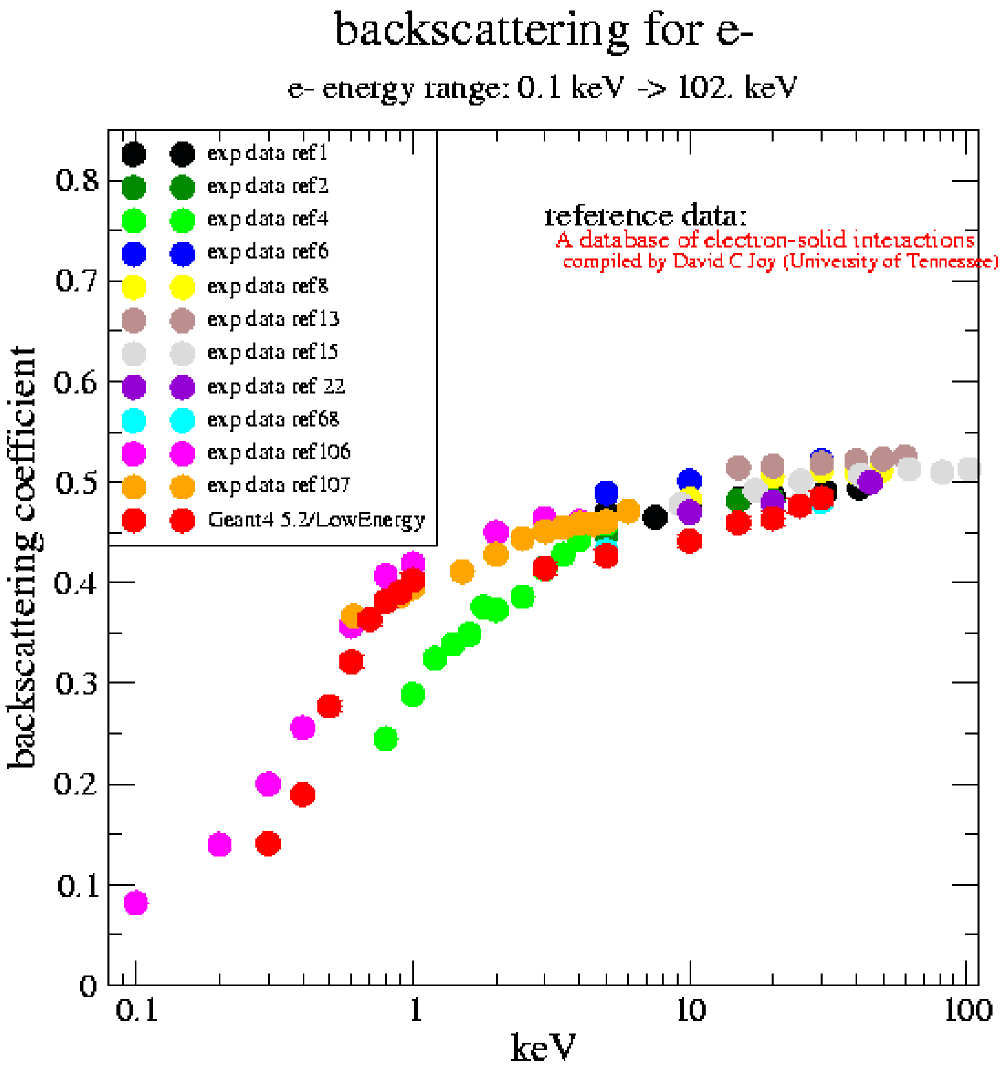
Also Fe, Ur

Electrons, transmitted

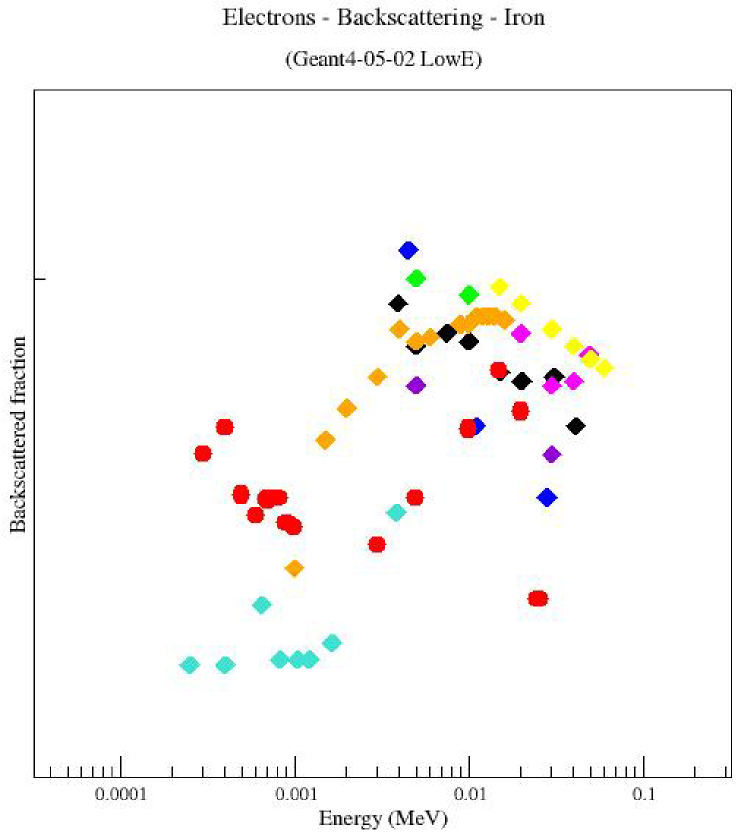
20 keV electrons, 0.32 and 1.04 μm Al



The problem of validation: finding reliable data



Backscattering low energies - Au



Note: Geant4 validation is not always easy

experimental data often exhibit large differences!

Hadrons and ions

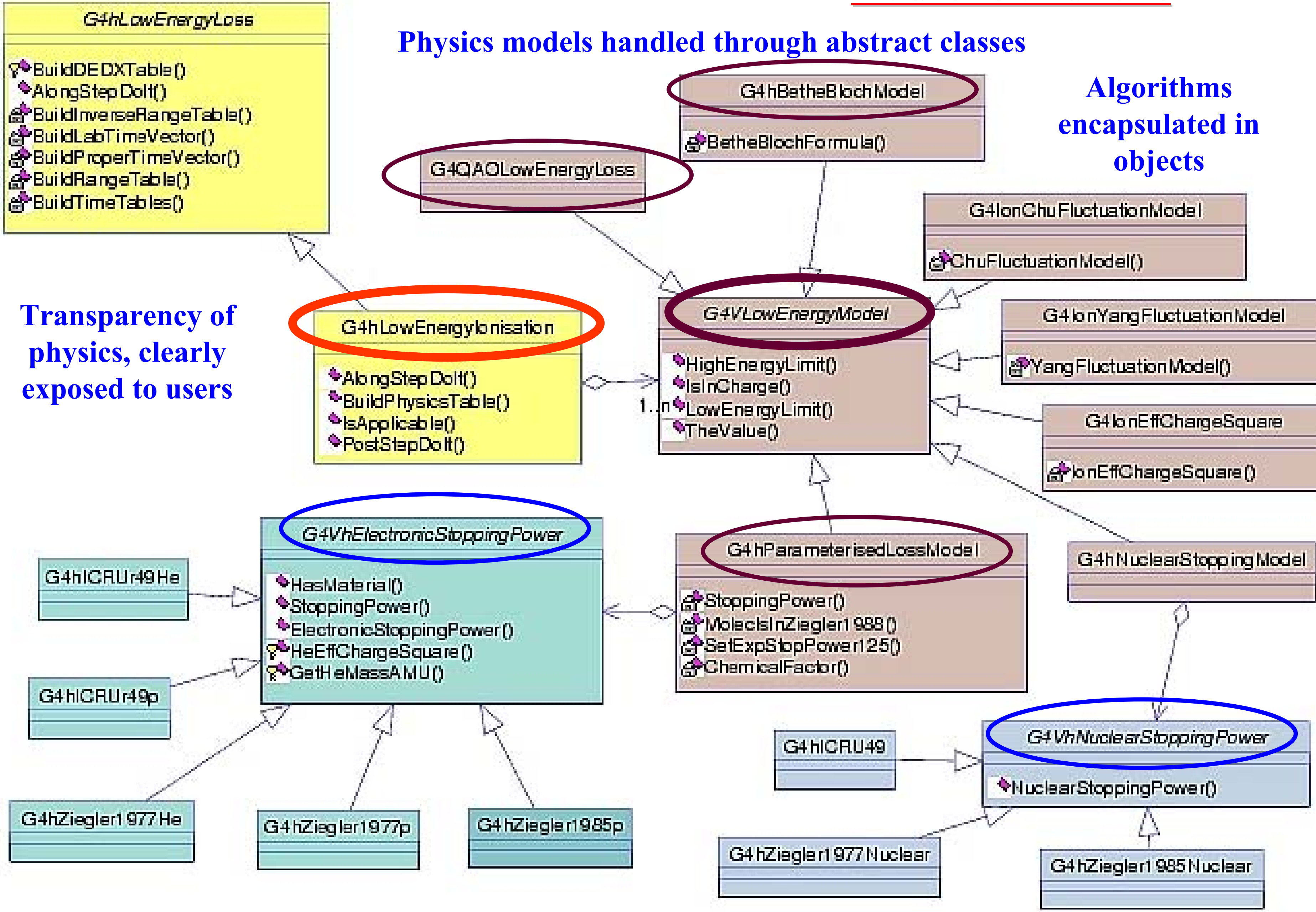
- Variety of models, depending on
  - energy range
  - particle type
  - charge
- Composition of models across the energy range, with different approaches
  - analytical
  - based on data reviews + parameterisations
- Specialised models for fluctuations
- Open to extension and evolution

Hadrons and ions

Physics models handled through abstract classes

Algorithms encapsulated in objects

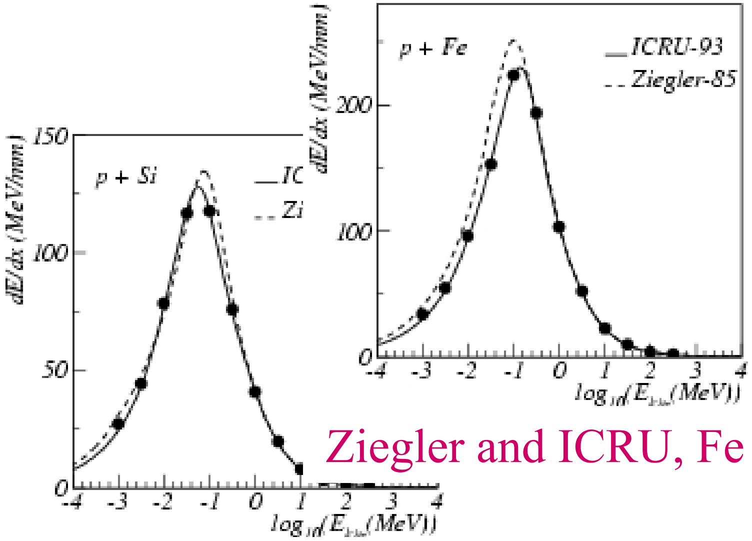
Transparency of physics, clearly exposed to users



Interchangeable and transparent access to data sets

Positive charged hadrons

- **Bethe-Bloch model of energy loss, E > 2 MeV**
- **5 parameterisation models, E < 2 MeV**
  - *based on Ziegler and ICRU reviews*
- **3 models of energy loss fluctuations**



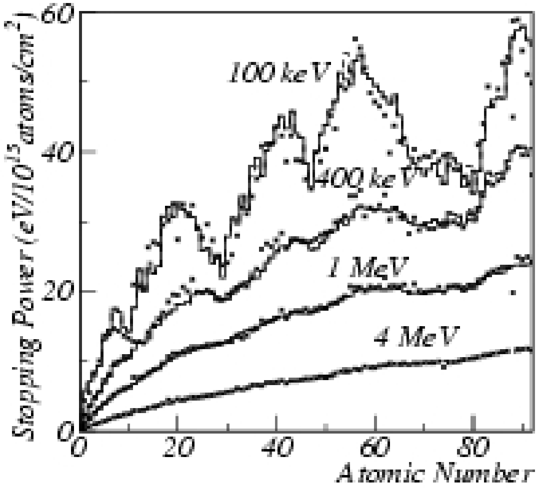
Ziegler and ICRU, Fe

Ziegler and ICRU, Si

- **Density correction for high energy**
- **Shell correction term for intermediate energy**

- **Spin dependent term**
- **Barkas and Bloch terms**

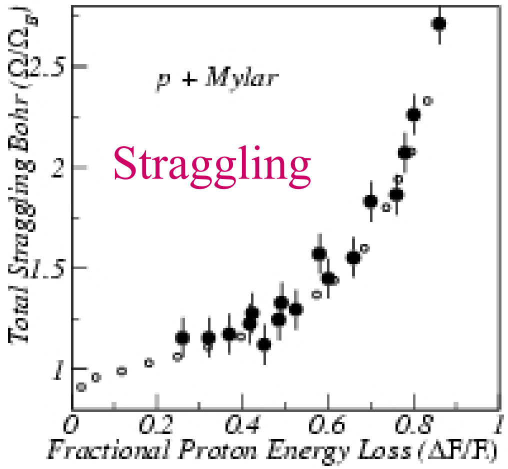
- **Chemical effect for compounds**
- **Nuclear stopping power**
- **PIXE included** *(preliminary)*



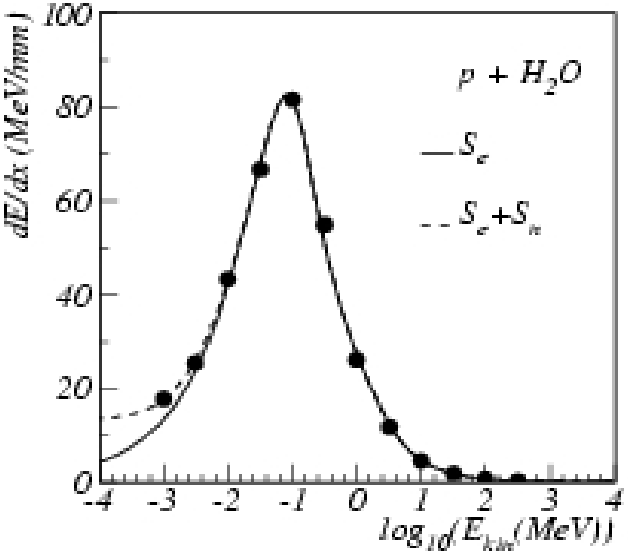
Stopping power

Z dependence for various energies

Ziegler and ICRU models

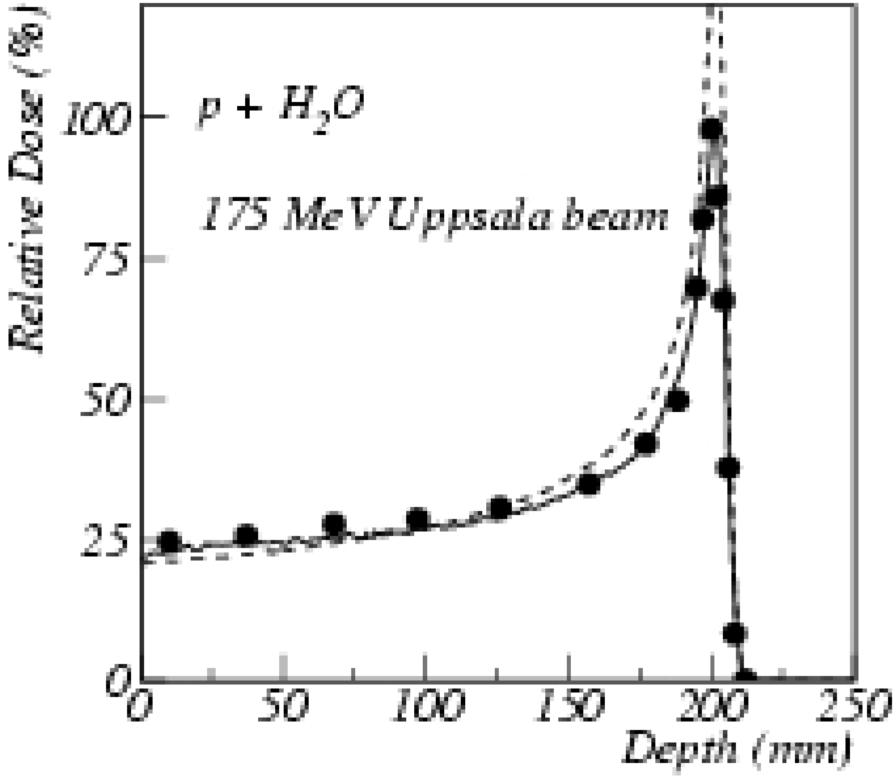


Straggling



Nuclear stopping power

The precision of the stopping power simulation for protons in the energy from 1 keV to 10 GeV is of the order of a few per cent

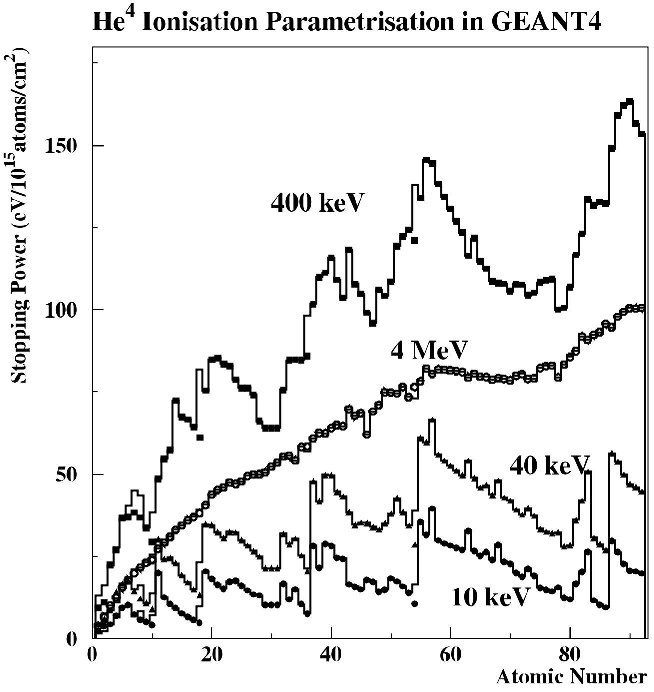


Bragg peak *(with hadronic interactions)*

Positive charged ions

- Scaling: $$S_{ion}(T) = Z_{ion}^2 S_p(T_p),\ T_p = T\frac{m_p}{m_{ion}}$$
- $0.01 < \beta < 0.05$ parameterisations, Bragg peak
  - *based on Ziegler and ICRU reviews*
- $\beta < 0.01$: Free Electron Gas Model

- Effective charge model
- Nuclear stopping power



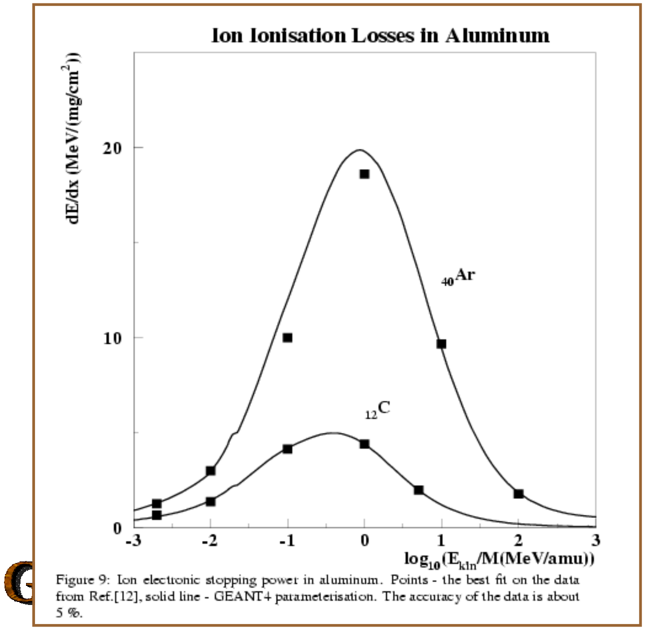
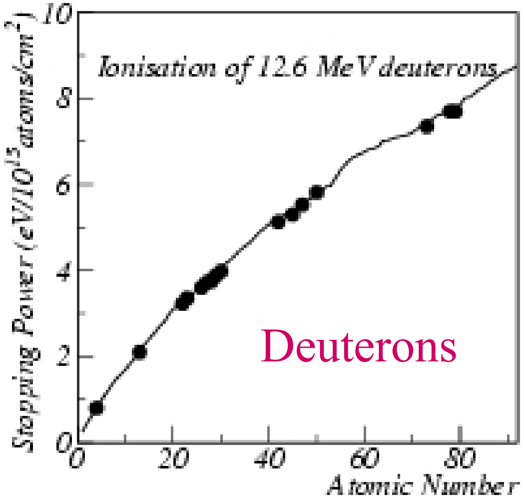
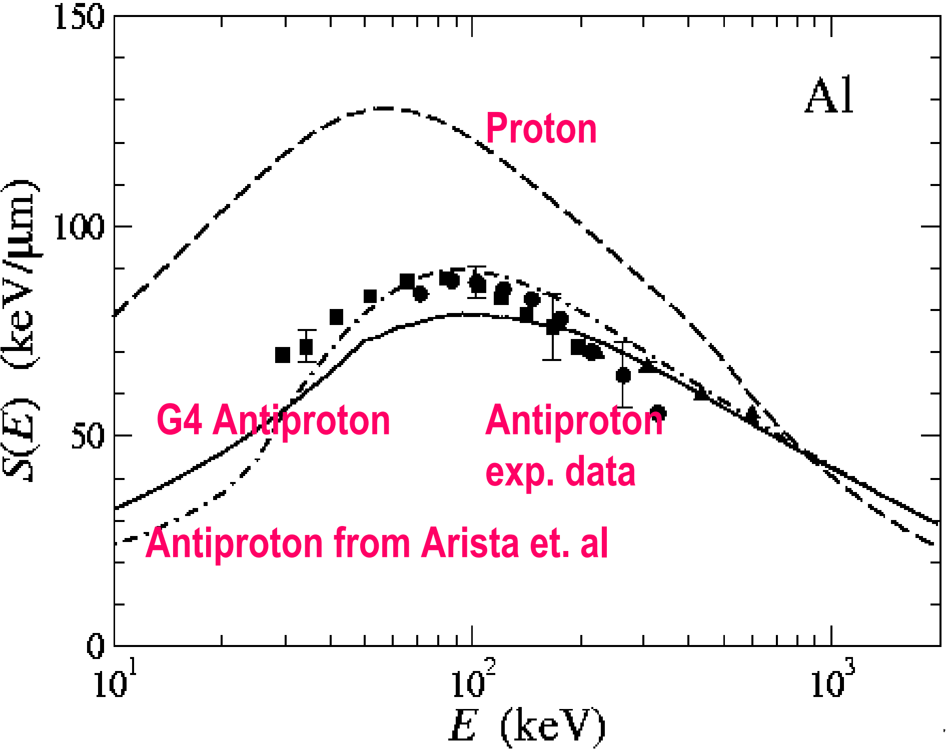


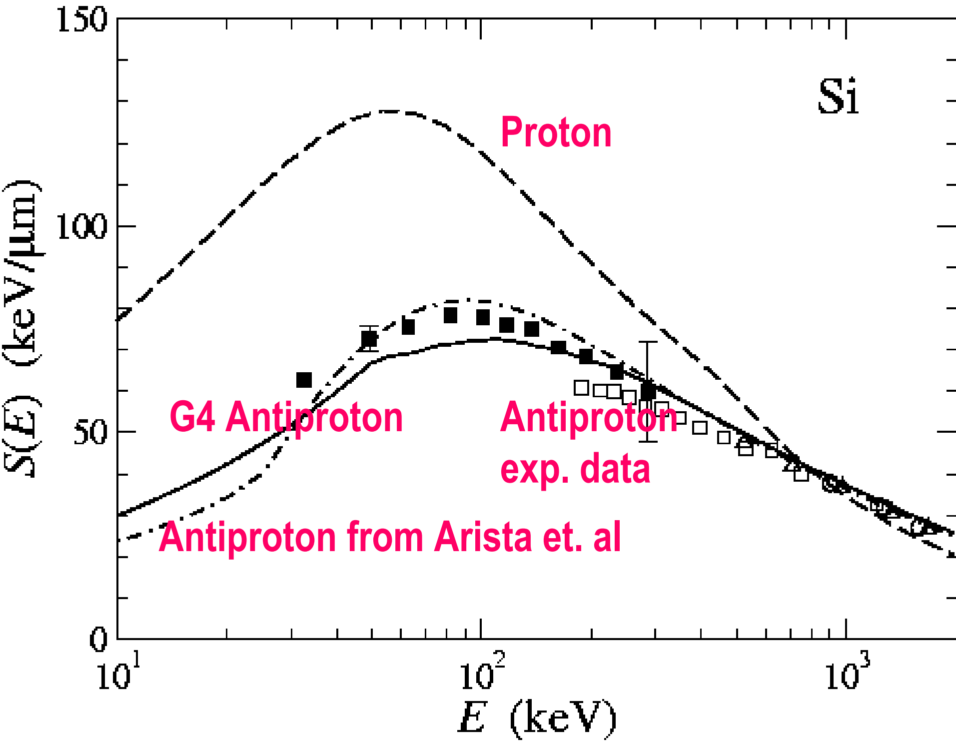
Figure 9: Ion electronic stopping power in aluminum. Points - the best fit on the data from Ref.[12], solid line - GEANT4 parameterisation. The accuracy of the data is about 5 %.



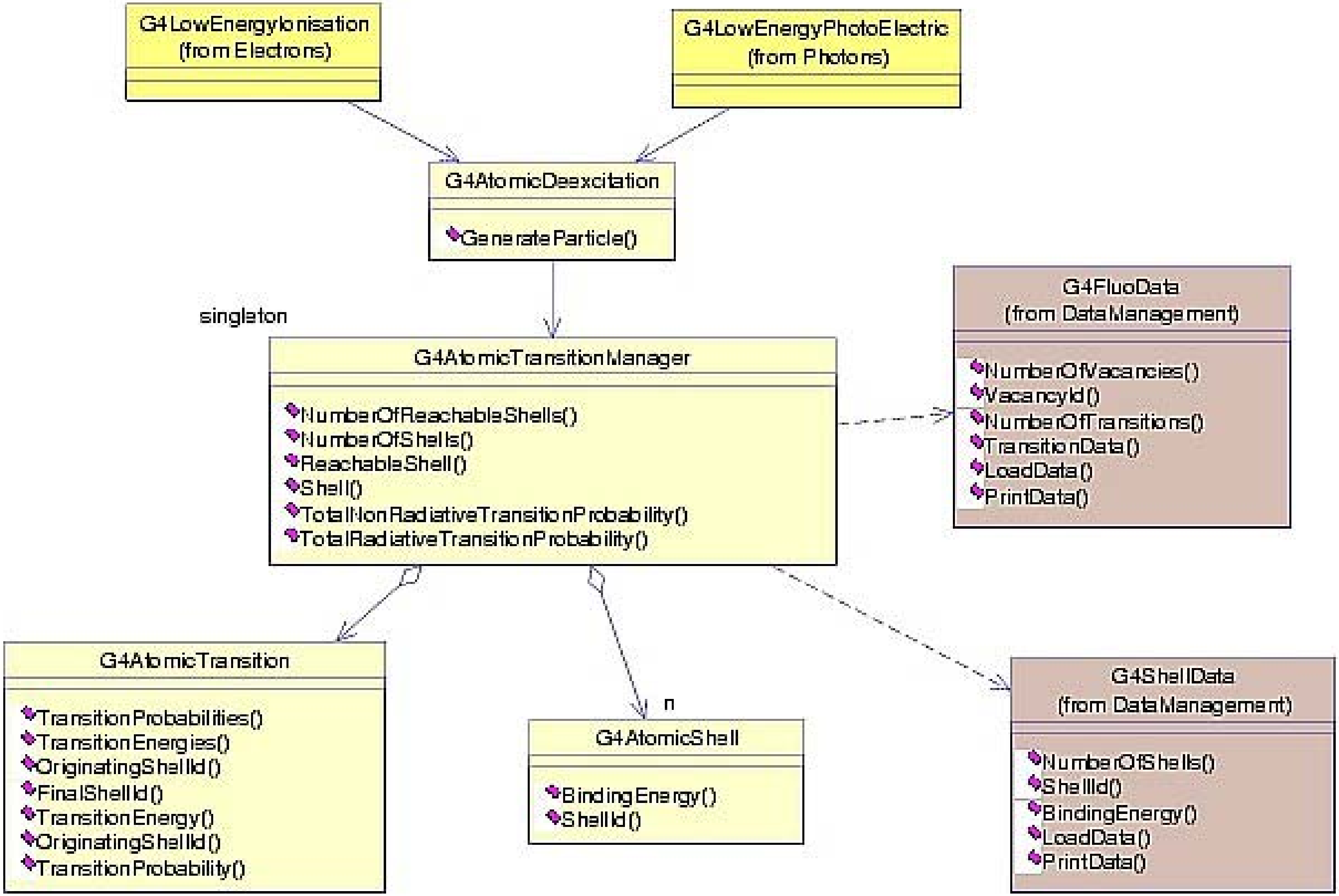
Models for antiprotons

$\beta > 0.5$	Bethe-Bloch formula
$0.01 < \beta < 0.5$	Quantum harmonic oscillator model
$\beta < 0.01$	Free electron gas mode





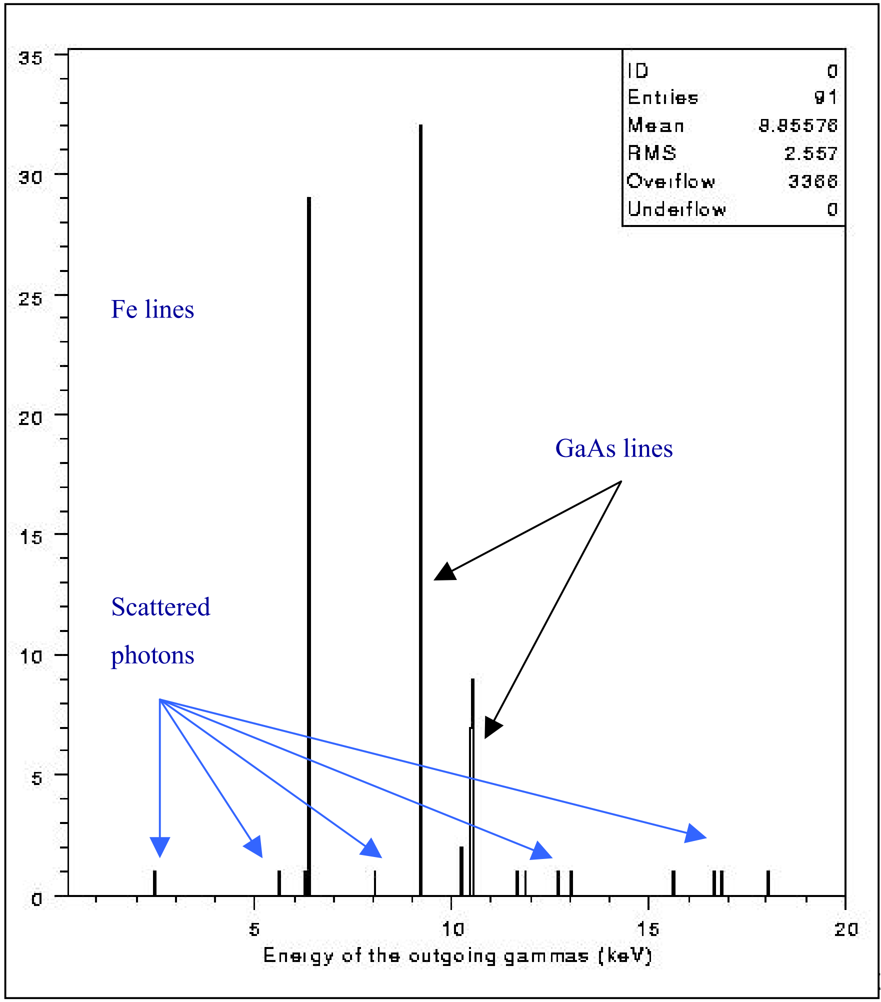
Atomic relaxation



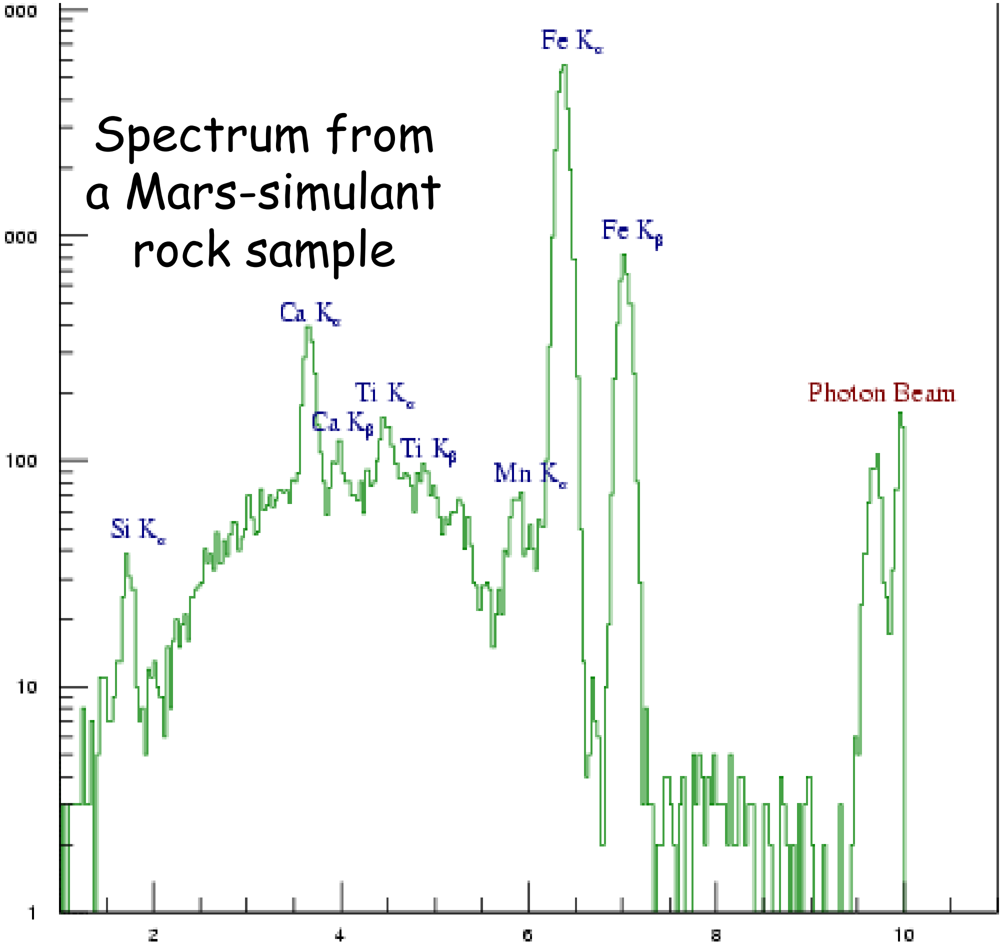
Fluorescence

Microscopic validation:
against reference data

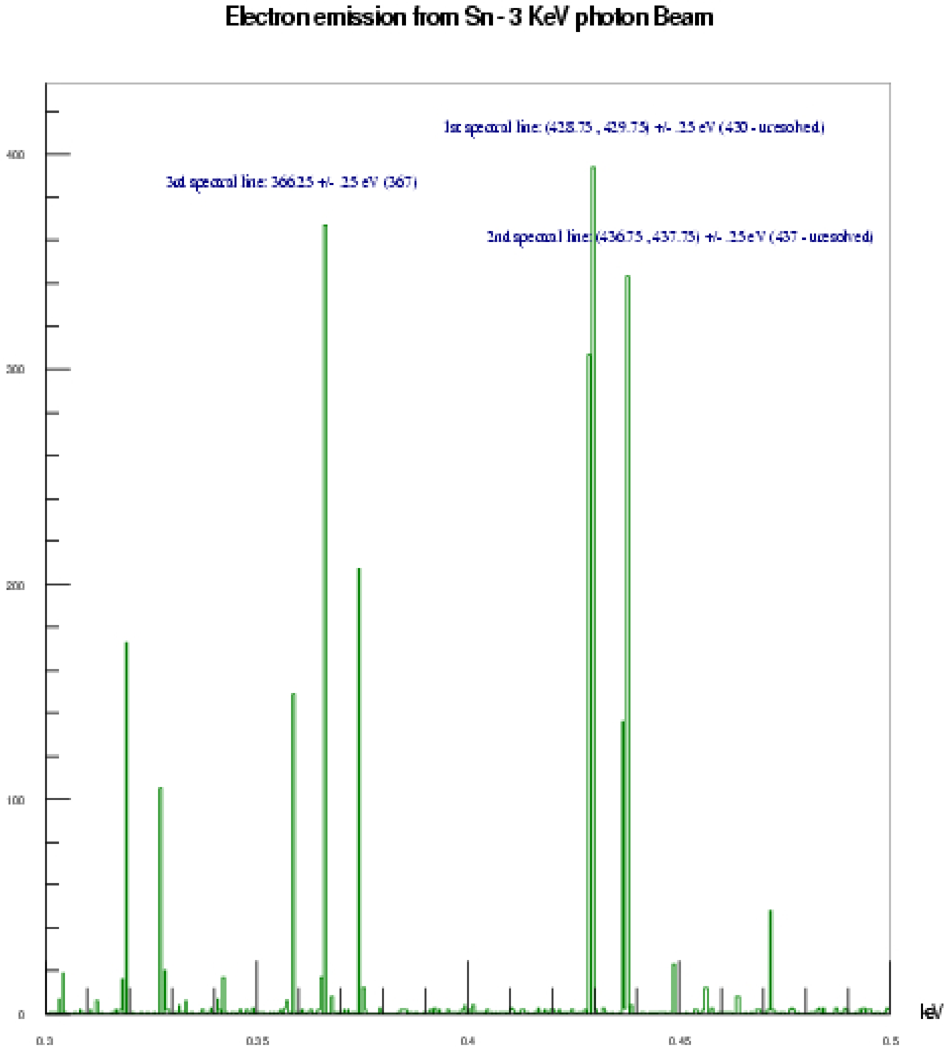
Experimental validation:
test beam data, in collaboration with
ESA Advanced Concepts & Science
Payload Division



Spectrum from
a Mars-simulant
rock sample



Auger effect



Sn, 3 keV photon beam,

electron lines w.r.t. published experimental results

Processes à la Penelope

- The whole physics content of the Penelope Monte Carlo code has been re-engineered into Geant4 *(except for multiple scattering)*
  - processes for photons: release 5.2, for electrons: release 6.0
- Physics models by F. Salvat et al.

- Power of the OO technology:
  - extending the software system is easy
  - all processes obey to the same abstract interfaces
  - using new implementations in application code is simple

- Profit of Geant4 advanced geometry modeling, interactive facilities *etc.*
  - same physics as original Penelope

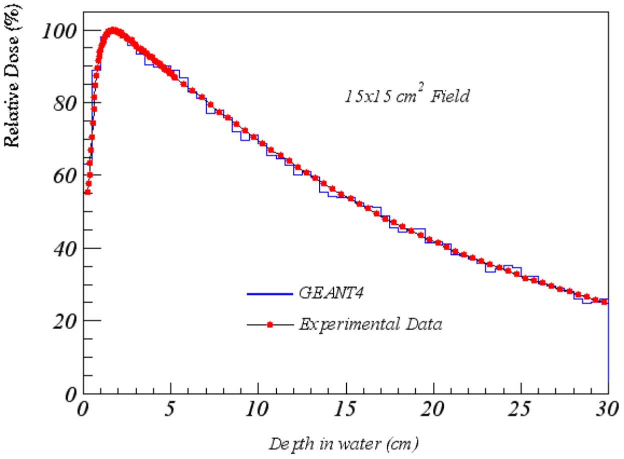
Contribution from users

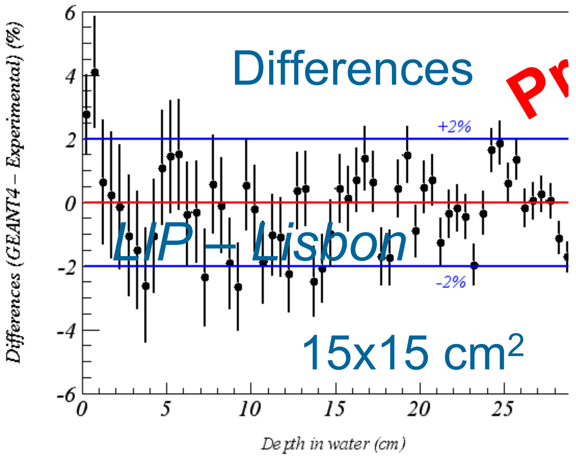
- Many valuable contributions to the validation of LowE physics from users all over the world
  - excellent relationship with our user community
- User comparisons with data usually involve the effect of several physics processes of the LowE package
- A small sample in the next slides
  - no time to show all!

Homogeneous Phantom

P. Rodrigues, A. Trindade, L.Peralta, J. Varela, LIP

- Simulation of photon beams produced by a Siemens Mevatron KD2 clinical linear accelerator
- Phase-space distributions interface with GEANT4
- Validation against experimental data: depth dose and profile curves

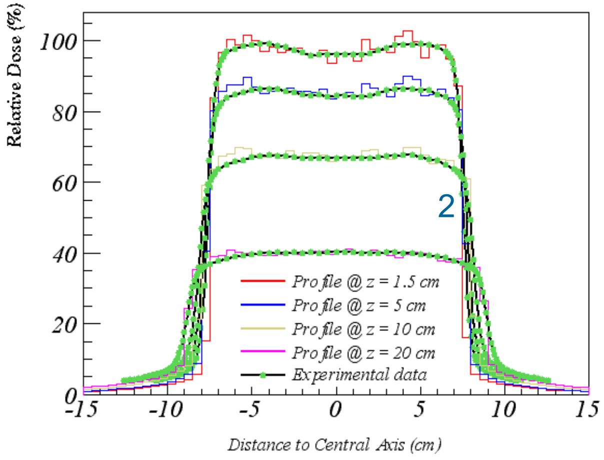




Differences

LIP – Lisbon

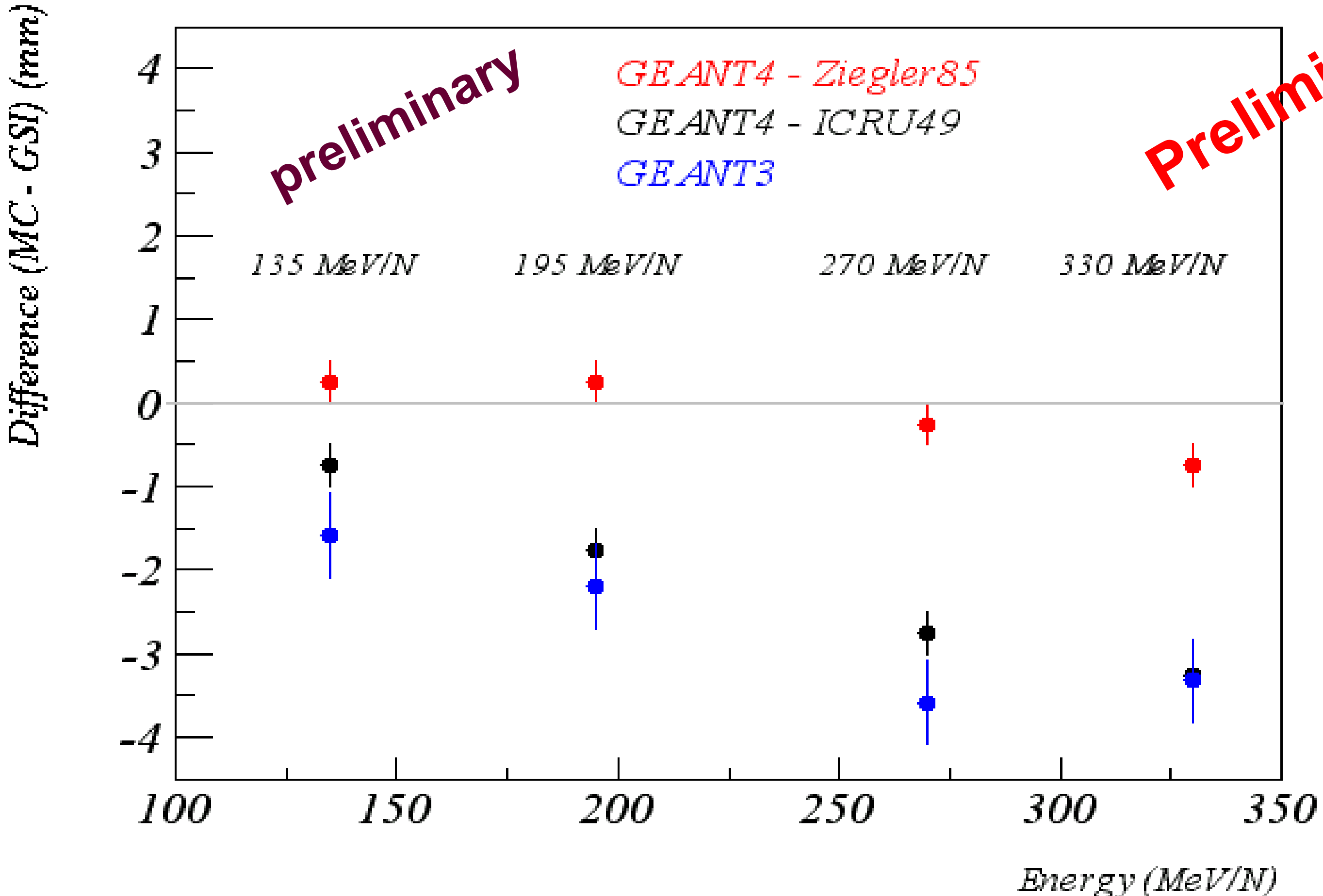
15x15 cm²



Dose Calculations with 12C

P. Rodrigues, A. Trindade, L.Peralta, J. Varela, LIP

- Bragg peak localization calculated with GEANT4 (stopping powers from ICRU49 and Ziegler85) and GEANT3 in a water phantom
- Comparison with GSI data

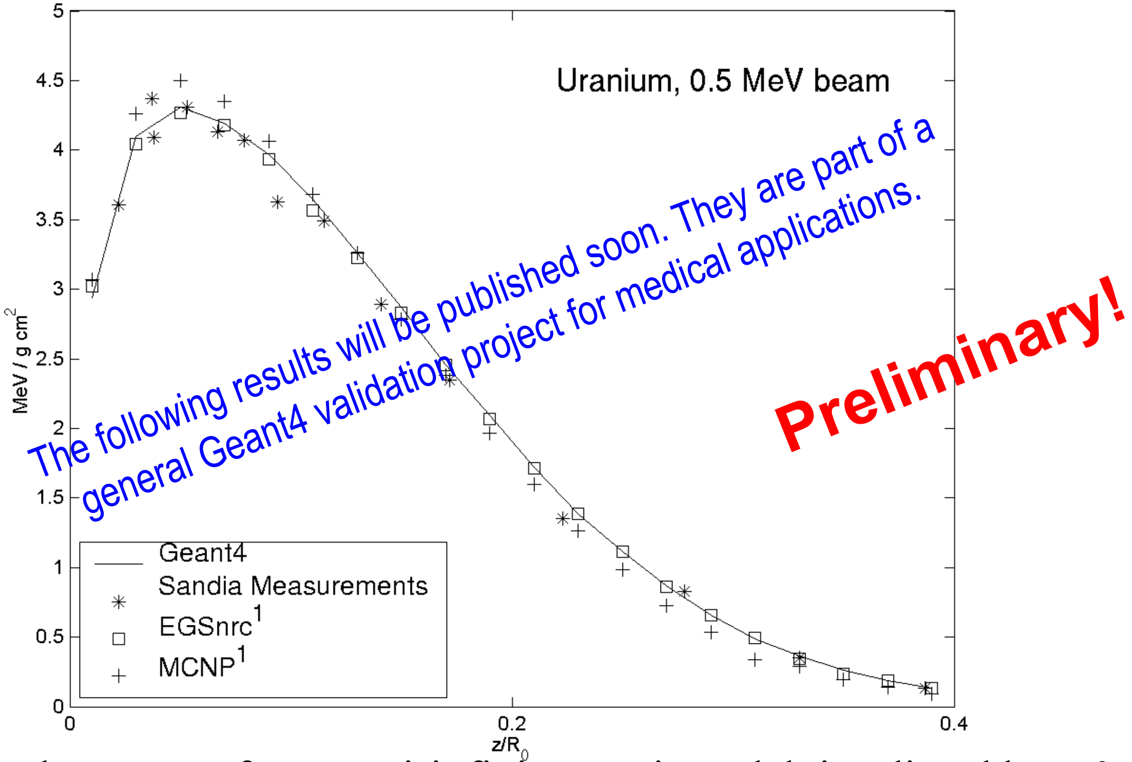


Preliminary!

Uranium irradiated by electron beam

Jean-Francois Carrier, Louis Archambault, Rene Roy and Luc Beaulieu

Service de radio-oncologie, Hotel-Dieu de Quebec, Quebec, Canada
Departement de physique, Universite Laval, Quebec, Canada



The following results will be published soon. They are part of a general Geant4 validation project for medical applications.

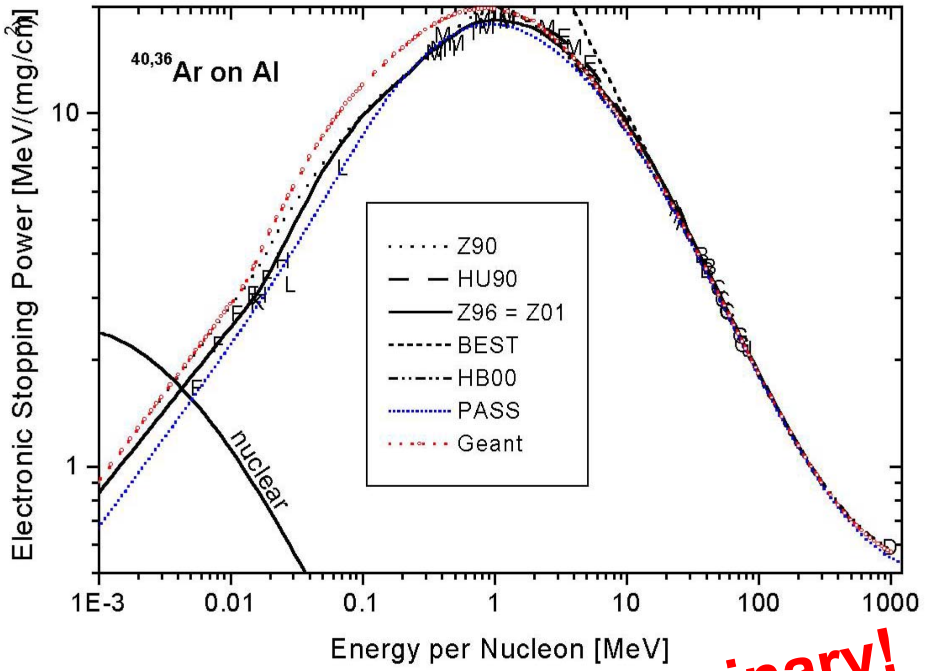
Preliminary!

Fig 1. Depth-dose curve for a semi-infinite uranium slab irradiated by a 0.5 MeV broad parallel electron beam

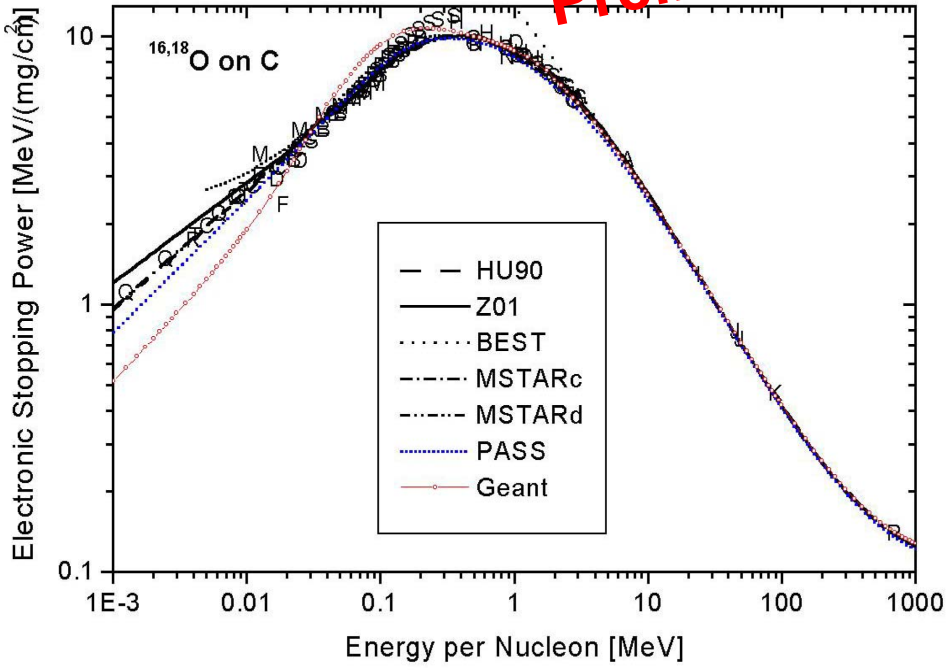
Ions

Independent validation at Univ. of Linz (H. Paul et al.)

Geant4-LowE reproduces the right side of the distribution precisely, but about 10-20% discrepancy is observed at lower energies



Preliminary!



To learn more

- Geant4 Physics Reference Manual
- Application Developer Guide

- http://www.ge.infn.it/geant4/lowE

Summary

- OO technology provides the mechanism for a rich set of electromagnetic physics models in Geant4
  - further extensions and refinements are possible, without affecting Geant4 kernel or user code
- Two main approaches in Geant4:
  - standard
  - Low Energy (Livermore Library / Penelope)

  each one offering a variety of models for specialised applications
- Extensive validation activity and results
- More on Physics Reference Manual and web site