Electromagnetic Physics II

Overview of
Low Energy Electromagnetic Processes

Sebastien Incerti

presenting

Geant4 Low Energy Electromagnetic
working group’s slides

Low Energy Electromagnetic Physics

- Introduction
- **Photons**, **electrons** and **hadrons**
- **Atomic effects**
- Penelope Physics alternative
- Advanced examples
- How to use the LE package
- Summary

What is it ?

- A package in the Geant4 electromagnetic package
  → in …**$G4INSTALL/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 approximately the ionization potential of the interacting material for hadrons and ions
  - up to 100 GeV (unless specified)
  - based on theoretical models and evaluated data sets ; they involve two distinct phases :
    - calculation and use of **total cross sections**
    - generation of the **final state**
- Models are detailed
  - shell structure of the atom
  - precise angular distributions
- Complementary to the "standard" electromagnetic package
- Driven by requirements which come from medicine and space research and from users in HEP instrumentation

Overview of physics

- **Photons**
  - Compton Scattering
  - Compton Scattering by Linearly Polarized Gamma Rays
  - Rayleigh Scattering
  - Gamma Conversion
  - Photoelectric effect
- **Electrons**
  - Bremsstrahlung
  - Ionisation

Come in **two "flavours"**
- based on the **Livermore Library**
- à la **Penelope** (+ positron annihil.)

- **Hadrons and ion ionisation**
  - Energy loss of slow & fast hadrons
  - Energy loss in compounds
  - Delta-ray production
  - Effective charge of ions
  - Barkas and Bloch effects (hadron sign + relativistic)
  - Nuclear stopping power
  - PIXE

Atomic relaxation
- Fluorescence
- Auger process

A set of LowE processes are based on the Livermore Library

User must download Geant4 version of this data, then set G4LEDATA environment variable to point to it

Photons and electrons

- 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

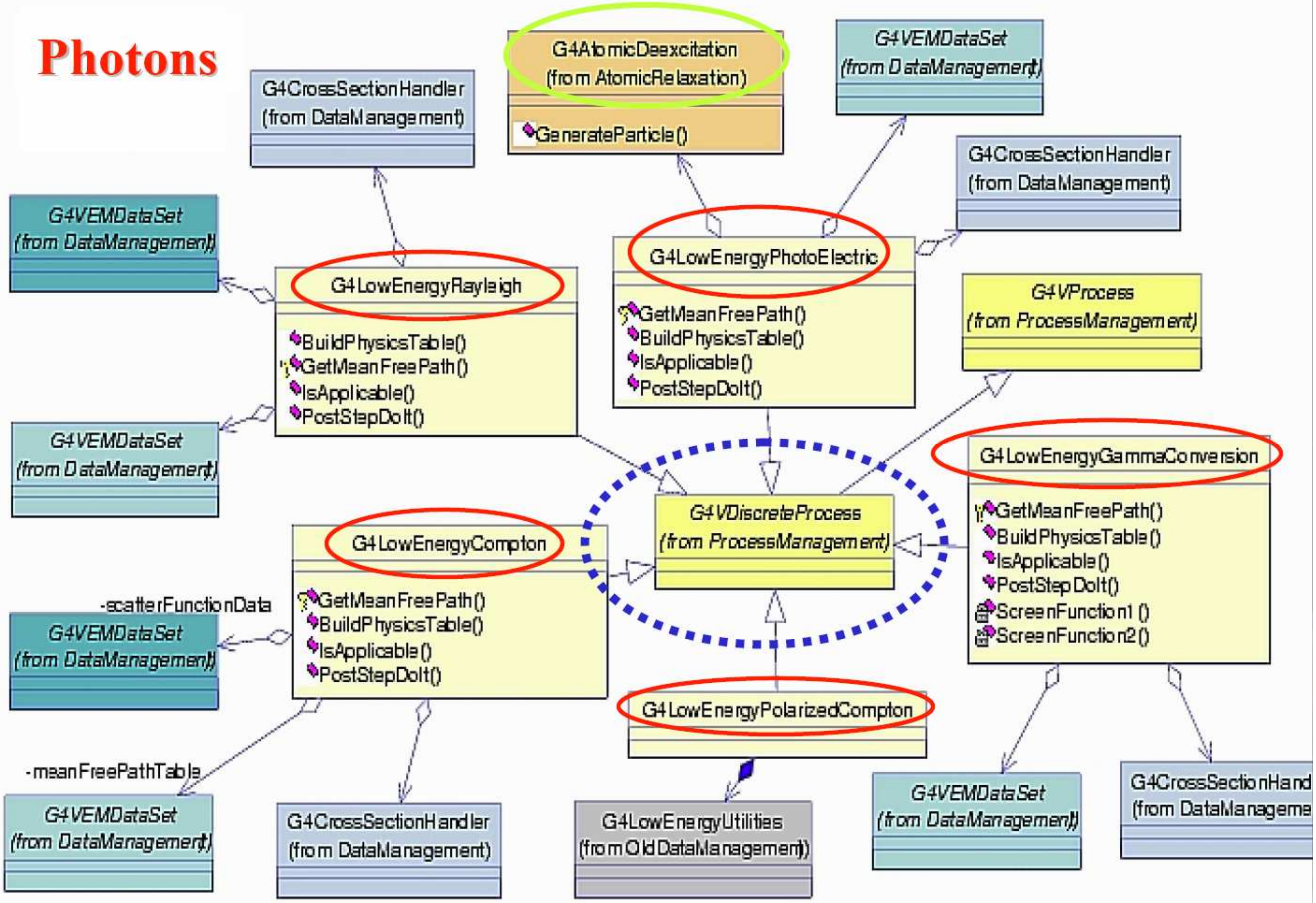
→ **Mean free path** for a process, at energy E :

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

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

Photons

Photons



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

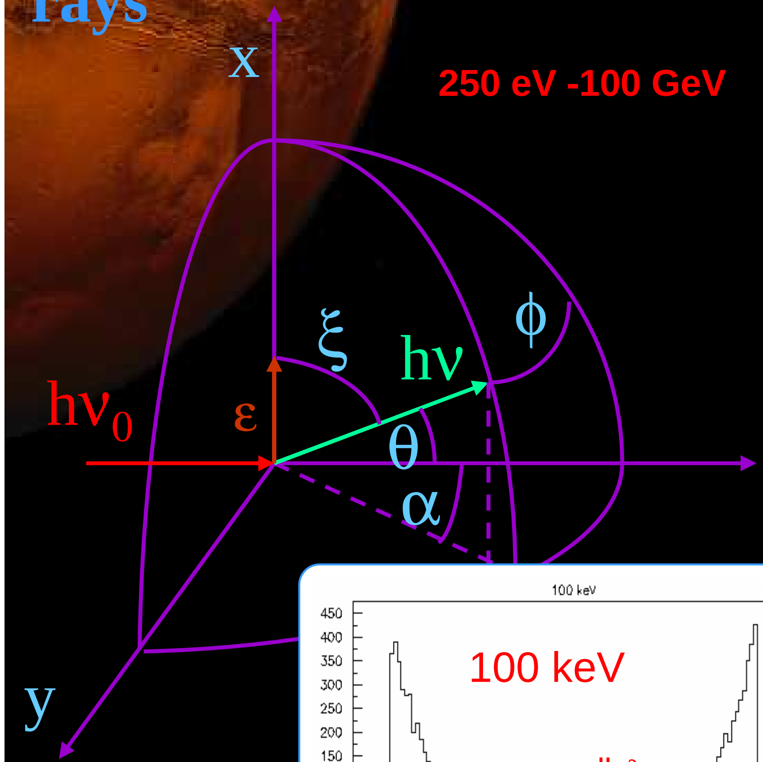
Compton scattering (incoherent)

Klein-Nishina cross section $(E'/E) \times$ Scattering Function (q)

$q = E \sin^2(\theta/2)$ momentum transfer

- **Energy distribution** of the scattered photon according to the **Klein-Nishina** formula, multiplied by **scattering function** F(q) (Hubbel's atomic factor) from **EPDL97** data library
- The effect of scattering function becomes significant at low energies in suppressing forward scattering
- **Angular distribution** of the scattered photon and the recoil electron also based on **EPDL97**

Compton scattering by linearly polarized gamma rays



Cross section

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

Scattered Photon Polarization

$$\overline{\varepsilon_{\perp}'} = \frac{1}{N}\left(\cos\theta \ \hat{j} - \sin\theta \sin\phi \ \hat{k}\right)\sin\beta$$

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

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

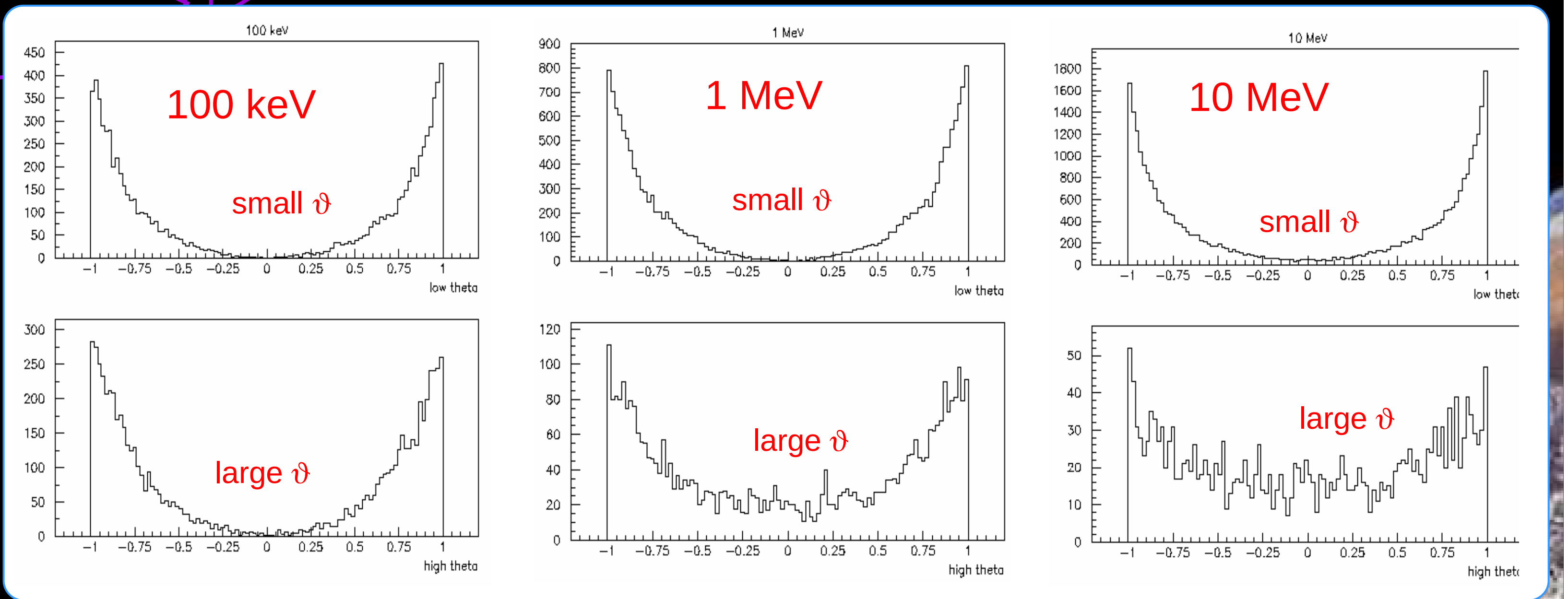
β angle between ε' par and perp components

θ Polar angle

φ azimuthal angle

ε Polarization vector

scalar product between two polarization vectors



http://www.ge.infn.it/geant4/talks/RoundTable/depaola.ppt

Rayleigh scattering (coherent)

- Depends on charge distribution of atom

- **Angular distribution**

$$F(E,\theta)=[1+\cos^2(\theta)]\sin\theta\cdot F^2(q)$$

$q = 2\,E\,\sin(\theta/2)$

Rayleigh formula times F(q), the energy dependent Hubbel's **form factor** obtained from **EPDL97** (forward peak at high energies)

- Only available in the *lowenergy* package

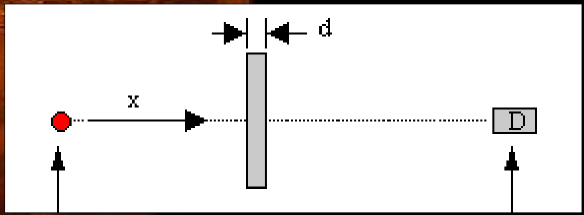
Photoelectric effect

- **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**
  - Various angular distribution generators ("naïve", Sauter-Gavrila, Gavrila)
- **De-excitation** via the atomic relaxation sub-process
  - Initial vacancy + following chain of vacancies created
- Improved angular distribution recently released

γ conversion

- The secondary e^- and e^+ energies are sampled using **Bethe-Heitler** cross sections with **Coulomb correction** (screening)
- 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



All simulation results lie with ± 3σ w.r.t. the corresponding NIST data (National Institute of Standards and Technologies)

Comparison against NIST data

photons in Iron

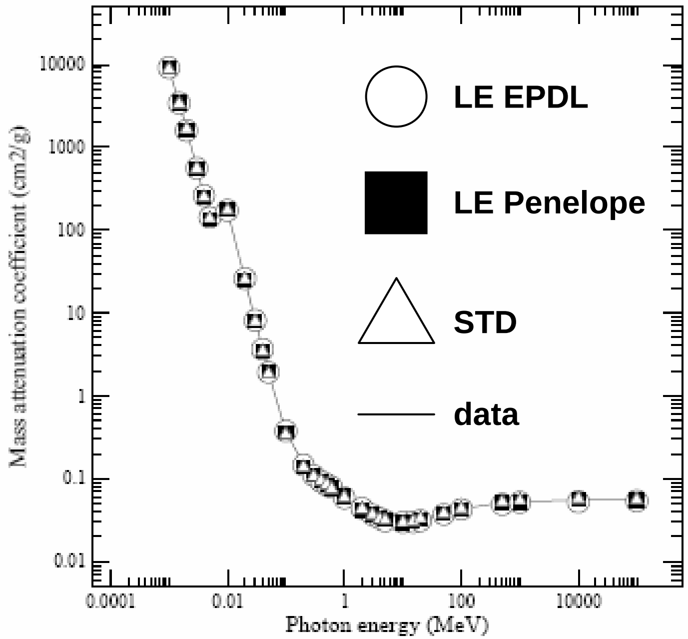
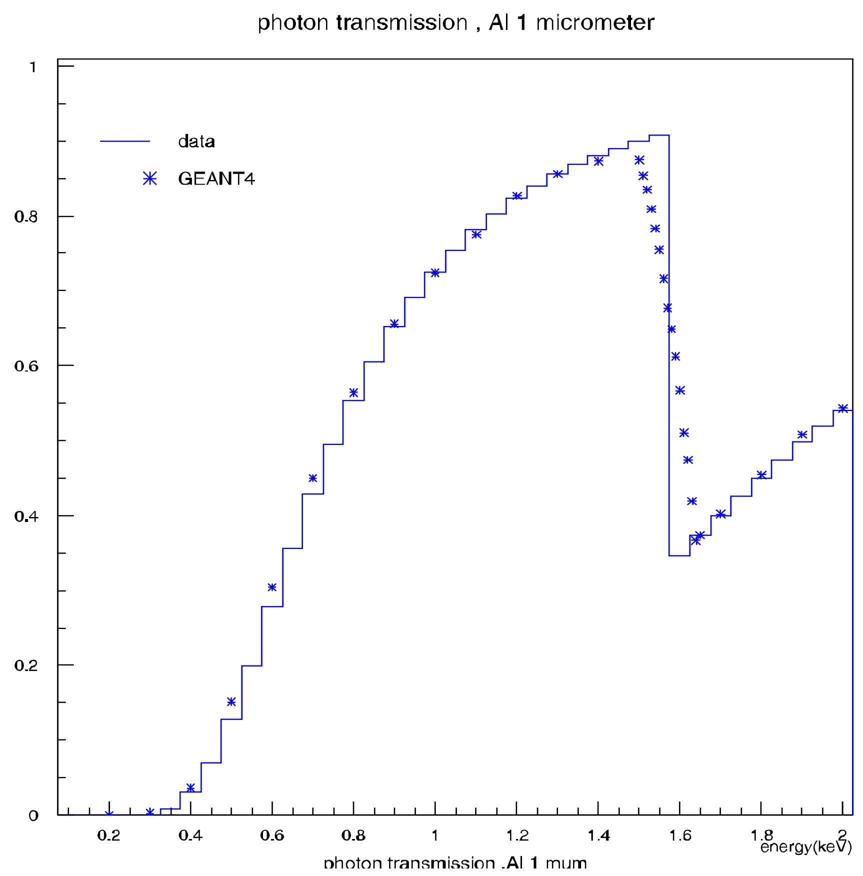
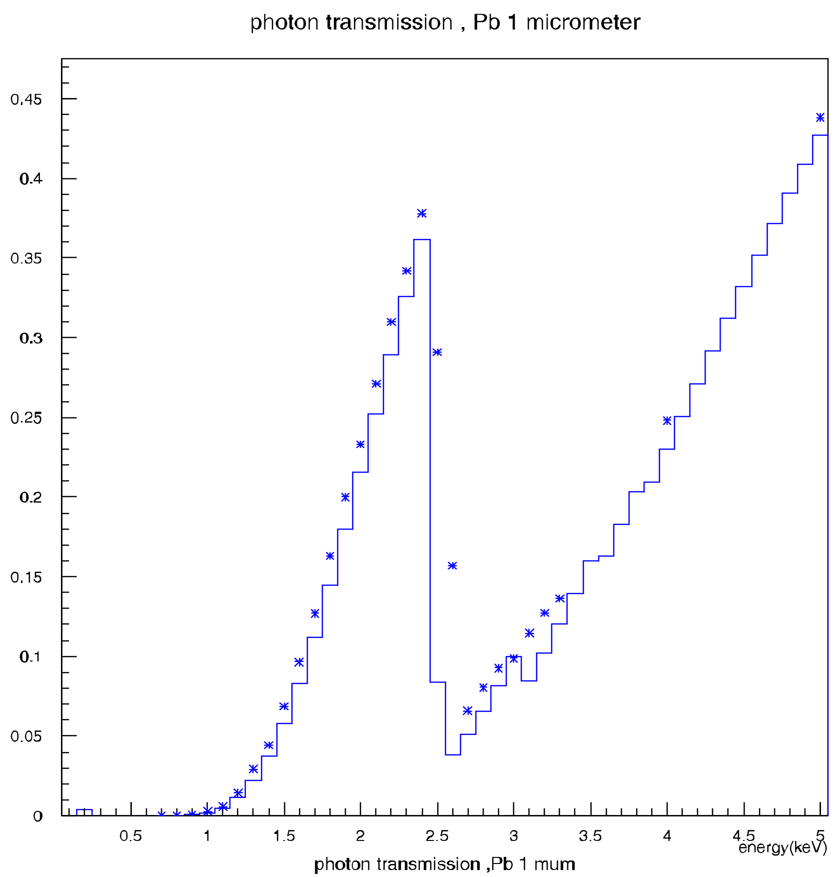


Fig. 2. Mass attenuation coefficient in iron as a function of the photon incident energy for the three sets of Geant4 models under test (circles: Low Energy EPDL; squares: Low Energy Penelope; triangles: Standard); the continuous line interpolates NIST-XCOM reference data.

Photons, evidence of shell effects

Photon transmission, 1 µm Al | **Photon transmission, 1 µm Pb**



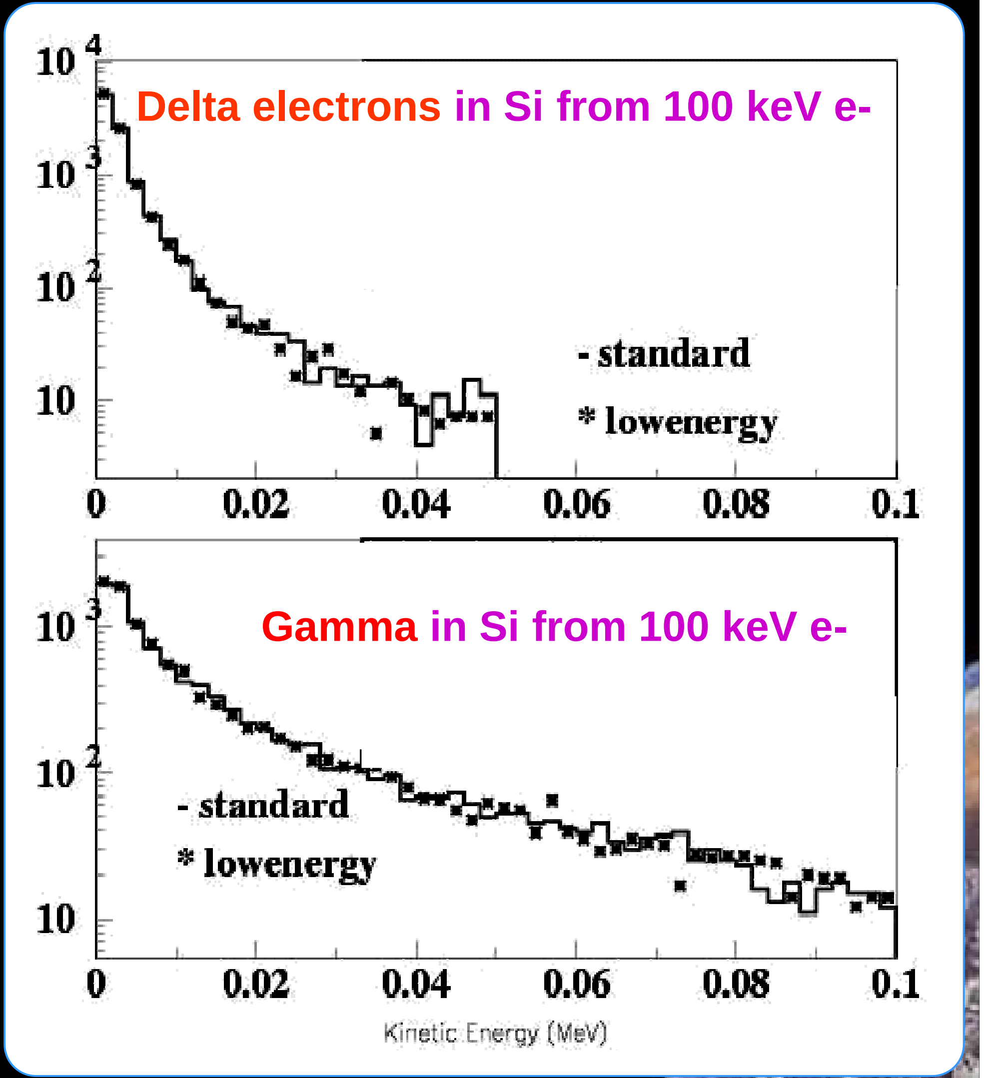


Electrons

Electron Bremsstrahlung

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

- Systematic verification over Z and energy planned

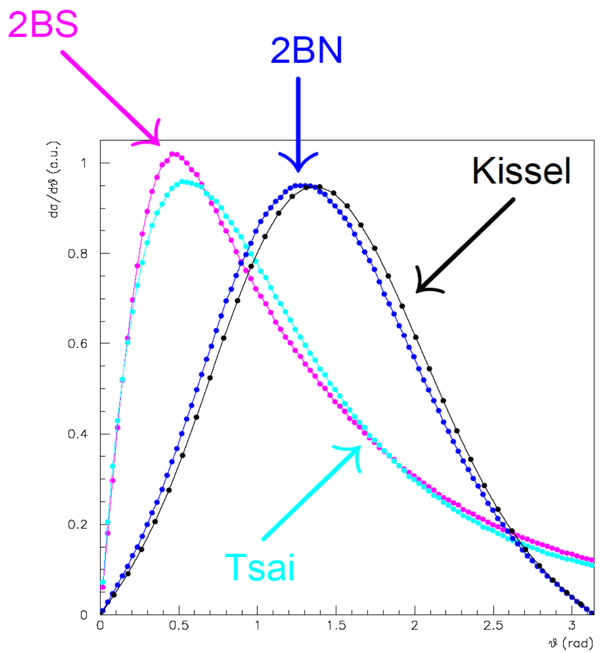


Bremsstrahlung Angular Distributions

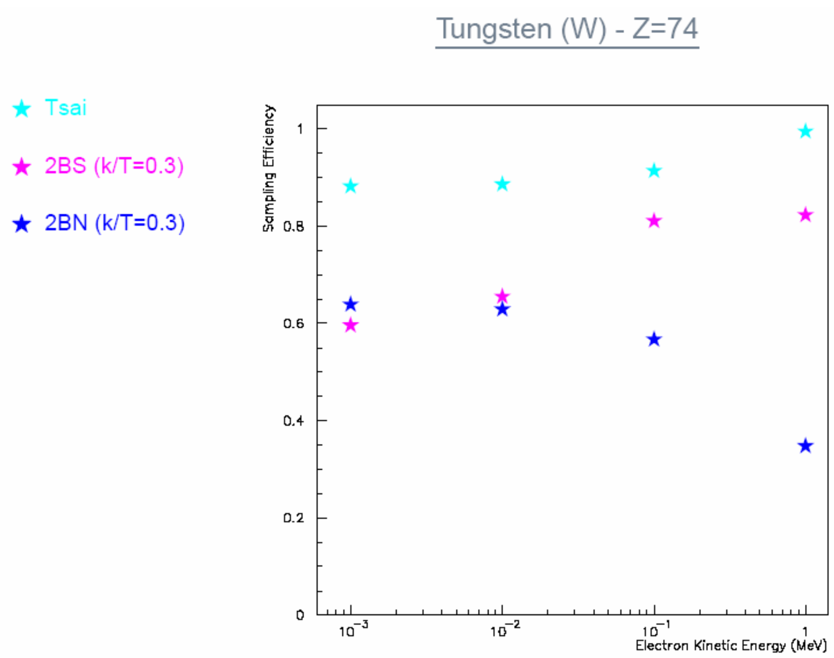
Three LowE generators available in GEANT4 6.0 release :

G4ModifiedTsai, G4Generator2BS and G4Generator2BN

G4Generator2BN allows a correct treatment **at low energies** (< 500 keV)



T=10 keV (k/T=0.5)

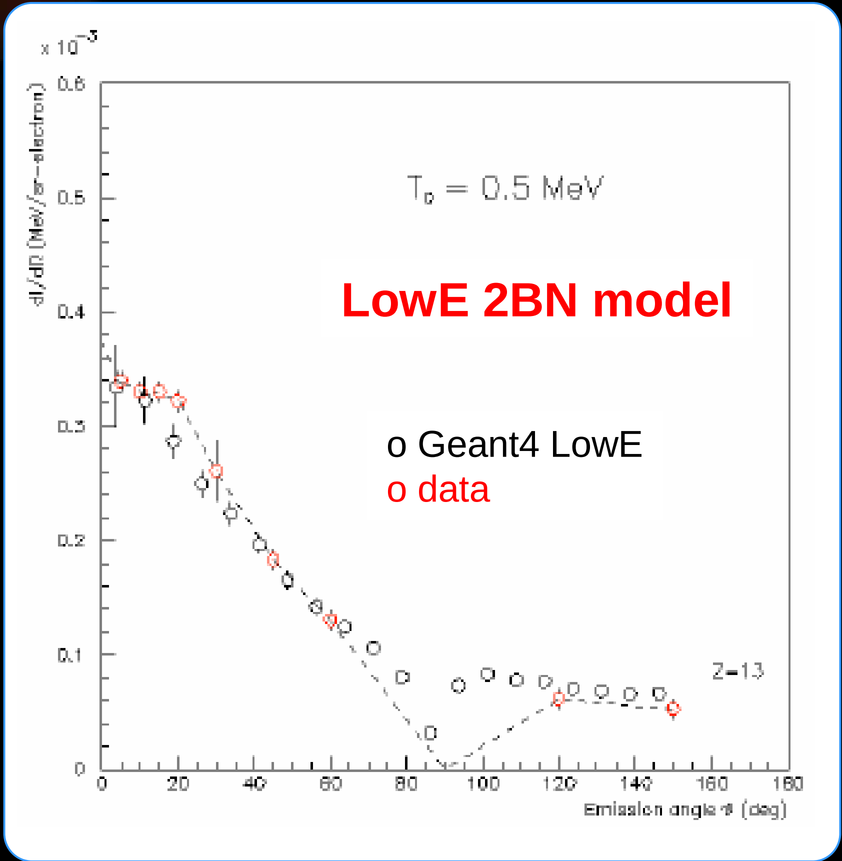


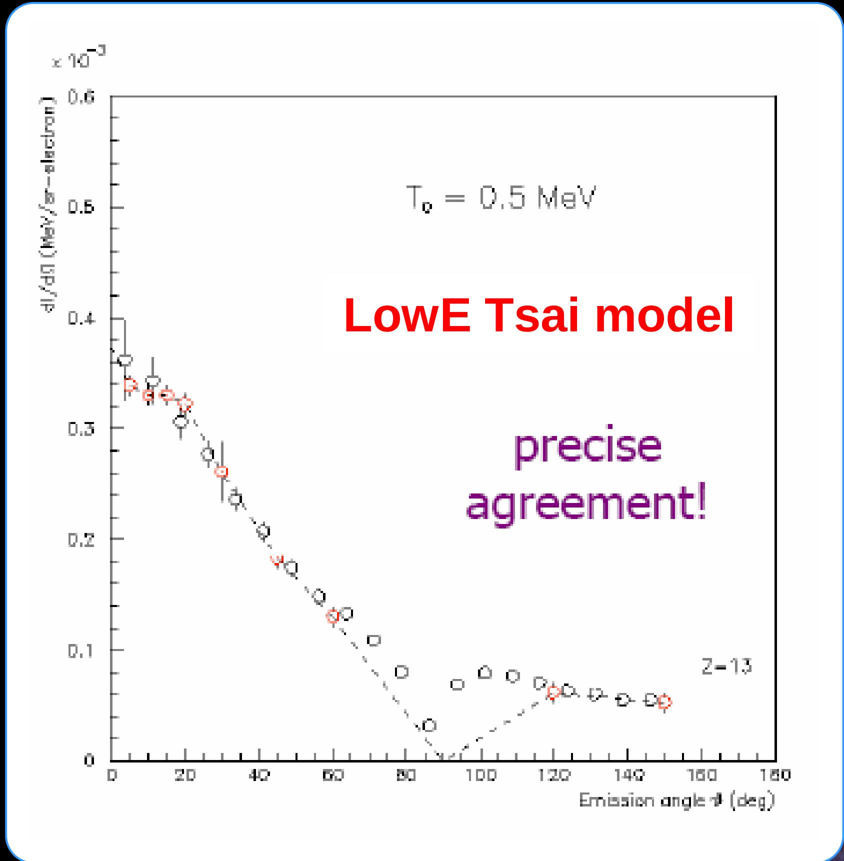
Sampling efficiency = ration between generated events and total number of trials

Bremsstrahlung Angular Distributions

Angular distribution is **strongly model dependent**

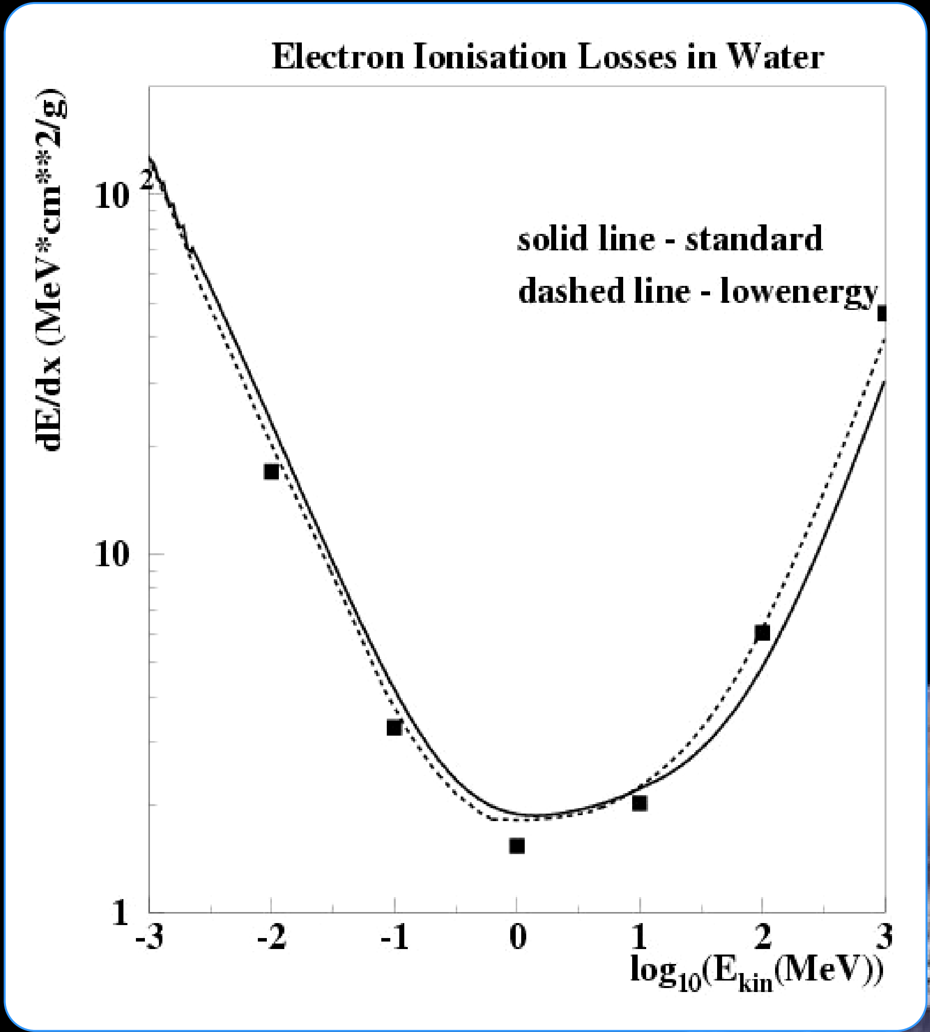
Exemple of validation : 500 keV electrons on Al and Fe, W.E. Dance et al., Journal of Applied Physics 39 (1968), 2881





Electron ionisation

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



Electrons: range

- Range in various simple and composite materials
- Compared to NIST database
- All simulation results lie within ± 3σ w.r.t. the corresponding NIST data

Comparison against NIST data

electrons in Uranium

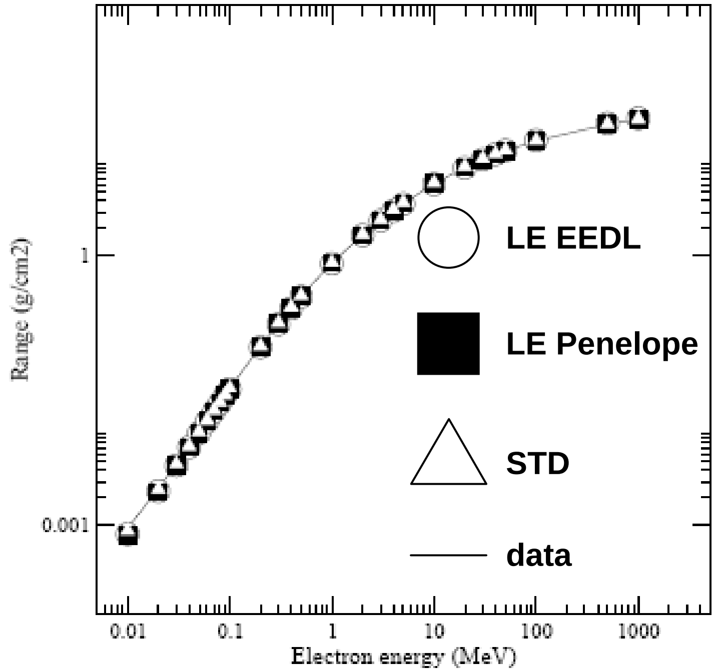
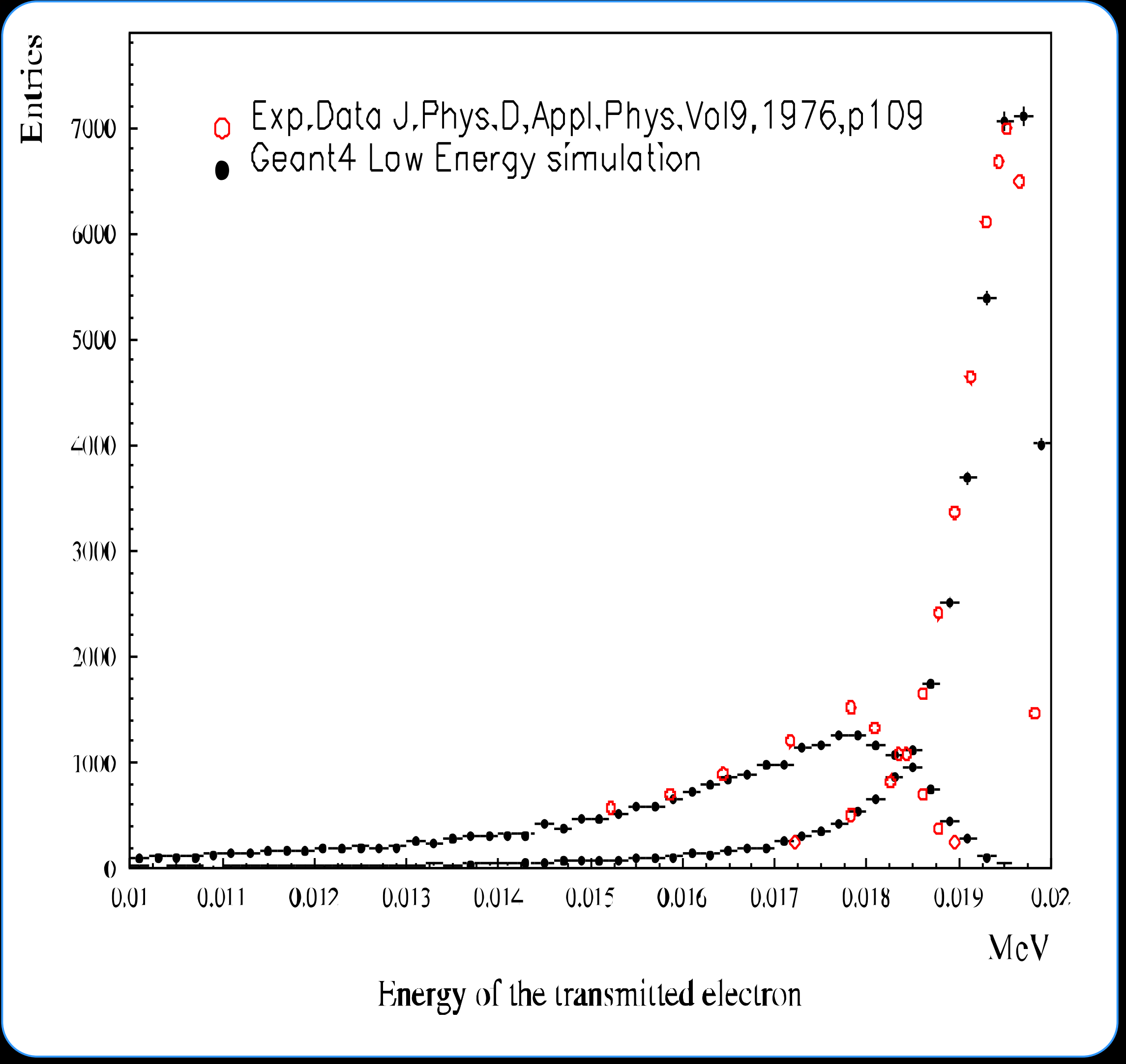


Fig. 7. Electron CSDA range in uranium as a function of the electron incident energy for the three sets of Geant4 models under test together with the NIST-ESTAR reference data for the three sets of Geant4 models under test (circles: Low Energy EEDL; squares: Low Energy Penelope; triangles: Standard); the continuous line interpolates NIST-ESTAR reference data.

The stopping power can be used to calculate the distance it takes to slow an electron down to a given energy. This distance is called the **continuous slowing down approximation range**, or **CSDA range**, because the calculation assumes that the electron slows down continuously from the initial energy *E* to the final energy.

Electrons, transmitted

20 keV electrons through 0.32 and 1.04 μm Al



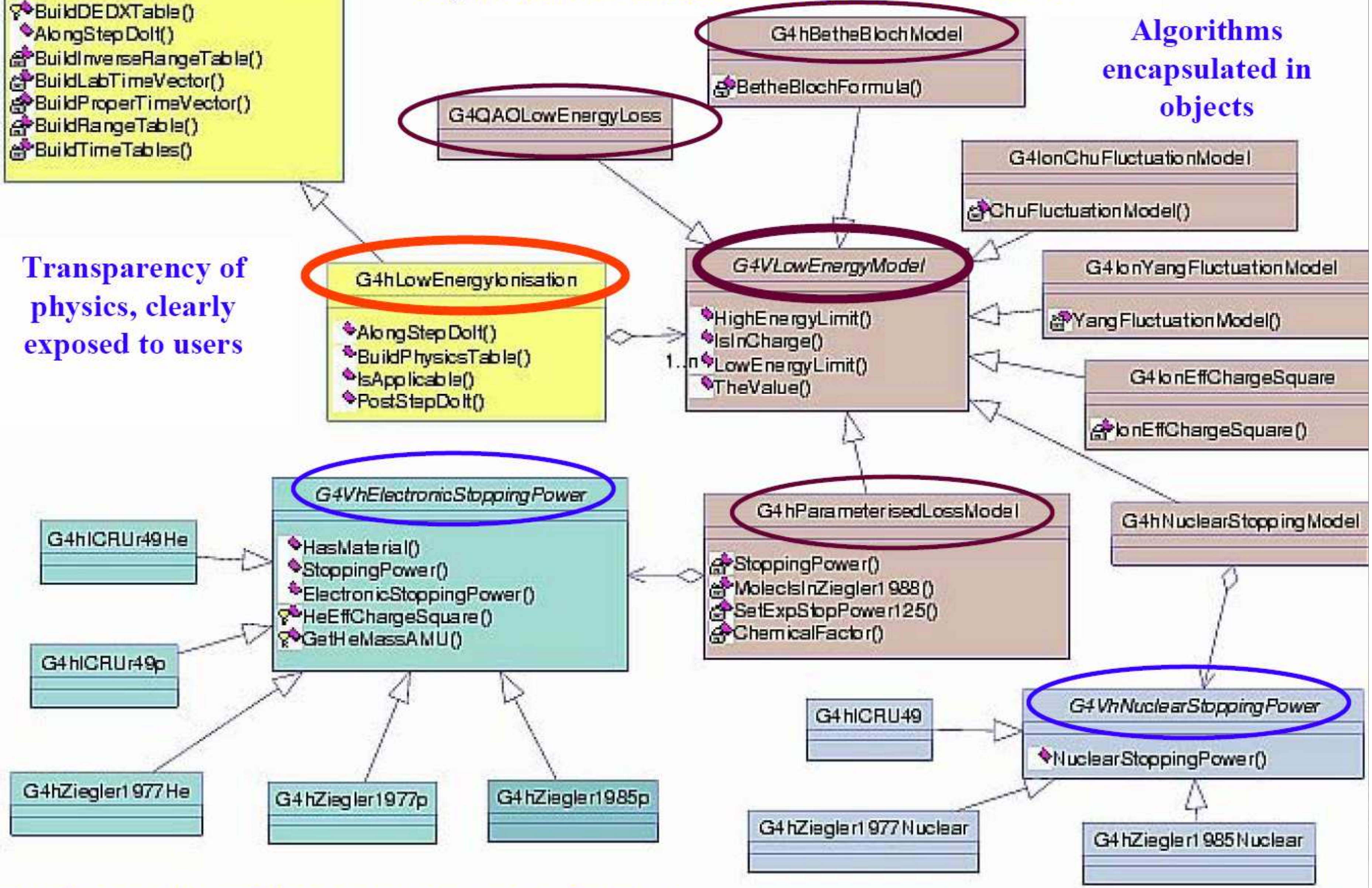
Hadrons

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

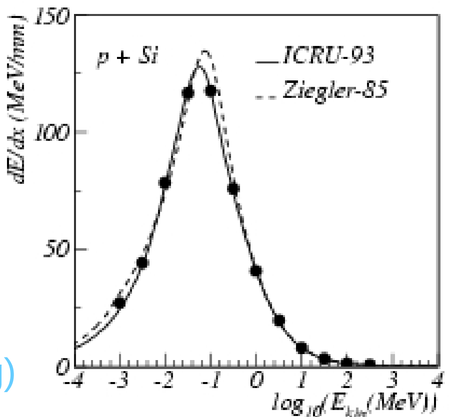
Hadrons and ions

- **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 + parameterizations
- Specialized models for fluctuations (stochastic straggling)
- Open to extension and evolution

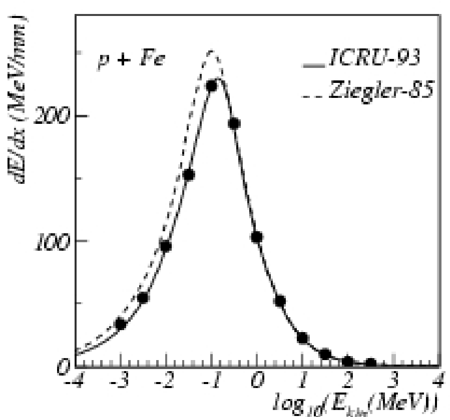
Positively charged hadrons : protons

- Bethe-Bloch model of energy loss, E > 2 MeV
- 5 parameterization models, E < 2 MeV based on Ziegler and ICRU reviews
- Free electron gas model below 1 keV

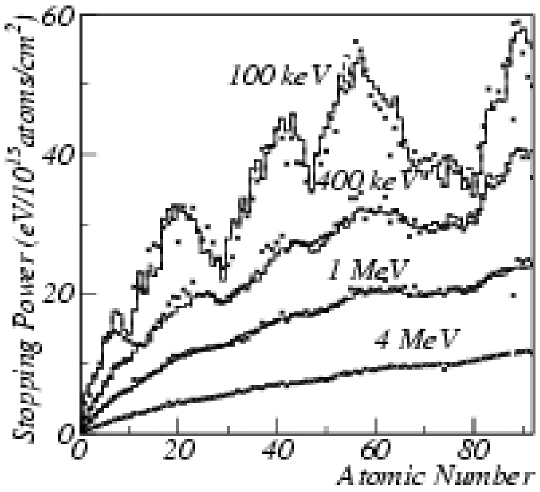
- 3 models of energy loss fluctuations
- Density correction for high energy
- Shell correction term for intermediate energy
- Chemical effect for compounds
- Nuclear stopping power (elastic Coulomb scattering)
- PIXE included
- Spin dependent term
- Barkas (+ vs -) and Bloch terms



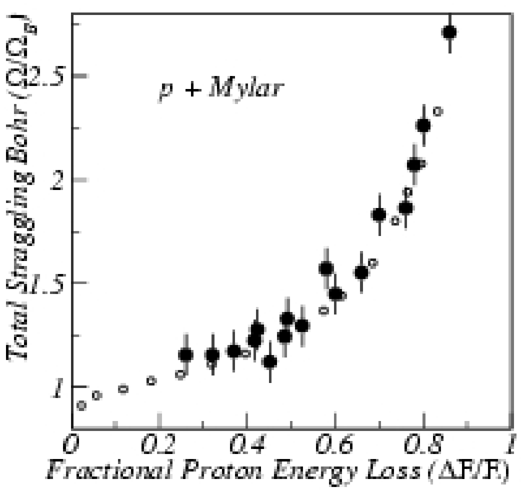
Ziegler and ICRU, Si



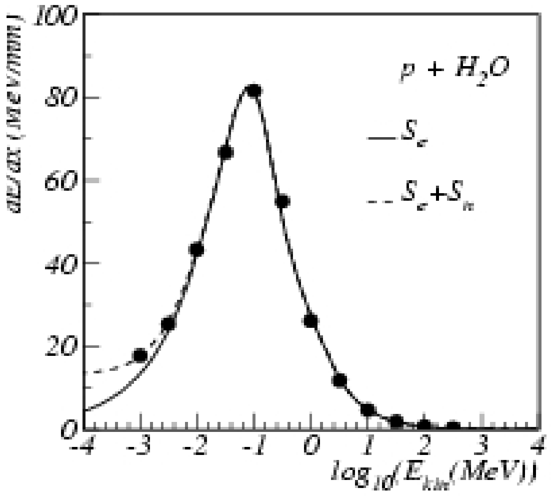
Ziegler and ICRU, Fe



Stopping power
Z dependence for various energies
Ziegler and ICRU models



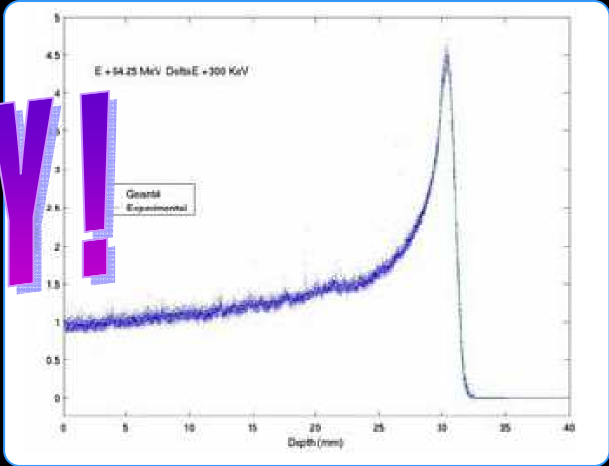
Straggling



Nuclear stopping power

Bragg peak simulation

PRELIMINARY !



see CHEP2007 in September

p value	Standard LElastic Precompound	LowE ICRU49 LElastic Precompound GEM	LowE ICRU49 LElastic Bertini Inelastic	LowE ICRU49 LElastic Precompound Fermi Break-up	LowE ICRU49 LElastic Precompound	LowE ICRU49 HadronElastic Precompound	LowE ICRU49 Bertini Elastic Bertini Inelastic
Left branch (CvM)	0.648	0.667	0.790	0.814	0.836	0.973	**0.977**
Right branch (KS)	0.760	0.985	0.985	0.985	0.985	0.985	**0.985**
Whole curve (AD)	0.666	0.858	0.936	0.945	0.946	0.982	**0.994**

Key ingredients

- precise **electromagnetic** physics
- good **elastic scattering** model
- good **pre-equilibrium** model

Positively charged hadrons (Z>1)

- **Scaling of Bethe-Bloch** : $S_{ion}(T) = Z_{ion}^2 S_p(T_p),\ T_p = T\frac{m_p}{m_{ion}}$
- $0.01 < \beta < 0.05$: **parameterizations**, Bragg p., based on Ziegler and ICRU reviews
- $\beta < 0.01$: **Free Electron Gas Model**
- Effective charge model (picks up e- in the medium)
- Nuclear stopping power (elastic Coulomb scattering with nuclei)

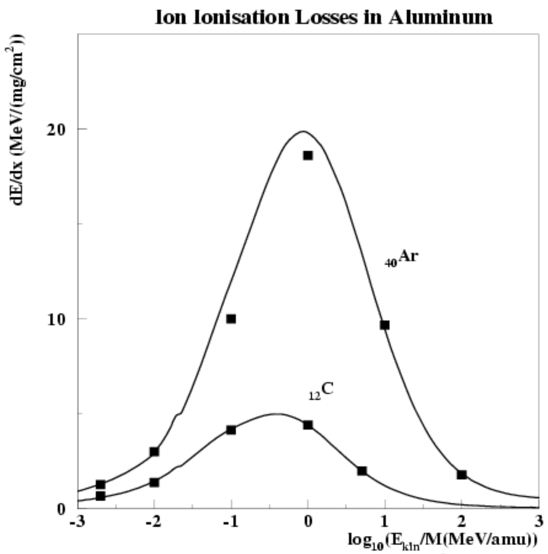
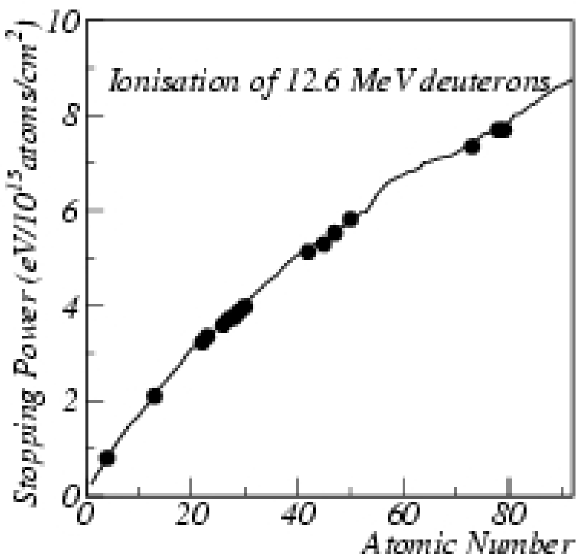
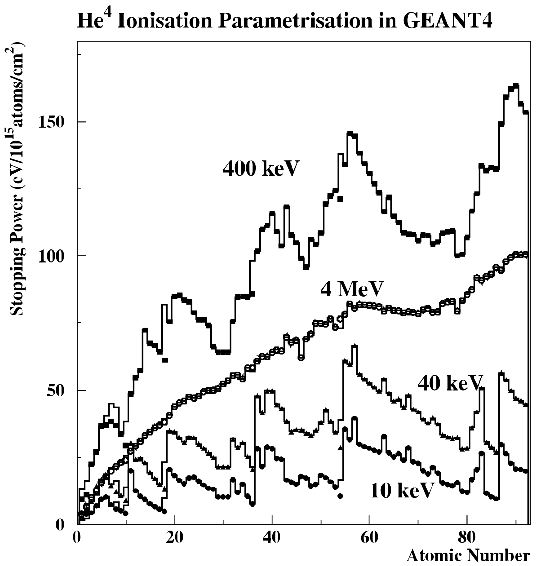


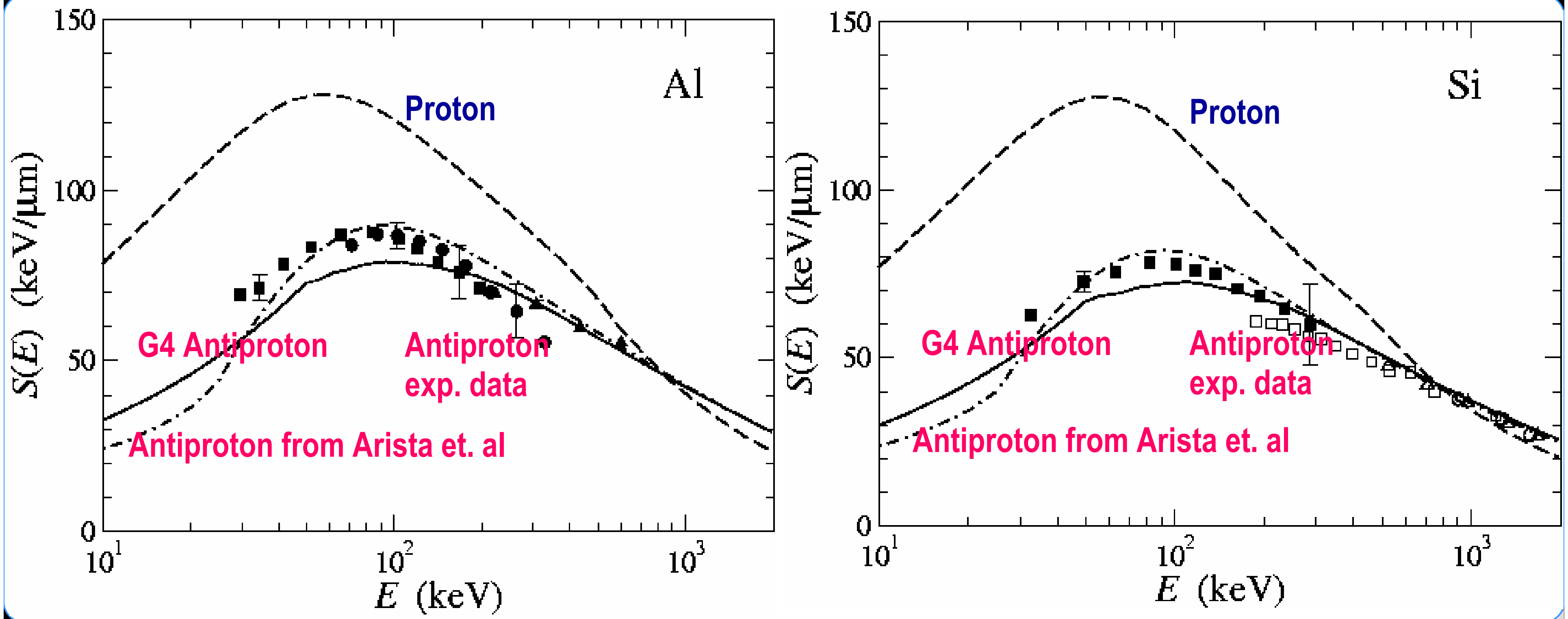
Figure 9: Ion electronic stopping power in aluminum. Points - the best fit on the data from Ref.[12], solid line - GEANT4 parameterisation. The accuracy of the data is about 5 %.





Models for antiprotons

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



Atomic relaxation

Atomic relaxation

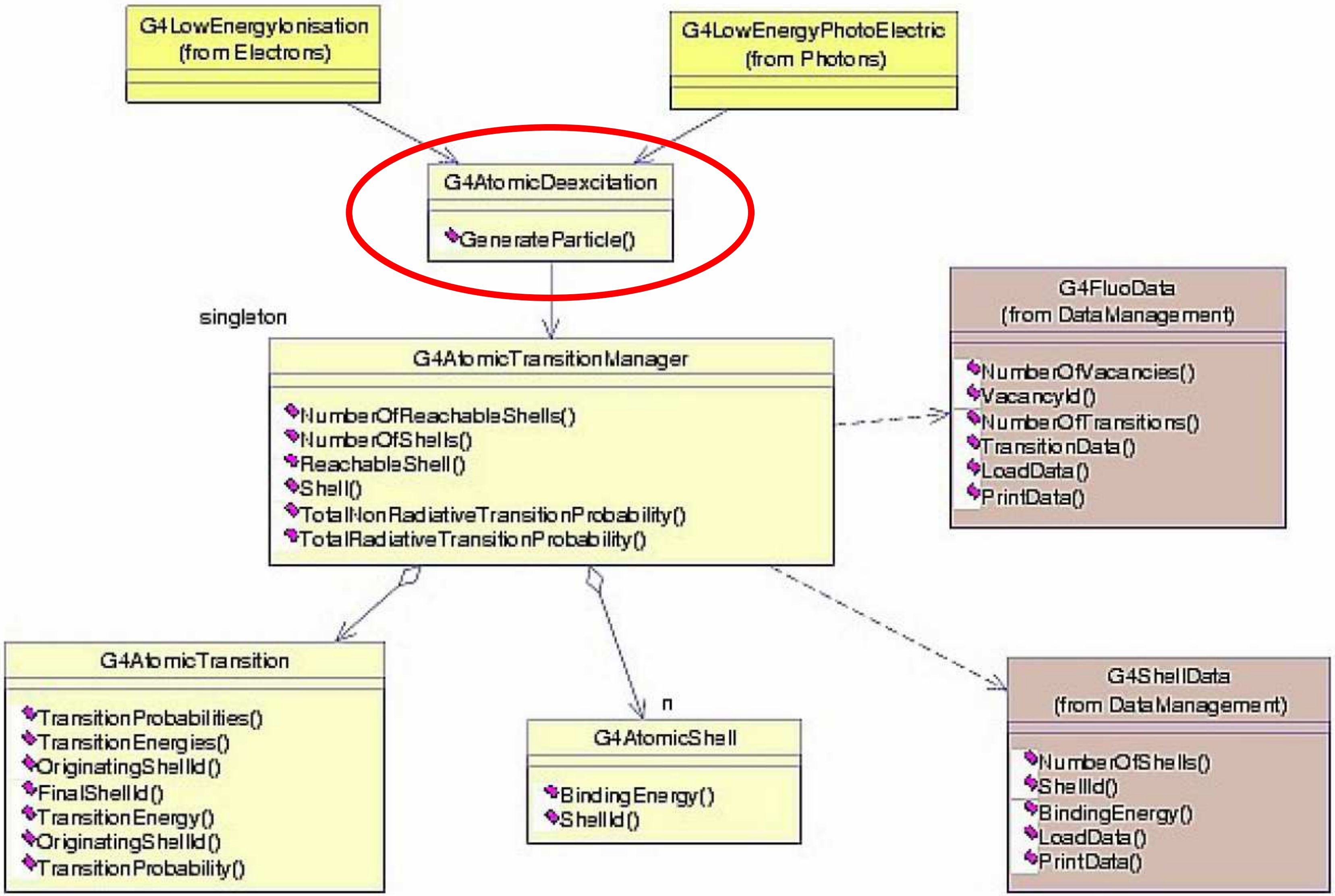
- The atomic relaxation can be triggered by other electromagnetic interactions such as the **photoelectric effect** or **ionisation**, which leave the atom in an **excited state**.

- The Livermore **Evaluation Atomic Data Library EADL** contains data to describe the relaxation of atoms back to neutrality after they are ionised.

- The data in EADL includes the radiative and non-radiative transition probabilities for each sub-shell of each element, for Z=1 to 100. The atom has been ionised by a process that has caused an electron to be ejected from an atom, leaving a vacancy or ``hole'' in a given subshell. The EADL data are then used to calculate the **complete radiative and non-radiative spectrum of X-rays and electrons emitted** as the atom relaxes back to neutrality.

  Non-radiative de-excitation can occur via the **Auger effect** (the initial and secondary vacancies are in different shells) or **Coster-Kronig effect** (transitions within the same shell).

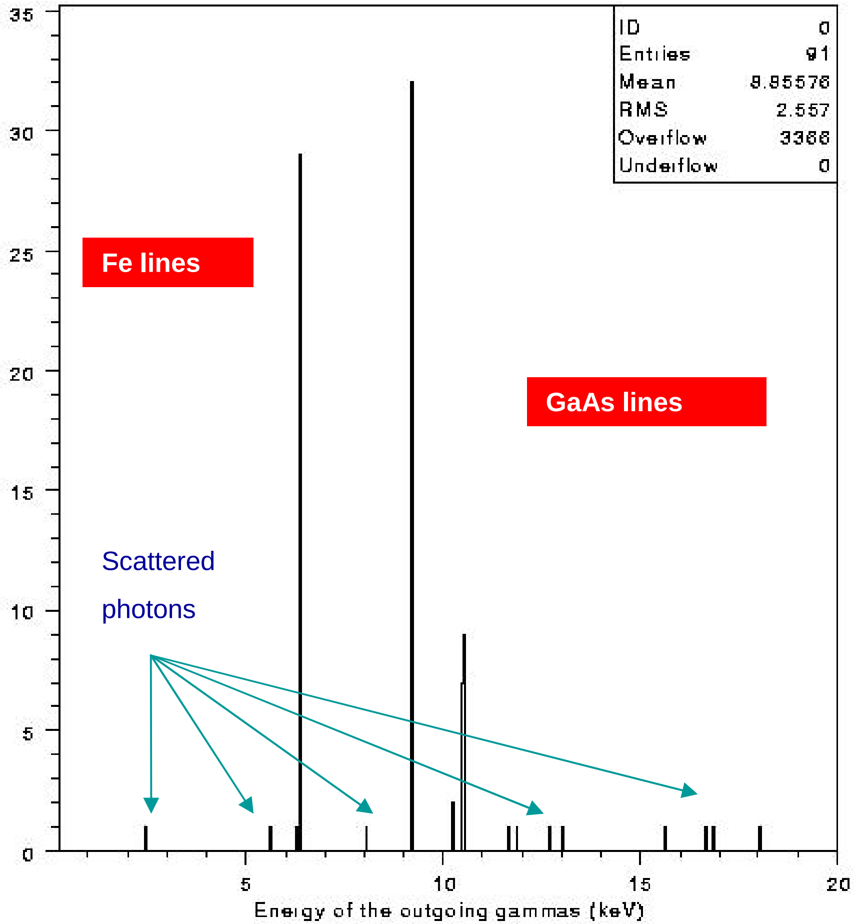
Atomic relaxation

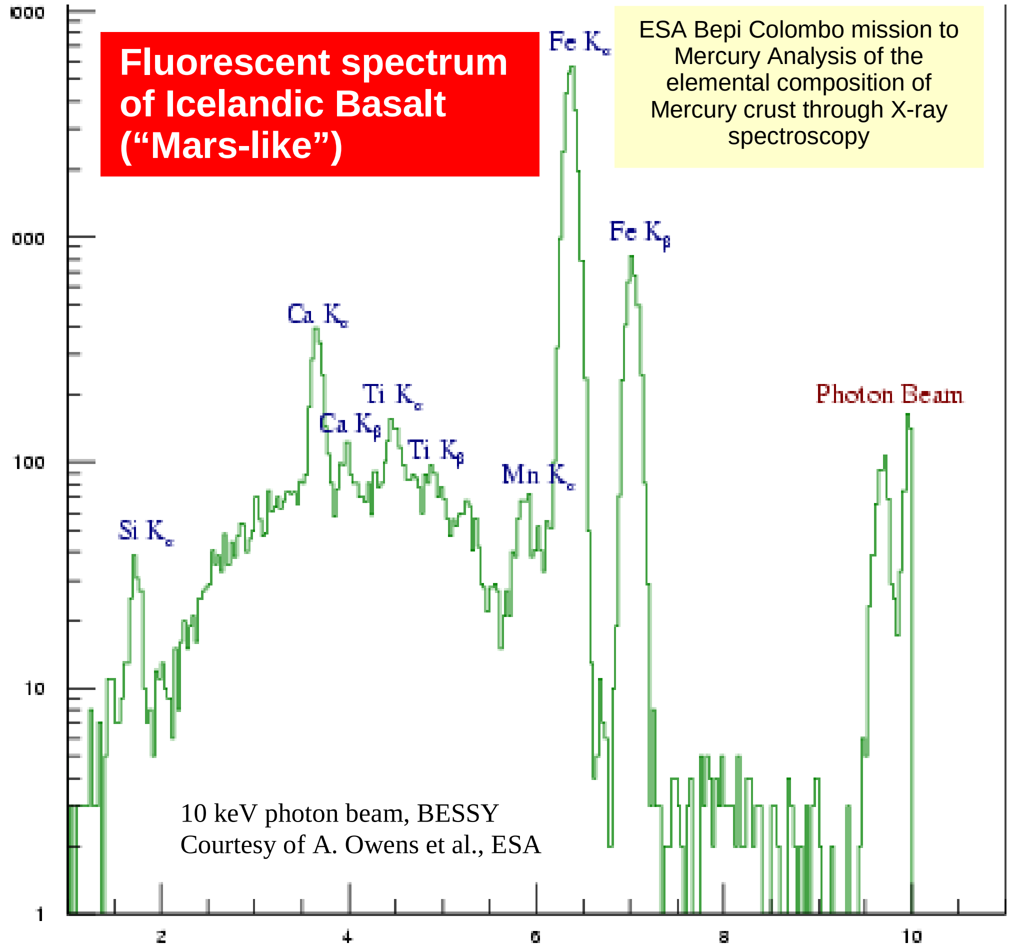


Fluorescence

Microscopic validation: against reference data

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

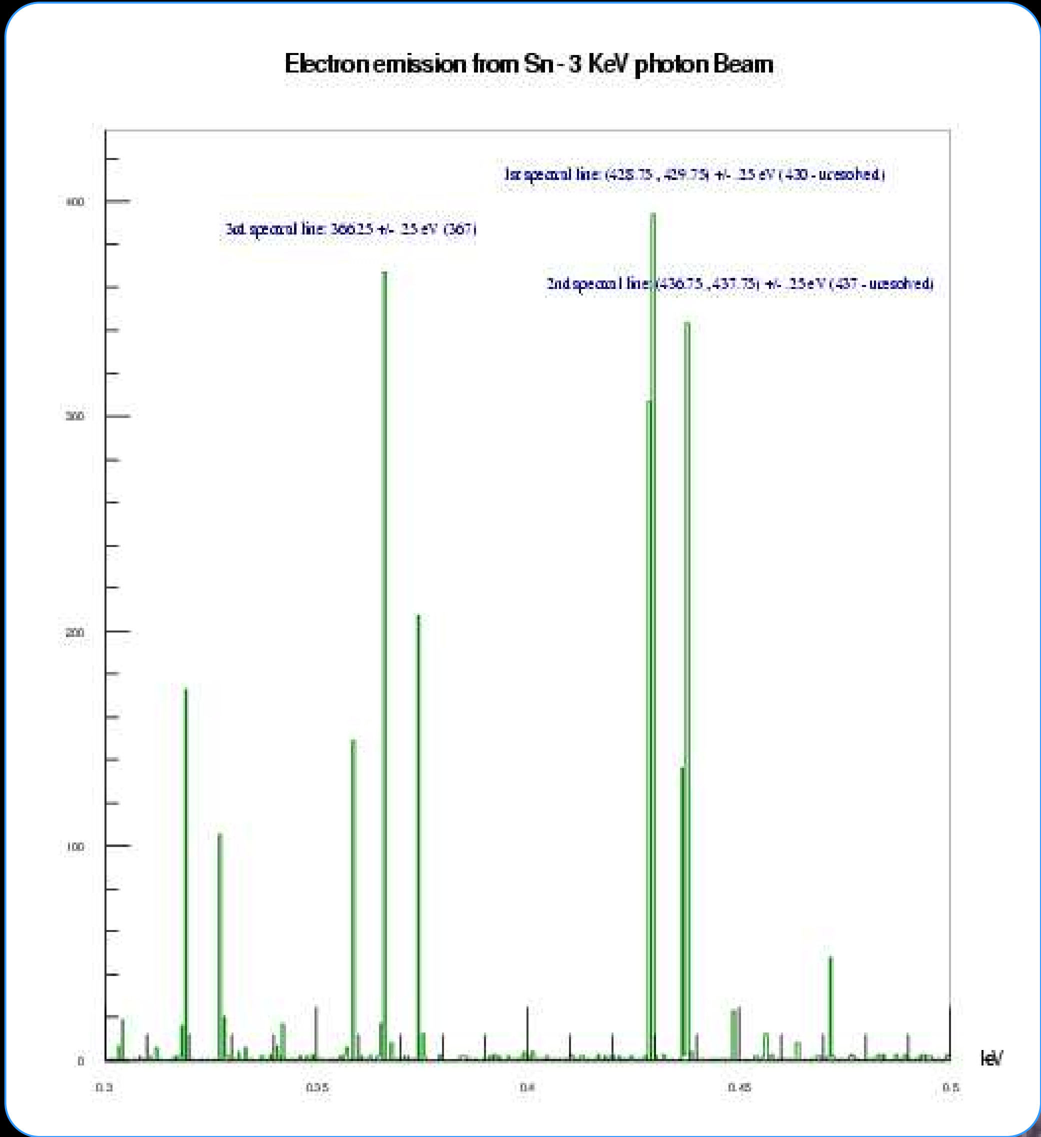




S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data
IEEE Transactions on Nuclear Science, Volume: 54, Issue: 3, Jun. 2007, *in press*

Auger effect

Auger electron emission
from various materials



Sn, 3 keV photon beam
electron lines w.r.t.
published experimental results

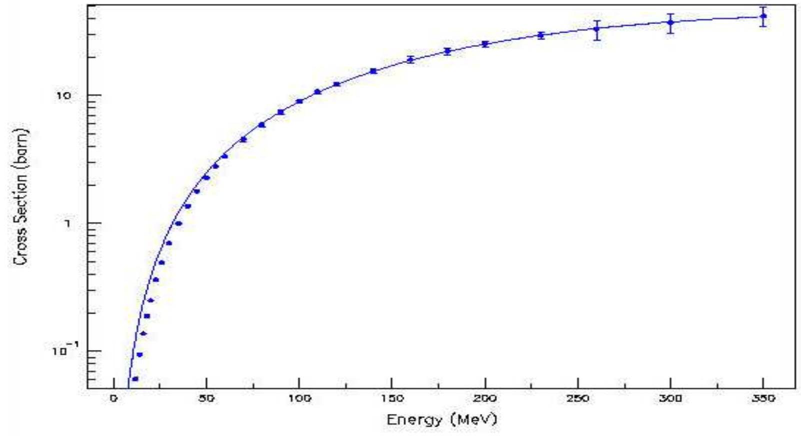
S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data
IEEE Transactions on Nuclear Science, Volume: 54, Issue: 3, Jun. 2007, *in press*

PIXE
(Particle Induced X-ray Emission)

- New model based on experimental data
  - Parameterisation of Paul & Sacher data library for **ionization cross sections**
  - Uses the EADL-based package of atomic de-excitation for the generation of **fluorescence and Auger secondary products**
- Current implementation: protons, K-shell
- Coming in future: protons, L-shell and α, K-shell

Example of p ionisation cross section, K shell

Geant4 parameterisation (solid line)
Experimental data



Penelope Physics alternative

Processes à la Penelope

- The **whole** Physics content of the **Penelope Monte Carlo code** has been re-engineered into Geant4 (except multiple scattering)
  - photons : release 5.2
  - electrons : 6.0

- Physics models by F. Salvat *et al.*

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

- Profit of Geant4 advanced geometry modelling, interactive capabilities, etc…
  - **same physics** as original Penelope

Processes à la Penelope

- Compton scattering
- Rayleigh scattering
- Gamma conversion
- Photoelectric effect

- Bremsstrahlung
- Ionisation

- Positron Annihilation

In your
Physics List

G4PenelopeAnnihilation
G4PenelopeBremsstrahlung
G4PenelopeCompton
G4PenelopeGammaConversion
G4PenelopeIonisation
G4PenelopePhotoElectric
G4PenelopeRayleigh

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
- Analytical 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

Advanced examples

Advanced examples

Stéphane Chauvie
Pablo Cirrone
GiacomoCuttone
Francesco Di Rosa
Alex Howard
Sébastien Incerti
Mikhail Kossov
Anton Lechner
Francesco Longo
Alfonso Mantero
Luciano Pandola
MG Pia
Michela Piergentili
Alberto Ribon
Giorgio Russo
Giovanni Santin
Bernardo Tomé
Jakub Moscicki
Andreas Pfeiffer
Witold Pokorski

Mission

- Investigate, evaluate and demonstrate Geant4 **capabilities in various experimental environments**
- Provide **guidance** to Geant4 users in realistic experimental applications
- Provide **feedback** to Geant4 developers about successful results, problems etc.
- Identify **requirements** for further Geant4 improvements and extensions to address new experimental domains

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

Advanced examples

1. air_shower
2. **brachytherapy**
3. ***cell_irradiation***
4. composite_calorimeter
5. cosmicray_charging
6. gammaray_telescope
7. **hadrontherapy**
8. **human_phantom**
9. lAr_calorimeter
10. **medical_linac**
11. **microbeam**
12. *nanotechnology*
13. **purging_magnet**
14. *radiation_monitor*
15. **radioprotection**
16. raredecay_calorimetry
17. RICH
18. Tiara
19. underground_physics
20. xray_fluorescence
21. xray_telescope

- in $G4INSTALL/examples/advanced

- Wide experimental coverage
  - HEP
  - Space science / astrophysics
  - Medical physics
  - Radiobiology
  - Detector technologies

- Wide Geant4 coverage
  - geometry features
  - magnetic field
  - Physics (EM and hadronic)
  - Biological processes
  - Hits & digis
  - Analysis
  - Visualization, UI

- Status

Released

In preparation

Published

How to use the package ?

How to use the package ?

Photon processes

- Compton scattering (class ***G4LowEnergyCompton***)
- Polarized Compton scattering (class ***G4LowEnergyPolarizedCompton***)
- Rayleigh scattering (class ***G4LowEnergyRayleigh***)
- Gamma conversion (also called pair production, class ***G4LowEnergyGammaConversion***)
- Photo-electric effect (class ***G4LowEnergyPhotoElectric***)

Electron processes

- Bremsstrahlung (class ***G4LowEnergyBremsstrahlung***)
- Ionisation and delta ray production (class ***G4LowEnergyIonisation***)

Hadron and ion processes

- Ionisation and delta ray production (class ***G4hLowEnergyIonisation***)

Refer to Geant4 User's guide !

►The user should **set the environment variable G4LEDATA** to the directory where he/she has copied the files.

► **Options** are available for low energy electromagnetic processes for hadrons and ions in terms of public member functions of the **G4hLowEnergyIonisation** class:
- SetHighEnergyForProtonParametrisation(G4double)
- SetLowEnergyForProtonParametrisation(G4double)
- SetHighEnergyForAntiProtonParametrisation(G4double)
- SetLowEnergyForAntiProtonParametrisation(G4double)
- SetElectronicStoppingPowerModel(const G4ParticleDefinition*,const G4String&)
- SetNuclearStoppingPowerModel(const G4String&)
- SetNuclearStoppingOn()
- SetNuclearStoppingOff()
- SetBarkasOn()
- SetBarkasOff()
- SetFluorescence(const G4bool)
- ActivateAugerElectronProduction(G4bool)
- SetCutForSecondaryPhotons(G4double)
- SetCutForSecondaryElectrons(G4double)

The available models for ElectronicStoppingPower and NuclearStoppingPower are documented in the class diagrams.

► **Options** are available for low energy electromagnetic processes for electrons in the **G4LowEnergyIonisation** class:
- ActivateAuger(G4bool)
- SetCutForLowEnSecPhotons(G4double)
- SetCutForLowEnSecElectrons(G4double)

► **Options** are available for low energy electromagnetic processes for electrons/positrons in the **G4LowEnergyBremsstrahlung class**, that allow the use of alternative bremsstrahlung angular generators:
- SetAngularGenerator(G4VBremAngularDistribution* distribution);
- SetAngularGenerator(const G4String& name);

Currently three angular generators are available: G4ModifiedTsai, 2BNGenerator and 2BSGenerator. G4ModifiedTsai is set by default, but it can be forced using the string "tsai". 2BNGenerator and 2BSGenerator can be set using the strings "2bs" and "2bn". Information regarding conditions of use, performance and energy limits of different models are available in the Physics Reference Manual and in the Geant4 Low Energy Electromagnetic Physics Working Group homepage.

► Other **options G4LowEnergyBremsstrahlung** class are:
- SetCutForLowEnSecPhotons(G4double)

Example of low energy processes registration in PhysicsList.cc

photons

electrons

hadrons

```
if (particleName == "gamma") {

    pmanager->AddDiscreteProcess(new G4LowEnergyCompton);

    G4LowEnergyPhotoElectric * LePeprocess = new G4LowEnergyPhotoElectric();
    LePeprocess->ActivateAuger(true);
    LePeprocess->SetCutForLowEnSecPhotons(0.250 * keV);
    LePeprocess->SetCutForLowEnSecElectrons(0.250 * keV);
    pmanager->AddDiscreteProcess(LePeprocess);

    pmanager->AddDiscreteProcess(new G4LowEnergyGammaConversion());
    pmanager->AddDiscreteProcess(new G4LowEnergyRayleigh());
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);


  } else if (particleName == "e-") {

    pmanager->AddProcess(new G4MultipleScattering,-1, 1,1);

    G4LowEnergyIonisation * LeIoprocess = new G4LowEnergyIonisation("IONI");
    LeIoprocess->ActivateAuger(true);
    LeIoprocess->SetCutForLowEnSecPhotons(0.1*keV);
    LeIoprocess->SetCutForLowEnSecElectrons(0.1*keV);
    pmanager->AddProcess(LeIoprocess, -1,  2, 2);

    G4LowEnergyBremsstrahlung * LeBrprocess = new G4LowEnergyBremsstrahlung();
    pmanager->AddProcess(LeBrprocess, -1, -1, 3);
    pmanager->AddProcess(new G4StepLimiter(), -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);
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);

  } else if( particleName == "mu+" ||
           particleName == "mu-"    ) {

  } else if ((!particle->IsShortLived()) &&
                              (particle->GetPDGCharge() != 0.0) &&
                              (particle->GetParticleName() != "chargedgeantino")) {

    pmanager->AddProcess(new G4MultipleScattering(),-1,1,1);

    G4hLowEnergyIonisation* hLowEnergyIonisation = new G4hLowEnergyIonisation();
    pmanager->AddProcess(hLowEnergyIonisation,-1,2,2);

    hLowEnergyIonisation->SetElectronicStoppingPowerModel(particle,"ICRU_R49He");
    hLowEnergyIonisation->SetNuclearStoppingOn();
    hLowEnergyIonisation->SetNuclearStoppingPowerModel("ICRU_R49");
    hLowEnergyIonisation->SetFluorescence(true);
    hLowEnergyIonisation->ActivateAugerElectronProduction(true);

    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);    }
```

Refer to Geant4 user's guide and advanced examples !

In progress

- Extensions down to the **eV scale :**
  The Geant4 DNA project
  – in water (for radiobiology studies)
  – in semiconductor materials (for radiation damage to components)

- Difficult domain
  – models must be specialized by material
  – cross sections, final state generation, angular distributions

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

Where to find more information ?

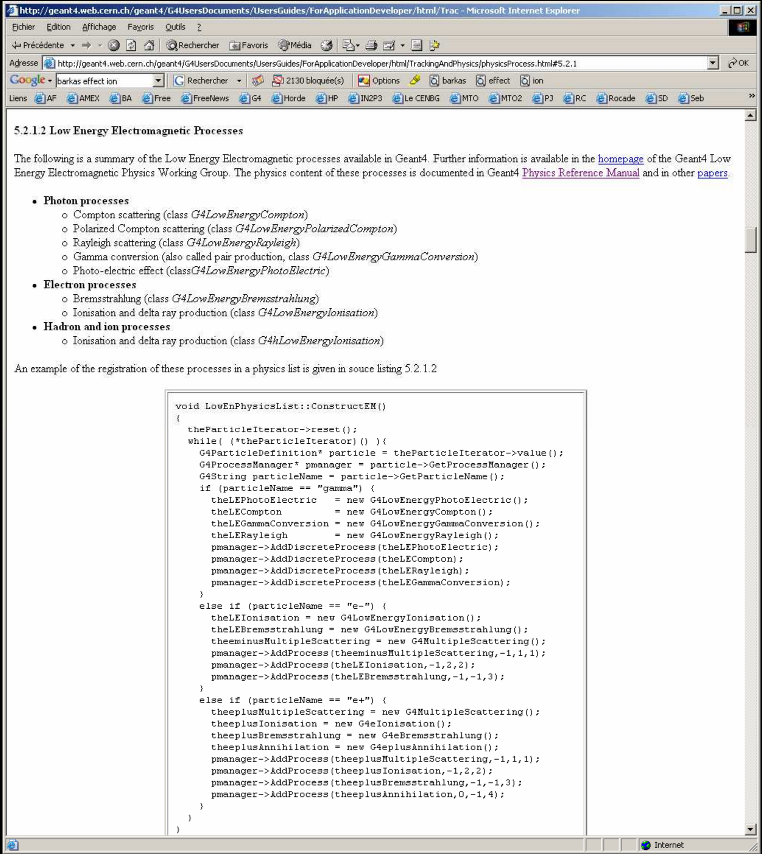
http://www.ge.infn.it/geant4/lowE

http://cern.ch/geant4

User guides

User's Guide : For Application Developers

Physics Reference Manual



http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/ForApplicationDeveloper/html/TrackingAndPhysics/physicsProcess.html#5.2.1

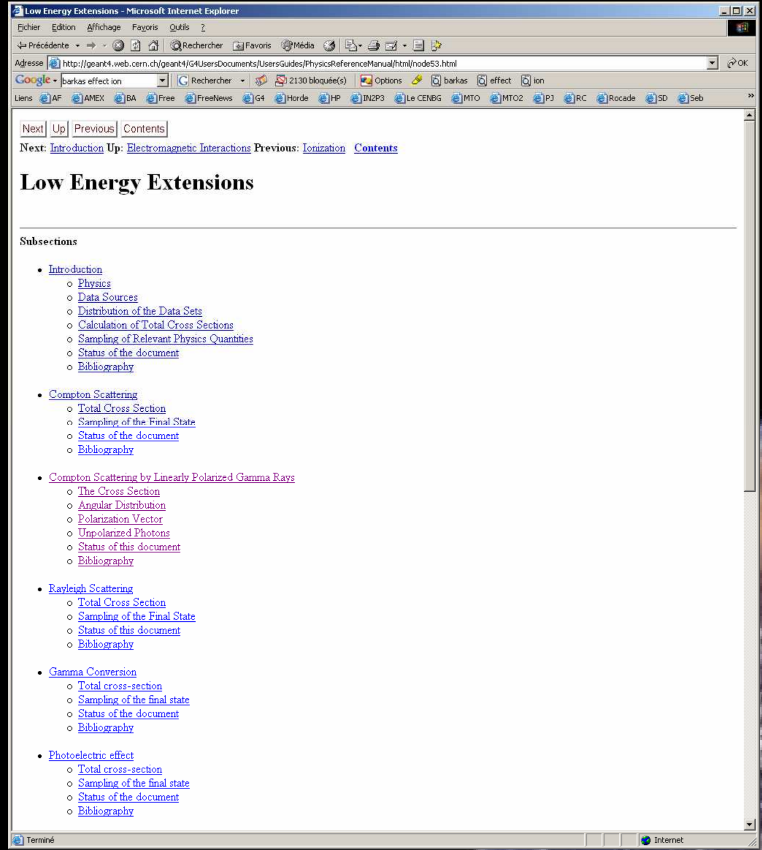
5.2.1.2 Low Energy Electromagnetic Processes

The following is a summary of the Low Energy Electromagnetic processes available in Geant4. Further information is available in the homepage of the Geant4 Low Energy Electromagnetic Physics Working Group. The physics content of these processes is documented in Geant4 Physics Reference Manual and in other papers.

- **Photon processes**
  - Compton scattering (class *G4LowEnergyCompton*)
  - Polarized Compton scattering (class *G4LowEnergyPolarizedCompton*)
  - Rayleigh scattering (class *G4LowEnergyRayleigh*)
  - Gamma conversion (also called pair production, class *G4LowEnergyGammaConversion*)
  - Photo-electric effect (class*G4LowEnergyPhotoElectric*)
- **Electron processes**
  - Bremsstrahlung (class *G4LowEnergyBremsstrahlung*)
  - Ionisation and delta ray production (class *G4LowEnergyIonisation*)
- **Hadron and ion processes**
  - Ionisation and delta ray production (class *G4hLowEnergyIonisation*)

An example of the registration of these processes in a physics list is given in souce listing 5.2.1.2

```
void LowEnPhysicsList::ConstructEM()
{
  theParticleIterator->reset();
  while( (*theParticleIterator)() ){
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    G4String particleName = particle->GetParticleName();
    if (particleName == "gamma") {
      theLEPhotoElectric   = new G4LowEnergyPhotoElectric();
      theLECompton         = new G4LowEnergyCompton();
      theLEGammaConversion = new G4LowEnergyGammaConversion();
      theLERayleigh        = new G4LowEnergyRayleigh();
      pmanager->AddDiscreteProcess(theLEPhotoElectric);
      pmanager->AddDiscreteProcess(theLECompton);
      pmanager->AddDiscreteProcess(theLERayleigh);
      pmanager->AddDiscreteProcess(theLEGammaConversion);
    }
    else if (particleName == "e-") {
      theLEIonisation = new G4LowEnergyIonisation();
      theLEBremsstrahlung = new G4LowEnergyBremsstrahlung();
      theeminusMultipleScattering = new G4MultipleScattering();
      pmanager->AddProcess(theeminusMultipleScattering,-1,1,1);
      pmanager->AddProcess(theLEIonisation,-1,2,2);
      pmanager->AddProcess(theLEBremsstrahlung,-1,-1,3);
    }
    else if (particleName == "e+") {
      theeplusMultipleScattering = new G4MultipleScattering();
      theeplusIonisation = new G4eIonisation();
      theeplusBremsstrahlung = new G4eBremsstrahlung();
      theeplusAnnihilation = new G4eplusAnnihilation();
      pmanager->AddProcess(theeplusMultipleScattering,-1,1,1);
      pmanager->AddProcess(theeplusIonisation,-1,2,2);
      pmanager->AddProcess(theeplusBremsstrahlung,-1,-1,3);
      pmanager->AddProcess(theeplusAnnihilation,0,-1,4);
    }
  }
}
```



Low Energy Extensions - Microsoft Internet Explorer

http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/node53.html

Next Up Previous Contents

Next: Introduction **Up:** Electromagnetic Interactions **Previous:** Ionization **Contents**

Low Energy Extensions

Subsections

- Introduction
  - Physics
  - Data Sources
  - Distribution of the Data Sets
  - Calculation of Total Cross Sections
  - Sampling of Relevant Physics Quantities
  - Status of the document
  - Bibliography
- Compton Scattering
  - Total Cross Section
  - Sampling of the Final State
  - Status of the document
  - Bibliography
- Compton Scattering by Linearly Polarized Gamma Rays
  - The Cross Section
  - Angular Distribution
  - Polarization Vector
  - Unpolarized Photons
  - Status of this document
  - Bibliography
- Rayleigh Scattering
  - Total Cross Section
  - Sampling of the Final State
  - Status of this document
  - Bibliography
- Gamma Conversion
  - Total cross-section
  - Sampling of the final state
  - Status of the document
  - Bibliography
- Photoelectric effect
  - Total cross-section
  - Sampling of the final state
  - Status of the document
  - Bibliography

Validation of Geant4 physics models

PUBLISHED

- K. Amako, S. Guatelli, V. N. Ivanchenko, M. Maire, B. Mascialino, K. Murakami, P. Nieminen, L. Pandola, S. Parlati, M. G. Pia, M. Piergentili, T. Sasaki, L. Urban
  Comparison of Geant4 electromagnetic physics models against the NIST reference data
  IEEE Trans. Nucl. Sci., Vol. 52, Issue 4, Aug. 2005, 910-918

IN PRESS

- S. Chauvie, P. Nieminen, M. G. Pia
  Geant4 model for the stopping power of low energy negatively charged hadrons
  IEEE Transactions on Nuclear Science, *in press*

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia
Geant4 Atomic Relaxation
IEEE Transactions on Nuclear Science, Volume: 54, Issue: 3, Jun. 2007, *in press*

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data
IEEE Transactions on Nuclear Science, Volume: 54, Issue: 3, Jun. 2007, *in press*

IN PREPARATION

G. A. P. Cirrone *et al.*
Validation of Geant4 Physics models for the simulation of the proton Bragg peak
IEEE Trans. Nucl. Sci.

S. Chauvie, Z. Francis, S. Guatelli, S. Incerti, B. Mascialino, P. Moretto, P. Nieminen, and M. G. Pia
Geant4 low energy physics processes for microdosimetry simulation: design foundation and implementation of the first set of models for particle interactions with water
IEEE Trans. Nucl. Sci.

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 **specialized applications**

- Extensive validation activity and results

- More on Physics Reference Manual and web site

Maria.Grazia.Pia@cern.ch