GEANT4 A SIMULATION TOOLKIT

Version 11.3.2

Geant4 Tutorial Course

Jefferson Lab, Newport News, VA, USA
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Electromagnetic Physics I

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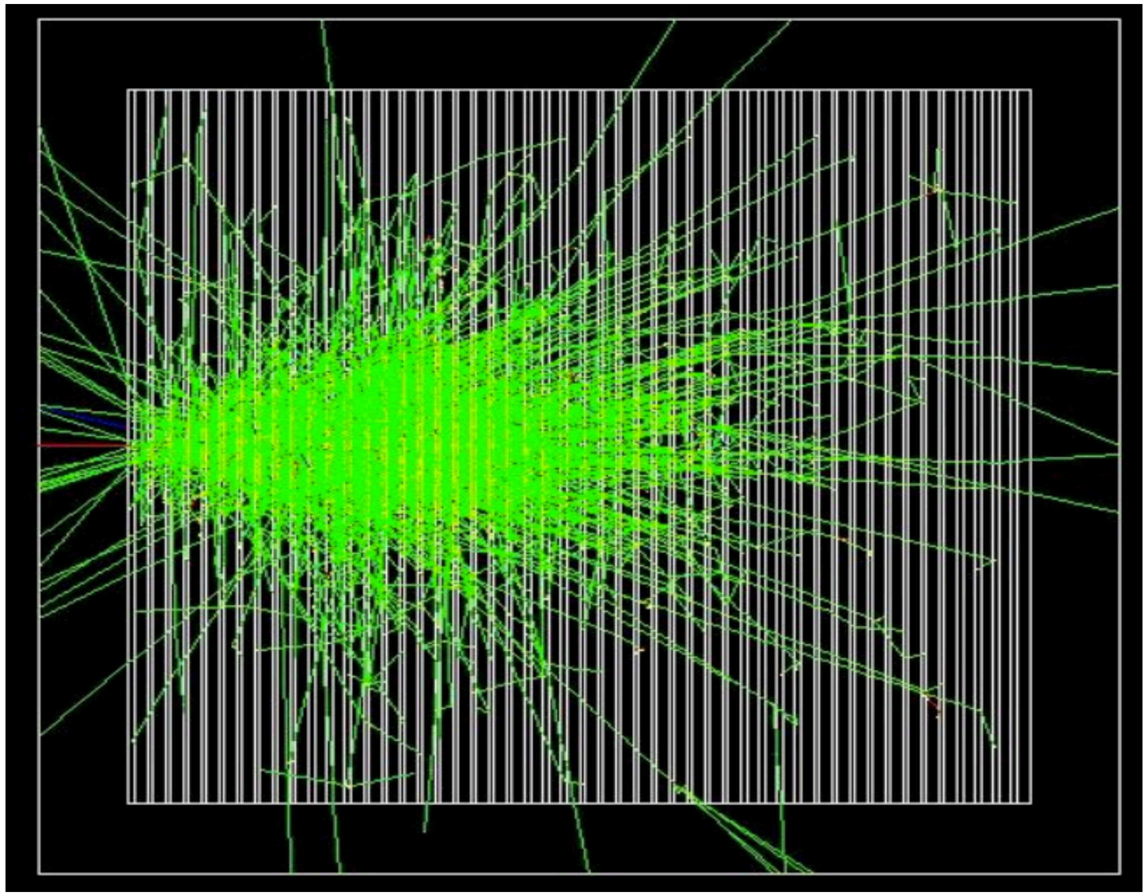
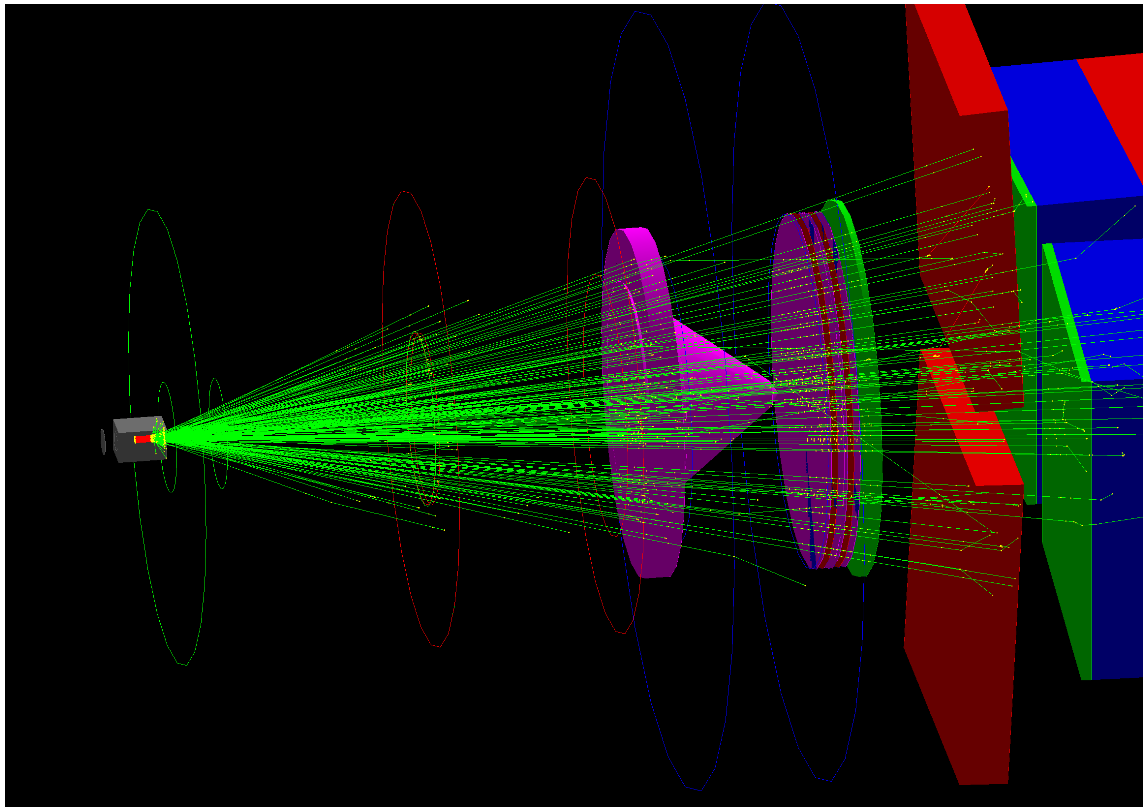
Introduction

HEP Calorimeter



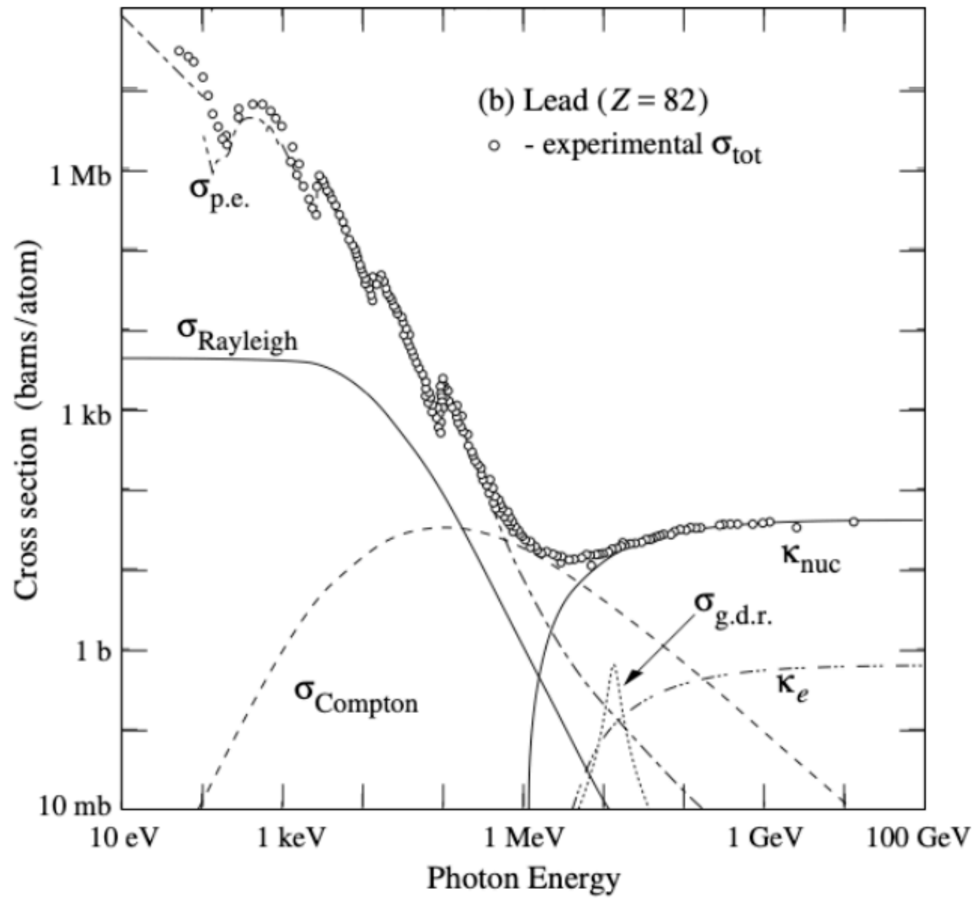
- Electromagnetic (EM) physics overview
- Gamma processes
- Charged particles processes
- Production Threshold
- EM Physics Constructors
- User Interfaces to EM physics



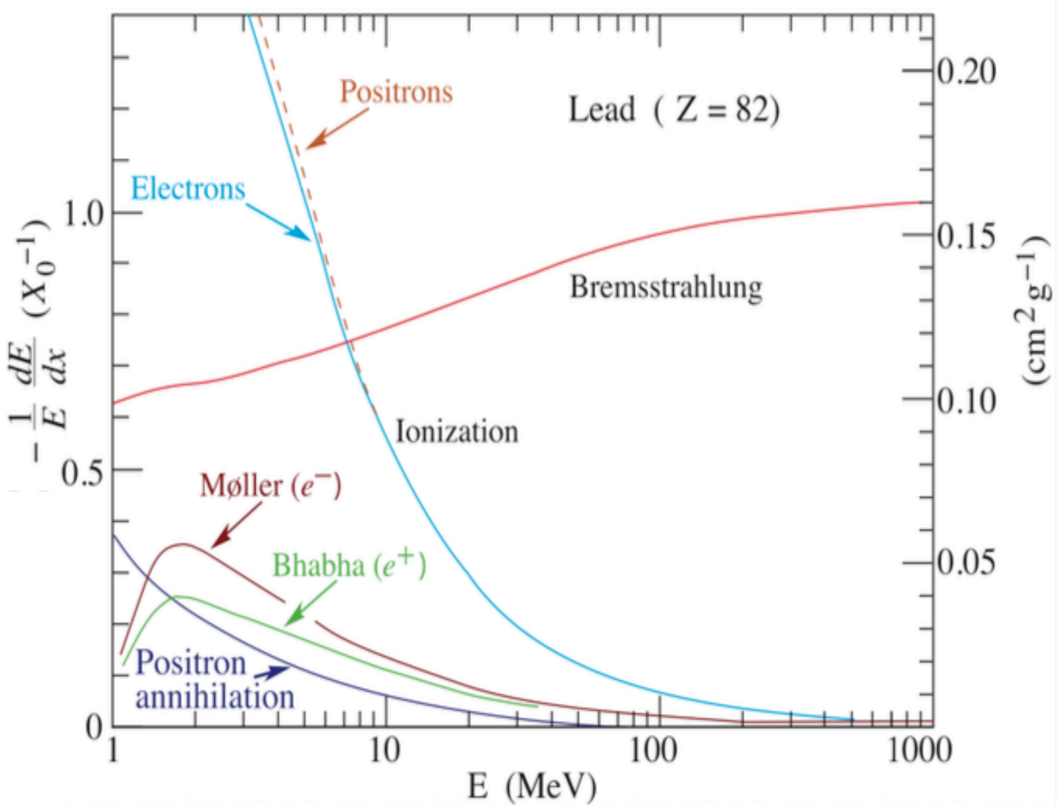
Medical Linac

EM Overview

- **Gamma processes**
  - γ conversion into e+e- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - ~~Gamma-nuclear interaction in hadronic library~~



- **Charged particles processes**
  - Ionization
  - Coulomb scattering
  - Bremsstrahlung
  - Production of e+e- pair
  - Positron annihilation
  - ~~Nuclear interaction in hadronic library~~



EM Libraries

Located in `$G4SOURCE/processes/electromagnetic`

- **Standard**
  - γ , e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- **Muons**
  - up to 1 PeV
  - energy loss propagator
- **X-rays**
  - Cherenkov, transition, synchrotron
- **High-energy**
  - processes at high energy (E>10GeV), for example γ to μ+μ- pairs, e-e+ to π- and π+
  - physics for exotic particles
- **Polarisation**
  - models/processes for polarized beam
- **Low-energy**
  - Livermore library γ, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE 2008 code rewrite γ, e- , e+ from 250 eV up to 6 GeV
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- **DNA**
  - Geant4 DNA modes and processes
  - Micro-dosimetry models for radiobiology
  - from 0.025 eV to 10 MeV
  - many of them material specific (water)
- **Adjoint**
  - sub-library for reverse Monte Carlo simulation from the detector of
  - interest back to source of radiation
- **Utils**
  - general EM interfaces and helper classes

Software Design of the EM packages

- **Uniform, coherent design approach over the different EM sub-parts**
  - Standard and low-energy EM models/processes can be combined

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  - Assigned to particle types in the Physics List (G4ComptonScattering is assigned to photon)

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- **Three EM process interfaces to describe 3 set of interactions with different characteristics. All classes derived from these 3.**
  - **G4VEmProcess** for discrete EM processes (e.g. Compton scattering)
  - **G4VEnergyLossProcess** for the continuous-discrete ionization and bremsstrahlung photon emission
  - **G4VMultipleScattering** for the Condensed History description of the multiple Coulomb scattering (along a given step)

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- **A EM process can be simulated according to several models**
  - Each model is described by a class that inherits from **G4VEmModel** base class
  - Naming convention: **G4ModelNameProcessNameModel** (e.g. **G4KleinNishinaComptonModel** describes Compton scattering of photons described by the **Klein-Nishina** differential cross section)
  - Models can be assigned to certain energy ranges and G4Regions

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- **Model classes provide the computation of:**
  - Computation of interaction cross section (and stopping power if any)
  - Computation/generation of the interaction final state (post-interaction kinematics, secondary production, etc.)

Registering electronss in Standard EM

```
msc:   for e-   SubType= 10
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV
          StepLim=DistanceToBoundary Rfact=0.04 Gfact=2.5 Sfact=0.6 DispFlag:1 Skin=1 Llim=1 mm

eIoni:  for e-  XStype:3  SubType=2
      dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      StepFunction=(0.2, 0.1 mm), integ: 3, fluct: 1, linLossLim= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha : Emin=    0 eV  Emax=  100 TeV  deltaVI

eBrem:  for e-  XStype:4  SubType=3
      dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      LPM flag: 1 for E > 1 GeV,  VertexHighEnergyTh(GeV)= 100000
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
             eBremSB : Emin=    0 eV  Emax=    1 GeV  AngularGen2BS
            eBremLPM : Emin=    1 GeV Emax=  100 TeV  AngularGen2BS

ePairProd:  for e-  XStype:1  SubType=4
      dE/dx and range tables from 10 eV  to 100 TeV in 260 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 0
      Sampling table 25x1001; from 0.1 GeV to 100 TeV
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           ePairProd : Emin=    0 eV  Emax=  100 TeV  ModifiedMephi
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```

Gamma Processes

- Main processes (low to high energy)
  - Photoelectric effect
  - Rayleigh scattering should not be neglected if an accurate dosimetry simulation is needed
  - Compton scattering
  - Gamma absorption by Nuclei (giant dipole resonance)
  - γ conversion into e+e- pair

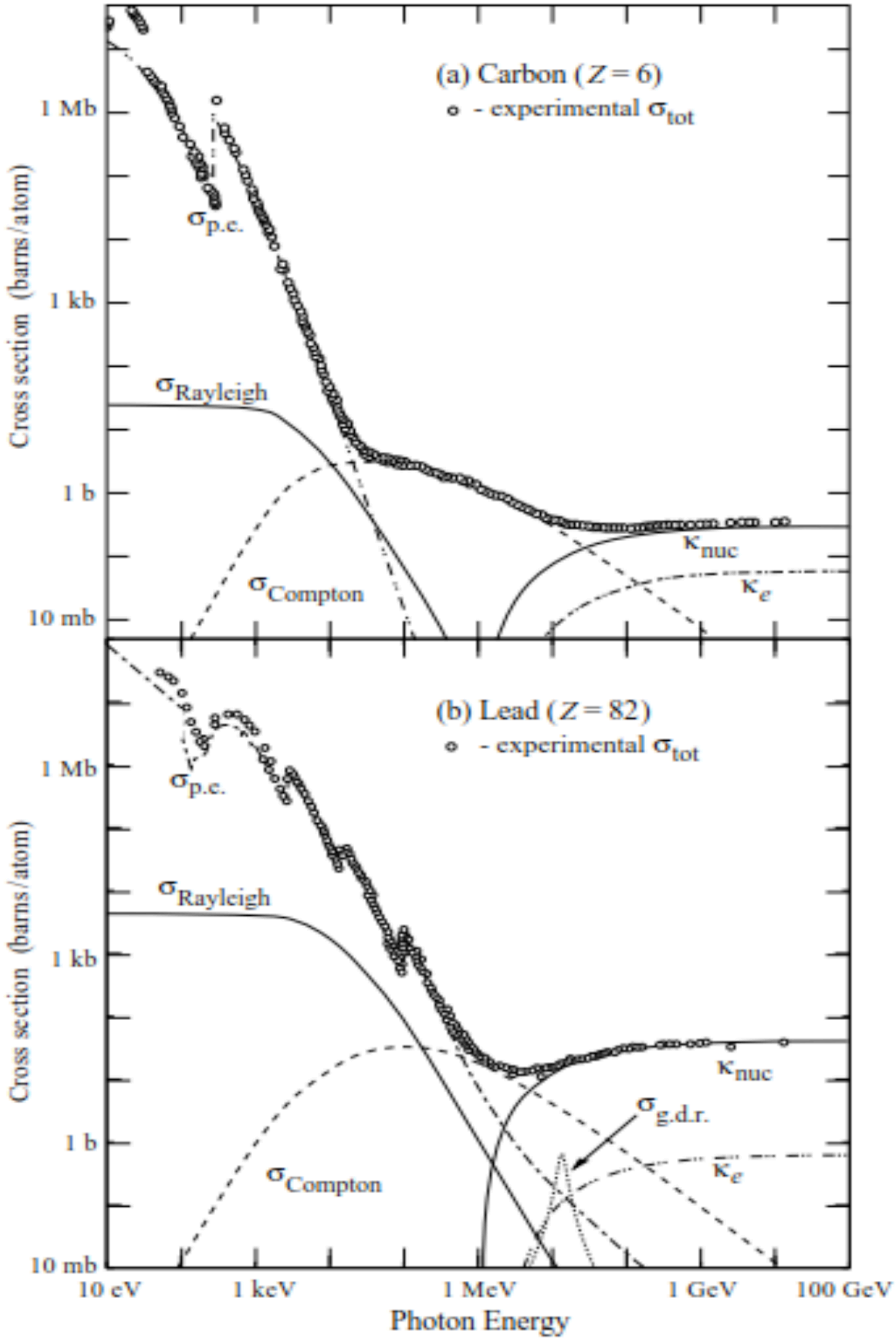
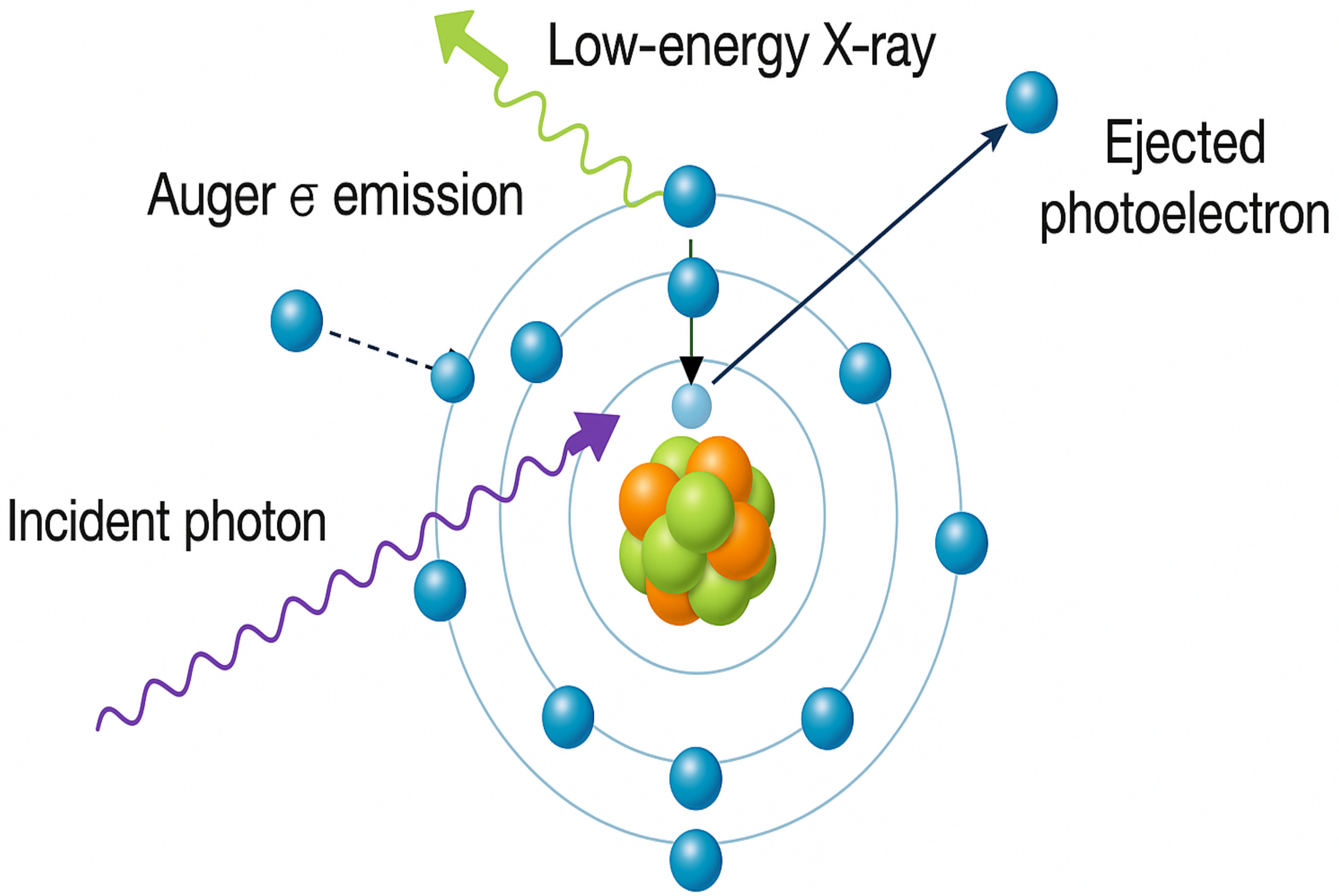


Photo-electric absorption and atomic de-excitation

- ✦ Photo-electric absorption leaves the atom in an excited state
- ✦ Vacancy in the ionized shell
- ✦ Decay through a cascade of radiated and non radiated transitions
- ✦ Emission of X-rays and other electrons



Atomic de-excitation

- Atomic de-excitation is **initiated** by other EM physics interactions
  - Photoelectric effect, ionization (by e- or ions), Compton scattering, …
  - These interactions leave the target atom in an excited state

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- The EADL (Evaluated Atomic Data Library) contains transition probabilities: Decay through a cascade of radiated and non radiated transitions
  - Radiative transition characteristic X-ray emission (fluoressence photon emission)
  - Auger e- emission: initial and final vacancies are in different shells
  - Coster-Kronig e- emission: initial and final vacancies are in the same shells

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  - Auger e- emission: initial and final vacancies are in different shells
  - Coster-Kronig e- emission: initial and final vacancies are in the same shells
- De-excitation has common interface so is compatible with both the standard and the low-energy EM physics categories
  - It can be enabled and controlled by UI command (before initialization)

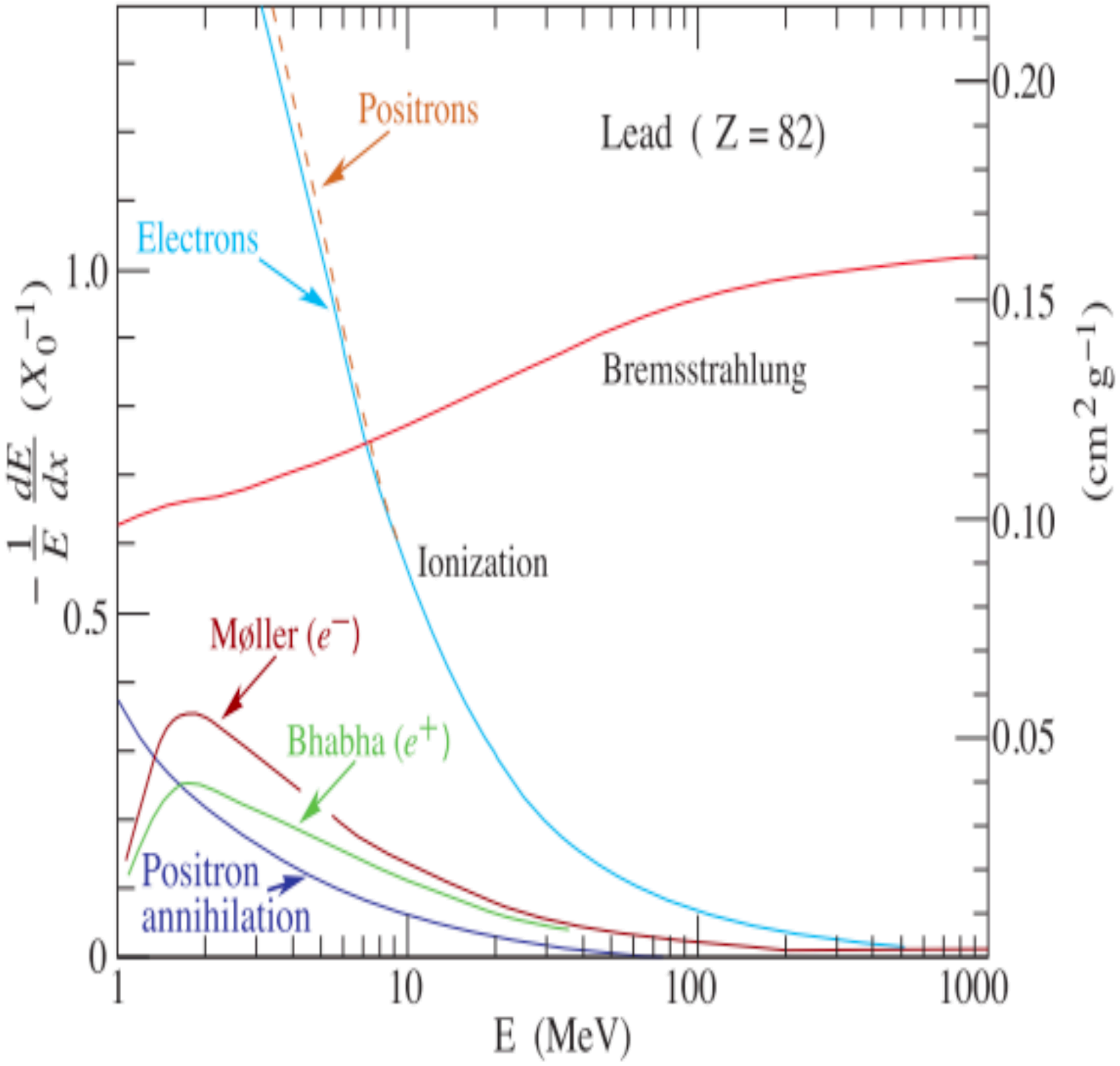
```
/process/em/fluo true
/process/em/auger true
/process/em/pixe true
/run/initialize
```

  - The fluorescence transition is active by default in some EM physics constructor while others (Auger, PIXE) not

Charged particles processes

✦ Charged particles processes (low to high energy)

- Positron annihilation
- Ionization dominates
- Bremsstrahlung
- Coulomb scattering
- Production of e+e- pair



Difference between electrons and positrons is significant for low energy but practically negligible above critical energy

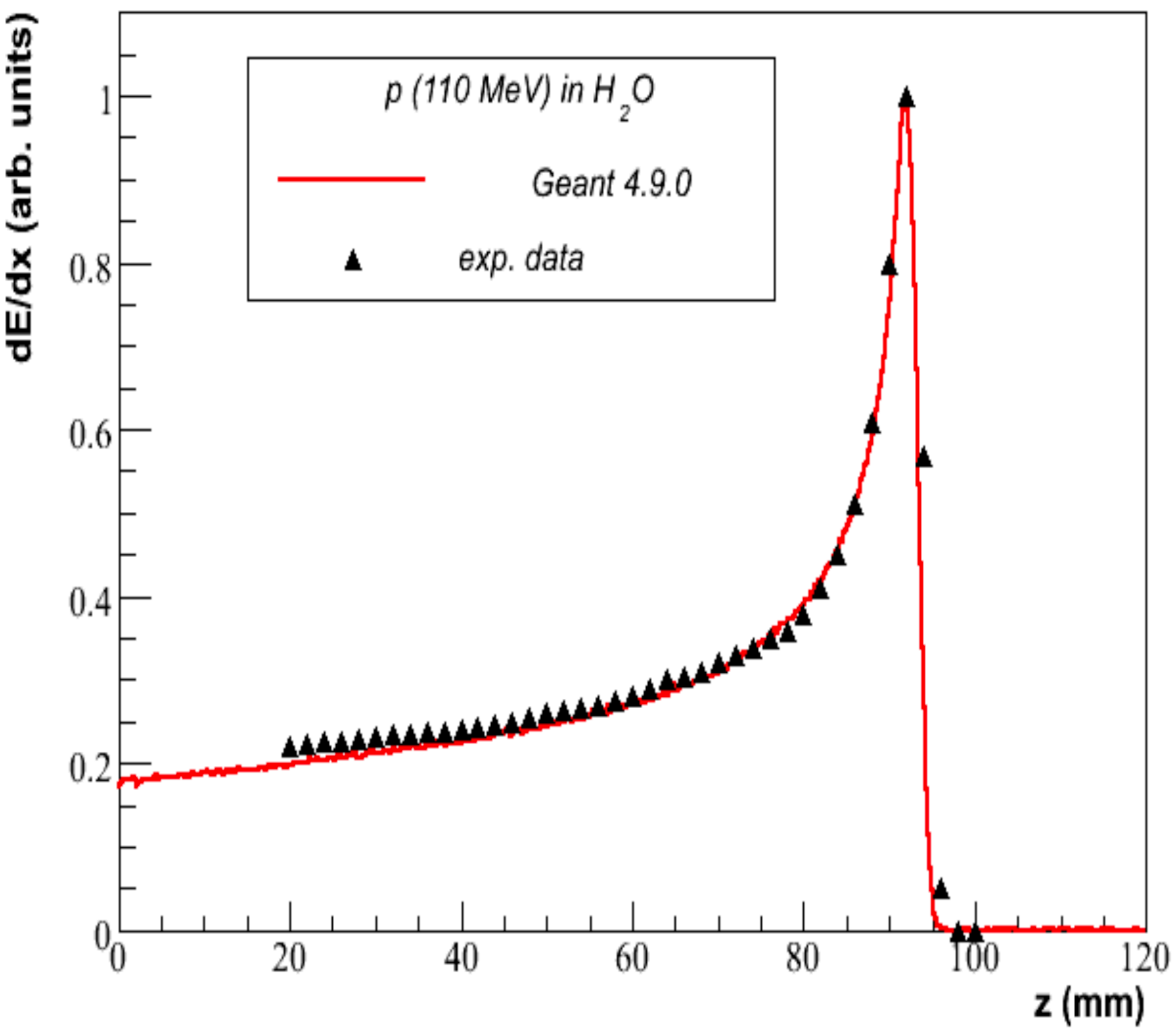
Charged particles: simulation of g4step

- Values of mean dE/dx, range, cross section of δ-electron production, and bremsstrahlung are pre-computed at initialization stage of Geant4 and are stored in a G4PhysicsTable
- At run time, for each simulation **g4step**
  1. a spline interpolation of tables is used to get the mean energy loss
  2. a call to the the general interface to a fluctuation model is G4VEmFluctuationModel
  3. a sampling of the energy loss fluctuation is performed
- the cross sections of δ-electron production and bremsstrahlung are used to sample production above the threshold T_{CUT} at PostStep
- If atomic de-excitation is active, then fluorescence and Auger electron production is sampled AlongStep and PostStep

1: Hadrons and ion ionization: get mean energy loss

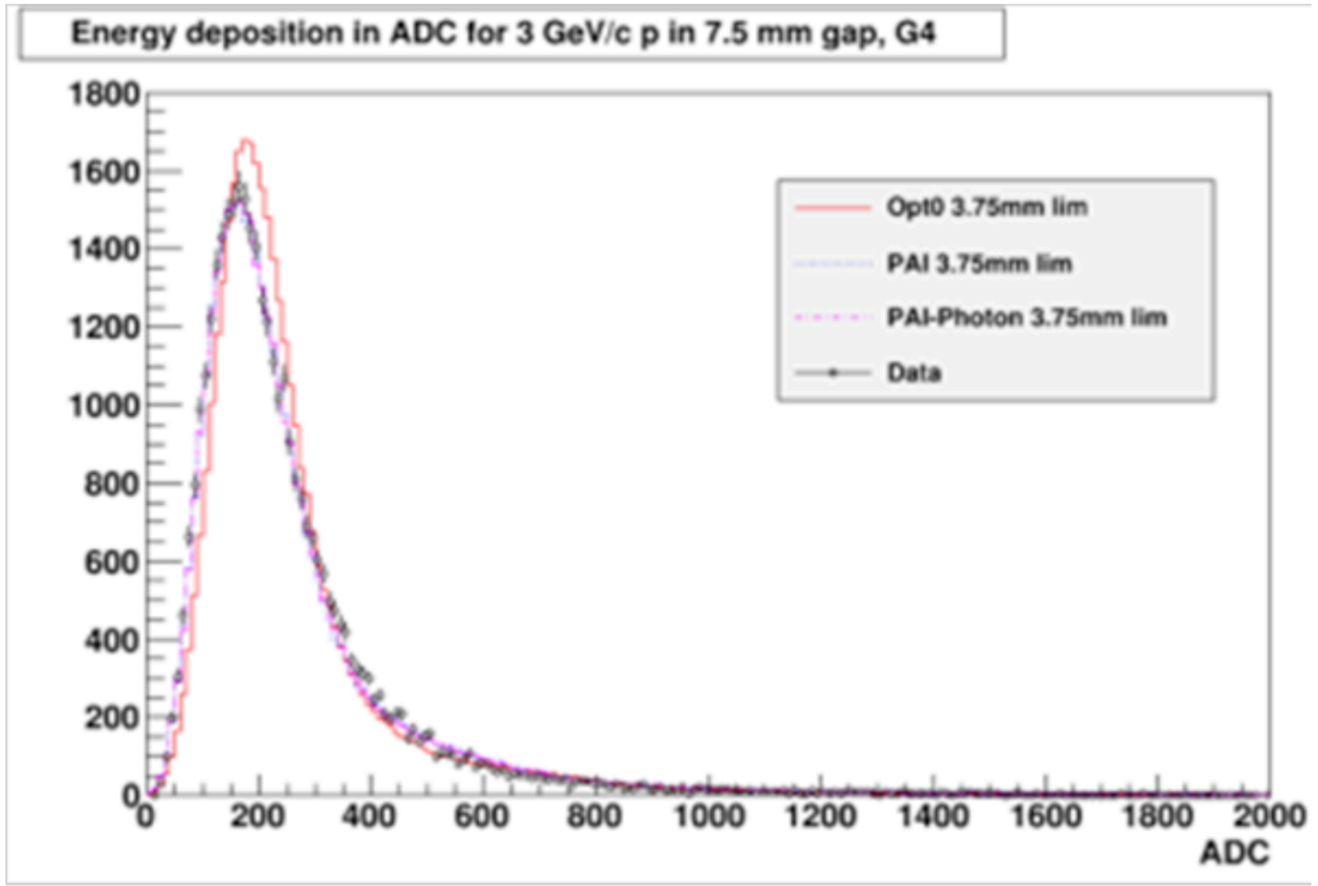
$$-\frac{dE}{dx} = 4\pi N_e r_0^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \frac{\beta^2}{2}\left(1-\frac{T_c}{T_{max}}\right) - \frac{C}{Z} + \frac{G-\delta-F}{2} + zL_1 + z^2L_2\right)$$

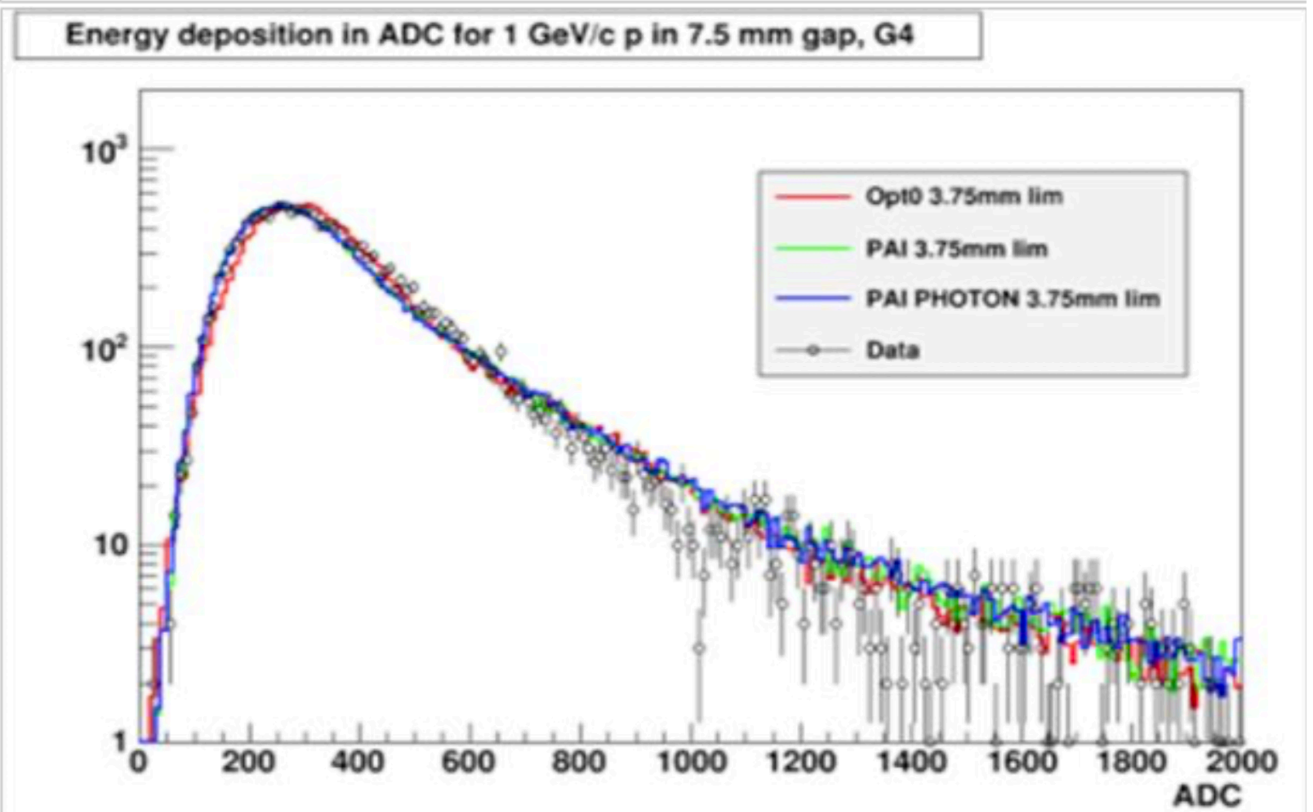
- C: shell correction
- G: Mott correction
- δ density correction
- F: finite size correction
- L_1: Barkas correction
- L_2: Block correction
- Nuclear stopping
- Ion effective range
- Scaling for heavy particles / ions



2, 3: Fluctuations models

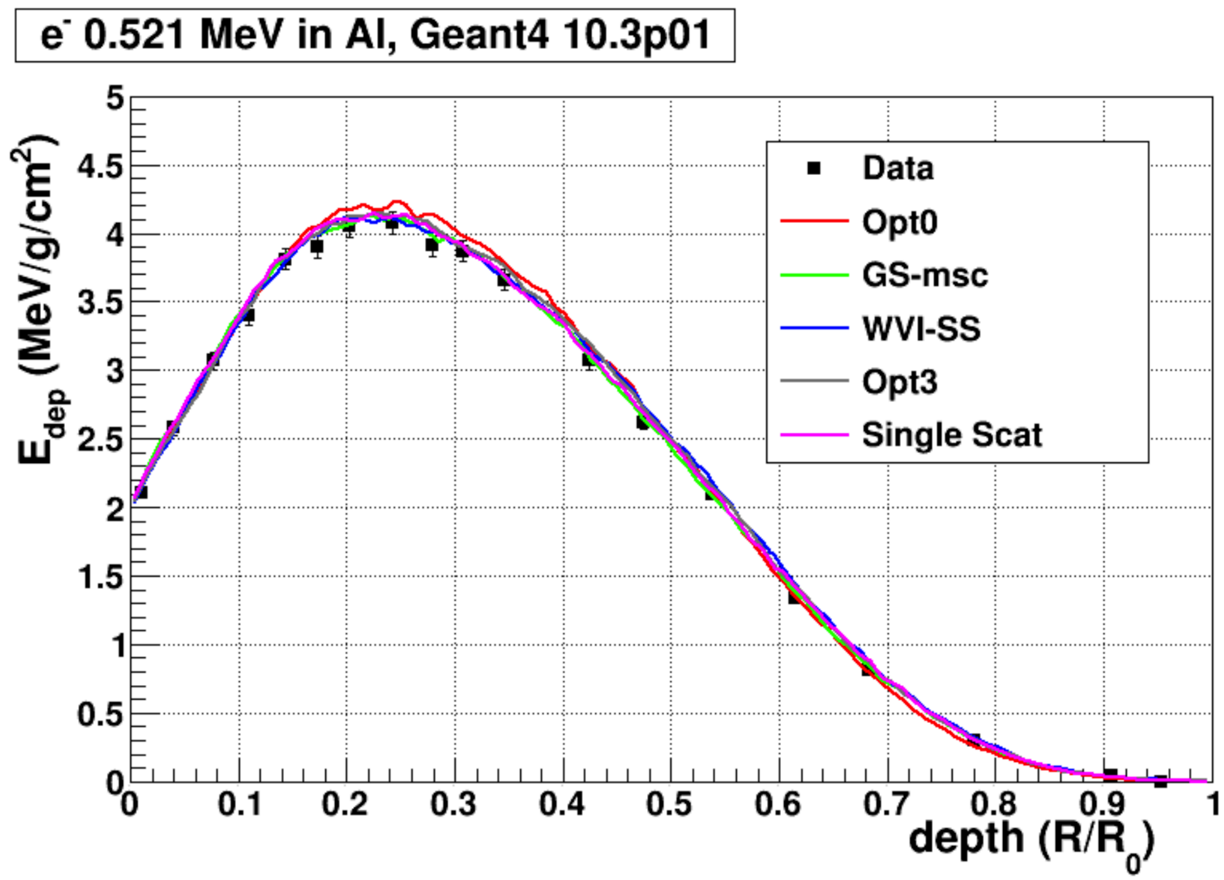
- **Urban model** based on a simple model of particle-atom interaction
  - Atoms are assumed to have only two energy levels: E_1 and E_2
  - Particle-atom interaction can be:
    - an excitation of the atom with energy loss $E = E_1 - E_2$
    - an ionization with energy loss distribution $g(E) \simeq 1/E^2$
- **PAI model** uses photo absorption cross section data
  - Relativistic model
  - Energy transfers are sampled with production of secondary e- or γ
  - Very slow model
  - Takes into account each ionization collision

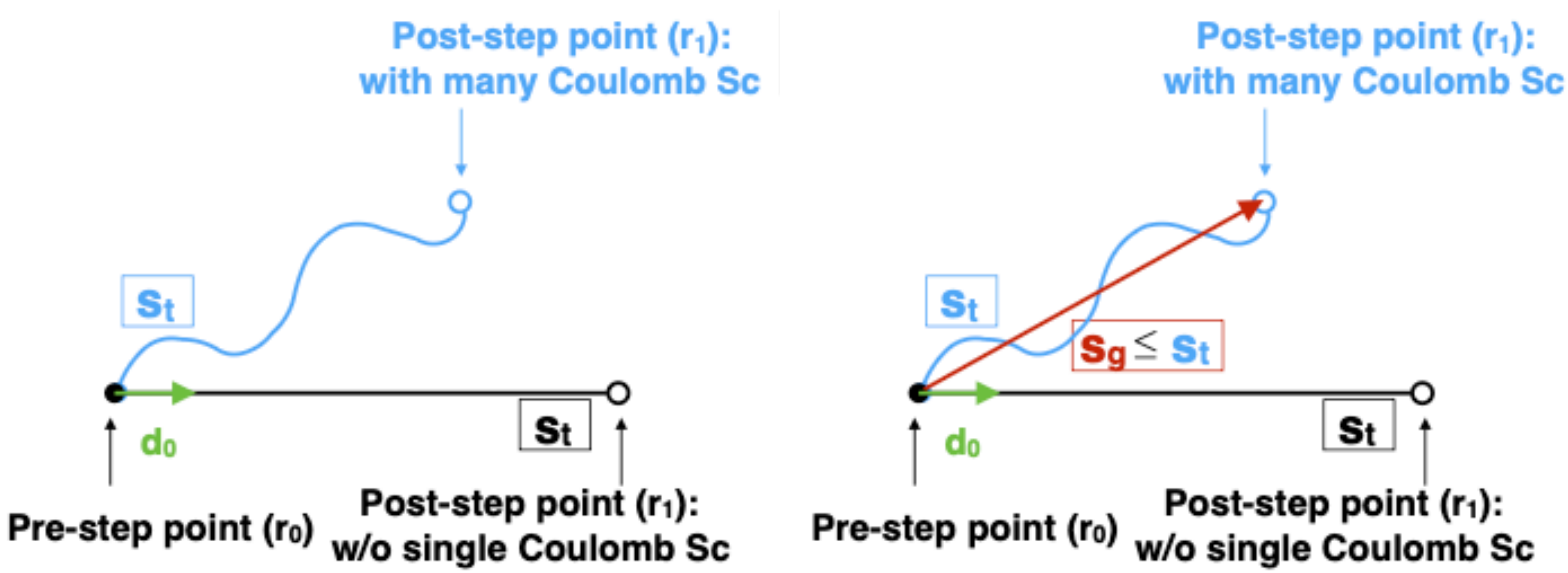




Electron/positron Multiple Scattering Models

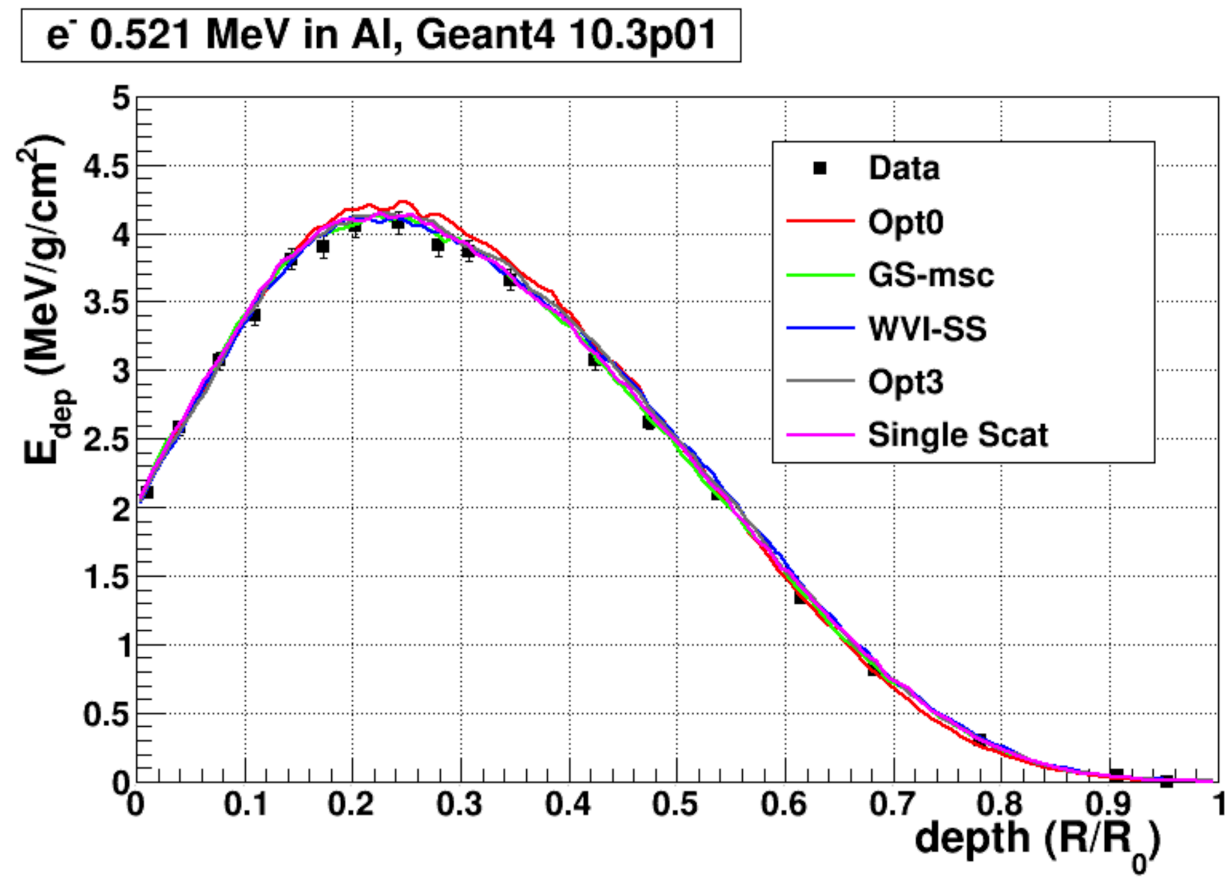
- **Coulomb scattering:** elastic scattering of charged particles on the atomic potential
- **Event-by-event** modeling of elastic scattering is feasible only if the mean number of interactions per track is below few hundred
- this limits the applicability of the detailed simulation model only for electrons with relatively low kinetic energies (up to E_{kin} ~100 keV) or thin targets
- **MSC model:** give the final position and direction of the particle while try to minimize the possible errors due to geometrical constraints





Electron/positron Multiple Scattering Models

- **MSC model:** give the final position and direction of the particle while try to minimize the possible errors due to geometrical constraints
- Can be controlled with UI command (in increasing accuracy and simulation time)




```
/process/msc/StepLimit UseSafety
/process/msc/StepLimit UseDistanceToBoundary
/process/msc/StepLimit UseSafetyPlus
```

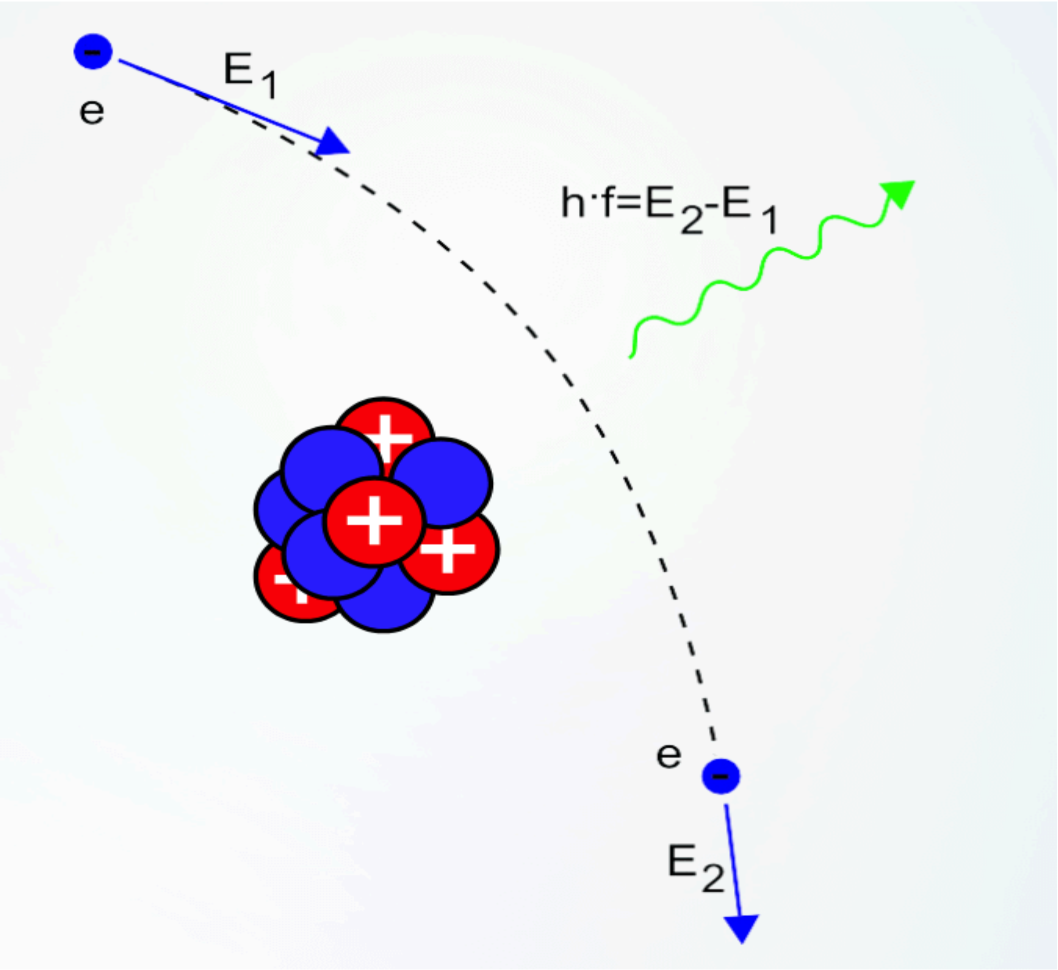
these are for e-/e+ but different UI command available for muons and hadrons

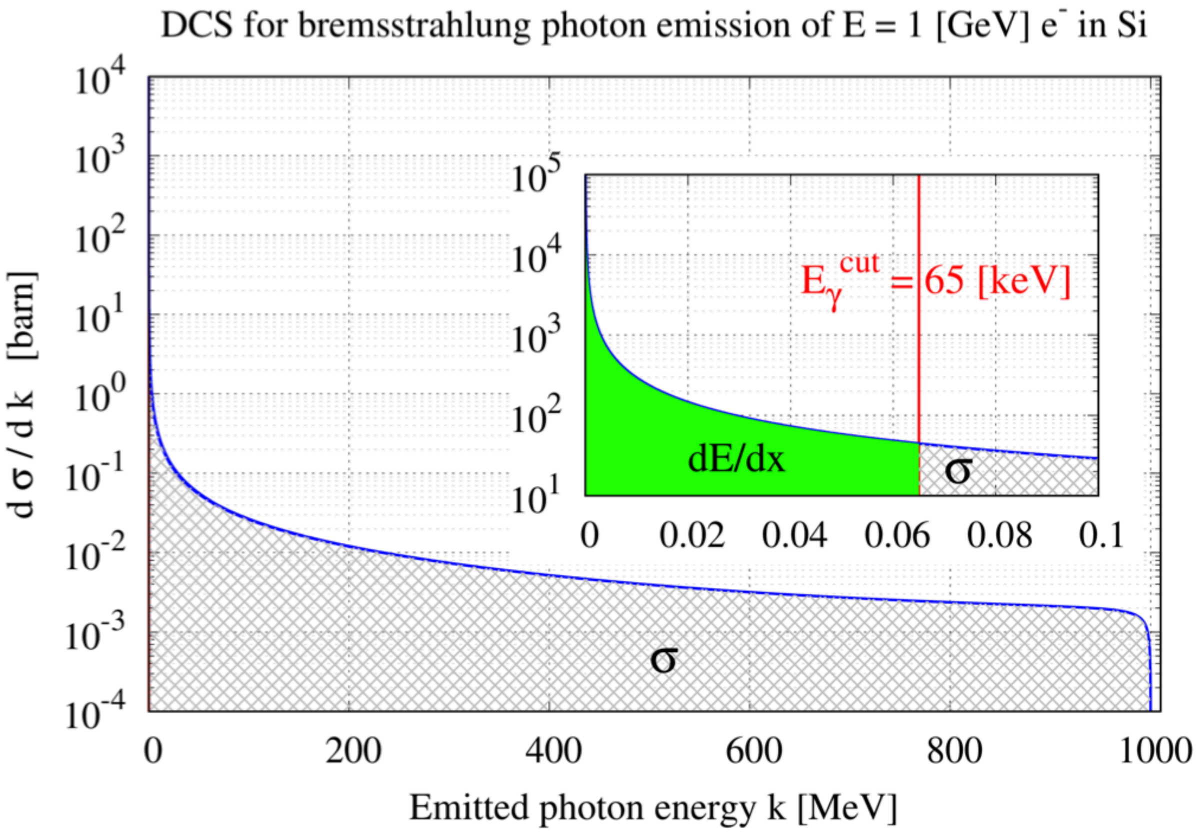
Production Threshold

For Bremsstrahlung

- Low energy photons (k) are emitted with high rate: **DCS ~ 1/k**
- The generation and tracking of all these low energy photons would not be feasible (CPU time)
- Low energy photons has a very small absorption length
- **If the detector spacial resolution is worse than this length** then the following scenario are exactly the same in terms of final result of a simulation:
  - A. Generating and tracking these low energy photons till all their energy will be deposited
  - B. Depositing their corresponding energy at the creation point (at a trajectory point)

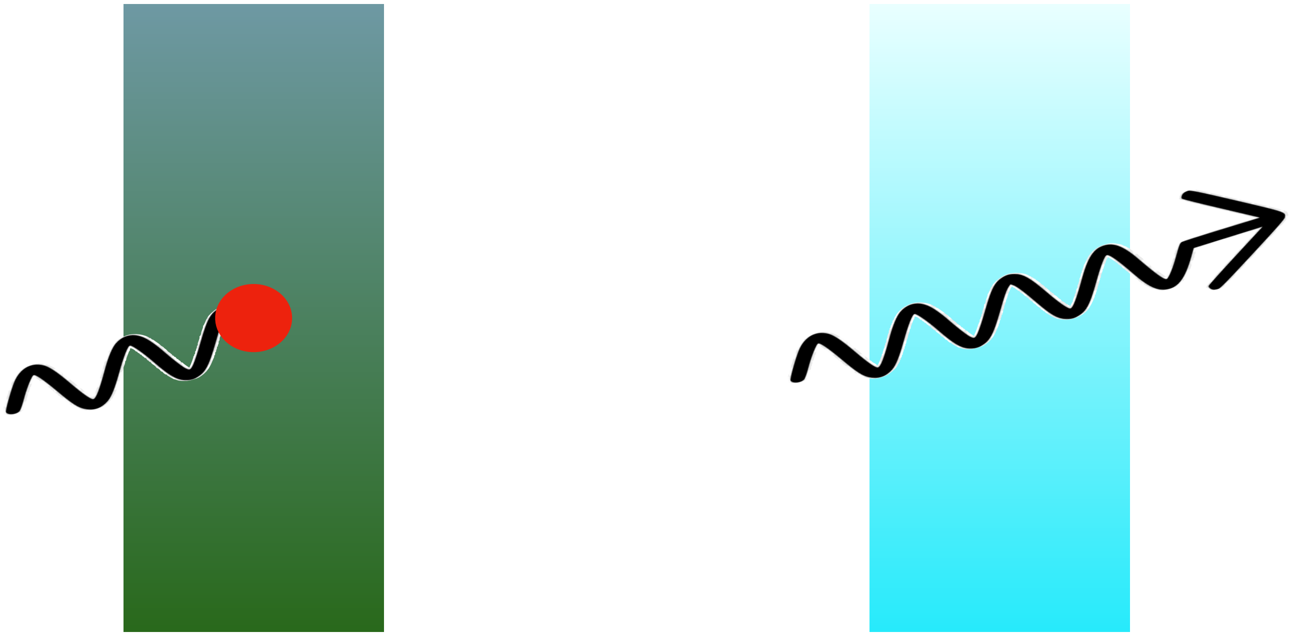
B is equivalent to A but much faster. We can control these situations with a production threshold cut.





Energy vs Length

- It may seem more intuitive at first for users to provide a threshold in ENERGY
- But the same energy will translate to different lengths (absorption length, range) in different materials: a 10 keV gamma has **very different absorption length in Pb or in Ar gas**



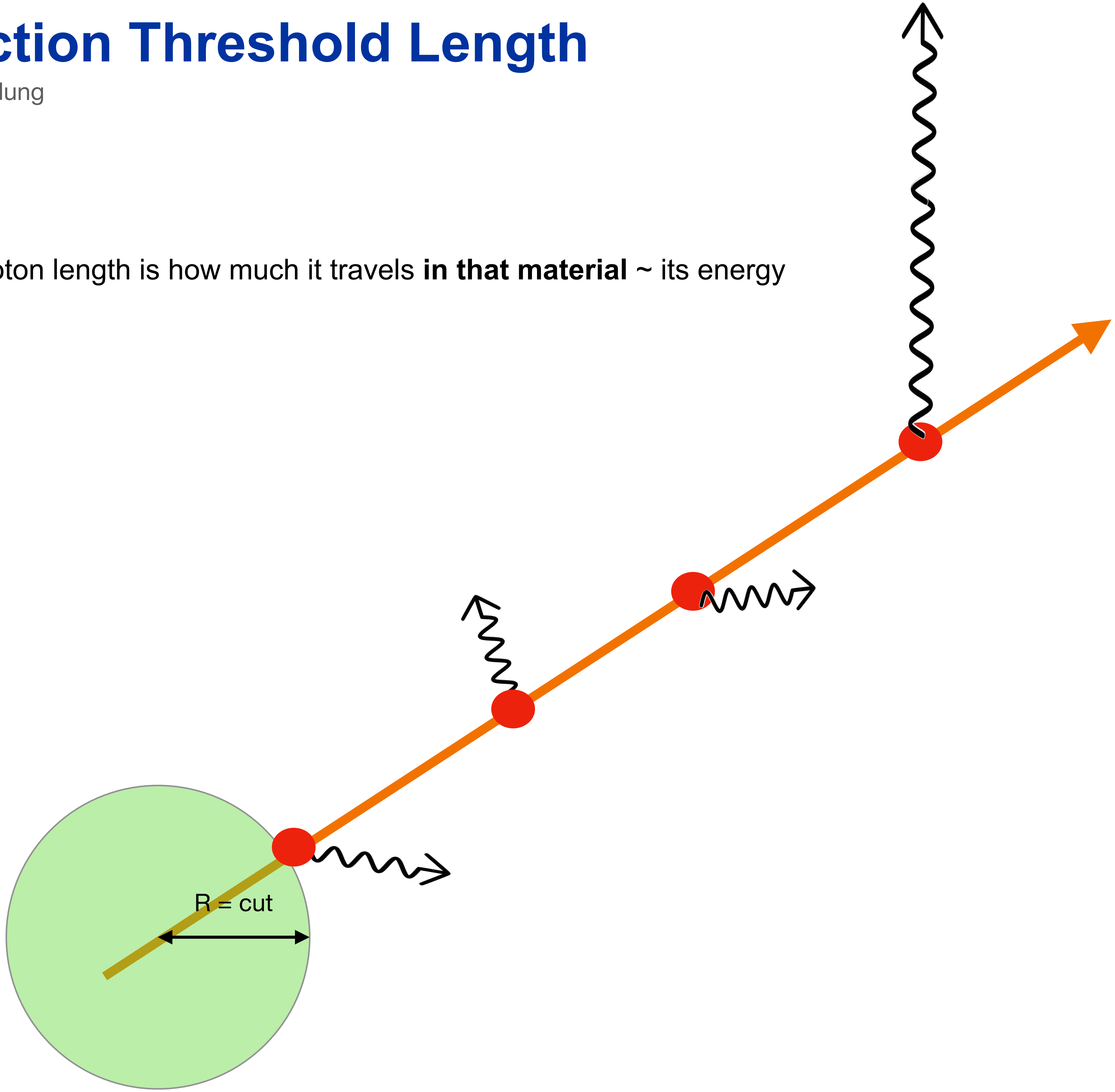
- Moreover, the same energy will translate to different lengths depending on the particle type (gamma => absorption length; e-/e+ => range) even in the same material: range of a 10 keV e- in Si is few micron while the absorption length of a 10 keV gamma in Si is few cm
- If we wanted to use energy threshold, we would need values per material and per particle!

A cut in length is more intuitive (after you think about it a bit) and directly related to detector dimensions

Production Threshold Length

For Bremsstrahlung

Here the photon length is how much it travels **in that material** ~ its energy



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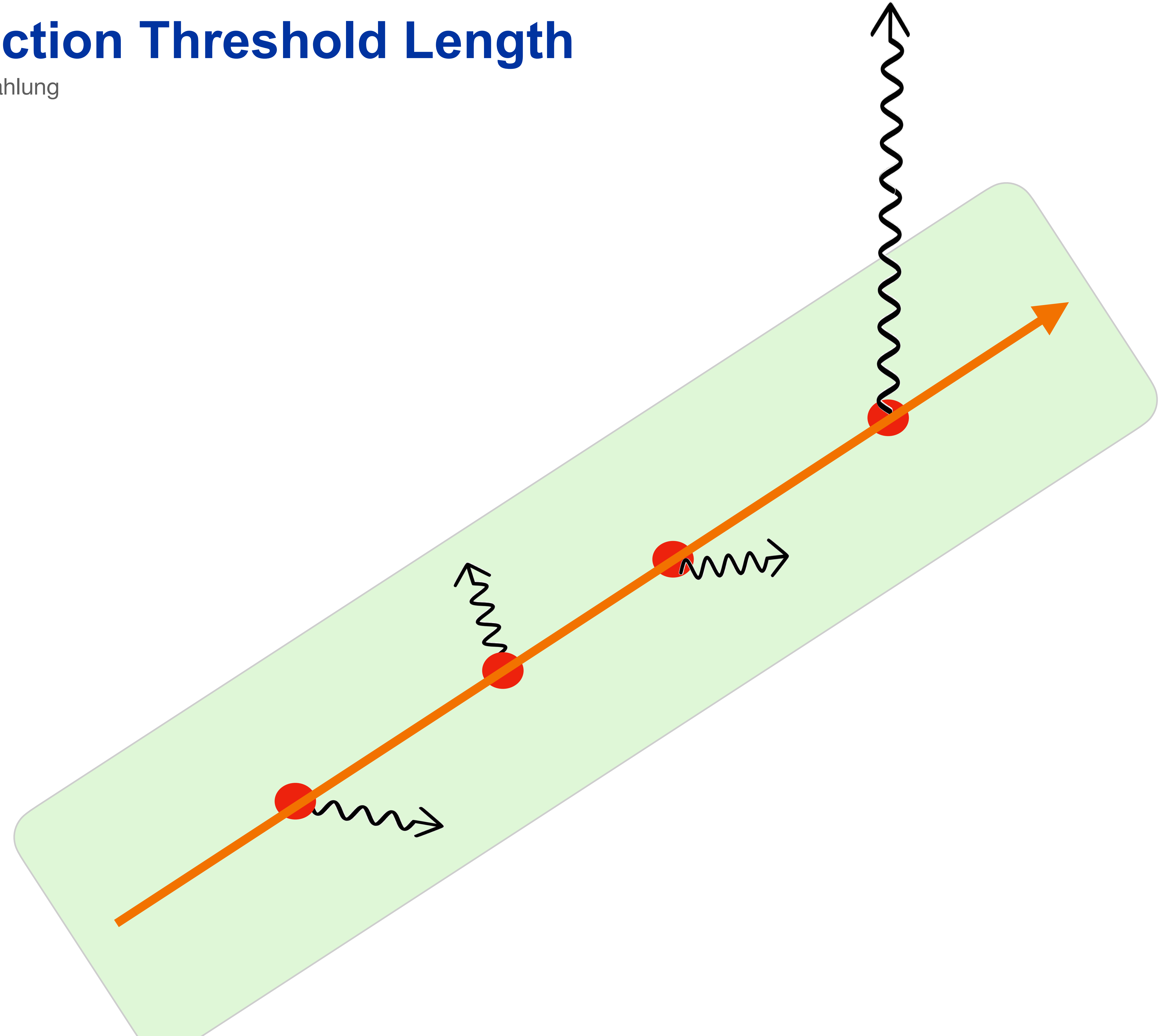


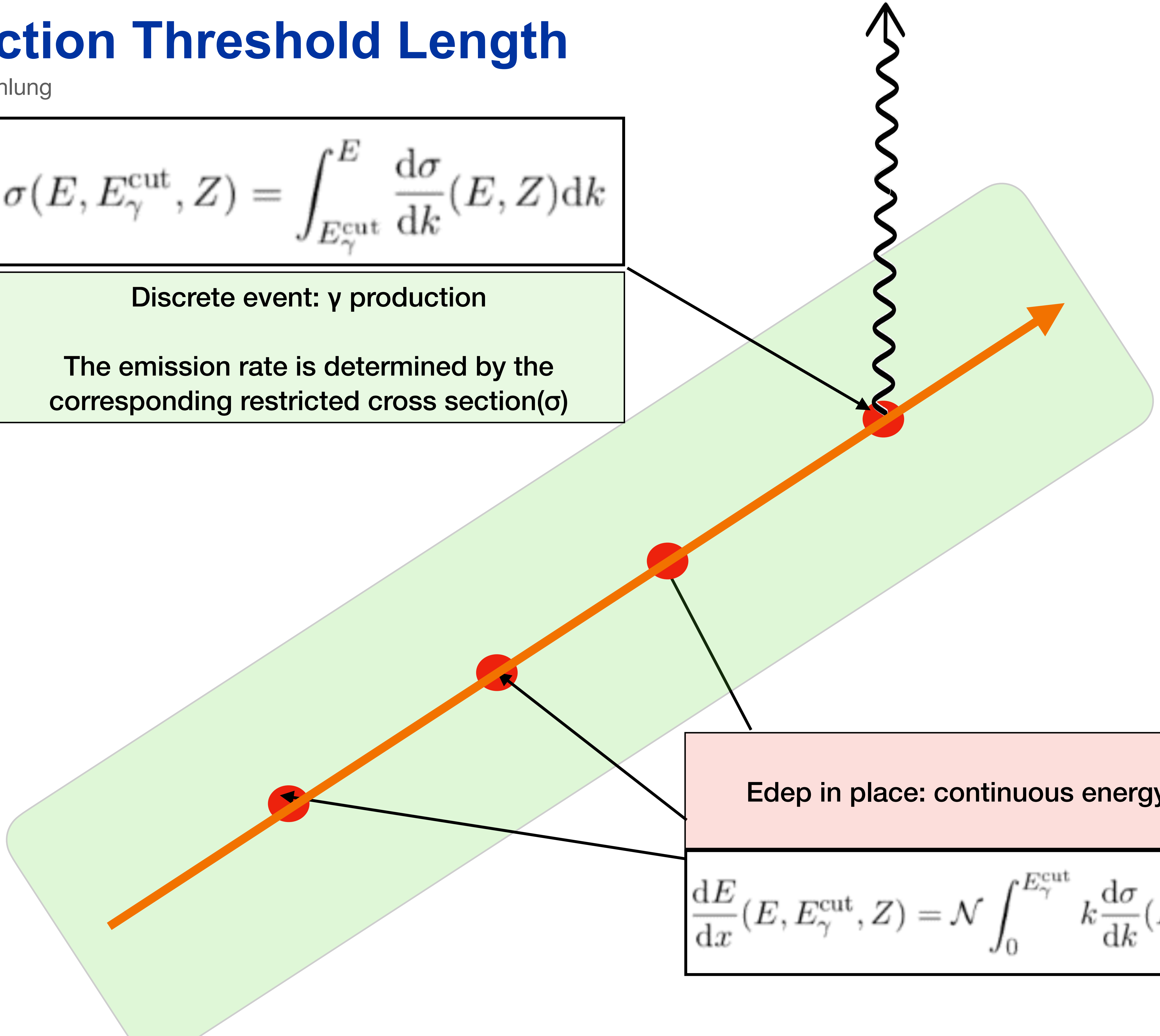
Production Threshold Length

For Bremsstrahlung

$$\sigma(E, E_\gamma^{\mathrm{cut}}, Z) = \int_{E_\gamma^{\mathrm{cut}}}^{E} \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E, Z)\mathrm{d}k$$

Discrete event: γ production

The emission rate is determined by the corresponding restricted cross section(σ)



Edep in place: continuous energy loss

$$\frac{\mathrm{d}E}{\mathrm{d}x}(E, E_\gamma^{\mathrm{cut}}, Z) = \mathcal{N}\int_0^{E_\gamma^{\mathrm{cut}}} k\frac{\mathrm{d}\sigma}{\mathrm{d}k}(E, Z)\mathrm{d}k$$

Production Threshold

- The corresponding **Edep** energy (that would have been taken away from the primary) is accounted as **CONTINUOUS energy loss** of the primary particle along its trajectory

- **Same applies to ionization with the difference:**
  - secondary gamma → secondary e- production threshold
  - absorption length → range

- Range and absorption production length is **internally translated to energies** at initialization, taking care of material and particle dependency

- Production threshold defined for gamma, e-, e+ and proton secondary particle:
  - gamma production threshold is used in bremsstrahlung while the e- in ionization
  - e+ production threshold might be used in case of e-/e+ pair production
  - proton production threshold is used as a kinetic energy threshold for nuclear recoil in case of elastic scattering of all hadrons and ions

- Production threshold are not mandatory, but many physics simulation would not be feasible w/o them

Production Threshold

- User needs to provide them in length (with a default value of 0.7 mm for the reference physics lists
- UI commands to define cuts:

```
/run/setCut 0.1 mm
/run/setCutForAGivenParticle e- 0.01 mm
/run/setCutForRegion GasDetector 0.001 mm
/cuts/setLowEdge 500 eV
```

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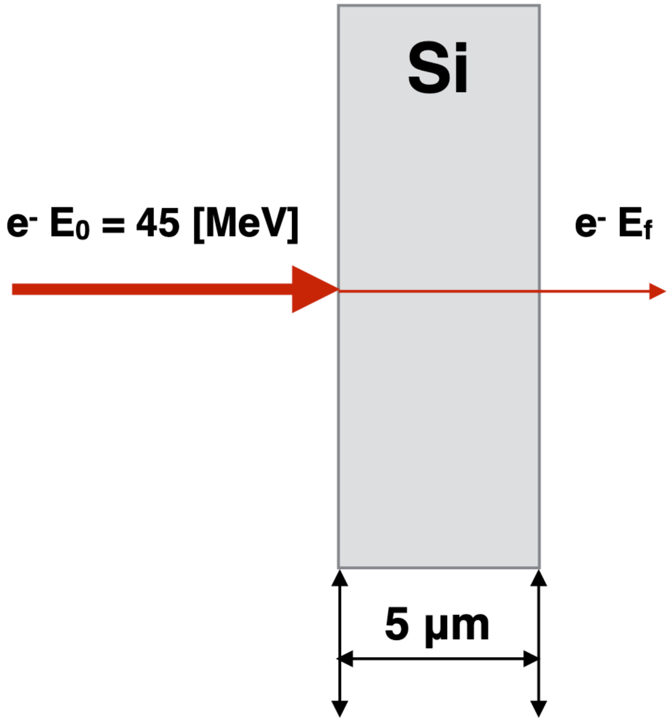

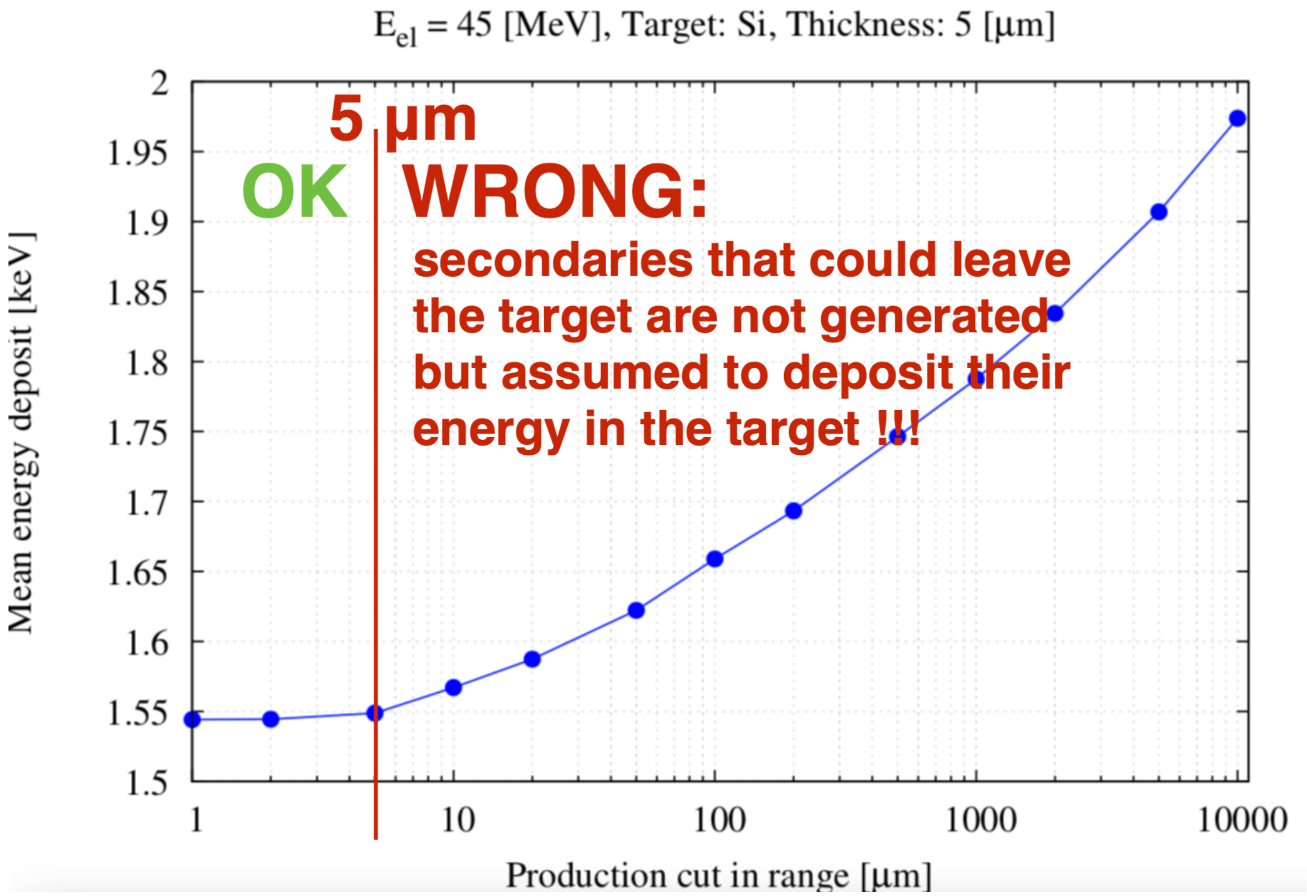

Production Threshold per detector region

- Different parts of a complex detector might require modeling with different level of details and have different spacial resolution
- Different detector **G4Regions** can be defined and a set of **G4LogicalVolumes** can be associated to such regions
- Different secondary production threshold values (as well as G4UserLimits) can be assigned to different detector region
- In the `DetectorConstruction::Construct()` method (e.g. examples/ extended/ electromagnetic/TestEm9)

```
// Production threshold for “Our-Region”
auto* cuts = new G4ProductionCuts;
cuts->SetProductionCut(0.5*mm); // same cuts for gamma, proton, e- and e+
cuts->SetProductionCut(0.2*mm,G4ProductionCuts::GetIndex("e-"));


// Create region and assign cuts
auto* region = new G4Region(“Our-Region”);
region->SetProductionCuts(cuts);

// Assign volume to region: all volumes will have these cuts
region->AddRootLogicalVolume(my_specific_logical_volume);
```

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```
Index : 0     used in the geometry : Yes
 Material : Galactic
 Range cuts        :  gamma  700 um     e-  700 um     e+  700 um  proton 700 um
 Energy thresholds :  gamma  990 eV     e-  990 eV     e+  990 eV  proton 70 keV
 Region(s) which use this couple :
    DefaultRegionForTheWorld

Index : 1     used in the geometry : Yes
 Material : G4_Pb
 Range cuts        :  gamma  700 um     e-  700 um     e+  700 um  proton 700 um
 Energy thresholds :  gamma  94.5861 keV    e-  1.00386 MeV    e+  951.321 keV proton 70 ke
 Region(s) which use this couple :
    DefaultRegionForTheWorld

Index : 2     used in the geometry : Yes
 Material : G4_lAr
 Range cuts        :  gamma  100 um     e-  100 um     e+  100 um  proton 100 um
 Energy thresholds :  gamma  2.00482 keV    e-  82.9692 keV    e+  81.8616 keV proton 10 ke
 Region(s) which use this couple :
    Our-Region
```

Standard EM Physics Constructors

List of particles for which EM physics processes are defined

- Photon, leptons, meson and baryons:

  γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\Sigma^{\pm}$, Ξ^{-}, Ω^{-}, anti($\Sigma^{\pm}$, Ξ^{-}, Ω^{-})
- Heavy leptons & heavy mesons, charmed baryons:

  $\tau^{\pm}$, $B^{\pm}$, $D^{\pm}$, $Ds^{\pm}$, Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{++}, anti(Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{+})
- Light nuclei:

  d, t, ^{3}He, ^{4}He, generic-ion, anti(d, t, ^{3}He, ^{4}He)
- 12 light hyper- and anti-hyper- nuclei

Standard EM Physics Constructors

- The modular Physics Lists (G4VModularPhysicsList) allows to build up a complete physics list from “physics modules”
- A given “physics module” handles a well defined category of physics (e.g.EM physics, decay physics, etc.) as a sub-set of a complete physics list
- **G4VPhysicsConstructor** is the Geant4 interface to describe such sub-sets of physics
- Several **EM physics constructors**, i.e. pre-defined EM sub-set of a complete physics list, are available in Geant4
- Each particle has its own **G4ProcessManager** that maintains the list of assigned processes (e.g., ionization, multiple scattering, decay)

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```
auto particleIterator = GetParticleIterator();
particleIterator->reset();
while( (*particleIterator)() ){

    G4ParticleDefinition* particle = particleIterator->value();

    auto* pmanager = particle->GetProcessManager();

    // Attach processes here
    pmanager->AddProcess(new G4eIonisation, ordInActive, ordAlongStep, ordPostStep);

}
```

Standard EM Physics Constructors for HEP

- SAME: Description of Coulomb scattering
  - e± : Urban - MSC model below 100 [MeV] and the Wentzel - WVI + Single scattering (mixed simulation) model above 100 [MeV]
  - muon and hadrons: Wentzel - WVI + Single scattering (mixed simulation) model
  - ions: Urban - MSC model
- Different MSC stepping algorithms and/or parameters: speed v.s. accuracy

Constructor	Components	Comment
EmStandardPhysics	Defaults (FTFP_BERT)	for ATLAS and other HEP simulation applications
G4EmStandardPhysics_option1	Fast: due to simpler MSC step limitation, cuts used by photon processes (FTFP_BERT_**EMV**)	similar to one used by CMS; good for crystals but not good for sampling calorimeters (i.e. with more detailed geometry)
G4EmStandardPhysics_option2	Experimental: similar to option1 with updated photoelectric model but no-displacement in MSC (FTFP_BERT_**EMX**)	similar to one used by LHCb

Standard EM Physics Constructors: more precise

- The primary goal is more the physics accuracy over the speed
- Combination of standard and low-energy EM models for more accurate physics description
- More accurate models for e± MSC (Goudsmit-Saunderson(GS)) and/or more accurate stepping algorithms (compared to HEP)
- Stronger continuous step limitation due to ionization (as others given per particle groups)
- Recommended for more accuracy sensitive applications: medical (hadron/ion therapy), space

Constructor	Components	Comment
G4EmStandardPhysics_option3	Urban MSC model for all charged particles (FTFP_BERT_**EMY**)	proton/ion therapy
G4EmStandardPhysics_option4	**most accurate combination of models (particle type and energy) GS MSC (FTFP_BERT_EMZ)**	**The most accurate EM physics**
G4EmLivermorePhysics	Livermore gamma and e- ionisation models GS MSC (FTFP_BERT_**LIV**)	Recommended for cross-checks of option4
G4EmPenelopePhysics	Penelope gamma and e± ionisation and bremsstrahlung models GS MSC (FTFP_BERT_**PEN**)	Recommended for cross-checks of option4

Extra experimental constructors are available in Geant4 examples

USER INTERFACE TO EM PHYSICS

EM parameters of any EM physics list may be accessed or modified at initialization of Geant4 using:

- UI commands

```
/process/eLoss/verbose 0
/process/eLoss/maxKinEnergyCSDA 100 TeV

/process/em/deexcitationIgnoreCut true
/process/eLoss/UseAngularGenerator true
/process/em/lowestElectronEnergy 50 eV
/process/em/lowestMuHadEnergy 100 keV
```

```
/process/em/printParameters
```

USER INTERFACE TO EM PHYSICS

EM parameters of any EM physics list may be accessed or modified at initialization of Geant4 using:

- C++ interface to the **G4EmParameter** (EM options) class

PhysListEmStandard.cc in extended/electromagnetic/TestEm0

```
PhysListEmStandard::PhysListEmStandard(const G4String& name) :
                    G4VPhysicsConstructor(name) {

    G4EmParameters* param = G4EmParameters::Instance();
    param->SetDefaults();
    param->SetVerbose(0);
    SetPhysicsType(bElectromagnetic);
}
```

PhysycsList.cc in extended/electromagnetic/TestEm0

```
void PhysicsList::AddPhysicsList(const G4String& name) {

    G4EmParameters::Instance()->SetBuildCSDARange(true);
    G4EmParameters::Instance()->SetGeneralProcessActive(false);
}
```

USER INTERFACE TO EM PHYSICS

EM parameters of any EM physics list may be accessed or modified at initialization of Geant4 using:

- C++ interface to the **G4EmCalculator** (access to cross sections and stopping powers) class

`RunAction.cc in extended/electromagnetic/TestEm0`

```
void RunAction::CriticalEnergy()
{
    // compute e- critical energy (Rossi definition) and Moliere radius.
    // Review of Particle Physics - Eur. Phys. J. C3 (1998) page 147

    G4EmCalculator emCal;
    const G4Material* material = fDetector->GetMaterial();
    const G4double radl = material->GetRadlen();
    G4double ekin = 5 * MeV;
    G4double deioni;
    G4double err = 1., errmax = 0.001;
    G4int iter = 0, itermax = 10;
    while (err > errmax && iter < itermax) {
        iter++;
        deioni = radl * emCal.ComputeDEDX(ekin, G4Electron::Electron(), "eIoni", material);
        err = std::abs(deioni - ekin) / ekin;
        ekin = deioni;
    }
}
```

USER INTERFACE TO EM PHYSICS

EM parameters of any EM physics list may be accessed or modified at initialization of Geant4 using:

- **G4EmCalculator**: easy access to cross sections and stopping powers (**TestEm0**)
- **G4EmParameters**: EM options alternative to UI commands
- **G4EmSaturation**: Birks effect (saturation of response of sensitive detectors)
- **G4ElectronIonPair**: sampling of ionization clusters in gaseous or silicon detectors
- **G4EmConfigurator**: add models per energy range and geometry region
- **G4NIELCalculator**: Helper class allowing computation of NIEL at a step, which should be added in user stepping actions or sensitive detector (**TestEm1**)

Extract EM PHYSICS

EM parameters of any EM physics list may be accessed or modified at initialization of Geant4 using:

- ✦ Use C++ interface to the **G4EmCalculator** (after physics list is initialized)
- ✦ Example for retrieving the total cross section of a process with name procName, for particle and material matName

```
#include "G4EmCalculator.hh"

{
    G4EmCalculator emCalculator;
    G4Material* material =
    G4NistManager::Instance()->FindOrBuildMaterial(matName);
    G4double density = material->GetDensity();
    G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
    (energy, particle, procName, material)/density;
    G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
}
```

Summary

- Overview of the main EM physics and classes in Geant4.
- There is a lot more physics in Geant4 (DNA project, etc, see also EM 2)
- Choosing the correct EM physics list while optimizing the simulation efficiency is the one of the most important issue you will face.
- We suggest starting with the standard list and if accuracy is extremely important to you, compare with option 4. This will give you an idea of your needs.