Geant4 10.6

Electromagnetic Physics I

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slides based on those of Mihaly Novak (CERN)

Outline

- Electromagnetic (EM) physics overview
  - Introduction, structure of Geant4 EM physics
  - Standard EM physics constructors
  - How to extract EM physics related quantities
- EM processes and stepping
- Multiple scattering and transportation
- Special EM topics:
  - EM models per region
  - Atomic de-excitation
  - Energy loss fluctuation

Code Location: source/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
- /xrays
  - Cerenkov, transition, synchrotron radiation
- /highenergy
  - e.g. γ to $\mu^+ \mu^-$ pairs, $e^+ e^-$ to $\pi^+ \pi^-$
- /polarisation
  - models, processes for polarized beams
- /utils
  - model/process interfaces, utilities
- /lowenergy
  - Livermore library: γ, e^- [10 eV – 1 GeV]
  - Penelope models (2008): γ , e^{+-} , [100 eV – 1 GeV]
  - Livermore polarized processes
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (Auger, fluor.)
- /dna
  - DNA models, processes (0.025 eV to 10 MeV)
  - microdosimetry models for radiology
  - many models are material-specific (water)
- /adjoint
  - reverse Monte Carlo
  - very fast, limited applications

Standard EM Interactions

- Photon (γ) :
  - conversion to $e^- e^+$ pairs
  - Compton (incoherent) scattering
  - photo-electric effect
  - Rayleigh (coherent) scattering
  - photo-nuclear interaction (see hadronic)

- Electron and positron interactions :
  - ionization
  - Coulomb (elastic) scattering
  - bremsstrahlung photon emission
  - positron annihilation
  - electron- and positron-nuclear interactions (see hadronic)

Standard EM Interactions

- Example of photon interactions (from log file)

```
phot:   for  gamma    SubType= 12  BuildTable= 0
      LambdaPrime table from 200 keV to 100 TeV in 61 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermorePhElectric :  Emin=        0 eV     Emax=      100 TeV   Angular

compt:   for  gamma    SubType= 13  BuildTable= 1
      Lambda table from 100 eV  to 1 MeV, 7 bins per decade, spline: 1
      LambdaPrime table from 1 MeV to 100 TeV in 56 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       Klein-Nishina :  Emin=        0 eV     Emax=      100 TeV

conv:   for  gamma    SubType= 14  BuildTable= 1
      Lambda table from 1.022 MeV to 100 TeV, 18 bins per decade, spline:
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        BetheHeitler :  Emin=        0 eV     Emax=       80 GeV   Angular
     BetheHeitlerLPM :  Emin=       80 GeV    Emax=      100 TeV   Angular

Rayl:   for  gamma    SubType= 11  BuildTable= 1
      Lambda table from 100 eV  to 100 keV, 7 bins per decade, spline: 0
      LambdaPrime table from 100 keV to 100 TeV in 63 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermoreRayleigh :  Emin=        0 eV     Emax=      100 TeV   CullenG
```

Structure of Geant4 EM Physics

- Uniform, coherent design approach covering EM sections
  - standard and low-energy EM models/processes can be combined
- Physical interactions described by processes (e.g. G4ComptonScattering)
  - assigned to a particle in the physics list (G4ComptonScattering assigned to photon)
- Processes categorized by their interfaces:
  - G4VEmProcess for discrete EM processes like Compton
  - G4VEnergyLossProcess for continuous-discrete ionization and bremsstrahlung
  - G4VMultipleScattering for the condensed history description of multiple Coulomb scattering (along a given step)

- A given EM process can be described by one or more models:
  - an EM model can handle the interaction in a given energy range
  - naming convention: G4ModelNameProcessNameModel (e.g. G4KleinNishinaComptonModel describes Compton scattering of photons as implemented by the Klein-Nishina differential cross section
  - each EM model follows the G4VEmModel interface:
    - computation of interaction cross section (and stopping power, if any)
    - computation/generation of the interaction final state (kinematics, secondaries, etc.)

Standard EM Example

- Gamma conversion process described by two EM models

```
phot:   for  gamma    SubType= 12  BuildTable= 0
      LambdaPrime table from 200 keV to 100 TeV in 61 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermorePhElectric :  Emin=        0 eV     Emax=      100 TeV    AngularGenSauter

compt:   for  gamma    SubType= 13  BuildTable= 1
      Lambda table from 100 eV  to 1 MeV, 7 bins per decade, spline: 1
      LambdaPrime table from 1 MeV to 100 TeV in 56 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       Klein-Nishina :  Emin=        0 eV     Emax=      100 TeV

conv:   for  gamma    SubType= 14  BuildTable= 1
      Lambda table from 1.022 MeV to 100 TeV, 18 bins per decade, spline: 1
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        BetheHeitler :  Emin=        0 eV     Emax=       80 GeV    AngularGenUrban
     BetheHeitlerLPM :  Emin=       80 GeV    Emax=      100 TeV    AngularGenUrban

Rayl:   for  gamma    SubType= 11  BuildTable= 1
      Lambda table from 100 eV  to 100 keV, 7 bins per decade, spline: 0
      LambdaPrime table from 100 keV to 100 TeV in 63 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermoreRayleigh :  Emin=        0 eV     Emax=      100 TeV    CullenGenerator
```

Standard EM Physics Constructors

- Physics processes are assigned to particles in the physics list
- Particles to which EM physics processes can be assigned:
  - γ, $e^{+/-}$, $\mu^{+/-}$, $\pi^{+/-}$, p, $\Sigma^{+/-}$, Ξ^{-}, Ω^{-}, anti ($\Sigma^{+/-}$, Ξ^{-}, Ω^{-})
  - $\tau^{+/-}$, $B^{+/-}$, $D^{+/-}$, $D_S^{+/-}$, Λ_C^{+}, Σ_C^{+}, Σ_C^{++}, Ξ_C^{+}, anti (Λ_C^{+}, Σ_C^{+}, Σ_C^{++}, Ξ_C^{+})
  - d, t, ^{3}He, α, generic ion, anti (d, t, ^{3}He, α)

- Each particle type is a static object which has its own G4ProcessManager
  - manager maintains list of assigned processes

- Modular physics lists (G4VModularPhysicsList) allow building up a complete physics list from "physics modules"
  - physics module handles well-defined subset of physics (EM physics, decay physics, etc.)
  - G4VPhysicsConstructor is the interface class describing such subsets
- Several pre-defined EM physics constructors are available in Geant4

Standard EM Physics Constructors for HEP

- Description of Coulomb scattering is the same for three of these:
  - $e^{+/-}$: Urban-MSC model below 100 MeV and the Wentzel-WVI + single scattering model above 100 MeV
  - muons and hadrons: Wentzel-WVI + single scattering model
  - ions: Urban-MSC model
- But different MSC stepping algorithms or parameters are used to optimize either speed or accuracy

Constructor	Components	Comments
`G4EmStandardPhysics`	Default: nothing or **_EM0** (QGSP_BERT, 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

Hybrid EM Physics Constructors

- Primary goal: best physics accuracy
- Combine standard and low energy EM models to do this
- More accurate $e^{+/-}$ MSC models (Goudsmit-Saunderson) and/or more accurate stepping algorithms (compared to HEP)
- More stringent continuous step limitations due to ionization
- Recommended for more sensitive applications: medical, space

Constructor	Components	Comments
`G4EmStandardPhysics_option3`	Urban MSC model for all particles	proton/ion therapy
`G4EmStandardPhysics_option4`	most accurate combination of models (particle type and energy); GS MSC model with Mott correction and error-free stepping for $e^{\pm}$)	the ultimate goal is to have the most accurate EM physics description
`G4EmLivermorePhysics`	Livermore models for e^-, γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in `option4`)	accurate Livermore based low energy e^- and γ transport
`G4EmPenelopePhysics`	PENELOPE models for $e^{\pm}$, γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in `option4`)	accurate PENELOPE based low energy e^-, e^+ and γ transport

Experimental EM Physics Constructors

- Usually used only by developers for validation and model improvement
- Main difference is in description of Coulomb scattering (GS, WVI, SS)

Constructor	Components	Comments
`G4EmStandardPhysicsGS`	standard EM physics and the GS MSC model for $e^{\pm}$ with HEP settings	may be considered as an alternative to EM0 i.e. for HEP
`G4EmStandardPhysicsWVI`	WentzelWVI + Single Scattering mixed simulation model for Coulomb scattering	high and intermediate energy applications
`G4EmStandardPhysicsSS`	single scattering (SS) model description of the Coulomb scattering	validation and verification of the MSC and mixed simulation models
`G4EmLowEPPhysics`	Monarsh University Compton scattering model, 5D gamma conversion model, WVI-LE model	testing some low energy models
`G4EmLivermorePolarized`	polarized gamma models	a (polarized) extension of the Livermore physics models

Extracting EM Physics-related Quantities

- You may want to know cross sections, energy loss, etc.
- Use the G4EmCalculator object
  - include the following lines in your application:

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

G4Material* material = G4NistManager::Instance()->FindOrBuildMaterial(matName);
G4double    macXSec  = emCalculator.ComputeCrossSectionPerVolume (energy,
                                                                  partDefinition,
                                                                  procName,
                                                                  material);
G4cout << G4BestUnit(macXSec, "1/Length") << G4endl;
```

  - make sure physics list is initialized first

- A good example of all the things you can do:
  - /examples/extended/electromagnetic/TestEm0
  - see especially RunAction::BeginOfRun() method

EM Processes and Stepping

Continuous-Discrete Processes

- Charged particle processes ionization, bremsstrahlung and multiple scattering are all continuous-discrete
  - discrete part has step limit (path length to next interaction) determined by restricted cross section
  - continuous part has a step limit due to maximum allowed energy loss along the step
  - because of along-step energy loss, kinetic energy is different at pre- and post-step points

Restricted Stopping Power

- Secondary electrons and gammas produced with energies below E^{cut} are not simulated explicitly

- They are described as continuous energy loss along the step and are based on a mean value

- This mean value is the restricted stopping power (mean energy loss along a unit step length)

$$-\frac{\mathrm{d}E}{\mathrm{d}x}_{\text{rest}}(E; E^{\text{cut}}, \ldots) = \int_0^{E^{\text{cut}}} k \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E, ..)\mathrm{d}k$$

Restricted Cross Section

- Electrons and gammas with energies above E^{cut} are simulated explicitly as discrete interactions
- Discrete interaction probability is determined by the restricted cross section

$$\sigma_{\text{rest}}(E; E^{\text{cut}}, \ldots) = \int_{E^{\text{cut}}}^{E} \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E, ..)\mathrm{d}k$$

- This covers only the interactions in which the secondary has kinetic energy above the production threshold

Discrete Part of Step Limit

- Interactions will propose a step length
  - target atom number density is N and atomic interaction cross section is σ (assumed constant for now)
  - p.d.f. of the interaction length *x* is

$$p(x) = N\sigma \exp(-xN\sigma)$$

  - the mean (expected value) of the interaction length *x* is

$$\mathbb{E}(x) = \frac{1}{N\sigma} \equiv \lambda = \frac{1}{\Sigma}$$

where λ is the mean free path and $\Sigma = N\sigma = 1/\lambda$ is the macroscopic cross section

- If there are M independent interactions with Σ_i the interaction with the shortest interaction length x_i is chosen by the simulation

Discrete Part of Step Limit

- Typically, Monte Carlo simulations will sample the path length to the next discrete interaction point using the distribution exp(Σ_t) where Σ_t is the total macroscopic cross section

$$\Sigma_t = \sum_{i=1}^{M} \Sigma_i = N \sum_{i=1}^{M} \sigma_i$$

- Then at the post step point, the type *i* of the discrete interaction is sampled according to the discrete probabilities

$$p(\text{proc} = i) = \Sigma_i / \Sigma_t$$

- But in Geant4, each discrete process proposes an interaction length sampled from its own macroscopic cross section: exp(Σ_i)
  - the process with the shortest interaction length is the one that occurs
- In this way Geant4 already selects at the pre-step point what (if anything) will happen at the post-step point

Discrete Part of Step Limit

- For particles that have ionization and bremsstrahlung the corresponding restricted macroscopic cross sections Σ_{rest} (E, E^{cut}) are used to propose the discrete step limit
- Due to the continuous part (along-step energy losses), the energies at the pre-step and post-step points will be different
- The cross section therefore is generally not constant along the step. This is accounted for by:
  - the addition of a fictitious interaction δ with cross section energy dependence such that

$$\Sigma_i^r(E) + \Sigma_i^\delta(E) = \Sigma_i(\not{E}) \equiv \Sigma_i^{\text{const}} \implies \text{constant along the step}$$

and $\Sigma_i^r(E) \leq \Sigma_i^{\text{const}}$ along the step, which implies that $\Sigma_i^{\text{const}} = \max\{\Sigma_i(E)\}$

- The new constant cross section is used to sample, at the pre-step point, the interaction length to the real or fictitious interaction
- At the post-step point, after energy loss has been accounted for, the probability that the fictitious interaction occurs is

$$p(\delta) = 1 - \Sigma_i^r(E^{\text{post}})/\Sigma_i^{\text{const}}$$

Continuous Part of Step Limit

- Up to now, the discrete part has been considered:
  - each process proposed a step length
  - the shortest of these was selected as a candidate step length
  - corresponding process was selected as the candidate process
  - flag set to indicate that current candidate step length was proposed by discrete part of candidate process
  - a possible energy loss along the step was considered
- Now, G4SteppingManager asks the continuous part of each process to propose its own step limits
  - starting with all the previous (discrete) settings and type flag
  - each proposed continuous limit is compared to the current candidate limit
  - if current continuous step limit is shorter than the current candidate, the candidate step length, process and type flag (continuous) are updated accordingly

Continuous Part of Step Limit

- For particles that have ionization and bremsstrahlung, the following continuous step limit function is used:

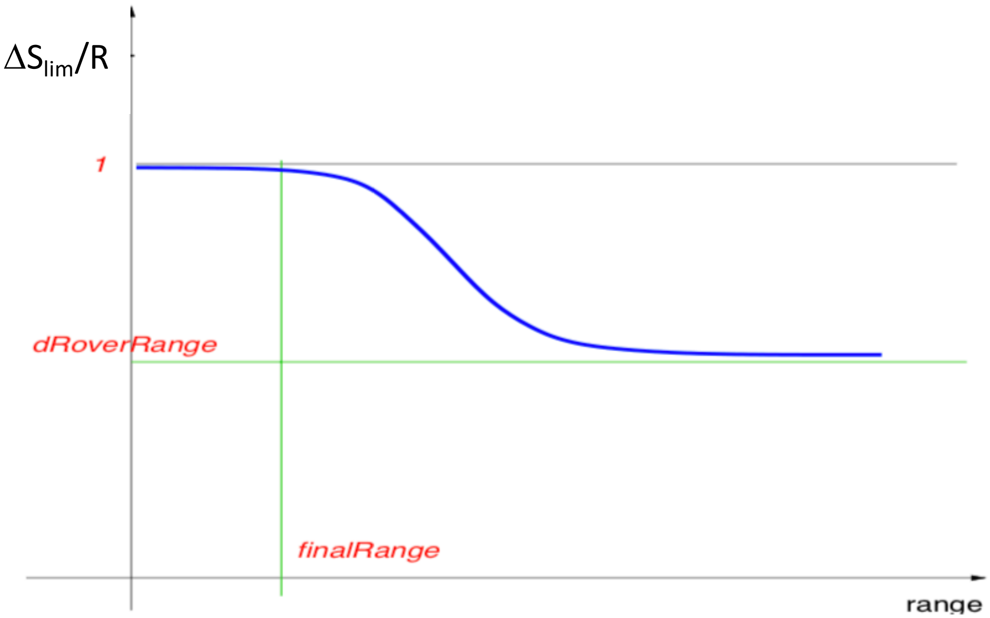
When the particle range $R > \rho_R \equiv finalRange$**:**

$$\Delta S_{lim} = \alpha_R R + \rho_R (1 - \alpha_R)\left(2 - \frac{\rho_R}{R}\right)$$

- **default value:** $\rho_R = 1.0[mm]$
- $\alpha_R \equiv dRoverRange$
- **default value:** $\alpha_R = 0.2$
- **at high energies:** $\Delta S_{lim} \approx \alpha_R R$

When the particle range $R < \rho_R$:

- **low energies:** $\Delta S_{lim} = R$



- Based on restricted range, computed from restricted stopping power

Multiple Scattering and Transportation

Multiple Scattering and Transportation

- Up to now, a candidate physics step length has been selected which is
  - the current maximum of the step lengths proposed by all discrete and continuous processes
  - and we have assumed that the particle will travel this length in a straight line in its original direction
    - to the post-step point where the selected discrete interaction takes place
    - to the post-step point where no discrete interaction takes place, if a continuous interaction proposed the shortest step length

- However, there are two special continuous processes left: transportation (which always occurs) and multiple scattering (which may occur). The end-of-step limitation depends on one of three conditions:
  - the particle has no Coulomb scattering (A)
  - it has Coulomb scattering and is described by a single-scattering model (discrete) (B)
  - it has Coulomb scattering and is described by a multiple scattering model (continuous process) (C)

Transportation

- For particles that do not have Coulomb scattering (A):
  - the only remaining continuous process is transportation
  - it is the last process to propose a step length
  - particle is supposed to be transported the selected distance from the pre-step point along its original direction, according to all the foregoing physics
  - but transportation now gets to propose its step limit:
    - if particle can be propagated to its selected distance without crossing a volume boundary, the transportation process accepts the proposed length
    - otherwise, particle is transported to volume boundary and proposed step length is shortened accordingly

Single Coulomb Scattering

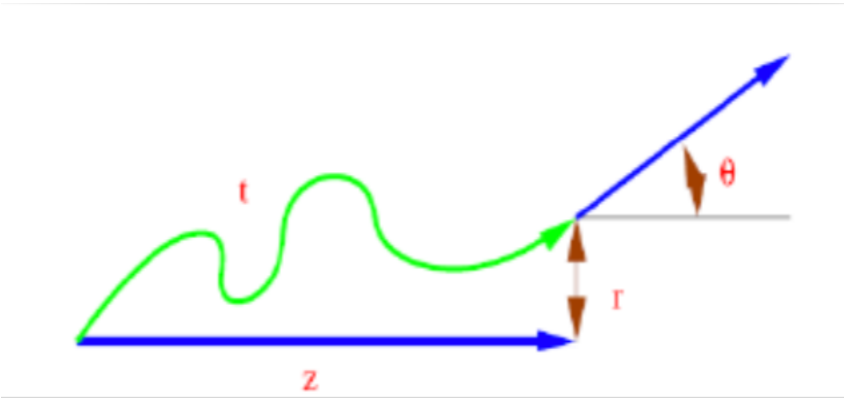
- For particles that have single Coulomb scattering (B)
  - elastic scattering was already accounted for in the step limit since it is included in the list of discrete processes
  - so everything is the same as in case A, since the only remaining continuous process is transportation

A. and B.

$$\mathbf{r}_1 = \mathbf{r}_0 + \mathbf{d}_0 S_t$$

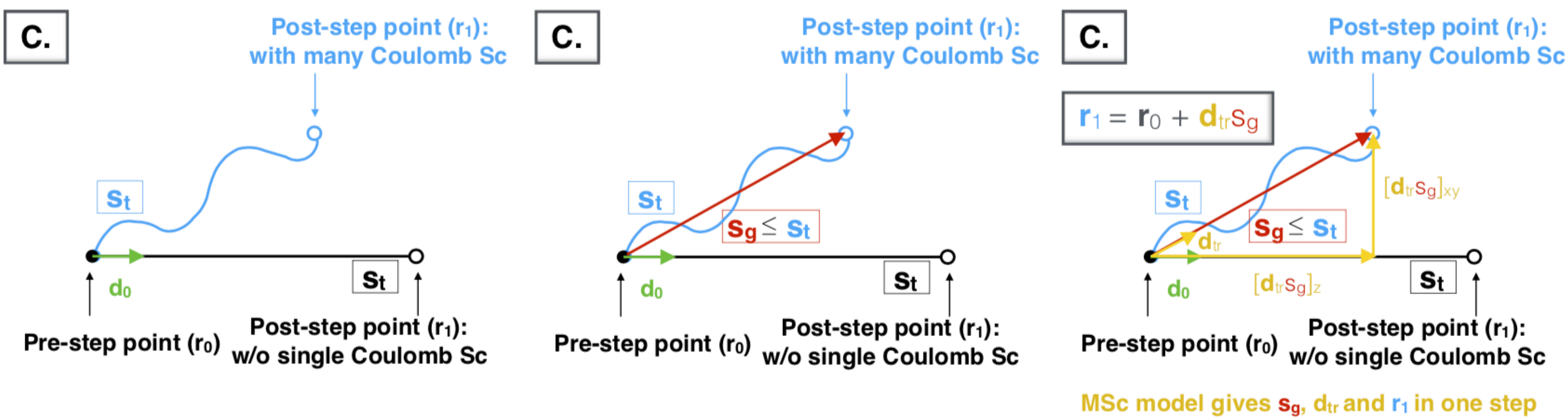
Multiple Coulomb Scattering

- Elastic scattering of charged particles by the atomic potential
- Event-by-event modeling of elastic scattering is feasible only if mean number of interactions per track is less than a few hundred
- Detailed simulation therefore limited to electrons with low kinetic energies (< 100 keV) or thin targets
- Electrons with E_{kin} > 100 keV undergo a large number of elastic while slowing down in thick targets → condensed history approach
- MSC models simulate each particle by allowing individual steps which are much larger than average step length between two successive elastic scatterings → only summed effects are modeled



Multiple Coulomb Scattering

- For particles that have the continuous process multiple Coulomb scattering (C)
  - elastic scattering is not included in the list of discrete interactions → cannot propose an elastic step size
  - with elastic scattering there would be many scatterings and changes of direction along (s_t) the proposed step length → zig-zag trajectory instead of straight line
  - the multiple scattering model provides the real step length (s_g) and final direction of travel d_{tr}



Multiple Coulomb Scattering

- So, with transportation the last, multiple scattering is next to last to provide its step limitation
  - multiple scattering can further limit the current candidate path length s_t
  - after its own step limitation, multiple scattering will change the current true step length s_t to the geometrical step length s_g by computing the corresponding transport distance and transport direction d_{tr}

- After multiple scattering, transportation invokes its step limitation by providing the transport distance s_g instead of the true step length s_t
- From this point on, everything is identical to cases A and B

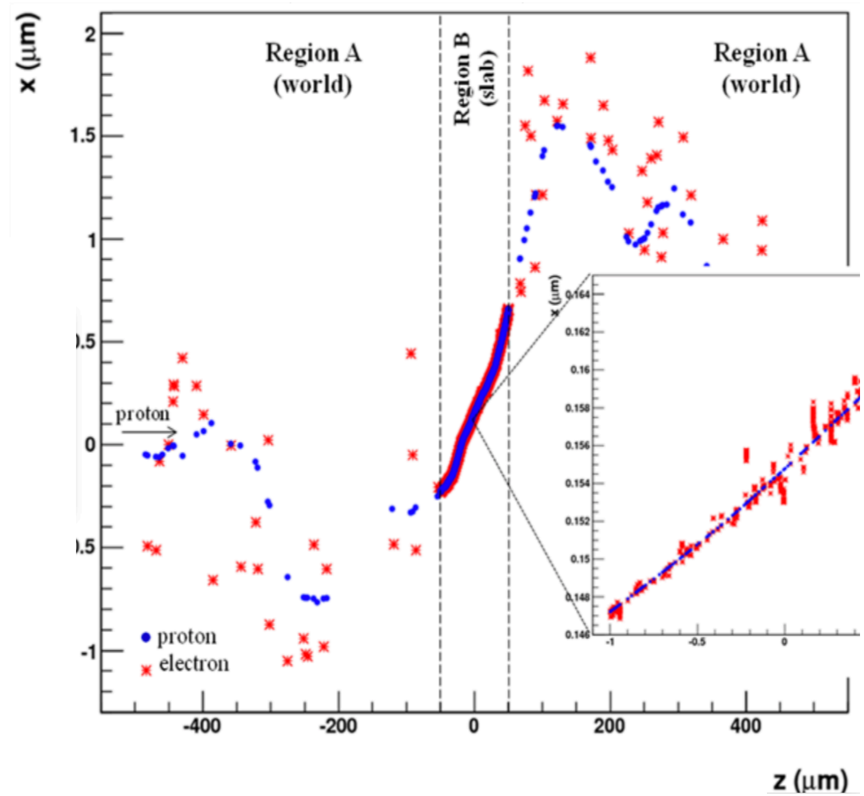
Geant4 Multiple Scattering Models

Model	Particle type	Energy limit	Specifics and applicability
Urban (L. Urban 2006)	Any	-	Default model (i.e. in EM-opt0) for electrons and positrons below 100 MeV, (Lewis 1950) approach, tuned to data, used for LHC production.
Screened Nuclear Recoil (Mendenhall and Weller 2005) TestEm5	p, ions	< 100 MeV/A	Theory based, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of in case of space applications
Goudsmit-Saunderson	e^+, e^-	-	Theory based angular distributions (Goudsmit and Saunderson 1950). Mott correction and several stepping option including error-free (Kawrakov et al. 1998), precise electron transport
Coulomb scattering (2008)	Any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (2009) LowEnergyWentzelVI (2014)	Any	-	Mixed simulation model: MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles. Focused on simulation for muons and hadrons; low-energy model is applicable for low-energy e-
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e^+, e^-	-	Model based on Wentzel DCS + relativistic effects + screening effects for projectile & target.

EM Special Topics

EM Models per Region

- Special models may be used in a particular G4Region, while all other parts of detector use general models
- Example: Geant4-DNA physics in a slice of volume (Region B) nested in World (Region A) which uses standard EM
- Use G4EmConfigurator to select special model, set energy limits within region
- UI commands allow optimization and easy configuration of models
- Can be used on top of any EM constructor:
  - /process/em/AddPAIRegion proton MYREGION pai
  - /process/em/AddMicroElecRegion MYREGION
  - /process/em/AddDNARegion MYREGION opt0

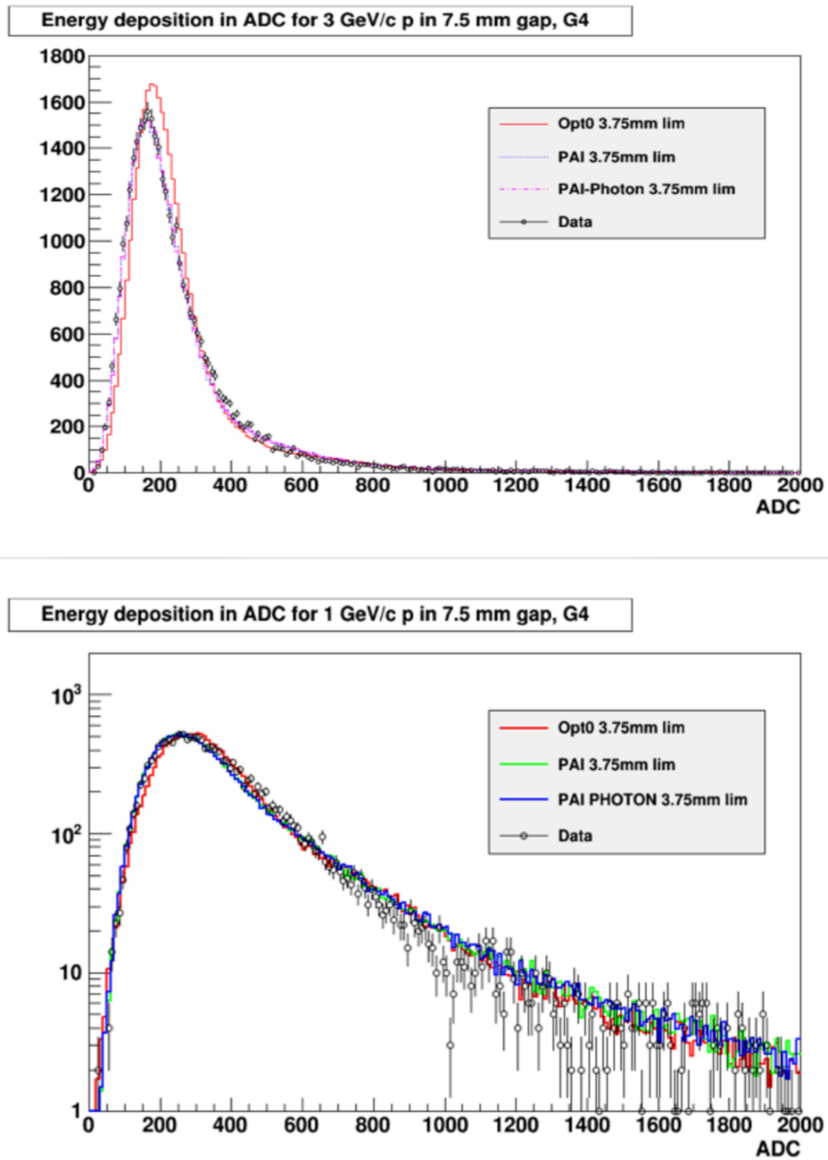


Atomic De-excitation

- Initiated by other physics interactions
  - e.g. photoelectric effect, ionization, radioactive decay
  - interactions leave target atom in excited state
- Evaluated Atomic Data Library (EADL) contains transition probabilities for:
  - radiative transitions (fluorescence photon emission)
  - Auger e- emission (initial and final vacancies are in different shells)
  - Coster-Kronig e- emission (initial and final vacancies are in same shell)
- Due to a common interface, Geant4 atomic de-excitation is compatible with both standard and low energy EM categories
  - can be enabled and controlled by UI commands (before initialization):
    - /process/em/fluo true
    - /process/em/auger true
    - /process/em/augerCascade true
    - /process/em/pixe true
    - /run/initialize
  - fluorescence transition is active by default in some EM constructors

Energy Loss Fluctuation

- For condensed history models:
    - secondary photons (e-) with initial energy below the photon (e-) production threshold, are not generated in bremsstrahlung (ionization)
- Corresponding energy loss (that would have been taken away by these secondaries) is counted as continuous energy loss of primary particle along its step
- Mean value of energy loss along step (due to these sub-threshold secondaries) can be calculated using the restricted stopping power
- So we have the mean – what about the distribution?
    - energy loss fluctuation models will tell us
- Urban and PAI models available in Geant4



Summary

- EM processes and models are available to cover all "long-lived" charged particles and photons
- Energy range covered: few eV up to ~PeV
  - often more than one model required for this coverage
- EM physics constructors build the models, cross sections and processes
  - many pre-packaged constructors have been prepared and tested by Geant4 developers – pick one
  - but you can still build your own!
- Possible to use different EM physics constructors in different regions of your geometry
- Ionization, bremsstrahlung, multiple scattering and transportation couple in a complicated way to limit the final step length and interaction at the post-step point, with process sampling and step limit proposals in the following order:
  - bremsstrahlung and ionization
  - multiple scattering
  - transportation