



Version 10.7

Electromagnetic Physics

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Geant4 beginner course at CERN
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- Electromagnetic Physics Overview
- Electromagnetic physics constructors
- Secondary production thresholds
- Condense history method
- Special topics for electromagnetic physics
- Hands-on

Electromagnetic Physics

ELECTROMAGNETIC PHYSICS OVERVIEW

Located under `source/processes/electromagnetic`

- `/standard`

- γ , e^\pm up to 100 [TeV]
- hadrons up to 100 [TeV]
- ions up to 100 [TeV]

- `/muons`

- up to 1 [PeV]
- energy loss propagator

- `/xrays`

- Cherenkov, transition, synchrotron

- `/highenergy`

- high energy, exotic processes
(γ to $\mu^+\mu^-$ pairs, e^-e^+ to π^- and π^+ , etc.)

- `/polarisation`

- models/processes for polarised beam

- `/lowenergy`

- Livermore library: γ , e^- [10 eV - 1 GeV]
- Livermore based polarised processes
- PENELOPE models (2008 version): γ , e^\pm [100 eV - 1 GeV]
- hadrons and ions up to 1 GeV
- atomic de-excitation (Auger, fluor.)

- `/dna`

- Geant4 DNA modes and processes
- microdosimetry models for radiobiology
- from 0.025 eV to 10 MeV
- many of them material specific (water)

- `/adjoint`

- reverse Monte Carlo: from target to source
- very fast, limited applications

- `/utils`

- EM model/process interfaces and utilities

- Uniform, coherent design approach over the different EM sub-parts:
 - standard and low-energy EM models/processes can be combined
- Physical interactions are described by a processes (`G4ComptonScattering` Compton scattering of photons) :
 - assigned to particle types in the Physics List (`G4ComptonScattering` is assigned to photon)
- There are 3 EM process interfaces to describe 3 set of interactions with different characteristics:
 - `G4VEmProcess` for discrete EM processes (e.g. Compton scattering)
 - `G4VEnergyLossProcess` for the continuous-discrete ionisation and bremsstrahlung photon emission (in the Condensed History description case)
 - `G4VMultipleScattering` for the Condensed History description of the multiple Coulomb scattering (along a given step)
- A given EM process can be described by (one or more) EM model(s):
 - an EM model can handle the interaction in a given energy range
 - naming convention: `G4ModelNameProcessNameModel`
`G4KleinNishinaComptonModel` describes Compton scattering of photons described 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 (post-interaction kinematics, secondary production, etc.)

- Geant4 standard EM interactions for:
 - photon (γ) interactions description in the log output:

```
phot: for gamma SubType= 12 BuildTable= 9
      LambdaPrime table from 200 keV to 100 TeV in 61 bins
      ===== EM models for the G4Region DefaultRegionForTheWorld =====
      LivermorePhElectric : Emin=      0 eV   Emax=    100 TeV   AngularGenSauterGavrila   FluoActive

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 50 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
```

interaction is

$$s(\theta_1)) \left[\sum_{\ell'=0}^{\infty} \frac{2\ell'+1}{4\pi} F_{\ell'} P_{\ell'}(\cos(\theta_2)) \right]$$

obtained above by using the addition

$$\cos(\theta_1)) \left[\sum_{\ell'=0}^{\infty} \frac{2\ell'+1}{4\pi} F_{\ell'} P_{\ell'}(\cos(\theta_1)) \right]$$

$$s(\theta_1)) P_{\ell'}(\cos(\theta_1)) \cos[m(\phi - \phi_1)] \left[\sin \right]$$

contributions coming from the last te

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EM PHYSICS CONSTRUCTORS

- **G4VUserPhysicsList** is the mandatory user class making the general interface between the physics the user needs and the Geant4 kernel
- List of particles: for which EM physics processes are defined
 - $\gamma, e^\pm, \mu^\pm, \pi^\pm, K^\pm, p, \Sigma^\pm, \Xi^-, \Omega^-, \text{anti}(\Sigma^\pm, \Xi^-, \Omega^-)$
 - $\tau^\pm, B^\pm, D^\pm, D_s^\pm, \Lambda_c^+, \Sigma_c^+, \Sigma_c^{++}, \Xi_c^+, \text{anti}(\Lambda_c^+, \Sigma_c^+, \Sigma_c^{++}, \Xi_c^+)$
 - d, t, He3, He4, **Genericlon**, anti(d, t, He3, He4)
 - Baryons and mesons with b- and c- quarks
- The **G4ProcessManager** class of each particle maintains a **list of processes**
- Geant4 provides several configurations of EM physics lists called **constructors** (**G4VPhysicsConstructor**) in the **physics_lists** library of Geant4
- These constructors can be included into a **modular Physics list** in a user application
 - **G4VModularPhysicsList** – an extension of the G4VUserPhysicsList

Geant4 standard EM Physics Constructors for HEP applications

- Description of Coulomb scattering:
 - e^{\pm} : 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 parameters are selected: speed v.s. accuracy

Constructor	Components	Comments
<code>G4EmStandardPhysics</code>	Default: nothing or <code>_EM0</code> (QGSP_BERT, FTFP_BERT,...)	for ATLAS and other HEP simulation applications
<code>G4EmStandardPhysics_option1</code>	Fast: due to simpler MSC step limitation, cuts used by photon processes (FTFP_BERT_EMV)	like one used by CMS; good for crystals but not good for sampling calorimeters (i.e., with more detailed geometry)
<code>G4EmStandardPhysics_option2</code>	like option1 with updated photoelectric model but no-displacement in MSC (FTFP_BERT_EMX)	like one used by LHCb

Combined Geant4 EM Physics Constructors for wide variety of applications

- 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^\pm MSC (Goudsmit-Saunderson(GS)) and/or more accurate stepping algorithms (compared to HEP)
- Stronger continuous step limitation due to ionisation (as others given per particle groups)
- Recommended for more accuracy sensitive applications: medical (hadron/ion therapy), space

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

Experimental Geant4 EM Physics Constructors

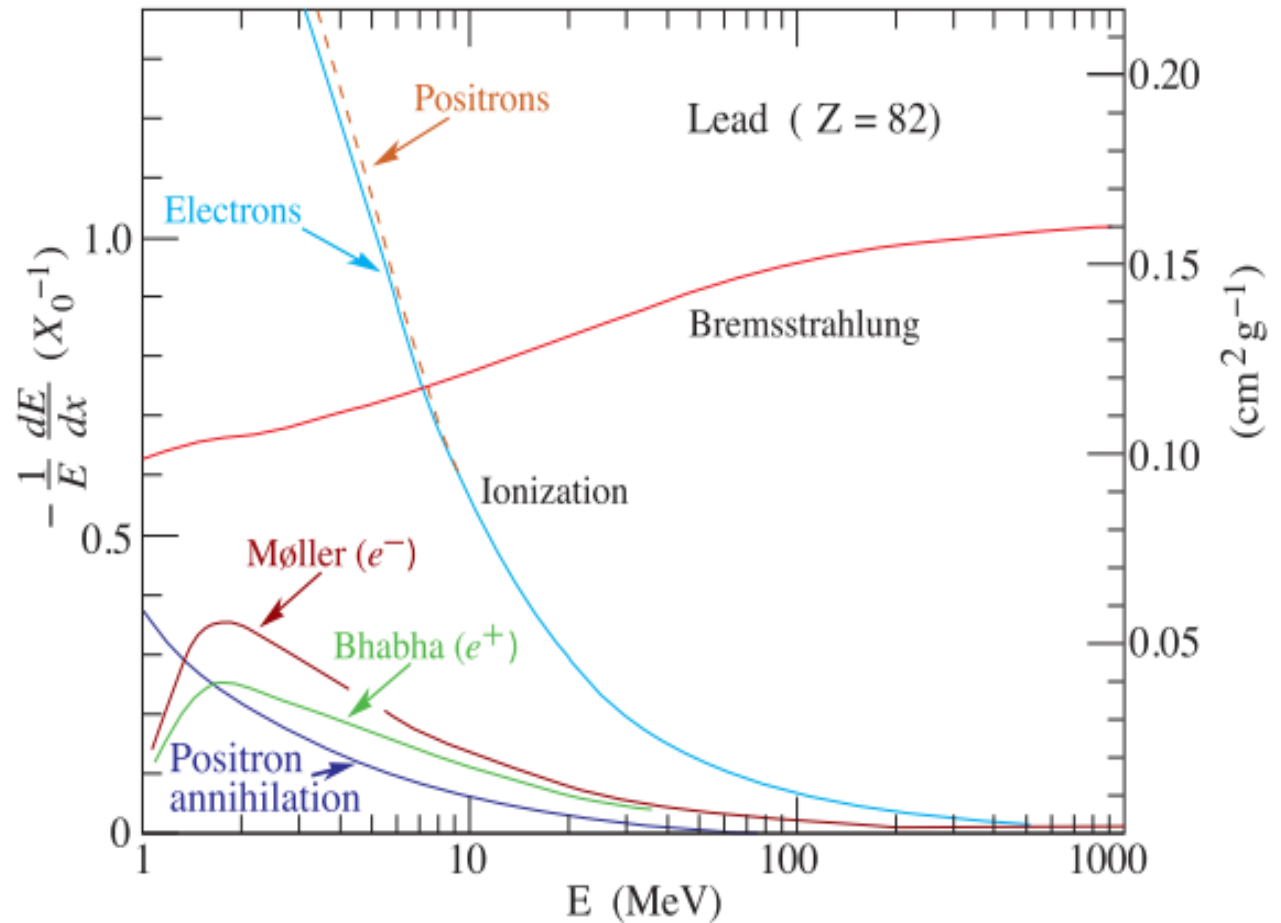
- Supposed to be used only by the developers for validations and model developments
- The main difference is in the description of the Coulomb scattering (GS, WVI, SS)
- New models often are included in these constructors before will be adopted for productions

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

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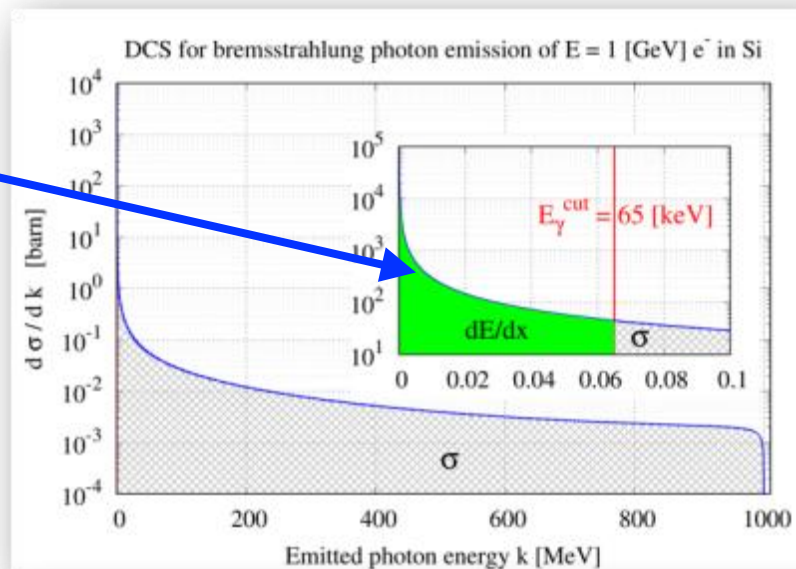
SECONDARY PRODUCTION THRESHOLDS

- At low energies ionisation dominates
- Above critical energy bremsstrahlung is the main process
 - Radiation energy loss exceed ionization energy loss

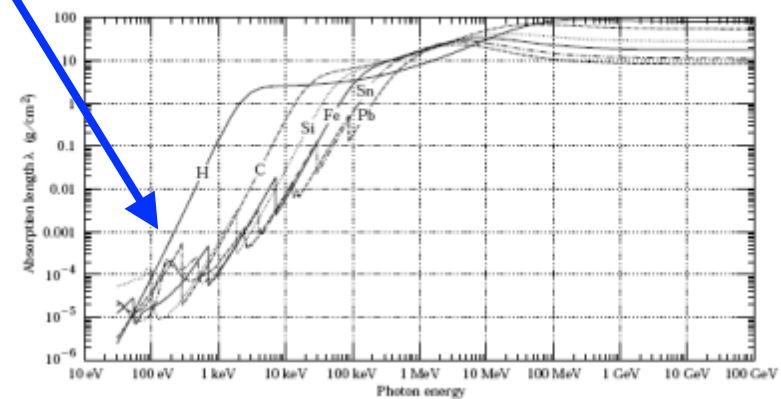


Secondary production threshold

- **Bremsstrahlung photon emission:**
 - low energy photons (k small) will be emitted with high rate DCS $\sim 1/k$
 - generation and tracking of all these low energy photons would not be feasible (CPU time)
 - but low energy photons has a very small absorption length (don't go far)
 - so, if the detector spacial resolution is worst than this length (i.e. all volume boundaries are further), then the followings are *equivalent*:
 - **a:** generating and tracking these low energy photons till all their energy will be deposited
 - **b:** or just depositing the corresponding energy at the creation point (at a trajectory point)
 - note, that we think in energy scale at the model level that translates to length (spacial) at the transport level
 - a secondary production threshold might be introduced (either in energy or length)
 - here is a clear translation from one to the other

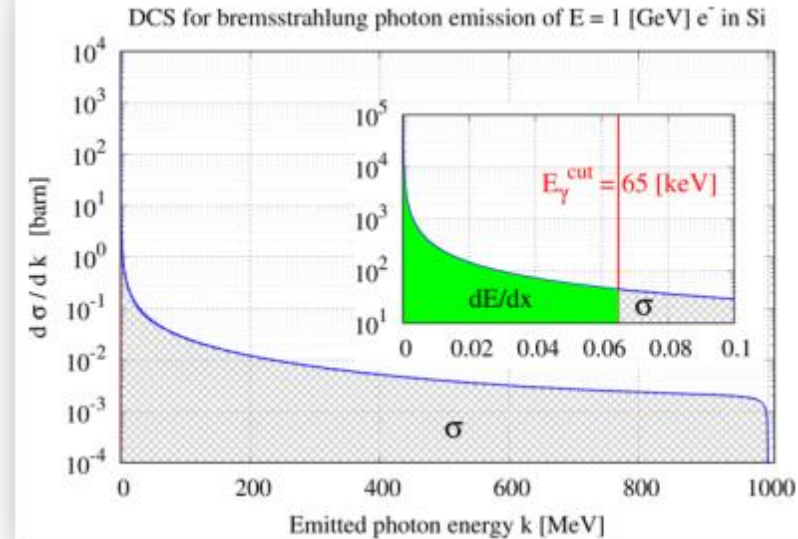


22 27. Passage of particles through matter



Secondary production threshold

- Introduce secondary photon production threshold:
 - *secondary photons*, with initial energy below a gamma production threshold ($k < E_\gamma^{cut}$), are not generated
 - the corresponding energy (that would have been taken away from the primary) is accounted as **CONTINUOUS** energy loss of the primary particle along its trajectory
 - described by the radiative contribution of the (restricted) stopping power (dE/dx): mean energy loss due to sub-threshold photon emissions in unit (path) length
 - when an electron makes a step with a given length L , one can compute the mean energy loss (due to sub-threshold photon emissions) along the step as $L \times dE/dx$ (would be true only if $E = const$ along the step)
 - *secondary photons*, with initial energy above a gamma production threshold ($k < E_\gamma^{cut}$), are generated (**DISCRETE**)
 - the emission rate is determined by the corresponding (**restricted**) cross section (σ)

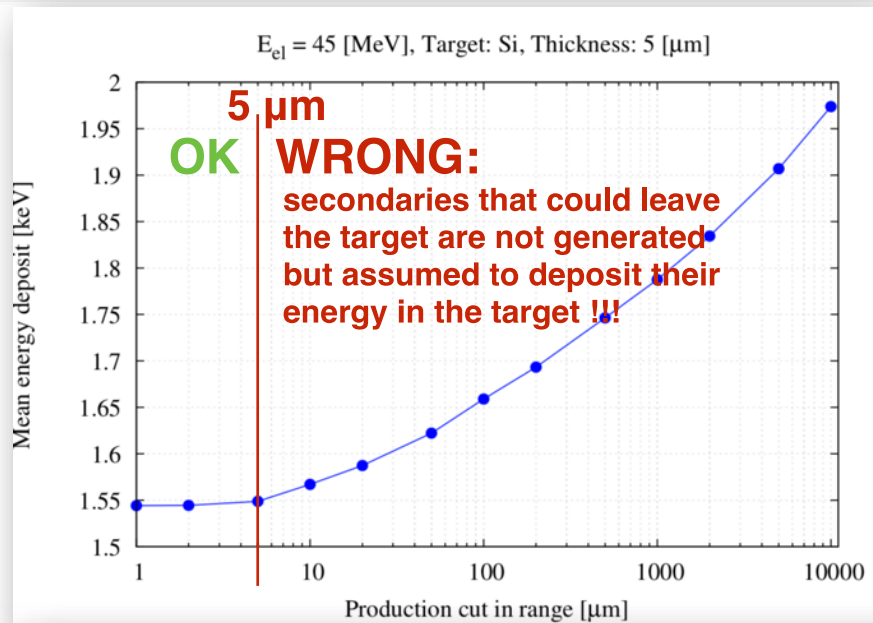


$$\frac{dE}{dx}(E, E_\gamma^{cut}, Z) = \mathcal{N} \int_0^{E_\gamma^{cut}} k \frac{d\sigma}{dk}(E, Z) dk$$

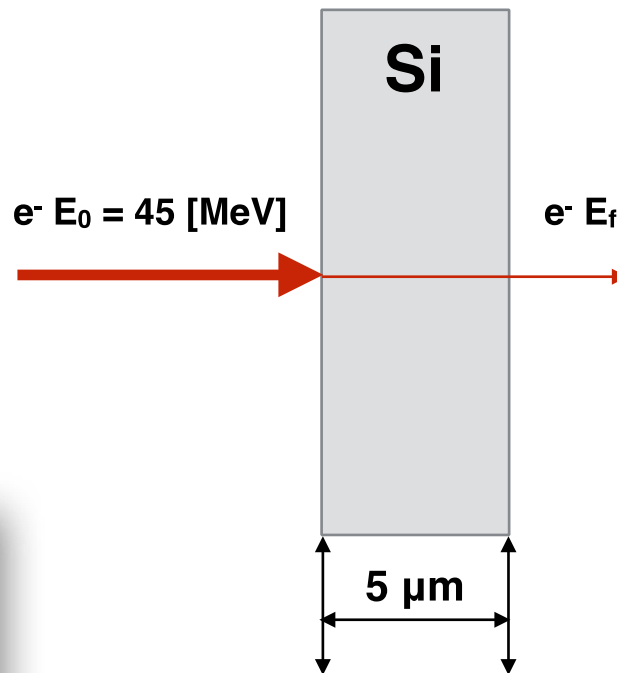
$$\sigma(E, E_\gamma^{cut}, Z) = \int_{E_\gamma^{cut}}^E \frac{d\sigma}{dk}(E, Z) dk$$

- Secondary production thresholds in Geant4:
 - user needs to provide them in length (the default value 0.7 mm in the reference physics lists)
 - its proper value application dependent (size of the sensitive volume, CPU)
- the user can use C++ interface or via UI commands
 - `/run/setCut 0.1 mm` or `/run/setCutForAGivenParticle e- 0.1 mm`
 - internally translated to energies at initialisation (depending on material a particle type)
 - the corresponding energy has a minimum value: default 990 [eV] but the user can set it
 - UI command: `/cuts/setLowEdge 500 eV`
- production threshold defined for gamma, e^- , e^+ and proton secondary particle types
 - 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*
 - gamma and e^- production thresholds might be used (optionally: `/process/em/applyCuts true`) in all discrete EM interactions producing such secondaries e.g., Compton, Photoelectric, etc.
- it's not mandatory to use production thresholds (Condensed History; depends on the model) however, high energy physics simulation would not be feasible without them!

Secondary production threshold



Compute the mean of the energy deposit in the target: E_0 - primary, E_f - final energy



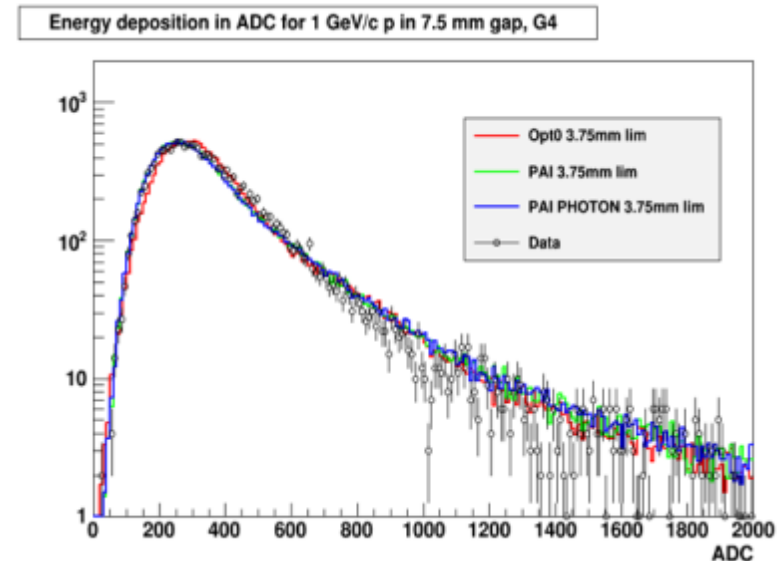
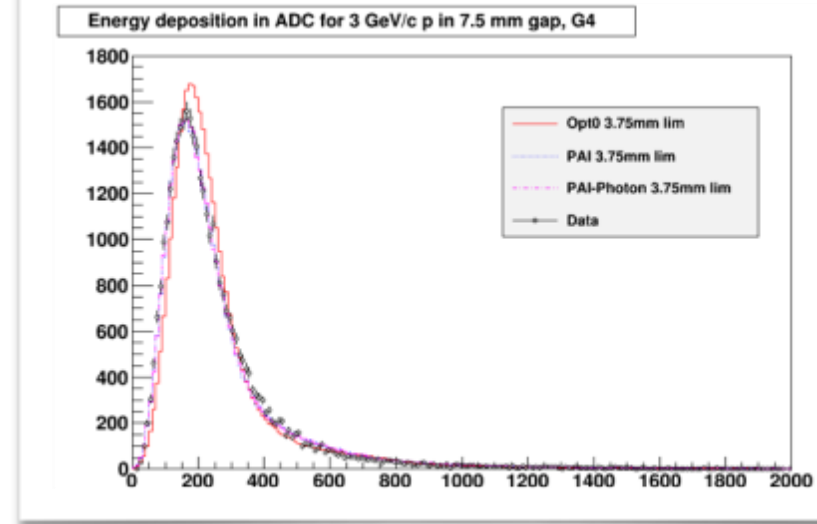
cut [μm]	mean E_{dep}	rms E_{dep}	prod. thres. [keV]		mean num. sec.	
			γ	e^-	γ	e^-
1	1.54423	0.000573911	0.99	0.99	0.0006811	0.1018230
2	1.54443	0.000583879	0.99	2.9547	0.0006843	0.0316897
5	1.54882	0.000605834	0.99	13.1884	0.0006857	0.0068261
10	1.56717	0.000665733	0.99	31.9516	0.0006730	0.0028232
20	1.58734	0.000743473	1.08038	47.8191	0.0006651	0.0018811
50	1.62223	0.000912408	1.67216	80.7687	0.0006557	0.0011304
100	1.65893	0.001108240	2.32425	121.694	0.0006518	0.0007536
200	1.69338	0.001342180	3.2198	187.091	0.0006465	0.000477
500	1.74642	0.001774670	5.00023	337.972	0.0006184	0.0002617
1000	1.78751	0.002219870	6.95018	548.291	0.0006054	0.0001622
2000	1.83440	0.002861020	9.66055	926.09	0.0005786	9.3e-05
5000	1.90700	0.004243030	14.9521	2074.3	0.0005427	4.07e-05
10000	1.97378	0.006036600	20.6438	4007.59	0.000521	2.22e-05

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CONDENSE HISTORY METHOD

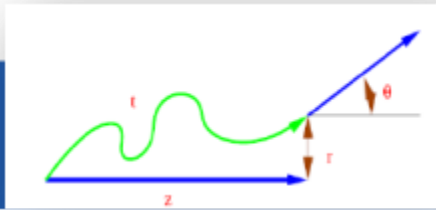
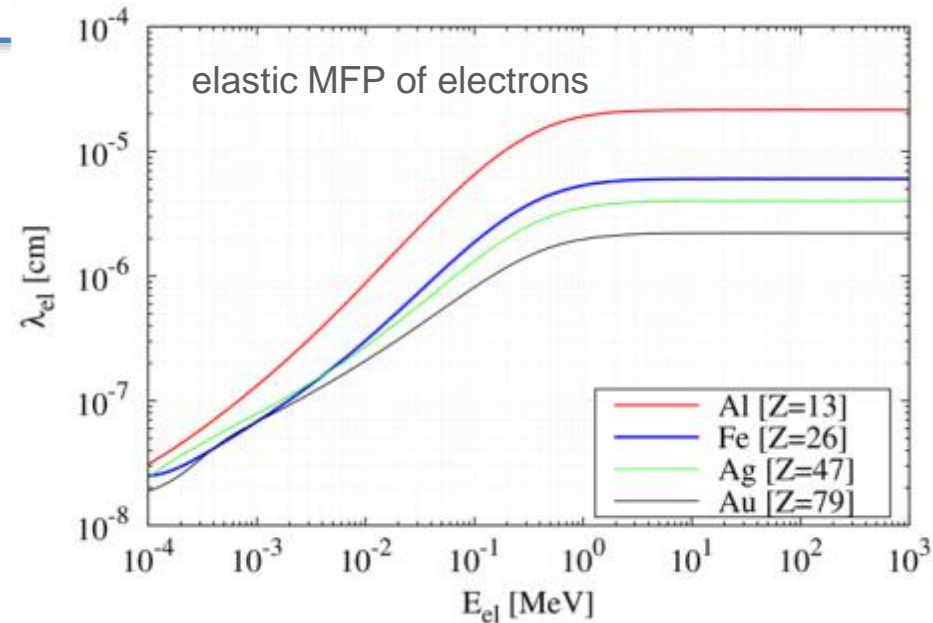
Special EM topics: energy loss fluctuation

- In case of **Condensed History simulation model**:
 - secondary photons (e-), with initial energy below the photon (e-) production threshold are not generated in bremsstrahlung (ionisation)
 - the corresponding energy loss (the energy that would have been taken away by these secondaries) is accounted as continuous energy loss of the primary particle along its step
 - **The MEAN value of the energy loss** along the step (due to these sub-threshold secondary photon (e-) production) can be computed by using the corresponding (restricted) stopping power: MEAN energy loss due to sub-threshold secondary photon (e-) production in bremsstrahlung (ionisation) in unit path length
 - **Energy loss fluctuation models in Geant4**:
Urban and PAI models are available in Geant4



Multiple Coulomb scattering

- **Coulomb scattering**: elastic scattering of charged particles on the atomic potential
- event-by-event modelling of elastic scattering is feasible only if the mean number of interactions per track is below few hundred
- limits of the applicability of the detailed simulation model only for electrons with relatively low kinetic energies (up to $E_{\text{kin}} \sim 100$ keV) or thin targets
- fast ($E_{\text{kin}} > \sim 100$ keV) electrons undergo a high number of elastic collisions during its slowing down in thick targets
- detailed simulation becomes very inefficient, high energy particle transport simulation codes employ condensed history simulation model
- **using an MSC model**, each particle track is simulated by allowing to make individual steps that are much larger than the average step length between two successive elastic interactions (elastic interactions are not accounted at this point)
- the net effects of these high number of elastic interactions such as angular deflection and spacial displacement is accounted at each individual condensed history step by using multiple scattering models



Electromagnetic Physics

SPECIAL EM TOPICS

- EM parameters of any EM physics list may be modified at initialization of Geant4 using C++ interface to the `G4EmParameter` class or via UI commands
- Example of interfaces of `G4EmParameters`:
 - `SetMuHadLateralDisplacement()`
 - `SetMscMuHadRangeFactor()`
 - `SetMscMuHadStepLimitType()`
- Corresponding UI commands:
 - `/process/msc/MuHadLateralDisplacement`
 - `/process/msc/RangeFactorMuHad`
 - `/process/msc/StepLimitMuHad`
- Some other UI commands:
 - `/process/em/deexcitationIgnoreCut true`
 - `/process/eLoss/UseAngularGenerator true`
 - `/process/em/lowestElectronEnergy 50 eV`
 - `/process/em/lowestMuHadEnergy 100 keV`
 -

- Geant4 UI commands to define cuts and other EM parameters
- G4EmCalculator
 - easy access to cross sections and stopping powers (TestEm0)
- G4EmParameters
 - C++ interface to EM options alternative to UI commands
- G4EmSaturation
 - Birks effect (recombination effects)
- G4ElectronIonPair
 - sampling of ionisation clusters in gaseous or silicon detectors
- G4EmConfigurator
 - add models per energy range and geometry region
- G4EmNIELCalculator
 - Helper class to compute single event effects

How to extract Physics ?

- Possible to retrieve Physics quantities using a **G4EmCalculator** object
- Physics List should be **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();
```

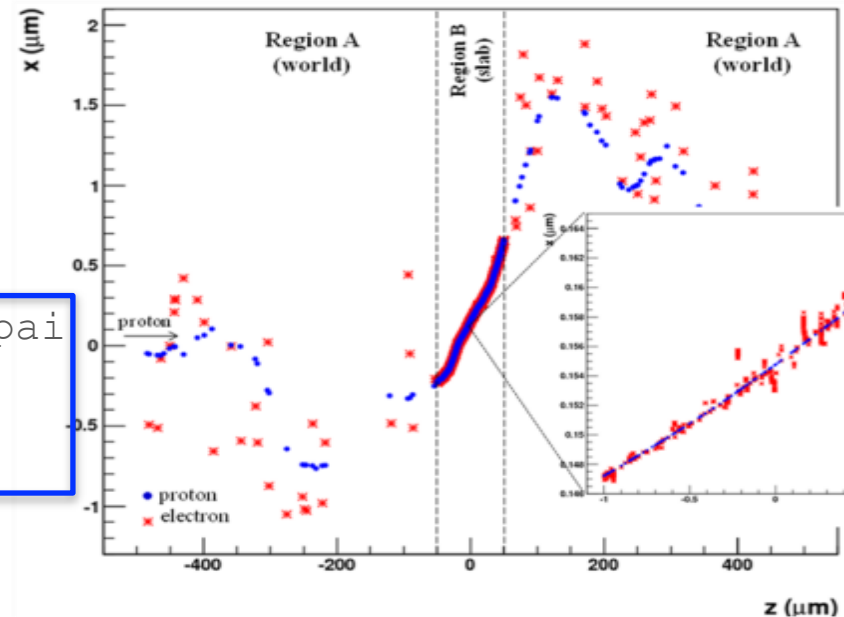
```
G4double massSigma = emCalculator.ComputeCrossSectionPerVolume  
  (energy,particle,procName,material)/density;
```

```
G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
```

- A good example: [\\$G4INSTALL/examples/extended/electromagnetic/TestEm0](#)
Look in particular at the **RunAction.cc** class

- Special EM models can be set to be used only in a given detector **G4Region**
- Example to use Geant4-DNA physics in a given detector region on the top of the standard EM physics:
 - the **G4EmConfigurator** can be used to add Geant4-DNA models
 - the DNA models are used only in the region B. for energies below 10 MeV
 - makes possible CPU and physics performance optimisation
 - the more accurate CPU intense simulation is done only in the region of interest
 - UI commands are available from Geant4 10.2 that allow easy configuration of some models per-region on the top of any EM constructor:

```
/process/em/AddPAIRegion proton MYREGION pai  
/process/em/AddMicroElecRegion MYREGION  
/process/em/AddDNARegion MYREGION opt0
```



- Atomic de-excitation is initiated by other EM physics interactions:
 - e.g., photoelectric effect, ionisation (by e-, p, or ions PIXE)
 - these interactions leave the target atom in an excited state
- The EADL (Evaluated Atomic Data Library) contains transition probabilities:
 - radiative transition - characteristic X-ray emission (fluorescence 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
- Due to a common interface, the atomic de-excitation is compatible with both the standard and the low-energy EM physics categories:

- can be enabled and controlled by UI command (before initialization):

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

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

Electromagnetic Physics

QUESTIONS