Version 10.5

Electromagnetic Physics I.

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Geant4 beginners course at CERN

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- Electromagnetic (EM) physics overview
  - Introduction, structure of Geant4 EM physics
  - Standard EM physics constructors
- Special EM topics:
  - EM models per region
  - Atomic de-excitation
  - Secondary production thresholds
  - Energy loss fluctuation
  - Multiple Coulomb scattering
- Where to find help?

Electromagnetic Physics I.

ELECTROMAGNETIC PHYSICS OVERVIEW

Located under `$G4SOURCE/processes/electromagnetic`

- `/standrad`
  - 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 (e.g. 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

- Geant4 **standard EM** interactions for:
  - **photon (γ)** interactions:
    - conversion to e^--e^+ pairs
    - Compton (incoherent) scattering
    - photoelectric effect
    - Rayleigh (coherent) scattering
    - photo-nuclear interaction (in the hadronic part!)
  - **electron** and **positron** interactions:
    - ionisation
    - Coulomb (elastic) scattering
    - bremsstrahlung photon emission
    - positron annihilation (only for e^+ of course)
    - electron-, positron-nuclear interactions (in the hadronic part!)

- Geant4 **standard EM** interactions for:
  - **photon (γ)** interactions (example):

```
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   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 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
```

- 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 **process**es (e.g. `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`** (e.g. **`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** example:
  - gamma conversion **process** described by **2** 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   AngularGenSauterGavrila  FluoActive

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      Lambda table from 100 eV  to 1 MeV, 7 bins per decade, spline: 1
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      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   LivermoreRayleigh :  Emin=        0 eV    Emax=      100 TeV   CullenGenerator
```

Electromagnetic Physics I.

STANDARD EM PHYSICS CONSTRUCTORS

- Physics **processes** are **assigned to particle**s **in** the **Physics List**
- Particles which EM physics processes can be assigned to:
  - γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\Sigma^{\pm}$, Ξ^{-}, Ω^{-} , anti($\Sigma^{\pm}$, Ξ^{-}, Ω^{-})
  - $\tau^{\pm}$, $B^{\pm}$, $D^{\pm}$, $D_s^{\pm}$, Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{+} , anti(Λ_c^{+}, Σ_c^{+}, Σ_c^{++}, Ξ_c^{+})
  - d, t, ^{3}He, ^{4}He, generic-ion, anti(d, t, ^{3}He, ^{4}He)
- Each static **particle** object **has its** own `G4ProcessManager` that **maintains the** list of **assigned processes**
- The **modular Physics List**s (`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

Geant4 standard EM Physics Constructors for HEP applications

- Description of Coulomb scattering (the same):
  - $e^{\pm}$: **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
- But different MSC stepping algorithms and/or parameters: speed v.s. 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

Combined Geant4 EM Physics Constructors

- 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
`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 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)

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

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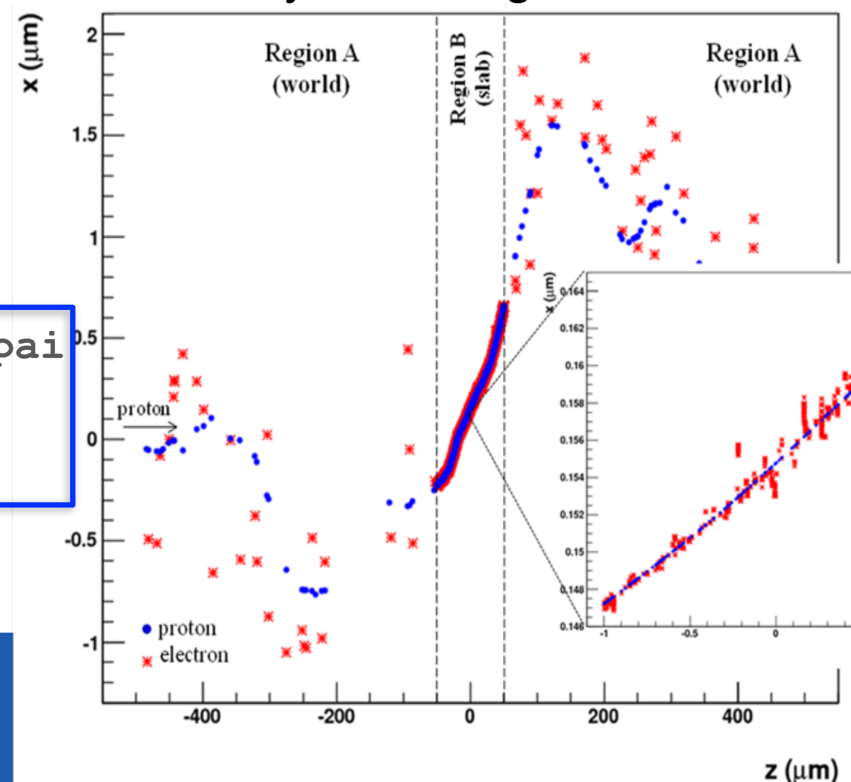
SPECIAL EM TOPICS

- 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:

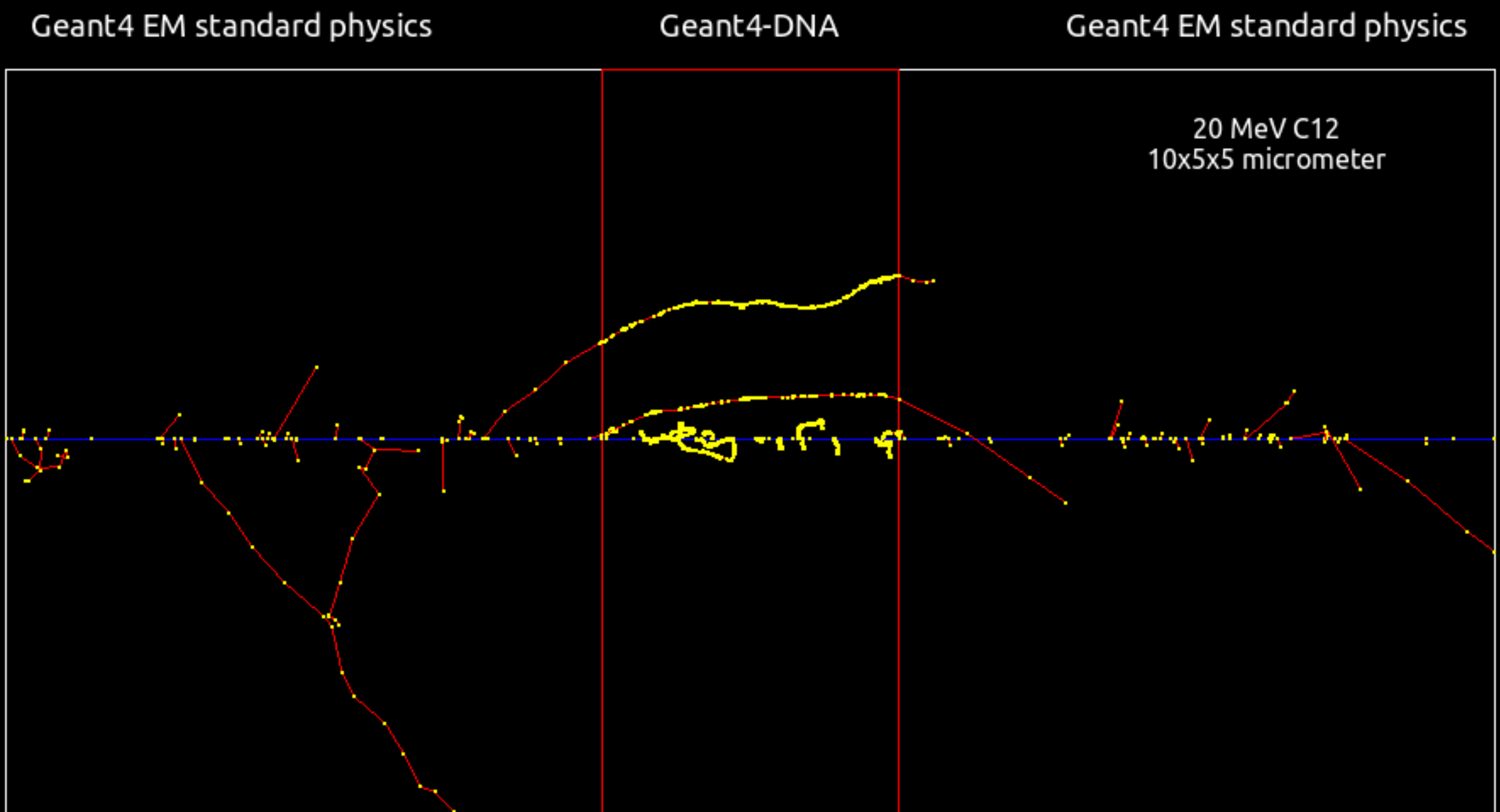
```
/process/em/AddPAIRegion proton MYREGION pai
/process/em/AddMicroElecRegion MYREGION
/process/em/AddDNARegion MYREGION opt0
```



Special EM topics: EM models per region

- 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 `microdosimetry` extended example:




```
/gps/particle ion
/gps/ion 6 12 6
/gps/energy 20 MeV
```

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Prog. Nucl. Sci. Tec. 2 (2011) 898

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ATOMIC DE-EXCITATION

- Atomic de-excitation is initiated by other EM physics interactions:
  - e.g. photoelectric effect, ionisation (by e- or ions e.g. **PIXE**)
  - these interactions leave the target atom in an excited state
- The EADL (Evaluated Atomic Data Library) contains transition probabilities:
  - radiative transition i.e. characteristic X-ray emission (**fluo**ressence 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/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 physics constructor (e.g. the combined EM physics constructors) while others (Auger, PIXE) not

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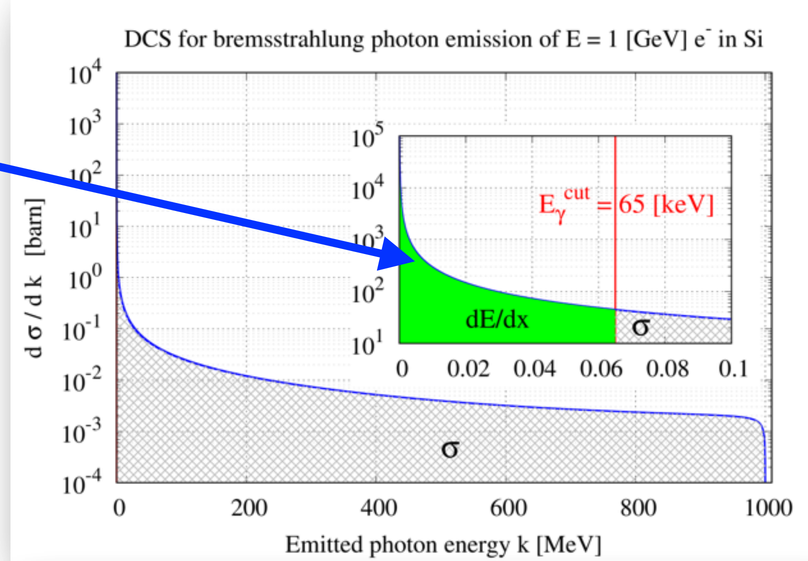
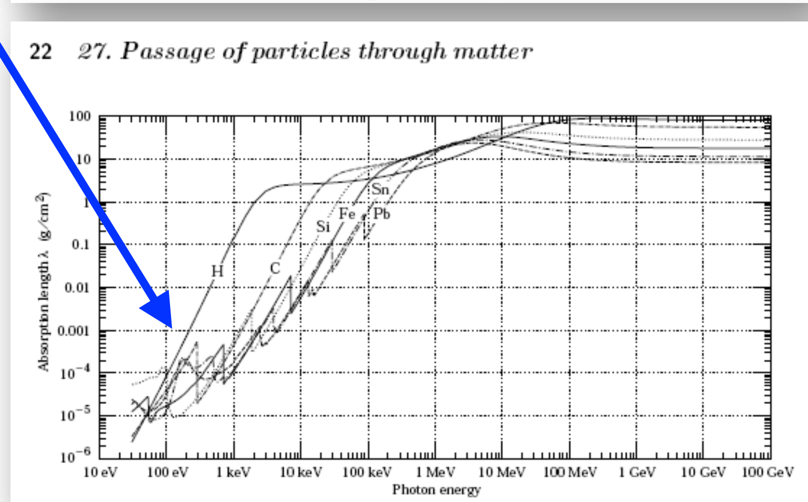
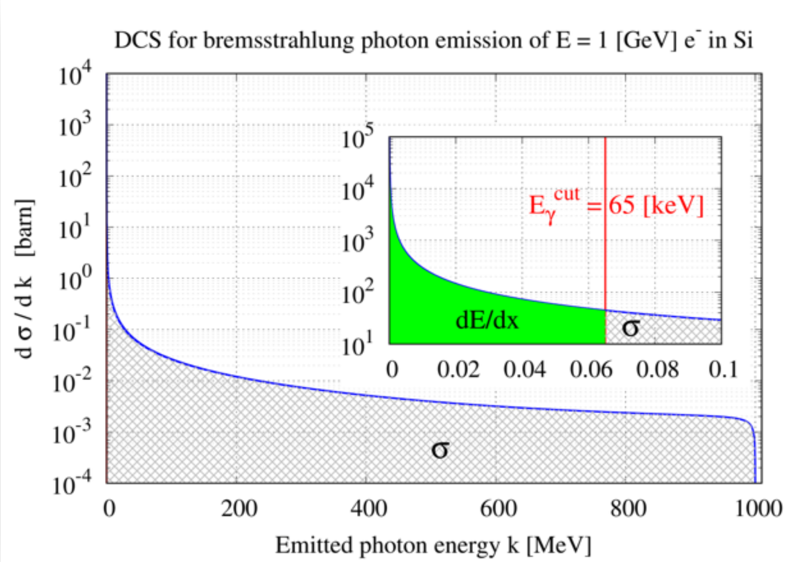
SECONDARY PRODUCTION THRESHOLDS

- **See bremsstrahlung photon emission**:
  - low **energy** photons (k small) will be emitted with high rate i.e. DCS ~ 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 (i.e. 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





- **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
  - i.e. 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*** x ***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**)



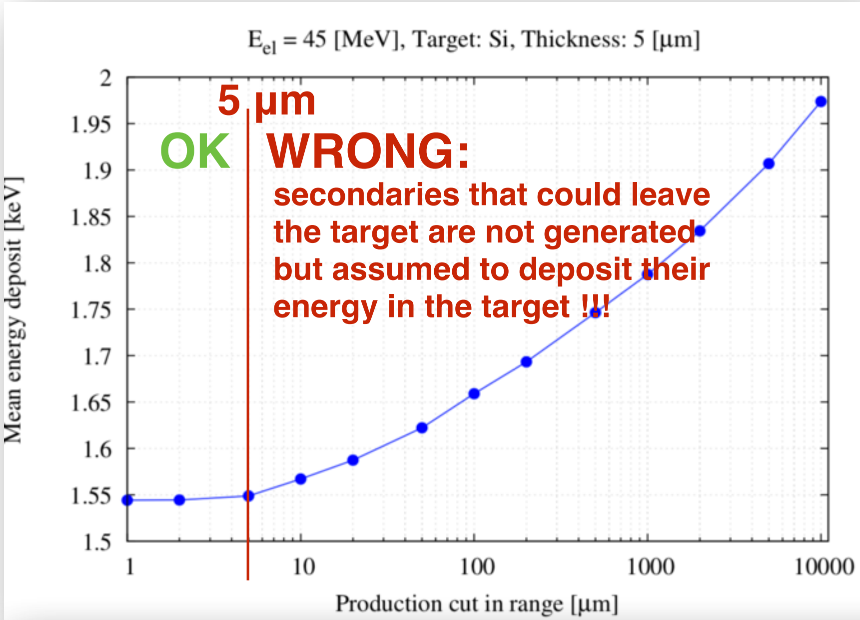
$$\frac{\mathrm{d}E}{\mathrm{d}x}(E, E_{\gamma}^{\mathrm{cut}}, Z) = \mathcal{N}\int_0^{E_{\gamma}^{\mathrm{cut}}} k\frac{\mathrm{d}\sigma}{\mathrm{d}k}(E,Z)\mathrm{d}k$$

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

- **Same concept applies to ionization with the difference**:
  - secondary gamma => secondary e^- production threshold
  - absorption length => range

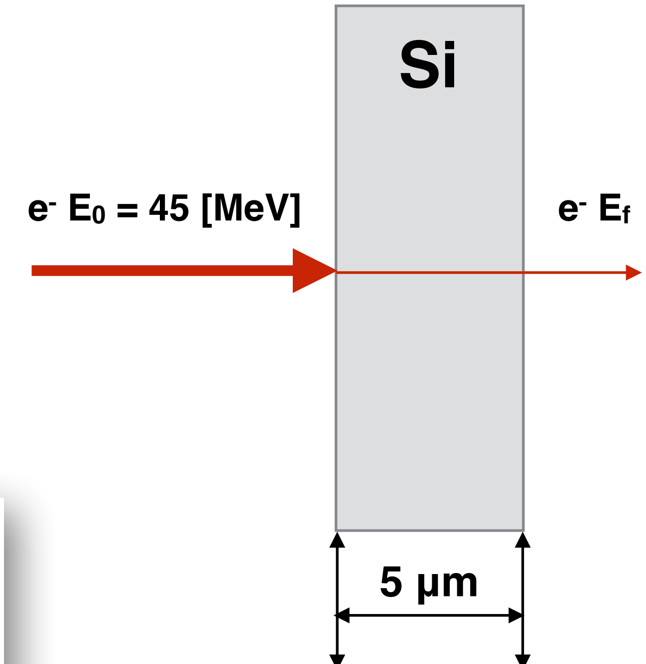
- **Secondary production threshold in energy or length?**
  - there is a clear translation from **energy** to **length** and vice versa
  - **if secondary production threshold** would be given **in energy:**
    - it the will be required in **energy** at the model level (limits in integrals)
    - but its proper value is determined by spacial variables i.e. target size, **length**
    - 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
    - one should set **different secondary production energy threshold** in **different materials** by keeping in mind the corresponding lengths that they translates depending on the particle type
  - easier and more intuitive to **use length** directly (different values per particle types)

- **Secondary production thresholds in Geant4**:
  - user needs to provide them **in length** (with a **default value** of **1.0 [mm]; 0.7 [mm]** for the reference physics lists)
  - its proper value **application dependent** (size of the sensitive volume, CPU)
  - the user need to provide the proper value(s) in the `PhysicsList::SetCuts()` method
    - UI command: `/run/setCut 0.1 mm` or `/run/setCutForAGivenParticle e- 0.1 mm`
  - internally **translated to energies** at initialisation (depending on material an 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 !!!



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

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

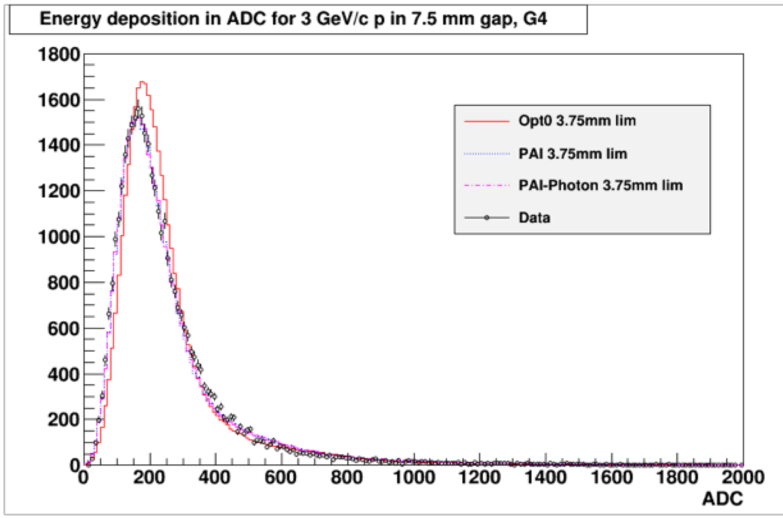


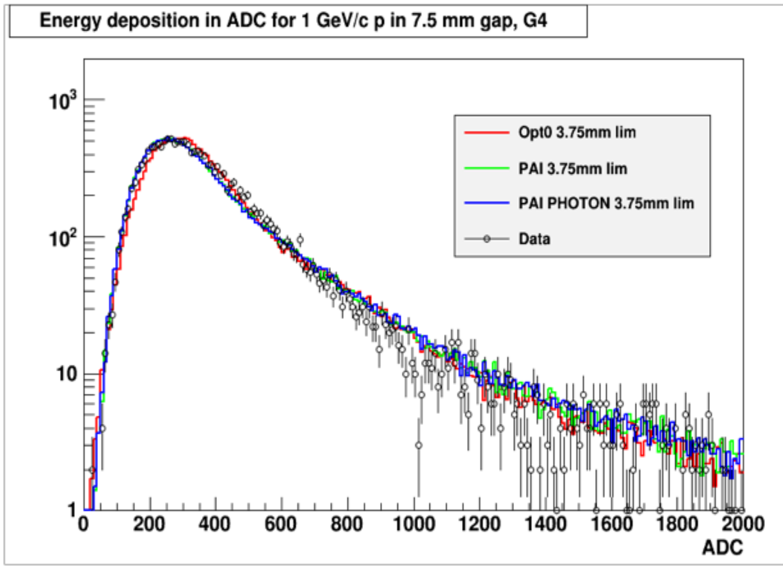
Electromagnetic Physics I.

ENERGY LOSS FLUCTUATION

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 (i.e. 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
  - this **gives only the MEAN value**: **what is the** real sub-threshold energy loss **distribution**?
  - **energy loss fluctuation model** will tell us: **Urban** and **PAI models** are available in Geant4



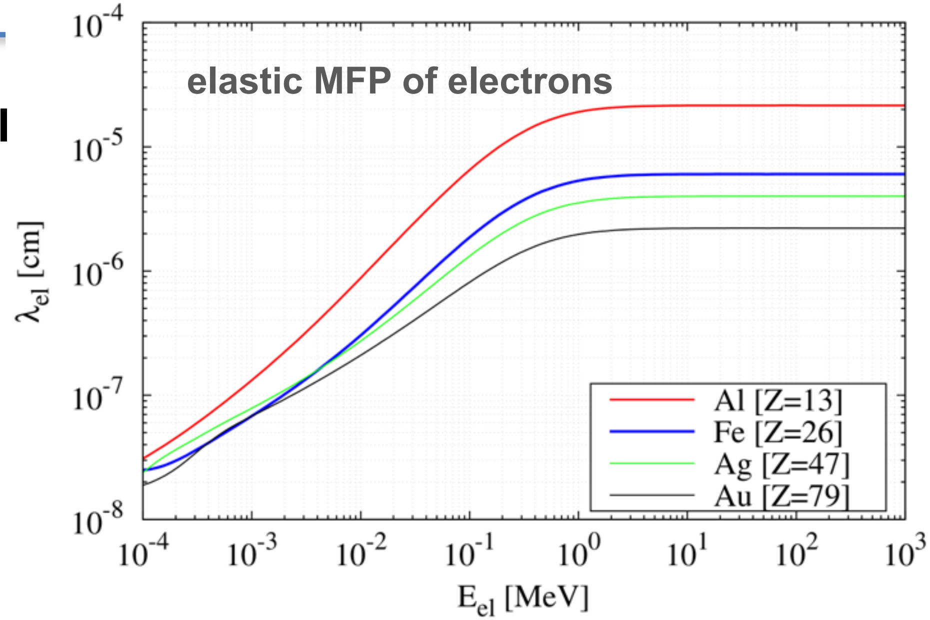


Electromagnetic Physics I.

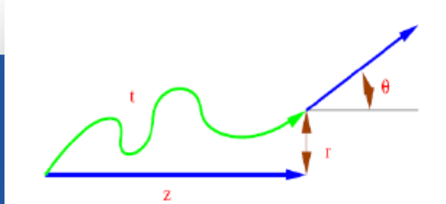
MULTIPLE COULOMB SCATTERING

Special EM topics: 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
- 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



- fast (E_{kin}> ~100 keV) electrons undergo a high number of elastic collisions in the course of its slowing down in tick 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** (i.e. 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**

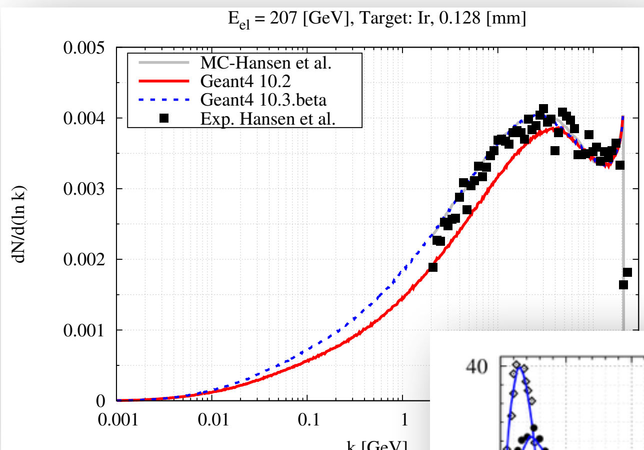


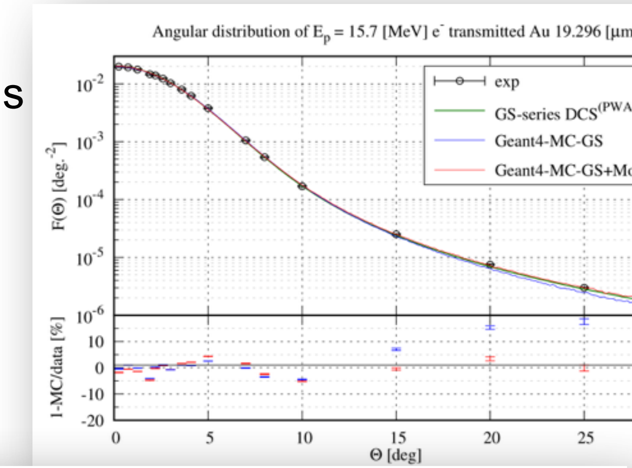
Electromagnetic Physics I.

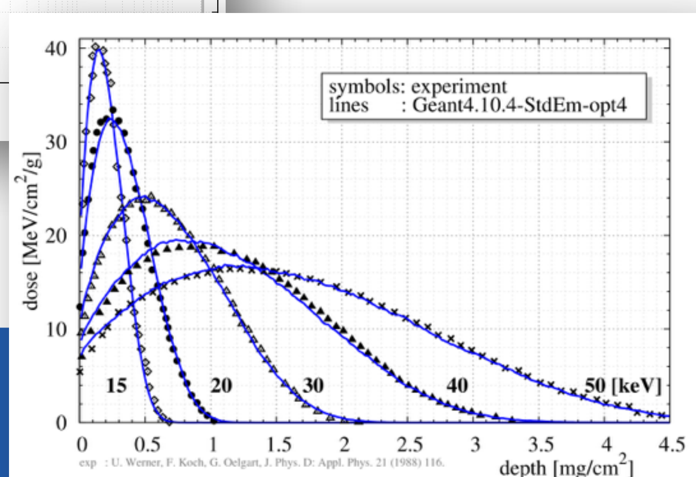
WHERE TO FIND HELP?

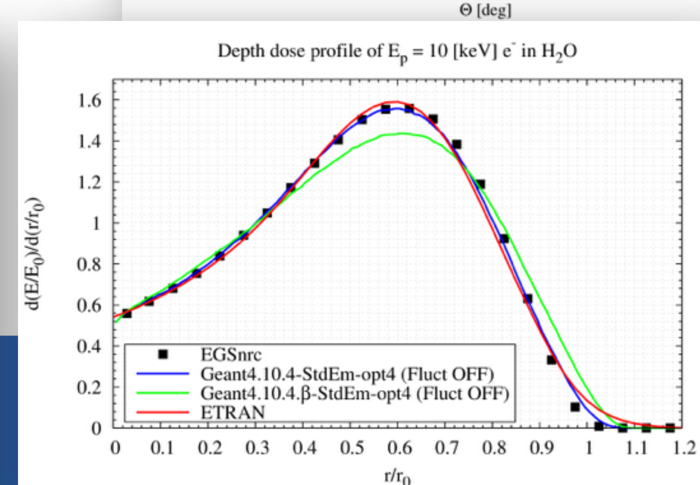
Where to find help?

- The **EM physics** processes and models are **developed and maintained by the electromagnetic working groups** of the **Geant4 collaboration.** See more here!
- The **Geant4 `extended` and `advanced` examples** demonstrate how to use the available EM physics processes, models and functionalities
- Visit the web based **verification and validation tools** (geant-val) (see examples below)
- Visit the **Geant4 HyperNews forum** (here), “electromagnetic processes” section for discussion
- Use the **Geant4 bug report system** (here) in case of problems









Electromagnetic Physics I.

QUESTIONS

Electromagnetic Physics I.

HANDS-ON

Hands-on extra: change physics list by using the `G4PhysicsListFactory` object

```
// IM YOUR MAIN APPLICATION
//
  // create your run manager
#ifdef G4MULTITHREADED
  G4MTRunManager* runManager = new G4MTRunManager;
  // number of threads can be defined via macro command
  runManager->SetNumberOfThreads(4);
#else
  G4RunManager* runManager = new G4RunManager;
#endif
  //
  // create a physics list factory object that knows
  // everything about the available reference physics lists
  // and can replace their default EM option
  G4PhysListFactory physListFactory;
  // obtain the QGSP_BIC_HP_EMZ reference physics lists
  // which is the QGSP_BIC_HP refrence list with opt4 EM
  const G4String plName = "QGSP_BIC_HP_EMZ";
  G4VModularPhysicsList* pList = physListFactory.GetReferencePhysList(plName);
  // (check that pList is not nullptr, that I skipp now)
  // register your physics list in the run manager
  runManager->SetUserInitialization(pList);
  // register further mandatory objects i.e. Detector and Primary-generator
  ...
```