Electromagnetic Physics: special EM topics

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Geant4 advanced course at CERN

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- Energy loss processes:
  - Secondary production thresholds (cuts)
  - Cuts per-region
  - Energy loss fluctuation
  - Continuous step limit
- Models per-region
- Multiple vs single Coulomb scattering
- Where to find help?

Electromagnetic Physics: special EM topics

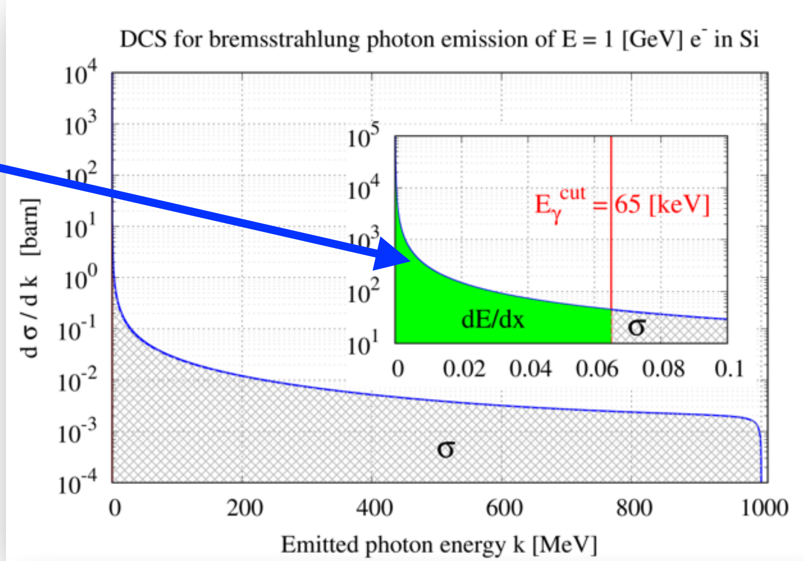
ENERGY LOSS PROCESSES

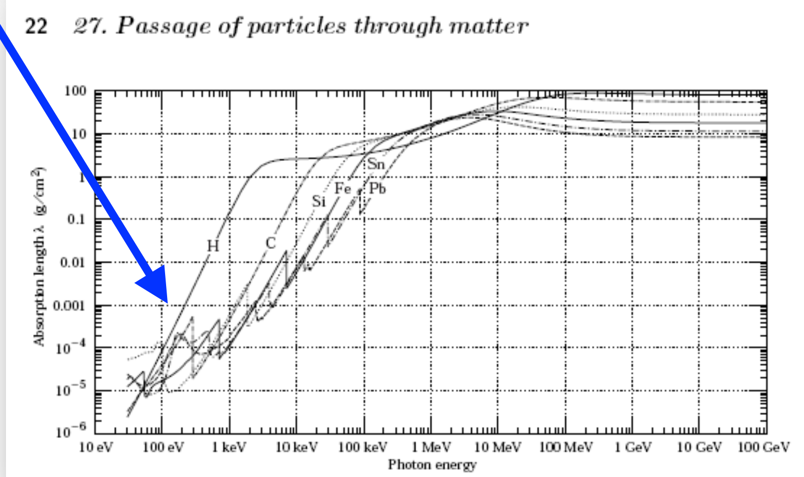
Energy loss processes:

SECONDARY PRODUCTION THRESHOLDS

Energy loss processes: secondary production threshold

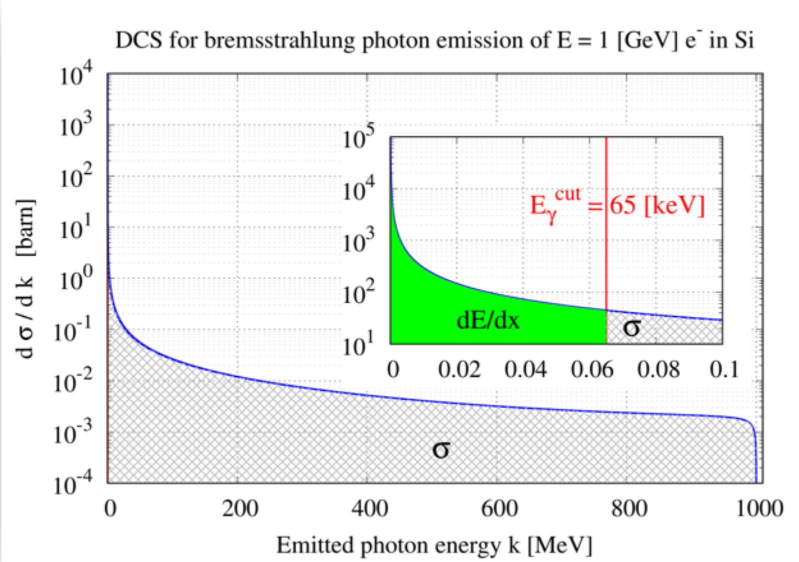
- **Bremsstrahlung photon emission**:
  - low **energy** photons (k small) will be emitted with high rate i.e. DCS ~ 1/k
  - generation and tracking of all these low energy photons would not be feasible (CPU time)
  - but low energy photons has a very small absorption **length** (don't go far)
  - so 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)**
    - there is a clear translation from one to the other





Energy loss processes: secondary production threshold

- **Introduce secondary photon production threshold**:
  - ***secondary photons***, **with** initial **energy below** a gamma production **threshold**(**k<E_γ^{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_γ^{cut}**), are **generated** (***DISCRETE***)
  - the emission rate is determined by the corresponding (restricted) cross section(**σ**)



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

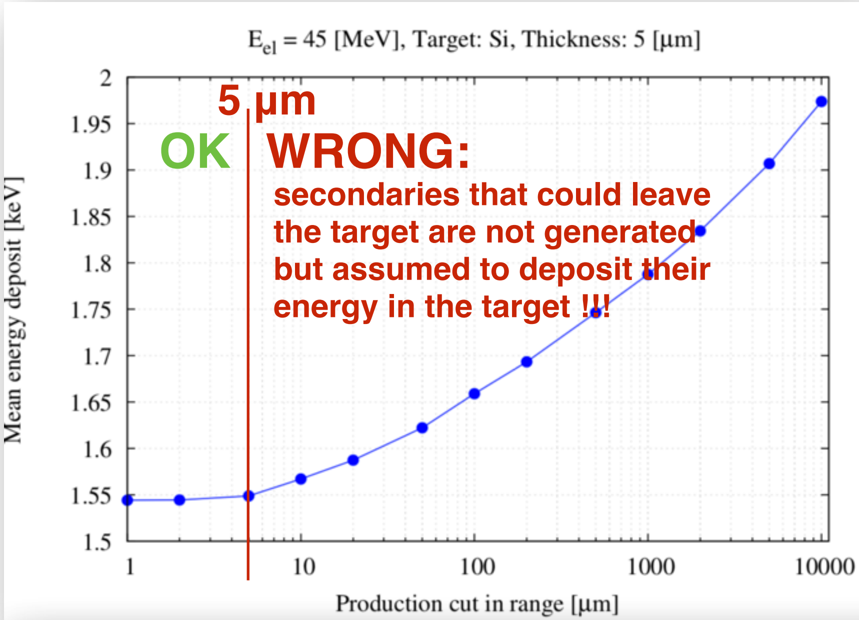
$$\sigma(E, E_\gamma^{\mathrm{cut}}, Z) = \int_{E_\gamma^{\mathrm{cut}}}^{E} \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E,Z)\mathrm{d}k$$

- **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 will be required in **energy** at the model level (limits in integrals) so it's good
    - 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)

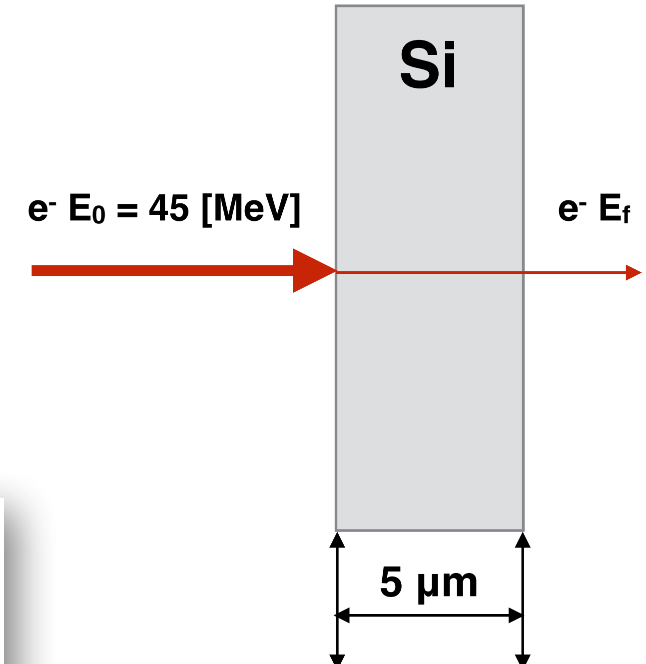
- **Secondary production thresholds in Geant4**:
  - user needs to provide them **in length** (with a **default value** of **1.0 [mm]; 0.7 [mm]** for the reference physics lists)
  - its proper value **application dependent** (size of the sensitive volume, CPU)
  - the user needs to provide the proper 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 **ionisation**
    - 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 !!!

Energy loss processes: secondary production threshold (**EXAMPLE)**



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



- **Secondary production cuts vs tracking cut:**
  - there is no tracking cut in Geant4 !
  - Geant4 will "range-out" the particles properly: appropriate final positions (see more in slide #17)
  - however, the user can easily introduce any limits on tracking (see the lecture on ***User classes***)
  - a kinetic energy limit has been introduced recently:
    - only for computing performance reasons: to kill low energy "loopers" (low energy charged particles moving in low density material in external magnetic field)
    - this kinetic energy limit can be set to any (even to zero) energy values
    - different values for e^-,e^+ and for hadrons, muons
    - UI commands:

```
/process/em/lowestElectronEnergy 100 eV
/process/em/lowestMuHadEnergy 10 keV
```

  - particles are killed when their kinetic energy drops below the limit and their energy is deposited (at the given point!)

Energy loss processes:

CUTS PER REGION

- **Secondary production thresholds per detector region**:
  - our example (slide #9) was very simple but usually (HEP) detectors are complex
  - different parts of a complex detector might require modelling with different level of details and have **different spacial resolution**
  - the user can define different detector `G4Region`-s and associate `G4LogicalVolume`(s) to them (as was shown in the ***Geometry*** lecture)
  - secondary production threshold values (as well as user limits) can be given per detector region
  - in the `DetectorConstruction::Construct()` method of `examples/extended/electromagnetic/TestEm3`:
  - (don't forget to include the `G4Region.hh` and `G4ProductionCuts.hh` headers)

```
// 1. Create a region with a name of "Our-Region"
G4Region* aRegion = new G4Region("Our-Region");
// 2. Set a (0.1 mm) secondary production threshold to this region:
//    # note: that the G4Region can be accessed by its name as
//    G4Region* theRegion = G4RegionStore::GetInstance()->GetRegion("Our-Region");
G4double      cutValue = 0.1 * CLHEP::mm;
G4ProductionCuts* cuts = new G4ProductionCuts();
cuts->SetProductionCut(cutValue);
aRegion->SetProductionCuts(cuts);
// 3. Add the gap (liquid Ar) to this region (as root logical volume)
aRegion->AddRootLogicalVolume(fLogicAbsor[2]);
```

Energy loss processes: cuts per-region

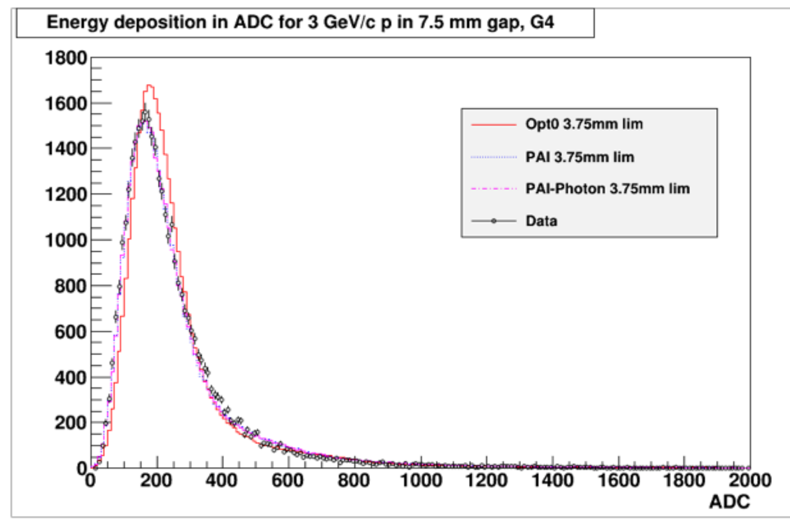
```
/run/setCut 0.7 mm
/run/initialize
/tracking/verbose 0
/run/beamOn 100

========= Table of registered couples ==============================

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 keV
 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 keV
 Region(s) which use this couple :
    Our-Region

====================================================================
```

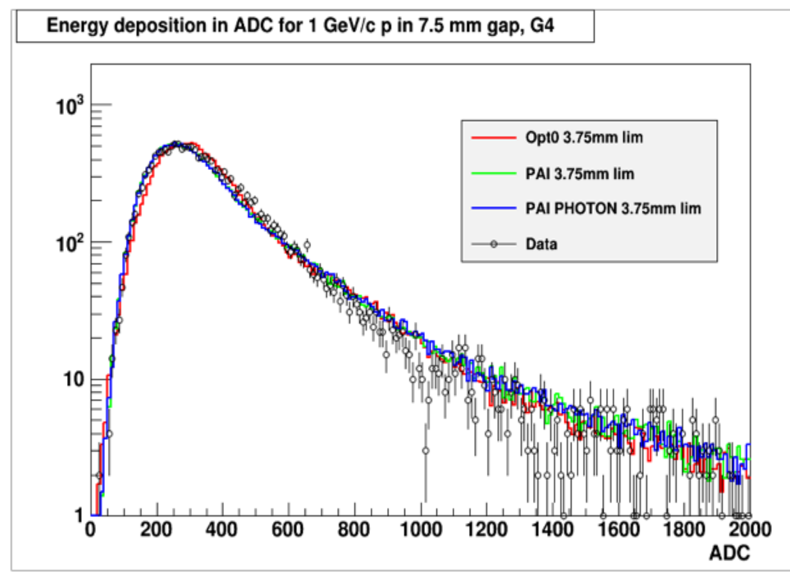
Energy loss processes:

ENERGY LOSS FLUCTUATION

Energy loss processes: 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





Energy loss processes:

CONTINUOUS STEP LIMIT

- In case of **Condensed History** simulation model:
  - charged particles (continuously) lose energy while moving from the pre- to the post-step point
  - the energy, lost in a single simulation step, will be limited in order to preserve the stability of the simulation even in the presence of energy loss
  - this implies a continuous step limit for charged particles (beyond the discrete one determined by the restricted cross section)
  - this continuous step limit is determined by the following function:

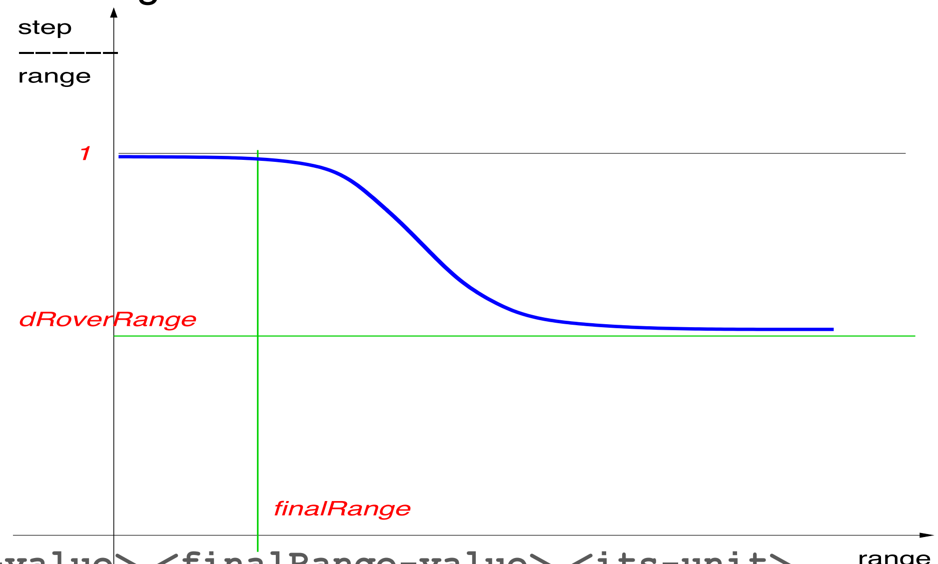
When the particle range $R > \rho_R \equiv finalRange$**:**

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

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



- UI command to set the parameters:

```
/process/eLoss/StepFunction <dRoverRange-value> <finalRange-value> <its-unit>
/process/eLoss/StepFunctionMuHad" <dRoverRange-value> <finalRange-value> <its-unit>
```

- the lower the `finalRange` value the “later” (in range) the particle will be ranged-out
- the lower the `dRoverRange` value the smaller energy losses (steps) will be allowed

- Default step function:

```
eIoni:   for  e-    SubType= 2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      finalRange(mm)= 1, dRoverRange= 0.2, integral: 1, fluct: 1, linLossLimit= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha :  Emin=        0 eV    Emax=      100 TeV
```

- Applying the UI command:

```
/process/eLoss/StepFunction 0.15 0.1 mm
```

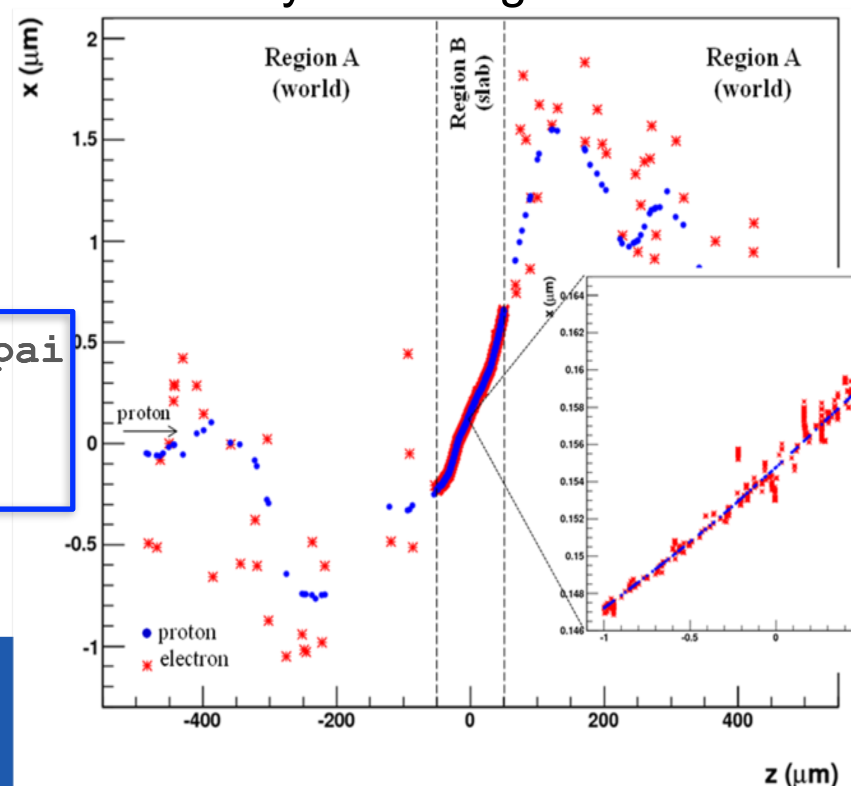
```
eIoni:   for  e-    SubType= 2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      finalRange(mm)= 0.1, dRoverRange= 0.15, integral: 1, fluct: 1, linLossLimit= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha :  Emin=        0 eV    Emax=      100 TeV
```

Electromagnetic Physics: special EM topics

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 `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
```



- Using our previous `/examples/extended/electromagnetic/TestEm3` region with the name "`Our-Region`" (see slide #12)
- Changing the default `Moller-Bhabha` model for e- ionisation in "`Our-Region`" to `PAI` model:
  - using G4EmConfigurator and working directly in the code (physics list or CTR)

```
void G4EmConfigurator::SetExtraEmModel(const G4String& particleName,
                                       const G4String& processName,
                                       G4VEmModel* mod,
                                       const G4String& regionName,
                                       G4double emin,
                                       G4double emax,
                                       G4VEmFluctuationModel* fm)
```

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

  ph->RegisterProcess(new G4eMultipleScattering(), particle);

  // 1. Create the process with the default ionisation model
  G4eIonisation* eIoni = new G4eIonisation("eIoni");
  // 2. Register process for the particle (i.e. for the e-)
  ph->RegisterProcess(eIoni, particle);
  // 3. Create the extra EM model (i.e. the PAI model)
  G4PAIModel* thePAImodel = new G4PAIModel();
  // 4. Add the extra EM model for e- in "Our-Region"
  G4EmConfigurator* emConfig = G4LossTableManager::Instance()->EmConfigurator();
  emConfig->SetExtraEmModel("e-", "eIoni", thePAImodel, "Our-Region", 10*eV, 10*TeV, thePAImodel);
```

  - or the **UI command** (recommended): **/process/em/AddPAIRegion e- Our-Region pai**

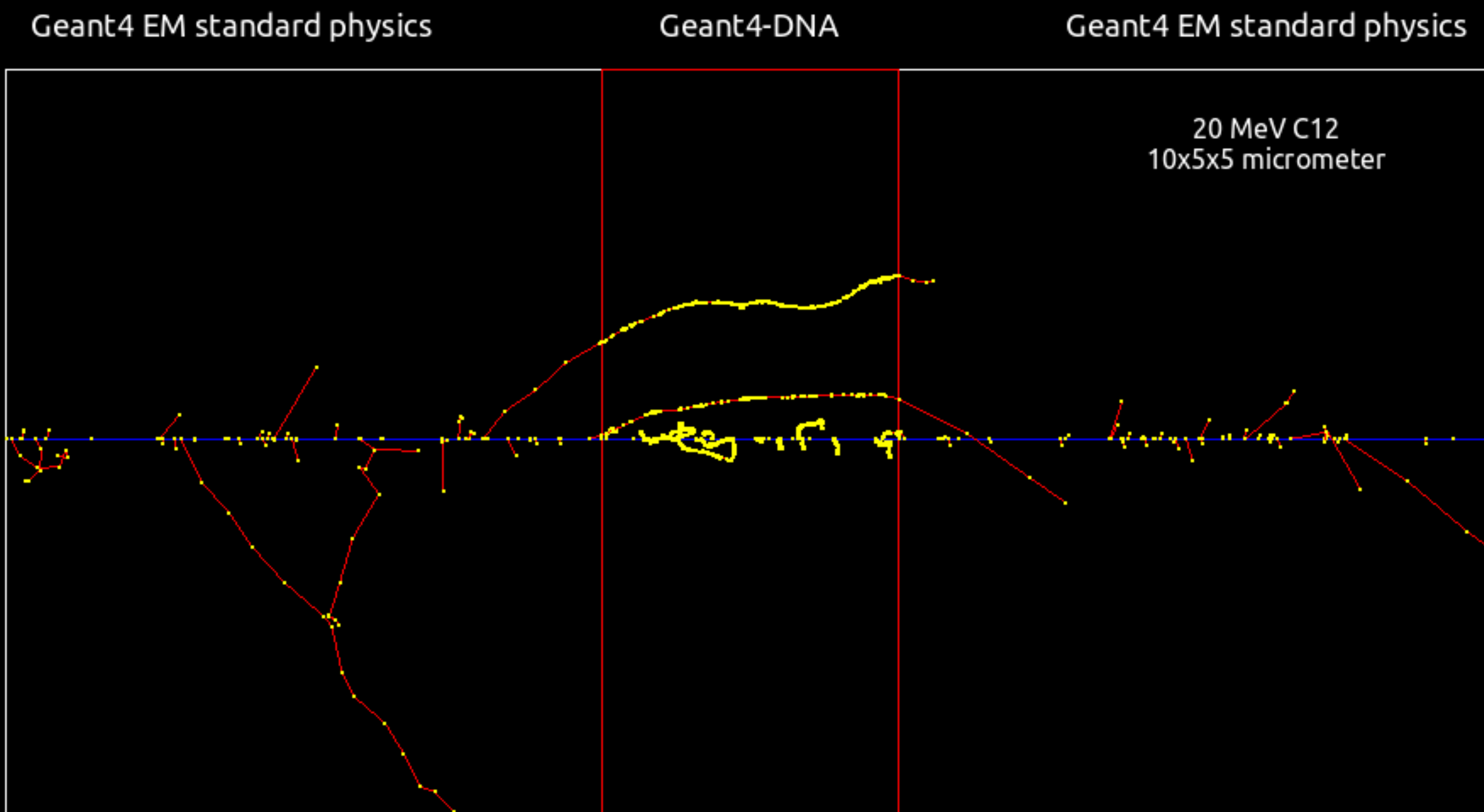
- Using our previous `/examples/extended/electromagnetic/TestEm3` region with the name “`Our-Region`” (see slide #12)
- Changing the default `Moller-Bhabha` model for e- ionisation in “`Our-Region`” to `PAI` model:

```
eIoni:   for  e-    SubType= 2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      finalRange(mm)= 1, dRoverRange= 0.2, integral: 1, fluct: 1, linLossLimit= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha :  Emin=        0 eV    Emax=      100 TeV
```

```
eIoni:   for  e-    SubType= 2
      dE/dx and range tables from 10 eV  to 10 TeV in 240 bins
      Lambda tables from threshold to 10 TeV, 20 bins per decade, spline: 1
      finalRange(mm)= 1, dRoverRange= 0.2, integral: 1, fluct: 1, linLossLimit= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        MollerBhabha :  Emin=        0 eV    Emax=       10 TeV
      ===== EM models for the G4Region  Our-Region ======
                 PAI :  Emin=        0 eV    Emax=       10 TeV   deltaVI
```

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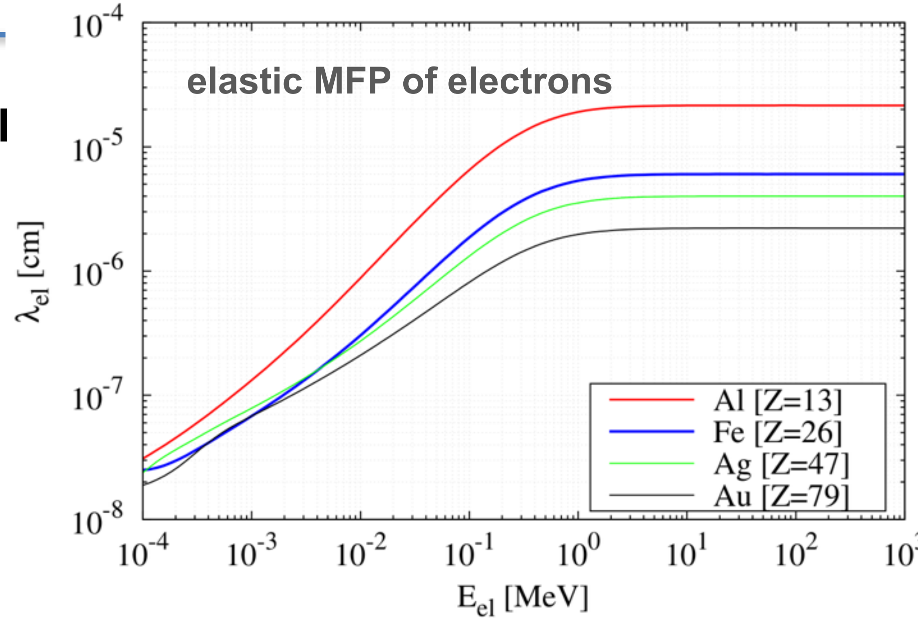
Prog. Nucl. Sci. Tec. 2 (2011) 898

Electromagnetic Physics: special EM topics

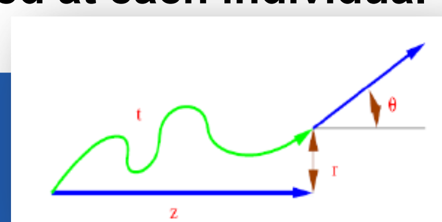
MULTIPLE COULOMB SCATTERING

Electromagnetic Physics: 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**



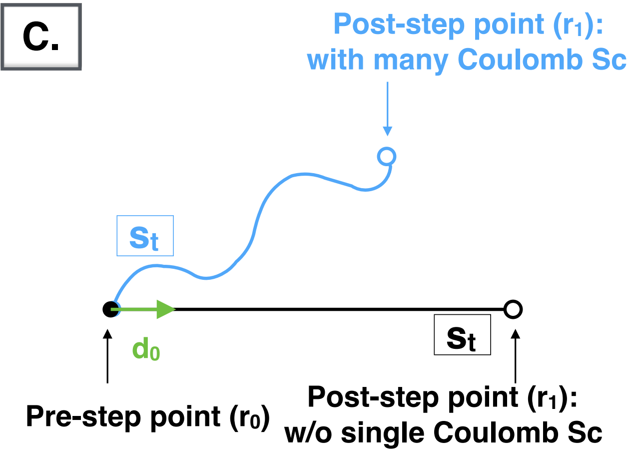
- Particles **without Coulomb** scattering process (**A**):
  - moves from the pre- to the post step point along straight line
- Particles **with Coulomb** scattering described by **single-scattering** model (**B**):
  - the corresponding cross section participated in the (discrete) step limit
  - moves from the pre- to the post step point along straight line (if no field)

A. and B.

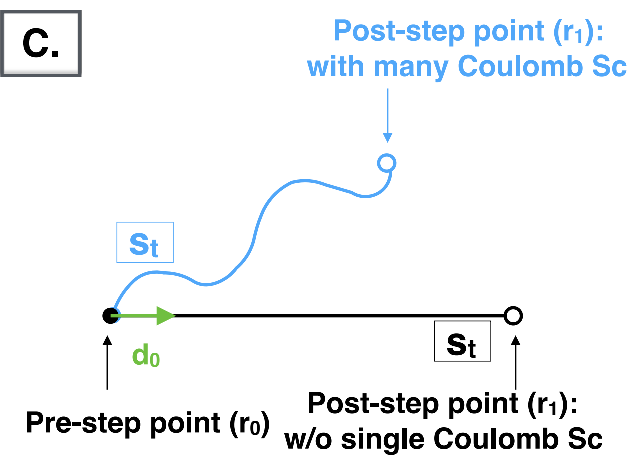
$$\mathbf{r}_1 = \mathbf{r}_0 + \mathbf{d}_0 s_t$$

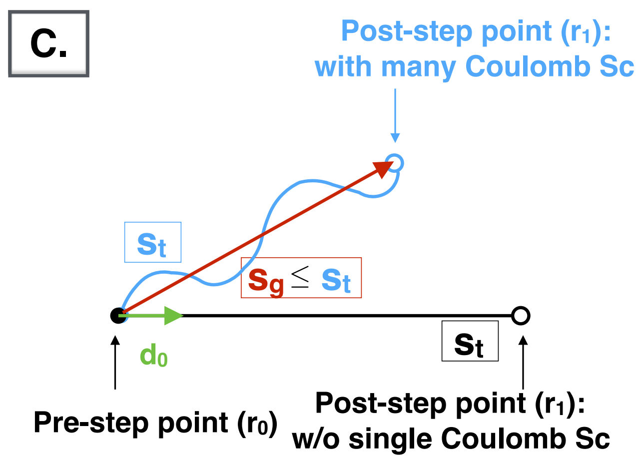
- Particles **without Coulomb** scattering process (**A**):
  - moves from the pre- to the post step point along straight line
- Particles **with Coulomb** scattering described by **single-scattering** model (**B**):
  - the corresponding cross section participated in the (discrete) step limit
  - moves from the pre- to the post step point along straight line (if no field)
- Particles **with Coulomb** scattering described by **multiple-scattering** model (**C**):

C.



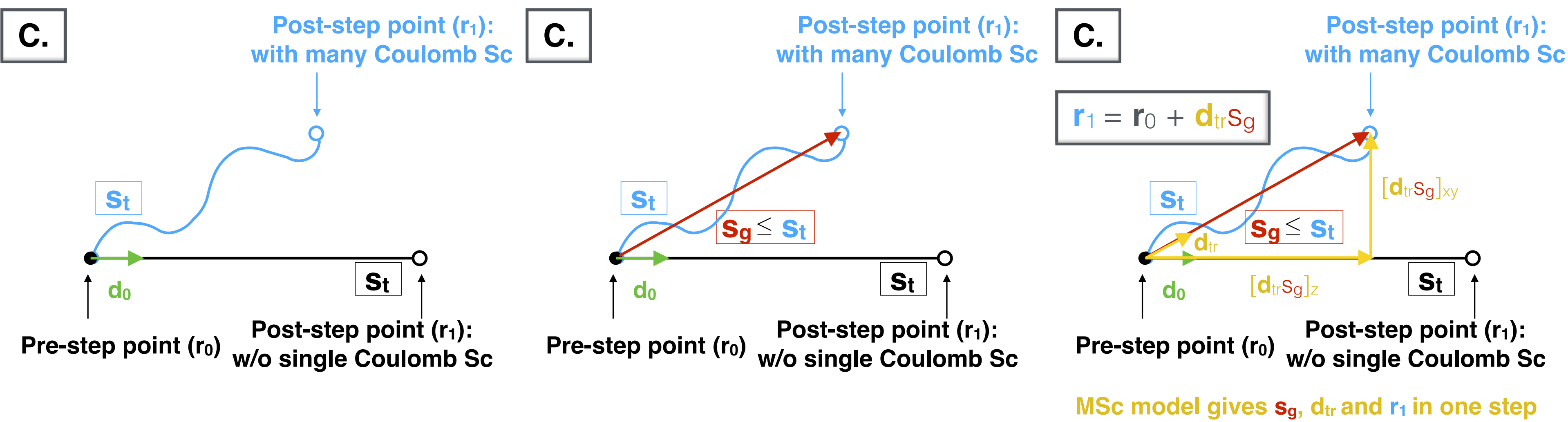
- Particles **without Coulomb** scattering process (**A**):
  - moves from the pre- to the post step point along straight line
- Particles **with Coulomb** scattering described by **single-scattering** model (**B**):
  - the corresponding cross section participated in the (discrete) step limit
  - moves from the pre- to the post step point along straight line (if no field)
- Particles **with Coulomb** scattering described by **multiple-scattering** model (**C**):





Electromagnetic Physics: Multiple Coulomb scattering

- Particles **without Coulomb** scattering process (**A**):
  - moves from the pre- to the post step point along straight line
- Particles **with Coulomb** scattering described by **single-scattering** model (**B**):
  - the corresponding cross section participated in the (discrete) step limit
  - moves from the pre- to the post step point along straight line (if no field)
- Particles **with Coulomb** scattering described by **multiple-scattering** model (**C**):



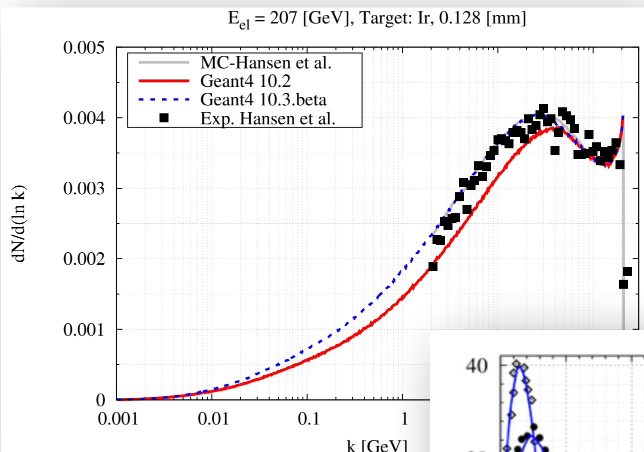
- Particles **without Coulomb** scattering process (**A**):
  - moves from the pre- to the post step point along straight line
- Particles **with Coulomb** scattering described by **single-scattering** model (**B**):
  - the corresponding cross section participated in the (discrete) step limit
  - moves from the pre- to the post step point along straight line (if no field)
- Particles **with Coulomb** scattering described by **multiple-scattering** model (**C**):
  - MSC algorithms give the final *position* and *directio*n of the particle while try to minimise the possible errors due to geometrical constraints:
    - each step, in which the expected final position cannot be achieved due to geometrical constraints, is considered to be a mistake in the stepping algorithm
  - different stepping algorithms are available with *different accuracy* and *computing cost*
  - can be set 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

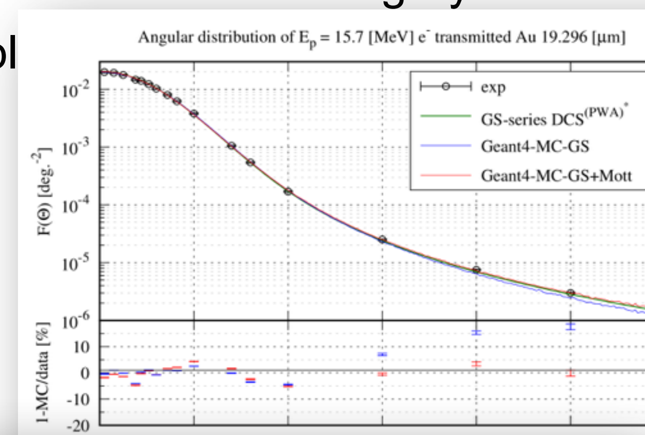
Electromagnetic Physics: special EM topics

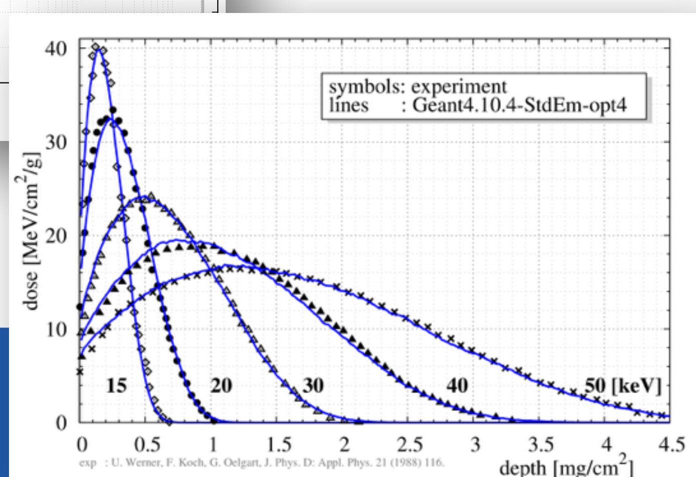
WHERE TO FIND HELP?

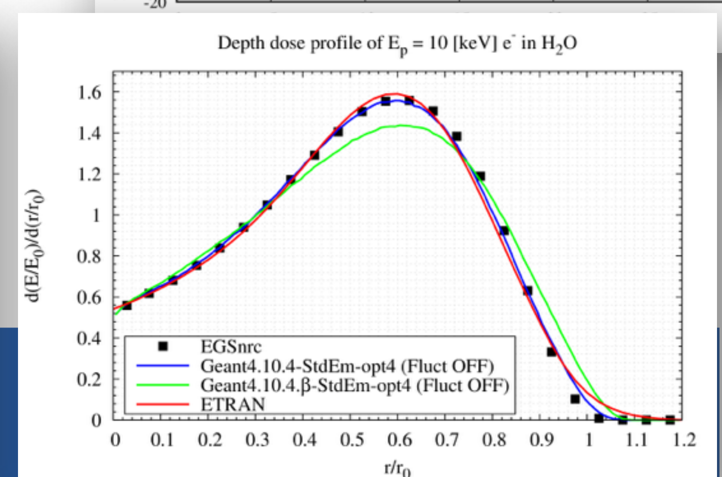
Where to find help?

- 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)
- **Geant4 forum** (**here**), "*Physics Processes, Models and Cross Sections*" category
- Use the **Geant4 bug report system** (**here**) in case of probl









Electromagnetic Physics: special EM topics

QUESTIONS