Version 11.2.p01

Electromagnetic Physics I and II

Mihaly Novak (CERN, EP-SFT)
Geant4 Tutorial at Jefferson Lab
27 March 2024

- Electromagnetic (EM) physics overview
  - Introduction, structure of Geant4 EM physics
  - Standard EM physics constructors
- Special EM topics:
  - Secondary production thresholds:
    - in Geant4
    - energy loss fluctuation
    - continuous step limit to to energy loss
    - v.s. tracking cut, `G4UserLimit`, step function
  - EM models per detector region
  - Atomic de-excitation
  - Multiple Coulomb scattering
    - dedicated slides at Electromagnetic Physics II.

Electromagnetic Physics

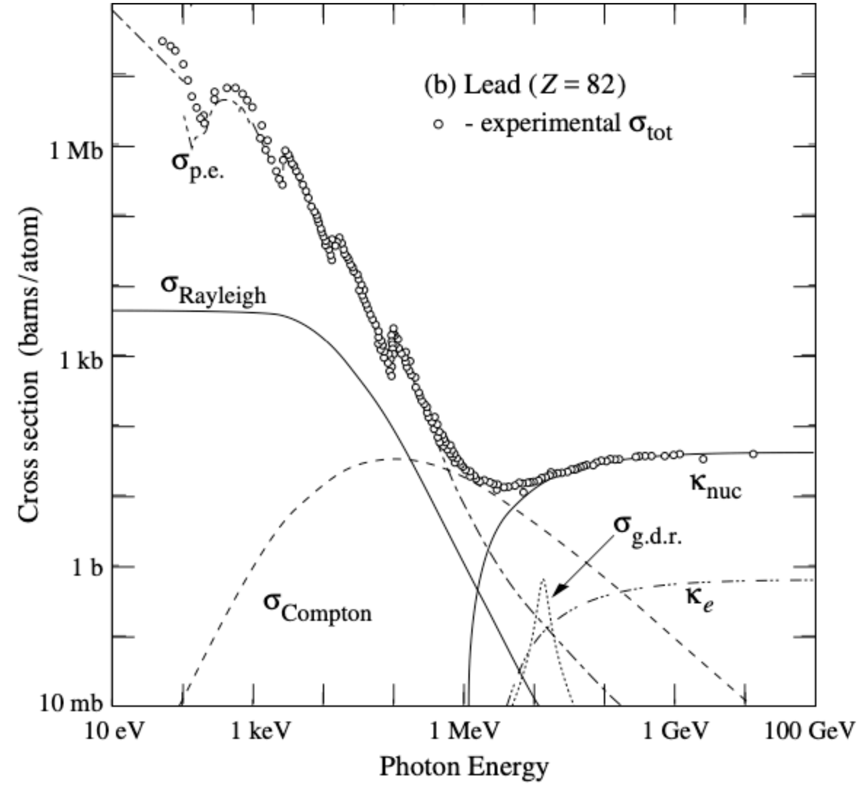
ELECTROMAGNETIC PHYSICS OVERVIEW

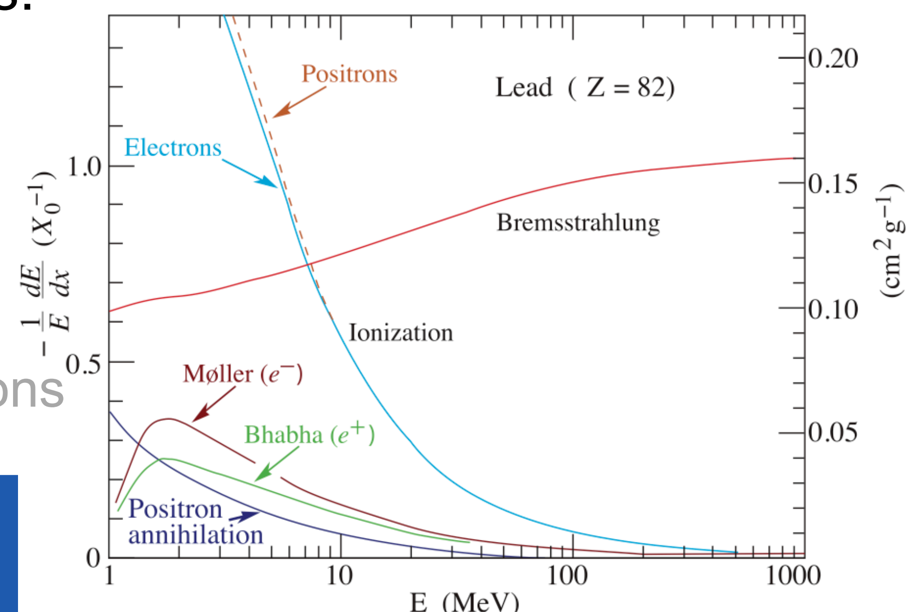
Located under `$G4SOURCE/processes/electromagnetic`

- `/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

Introduction, structure of the Geant4 EM physics

- **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⁺)
    - electron-, positron-nuclear interactions (in the hadronic part!)





Introduction, structure of the Geant4 EM physics

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

```
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.)

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

```
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
```

Electromagnetic Physics

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 for more precision sensitive 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± 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±)	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± as in `option4`)	accurate Livermore based low energy e^- and γ transport
`G4EmPenelopePhysics`	PENELOPE models for e±, γ below 1 GeV and standard above; same GS MSC for e± as in `option4`)	accurate PENELOPE based low energy e^-, e^+ and γ transport

Experimental Geant4 EM Physics Constructors (for specific developments)

- 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

Electromagnetic Physics

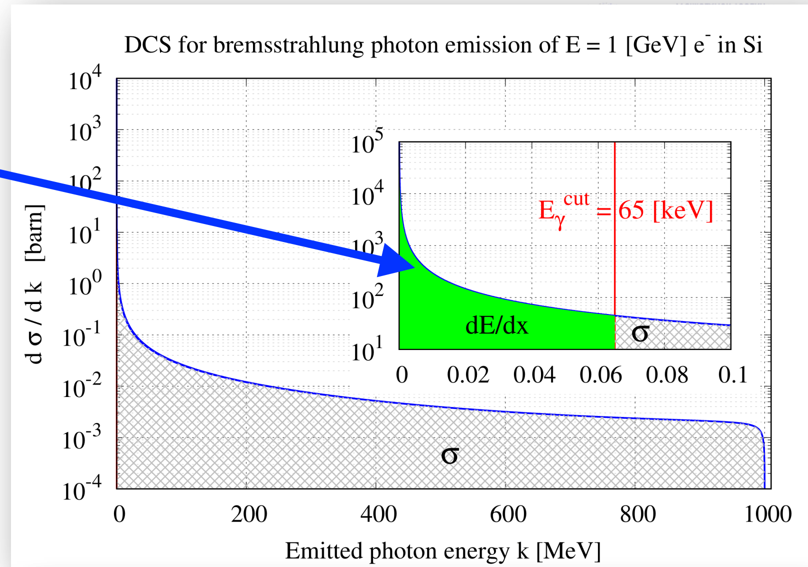
SPECIAL TOPICS

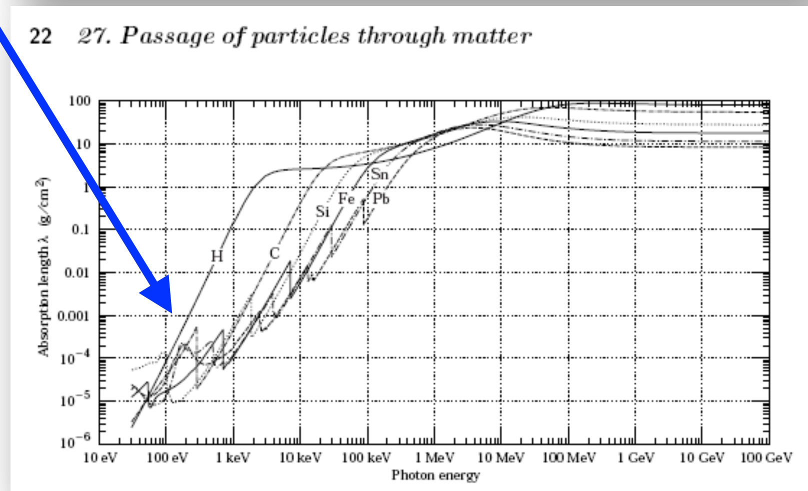
Electromagnetic Physics: special topics

SECONDARY PRODUCTION THRESHOLDS

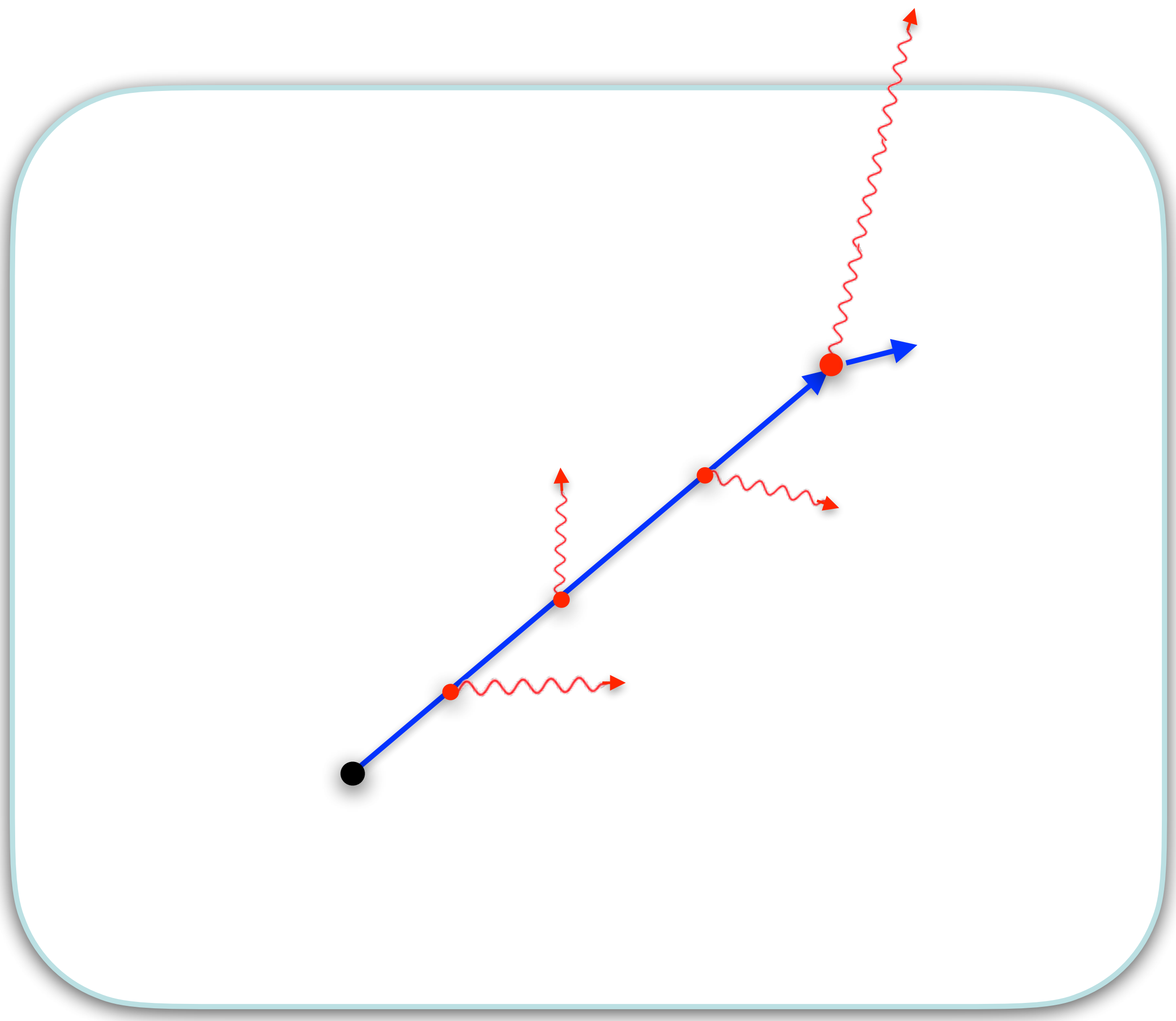
Secondary production threshold

- **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 worse than this length (i.e. all volume boundaries are further), then the followings are *equivalent*:
    - ***a***: **generating and tracking these low energy photons till they (the corresponding energy) will be absorbed**
    - ***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

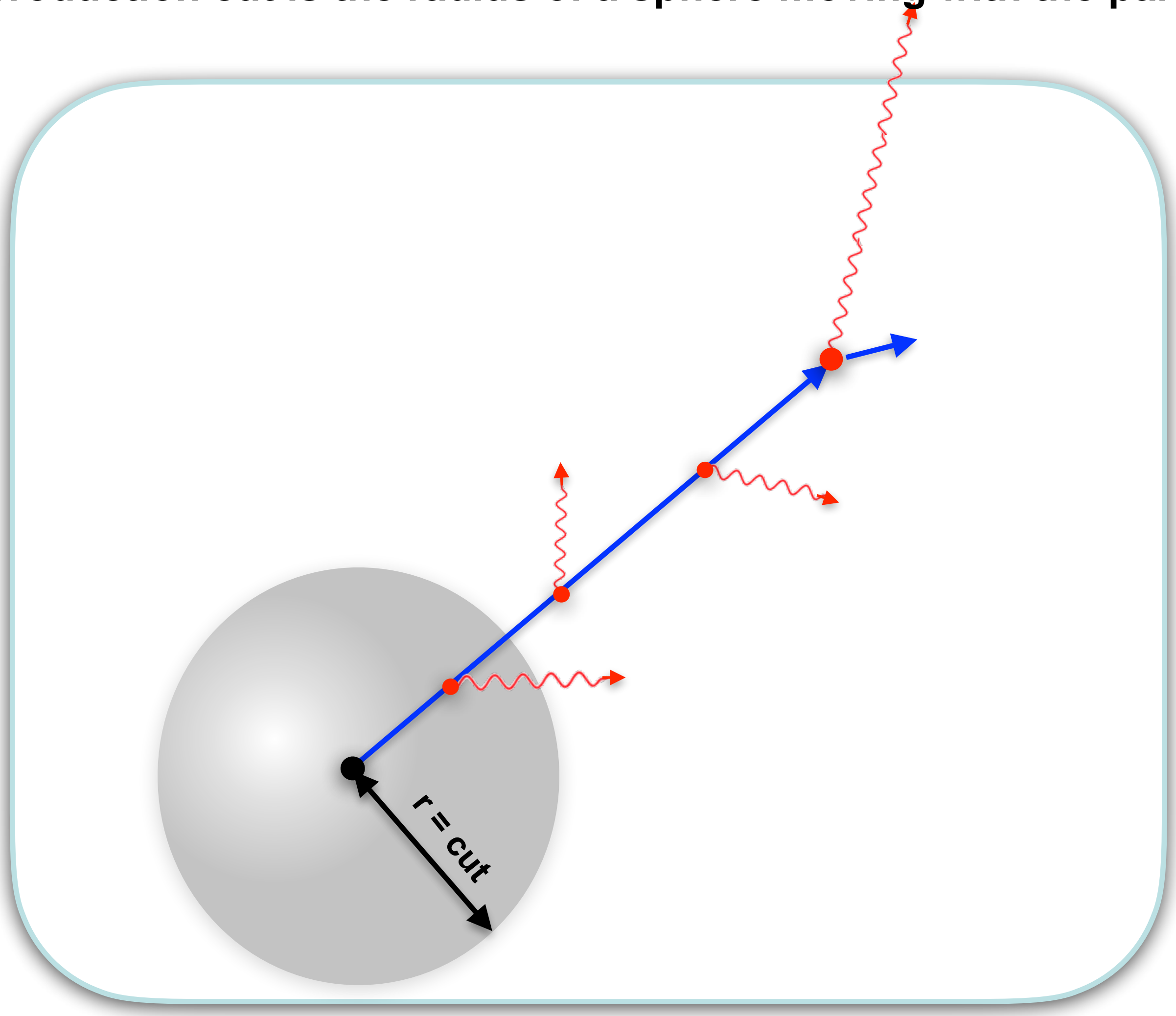




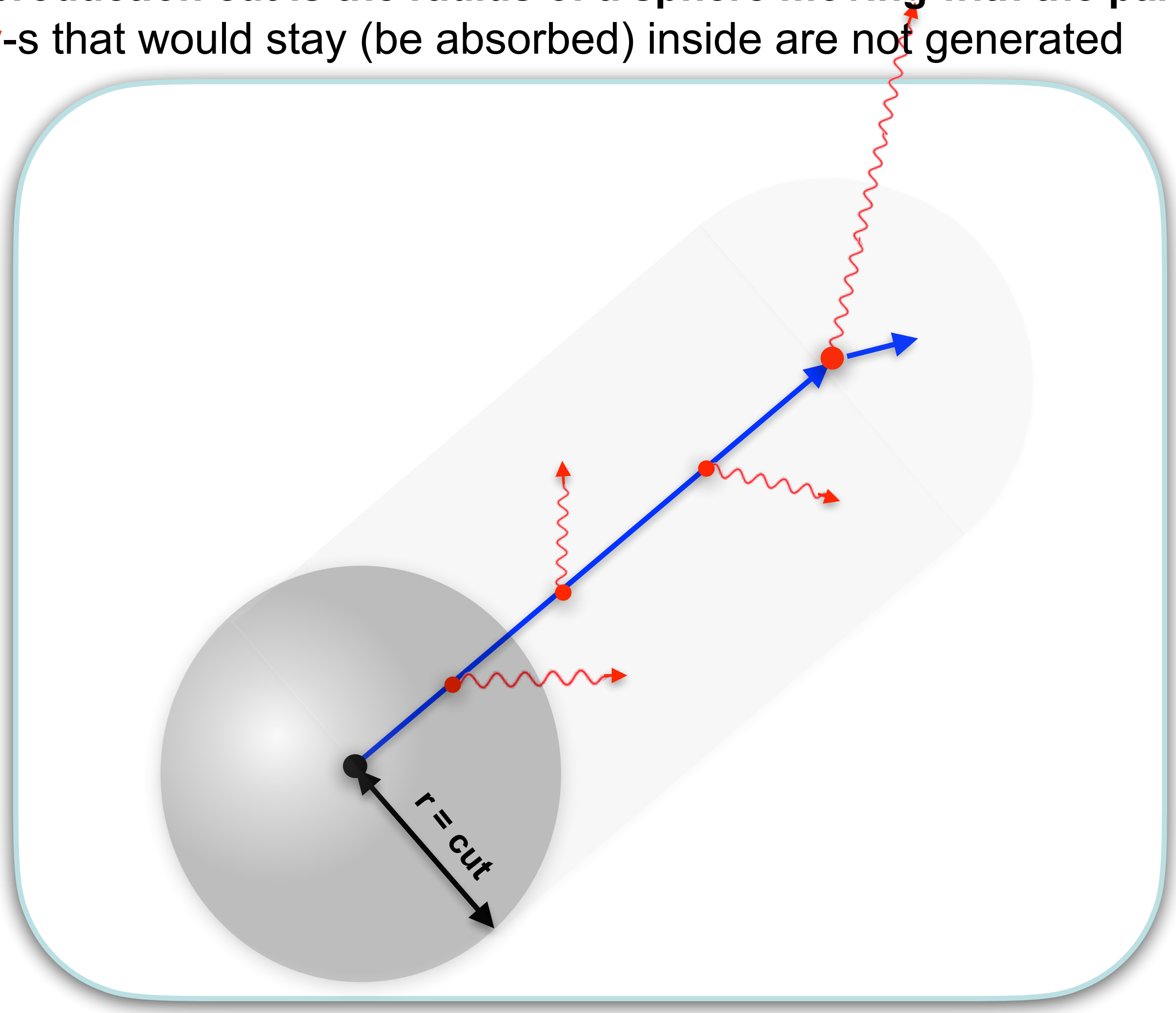
Secondary production threshold



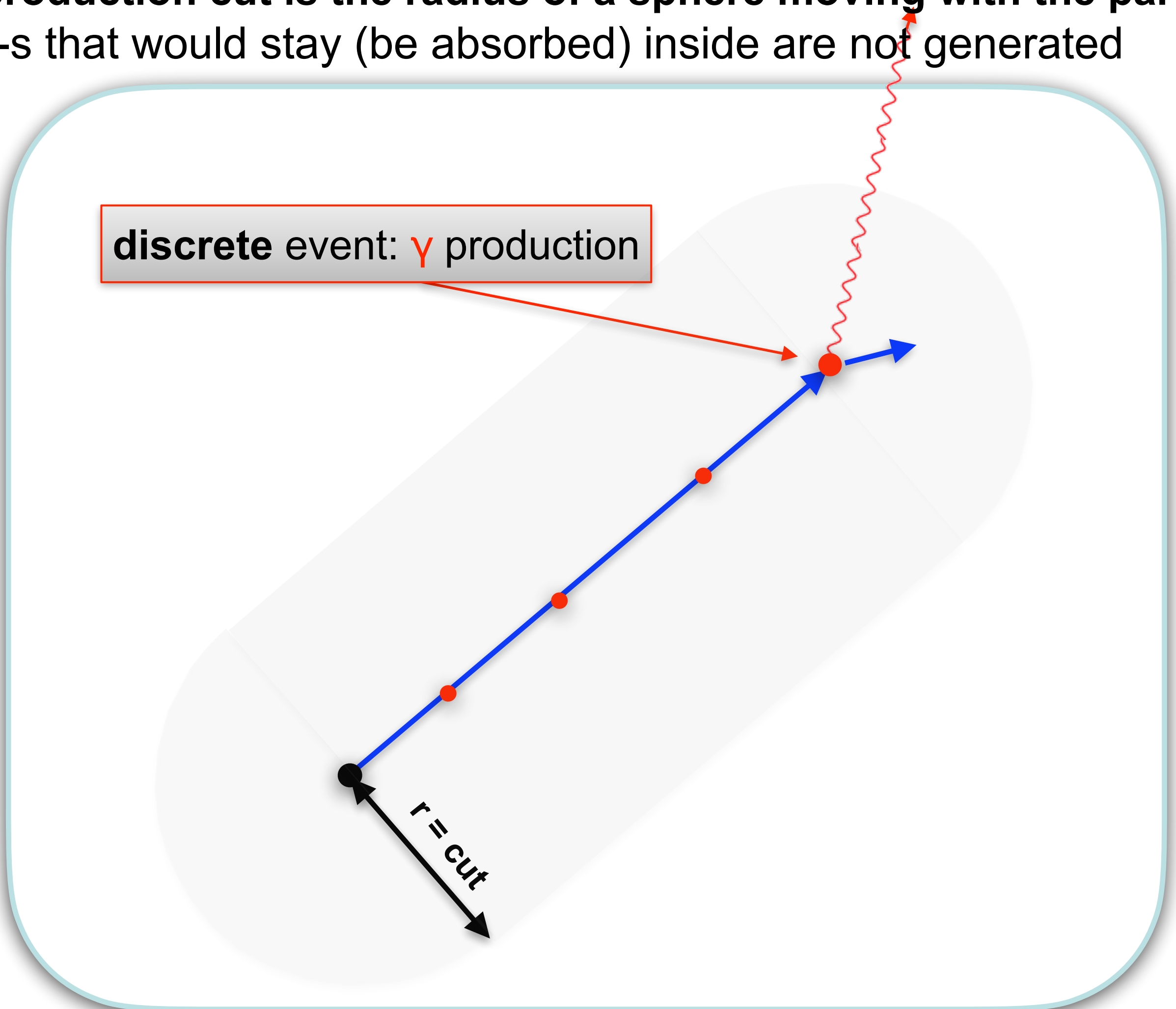
Secondary production cut is the radius of a sphere moving with the particle:



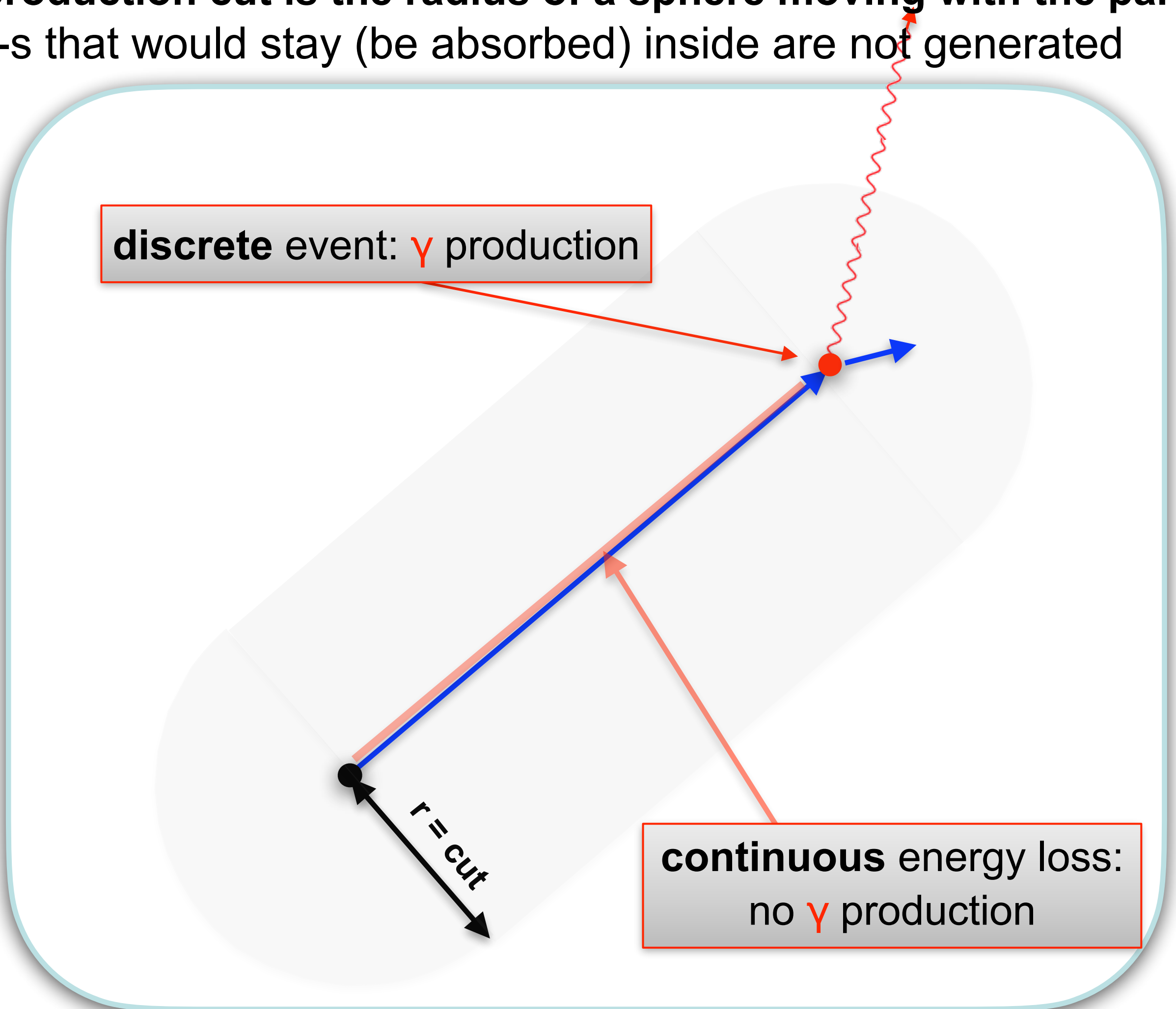
Secondary production cut is the radius of a sphere moving with the particle (tube):
secondary γ-s that would stay (be absorbed) inside are not generated



Secondary production cut is the radius of a sphere moving with the particle (tube)**:** secondary **γ**-s that would stay (be absorbed) inside are not generated

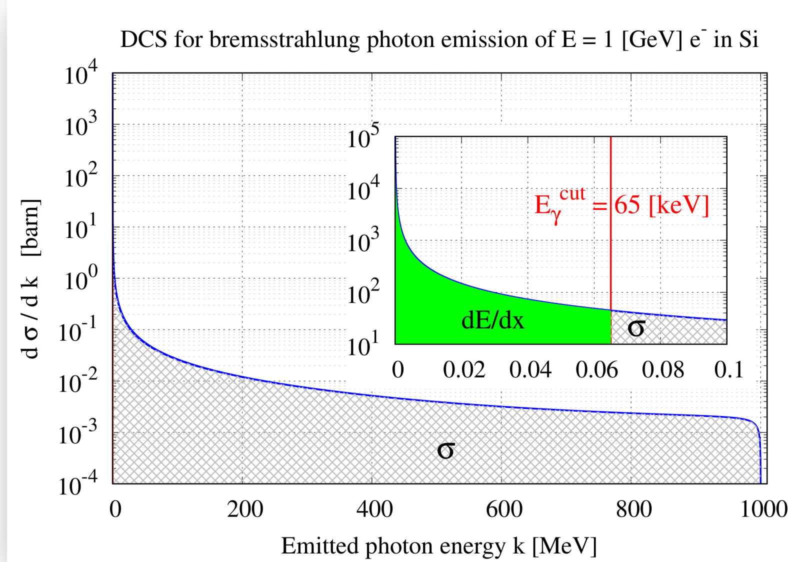


Secondary production cut is the radius of a sphere moving with the particle (tube)**:** secondary γ-s that would stay (be absorbed) inside are not generated



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**
  - *E_γ^{cut} is the **energy of the photon** that has **its absorption length equal to the cut** (**r**, i.e. the radius of the sphere)*
  - the corresponding **energy** (*that would have been taken away from the primary, but remained inside the sphere*) 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** (*since this energy is deposited outside of the sphere*) (***DISCRETE***)
  - the emission rate is determined by the corresponding (**restricted**) cross section(**σ**)

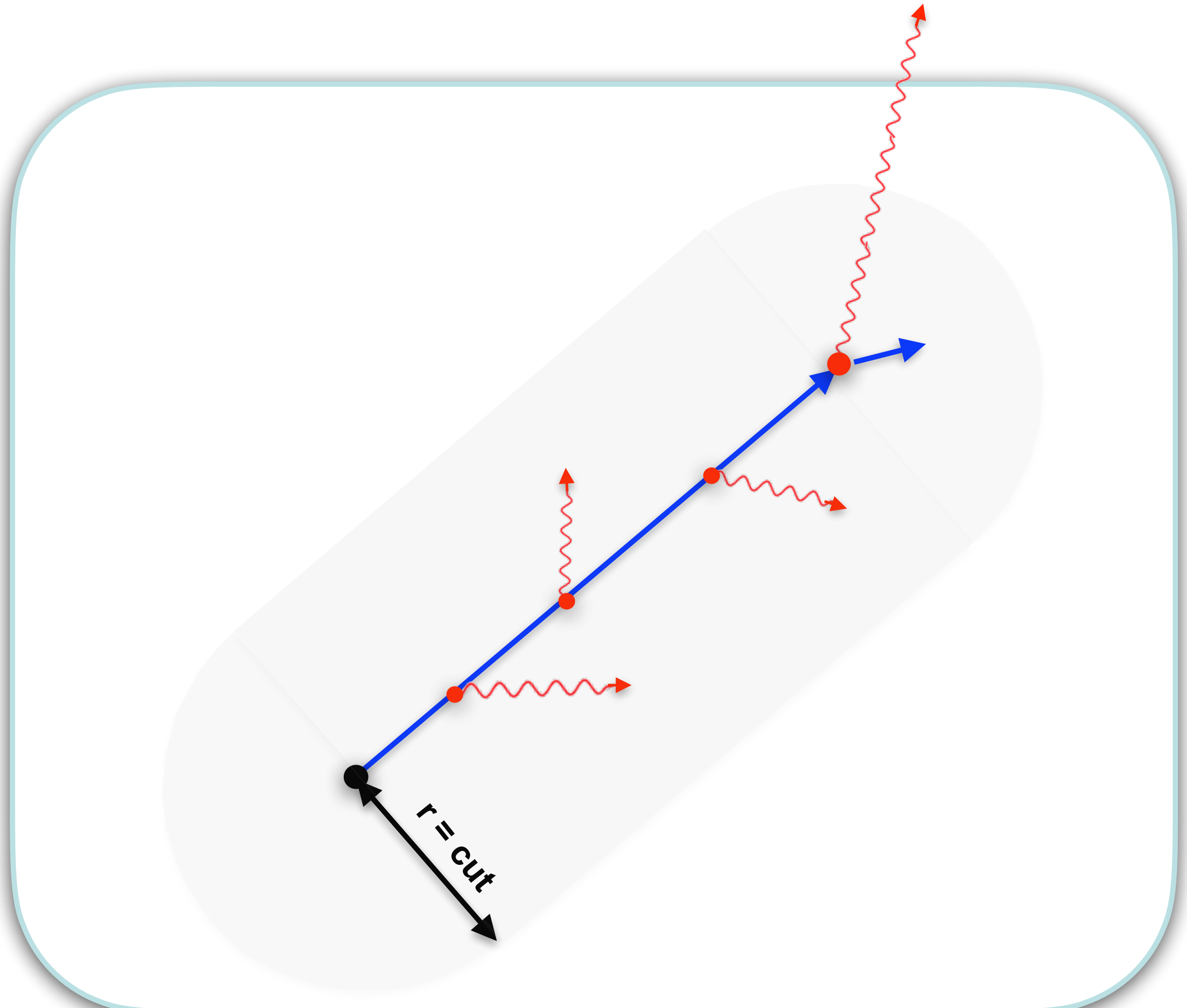


$$\frac{\mathrm{d}E}{\mathrm{d}x}(E, E_\gamma^{\mathrm{cut}}, Z) = \mathcal{N} \int_0^{E_\gamma^{\mathrm{cut}}} k \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E, Z)\mathrm{d}k$$

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

- **Same applies to ionization with the difference**:

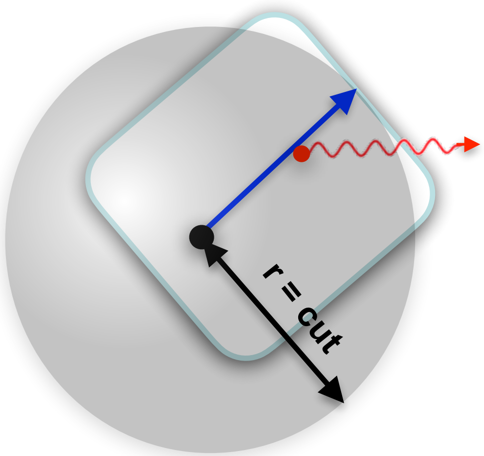
  - secondary gamma → secondary e^- production threshold
  - absorption length → range
  - ***E_{e^-}cut** is the **energy of the electron** that has **its range equal to the cut** (**r**, i.e. the radius of the sphere)*



Secondary production threshold << volume size : correct!

Secondary production threshold > volume size : not correct!

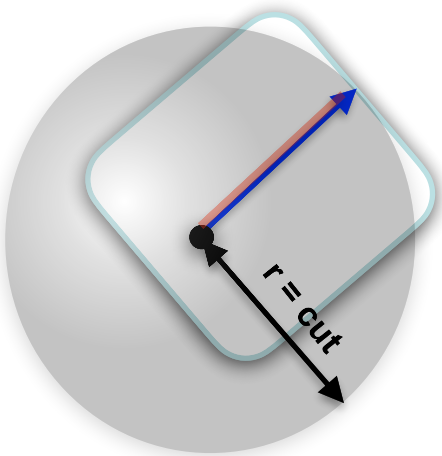
Secondaries, that would leave the volume, taking away their energy (or part of it in case of secondary e^-)**, are assumed to be absorbed within the volume!**



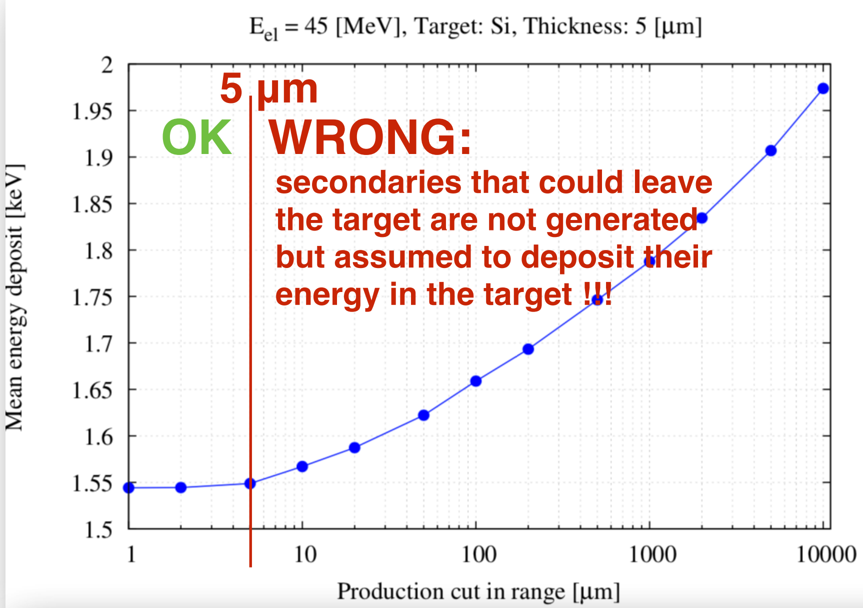
Secondary production threshold > volume size : not correct!

Secondaries, that would leave the volume, taking away their energy (or part of it in case of secondary e^-)**, are assumed to be absorbed within the volume!**

Wrong Energy Deposit: overestimated (in the volume)

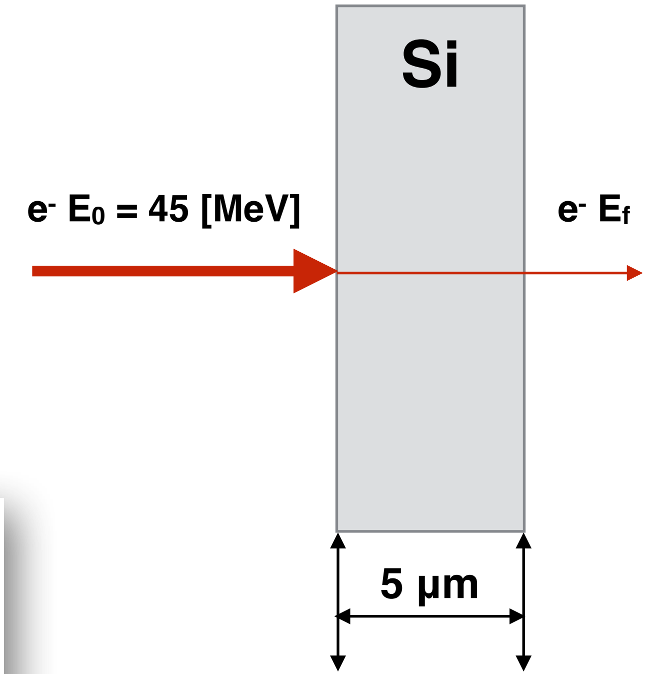


EXAMPLE



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



Electromagnetic Physics: special topics

SECONDARY PRODUCTION THRESHOLDS

In Genat4

- **Secondary production thresholds** **<u>in Geant4</u>**:
  - 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** (as we saw, 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`
  - (*range* and *absorption*) **length is** internally **translated to energies** at initialisation (mat. dep.)
  - 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 interactions producing such secondaries e.g. Compton, Photoelectric, etc.
  - it's not mandatory to use production thresholds(Condensed History; depends on the model)
  - however, mid and high energy simulations would not be feasible without them !!!

- **Secondary production thresholds <u>per detector region</u>**:
  - different parts of a complex detector might require modelling with different level of details and have **different spacial resolution**
  - different **detector** `G4Region`-s can be defined and a set of `G4LogicalVolume`-s can be associated to such regions
  - **different** secondary **production threshold** values (as well as `G4UserLimits`) **can be assigned to different detector region**
    - ✦ in the `DetectorConstruction::Construct()` method (e.g. `examples/extended/electromagnetic/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]);
```

Secondary production threshold: in Geant4

```
/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

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

- **Secondary production thresholds per detector region**:
  - different parts of a complex detector might require modelling with different level of details and have **different spacial resolution**
  - different **detector** `G4Region`-s can be defined and a set of `G4LogicalVolume-`s can be associated to such regions
  - **different** secondary **production threshold** values (as well as `G4UserLimits`) **can be assigned to different detector region**
    - ✦ in the `DetectorConstruction::Construct()` method (e.g. `examples/extended/electromagnetic/TestEm3`)
    - ✦ don't forget to include the `G4Region.hh` and `G4ProductionCuts.hh` headers

- **Secondary production thresholds <u>per detector region</u>**:
  - different parts of a complex detector might require modelling with different level of details and have **different spacial resolution**
  - different **detector** `G4Region`-s can be defined and a set of `G4LogicalVolume-`s can be associated to such regions
  - **different** secondary **production threshold** values (as well as `G4UserLimits`) **can be assigned to different detector region**
  - very important fine tuning of the simulation settings for the given application:
    - ✦ how **frequently** an electron **stops** and the **number of secondary e^-/γ** particles strongly **depend on the secondary production threshold**
    - ✦ the **appropriate values are determined solely by the volume sizes** (spacial resolution)
    - ✦ applying the **proper values** is an important optimisation that do not alter the results
    - ✦ identify regions of the detector with similar spacial resolutions (volume sizes), define the corresponding detector regions with the appropriate values (depending on the volume size) of secondary production threshold

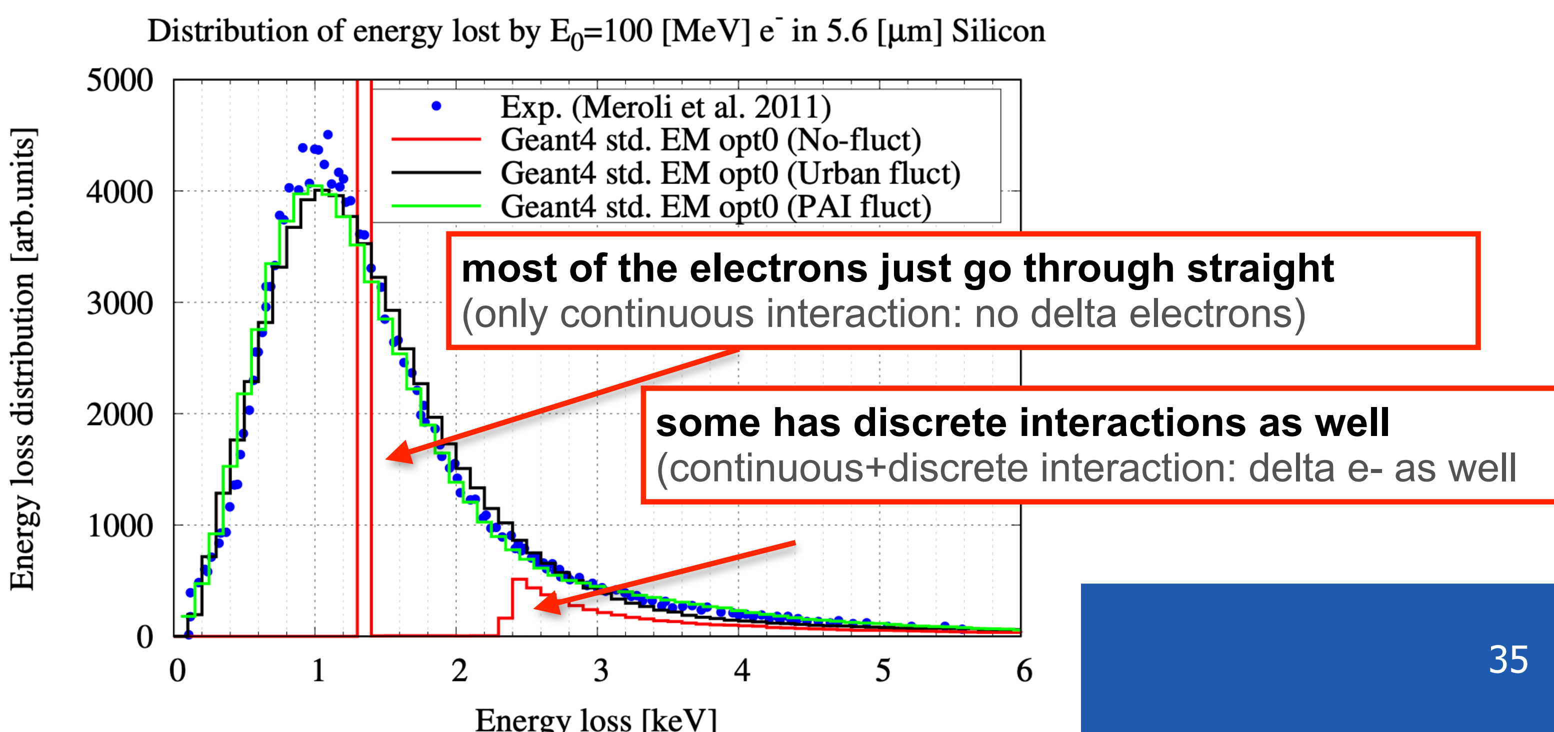
Electromagnetic Physics: special topics

SECONDARY PRODUCTION THRESHOLDS

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

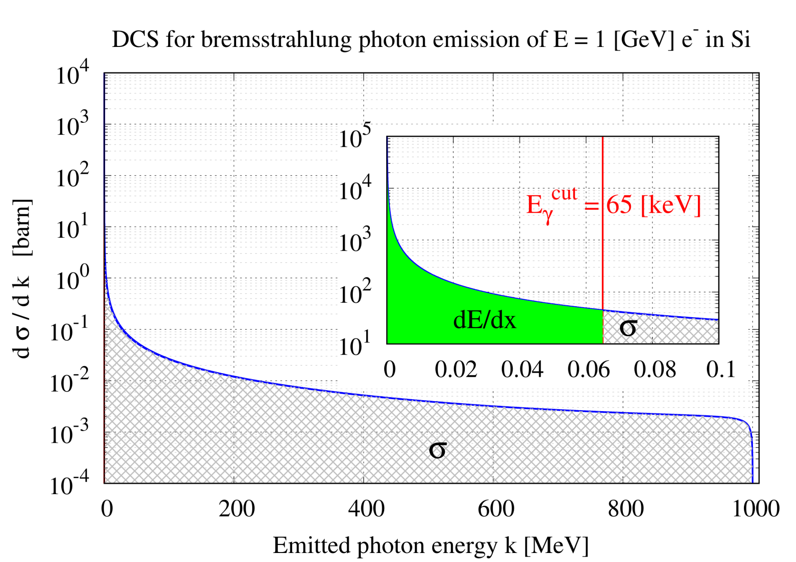


Electromagnetic Physics: special topics

SECONDARY PRODUCTION THRESHOLDS

Continuous step limit due to energy loss

- **Introduce secondary photon production threshold**:
  - ***secondary photons***, **with** initial **energy below** a gamma production **threshold**(**k<E_γ^{cut}**), are **not generated**
  - ***E_γ^{cut}*** *is the **energy of the photon** that has **its absorption length equal to the cut** (**r**, i.e. the radius of the sphere)*
  - the corresponding **energy** (*that would have been taken away from the primary, but remained inside the sphere*) 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** (*since this energy is deposited outside of the sphere*) (***DISCRETE***)
  - the emission rate is determined by the corresponding (**restricted**) cross section(**σ**)



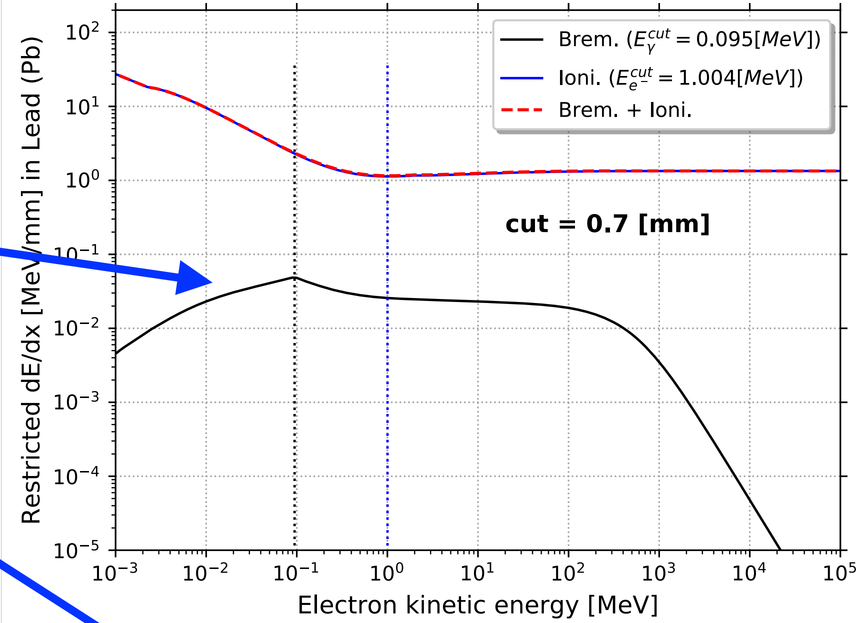
$$\frac{\mathrm{d}E}{\mathrm{d}x}(E, E_\gamma^{\mathrm{cut}}, Z) = \mathcal{N}\int_0^{E_\gamma^{\mathrm{cut}}} k\frac{\mathrm{d}\sigma}{\mathrm{d}k}(E,Z)\mathrm{d}k$$

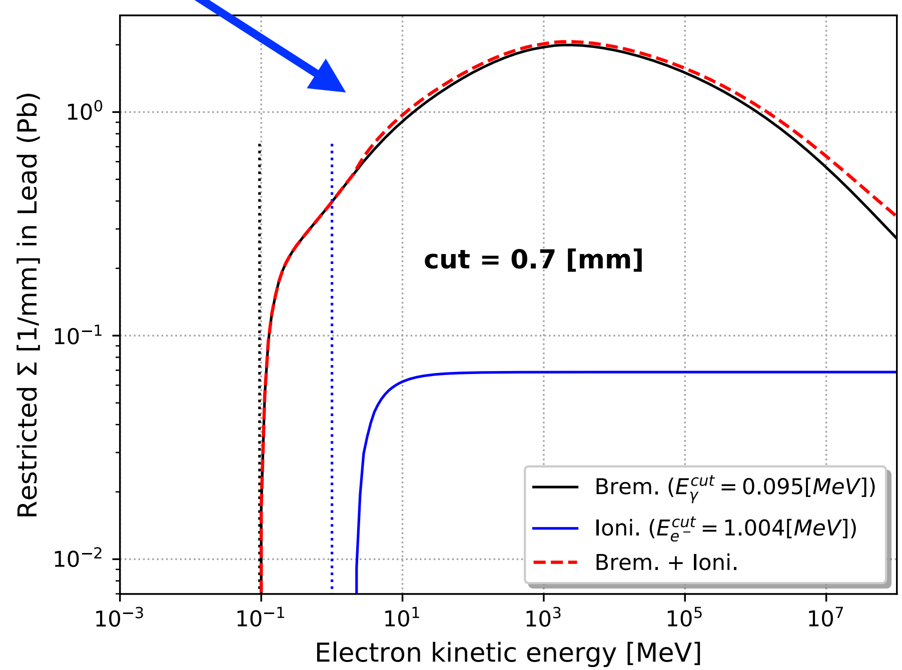
$$\sigma(E, E_\gamma^{\mathrm{cut}}, Z) = \int_{E_\gamma^{\mathrm{cut}}}^{E} \frac{\mathrm{d}\sigma}{\mathrm{d}k}(E,Z)\mathrm{d}k$$

Continuous step limit due to energy loss

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

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





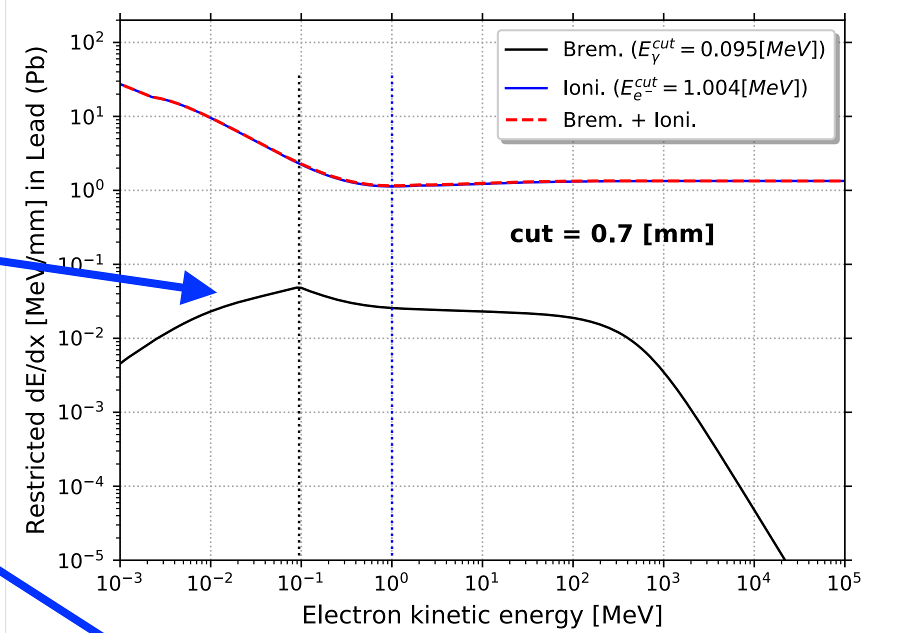
- **Note**
  - all quantities are "***restricted***" (covers only the sub/super secondary production threshold part of the interactions)
  - in case of ionisation, the minimum primary e^- energy to be able to produce secondary e^- with initial energy > $E_{e^-}^{cut}$ is 2x $E_{e^-}^{cut}$ (due to the indistinguishable two e^- at the final state; the one with the lower energy is considered to be the secondary e^-)

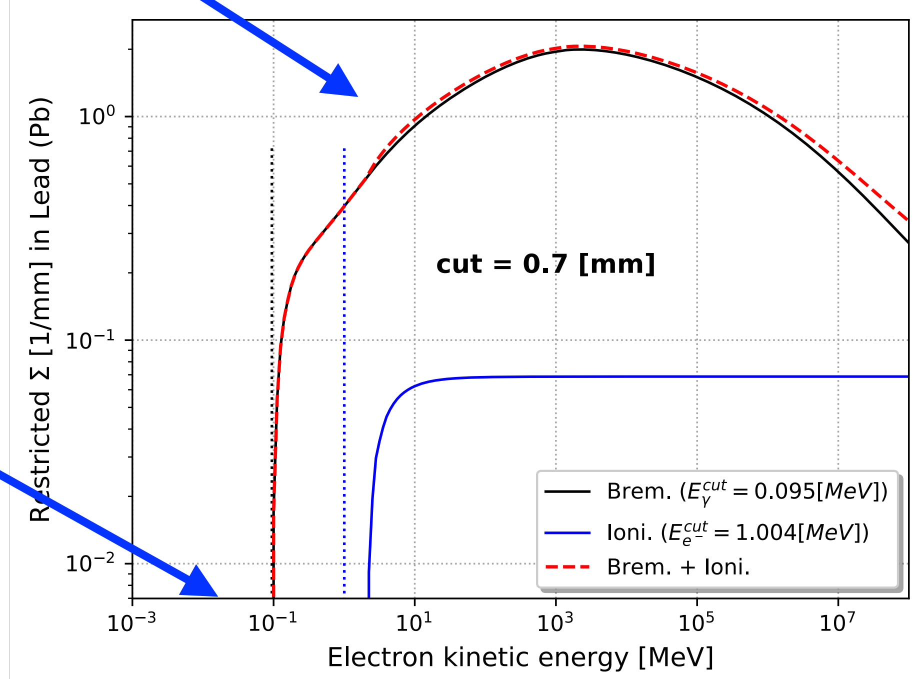
Continuous step limit due to energy loss

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

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

- **Consider the following:**
  - suppose, that an e- is in a *large volume*
  - furthermore, the **step length** would be determined solely **by the discrete part**, i.e. by the macroscopic cross section
  - **how far** this particle, with an initial kinetic energy of 80 [keV] **would go**, till the next (super threshold) e- or γ production?
  - **what would be its energy**, before the interaction, i.e. at the final position after removing the sub-threshold energy losses?
  - **?**





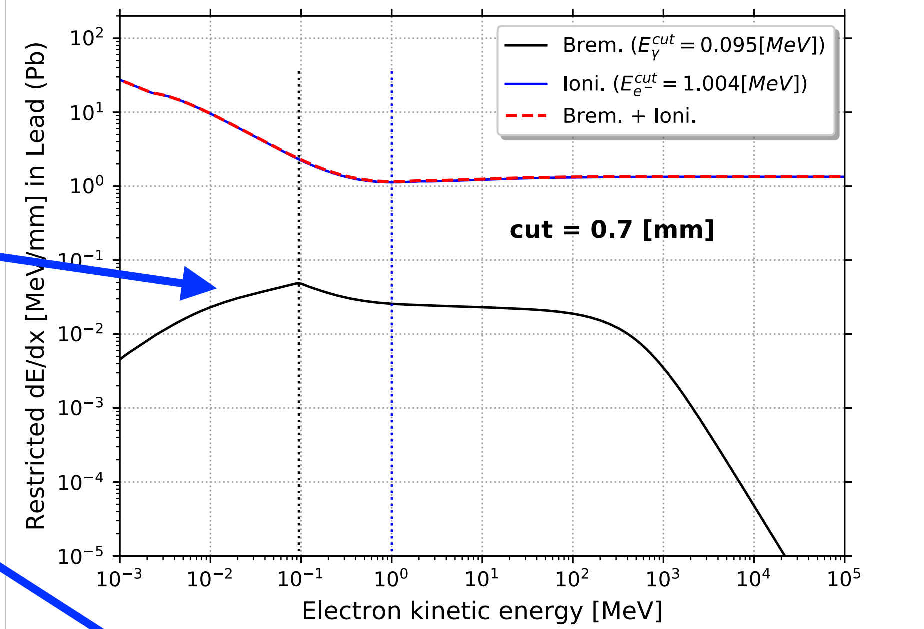
CERN

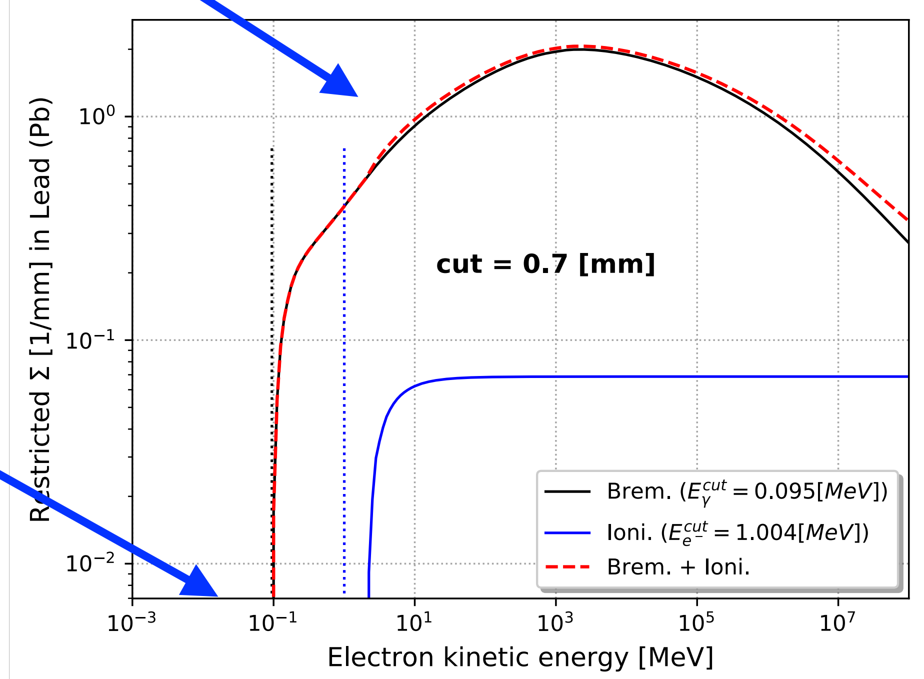
Continuous step limit due to energy loss

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

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

- **Consider the following:**
  - suppose, that an e- is in a *large volume*
  - furthermore, the **step length** would be determined solely **by the discrete part**, i.e. by the macroscopic cross section
  - **how far** this particle, with an initial kinetic energy of 80 [keV] **would go**, till the next (super threshold) e- or γ production?
  - **what would be its energy** before the interaction, i.e. at the final position after removing the sub-threshold energy losses?
  - **till the boundary**; **could even be negative**

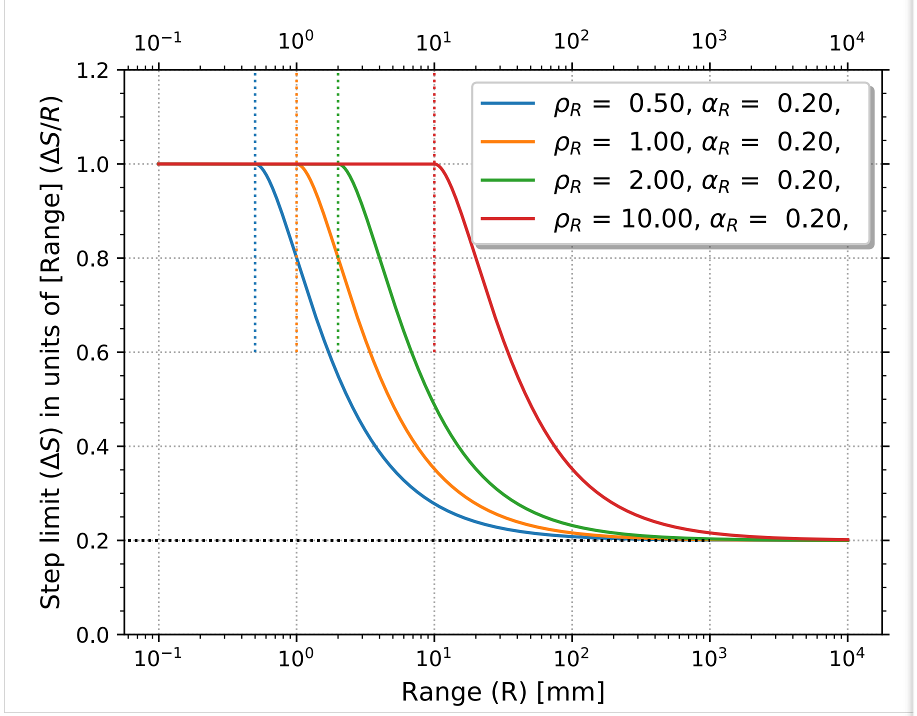


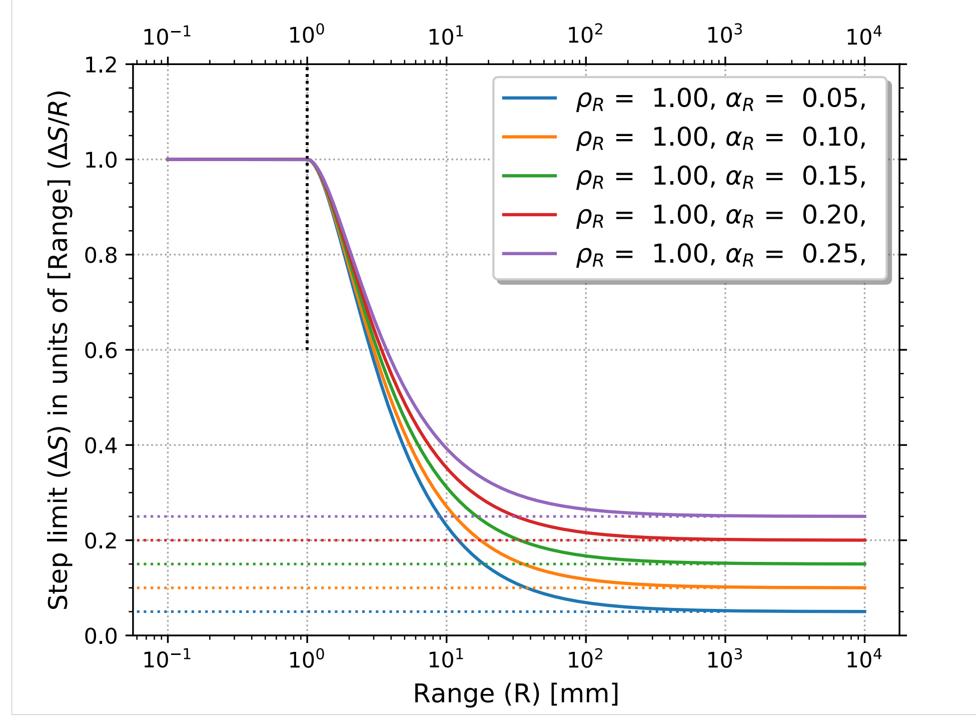


- **Continuous step limit due to energy loss:**
  - when using **condensed history** simulation, **continuous energy loss**es **impose a limit on the** charged particle **step** (beyond the discrete part)
  - an obvious choice of this limit **could be the** (pre-step, restricted) **range of the particle** (sum from collision and radiative, i.e. ionisation and bremsstrahlung)
  - this **would prevent** the particle **to go longer than the** (mean) **path length** at which **its energy** would **become zero due to** the (sub-threshold) **continuous energy loss**es
  - we **need to be even more strict** than this in order **to guarantee** the **stability** of the charged particle stepping: limit the allowed energy loss at most 20-25 % of the pre-step point energy of the particle (need to be relaxed at lower energies)
  - the ***loss function* below** ensures, that the **charged particle is stopped at the appropriate position** while its **energy is deposited in the correct volume**(s) **!**

$$\Delta S_{\text{eloss}}(E_0) = \begin{cases} R & \text{if } R < \rho_R \\ \alpha_R R + \rho_R(1-\alpha_R)(2-\rho_R/R) & \text{otherwise} \end{cases}$$

where $R := R(E_0)$ is the restricted range at energy E_0, $\boldsymbol{\rho_R}$ ***final range*** and $\boldsymbol{\alpha_R}$ ***rover range*** are two parameters.





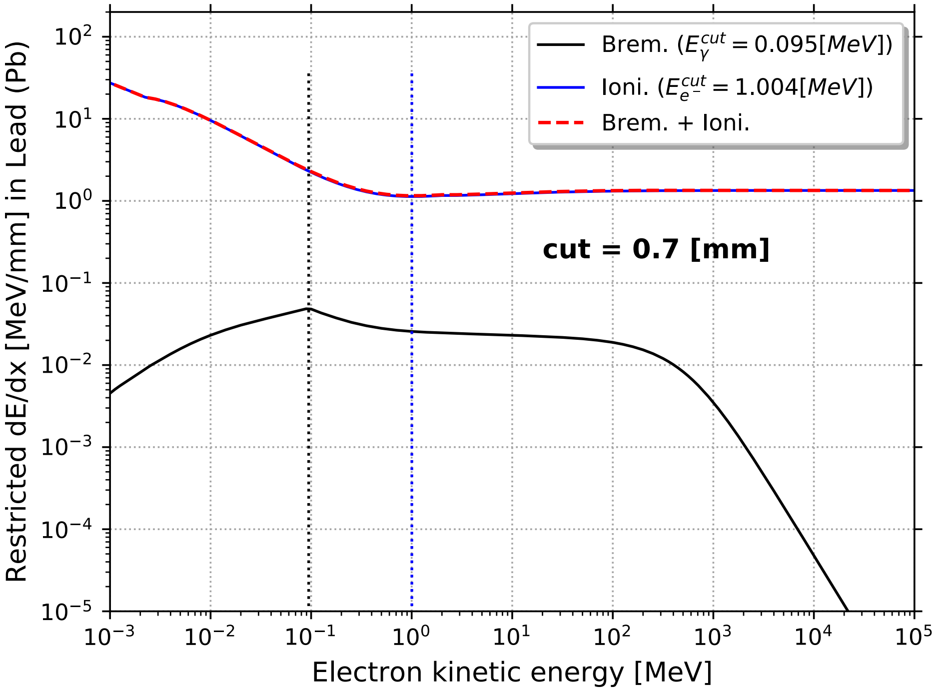
- UI command to set the parameters:

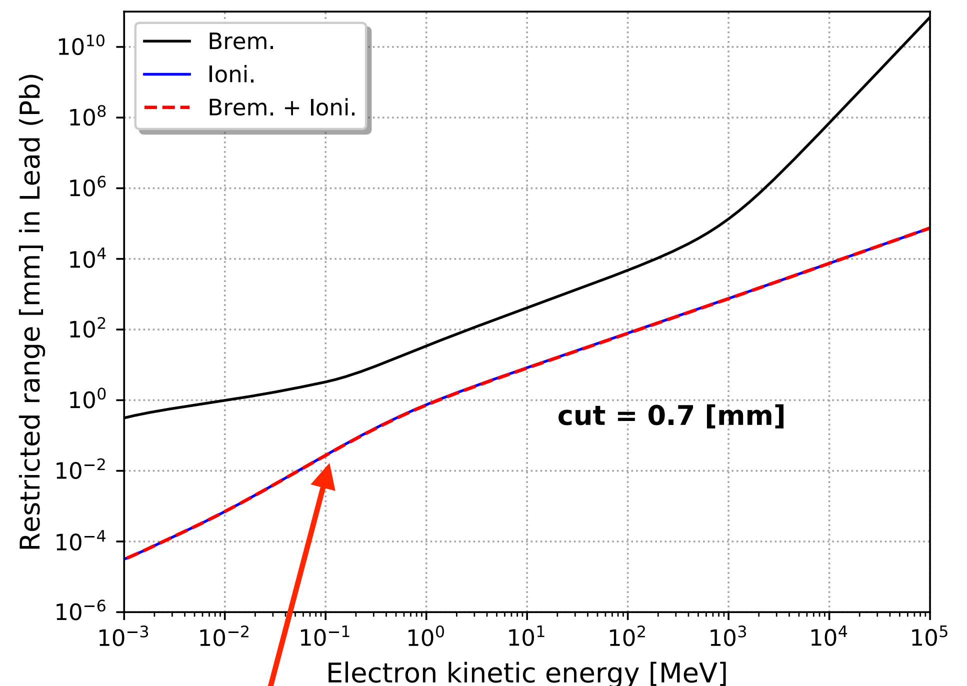
```
/process/eLoss/StepFunction <roverRange-value> <finalRange-value> <unit>
/process/eLoss/StepFunctionMuHad" <roverRange-value> <finalRange-value> <unit>
```

- the lower the `finalRange` value the “later” (in range) the particle will be ranged-out (**default 1 [mm]**)
- the lower the `roverRange` value the smaller the allowed steps will be (**default 0.2**, i.e. 20 % of R(E_0))

$$\Delta S_{\text{eloss}}(E_0) = \begin{cases} R & \text{if } R < \rho_R \\ \alpha_R R + \rho_R(1-\alpha_R)(2-\rho_R/R) & \text{otherwise} \end{cases}$$

where $R := R(E_0)$ is the restricted range at energy E_0, $\boldsymbol{\rho_R}$ ***final range*** and $\boldsymbol{\alpha_R}$ ***rover range*** are two parameters.





- UI command to set the parameters:

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

- the lower the `finalRange` value the “later” (in range) the particle will be ranged-out (**default 1 [mm]**)
- the lower the `roverRange` value the smaller the allowed steps will be (**default 0.2**, i.e. 20 % of $R(E_0)$)

$R := R(E_0)$: restricted range including both collision and radiative contributions

$$\Delta S_{\text{eloss}}(E_0) = \begin{cases} R & \text{if } R < \rho_R \\ \alpha_R R + \rho_R(1-\alpha_R)(2-\rho_R/R) & \text{otherwise} \end{cases}$$

where $R := R(E_0)$ is the restricted range at energy E_0, $\boldsymbol{\rho_R}$ ***final range*** and $\boldsymbol{\alpha_R}$ ***rover range*** are two parameters.

- Default step function (in the standard EM option0 constructor):

```
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 topics

SECONDARY PRODUCTION THRESHOLDS

v.s. tracking cut, `G4UserLimit`, **step function**

- **Secondary production cuts vs tracking cut**:
  - **`Geant4` do not require** any **tracking cuts**: charged particles (like e^-/e^+) are "ranged-out" **thanks to the *loss function*** discussed before (photons are absorbed)
  - "ranged-out": **appropriate final position** (resulting appropriate location of the energy deposit)
  - however, the user can easily introduce any limits on tracking by **`G4UserLimits`**
  - a **kinetic energy limit** (aka tracking cut in energy) is also available:
    - ✦ only for computing performance reasons: to kill low energy "loopers" (low density material and 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
```

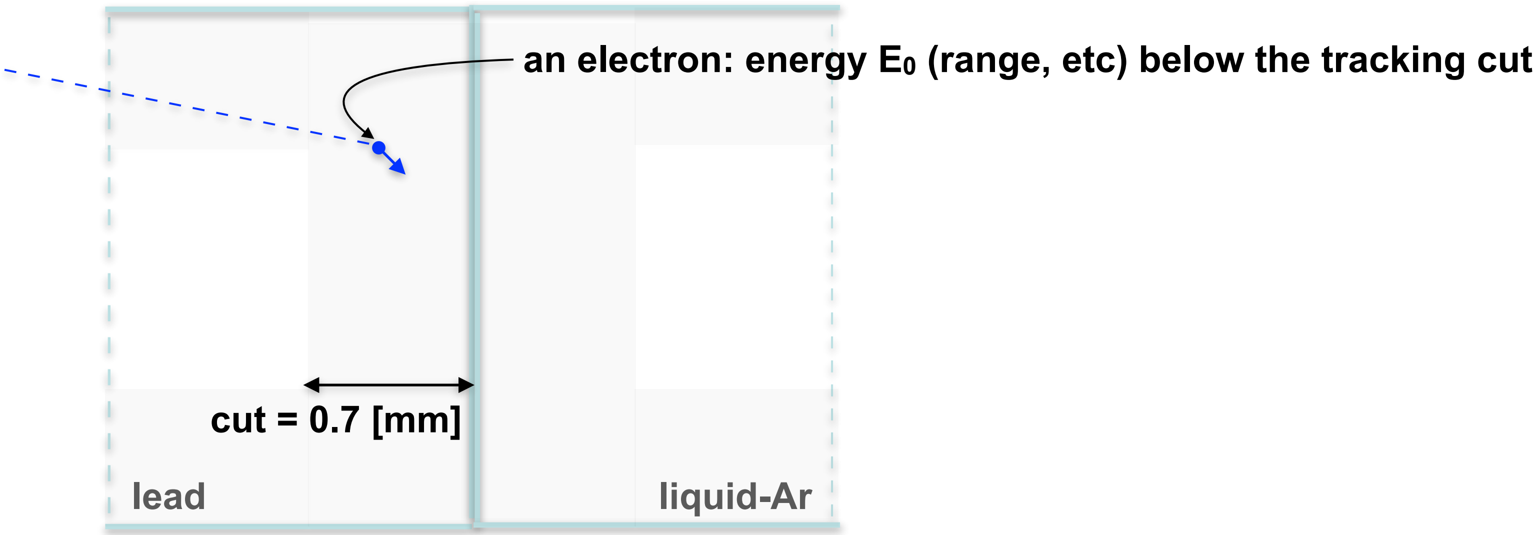
  - particles are **killed when their kinetic energy drops below the limit** and **their energy is deposited** (**at the given point!**)

- **Tracking cut (e.g. `G4UserLimits`):**
  - ***special user*** (limit) ***process***, can impose tracking cut in kinetic energy, range, etc.
  - **checked** at the step-limit phase of the step, i.e. **at the pre-step point**: if the given condition evaluates to be true, this special process is selected, the particle is **stopped immediately** and its kinetic **energy is deposited at the given point**
  - **+** many different type of limits even per detector region; **-** one extra step; inappropriate final position: the corresponding energy deposit (or a fraction of it) might be assigned to the wrong volume

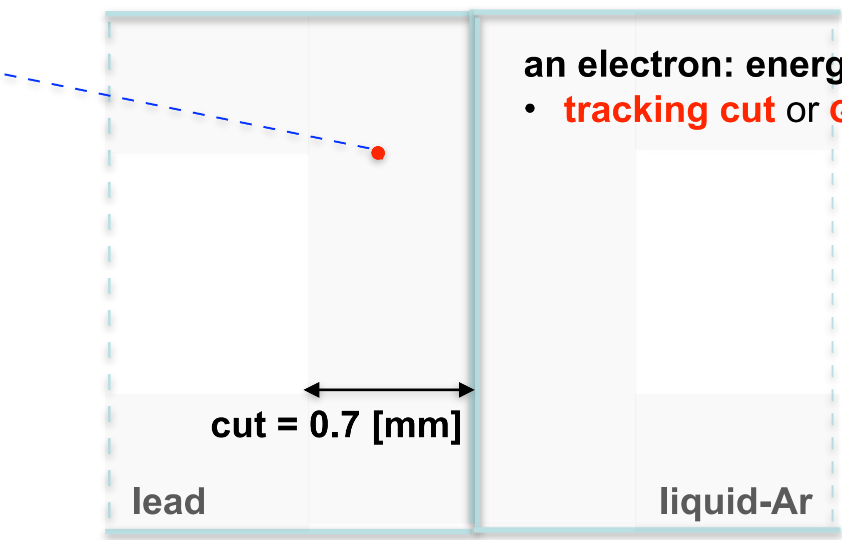
- **Tracking cut (e.g. kinetic energy limit):**
  - checked within the step (after the continuous energy loss and the discrete interaction) and the particle is **stopped immediately** when its kinetic energy drops below the (global) **kinetic energy limit** and its kinetic **energy is deposited at the given point**
  - **+** no any extra steps; **-** global, inappropriate final position: the corresponding energy deposit (or a fraction of it) might be assigned to the wrong volume
  - (note: since the corresponding kinetic energy limit is usually small (default 1 [keV]) it dose not cause any problems)

- **No racking cut (e.g. relying on the loss function):**
  - the only way to **ensure appropriate final position of the charged particle** (and energy deposit location; see below)
  - whenever the **particle range drops below** the ***final range*** parameter value, an extra step, with a continuous step limit equal to the particle range, is proposed
  - **+** only appropriate final position and energy deposit location;
  - **+** `/process/eLoss/useCutAsFinalRange true` can be used to set ***final range*** = cut
  - **-** requires an extra (last) step

- **No racking cut (e.g. relying on the loss function):**
  - the only way to **ensure appropriate final position of the charged particle** (and energy deposit location; see below)
  - whenever the **particle range drops below** the ***final range*** parameter value, an extra step, with a continuous step limit equal to the particle range, is proposed
  - **+** only appropriate final position and energy deposit location;
  - **+** `/process/eLoss/useCutAsFinalRange true` can be used to set ***final range*** = cut
  - **-** requires an extra (last) step



- **No racking cut (e.g. relying on the loss function):**
  - the only way to **ensure appropriate final position of the charged particle** (and energy deposit location; see below)
  - whenever the **particle range drops below** the ***final range*** parameter value, an extra step, with a continuous step limit equal to the particle range, is proposed
  - **+** only appropriate final position and energy deposit location;
  - **+** `/process/eLoss/useCutAsFinalRange true` can be used to set ***final range*** = cut
  - **-** requires an extra (last) step

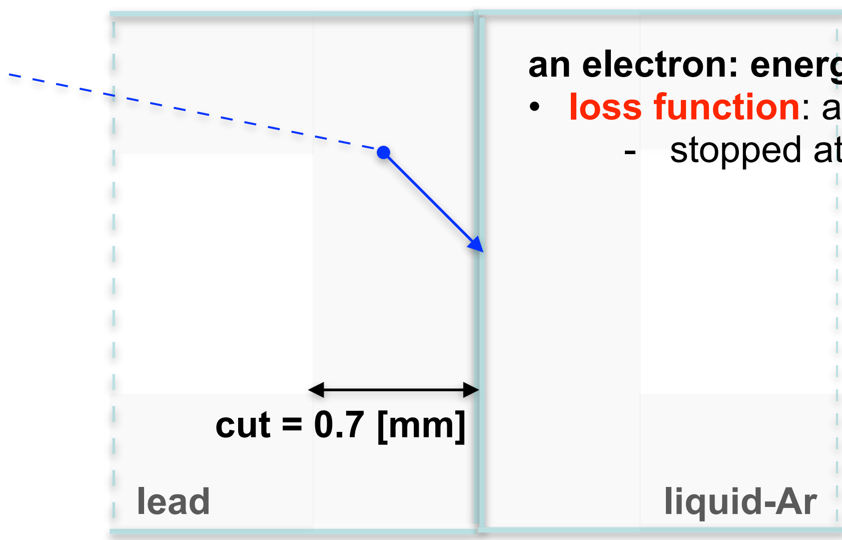


an electron: energy E_0 (range, etc) below the tracking cut

- **tracking cut** or **`G4UserLimits`**: stopped in **lead**, **E_{dep}= E_0**

Tracking cut, `G4UserLimits` v.s. the loss function

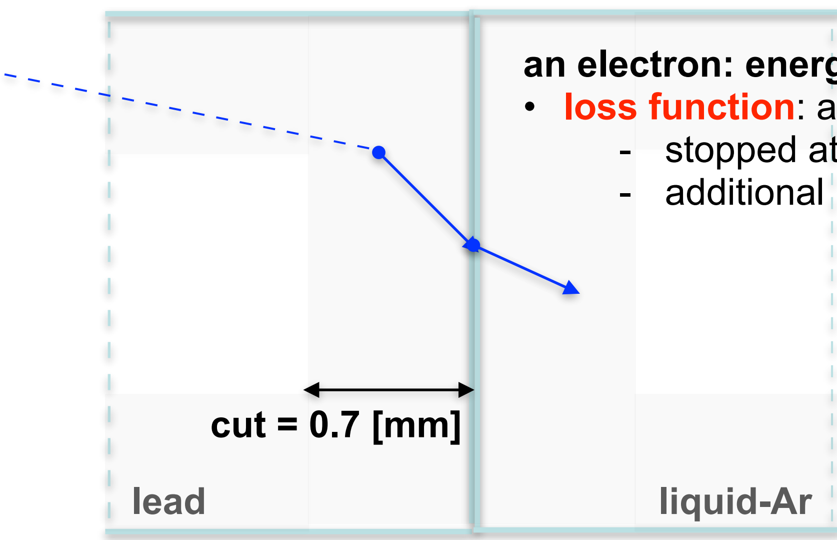
- **No racking cut (e.g. relying on the loss function):**
  - the only way to **ensure appropriate final position of the charged particle** (and energy deposit location; see below)
  - whenever the **particle range drops below** the ***final range*** parameter value, an extra step, with a continuous step limit equal to the particle range, is proposed
  - **+** only appropriate final position and energy deposit location;
  - **+** `/process/eLoss/useCutAsFinalRange true` can be used to set ***final range*** = cut
  - **-** requires an extra (last) step



an electron: energy E_0 (range, etc) below the tracking cut

- **loss function**: an extra step with the range R > $d_{boundary}$
  - stopped at the boundary **lead**, **$E_{dep} < E_0$**

- **No racking cut (e.g. relying on the loss function):**
  - the only way to **ensure appropriate final position of the charged particle** (and energy deposit location; see below)
  - whenever the **particle range drops below** the ***final range*** parameter value, an extra step, with a continuous step limit equal to the particle range, is proposed
  - **+** only appropriate final position and energy deposit location;
  - **+** `/process/eLoss/useCutAsFinalRange true` can be used to set ***final range*** = cut
  - **-** requires an extra (last) step



an electron: energy E_0 (range, etc) below the tracking cut

- **loss function**: an extra step with the range $R > d_{boundary}$
  - stopped at the boundary **lead: $E_{dep} < E_0$**
  - additional (rest of the) step in **liquid-Ar: $E_{dep} > 0$**

Electromagnetic Physics: special topics

SECONDARY PRODUCTION THRESHOLDS

Cuts beyond Ionisation and Bremsstrahlung

Secondary production threshold: beyond `ionisation` and `bremsstrahlung`

- Using **condensed history description of** **`ionisation`** and **`bremsstrahlung`**
  - has very **strong influence** already **at the model level**, **determining** also several characteristics of **the whole simulation** (continuous-discrete process, fluctuation)
  - the **value of the secondary production threshold** will have a **strong influence** to the (restricted) **macroscopic cross sections**, that determine **the mean step length between** the corresponding discrete events leading to **secondary e⁻/γ production**
- **This is not the case** **when** secondary e⁻/γ **production threshold is applied to other processes**:

  (UI command:`/process/em/applyCuts true`**)**
  - the secondary **production threshold has no influence to the** corresponding **models** at all
  - there is **no any influence to the** corresponding macroscopic cross sections, i.e. to the **mean step lengths between successive interactions**
  - **neither to the production of** the **secondary** e⁻/γ particles **at the model level**: ***always produced*** and ***the energy of the primary is always reduced accordingly***
  - however, **these sub-threshold secondary** e⁻/γ **particles** are **not pushed to the** track **stack** at the higher `G4SteppingManager` or `G4VEmProcess`(discrete EM, e.g. gamma interactions) level
  - this should not alter the result:
    - ✦ altering the result is a clear indication of wrong, i.e. too high production threshold values
  - there is a misconception that it alters the result due to the missing contribution to the fluctuation, but this is clearly wrong (as applying cut on processes other than ion. and brem. affects only the already produced secondary).

- Using **condensed history description of <u>`ionisation`</u>** and **<u>`bremsstrahlung`</u>**
  - **sub-threshold** e^-/γ **secondaries are not generated**, the primary is not even stopped to do so
  - the **corresponding** sub-threshold **energy loss**es are **accounted** as continuous energy losses of the primary along its steps
  - the **mean** value of these **energy losses along a** given **step** can be **computed by using the** corresponding (**restricted**) **stopping power**: **mean energy loss due to sub-threshold secondary** e^-/γ **production** in ionisation/bremsstrahlung **in unit path length**
  - having the length of a given step, the mean energy loss can be computed
  - **energy loss fluctuation model,** for providing samples according to the real distribution around this mean energy loss, is required

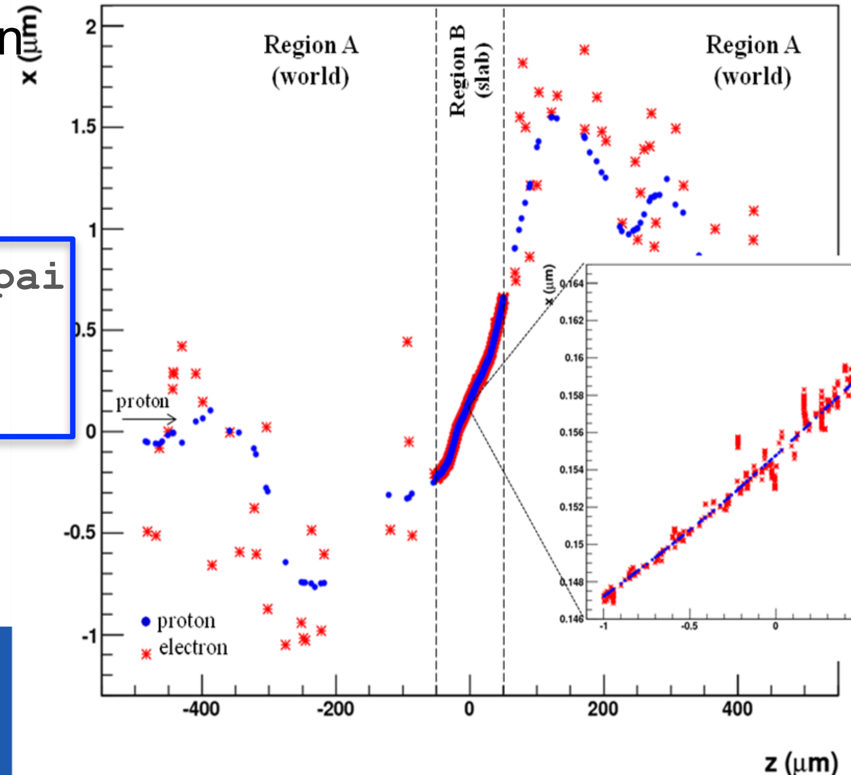
- **This is not the case when** secondary e^-/γ **production threshold is applied to <u>other processes</u>:**
  `/process/em/applyCuts true`
  - the secondary **production threshold has no influence to the** corresponding **models** at all
  - the **secondary** e^-/γ particles **at the model level**: ***always produced*** and ***the energy of the primary is always reduced accordingly***
  - independently if the corresponding secondary particle is used or discarded, **the post-interaction primary has the appropriate energy distribution**

Electromagnetic Physics: special topics

EM MODELS PER DETECTOR 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, allowing easy configuration of some models per-region on the top of any EM constructor, are also available:

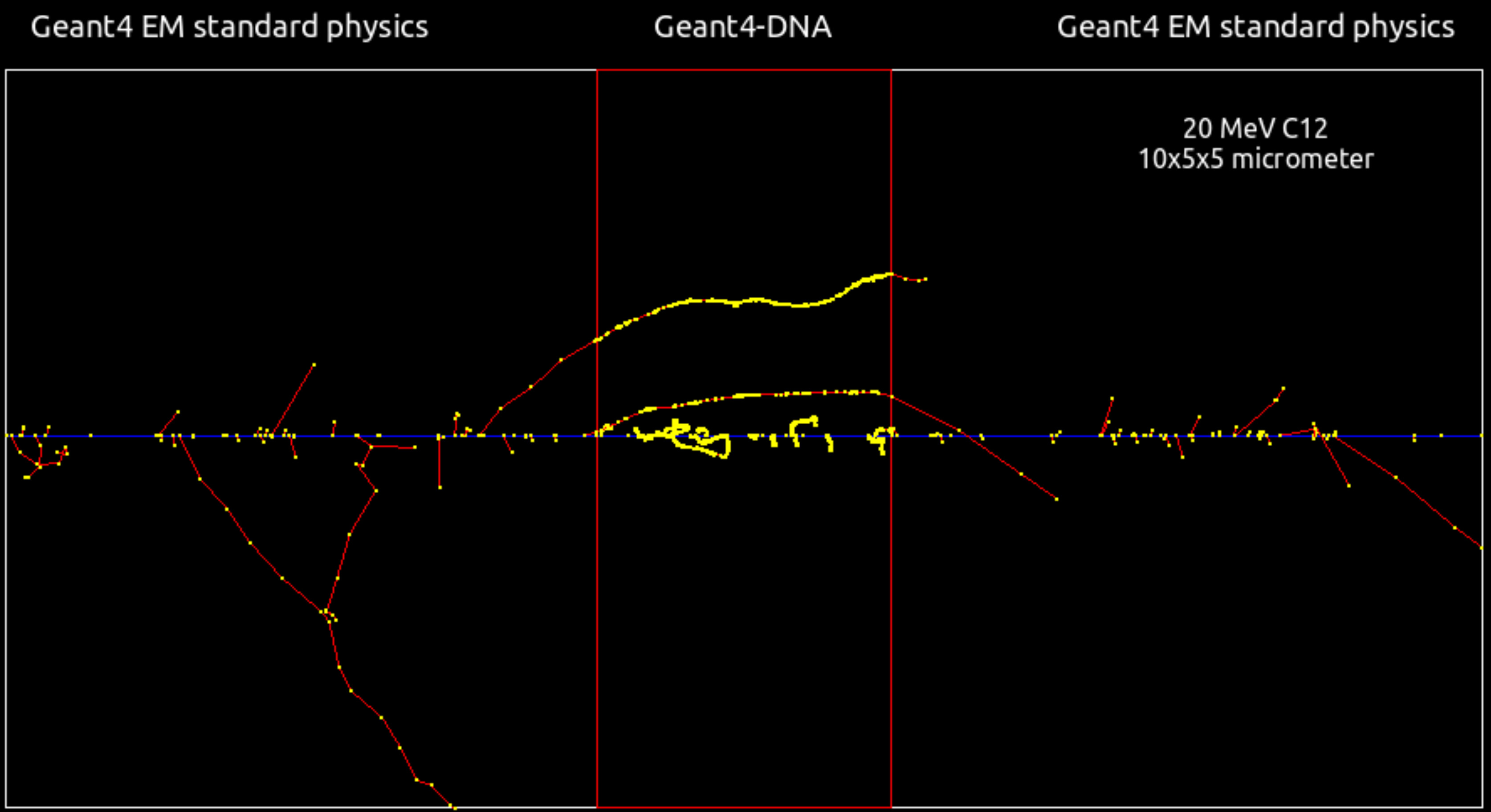
```
/process/em/AddPAIRegion proton MYREGION pai
/process/em/AddMicroElecRegion MYREGION
/process/em/AddDNARegion MYREGION opt0
```



EM models per detector 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
```

Nucl. Instrum. and Meth. B 273 (2012) 95
Prog. Nucl. Sci. Tec. 2 (2011) 898

- Using our previously created detector region with the name "`Our-Region`" (see slide #30)
- Change the default `MollerBhabha` ionisation model for e- in "`Our-Region`" to the `PAI`:
  - using the `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 previously created detector region with the name "`Our-Region`" (see slide #30)
- Change the default `MollerBhabha` ionisation model for e- in "`Our-Region`" to the `PAI`:

```
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
```

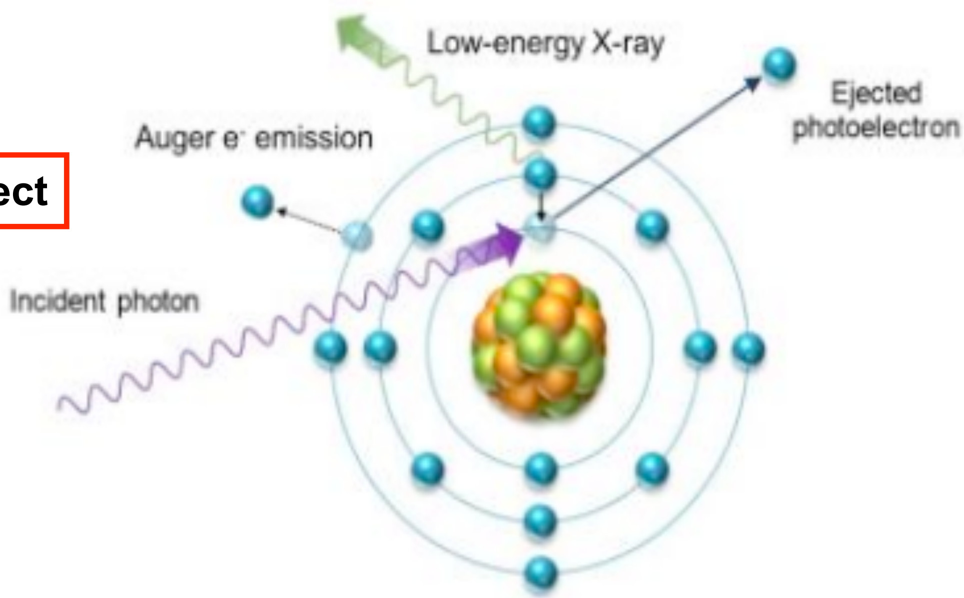
Electromagnetic Physics

ATOMIC DE-EXCITATION

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

photoelectric effect



- 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/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
  -

```
/process/em/deexcitationIgnoreCut true
```

Electromagnetic Physics

MULTIPLE COULOMB SCATTERING

See the dedicated material at Electromagnetic Physics II