Physics II.: Physics Process

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Geant4.10.5

Slides based on Dennis Wright (SLAC) & Vladimir Ivantchenko (CERN) lectures

OUTLINE

- **Overview of Geant4 physics components**

- **The Geant4 physics process interface(es)**
  - `G4VProcess` interface and its specialisations

- **Secondary particle production thresholds**
  - What is it? Why do we need them?
  - An example.
  - Production cuts per region.

PHYSICS COMPONENTS

- **Overview of Geant4 physics components**

- **The Geant4 physics process interface(es)**
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Physics Components

- **Geant4 provides a vide variety of physics components**
- **The building blocks of these components are *Process*es:**
  - a process describes a well defined interaction of (a) particle(s) with matter
  - describe = determines *when* the interaction happens and what the *result is*
  - processes provide these information through a `G4VProcess` interface (later)
  - Geant4 provides a huge number of such processes
  - users might introduce their own process(es) easily by implementing the general process interface
- **Processes are classified as:**
  - Electromagnetic
  - Hadronic
  - Decay
  - Parameterized
  - Transportation

Physics Components

- **Geant4 Physics: Electromagnetic**
  - *the standard EM part*: provides a complete set of EM interactions (processes) of charged particles and gammas from 1 keV to ~PeV
  - *the low energy EM part*: includes special treatments for low energy e-/+, gammas and charged hadrons:
    - more sophisticated approximations valid down to lower energies e.g. more atomic shell structure details
    - some of these processes will be valid down to below keV but some can be used only up to few GeV
  - *optical photons*: interactions special only for long wavelength photons
    - processes for reflection/refraction, absorption, wavelength shifting, (special) Rayleigh scattering

Physics Components

Geant4 Physics: Hadronic

- pure hadronic interactions for 0 to ~TeV
  - elastic, inelastic, capture, fission
- radioactive decay:
  - both at-rest and in-flight
- photo-nuclear interaction from ~10 MeV up to ~TeV
- lepto-nuclear interaction from ~10 MeV up to ~TeV
  - e+ and e- induced nuclear reactions
  - muon induced nuclear reactions

Physics Components

- **Geant4 Physics: Decay, Parameterized and Transportation**
  - decay processes includes:
    - weak decay (leptonic, semi-leptonic decay, radioactive decay of nuclei)
    - electromagnetic decay (π^0, Σ^0, etc.)
    - strong decay not included here (they are part of hadronic models)
  - parameterized process:
    - EM shower generation based on parameters obtained from averaged events
    - used as fast simulation in case of complex detectors: fast but less accurate
  - transportation process:
    - special process that responsible to propagate the particles through the geometry
    - need to be assigned to each particle

PHYSICS PROCESS INTERFACE

- Overview of Geant4 physics components

- **The Geant4 physics process interface(es)**
  - `G4VProcess` interface and its specialisations

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Physics Process Interface

- **Geant4 propagates `G4Track` objects in a step-by-step way**
- **A `G4Track` objects is a snapshot of the particle state**
  - with *dynamic* particle properties `G4DynamicParticle` (energy, position, etc.)
  - and *static* particle properties `G4ParticleDefinition` (charge, rest mass, etc.)
  - there are as many `G4ParticleDefinition` objects as particles constructed (i.e. one `G4Electron`, one `G4Gamma`, etc.)
  - but many `G4Track` objects might represent the same particle type (i.e. many electron tracks with different energy, position, etc.)
- **The possible interactions depend (primarily) on the particle type**
- **The list of possible interactions of a given particle is declared in the Physics List**
- **This list is stored in a `G4ProcessManager` object:**
  - each `G4ParticleDefinition` object (particle) has one process manager
  - that holds a list of `G4VProcess` objects that has been assigned to the particle

Physics Process Interface

- **The G4VProcess is:**
  - the general Geant4 physics process interface to describe any interactions
  - at each step, each interaction must provide information such as:
    - How far(space/time) this particle goes till the next interaction of the given type ?
    - What happens in the interaction ? (post interaction primary state + secondaries)
  - G4VProcess provides *interface methods* for this information flow:
    - GetPhysicalInteractionLength() - to provide the interaction length
    - DoIt() - to perform the transformation from the pre- to the post-interaction state
  - in general, the particle can interact with matter:
    - AlongStep - **continuously**, while moves from the pre- to the post-step point
    - PostStep - at the **discrete** post-step point of the step (*well-located in space*)
    - **AtRest** - when it stopes (*well-located in time*)
  - for each form of the above interactions, the process needs to implement both the corresponding GetPhysicalInteractionLength() and DoIt() methods
  - a process might be the combination of some or all of the above(6 methods)

Physics Process Interface: example processes

- **Discrete process: Compton scattering**
  - length of the step to the interaction determined by cross section and the interaction happens at the post-step point
    - `PostStepGetPhysicalInteractionLength()` and `PostStepDoIt()`
- **Continuous process: Cherenkov effect**
  - photons are created along the step (# proportional to the step length)
    - `AlongStepGetPhysicalInteractionLength()` and `AlongStepDoIt()`
- **At-Rest process: muon minus capture at rest**
  - muon has already stopped (zero kinetic energy) so time is the relevant
    - `AtRestGetPhysicalInteractionLength()` and `AtRestDoIt()`
- **Continuous + Discrete process: bremsstrahlung (ionization)**
  - low energy photons (electrons) are not generated, the corresponding energy loss is deposited along the step as continuous process
  - energetic photons (electrons) are generated in discrete interaction
  - secondary photon (electron) production threshold separates the two continuous and discrete parts (see later)
- **Discrete + At-Rest process: positron annihilation**
  - in-flight annihilation as a discrete process, determined by the cross section
  - at rest annihilation, when the positron has already stopped

Physics Process Interface: process management

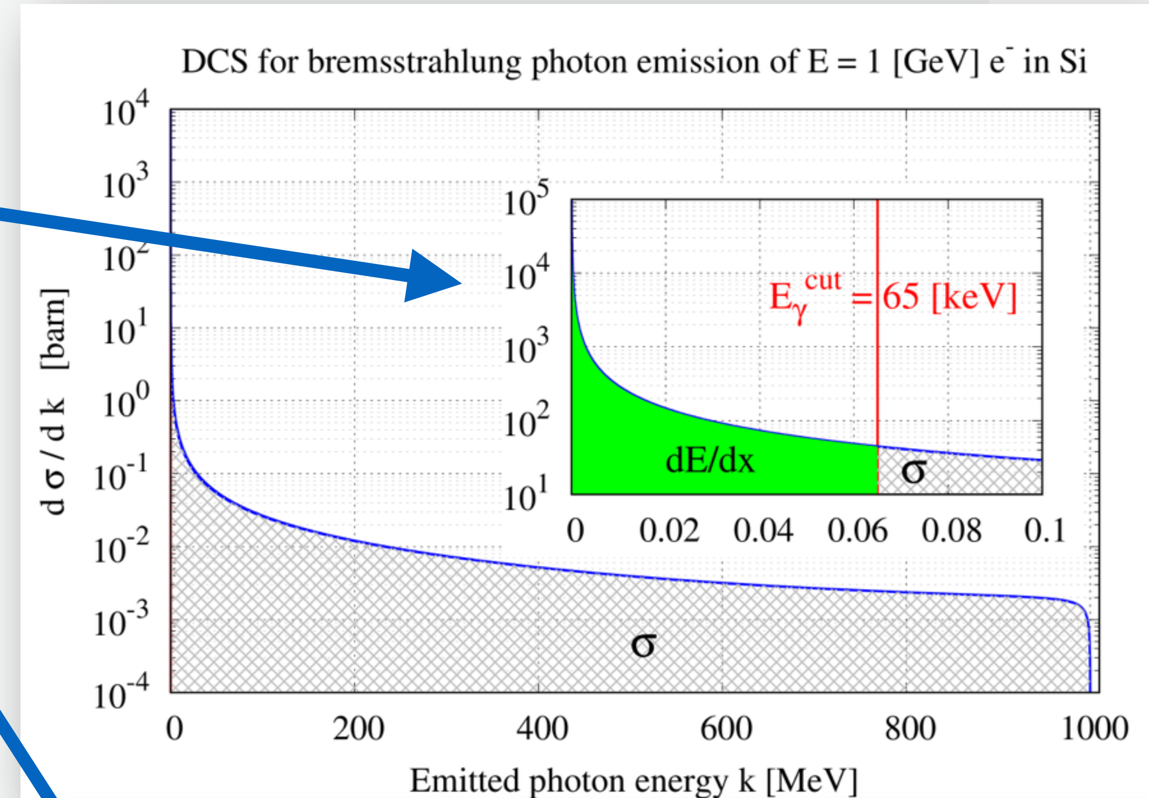
- **Many processes (i.e. possible interactions) might be assigned to a given particle**
  - e.g. gamma: e+/e- pair-production, Compton scat., photoelectric effect, etc.
  - particle, process constructions and assignment is declared in the *physics list*
  - each *particle* will store the list of assigned *processes* in its `G4ProcessManager`
  - the *static particle* object can be obtained from the *track* at any time
  - and its *process manager* can provide access to the l*ist of the assigned processes* per type:
    - list of discrete, or continuous or at-rest processes assigned to the particle
  - each of these processes must follow the `G4VProcess` process interface:
    - implement the type dependent interaction-length and do-it interface method(s)
  - at the pre-step point, each processes assigned to the particle:
    - will be asked to provide its physics-interaction length
    - transportation will also provide its length i.e. distance to the next volume boundary
    - the shortest among these length will be selected
    - it determines the post-step point (without field in case of charged particles)
    - it determines the interaction (i.e. process) that happens in this step
  - the track will be transported to the post step point:
    - the `DoIt()` process interface method(s) will be invoked to perform the interaction(s)
  - see more on these later in the special EM processes and stepping lecture

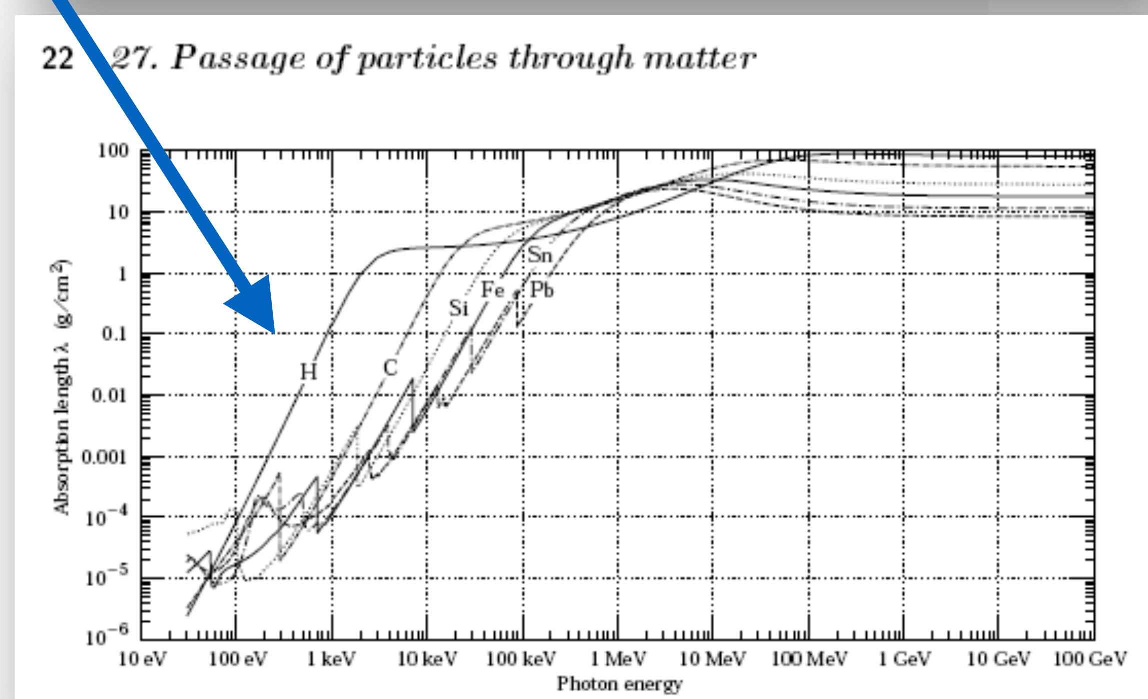
SECONDARY PARTICLE PRODUCTION THRESHOLDS

- Overview of Geant4 physics components
- The Geant4 physics process interface(es)
  - `G4VProcess` interface and its specialisations
- **Secondary particle production thresholds**
  - What is it? Why do we need them?
  - An example.
  - Production cuts per region.

Secondary production threshold: why?

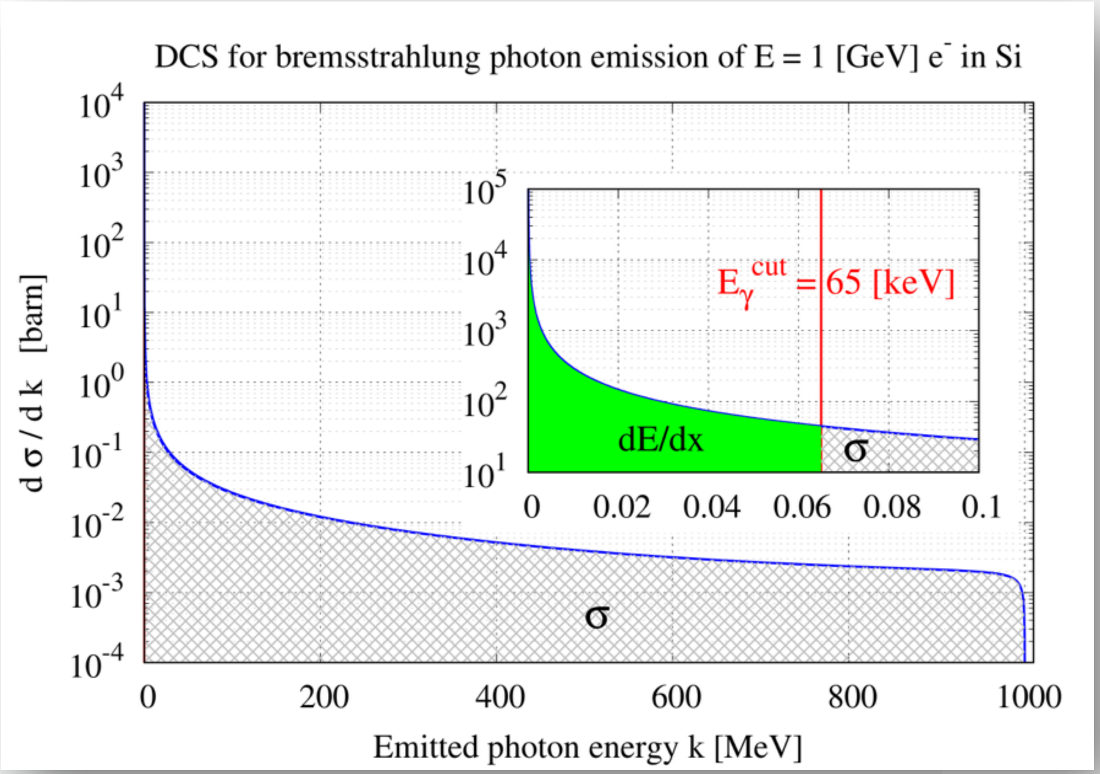
- **Bremsstrahlung:**
  - low **energy** photons (k small) will be emitted with high rate i.e. DCS ~ 1/k
  - generation and tracking of all these low energy photons would not be feasible (CPU time)
  - but low energy photons has a very small absorption **length** (don't go far)
  - so if the detector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





Secondary production threshold: why?

- **Gamma production threshold:**
  - *secondary photons*, with initial energy below a gamma production threshold(**$k<E_\gamma^{cut}$**), are not generated
  - the corresponding energy is accounted as ***CONTINUOUS*** energy loss of the primary particle along its trajectory
  - this gives the radiative contribution of the (restricted) stopping power (**dE/dx**): mean energy loss due to sub-threshold photon emissions in unit (path) length



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

  - e.g. 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 simple 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**)

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

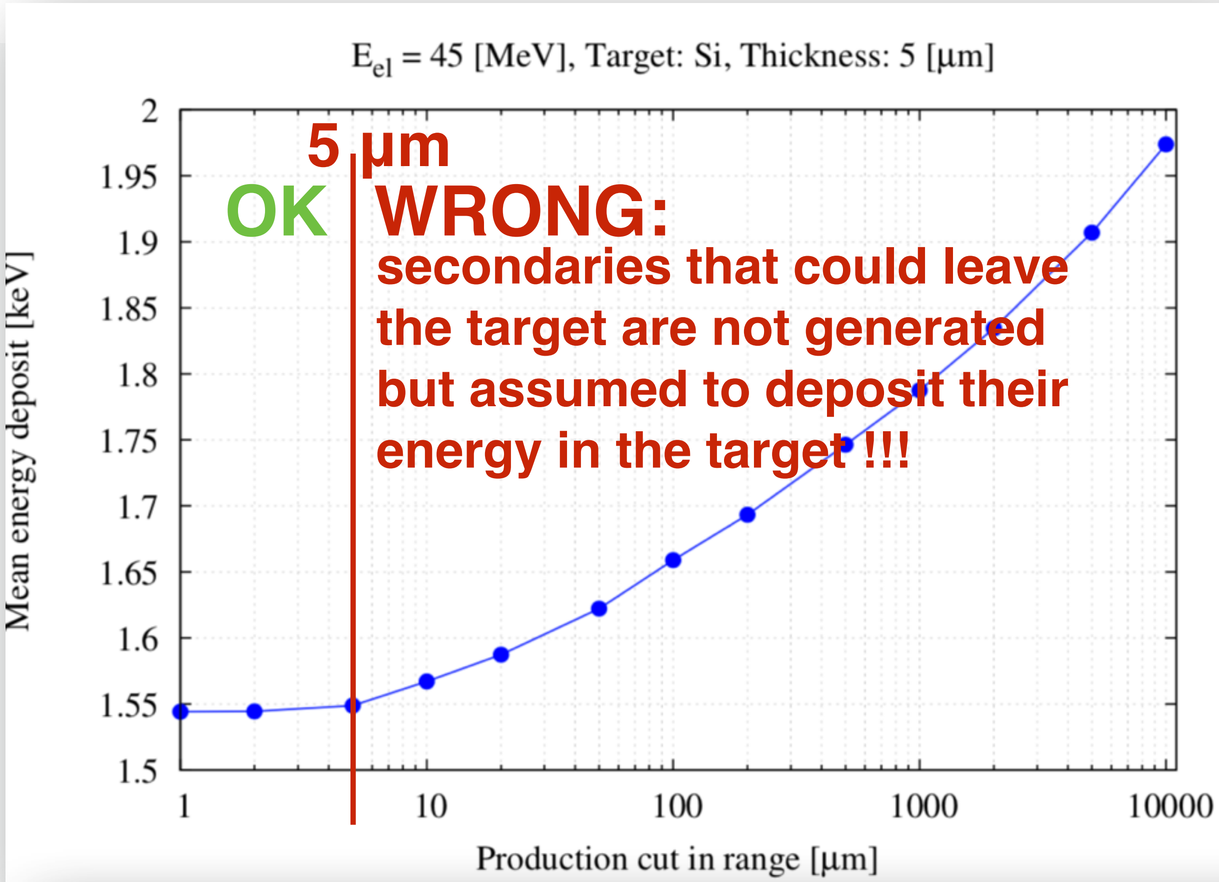
Secondary production threshold: why?

- **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 production threshold would be given in **energy:**
    - the secondary production threshold will be required in **energy** at the model level
    - 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
    - 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 to use **length** directly (different values depending on the particle types)

Secondary production threshold: Geant4

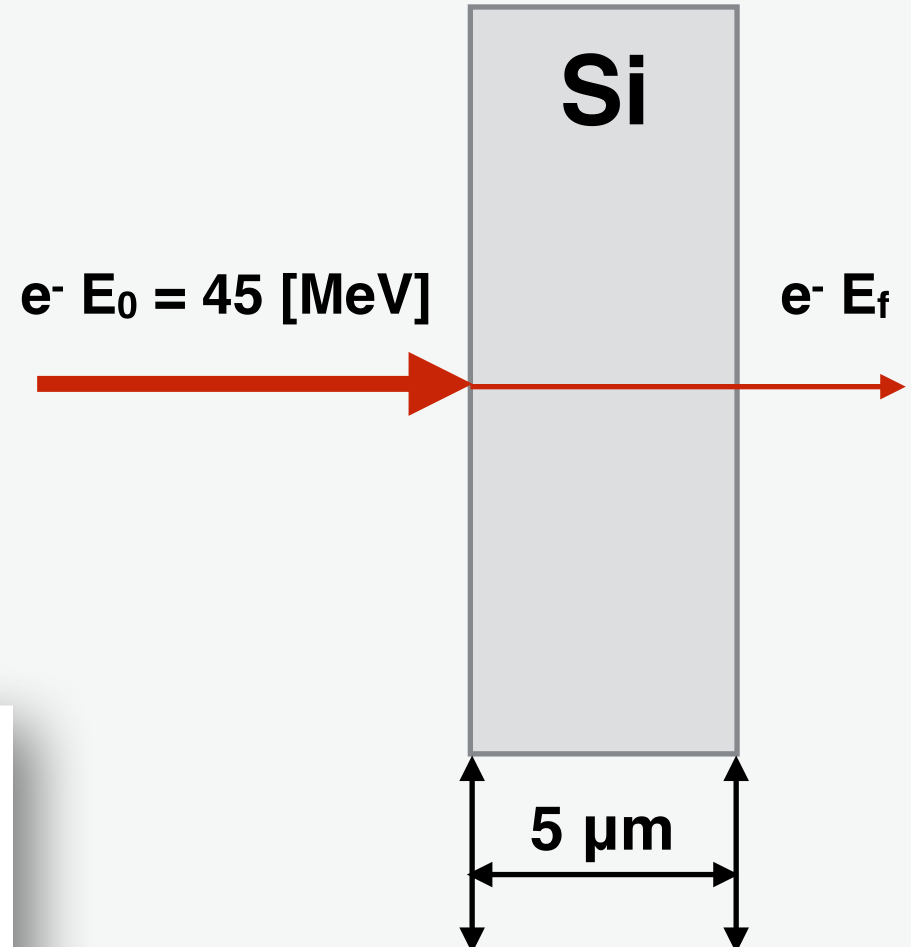
- **Secondary production thresholds in Geant4:**
  - are given in **length** with a default of 1.0 [mm]
  - its proper value application dependent (size of the sensitive volume, CPU)
  - the user need to provide the proper value(s) in the `PhysicsList::SetCuts()`
    - UI command: `/run/setCut 0.1 mm` or `/run/setCutForAGivenParticle e- 0.1 mm`
  - translated to energies at initialisation depending on material an particle type
  - this energy has a minimum value: default 990 [eV] but the user can set it
    - UI command: `/cuts/setLowEdge 500 eV`
  - defined for gamma, e^-, e^+ and proton secondary particle types
    - gamma production threshold is used in bremsstrahlung
    - e^- production threshold is used in ionization
    - e^+ production threshold might be used in 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: `ApplyCuts()`) in all discrete interactions producing such secondaries e.g. Compton, Photoelectric, etc.
  - it's not mandatory to use production thresholds (depends only on the models)
  - however, high energy physics simulation would simple not be feasible without

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 (E_f-E_0) in the target



Secondary production threshold: Geant4

- **Final remarks:**
  - instead of "*secondary production threshold length*" it's more convenient to say simple *"production cut*" or even just "cut(s)"
  - secondary ***production*** *cut* and ***tracking*** *cut* are two different concepts:
    - production cut applies to secondary particles in their production
    - tracking cut, as a kinetic energy limit, applies to particles already under transportation
  - by default, Geant4 do not need to use tracking cuts
  - however:
    - the user can introduce and define *tracking cut*s for particles (in energy, time, etc.)
    - there is a low energy *tracking limit* applied to *charged particles* (having the special continuous-discrete energy loss process) with a default value of 100 [eV] - 1 [keV]
    - was introduced in Geant4.10.2 purely from performance reasons
    - can be set by the user to any value (even to 0) with the following UI command: `process/em/lowestElectronEnergy 0.1 eV`
  - in case of complex detectors (e.g. ATLAS, CMS) there are very different spacial granularities of the different parts of the detector with different sensitivities
  - a single production cut value might not be the appropriate one everywhere
  - Geant4 provides the possibility to define detector `G4Regions` with volumes of having similar sensitivity and granularity
  - a different set of secondary production threshold can be defined for each region

SUMMARY

- **Processes describe all the details of interactions**
- **Geant4 provides processes to cover nearly all particles over a wide energy range from 0 to ~TeV**
    - user might implement and use their own processes as well
- **Many processes might be assigned to a given particle**
- **Secondary production cuts are essential in high energy simulation**
- **Setting the proper production thresholds essential to get appropriate simulation results**
- **Geant4 provides the possibility to set proper production thresholds in length for several particles even in the case of the most complex detectors**