Physics II: Overview, Processes, Production Threshold, Regions & Cuts per region

Geant4 PHENIICS & IN2P3 Tutorial,
16 – 20 May 2022,
Orsay

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Credits…

- Daniel Brandt, Makoto Asai, Dennis Wright (SLAC),
- Gunter Folger (CERN), etc.
- Ivana,
- …

Introduction

- In this presentation, we will give an overview of the physics catalog of Geant4
- We will explain also how physics processes
  - are modeled, in term of C++ class
  - and how they are used during the tracking
- This is for "cultural" aspects, as in general, you will not have to worry about the structure of the process class
  - Because you will be using existing physics lists
  - Which setup properly processes and take care of technical details
- We will speak also about "cuts", which, at the opposite are something you must care about.
  - They must be defined for some physics processes
    - to run the simulation under time $< \infty$
  - "Cuts" is actually a bad usage name…
  - … and the issue is « production threshold »
  - But some care has to be taken in defining them

Outline

I. Physics Overview
   - Overview of Geant4 physics capability

II. Processes
   - How physics processes are modeled in Geant4

III. Production Thresholds (aka cuts)

IV. Regions

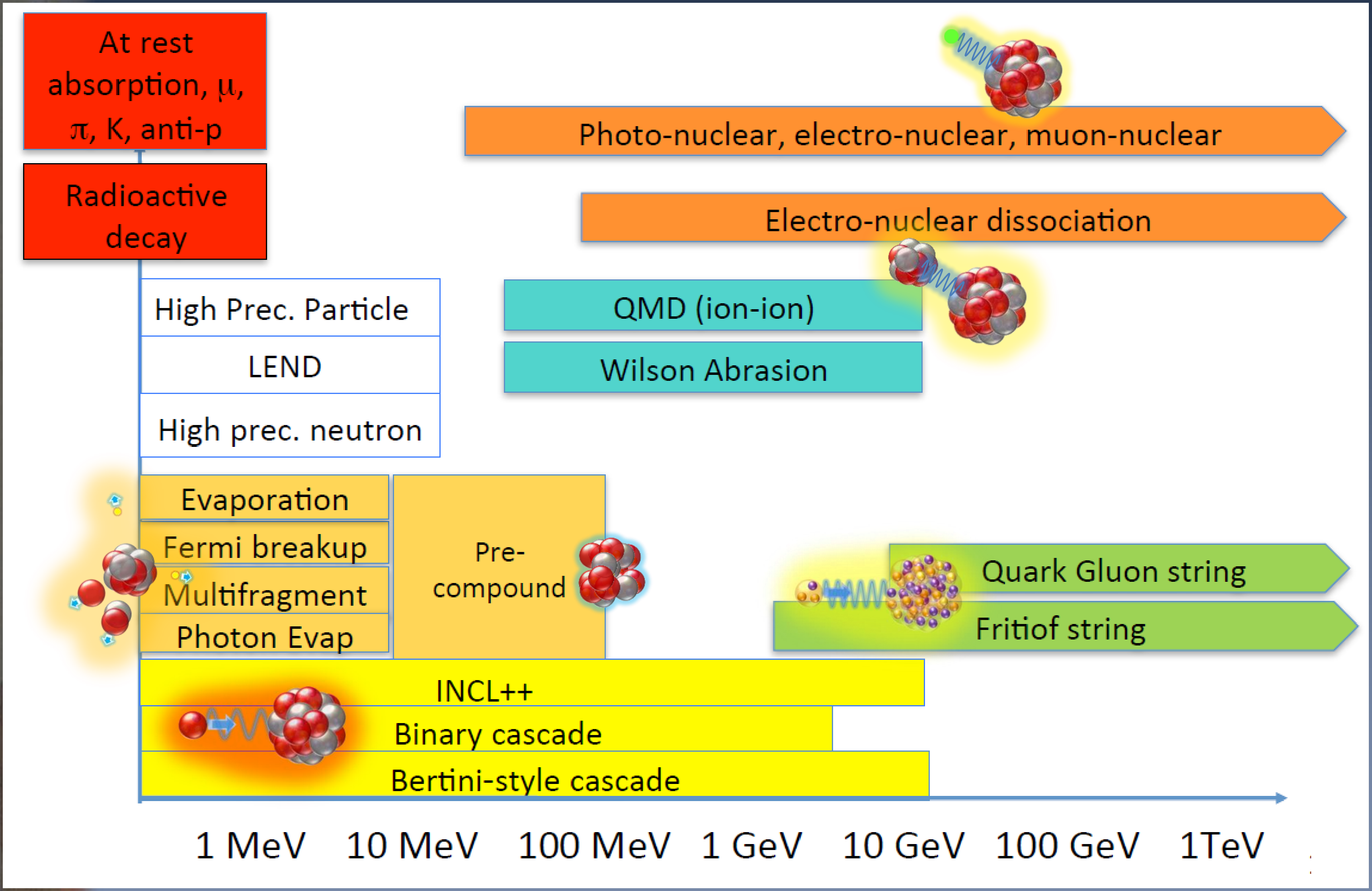
V. Cuts per region

I. Physics Overview

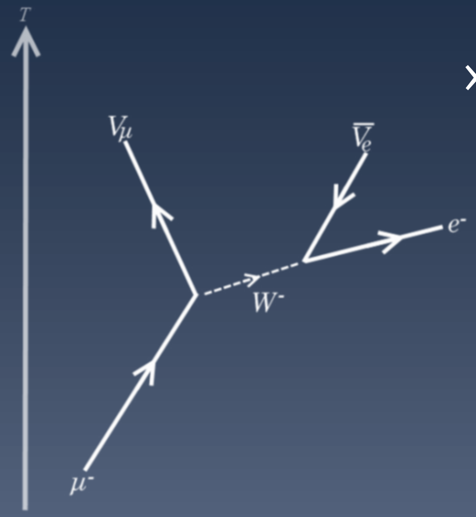
Electromagnetic Processes

- **Standard** : Complete set of processes covering charged particles and gammas.
  - Energy range 1 keV - ~PeV
- **Low energy** : More precise description at low energy for e^+, e^-, γ, charged hadrons incident particle.
  - More atomic shell structure detail
  - Some processes valid down to hundreds of eV
  - Some processes not valid above 1 GeV
- **DNA & MuElec** : for microdosimetry studies
  - Processes down to a few eV (!)
  - Plus chemistry stage for DNA
- **Optical photon** : Long wavelength γ (X-ray, UV, visible)
  - Reflection, refraction, absorption, wavelength shifts, Rayleigh scattering
- **Phonons** : under development. Acoustic phonons, for now. Suited for low-temperature (tens of mK) detectors.

Hadronic Processes

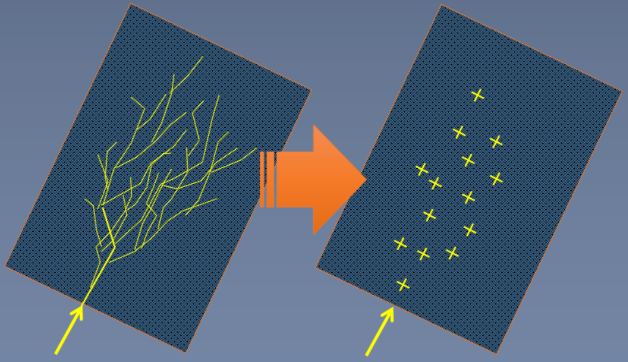


Decay & « Technical »



- Decay processes
  - Decay of particles of width narrow enough
    - i.e. : exclude hadronic resonances
  - weak decay (leptonic decays, semi-leptonic decays, radioactive decay of nuclei)
  - electromagnetic decay (e.g. π^0, Σ^0)

- « Technical » processes:
  - Processes without physics content but which act as interfaces for:
  - Parameterization
    - Fast Simulation functionnality
    - Hook to shortcut the detailed tracking
  - Parallel geometries
    - Limit the step on parallel geometry boundaries / switch tracking geometries
  - Scoring
    - Collect user requested information
  - Biasing
    - Modify physics behavior wrt to the reference standard one



Fast simulation : a full shower is replaced by a parametrized version of it

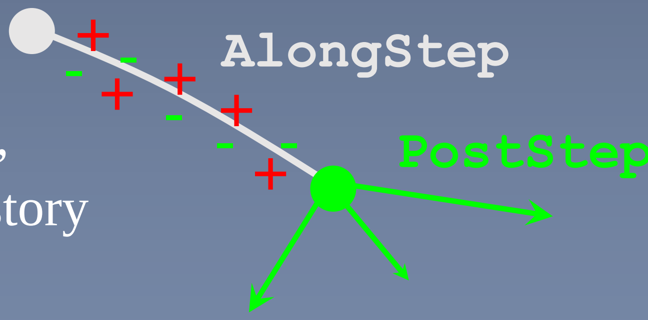
II. Processes

How Geant4 models processes

G4VProcess: 3 kind of actions (1/2)

- Abstract class defining the common interface of all processes in Geant4:
  - Used by all « physics » processes
  - but is also used by the transportation, etc…
  - Defined in `source/processes/management`
- Define three kinds of actions:
  - `AtRest` actions:
    - Decay, e^+ annih., absorption …

  - `AlongStep` actions:
    - To describe continuous (inter)actions, occuring along the path of the particle, like ionisation; used for condensed history



  - `PostStep` actions:
    - For describing point-like (inter)actions, like decay in flight, hard radiation…

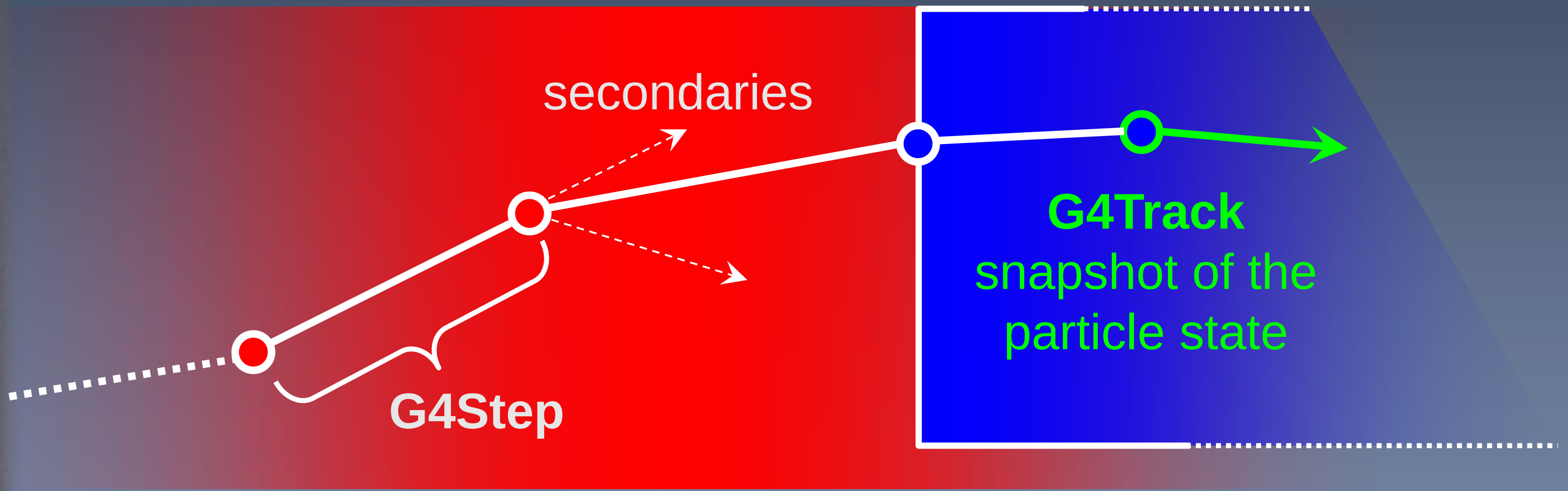
`G4VProcess`: 3 kind of actions (2/2)

- A process can implement any combination of the three **`AtRest`**, **`AlongStep`** and **`PostStep`** actions:
  - eg: decay = **`AtRest`** + **`PostStep`**

- Each action defines two methods:
  - **`GetPhysicalInteractionLength()`**:
    - Used to ***limit the step***:
      - either because the process « triggers » an interaction, a decay
      - or any other reasons, like fraction of energy loss, geometry boundary, user's limit …
  - **`DoIt()`**:
    - Implements the ***actual action*** to be applied on the track;
    - And the related production of secondaries.

How Geant4 uses the processes during tracking ?

› Remember:
  – Tracks are moved step by step :

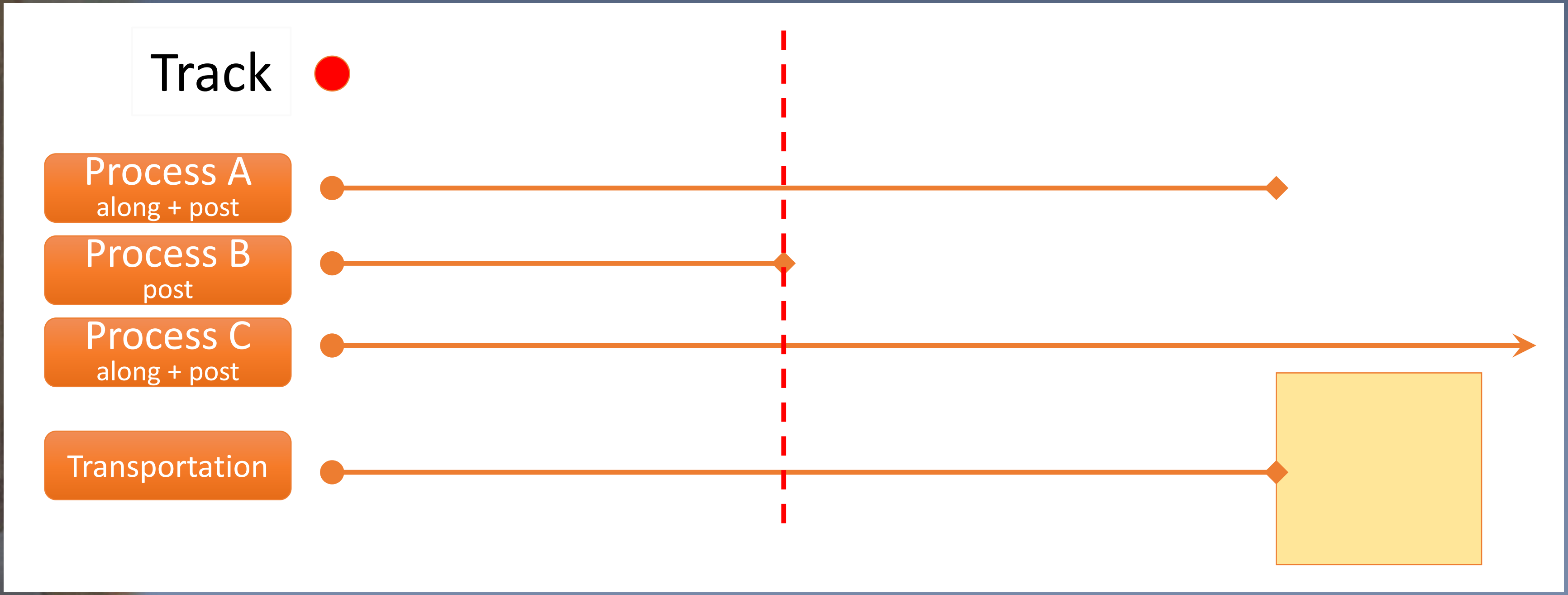


  – And several processes are attached to the track

› So what happens during a step ?

Process Handling by the Stepping

1. At the beginning of the step, the step length is determined:
   - Consider all processes attached to the current `G4Track`;
   - Define the step length as the smallest of the lengths among:
     - All `AlongStepGetPhysicalInteractionLenght()`
     - All `PostStepGetPhysicalInteractionLength()`



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2. Apply ***all*** **`AlongStepDoIt()`** actions, « at once »:
   - Changes computed from particle state at the beginning of the step;
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   - Then applied to the **`G4Track`**, from the **`G4Step`**.

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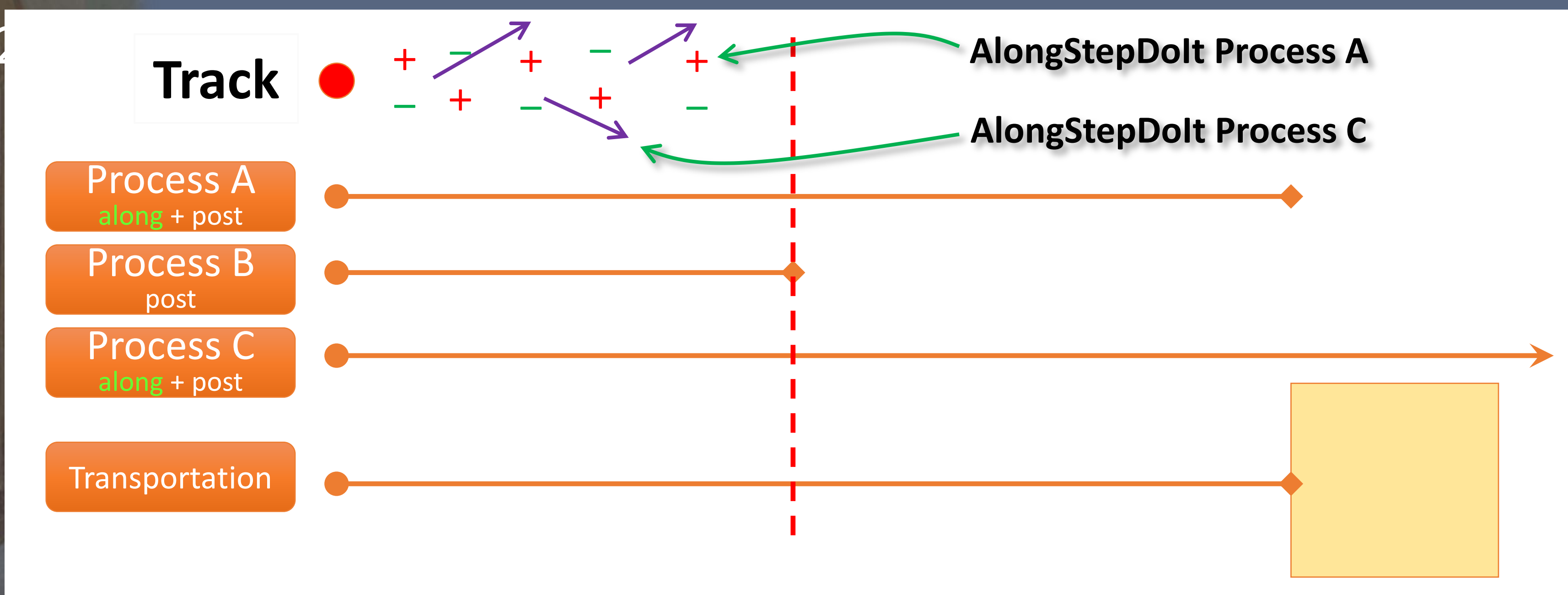

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   - Apply `PostStepDoIt()` of process which limited the step (if any);
   - And apply any other « forced » processes (not discussed here)

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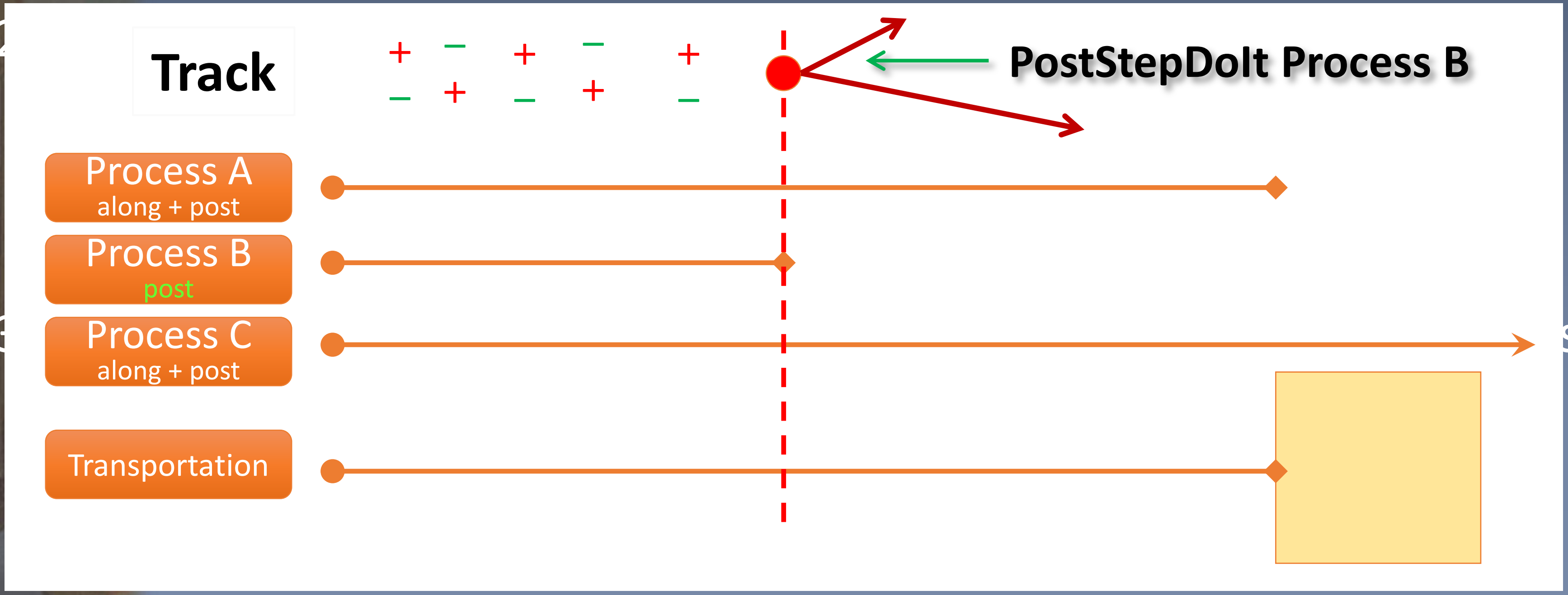

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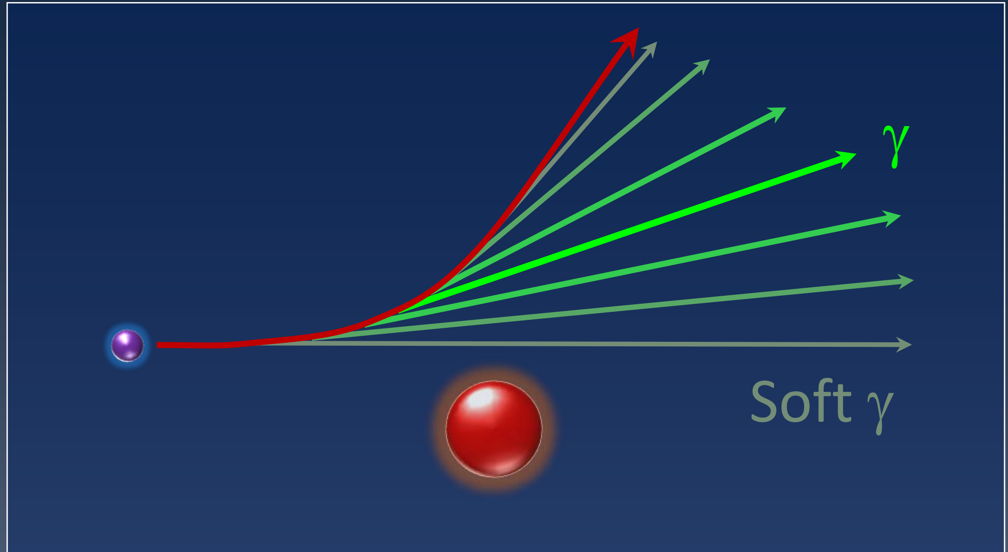
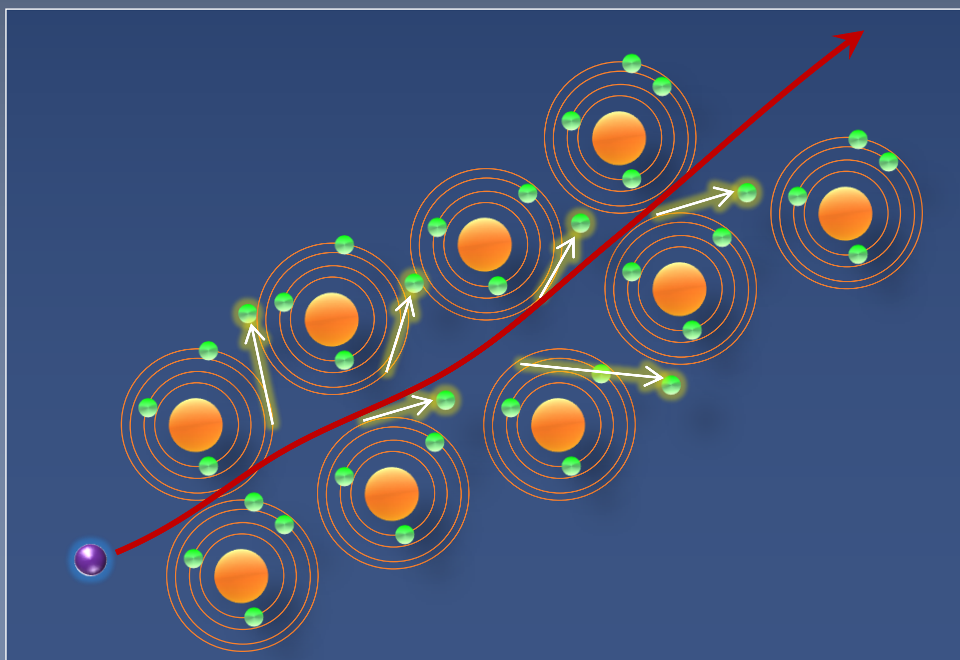
III. Production Thresholds (aka « cuts »)

Threshold for Secondary Production

- Simulation accuracy limited by:
  - Intrinsic limitation of physics process modeling
    - For example details of atomic or molecular structure, etc.
  - Finite computing power
    - Which forces to limit the production to some # of events
    - Which restricts the usage to models “fast enough”
      - Ie : no way to use lattice QCD in detector simulation
    - **Which forces to suppress the production of very low energy particles for processes having infrared divergences**
      - Infinite or very large number of produced secondaries



Bremstralhung: actual divergence in forward production of ultra-soft gammas.



Ionisation : large production of ionisation electrons, from loosely bound atomic ones.

Threshold for Secondary Production

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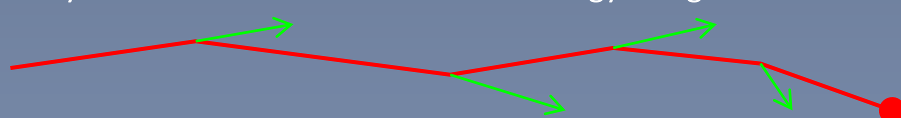
- Every simulation developer must answer the question:
  - How low can I go?
- This is a balancing act:
  - Need to go low enough to get the physics you’re interested in
  - Can’t go too low because of CPU time consumption
-

Threshold for Secondary Production

- **Geant4 solution: impose a production threshold**
  - this threshold is a distance, not an energy
    - This a “range threshold”
  - default = 0.7 mm
  - What makes this “range threshold” ?
    - In Nature, the primary particle loses energy by producing secondary electrons or gammas
      - (or by exciting atoms, molecules, etc. : not of interest here)
    - In Geant4, the threshold makes only secondary particles able to travel > 0.7 mm to be created
      - The rest is accounted for a “continuous energy loss” (condensed history)

- Only one value (per region) of range threshold is needed for all materials
  - And this distance is internally converted into the related energy thresholds by Geant4
  - Conversion “range $\rightarrow$ energy” is made to according to material

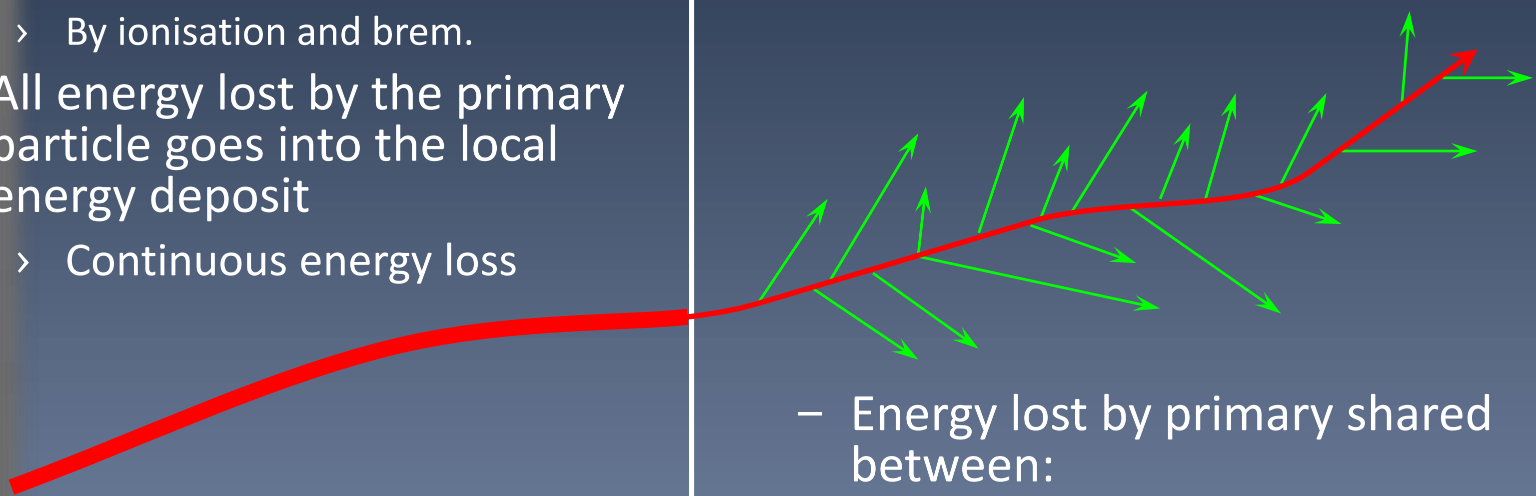
- Near the primary particle end-point:
  - When the primary becomes of too low energy to produce secondaries above threshold:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero kinetic energy using continuous energy loss



  - Note that this makes Geant4 having “no tracking cuts”

High and low thresholds : what differences ?

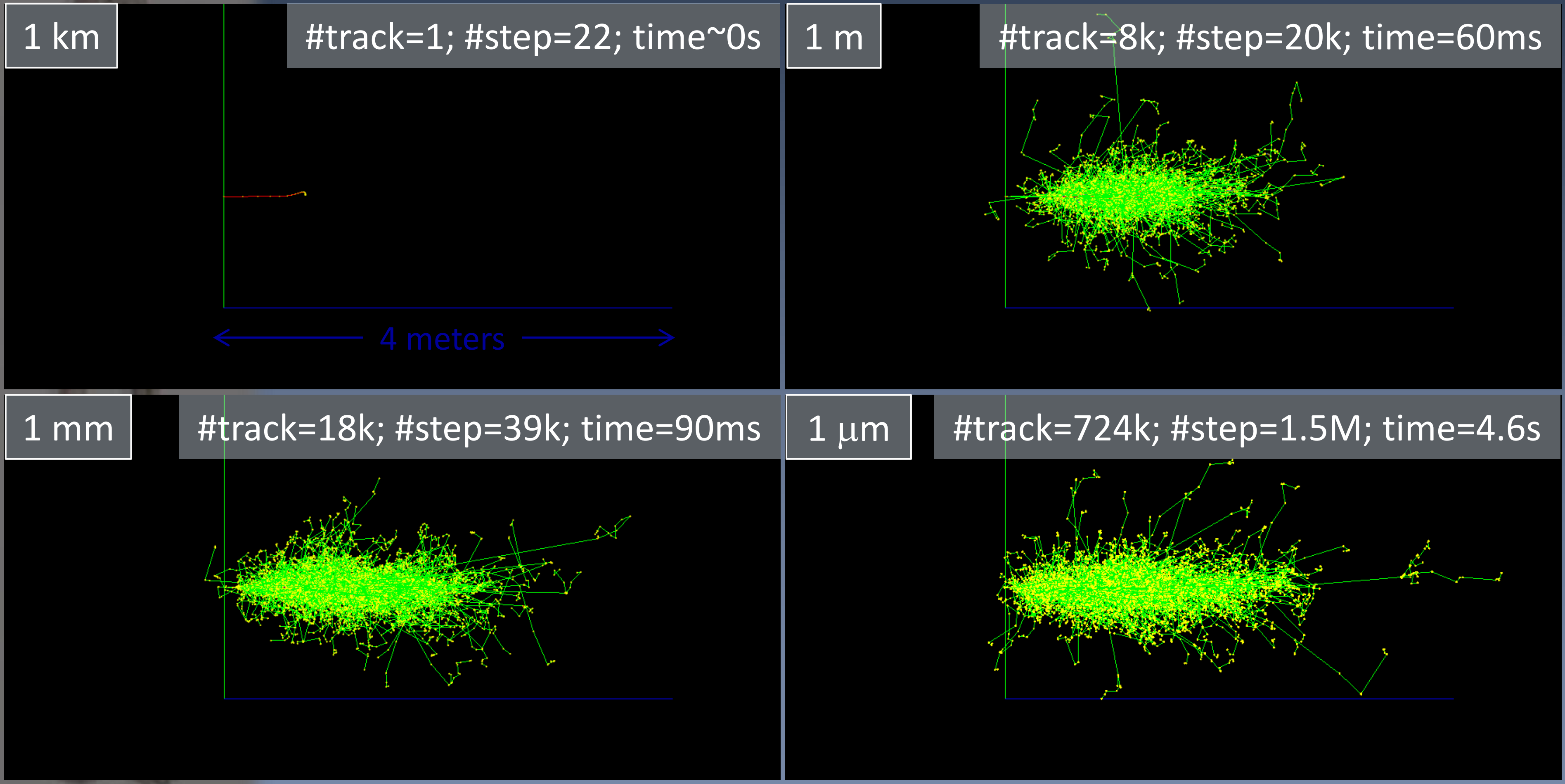
- **High Threshold**
  - No secondary production
    - By ionisation and brem.
  - All energy lost by the primary particle goes into the local energy deposit
    - Continuous energy loss



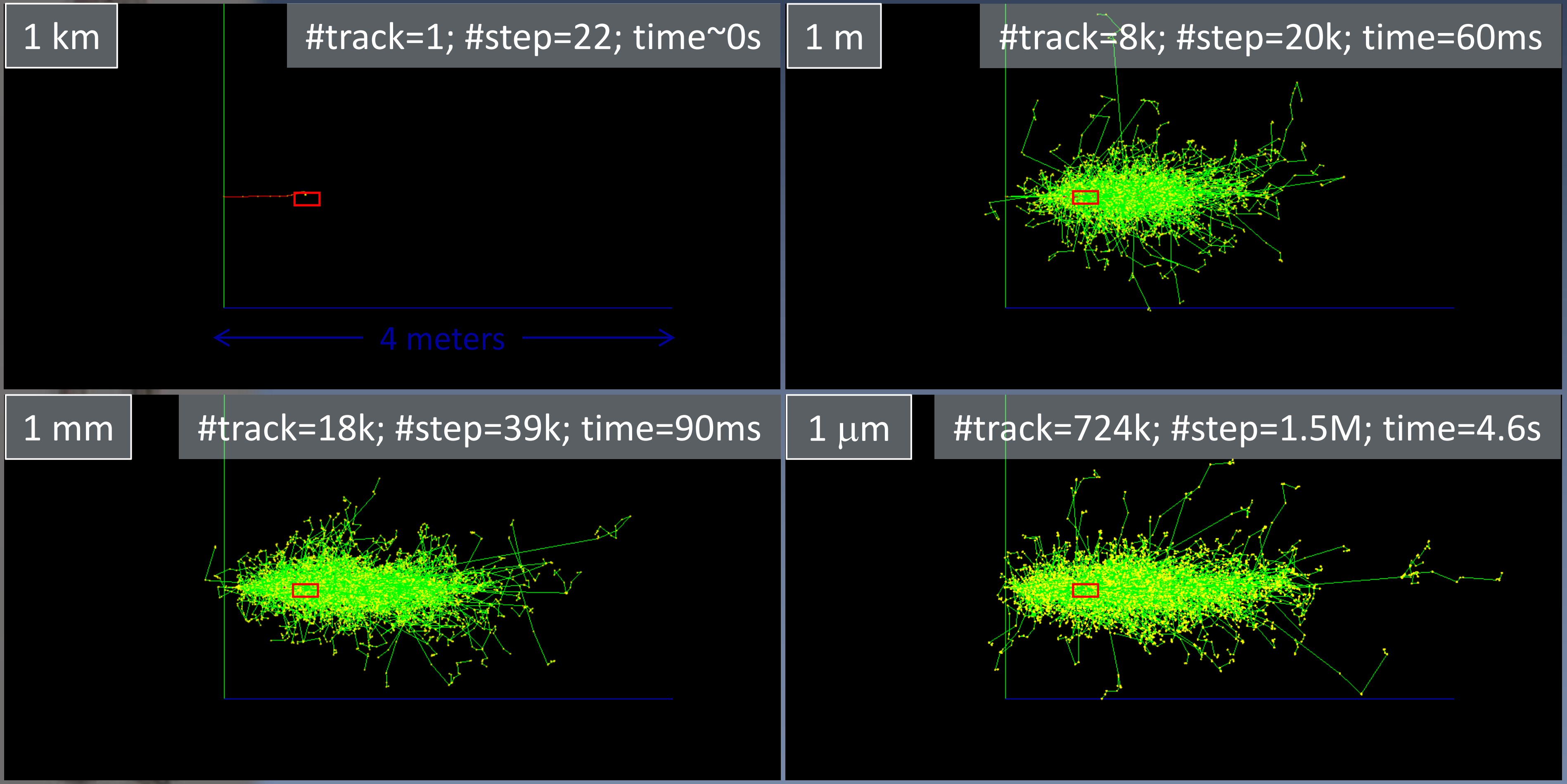
  - You'll see as:
    - step-> GetTotalEnergyDeposit() is high
    - You don't have energy deposit elsewhere than on primary path

- **Low Threshold**
  - Many secondaries produced
  - Energy lost by primary shared between:
    - Local energy deposit
    - discrete secondary production
  - You'll see as:
    - step->GetTotalEnergyDeposit() is lower than before
    - Energy deposit more scattered due to subsequent deposit of secondary particles

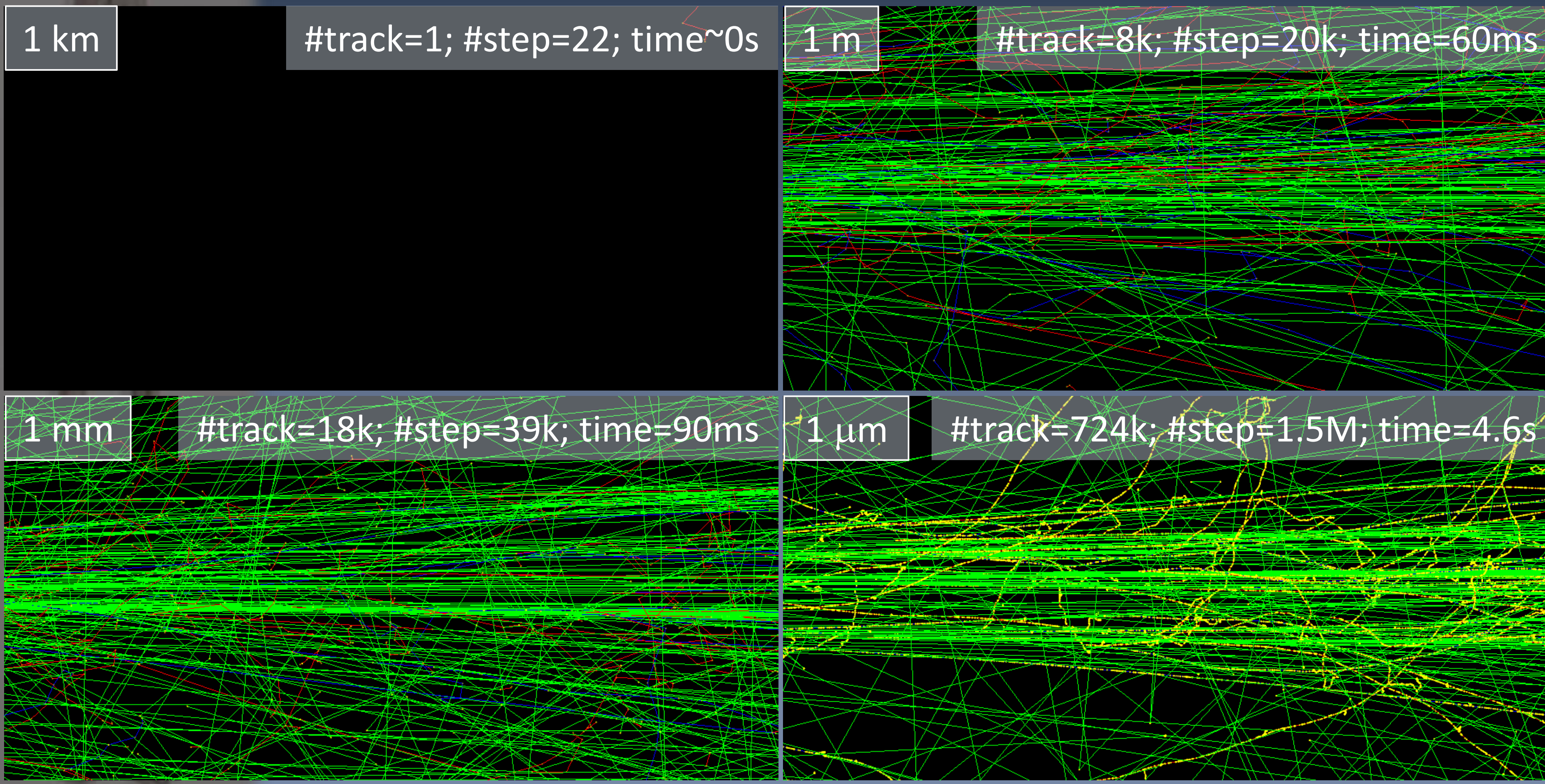
10 GeV e^- in liquid Argon, with cuts of 1 km, 1 m, 1 mm and 1 μm



10 GeV e^- in liquid Argon, with cuts of 1 km, 1 m, 1 mm and 1 μm



10 GeV e⁻ in liquid Argon, with cuts of 1 km, 1 m, 1 mm and 1 µm



Assigning cuts to your simulation

- You must assign cuts to γ, e^- and e^+.
  - For γ's : needed to limit production from infrared divergence of brem. process
  - For e^-'s : needed to limit high production from ionization
  - For e^+'s : bit of historical reasons (no infrared divergence process)
    - (Plans in Geant4 to review this)
- You may assign cuts to protons
  - To define the threshold for producing proton by **recoil in elastic collisions**
  - Threshold used for recoil ions too.
- The easiest way to define cuts is at run time
  - On command line or with a macro
  - For γ, e^- and e^+ and p in one go, eg:

```
/run/setCut 2 mm
```

  - Per particle threshold, eg:

```
/run/setCutForAGivenParticle e- 0.1 mm
```

  - (later we'll add the case of "region")

Getting information on range to energy conversion

```
/run/setCut 1 mm
/run/beamOn 1 (to force calculations of thresholds)
/run/dumpCouples

========= Table of registered couples ============================
Index : 0     used in the geometry : Yes
Material : G4_Galactic
Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
Energy thresholds :  gamma  990 eV     e-  990 eV     e+  990 eV  proton 100 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
Index : 1     used in the geometry : Yes
Material : G4_Pb
Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
Energy thresholds :  gamma  101.843 keV    e-  1.36749 MeV    e+  1.27862 MeV proton 100 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
Index : 2     used in the geometry : Yes
Material : G4_PLASTIC_SC_VINYLTOLUENE
Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
Energy thresholds :  gamma  2.40367 keV    e-  356.639 keV    e+  344.855 keV proton 100 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
==================================================================
```

Getting information on range to energy conversion

```
/run/setCut 0.01 mm
/run/beamOn 1 (to force calculations of thresholds)
/run/dumpCouples

========= Table of registered couples ==============================
Index : 0     used in the geometry : Yes
Material : G4_Galactic
Range cuts        :  gamma  10 um     e-  10 um     e+  10 um  proton 10 um
Energy thresholds :  gamma  990 eV     e-  990 eV     e+  990 eV  proton 1 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
Index : 1     used in the geometry : Yes
Material : G4_Pb
Range cuts        :  gamma  10 um     e-  10 um     e+  10 um  proton 10 um
Energy thresholds :  gamma  5.995 keV    e-  58.1082 keV    e+  56.9484 keV proton 1 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
Index : 2     used in the geometry : Yes
Material : G4_PLASTIC_SC_VINYLTOLUENE
Range cuts        :  gamma  10 um     e-  10 um     e+  10 um  proton 10 um
Energy thresholds :  gamma  990 eV     e-  15.1173 keV    e+  14.6763 keV proton 1 keV
Region(s) which use this couple :
DefaultRegionForTheWorld
====================================================================
```

Getting information on range to energy conversion

```
/run/setCut 1 nm
/run/beamOn 1 (to force calculations of thresholds)
/run/dumpCouples

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Energy thresholds :  gamma  990 eV     e-  990 eV     e+  990 eV  proton 0.1 eV
Region(s) which use this couple :
DefaultRegionForTheWorld
====================================================================
```
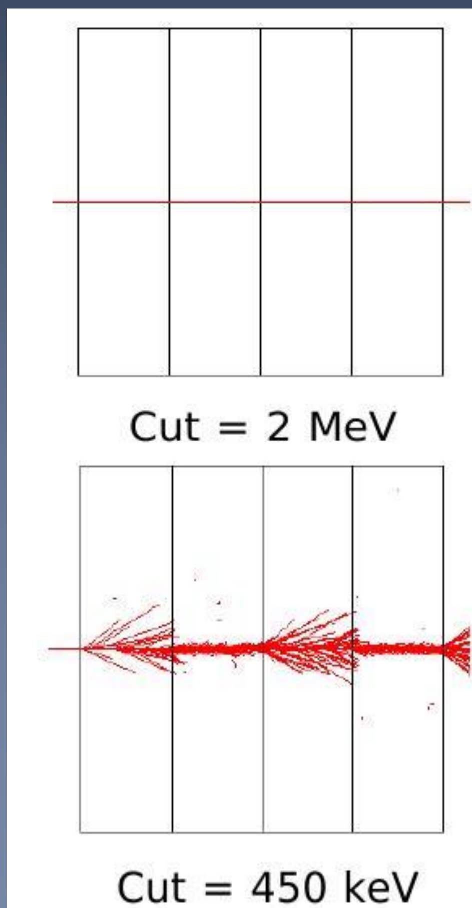
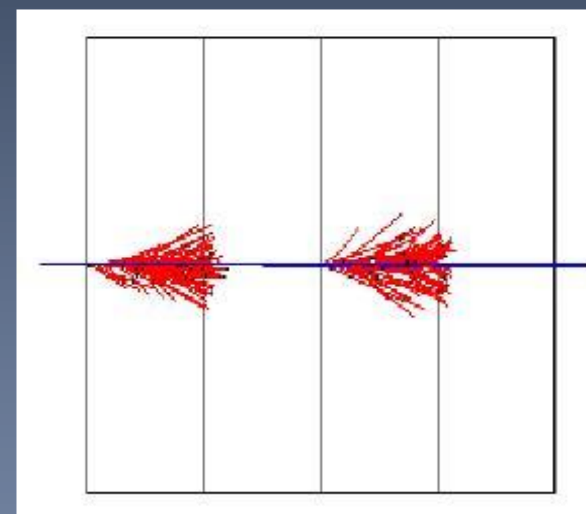

Production Threshold vs. Energy Cut

Example: 500 MeV p in LAr-Pb Sampling Calorimeter

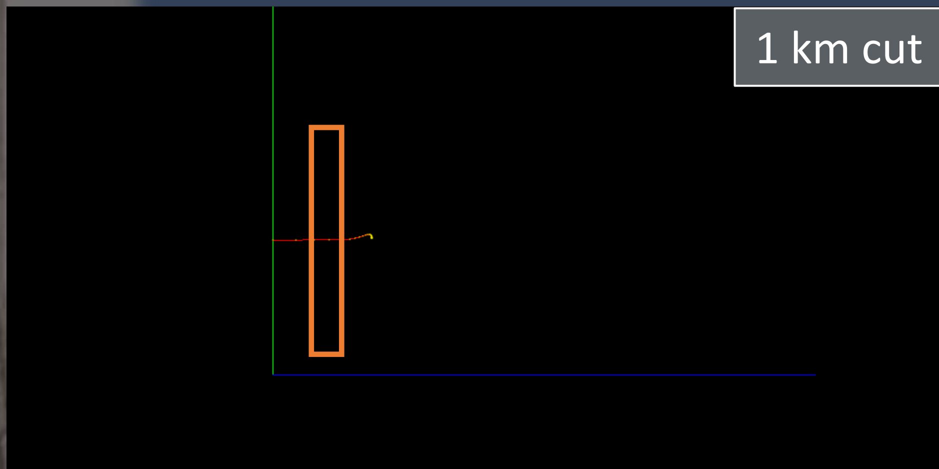
Energy Threshold

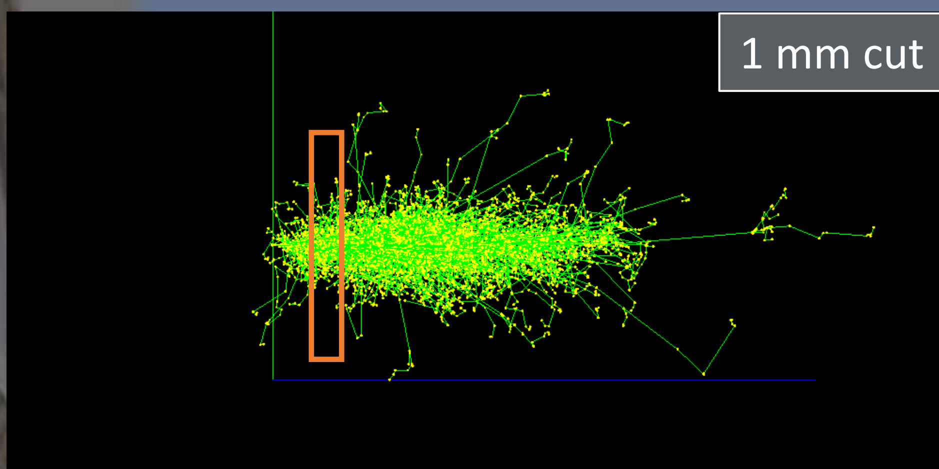


Geant4 Production Range Threshold



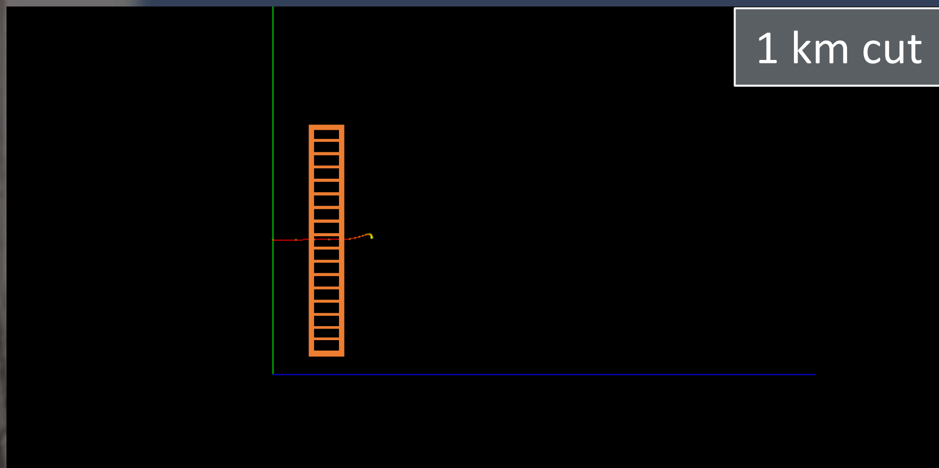
Energy recorded

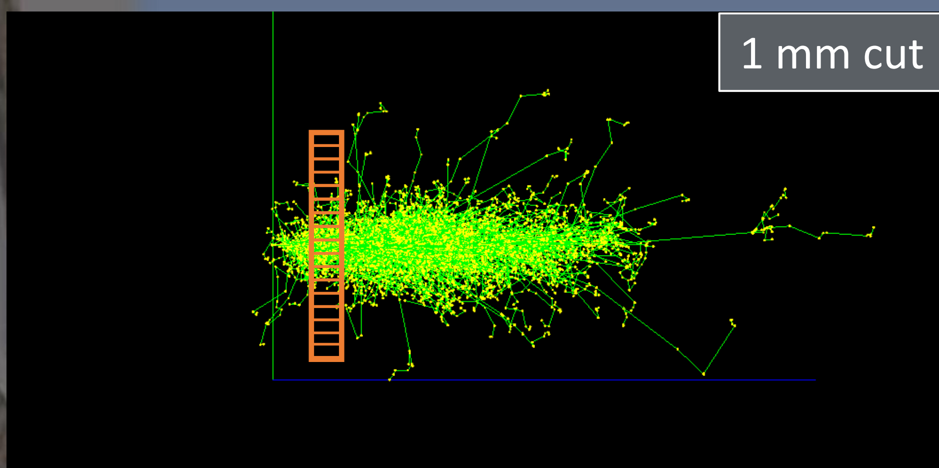




- If recording energy deposit in a big volume
  - No difference between high and low energy threholds

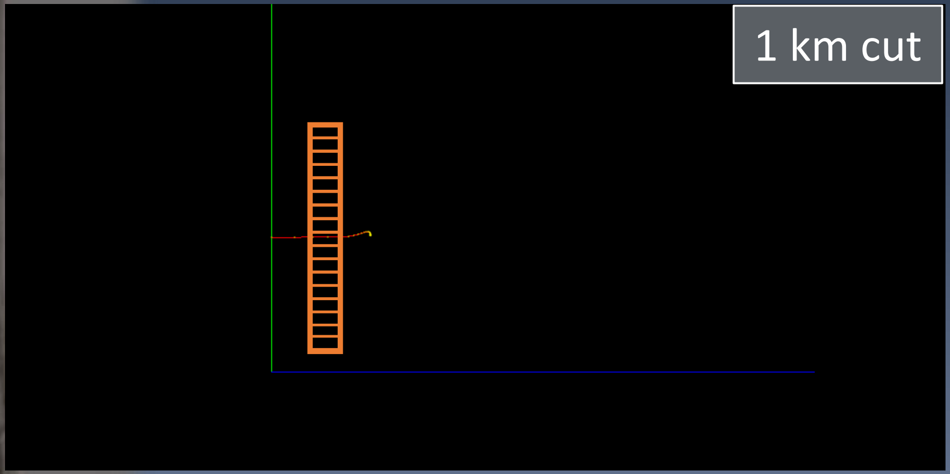
Energy recorded

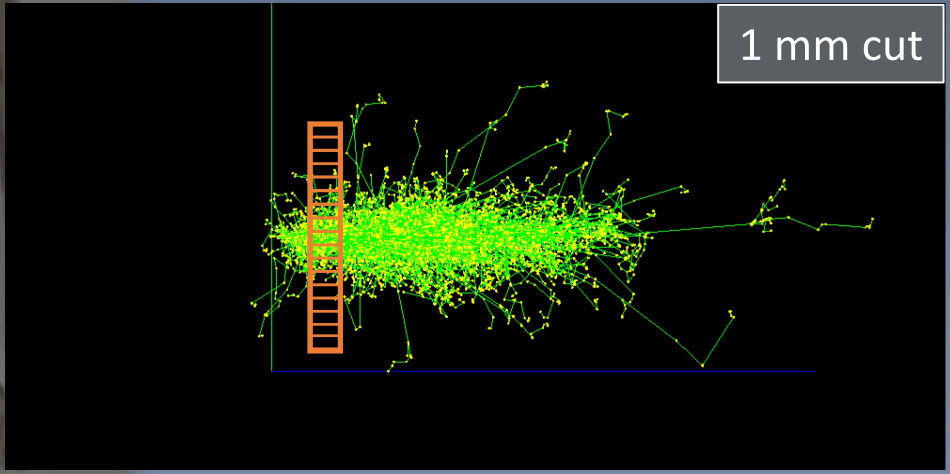




- If recording energy deposit in a big volume
  - No difference between high and low energy threholds
- But if recording in small volumes
  - Big differences !

Energy recorded





- If recording energy deposit in a big volume
  - No difference between high and low energy threholds
- But if recording in small volumes
  - Big differences !
- Typically : range cut ~ volume dimension

IV. Regions

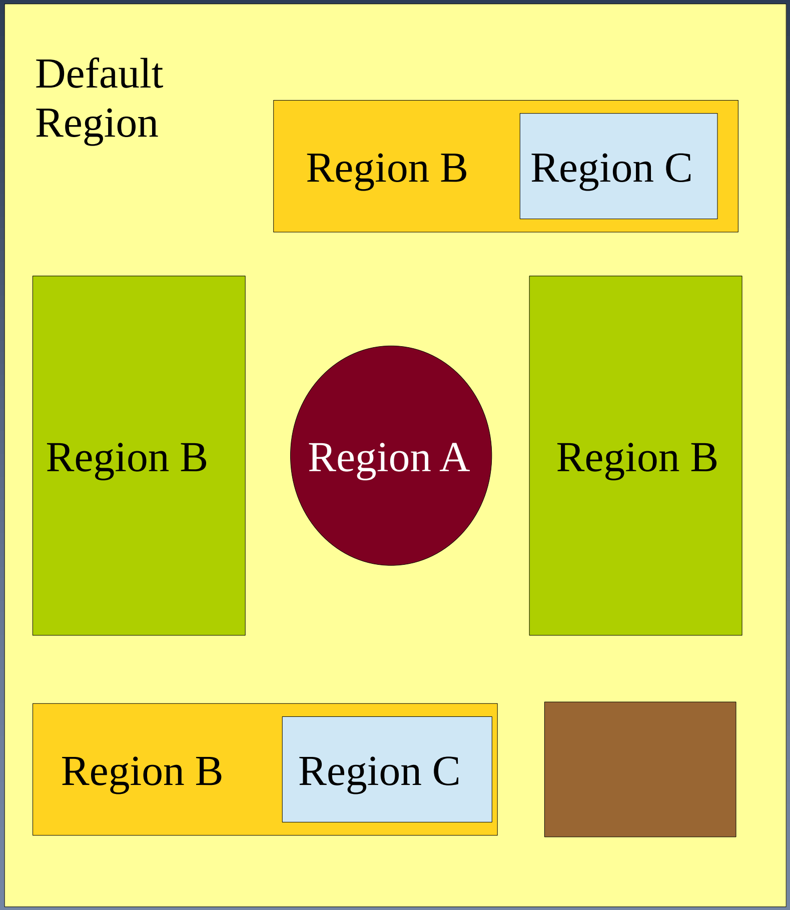
A quick geometry detour

Concept of Regions (1/2)

- On the top of the volume hierarchy users can define regions which are selected sets of volumes, typically of sub-systems
  - E.g. barrel + end-caps of the calorimeter, “deep” areas of support structures can be a region.
- A region can be any group of volumes
- A region can hold a set of various properties:
  - Production thresholds (cuts)
  - User limits
  - User region information
  - Fast simulation manager
  - Regional user stepping action
  - Field manager

Concept of Regions (2/2)

- A region is always associated with one or more logical volumes
- A root logical volume = volume associated to a region
  - All daughter volumes share the same region, unless a daughter volume itself becomes an other root.
  - A logical volume can not be shared among regions.
- World logical volume is always associated with the default region
  - Users do not need to define it.



Creating a region, accessing it, creating a user region information object

MyDetectorConstruction.cc

```
#include "G4Region.hh"

// Create a region
G4Region* myRegion = new G4Region("MyRegion");
// Attach a logical volume to the region
myRegion->AddRootLogicalVolume(myLV);
```

MyOtherClass.cc

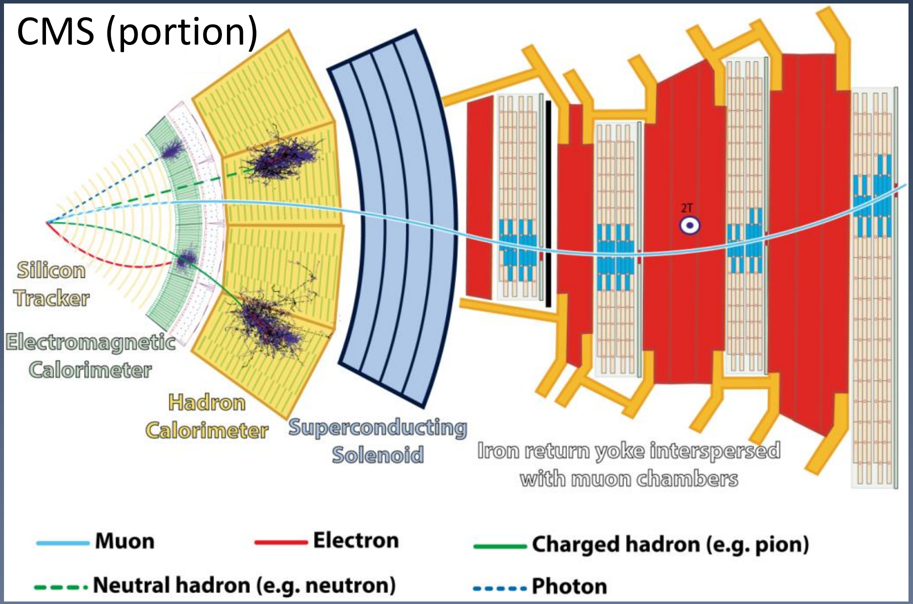
```
#include "G4RegionStore.hh"
#include "MyRegionInformation.hh"

// Retrieve the region by its name
G4Region* region
  = G4RegionStore::GetInstance()->GetRegion("MyRegion");

// Create some property to be assigned to a region
MyRegionInformation* myInfo = new MyRegionInformation();

// Set myInfo to the region
region->SetUserInformation(myInfo);
```

- We will see just after how to assign « cuts » to a region.

V. Cuts per region

Why cuts per region ?

- Running with "as low as possible" cuts is:
  - Good for physics quality
  - Bad for CPU consumption
- In large applications (ie : HEP) not all parts of detector simulation require the same level of accuracy:
  - Tracking systems:
    - Good accuracy needed
    - So, low cuts needed
  - Hadron calorimeter:
    - Low accuracy is enough
    - So high cuts ok



- Issue:
  - Low cuts : Accuracy in tracking systems ✔ Processing time for hadron calorimeter ✘
  - High cuts : Accuracy in tracking systems ✘ Processing time for hadron calorimeter ✔
  - Medium cuts: Make everybody unhappy ;)
- **Solution:**
  - Allow "cuts per region"
  - Tracking system = a region with low cuts
  - Hadron calorimeter = a region with high cuts

Assigning cuts to a region

- Assume you define a region with name “MyRegion” in your detector construction
- To assign cuts to it, you do:

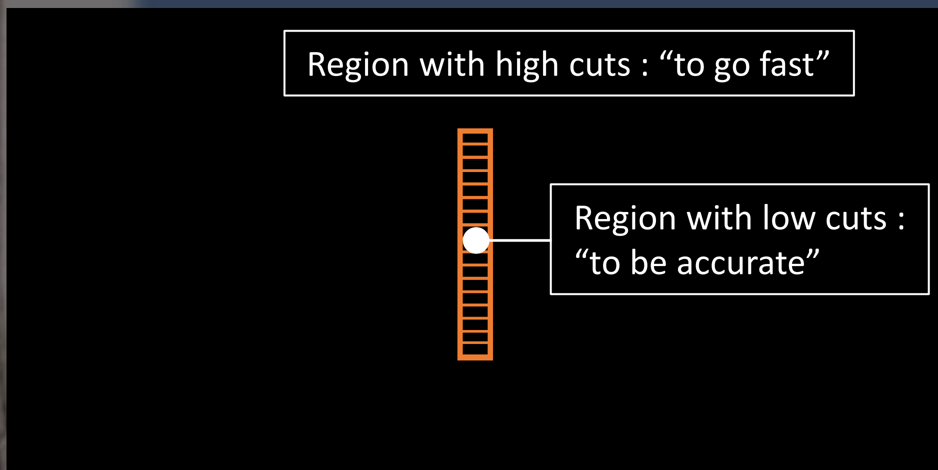
```
 …
 // Greate the region
 G4Region* myRegion = new G4Region("MyRegion");
 …
 …
// Define cuts object for the new region and set values
G4ProductionCuts* cuts = new G4ProductionCuts;
cuts->SetProductionCut(0.01*mm); // for gamma, e+, e-, p
// Assign cuts to region
myRegion->SetProductionCuts(cuts);
…
```

- And you can change cut values with command line (or macro) as:

```
/run/setCutForRegion MyRegion 1 mm
```

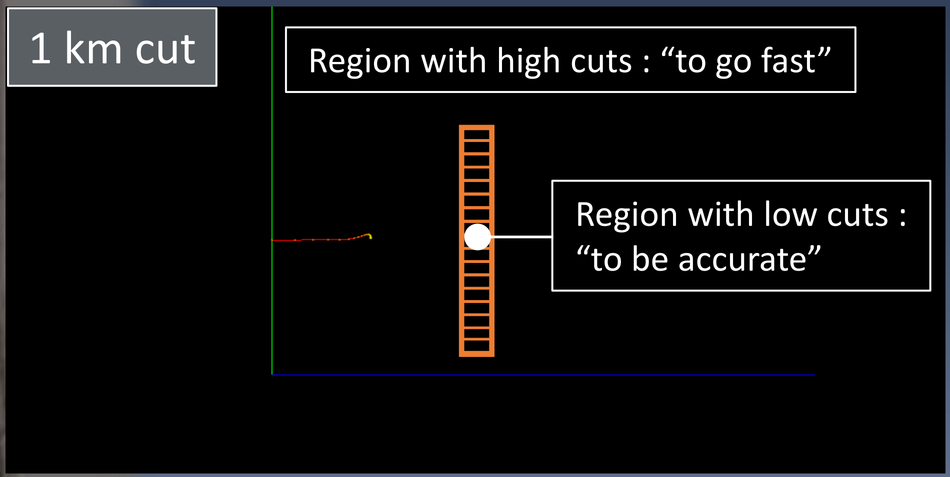
- Note that the world volume is in fact a region : it is the “default” one.

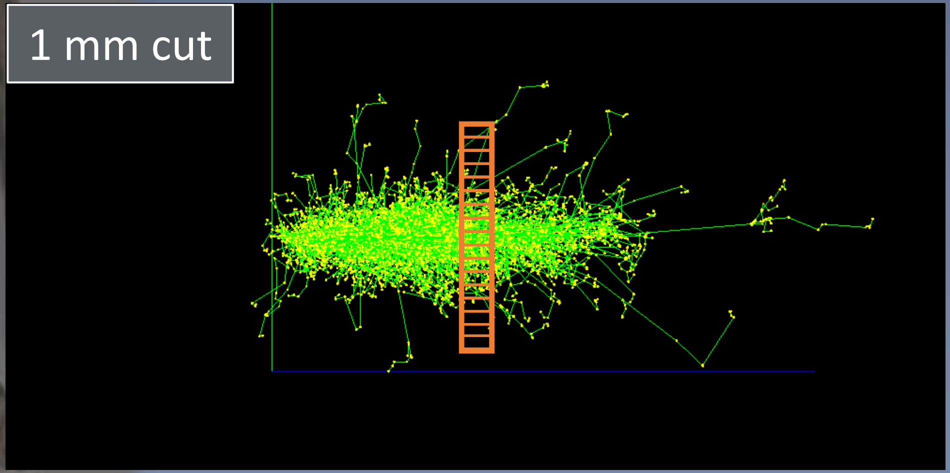
Be critical : temptation for mistake



- Temptation:
  - *“Let me gain time putting a high energy threshold in the parts where I am not interested in details and putting low thresholds where I am interested in details !”*

Be critical : temptation for mistake





- Temptation:
  - *“Let me gain time putting a high energy threshold in the parts where I am not interested in details and putting low thresholds where I am interested in details !”*
- Bad idea !
  - What happens in one volume is not only determined by this volume, but also by what happens ***before*** this volume.
  - Our example with two extreme threshold cases makes it clear…

Threshold for Secondary Production

- Instead of “secondary production threshold distance” it is more convenient to simply say “cuts”
- The cuts values are set in the SetCuts() method of your physics list
  - Either for the entire simulation (ie for the entire world volume)
  - Or per region
  - Geant4 proposes the default value of 0.7 mm
- They can be defined with command line, eg:
  - Idle> /run/setCuts 1 mm
- User needs to decide the best value:
  - The lower the better
    - To be balanced with your available computing power
  - Typically range cut ~ volume dimension is fine
    - Being careful of not having cut too severely before this volume

Summary

- Geant4 supplies many physics processes which cover electromagnetic, hadronic, decay physics and “technical”.
- A unique interface, G4VProcess, allows processes to specify their nature: AtRest, Along (continuous), PostStep (discrete)
  - A process may mix several of these
- Geant4 does not have “tracking cut”
  - Produced particles are tracked down to zero energy.
- Geant4 makes use of a “range cut” for controlling the production of secondary particles
  - For some particles and some processes only
- It is recommended to use a range cut ~ smallest dimension you’re interested in.

A QUICK ADDED INFORMATION ON PHYSICS LISTS

Physics List Naming Convention

- The following acronyms refer to various hadronic options
  - FTF -> Fritiof string model (>~ 3 GeV)
  - QGS -> Quark Gluon String model (>~ 12 GeV)
  - BERT -> Bertini-style Cascade (~< 10 GeV)
  - BIC -> Binary Cascade (~< 10 GeV)
  - P -> Precompound model used for nuclear de-excitation (~< 150 MeV)
  - HP -> High Precision neutron model (< 20 MeV)
- EM options designated by
  - No suffix : standard EM physics
  - _EMV , _EMX : fast options for high-energy physics
  - _EMY , _EMZ , _LIV , _PEN : more precise options, for medical and space science applications
  - _GS Goudsmith-Sanderson is used for MSC of e- and e+

When the application starts…

- Large amount of information displayed by the physics list

```
…
FTFP_BERT : new threshold between BERT and FTFP is over the interval
 for pions :   3 to 12 GeV
 for kaons :   3 to 12 GeV
 for proton :  3 to 12 GeV
 for neutron : 3 to 12 GeV
…
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
     BetheHeitlerLPM :  Emin=       80 GeV   Emax=      100 TeV
…
Hadronic Processes for anti_deuteron

  Process: hadElastic
        Model:              hElasticLHEP: 0 eV /n ---> 100.1 MeV/n
        Model:              AntiAElastic: 100 MeV/n ---> 100 TeV/n
     Cr_sctns:              AntiAGlauber: 0 eV  ---> 2.88022e+295 J
     Cr_sctns:            GheishaElastic: 0 eV  ---> 100 TeV

  Process: anti_deuteronInelastic
        Model:                      FTFP: 0 eV /n ---> 100 TeV/n
     Cr_sctns:              AntiAGlauber: 0 eV  ---> 2.88022e+295 J
     Cr_sctns:          GheishaInelastic: 0 eV  ---> 100 TeV

  Process: hFritiofCaptureAtRest
…
```

- The most up-to-date information you can find on a given physics list is here !

Reference Physics Lists (1/3)

- **FTFP_BERT**
  - Recommended by Geant4 for HEP
  - Contains all standard EM processes
  - Uses Bertini-style cascade for hadrons < 5 GeV
  - Uses Fritiof model for high energies > 4 GeV
  - Uses Precompound + evaporation for nuclear de-excitation
  - Includes neutron capture
  - Includes nuclear stopping at rest of negatively charged hadrons
  - Includes gamma- and electro-nuclear
  - No neutron-HP, radioactive decay, optical photons

Reference Physics Lists (2/3)

- **QGSP_FTFP_BERT**
  - All standard EM processes
  - Bertini-style cascade for hadrons < 8 GeV
  - Quark Gluon String model for high energies > 12 GeV
  - Fritiof model in between 6 – 25 GeV
- **QGSP_BERT**
  - All standard EM processes
  - Bertini-style cascade for hadrons < 9.9 GeV
  - Quark Gluon String model for high energies > 12 GeV
  - Fritiof in between 9.5 – 25 GeV
  - NB) We are working to extend QGS at lower energies, so that the transition with BERT can be done directly, without FTF (in this physics list)

Reference Physics Lists (3/3)

- **QGSP_BIC**
  - Same as QGSP_BERT, but replaces Bertini-style cascade with Binary cascade model (+ Precompound model)
  - Recommended for use at energies below 200 MeV
    - Many medical applications
    - Suggested EM option: _EMY or _EMZ
- **FTFP_BERT_HP (QGSP_BERT_HP)**
  - Same as FTFP_BERT (QGSP_BERT), but with the high-precision neutron model used for neutrons below 20 MeV
  - Significantly slower than FTFP_BERT (QGSP_BERT), especially when Doppler broadening on-the-fly is used
    - There is an option to turn this off
  - For radiation protection and shielding applications