Processes and Production Thresholds

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Outline

- Overview of Geant4 Physics
- Processes
- Production Thresholds (aka cuts)
- Cuts per Region

Geant4 Physics

- Geant4 provides a wide variety of physics components for use in simulation

- Physics components are coded as processes
  - a process is a class which tells a particle how to interact
  - Geant4 provides many of these
  - users may write their own, but must be derived from a Geant4 process

- Processes are classified as
  - electromagnetic, hadronic, decay, parameterized or transportation

Geant4 Physics: Electromagnetic

- standard – complete set of processes covering charged particles and gammas
  - energy range 1 keV to ~PeV
- low energy – specialized routines for e-, γ, charged hadrons
  - more atomic shell structure details
  - some processes valid down to 250 eV or below
  - others not valid above a few GeV
- Optical photon – only for long wavelength photons (x-rays, UV, visible)
  - processes for reflection/refraction, absorption, wavelength shifting, Rayleigh scattering

Geant4 Physics: Hadronic

- pure hadronic (0 - ~TeV)
  - elastic
  - inelastic
  - capture
  - fission
- radioactive decay
  - at rest and in-flight
- photo-nuclear (~10 MeV – ~TeV)
- lepto-nuclear (~10 MeV - ~TeV)
  - e+, e- induced nuclear reactions
  - muon induced nuclear reactions

Geant4 Physics: Decay, Parameterized and Transportation

- decay processes include
  - weak decay (leptonic, semi-leptonic decays, radioactive decay of nuclei)
  - electromagnetic decay (π^0 , Σ^0 , etc.)
  - strong decays not included here (they are part of hadronic models)
- parameterized process
  - electromagnetic showers propagated according to parameters averaged over many events
  - faster than detailed shower simulation
- transportation
  - only one process which is responsible for moving the particle through the geometry

Physics Processes

- All the work of particle decays and interactions is done by processes

- A process does two things:
  - decides when and where an interaction will occur
    - method: GetPhysicalInteractionLength()
    - this requires a cross section or decay lifetime
    - for the transportation process, the distance to the nearest object along the track is required

  - generates the final state of the interaction (changes momentum, generates secondaries, etc.)
    - method: DoIt()
    - this requires a model of the physics

Physics Processes

- There are three flavors of processes:
  - well-located in space -> PostStep
  - distributed in space -> AlongStep
  - well-located in time -> AtRest
- A process may be a combination of all three of the above
  - in that case six methods must be implemented, one GetPhysicalInteractionLength() and one DoIt() for each type
- "Shortcut" processes are defined which invoke only one
  - Discrete process (has only PostStep physics)
  - Continuous process (has only AlongStep physics)
  - AtRest process (has only AtRest physics)

Example Processes

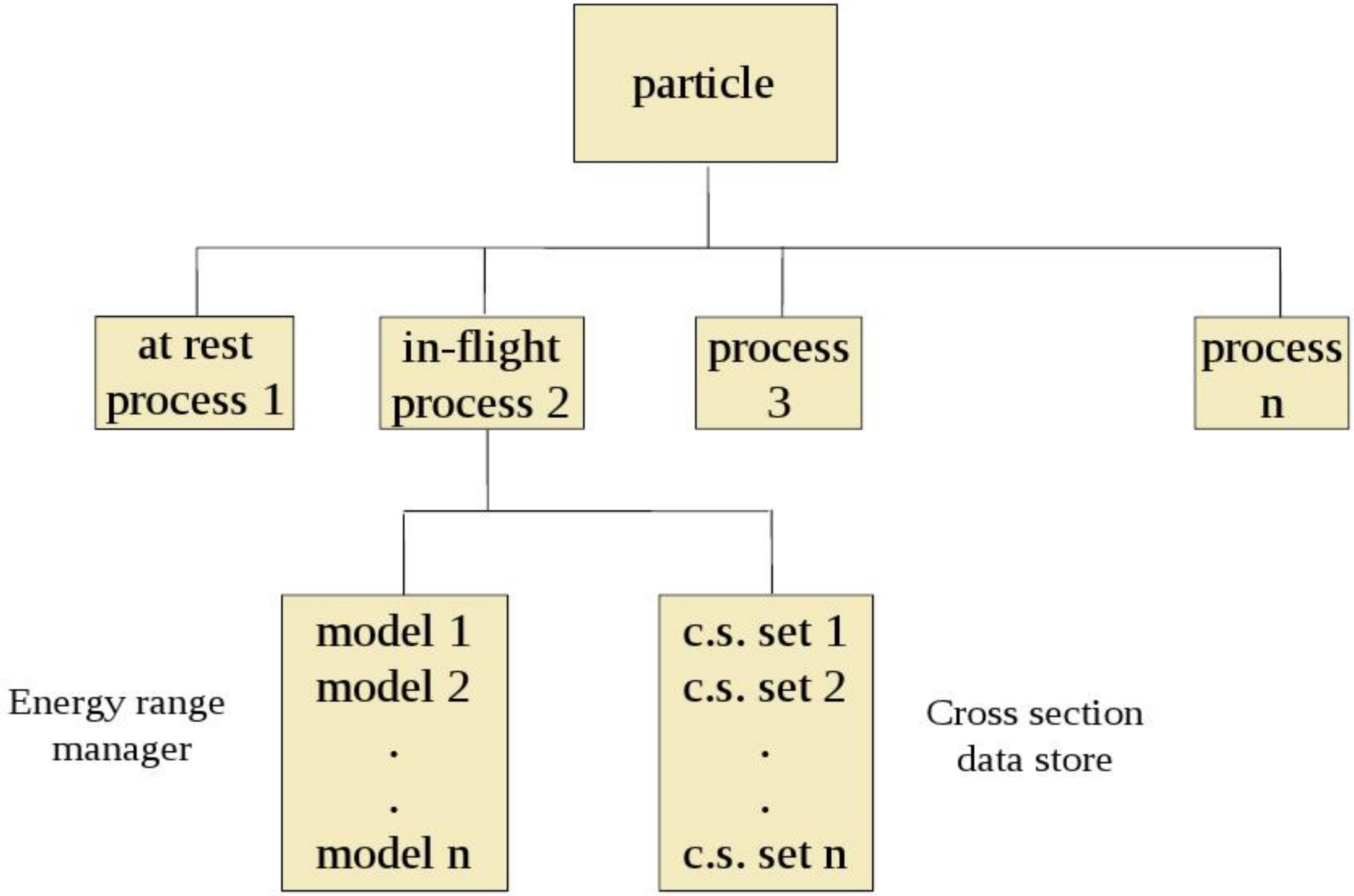
- Discrete process: Compton scattering
  - length of step determined by cross section, interaction is at end of step
    - PostStepGetPhysicalInteractionLength()
    - PostStepDoIt()
- Continuous process: Cerenkov effect
  - photons created along step, # proportional to step length
    - AlongStepGetPhysicalInteractionLength()
    - AlongStepDoIt()
- At rest process: positron annihilation at rest
  - no spatial displacement, time is the relevant variable
    - AtRestGetPhysicalInteractionLength()
    - AtRestDoIt()

Example Processes

- Continuous + discrete: ionization
  - energy loss is continuous
  - Moller/Bhabha scattering and knock-on electrons are discrete
- Continuous + discrete: process: bremsstrahlung
  - energy loss due to soft photons is continuous
  - hard photon emission is discrete
- In both cases, the production threshold separates the continuous and discrete parts of the process
  - more on this later
- Multiple scattering is also continuous + discrete

Handling Multiple Processes

- Many processes (and therefore many interactions) may be assigned to the same particle



Handling Multiple Processes

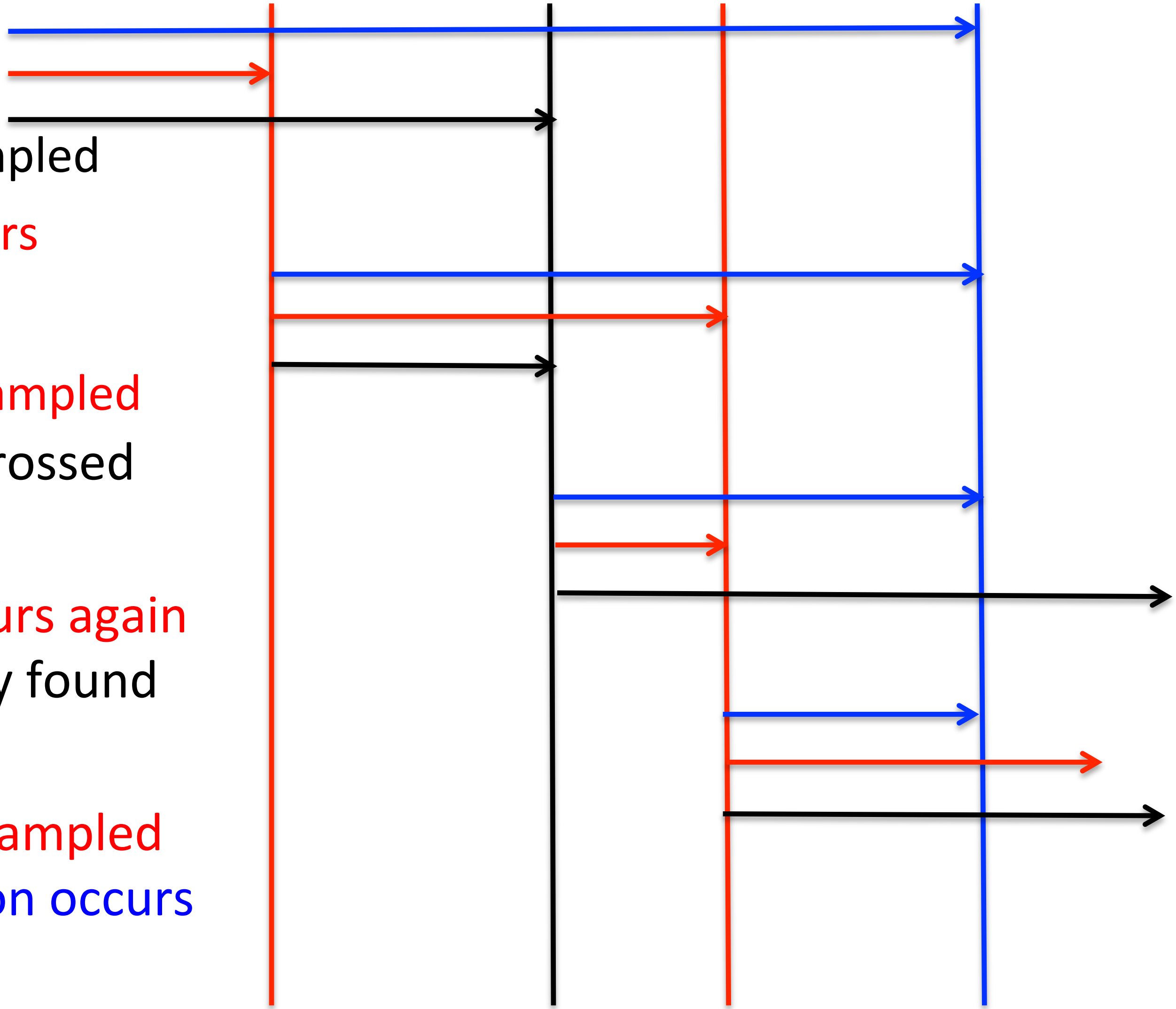
- How does Geant4 decide which interaction happens at any one time?
  - interaction length (or decay length) is sampled from each process
  - sampling is done from the distribution $1 - e^{-\sigma\rho L}$
  - done for each process assigned to the particle

  - now we have several lengths, including distance to next volume boundary
  - the interaction (or boundary crossing) that happens is the one with the shortest length

  - processes which did not occur are not re-sampled, but have the previous step length subtracted from their originally sampled lengths

Handling Multiple Processes

- Step 1:
  - all lengths sampled
  - Compton occurs
- Step 2:
  - Compton re-sampled
  - boundary is crossed
- Step 3:
  - Compton occurs again
  - new boundary found
- Step 4:
  - Compton re-sampled
  - pair production occurs



Threshold for Secondary Production

- Every simulation developer must answer the question: how low can you go?
  - at what energy do I stop tracking particles?
- This is a balancing act:
  - need to go low enough to get the physics you're interested in
  - can't go too low because some processes have infrared divergence causing CPU to skyrocket
- The traditional Monte Carlo solution is to impose an absolute cutoff in energy
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point

Threshold for Secondary Production

- But, such a cut may cause imprecise stopping location and deposition of energy

- There is also a particle dependence
  - range of a 10 keV γ in Si is a few cm
  - range of a 10 keV e- in Si is a few microns

- And a material dependence
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - if the cutoff is OK for Pb it will likely be wrong for the scintillator which does the actual energy measurement

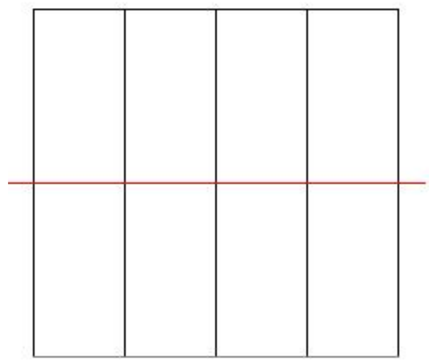
Threshold for Secondary Production

- Geant4 solution: impose a production threshold
  - this threshold is a distance, not an energy
  - default = 0.7 mm
  - the primary particle loses energy by producing secondary electrons or gammas
  - if primary no longer has enough energy to produce secondaries which travel at least 0.7 mm, two things happen:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero energy using continuous energy loss
- Stopping location is therefore correct
- Only one value of production threshold distance is needed for all materials because it corresponds to different energies depending on material

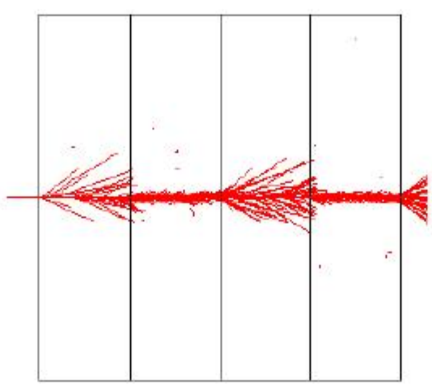
Production Threshold vs. Energy Cut

Example: 500 MeV p in LAr-Pb Sampling Calorimeter

Geant3 (and others)

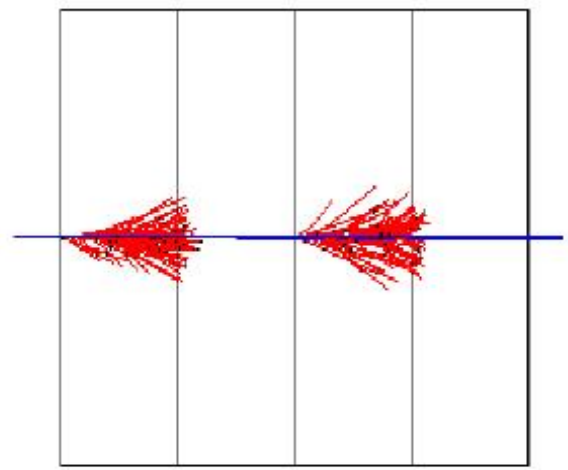


Cut = 2 MeV



Cut = 450 keV

Geant4



Production range = 1.5 mm

Threshold for Secondary Production

- Geant4 recommends the default value of 0.7 mm
  - user needs to decide the best value
  - this will depend on the size and sensitive elements within the simulated detector, and on available CPU

- This value is set in the SetCuts() method of your physics list

- Instead of "secondary production threshold distance" it is more convenient to simply say "cuts"
  - but please remember that this does not mean that any particle is actually stopped before it runs out of energy

Cuts per Region

- In a complex detector there may be many different types of sub-detectors involving
  - finely segmented volumes
  - very sensitive materials
  - large, undivided volumes
  - inert materials
- The same value of the secondary production threshold may not be appropriate for all of these
  - user must define regions of similar sensitivity and granularity and assign a different set of production thresholds (cuts) for each
- Warning: this feature is for users who are
  - simulating the most complex detectors
  - experienced at simulating EM showers in matter

Cuts per Region

- A default region is created automatically for the world volume
  - it has the cuts which you set in SetCuts() in your physics list
  - these will be used everywhere except for user-defined regions
- In the geometry an instance of G4Region must be created which corresponds to the volume where the cuts are to be changed
- To define different cuts for this special region, user must
  - create a G4ProductionCuts object
  - initialize it with the the new cuts
  - assign it to a region which has already been created

Cuts per Region

- void MyPhysicsList::SetCuts() {

```
  SetCutValue(defaultCutValue, “gamma”);  // same for e-, e+, p

  // Get the region
  G4Region* aRegion =
     G4RegionStore::GetInstance()->GetRegion(“RegionA”);

   // Define cuts object for the new region and set values
  G4ProductionCuts* cuts = new G4ProductionCuts();
  cuts->SetProductionCut(0.01*mm);  // here, same for all
  // Assign cuts to region
  aRegion-> SetProductionCuts(cuts);
}
```

Summary

- Processes handle all the physics of particle interactions
- Geant4 provides processes to cover nearly all particles over energies ranging from 0 to ~TeV
  - users may define their own processes
- Many processes may be assigned to a particle

- The precision of particle stopping and the production of secondary particles are determined by a secondary production threshold
- For complex detectors with different types of sensitive volumes, different production thresholds may be defined for different regions within the detector