Physics III : Cuts, Decay and Optical Physics

SLAC Geant4 Tutorial

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Outline

- Production Thresholds
- Cuts per Region
- The Decay Process
  - applicability
  - available decay modes
- Optical Photons
  - available processes

Threshold for Secondary Production (1)

- 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 time 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 (2)

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

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

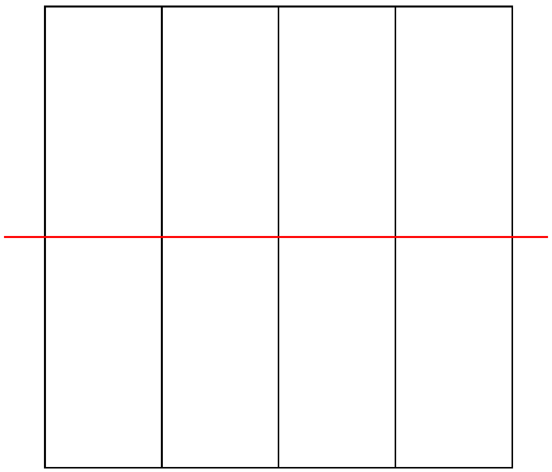
- And a material dependence
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - if the cutoff is OK for Pb, it will likely be wrong for the scintillator which does the actual energy deposition measurement

Threshold for Secondary Production (3)

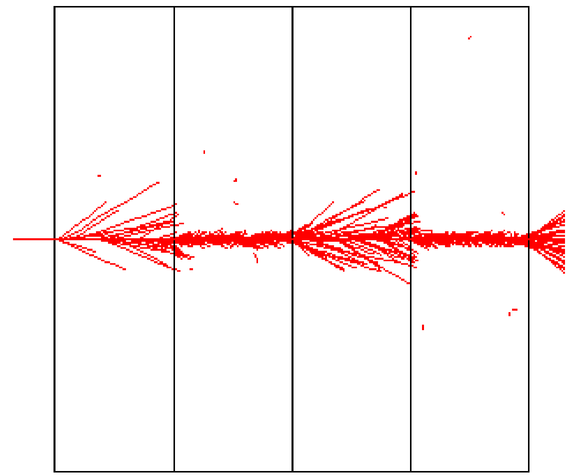
- Geant4 solution: impose a production threshold
  - this threshold is a distance, not an energy
  - default = 1 mm
  - the primary particle loses energy by producing secondary electrons or gammas
  - if primary no longer has enough energy to produce secondaries which travel at least 1mm, two things 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

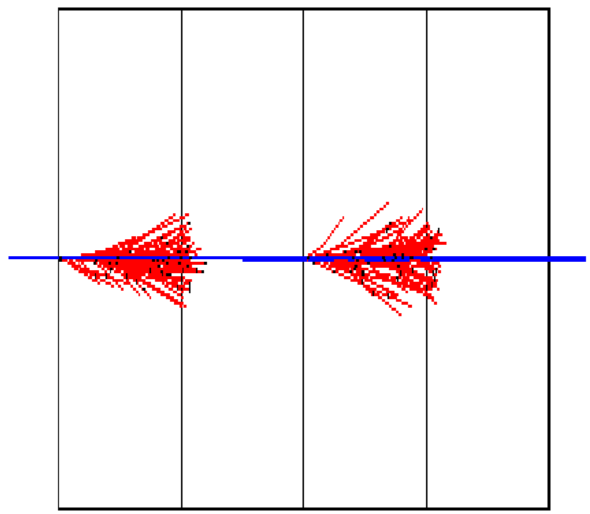
500 MeV p in
LAr-Pb sampling
calorimeter



Cut = 2 MeV



Cut = 450 keV



Production range =1.5 mm

Threshold for Secondary Production (4)

- Geant4 recommends the default value of 1mm
  - user needs to decide the best value
  - this will depend on the size of 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 (1)

- 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 (2)

- 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

- To define a special region with different cuts, user must
  - create a G4ProductionCuts object
  - initialize it with the new cuts
  - assign it to a region which has already been created

Cuts per Region (3)

- void BeamTestPhysicsList::SetCuts()

```
{
   SetCutValue(defaultCutValue, “gamma”);
   SetCutValue(defaultCutValue, “e-”);
   SetCutValue(defaultCutValue, “e+”);
   // Get the region
   G4Region*  aRegion =
            G4RegionStore::GetInstance()->GetRegion(“NewRegion”);

   // Define cuts object for the new region and set values
   G4ProductionCuts* cuts = new G4ProductionCuts;
   cuts->SetProductionCut(0.01*mm);     // same cut for gamma, e+, e-

   // Assign cuts to region
   aRegion->SetProductionCuts(cuts);
}
```

The Decay Process

- Derived from G4VRestDiscreteProcess
  - decay can happen in-flight or at rest

- Should be applied to all unstable, long-lived particles

- Different from other physical processes:
  - mean free path for most processes: $\lambda = N\rho\sigma / A$
  - for decay in-flight: $\lambda = \gamma\beta c\tau$

- Same decay process for all eligible particles
  - decay process retrieves BR and decay modes from decay table stored in each particle type

Available Decay Modes

- Phase space:
  - 2-body e.g. $\pi^0 \to \gamma\gamma$, $\Lambda \to p\, \pi^-$
  - 3-body e.g. $K^0_L \to \pi^0 \pi^+ \pi^-$
  - many body
- Dalitz: $P^0 \to \gamma\, l^+ l^-$
- Muon decay
  - V – A, no radiative corrections, mono-energetic neutrinos
- Leptonic tau decay
  - like muon decay
- Semi-leptonic K decay: $K \to \pi\, l\, \nu$

Pre-assigned Decays

- Geant4 provides decay modes for long-lived particles
  - user can re-define decay channels if necessary
- But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4
  - user must "pre-assign" to particle:
    - proper lifetime
    - decay modes
    - decay products
  - decay process can invoke decay handler from the generator
    - must use G4VExtDecayer interface
- Take care that pre-assigned decays from generators do not overlap with those defined by Geant4
  - K^0_S , τ

Specialized Decay Processes

- G4DecayWithSpin
  - produces Michel positron spectrum with 1st order radiative corrections
  - initial muon spin is required
  - propagates spin in magnetic field (precession) over remainder of muon lifetime

- G4UnknownDecay
  - only for “unknown” particles (Higgs, SUSY, etc.)
  - discrete process – only in-flight decays allowed
  - pre-assigned decay channels must be supplied by user or generator

Optical Photons (1)

- Technically, should belong to electromagnetic category, but:
  - optical photon wavelength is >> atomic spacing
  - treated as waves -> no smooth transition between optical and gamma particle classes

- Optical photons are produced by the following Geant4 processes:
  - G4Cerenkov
  - G4Scintillation
  - G4TransitionRadiation

- Warning: these processes generate optical photons without energy conservation

Optical Photons (2)

- Optical photons undergo:
  - Rayleigh scattering
  - refraction and reflection at medium boundaries
  - bulk absorption
  - wavelength shifting

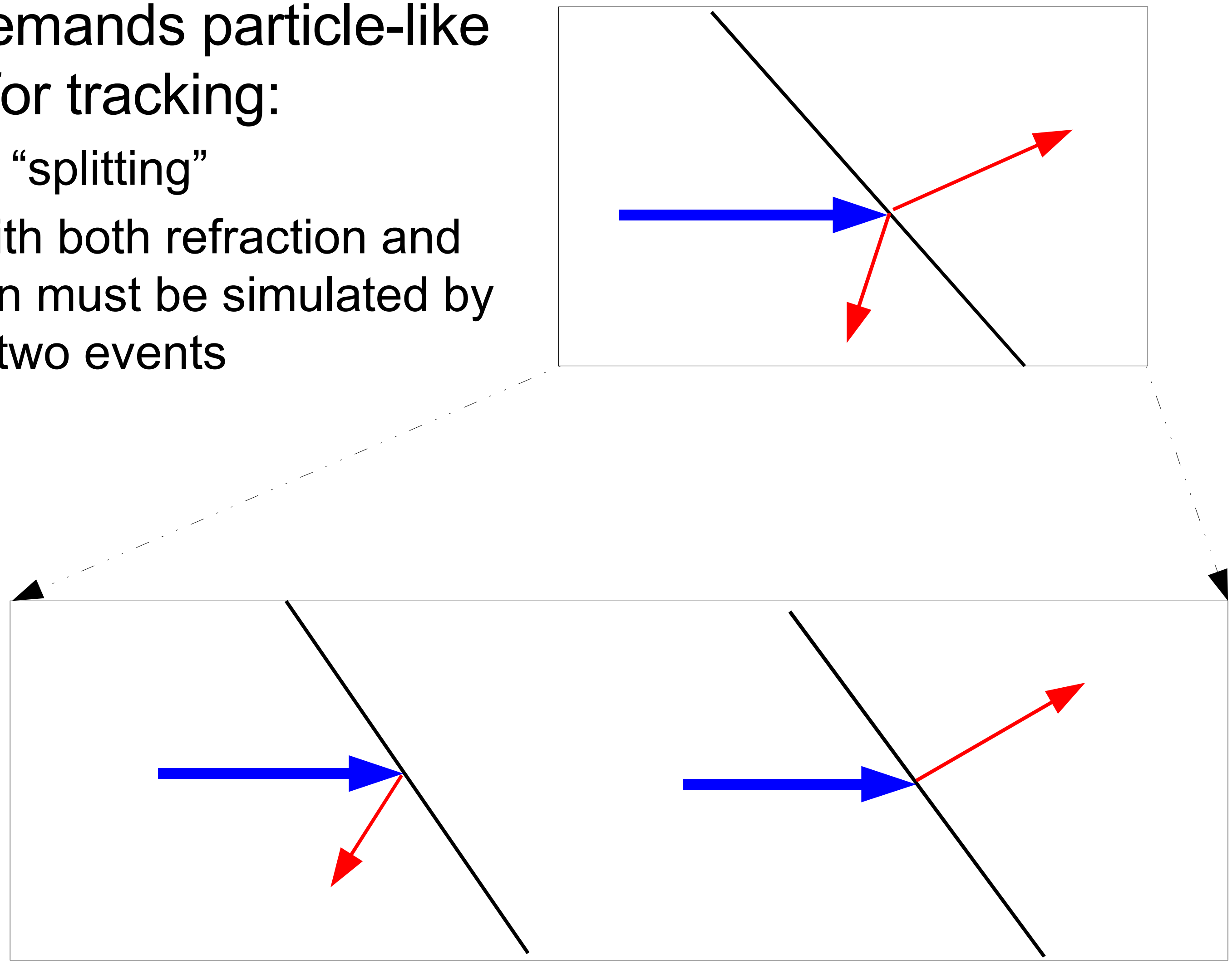
- Geant4 keeps track of polarization
  - but not overall phase -> no interference

- Optical properties can be specified in G4Material
  - reflectivity, transmission efficiency, dielectric constants, surface properties

- Photon spectrum properties also defined in G4Material
  - scintillation yield, time structure (fast, slow components)

Optical Photons (3)

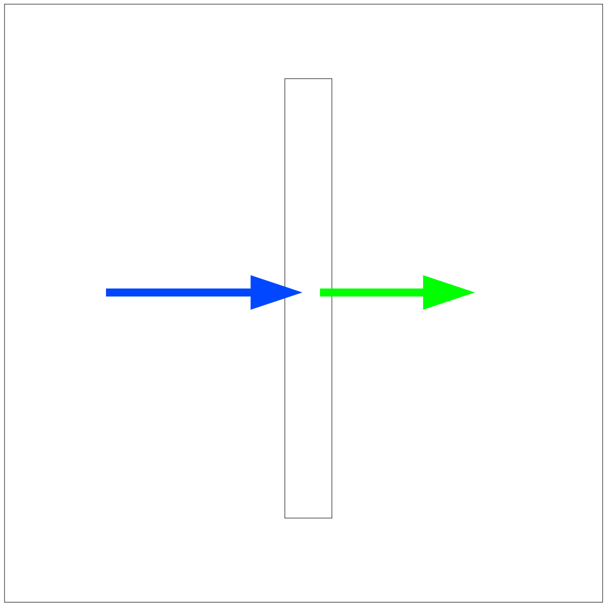
- Geant4 demands particle-like behavior for tracking:
  - thus, no “splitting”
  - event with both refraction and reflection must be simulated by at least two events



Wavelength Shifting

- Handled by G4OpWLS
  - initial photon is killed, one with new wavelength is created
  - builds it own physics table for mean free path

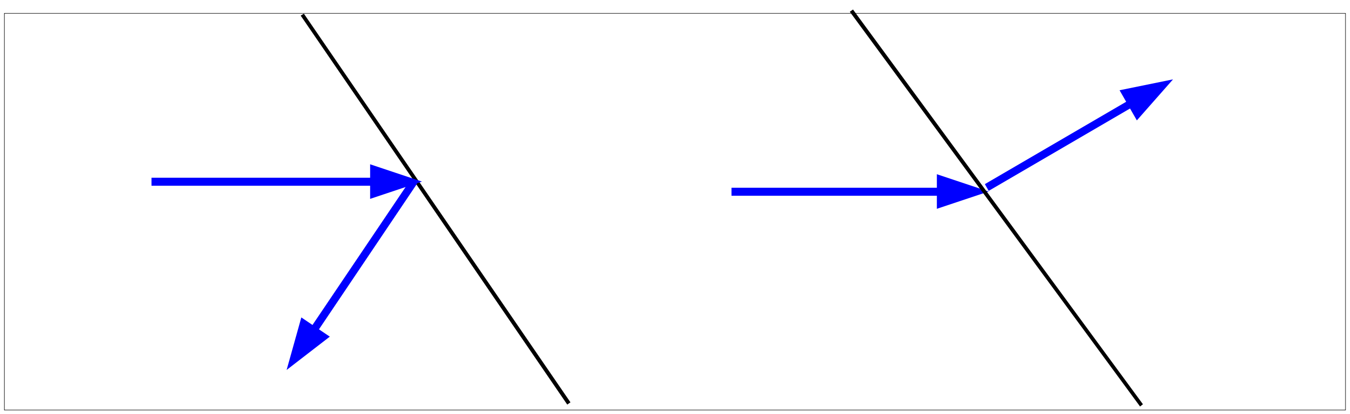
- User must supply:
  - absorption length as function of photon energy
  - emission spectra parameters as function of energy
  - time delay between absorption and re-emission



Boundary Interactions

- Handled by G4OpBoundaryProcess
  - refraction
  - reflection
- User must supply surface properties using G4OpticalSurfaceModel

- Boundary properties
  - dielectric-dielectric
  - dielectric-metal
  - dielectric-black material
- Surface properties:
  - polished
  - ground
  - front- or back-painted, ...



Absorption and Rayleigh Scattering

- G4OpAbsorption
  - uses photon attenuation length from material properties to get mean free path
  - photon is simply killed after a selected path length
- G4OpRayleigh
  - elastic scattering including polarization of initial and final photons
  - builds it own private physics table (for mean free path) using G4MaterialTable
  - may only be used for optical photons

Summary

- 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
- There is one decay process for all long-lived, unstable particles
- Optical processes handle the reflection, refraction, absorption, wavelength shifting and scattering of long-wavelength photons