GEANT4 BEGINNERS COURSE

GSSI, L'Aquila (Italy)
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Physics in Geant4: Particles, processes, cuts and models

Geant 4 **tutorial course**

Introduction

Mandatory user classes in a Geant4:

- **`G4VUserPrimaryGeneratorAction`**
- **`G4VUserDetectorConstruction`**
- **`G4VUserPhysicsList`**

***Particles**, **physics processes**, and **cut-off parameters** to be used in the simulation must be defined in the **`G4VUserPhysicsList`** class*

Why a physics list?

- "*Physics is physics* – shouldn't Geant4 provide, as a default, a complete set of physics that everyone can use?"
- **NO**:
  - Software can only capture Physics through a modelling
    - No unique Physics modelling
      - Very much the case for hadronic physics
      - But also the electromagnetic physics
      - Existing models still evolve and new models are created
    - Some models are more suited to some energy ranges
      - Medical applications not interested in multi-GeV physics in general
      - HEP experiments not interested in effects due to atomic shell structure
  - computation speed is an issue
    - a user may want a less-detailed, but faster approximation

Why a physics list?

- For this reason Geant4 takes an atomistic, rather than an integral approach to physics
  - provide many physics independent components (processes)
  - user selects these components in custom physics lists

- This physics environment is built by the user in a flexible way:
  - picking up the particles he/she wants
  - picking up the physics to assign to each particle

- User must have a good understanding of the physics required
  - omission of particles or physics could cause errors or poor simulation

User may also use some provided “ready-to-use” physics list

G4VUserPhysicsList: required methods

ConstructParticle():

– choose the particles you need in your simulation, define all of them here

ConstructProcess() :

– for each particle, assign all the physics processes relevant to your simulation

- What's a process ?
  – a class that defines how a particle should interact with matter, or decays
    » it's where the physics is!

SetCuts() :

– Set range cuts for secondary particle production

- What's a range cut ?
  – a threshold on particle production
    » Secondary Particles unable to travel at least the range cut value are not produced

Particles: basic concepts

There are three levels of class to describe particles in Geant4:

- **G4ParticleDefinition**
  – defines a particle
  aggregates information to characterize a particle's properties (name, mass, spin, etc…)

- **G4VDynamicParticle**
  – describes a particle interacting with materials
  aggregates information to describe the dynamic of particles (energy, momentum, polarization, etc…)

- **G4VTrack**
  – describes a particle travelling in space and time
  includes all the information for tracking in a detector simulation (position, step, current volume, track ID, parent ID, etc…)

Definition of a particle

Geant4 provides the **`G4ParticleDefinition`** definition class to represent a large number of elementary particles and nuclei, organized in six major categories:
lepton, meson, baryon, boson, shortlived and ion

- Each particle is represented by its own class, for example **`G4Electron`**, which is derived from `G4ParticleDefinition`

- Properties characterizing individual particles are "read only" and can not be changed directly

*User must define **all particles** type which are used in the application: not only **primary particles** but also all other particles which may appear as **secondaries** generated by the used physics processes*

Constructing particles

Due to the large number of particles can be necessary to define, this method sometimes can be not so comfortable

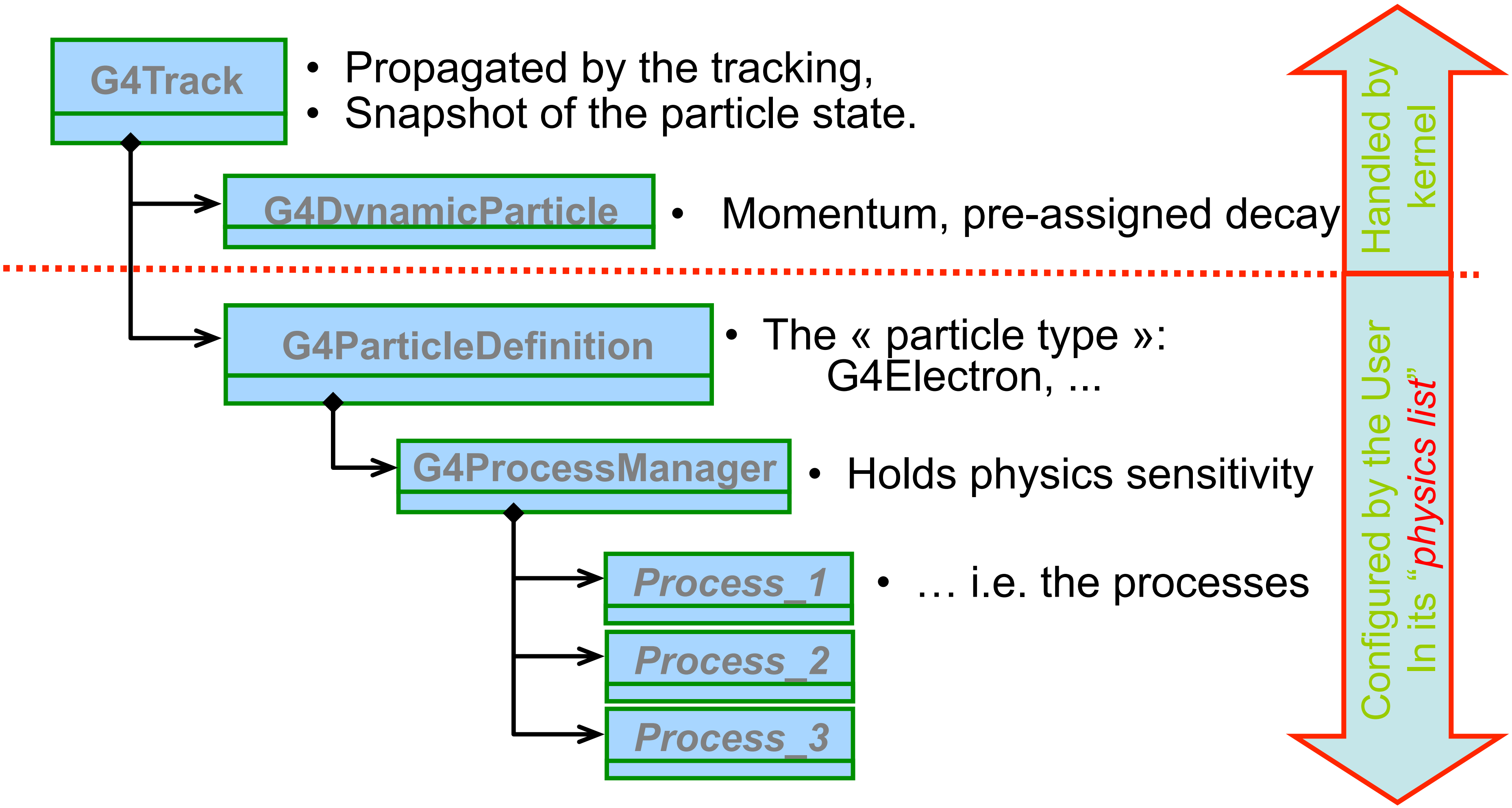
```
void
 MyPhysicsList::ConstructParticle()
{
    G4Electron::ElectronDefinition();
    G4Proton::ProtonDefinition();
    G4Neutron::NeutronDefinition();
    G4Gamma::GammaDefinition();
    ....
}
```

It is possible to define **all** the particles belonging to a **Geant4 category:**

- **`G4LeptonConstructor`**
- **`G4MesonContructor`**
- **`G4BaryonConstructor`**
- **`G4BosonConstructor`**
- **`G4ShortlivedConstructor`**
- **`G4IonConstructor`**

```
void
 MyPhysicsList::ConstructBaryons()
{
    // Construct all baryons
 G4BaryonConstructor pConstructor;
 pConstructor.ConstructParticle();
}
```

From particles to processes



Processes

Physics processes describe how particles interact with materials

Geant4 provides seven major categories of processes:

- Electromagnetic
- Hadronic
- Decay
- Optical
- Photolepton_hadron
- Parameterization
- Transportation

A process does two things:

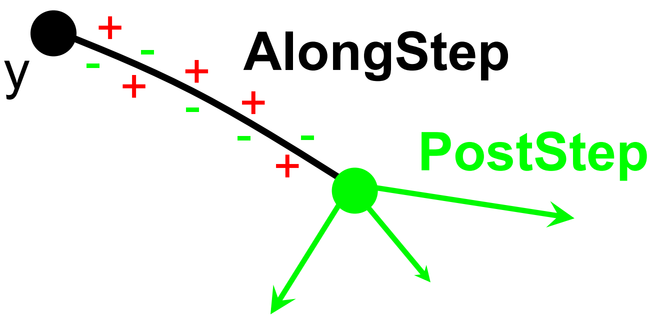
1) decides when and where an interaction will occur
   - methodS: **`GetPhysicalInteractionLength`** → *limit the step*
   - this requires a cross section
   - for the transportation process, the distance to the nearest object
2) generates the final state of the interaction (changes momentum, generates secondaries, etc.)
   - methodS: **`DoIt`**
   - this requires a model of the physics

G4VProcess class

Physics processes are derived from the **G4VProcess** base class

- Abstract class defining the common interface of all processes in Geant4:
  - Used by all physics processes (also by the transportation, etc…)
  - Defined in **source/processes/management**
- Define three kinds of actions:
  - **AtRest** actions:

    - Decay, e^+ annihilation …
  - **AlongStep** actions:
    - To describe (inter)actions, continuously occurring along the particle path, like ionisation;



  - **PostStep** actions:
    - To describe point-like (inter)actions, like decay in flight, hadronic interactions …

A process can implement a combination of them (decay = AtRest + PostStep)

Example processes

- Discrete process: Compton Scattering, hadronic inelastic, ...
  - step determined by cross section, interaction at end of step
    - PostStepGPIL(), PostStepDoIt()
- Continuous process: Cerenkov effect
  - photons created along step, roughly proportional to step length
    - AlongStepGPIL(), AlongStepDoIt()
- At rest process: mu- capture at rest
  - interaction at rest
    - AtRestGPIL(), AtRestDoIt()

pure

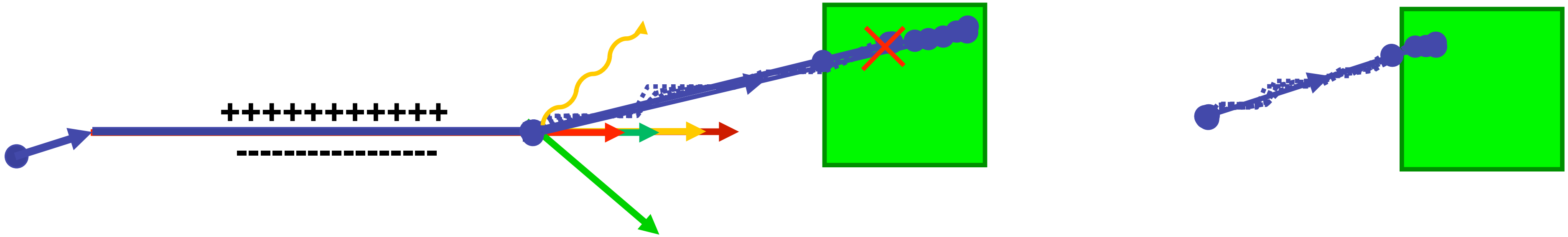
- Rest + discrete: e+ annihilation, decay, ...
  - both in flight and at rest
- Continuous + discrete: ionization
  - energy loss is continuous
  - knock-on electrons (δ-ray) are discrete

combined

Handling multiple processes

- STAGE 1: a particle is shot and “transported”
- STAGE 2: all processes associated to the particle propose a geometrical step length (depends on process cross-section)
- STAGE 3: The process proposing the shortest step “wins” and the particle is moved to destination (if shorter than “Safety”)
- STAGE 4: All processes “along the step” are executed (e.g. ionization)
- STAGE 5: “post step” phase of the process that limited the step is executed New tracks are “pushed” to the stack
- STAGE 6: If E_{kin}=0 all “at rest” processes are executed; if particle is stable the track is killed. Else:
- STAGE 7: A new step starts and sequence repeats...

Processes return a “true path length”. The multiple scattering “virtually folds up” this true path length into a shorter ”geometrical” path length. Transportation process can limit the step to geometrical boundaries.

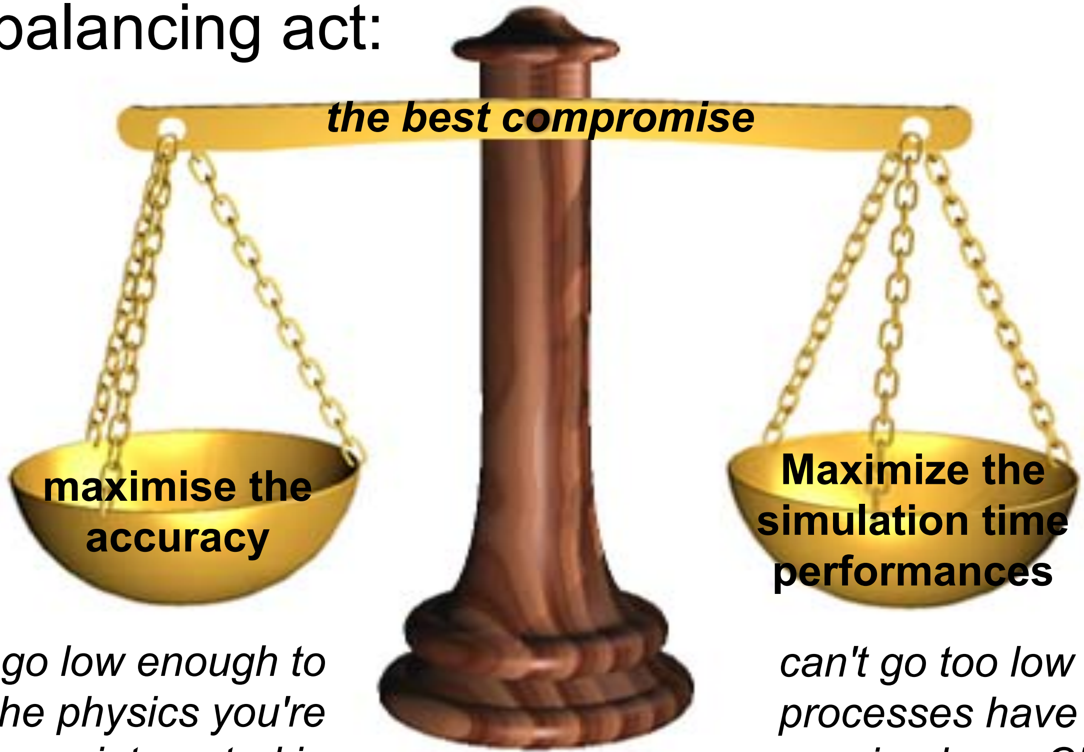


Production thresholds: cut

Each simulation developer must answer the question:
how low can I go?

- should I produce (and track) every secondary or should I consider thresholds?

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 huge CPU time

Production thresholds: cut

- 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
- But, such a cut may cause **imprecise stopping location** and localization of energy deposition
- There is also a **particle dependence**
  - range of 10 keV p in Si is different from range of 10 keV e- in Si
- 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

Production thresholds: cut

- In Geant4 there are no tracking cuts
  - *particles are tracked down to a zero range/kinetic energy*
- Only **production cuts** exist
  - i.e. cuts allowing a particle to be born or not
  - Applied to: ***gamma***, ***electron***, ***positron***, ***proton***
- *Why are production cuts needed ?*

  Some electromagnetic processes involve infrared divergences
  - this leads to a huge number of smaller and smaller energy photons/ electrons (such as in Bremsstrahlung, d-ray production)
  - production cuts limit this production to particles above the threshold
  - the remaining, divergent part is treated as a continuous effect (i.e. AlongStep action) → Energy balance is preserved

Production thresholds: cut

- Geant4 solution: impose a “range” production threshold
  - this threshold is a distance, not an energy
  - default = 1 mm
- Only one production threshold cut is uniformly set
- Production threshold is internally converted to an energy threshold, depending on particle type and material

- When primary no longer has enough energy to produce secondaries which travel at least 1mm, two things happen:

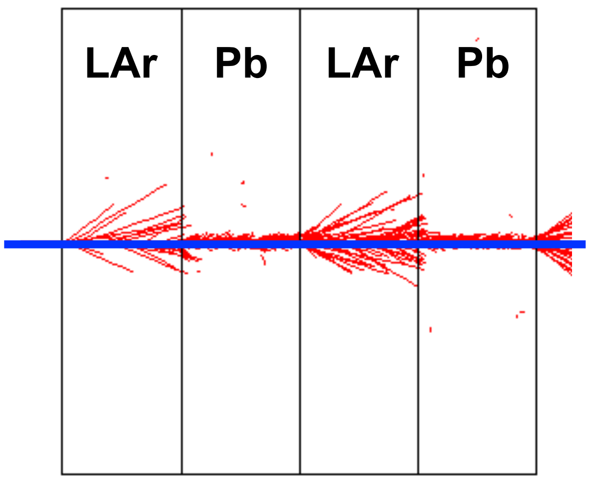
  - discrete energy loss stops (no more secondaries produced)

  - the primary is tracked down to zero energy using continuous energy loss

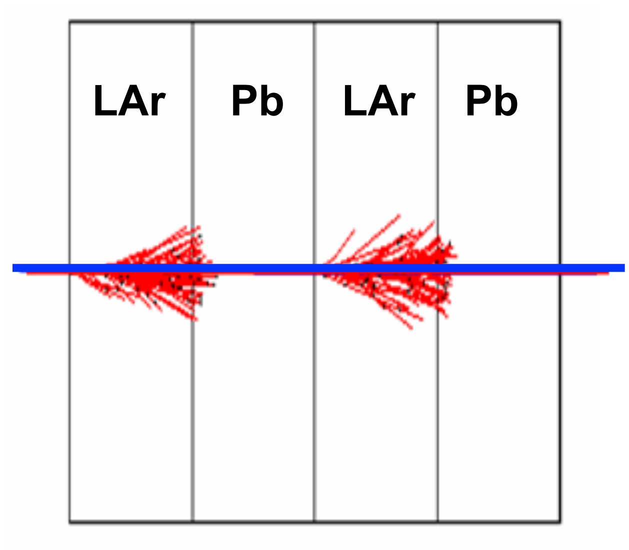
    → Stopping location is therefore correct

Production thresholds: cut

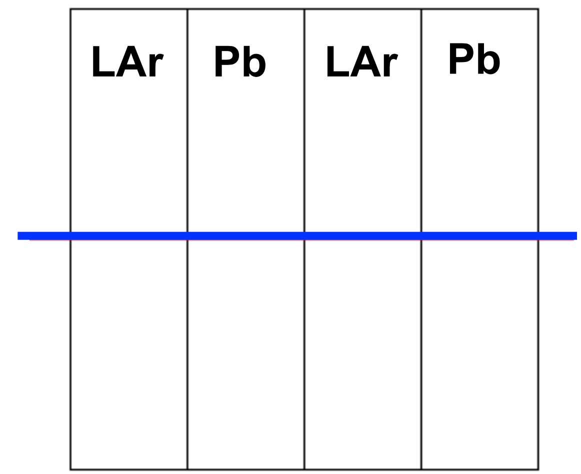
500 MeV p in LAr-Pb sampling calorimeter



Cut = 455 keV
(range in LAr = 1.5 mm)



Production range =1.5 mm



Cut = 2 MeV

Threshold in range: 1.5 mm

455 keV electron energy in liquid Ar

2 MeV electron energy in Pb

Cuts per region

- A complex detector may be composed by many different sub-detectors:
  - finely segmented volumes
  - very sensitive materials
  - large, undivided volumes
  - inert materials
- The same cuts may not be appropriate for all of these
  - User can define regions (logical volume envelopes) and assign different cuts for each region
- Warning: this feature is for users who are
  - simulating complex detectors
  - experienced at simulating EM showers in matter
  - Good practice: cross check with uniform set of cuts to avoid biases

Thanks for your attention