IV INTERNATIONAL GEANT4 SCHOOL

Belgrade, Serbia
23-28 October 2016

Physics in Geant4: Particles, processes and cuts

Geant 4 tutorial

INFN Geant4

G4VUserPhysicsList: implementation

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*

SetCuts() :

- set the range cuts for secondary production
  - What's a range cut ?
    - *a threshold on particle production*
      - » *Particle 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`

  Particle static properties: name, mass, spin, PDG number, etc.

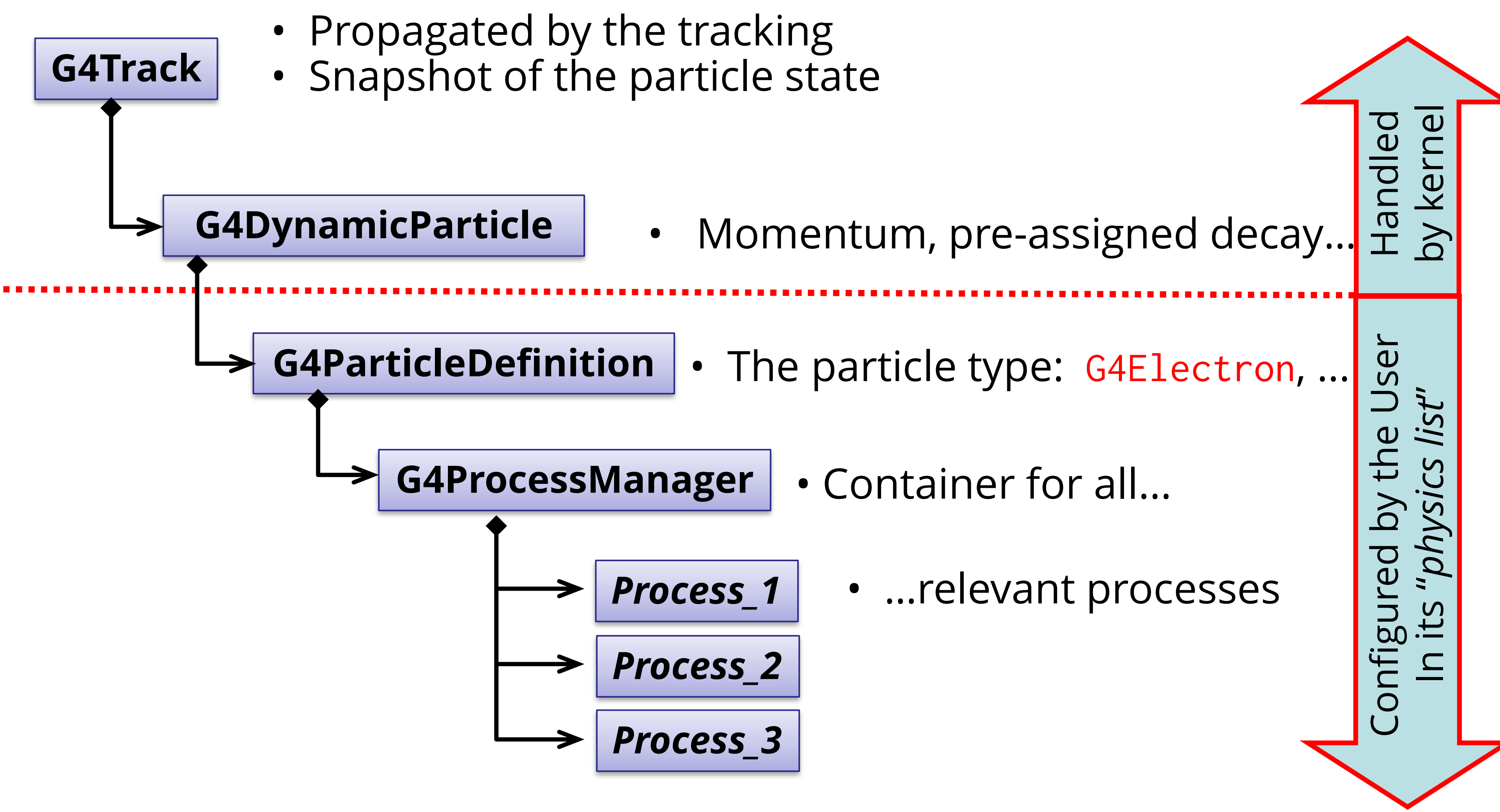
- `G4DynamicParticle`

  Particle dynamic state: energy, momentum, polarization, etc.

- `G4Track`

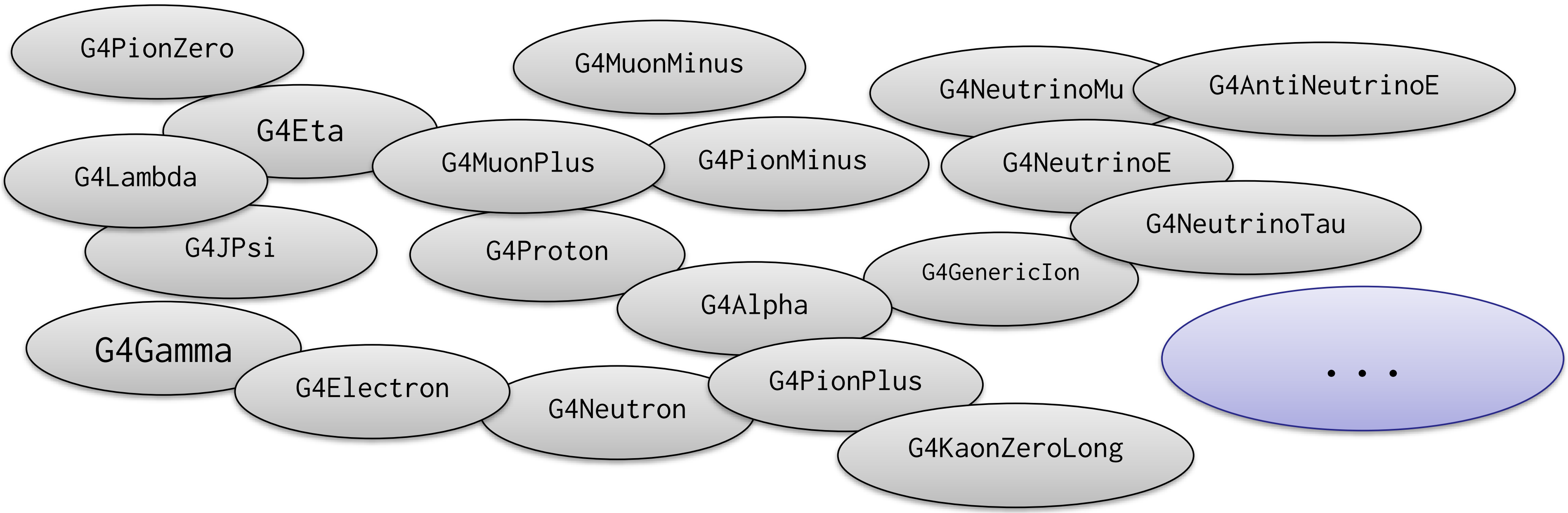
  Information for tracking in a detector simulation: position, step, current volume, track ID, parent ID, etc.

From particles to processes



Definition of a particle

Geant4 provides `G4ParticleDefinition` daughter classes to represent a large number of elementary particles and nuclei, organized in six major categories:
leptons, ***mesons***, ***baryons***, ***bosons***, ***short-lived*** *and* ***ions***



*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 instantiate, 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::ConstructParticle()
{
    // Construct all baryons
    G4BaryonConstructor pConstructor;
    pConstructor.ConstructParticle();
    ....
}
```

Processes

Physics processes describe how particles interact with materials

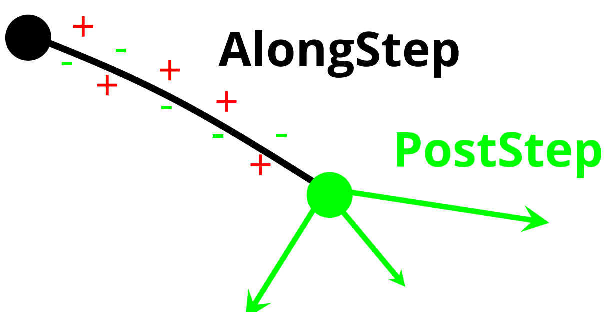
A process does two things:

1. *decides when and where an interaction will occur*
   - **`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.)
   - method: **`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 continuous (inter)actions, occurring along the path of the particle, like ionisation;



  - **PostStep** actions:
    - For describing 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: Čerenkov effect
  - photons created along step, roughly proportional to step length
    - AlongStepGPIL(), AlongStepDoIt()
- At rest process: muon capture at rest
  - interaction at rest
    - AtRestGPIL(), AtRestDoIt()

pure

- Rest + discrete: positron 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

1 a particle is shot and "transported"

2 all processes associated to the particle propose a geometrical step length (depends on process cross-section)

3 The process proposing the shortest step "wins" and the particle is moved to destination (if shorter than "Safety")

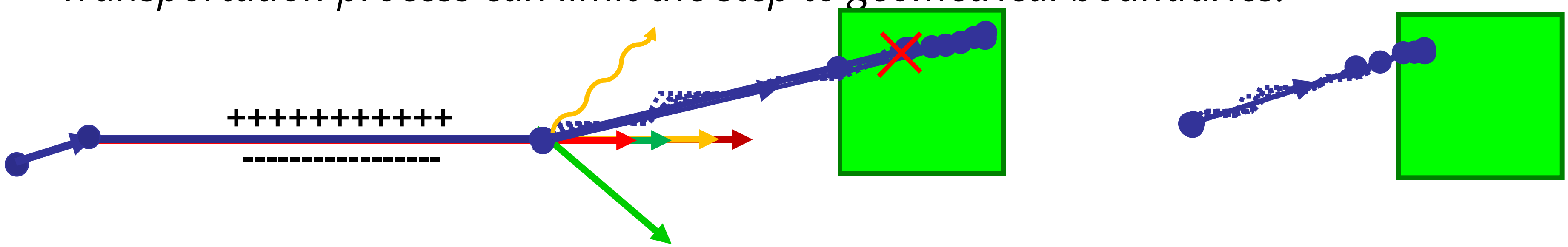
4 All processes along the step are executed (e.g. ionization)

5 post step phase of the process that limited the step is executed. New tracks are "pushed" to the stack

6 If E_{kin}=0 all at rest processes are executed; if particle is stable the track is killed. Else:

7 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 you go?

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

the best compromise

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 cut-off 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 deposition of energy
- There is also a **particle dependence**
  - in Si, range of 10 keV gamma is different from 10 keV e-
- And a **material dependence**
  - e.g. detector made of alternating sheets of Pb and plastic scintillator
  - if the cut-off 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*
  - *however, in principle you can implement this yourself (stacking, tracking, stepping action...)*

- Only **production cuts** exist
  - i.e. cuts deciding whether a particle to be produced or not
  - Applied to: ***gamma***, ***electron*** (***positron***, ***proton)***
  - ***Applied to: ionisation, bremsstrahlung***
- *Why?*

  These EM processes involve **infrared divergences**
  - this leads to a huge number of smaller and smaller energy photons/electrons (such as in Bremsstrahlung, δ-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

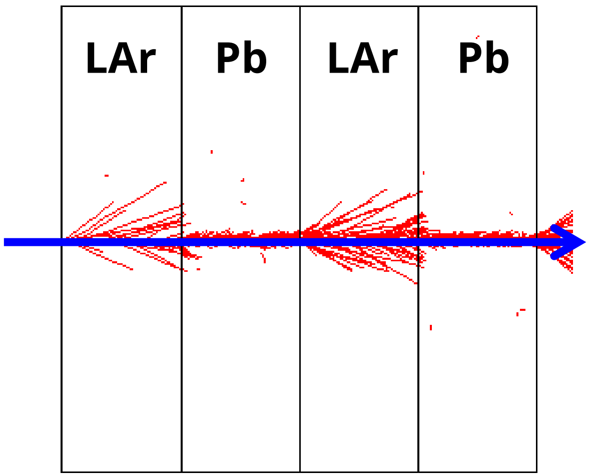
  Particles unable to travel at least the range cut value are not produced !

- Only one production threshold cut is *uniformly* set
- Production threshold is *internally converted* to an energy threshold, depending on **particle type** and **material**

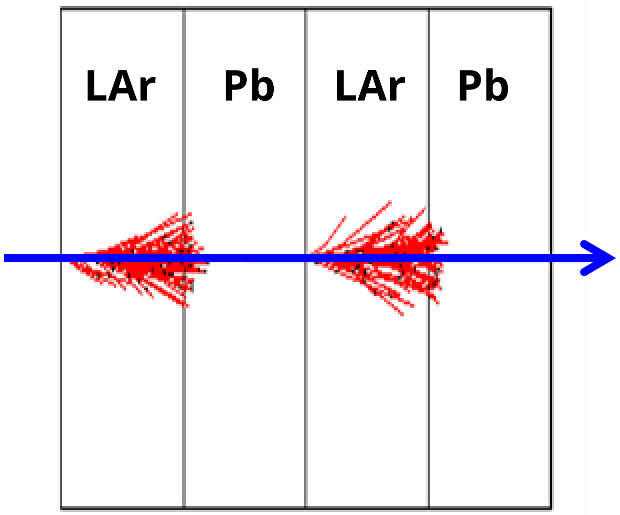
- When primary no longer has enough energy to produce secondaries which travel at least 1 mm, two things happen:
  - discrete energy loss stops (no more secondaries produced)
  - the primary is tracked down to zero energy using continuous energy loss

Production thresholds: cut

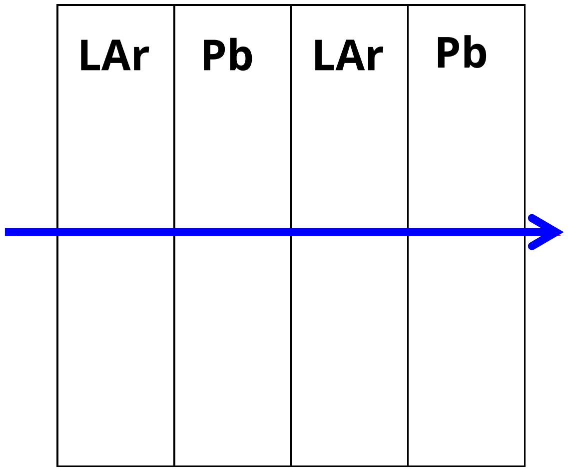
500 MeV p in LAr-Pb sampling calorimeter



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

Production cuts: C++ code

in `G4VUserPhysicsList` class

```
void MyPhysicsList::SetCuts()
{
    defaultCutValue = 0.5 * mm;
    SetCutsWithDefault();

    SetCutValue(0.1 * mm, "gamma");
    SetCutValue(0.01 * mm, "e+");
}
```

Default value: 1.0 mm

Forcing low-energy limit for production

```
void MyPhysicsList::SetCuts()
{
    ...
    G4ProductionCutsTable::GetProductionCutsTable()
        ->SetEnergyRange(100*eV, 100.*GeV);
    ...
}
```

Default low limit: 990 eV

Cuts per region

- Complex detector may contain many different sub-detectors involving
  - finely segmented volumes
  - very sensitive materials
  - large, undivided volumes
  - inert materials
- The same cut may not be appropriate for all of these
  - user can define regions (indepent of geometry hierarchy tree) and assign different cuts for each region

`G4Region` class

- Warning: it is very difficult topic and requires experience!

Cuts per region – C++ code

```
void MyPhysicsList::SetCuts()
{
    // default production thresholds for the world volume
    SetCutsWithDefault();

    // Same cuts for all particle types
    G4Region* region = G4RegionStore::GetInstance()->GetRegion("myRegion1");
    G4ProductionCuts* cuts = new G4ProductionCuts;
    cuts->SetProductionCut(0.01*mm); // same cuts for gamma, e-
    region->SetProductionCuts(cuts);

    // individual production thresholds for different particles
    region = G4RegionStore::GetInstance()->GetRegion("myRegion2");
    cuts = new G4ProductionCuts;
    cuts->SetProductionCut(1 * mm, "gamma");
    cuts->SetProductionCut(0.1 * mm, "e-");
    region->SetProductionCuts(cuts);

     // ... or (simpler)
    SetCuts(0.01 * mm, "gamma", "absorber");
}
```

Production cuts: macro commands

```
# Universal cut (whole world, all particles)
/run/setCut 10 mm

# Override low-energy limit
/cuts/setLowEdge 100 eV

# Set cut for a specific particle (whole world)
/run/setCutForAGivenParticle gamma 0.1 mm

# Set cut for a region (all particles)
/run/setCutForARegion myRegion 0.01 mm

# Print a summary of particles/regions/cuts
/run/dumpCouples
```

G4StepLimiter

- •max allowed step size
- •max total track length
- •max total time of flight
- •min kinetic energy
- •min remaining range

- Alternative to limit the level of tracking detail
- Why?
  - you want to see the exact track of the particle
  - you don't trust the chord finder for your magnetic field
- How?
  - Include **G4StepLimiter** process in your physics list
  - Set "user limits" for the *logical volumes* or *regions* of interest: **SetUserLimits()**

```
logVol->SetUserLimits(new G4UserLimits(1.0 * mm));
```

Example: Put it together

```
void StandardPhysics::ConstructParticle()
{
        // We are interested in gamma, electrons and possibly positrons
        G4Electron::ElectronDefinition();
        G4Positron::PositronDefinition();
        G4Gamma::GammaDefinition();
}

void StandardPhysics::ConstructProcess()
{
        // Transportation is necessary
        AddTransportation();

        // Electrons
        G4ProcessManager *elManager = G4Electron::ElectronDefinition()->GetProcessManager();
        elManager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
        elManager->AddProcess(new G4eIonisation, -1, 2, 2);
        elManager->AddProcess(new G4eBremsstrahlung, -1, -1, 3);
        elManager->AddDiscreteProcess(new G4StepLimiter);

        // Positrons
        G4ProcessManager *posManager = G4Positron::PositronDefinition()->GetProcessManager();
        posManager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
        posManager->AddProcess(new G4eIonisation, -1, 2, 2);
        posManager->AddProcess(new G4eBremsstrahlung, -1, -1, 3);
        posManager->AddProcess(new G4eplusAnnihilation, 0, -1, 4);
        posManager->AddDiscreteProcess(new G4StepLimiter);

        // Gamma
        G4ProcessManager *phManager = G4Gamma::GammaDefinition()->GetProcessManager();
        phManager->AddDiscreteProcess(new G4ComptonScattering);
        phManager->AddDiscreteProcess(new G4PhotoElectricEffect);
        phManager->AddDiscreteProcess(new G4GammaConversion);

        // TODO: Introduce Rayleigh scattering. It has large cross-section than Pair production
}

void StandardPhysics::SetCuts()
{
        // TODO: Create a messenger for this
        defaultCutValue = 0.03 * mm;
        SetCutsWithDefault();
}
```

Conclusion

- Geant4 description of physics is very flexible
  - many particles
  - many processes
  - many models
  - many physics lists

...End of process