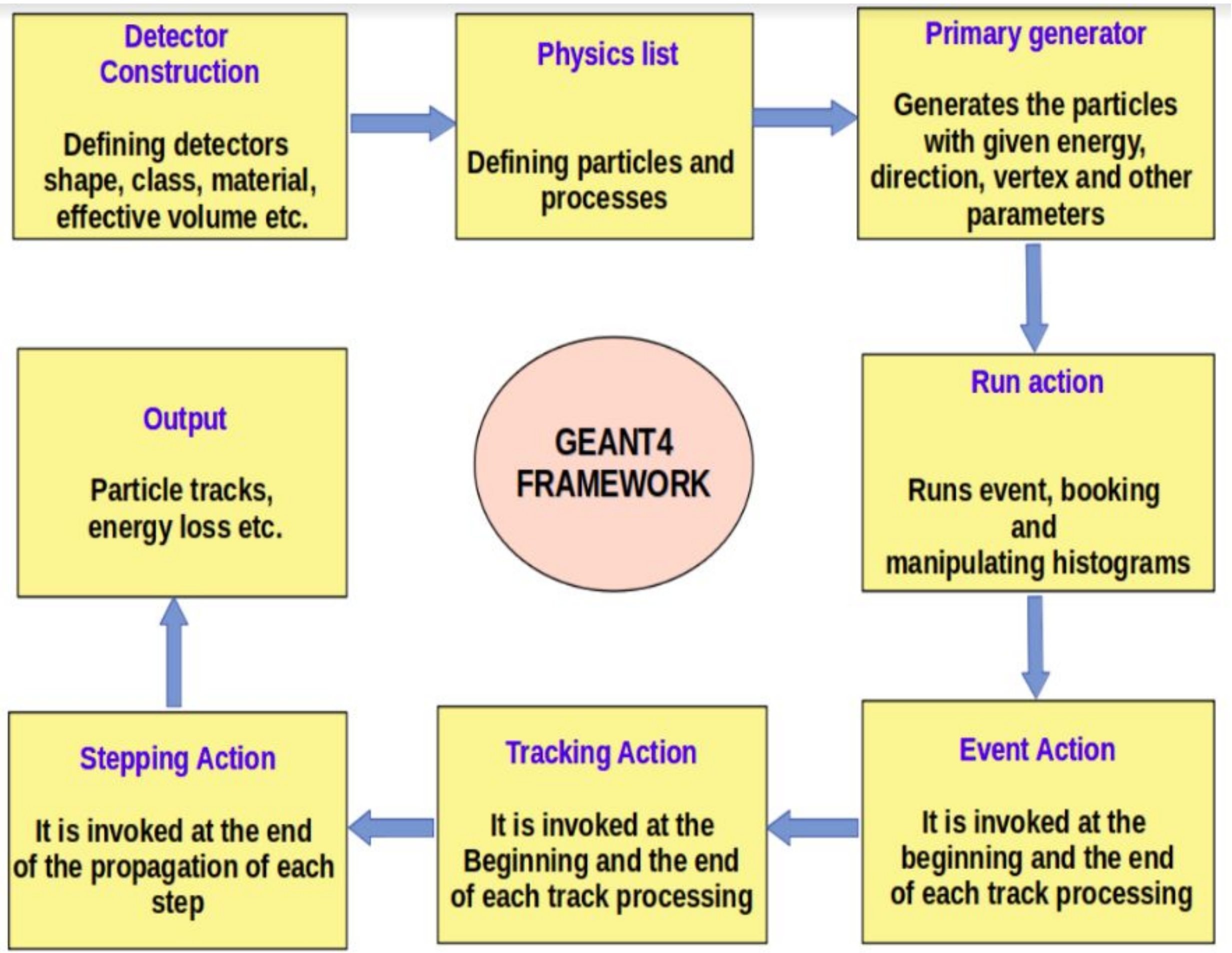
EM & Optical Physics in GEANT4

1st National Workshop on GEANT4 and its Application to High Energy Physics & Astrophysics
December 5-9, 2022
IUCAA, Pune

M.M. Devi
Tezpur Central University
Assam 784028
devimm@tezu.ernet.in


Detector Construction
Defining detectors shape, class, material, effective volume etc.
Physics list
Defining particles and processes
Primary generator
Generates the particles with given energy, direction, vertex and other parameters
GEANT4 FRAMEWORK
Run action
Runs event, booking and manipulating histograms
Event Action
It is invoked at the beginning and the end of each track processing
Tracking Action
It is invoked at the Beginning and the end of each track processing
Stepping Action
It is invoked at the end of the propagation of each step
Output
Particle tracks, energy loss etc.

GEANT4 Physics Categories

- Electromagnetic
- Hadronic
- Decay
- Optical
- Transportation
- Parameterisation

Electromagnetic Processes

Electromagnetic Processes (EM) include:

- Processes of gamma
- e- and e+ interactions
- Hadron interaction with atomic electrons

- Muon Physics

- The hadron photo- and electro- productions are simulated in framework of G4 hadronic physics.

Processes of gamma

- γ -> e+e- pair
- Compton scattering
- Photoelectric effect
- Rayleigh scattering
- Gamma-nuclear interaction in hadronic subpackage CHIPS

Process of e+ & e-

- Ionization
- Coulomb scattering
- Bremsstrahlung
- Nuclear interaction in hadronic sub-package CHIPS
- e+ annihilation

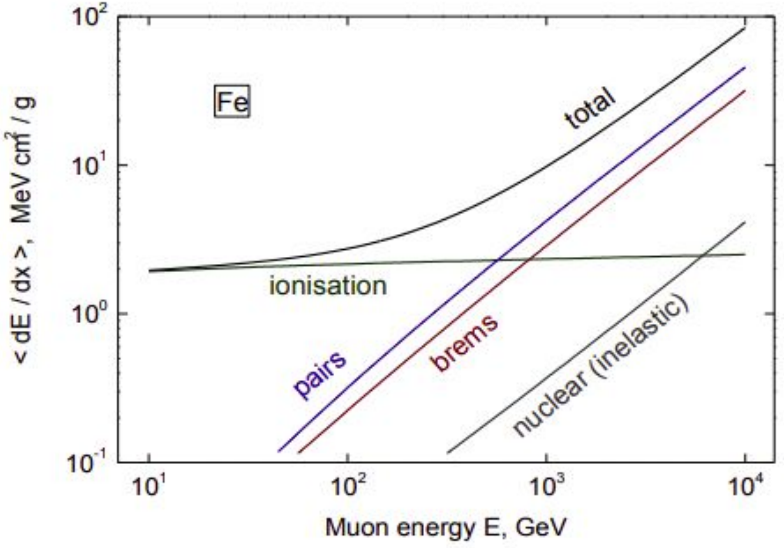
Energy loss of μ

Continuous energy loss from processes

- Ionisation
- Production of e+e-
- Bremsstrahlung

$$\frac{dE(E,T_{cut})}{dx} = n_{at} \int_0^{T_{cut}} T \frac{d\sigma(Z,E,T)}{dT} dT$$

- G4BetheBlochModel: Ionisation and delta-electron production
- G4BraggIonModel: Below 200 keV, parameterization of dE/dx
- G4MuBetheBlochModel: Radiative corrections to ionization at E > 1 GeV



EM Packages in GEANT4

(sources/processes/electromagnetic)

Standard:

- gammas, e+- up to 100 TeV
- hadrons up to 100 TeV
- ions up to 100 TeV

Muons:

- up to 1 PeV
- energy loss propagator

X-rays:

- X-ray and optical photon production processes

High-energy:

- processes at high energy (E>10GeV)
- physics for exotic particles

Polarisation:

- simulation of polarised beams

Optical:

- optical photon interactions

EM Packages in GEANT4

(sources/processes/electromagnetic)

Low Energy:

- Livermore library γ, e- from 250 eV up to 1 GeV
- Livermore library based polarized processes
- PENELOPE code rewriten, γ, e- , e+ from 250 eV up to 1 GeV (2001 version & 2008 version as beta)
- Hadrons and ions up to 1 GeV
- Atomic de-excitation (fluorescence + Auger)

Geant4-DNA:

- Micro dosimetry models for radiobiology (Geant4-DNA project) from 0.025 eV to 10 MeV

Adjoint:

- New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation

Utils:

- Common classes and general interfaces for other EM packages

Scheme of EM processes in GEANT4

(Uniform design : coherent approach for high-energy and low-energy applications)

A physical interaction or process is described by a process class

- Naming scheme : « G4ProcessName »
- e.g., photon Compton scattering -> G4Compton
- Assigned to Geant4 particle types
- Inherits from G4VEmProcess base class

Model classes provide the computation of

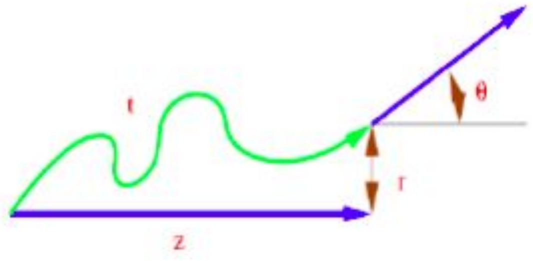
- Cross section and stopping power
- Sample selection of atom in compound Final state (kinematics, production of secondaries…)

A physical process: can be simulated according to several models, each model being described by a model class

- Naming scheme : « G4ModelNameProcessNameModel »
- e.g., G4LivermoreComptonModel
- Models can be assigned to certain energy ranges and G4Regions
- Inherits from G4VEmModel base class

Multiple Coulomb scattering

- Charged particles traversing a finite thickness of matter → suffer elastic Coulomb scattering.
- The cumulative effect of these small angle scatterings → a net deflection from the original particle direction.



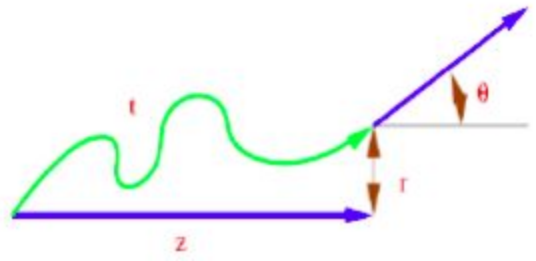
Multiple Coulomb scattering Models:

Model	Particle type	Energy limit	Specifics and applicability
Urban (Urban 2006)	Any	-	Default model, (Lewis 1950) approach, tuned to data, used for LHC production.
Screened Nuclear Recoil (Mendenhall and Weller 2005)	p, ions	< 100 MeV/A	Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space app.
Goudsmit-Saunderson (Kadri 2009)	e^+, e^-	< 1 GeV	Theory based cross sections (Goudsmit and Saunderson 1950). EPSEPA code developed by Penelope group, final state using EGSnrc method (Kawrakov et al. 1998), precise electron transport
Coulomb scattering (2008)	any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (2009)	any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons.
Ion Coulomb scattering (2010)	ions	-	Model based on Wentzel formula + relativistic effects + screening effects for projectile & target. From the work of P. G. Rancoita, C. Consolandi and V. Ivantchenko.

Algorithm for Multiple Coulomb Scattering (MSC):

Legend

- t (True path length)
- z (Longitudinal or geometrical displacement)
- r (Lateral displacement)
- θ, f (Angular deflection)



The algorithm performs several steps for the simulation of MSC.

- Step length: selected by the physics processes and the geometry (MSC performs the t ↔ z transformation only)
- What the algorithm does not look into: The transport along the initial direction
- Sampling of scattering angle (θ, φ)
- Computation of lateral displacement and relocation of particle

Multiple Coulomb Scattering (MSC) Classes

Processes per particle type are available

- G4eMultipleScattering (e+/e-)
- G4MuMultipleScattering (μ+/μ-)
- G4hMultipleScattering (hadrons and ions)

L. Urban models

- G4UrbanMscModel93 : used by default in G4eMultipleScattering
- G4UrbanMscModel90 : G4MuMultipleScattering (for μ), G4hMultipleScattering (for hadrons)
- Alternative single and multiple scattering models are available

Urban MSC model in GEANT4

- Based on Lewis' MSC theory of transport of charged particles (1950)
- Uses phenomenological functions to determine the angular and spatial distributions after a simulation step

EMStandard: Physics List Constructor

Default EM constructor, used in major part of reference Physics Lists

- G4LivermorePhotoelectricModel
- G4RayleighScattering process
- G4UrbanMscModel (for multiple scattering of e+ and e- below 100 MeV)
- G4WentzelVIModel (for multiple scattering, combined with G4eCoulombScatteringModel for large angle scattering for muons, pions, kaions, protons, and anti-protons at all enegries, for e+ and e- above 100 MeV)
- G4UrbanMscModel for all other chaged particles.

(https://geant4.kek.jp/lxr/source/physics_lists/constructors/electromagnetic/src/G4EmStandardPhysics.cc?v=10.4)

Physics processes in GEANT4

(The particle decays and interactions are performed by processes)

A process does two things:

- Decides when and where an interaction will occur [GetPhysicalInteractionLength()]

    Requires a cross section or decay lifetime

- Generates the final state of the interaction (changes momentum, position, generates secondaries, etc.) [DoIt()]

    Requires a model of the physics

Physics processes in GEANT4

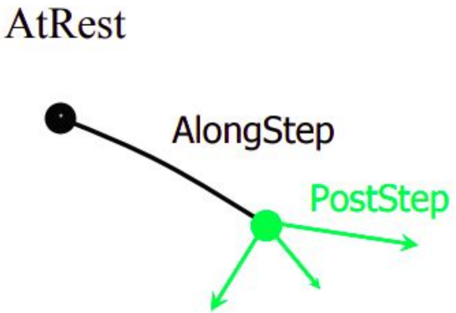
There are three categories of processes:

- well-located in space -> PostStep
- distributed in space -> AlongStep
- well-located in time -> AtRest

A process may be a combination of all three categories → six methods must be implemented [GetPhysicalInteractionLength() and DoIt() for each action)]

"Shortcut" processes: which invoke only one

- Discrete process (only PostStep)
- Continuous process (only AlongStep)
- AtRest process (only AtRest)



Physics processes in GEANT4: Examples

Compton Scattering (Discrete process)

- step determined by: cross section, interaction at end of step
- PostStepGPIL()
- PostStepDoIt()

Cherenkov (Continuous process)

- photons created along step, # roughly proportional to step length
- AlongStepGPIL()
- AlongStepDoIt()

Positron annihilation (at rest)

- no displacement, relevant variable is time
- AtRestGPIL()
- AtRestDoIt()

Physics processes in GEANT4: Examples

Ionization (Continuous + discrete)

- Energy loss is continuous
- Moller/Bhabha scattering and knock-on electrons are discrete

Multiple scattering (continuous + discrete)

Bremsstrahlung (Continuous + discrete)

- Energy loss due to soft photons -> continuous
- Emission of hard photons -> discrete
- The production threshold separates the continuous and discrete parts

Optical Photons

- Should belong to electromagnetic category technically
- Optical photon wavelength is >> atomic spacing
- Treated as waves -> no smooth transition between optical and gamma particle classes

```
G4OpticalPhysics* opticalPhysics = new G4OpticalPhysics();

// adjust some parameters for the optical physics

// wave lenght shifting
opticalPhysics->SetWLSTimeProfile("delta");

// scintillation
opticalPhysics->SetScintillationYieldFactor(1.0);
opticalPhysics->SetScintillationExcitationRatio(0.0);

// cerenkov
opticalPhysics->SetMaxNumPhotonsPerStep(100);
opticalPhysics->SetMaxBetaChangePerStep(10.0);

// general
opticalPhysics->SetTrackSecondariesFirst(true);
```

- G4OpticalPhoton <> G4Photon
  particleGun->SetParticleDefinition(G4OpticalPhoton::OpticalPhotonDefinition());
- UI command : /gps/particle opticalphoton

Optical Photons: Production Processes

Optical photons are produced by:

- G4Cerenkov
- G4Scintillation
- G4TransitionRadiation

Optical Photons: Interactions

- Rayleigh scattering
- Refraction and reflection at medium boundaries
- Bulk absorption
- Wavelength shifting

- Classes located in processes/optical:

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

- Optical properties can be specified in G4Material by user.
- G4Material : Reflectivity, transmission efficiency, dielectric constants, surface properties, Photon spectrum properties
- Geant4 demands particle-like behavior for tracking -> an event with both refraction and reflection must be simulated by at least two events

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

Inclusion of Optical Properties

- Optical properties -> stored in the G4MaterialPropertiesTable

```
// *** Material definition
G4NistManager *man = G4NistManager::Instance();
G4Material *LXe = man->FindOrBuildMaterial("G4_lXe");

// *** Material properties tables
const G4int nE = 3;
G4double LXe_energy[nE]    = { 7.0*eV , 7.07*eV, 7.14*eV };

G4double LXe_scint[nE] = { 0.1, 1.0, 0.1 };
G4double LXe_rindex[nE]  = { 1.59 , 1.57, 1.54 };
G4double LXe_abslength[nE]  = { 35.*cm, 35.*cm, 35.*cm};

LXe_mt = new G4MaterialPropertiesTable();
LXe->SetMaterialPropertiesTable(LXe_mt);

LXe_mt->AddProperty("FASTCOMPONENT", LXe_energy, LXe_scint, nE);
LXe_mt->AddProperty("SLOWCOMPONENT", LXe_energy, LXe_scint, nE);
LXe_mt->AddProperty("RINDEX",        LXe_energy, LXe_rindex, nE);
LXe_mt->AddProperty("ABSLENGTH",     LXe_energy, LXe_abslength, nE);
LXe_mt->AddConstProperty("SCINTILLATIONYIELD",12000./MeV);
LXe_mt->AddConstProperty("RESOLUTIONSCALE",1.0);
LXe_mt->AddConstProperty("FASTTIMECONSTANT",20.*ns);
LXe_mt->AddConstProperty("SLOWTIMECONSTANT",45.*ns);
LXe_mt->AddConstProperty("YIELDRATIO",1.0);
```

Example: Wavelength Shifting

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

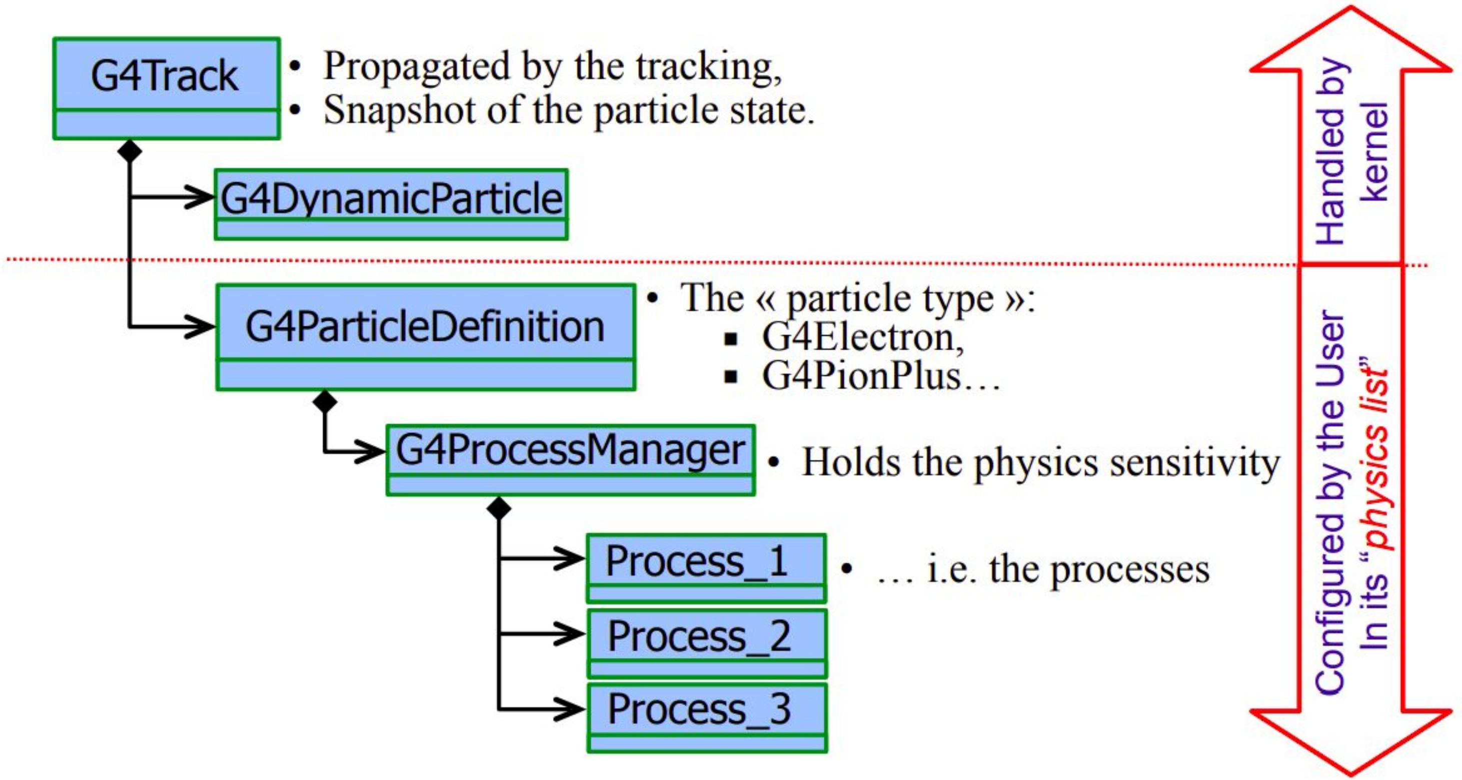
G4OpBoundaryProcess

- Refraction
- Reflection
- Absorbed/detected

User must supply

- Surface properties (using G4OpticalSurfaceModel)
- G4SurfaceType: dielectric-dielectric, dielectric-metal etc.
- G4OpticalSurfaceFinish: polished, front/back-painted etc.

Processes in GEANT4-flow



How to build a physics list

Physics list: Mandatory user class making the general interface between the physics the user needs and the Geant4 kernel

- Should include the list of particles
- The G4ProcessManager maintains a list of processes of each particle
- Collects all the particles, physics processes and production thresholds
- Tells the run manager how and when to invoke physics

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

G4VUserPhysicsList

Virtual methods:

- ConstructParticle() [Mandatory]
- ConstructProcess() [Mandatory]
- SetCuts() [Optional]

```
class YourPhysicsList: public G4VUserPhysicsList {
  public:
    // CTR
    YourPhysicsList();
    // DTR
    virtual ~YourPhysicsList();

    // pure virtual => needs to be implemented
    virtual void ConstructParticle();
    // pure virtual => needs to be implemented
    virtual void ConstructProcess();

    // virtual method
    virtual void SetCuts();
    ...
    ...
};
```

Construct Particle

- Interface method: define the list of particles to be used in the simulation
- Construct particles individually

```
void YourPhysicsList::ConstructParticle() {
        G4Electron::Definition();
        G4Gamma::Definition();
        G4Proton::Definition();
        G4Neutron::Definition();
        // other particle definitions
        …
        …
}
```

- Construct particles by using helpers

Construct Process

- Interface method to define the list of physics processes to be used in the simulation for a given particle

```cpp
void YourPhysicsList::ConstructProcess() {
    // method (provided by the G4VUserPhysicsList base class)
    // that assigns transportation process to all particles
    // defined in ConstructParticle()
    AddTransportation();
    // helper method might be defined by the user (for convenience)
    // to add electromagnetic physics processes
    ConstructEM();
    // helper method might be defined by the user
    // to add all other physics processes
    ConstructGeneral();
}
```

Construct EM Process

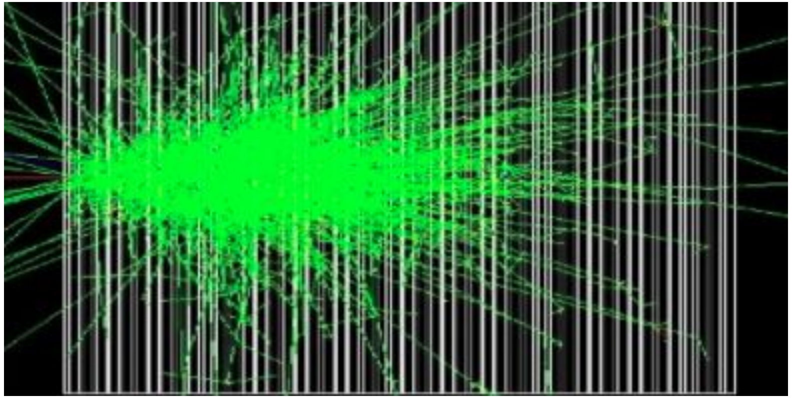
```
void YourPhysicsList::ConstructEM() {
  // get the physics list helper
  // it will be used to assign processes to particles
  G4PhysicsListHelper* ph = G4PhysicsListHelper::GetPhysicsListHelper();
  auto particleIterator   = GetParticleIterator();
  particleIterator->reset();
  // iterate over the list of particles constructed in ConstructParticle()
  while( (*particleIterator)() ) {
    // get the current particle definition
    G4ParticleDefinition* particleDef  = particleIterator->value();
    // if the current particle is the appropriate one => add EM processes
    if ( particleDef == G4Gamma::Definition() ) {
      // add physics processes to gamma particle here
      ph->RegisterProcess(new G4GammaConversion(),  particleDef);
      ...
      ...
    } else if ( particleDef == G4Electron::Definition() ) {
      // add physics processes to electron here
      ph->RegisterProcess(new G4eBremsstrahlung(), particleDef);
      ...
      ...
    } else if (...) {
      // do the same for all other particles like e+, mu+, mu-, etc.
      ...
    }
  }
}
```

Example of EM: examples/extended/electromagnetic

- **TestEm0:** how to print cross-sections and stopping power used in input by the standard EM package.
- **TestEm1**: how to count processes, activate/inactivate them and survey the range of charged particles. How to define a maximum step size
- **TestEm2:** shower development in an homogeneous material : longitudinal and lateral profiles
- **Test EM3:** shower development in a sampling calorimeter : collect energy deposited, survey energy flow and print stopping power
- **TestEM4:** 9 MeV point like photon source: plot spectrum of energy deposited in a single media
- **TestEm5:** how to study transmission, absorption and reflection of particles through a single, thin or thick, layer.
- **TestEm6:** physics list for rare, high energy, electromagnetic processes: gamma conversion and e+ annihilation into pair of muons

Examples: optical photon

- examples/novice/N06
- examples/extended/optical/LXe



Stay Tuned for the tutorials
Thank You for the kind attention!