Geant4 11.3.2

Physics Overview

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Geant4 Tutorial at Jefferson Lab

18 August 2025

Outline

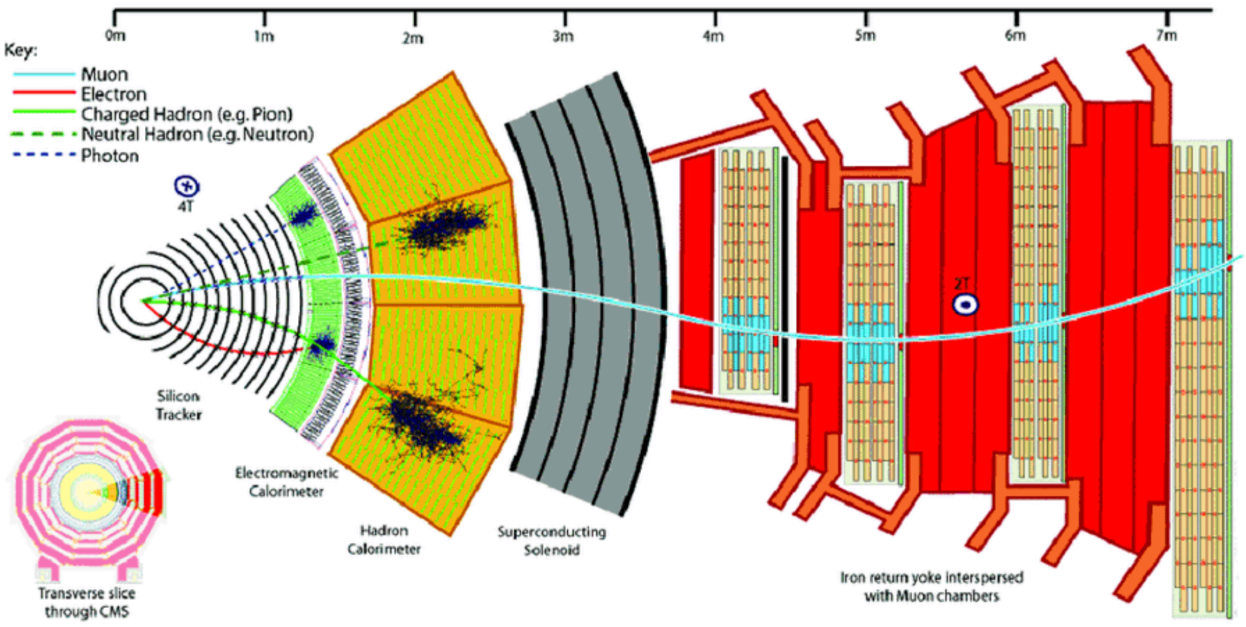
- Introduction - Geant4 physics

- Geant4 physics overview
  - Processes
  - EM, hadronic, decay, transportation

- Physics lists
  - What is a physics list? Why do we need it?
  - G4VUserPhysicsList
  - Modular physics lists - a more convenient way to go
  - Pre-packaged physics lists - provided by the toolkit
  - Examples

Introduction

- Geant4 provides a variety of physics simulation components over a wide range of energies and particles
  - Primary generation → event → projectile particles
  - Detector description → geometry and material → target nuclei
  - Physics interaction → (particle, target, energy) → final state



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 at end of step
    - PostStepGetPhysicalInteractionLength()
    - PostStepDoIt()

- Continuous process: Cerenkov effect
  - photons created along step, # proportional to step length
    - AlongStepGetPhysicalInteractionLength()
    - AlongStepDoIt()

- At rest process: μ^- capture at rest
  - muon has already stopped so time is the relevant variable
    - AtRestGetPhysicalInteractionLength()
    - AtRestDoIt()

Example Processes

- Continuous + discrete: ionization
  - energy loss is continuous (low energy electrons not generated)
  - Moller/Bhabha scattering and knock-on electrons are discrete
- Continuous + discrete: bremsstrahlung
  - energy loss is continuous (soft photon emission not performed)
  - hard photon emission is discrete
- Discrete + at-rest: e^+ annihilation
  - in-flight annihilation is discrete
  - at rest annihilation when positron stops
- Multiple scattering is also continuous + discrete

Physics Processes Provided by Geant4

- Electromagnetic physics
  - “standard”: the default processes valid between ~keV and PeV
  - ”low energy”: processes available for ~100 eV to 1 PeV
  - Geant4 DNA: valid down to ~eV (but mostly just for liquid water)
  - optical photons

- Weak interactions
  - decay of subatomic particles
  - radioactive decay of nuclei
  - neutrino scattering

- Hadronic physics
  - pure strong interaction physics valid from 0 to ~1 TeV
  - electro- and gamma-nuclear interactions valid from 10 MeV to ~TeV
  - high precision neutron (and other particles) package valid from thermal energies to ~20 MeV
- Parameterized or “fast simulation” physics

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 photons – only for long wavelength photons (x-rays, UV, visible)
  - processes for reflection/refraction, absorption, wavelength shifting, Rayleigh scattering
  - users select these components in their physics lists

Geant4 Physics: Hadronic

- Pure hadronic (0 to ~TeV)
    - elastic
    - inelastic
    - capture
    - fission

- Radioactive decay
    - at rest and in-flight

- Photo-nuclear (~10 MeV - ~TeV)
    - gamma-induced nuclear reactions

- Lepto-nuclear (~10 MeV - ~TeV)
    - e^+, e^- induced nuclear reactions
    - muon-induced nuclear reactions
    - neutrino scattering

Geant4 Physics: Decay, Parameterized and Transportation

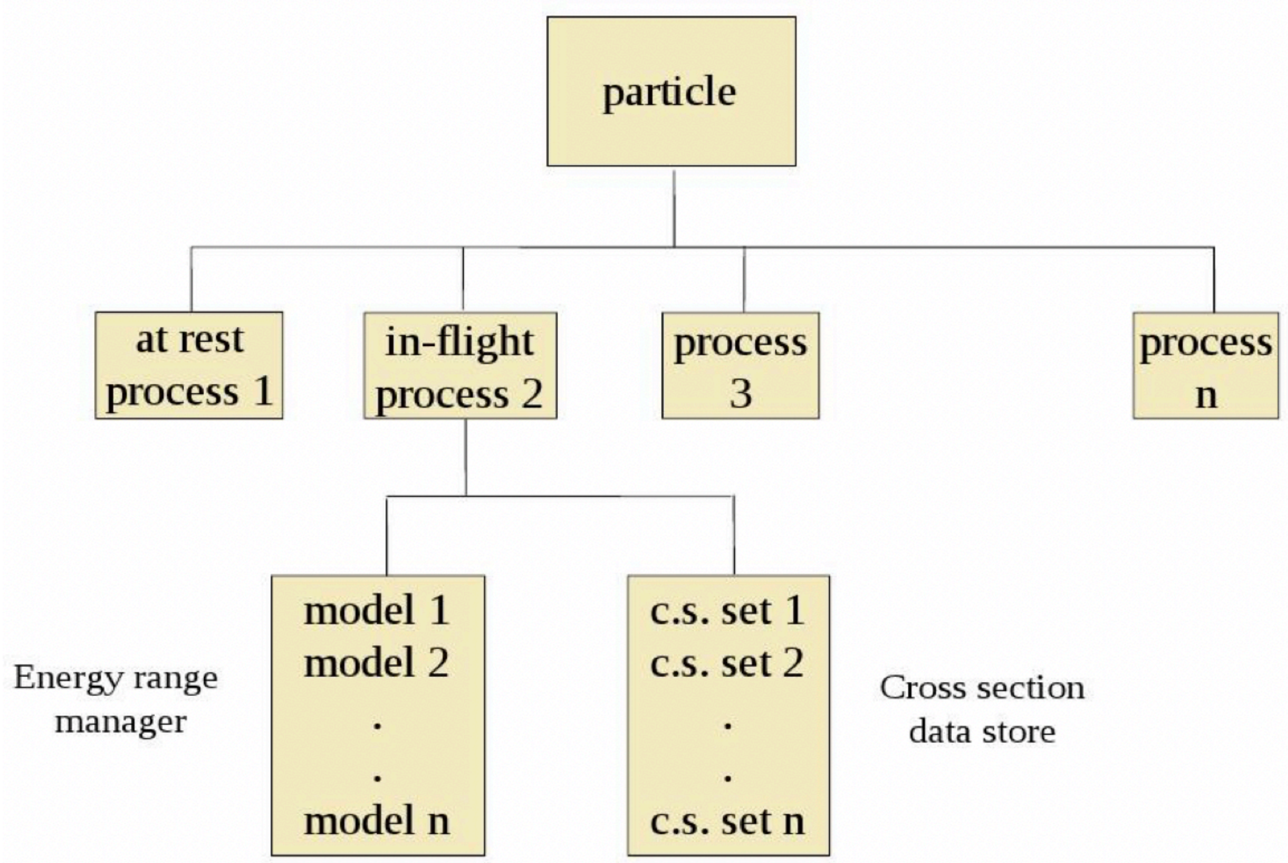
- Decay processes include
  - weak decay (leptonic, semi-leptonic decays, radioactive decay of nuclei)
  - electromagnetic decay (π^0 , Σ^0 , etc.)
  - strong decays not included here (they are part of hadronic models)

- 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
  - must be assigned to each particle type

Handling Multiple Processes

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



What is a Physics List?

- An object responsible for:
    - specifying all particles to be used in a simulation application
    - specifying physics processes and assigning them to each particle type

- One of three mandatory objects that the user must provide to the G4RunManager in any application
    - tells run manager what physics needs to be invoked and when

- Provides a very flexible way to set up the physics environment
    - user can choose and specify particles he wants
    - user can choose the physics (processes) to assign to each particle

- BUT, user must have a good understanding of the physics required to describe the problem
    - omission of relevant particles and/or physics interactions could lead to poor modeling results

Why Do We Need a Physics List?

- Physics is physics – shouldn’t Geant4 provide, as a default, a complete set of physics that everyone can use?

- NO:
  - there are many different approximations and models to describe the same interaction
    - very much the case for hadronic but also for electromagnetic physics
  - computation time is an issue:
    - some users may want a less accurate but significantly faster model for a given interaction while others need the most accurate description regardless of CPU time
  - there is no simulation application that would require all the particles and all the possible interactions that Geant4 can provide
    - e.g. most medical applications are not interested in multi-GeV physics

- For this reason Geant4 takes an atomistic, rather than an integral approach to physics
  - provides many independent (for the most part) physics components (i.e. physics processes)
  - users select these components in their custom-designed physics lists
  - exceptions: a few electromagnetic processes must be used together

Physics List Interface

- G4VUserPhysicsList is the Geant4 physics list interface
- All physics lists must derive from this base class

```
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();
    ...
    ...
};
```

- User must implement the two pure virtual methods ConstructParticle() and ConstructProcess()
- User can implement the SetCuts() method (optional)

Physics List Interface: ConstructParticle()

- Interface method defines list of particles to be used in the application
- Can construct particles individually

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

- Or using toolkit-provided helper classes

```
void YourPhysicsList::ConstructParticle() {
    // construct baryons
    G4BaryonConstructor baryonConstructor;
    baryonConstructor.ConstructParticle();
    // construct bosons
    G4BosonConstructor bosonConstructor;
    bosonConstructor.ConstructParticle();
    // more particle definitions
    …
    …
}
```

Physics List Interface: ConstructProcess()

- Defines the list of physics processes to be used in the simulation for a given particle type

```
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();
}
```

Physics List Interface: ConstructProcess()

```
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.
      ...
    }
  }
}
```

Physics List Interface: ConstructProcess()

```
void YourPhysicsList::ConstructGeneral() {
  // get the physics list helper
  // it will be used to assign processes to particles
  G4PhysicsListHelper* ph  = G4PhysicsListHelper::GetPhysicsListHelper();
  auto particleIterator    = GetParticleIterator();
  particleIterator->reset();
  // create processes that need to be assigned to particles
  // e.g. create decay process
  G4Decay* theDecayProcess = new G4Decay();
  ...
  ...
  // iterate over the list of particles constructed in ConstructParticle()
  while( (*particleIterator)() ) {
    // get the current particle definition
    G4ParticleDefinition* particleDef  = particleIterator->value();
    // if the process can be assigned to the current particle => do it!
    if ( theDecayProcess->IsApplicable( *particleDef ) ) {
      // add the physics processes to the particle
      ph->RegisterProcess(theDecayProcess, particleDef);
    }
    // other processes might be assigned to the current particle as well
    ...
    ...
  }
}
```

Physics List Interface: SetCuts()

- Interface method (optional):

```
// optional: default cut value = 1.0 mm
void YourPhysicsList::SetCuts() {
  // set the base (G4VUserPhysicsList) class member value
  // to the required one
  defaultCutValue = 0.7*CLHEP::mm;
  // then set each production threshold individually
  // NOTE: order is important! First "gamma" then the others.
  SetCutValue(defaultCutValue, "gamma");
  SetCutValue(defaultCutValue, "e-");
  SetCutValue(defaultCutValue, "e+");
  SetCutValue(defaultCutValue, "proton");
  //
  // These are all the production cuts:
  // - not required for any other particle
}
```

- Or a simpler (and equivalent) way:

```
// optional: default cut value = 1.0 mm
void YourPhysicsList::SetCuts() {
  G4double yourCutValue = 0.7*CLHEP::mm;
  // use the base (G4VUserPhysicsList) class method
  SetDefaultCutValue( yourCutValue );
}
```

Modular Physics List

- Why use this?
  - previous physics list example was very simple and incomplete
  - realistic physics lists will have many more particles and processes
  - such a list can be quite long, complicated and hard to maintain

- Modular physics list provides a solution:
  - interface is defined in G4VModularPhysicsList
  - this interface is derived from the G4VUserPhysicsList base class (as YourPhysicsList in the previous example)
  - the transportation process is automatically added to all constructed particles
  - allows the use of "physics modules"
  - a given physics module handles a well-defined category of physics e.g. EM physics, hadronic physics, decay, etc.

Modular Physics List

```cpp
class YourModularPhysicsList : public G4VModularPhysicsList {
  public:
    // CTR
    YourModularPhysicsList();
    ...
};

// CTR implementation
YourModularPhysicsList::YourModularPhysicsList()
: G4VModularPhysicsList() {
  // set default cut value (optional)
  defaultCutValue = 0.7*CLHEP::mm;
  // use pre-defined physics constructors
  // e.g. register standard EM physics using the pre-defined constructor
  // (includes constructions of all EM processes as well as the
  // corresponding particles)
  RegisterPhysics( new G4EmStandardPhysics() );
  // user might create their own constructor and register it
  // e.g. all physics processes having to do with protons (see below)
  RegisterPhysics( new YourProtonPhysics()   );
  // add more constructors to complete the physics
  ...
}
```

Modular Physics List: Physics Constructors

- Physics constructor
  - allows particles and their associated processes to be grouped together according to a physics domain
  - implements the G4VPhysicsConstructor
  - can be viewed as a subset of a complete physics list
  - user may create his own (e.g. YourProtonPhysics) or use pre-defined physics constructors (G4EmStandardPhysics, G4DecayPhysics, …)

```
class YourProtonPhysics : public G4VPhysicsConstructor {
  public:
    // CTR
    YourProtonPhysics(const G4String& name = "proton-physics");
    // DTR
    virtual ~YourProtonPhysics();
    // particle construction:
    // only one particle i.e. proton needs to be constructed
    virtual ConstructParticle();
    // process construction:
    // create and assign all processes to proton that it can have
    virtual ConstructProcess();
};
```

Packaged Physics Lists

- Our examples dealt mainly with EM physics
- A realistic physics list is found in basic example B3
  - modular physics list including standard EM physics and decay physics built with physics constructors
  - good starting point to construct your own physics list
  - add other physics to suit your needs
- For both hadronic and electromagnetic physics, processes may be implemented by “models”
  - user may choose from several “models”
  - choosing the most appropriate model for a given application requires significant experience
- Pre-packaged physics lists
  - provided by toolkit and developed for a few reference cases
  - ready-to-use, developed by experts in certain application areas
  - each pre-packaged list contains different combinations of EM and hadronic physics
  - list of these found in toolkit at geant4/source/physics_lists/lists/include

Packaged Physics Lists

- Caveats:
  - these lists are provided as a best guess of the physics needed in some given use cases
  - user is responsible for validating the particular physics list for a given application and adding or removing physics if necessary
  - intended as starting points or templates

- Production physics lists
  - used by a large user groups such as ATLAS and CMS
  - well-maintained and tested
  - very stable: fewer changes, less frequent updates

- Pre-packaged physics lists
  - provided by toolkit and developed for a few reference cases
  - ready-to-use, developed by experts in certain application areas
  - extensively validated by developers and the user communities
  - FTFP_BERT, QGSP_BERT, QGSP_FTFP_BERT_EMV, FTFP_BERT_HP, …

Example Using Physics Constructors

- QGSP_BIC_HP_EMZ
  - not currently a packaged list – we’re going to to build it here
  - using constructors G4HadronPhysicsQGSP_BIC_HP and G4EmStandard_option4 (EMZ)

```
class YourQGSP_BIC_HP_EMZ : public G4VModularPhysicsList {
  public:
    // CTR
    YourQGSP_BIC_HP_EMZ();
    ...
};


// CTR implementation
YourQGSP_BIC_HP_EMZ::YourQGSP_BIC_HP_EMZ()
: G4VModularPhysicsList() {
  // set default cut value (optional)
  defaultCutValue = 0.7*CLHEP::mm;
  // use pre-defined physics constructor for EM: EM-opt4
  RegisterPhysics( new G4EmStandardPhysics_option4() );
  // use pre-defined physics constructor for hadron inelastic: QGSP_BIC_HP
  RegisterPhysics( new G4HadronPhysicsQGSP_BIC_HP()  );
  // ADD MORE CONSTRUCTORS TO COMPLETE THE PHYSICS WITH:
  // Hadron Elastic, Decay, Stopping, Ion, etc. Physics !!!!
  ...
}
```

Example Using Reference Physics Lists

- QGSP_BIC_HP_EMZ
  - the QGSP_BIC_HP reference physics list includes all the above physics constructors (but with standard EM physics)
  - G4PhysicsListFactory knows about all the available reference lists and makes possible the replacement of one EM option with another

```
// IM YOUR MAIN APPLICATION
//
  // create your run manager
#ifdef G4MULTITHREADED
  G4MTRunManager* runManager = new G4MTRunManager;
  // number of threads can be defined via macro command
  runManager->SetNumberOfThreads(4);
#else
  G4RunManager* runManager = new G4RunManager;
#endif
  //
  // create a physics list factory object that knows
  // everything about the available reference physics lists
  // and can replace their default EM option
  G4PhysListFactory physListFactory;
  // obtain the QGSP_BIC_HP_EMZ reference physics lists
  // which is the QGSP_BIC_HP refrence list with opt4 EM
  const G4String plName = "QGSP_BIC_HP_EMZ";
  G4VModularPhysicsList* pList = physListFactory.GetReferencePhysList(plName);
  // (check that pList is not nullptr, that I skipp now)
  // register your physics list in the run manager
  runManager->SetUserInitialization(pList);
  // register further mandatory objects i.e. Detector and Primary-generator
  ...
```

Summary

- Geant4 physics covers nearly all particles over energies ranging from 0 to ~TeV
- Processes handle all the physics of particle interactions
  - users may define their own processes
- Many processes may be assigned to a given particle type
- Physics lists collect all the particle definitions, processes and models
  - may be written or customized by user
  - Geant4 provides already written physics lists
- Choosing the appropriate physics list for a given application requires care and validation