Physics and Physics List in Geant4

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Based on a presentation by G.A.P. Cirrone (INFN-LNS) and Luciano Pandola
Outline

• The philosophy of the physics definition
• How to define and activate models
• Electromagnetic physics
• Hadronic physics
Philosophy

• Provide a **general model framework** that allows the implementation of **alternative models** to **describe the same process** (e.g. Compton scattering)

• A given **model** could work better in a certain **energy range**

MULTIPLE MODELS FOR THE SAME PROCESS

• **Decouple** modeling of **cross sections** and of **final state generation**

• Provide **processes** containing
  
  o **Many possible models** and cross sections
  
  o **Default cross sections** for each model

Models under continuous development
User Classes

Initialisation classes
Invoked at the initialization

G4VUserDetectorConstruction
  G4VUserPhysicsList

*Global*: only one instance of them exists in memory, shared by all threads *(readonly)*.
Managed only by the *master* thread.
G4VUserPhysicsList

All physics lists must derive from this class
  - And then be registered to the G4(MT)RunManager in the main()
  - Mandatory class in Geant4

```cpp
class MyPhysicsList: public G4VUserPhysicsList {
  public:
    MyPhysicsList();
    ~MyPhysicsList();
    void ConstructParticle();
    void ConstructProcess();
    void SetCuts();
}
```

User must implement the following (purely virtual) methods:
  - ConstructParticle(), ConstructProcess(), SetCuts()
ConstructParticle()

- Choose the **particles** you need in your simulation and **define** all of them here

  - `G4Electron::ElectronDefinition()`
  - `G4Gamma::GammaDefinition()`
  - ...

- It is possible to use **Geant4 classes** that **create categories** of particles

  - `G4BosonConstructor()`
  - `G4LeptonConstructor()`
  - ...

SetCuts()

Define all **production** cuts for **gamma**, **electrons** and **positrons**

- Recently also for **protons**

This is a **production cut**, not a tracking cut

- All particles, once created, are **tracked** down to zero kinetic energy
- The cut is used to **limit the generation of secondaries** (e.g. δ-rays from ionization, or gammas from bremsstrahlung)
- The cut is expressed in **equivalent range**
  - This is converted in **energy** for each material
The definition of physics

Three different ways to implement physics models:

Explicitly associating a given model to a given particle for a given energy range
  • Done at code level

Use of Builders or Constructors and reference physics lists

• THE CONSTRUCTORS are process related (Electromagnetic, Hadronic, Elastic, etc.)

• THE REFERENCE PHYSICS LISTS are complete physics lists
  Can be also called by the macro file
The definition of physics - 2

Modular physics lists: the list is built from basic "blocks" (the constructors)

- The constructors are process-related (standard, low energy, Bertini, etc.)
- Some constructors are provided by Geant4, but users can create and register their own customized

Class derives from G4VModularPhysicsList
which inherits from G4VUserPhysicsList

- SetCuts() is the only mandatory virtual method
- ConstructParticle() and ConstructProcess() are optional
How to build a modular physics list

Create a class derived by `G4VModularPhysicsList`

- `class myList : public G4VModularPhysicsList`

Implement the mandatory method `SetCuts()`

Register the appropriate constructors (or create your own) in the constructor or in `ConstructProcess()`

- In the first case, you cannot change at run-time

```cpp
void myList::myList ()
{
    // Hadronic physics
    RegisterPhysics(new G4HadronElasticPhysics ());
    RegisterPhysics(new G4HadronPhysicsFTFP_BERT_TRV());
    // EM physics
    RegisterPhysics(new G4EmStandardPhysics());
}
```
How to build a modular physics list

- Other option: instantiate the constructors in `ConstructProcess()` and invoke their own `ConstructProcess()`.
- Constructors made out from "elementary" builders

```cpp
void myList::ConstructProcess()
{
    //Em physics
    G4VPhysicsConstructor* emList = new G4EmStandardPhysics();
    emList->ConstructProcess();
    //Inelastic physics for protons
    G4VPhysicsConstructor* pList = new G4HadronPhysicsQGS_BIC();
    pList->ConstructProcess();
}
```
The definition of physics

Geant4 provides a few ready-for-the-use physics lists
- Complete physics lists
- Can be instantiated by UI (macro files)

Provide a complete and realistic physics with ALL models of interest
- Many options available for EM and hadronic physics

They are intended as starting point and their builders can be reused
- They are made up of constructors, so easy to change/replace each given block
Reference physics lists

These families share components to attach certain types of processes to groups of particles. These components are:

- Electromagnetic interactions for all particles
- Inelastic interactions
- Elastic scattering
- Capture
- Decay of unstable particles
- Specialised treatment of low energy neutrons (< 20 MeV)

They are modular physics lists by themselves, so you can register additional constructors (e.g. optical physics)
How to use a Geant4 physics list

In your main(), just **register** an **instance** of the physics list to the **G4 (MT) RunManager**

```cpp
#include "QGSP_BERT.hh"
int main()
{
    // Run manager
    G4RunManager * runManager = new G4RunManager();

    ...

    G4VUserPhysicsList* physics = new QGSP_BERT();
    runManager->SetUserInitialization(physics);
}
```
Where are the constructors?
Where are the physics lists?

```cpp
// EM Physics
this->RegisterPhysics( new G4EmStandardPhysics(ver) );

// Synchrotron Radiation & GN Physics
this->RegisterPhysics( new G4EmExtraPhysics(ver) );

// Decays
this->RegisterPhysics( new G4DecayPhysics(ver) );

// Hadron Elastic scattering
this->RegisterPhysics( new G4HadronElasticPhysics(ver) );

// Hadron Physics
this->RegisterPhysics( new G4HadronPhysicsQGSP_BERT(ver) );

// Stopping Physics
this->RegisterPhysics( new G4StoppingPhysics(ver) );

// Ion Physics
this->RegisterPhysics( new G4IonPhysics(ver) );

// Neutron tracking cut
this->RegisterPhysics( new G4NeutronTrackingCut(ver) );
```
Reference Physics Lists

A web page recommending physics lists according to the use case is under construction. The previous version of physics list web pages referring to are still available.

String model based physics lists

These Physics lists apply a string model for the modeling of interactions of high energy hadrons, i.e., for protons, neutrons, pions and kaons above ~5~50 GeV depending on the exact physics list. Interactions at lower energies are handled by one of the intranuclear cascade models or the precompound model. Nuclear capture of negative particles and neutrons at rest is handled using either the Chiral Invariant Phase Space (CHIPs) model or the Bertini intranuclear cascade. Hadronic inelastic interactions use:

- a tabulation of the Barashenkov pion cross sections
- the Axen-Wellisch parameterization of the proton and neutron cross sections

The physics lists are:
Where to find information?

User Support

1. Getting started
2. Training courses and materials
3. Source code
   a. Download page
   b. LXR code browser -or- draft doxygen documentation
4. Frequently Asked Questions (FAQ)
5. Bug reports and fixes
6. User requirements tracker
7. User Forum
8. Documentation
   a. Introduction to Geant4
   b. Installation Guide
   c. Application Developers Guide
   d. Toolkit Developers Guide
   e. Physics Reference Manual
9. Physics lists
   a. Electromagnetic
   b. Hadronic
Electromagnetic physics
EM concept

The same physics processes (e.g. Compton scattering) can be described by different models, that can be alternative or complementary in a given energy range.

For instance: Compton scattering can be described by

- G4KleinNishinaCompton
- G4LivermoreComptonModel (specialized low-energy, based on the Livermore database)
- G4PenelopeComptonModel (specialized low-energy, based on the Penelope analytical model)
- G4LivermorePolarizedComptonModel (specialized low-energy, Livermore database with polarization)
- G4PolarizedComptonModel (Klein-Nishina with polarization)
- G4LowEPComptonModel (full relativistic 3D simulation)

Different models can be combined, so that the appropriate one is used in each given energy range (➔ performance optimization)
A physical interaction or process is described by a process class

- Naming scheme: « G4ProcessName »
- Eg. : « G4Compton » for photon Compton scattering

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

- The usual naming scheme is: « G4ModelNameProcessNameModel »
- Eg. : « G4LivermoreComptonModel » for the Livermore Compton model
- Models can be alternative and/or complementary on certain energy ranges
Packages overview

Models and processes for the description of the EM interactions in Geant4 have been grouped in several packages

<table>
<thead>
<tr>
<th>Package</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>$\gamma$-rays, e$^\pm$ up to 100 TeV, Hadrons, ions up to 100 TeV</td>
</tr>
<tr>
<td>Muons</td>
<td>Muons up to 1 PeV</td>
</tr>
<tr>
<td>X-rays</td>
<td>X-rays and optical photon production</td>
</tr>
<tr>
<td>Optical</td>
<td>Optical photons interactions</td>
</tr>
<tr>
<td>High-Energy</td>
<td>Processes at high energy (&gt; 10 GeV). Physics for exotic particles</td>
</tr>
<tr>
<td>Low-Energy</td>
<td>Specialized processes for low-energy (down to 250 eV), including atomic effects</td>
</tr>
<tr>
<td>Polarization</td>
<td>Simulation of polarized beams</td>
</tr>
</tbody>
</table>
EM processes for $\gamma$-rays, $e^{\pm}$

<table>
<thead>
<tr>
<th>Particle</th>
<th>Process</th>
<th>G4Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>Gamma Conversion in $e^{\pm}$</td>
<td>G4GammaConversion</td>
</tr>
<tr>
<td></td>
<td>Compton scattering</td>
<td>G4ComptonScattering</td>
</tr>
<tr>
<td></td>
<td>Photoelectric effect</td>
<td>G4PhotoElectricEffect</td>
</tr>
<tr>
<td></td>
<td>Rayleigh scattering</td>
<td>G4RayleighScattering</td>
</tr>
<tr>
<td>$e^{\pm}$</td>
<td>Ionisation</td>
<td>G4eIonisation</td>
</tr>
<tr>
<td></td>
<td>Bremsstrahlung</td>
<td>G4eBremsstrahlung</td>
</tr>
<tr>
<td></td>
<td>Multiple scattering</td>
<td>G4eMultipleScattering</td>
</tr>
<tr>
<td>$e^+$</td>
<td>Annihilation</td>
<td>G4eplusAnnihilation</td>
</tr>
</tbody>
</table>
EM processes muons

<table>
<thead>
<tr>
<th>Particle</th>
<th>Process</th>
<th>G4Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>Ionisation</td>
<td>G4MuIonisation</td>
</tr>
<tr>
<td></td>
<td>Bremsstrahlung</td>
<td>G4MuBremsstrahlung</td>
</tr>
<tr>
<td></td>
<td>Multiple scattering</td>
<td>G4MuMultipleScattering</td>
</tr>
<tr>
<td></td>
<td>$e^\pm$ pair production</td>
<td>G4MuPairProduction</td>
</tr>
</tbody>
</table>

Only one model available for these processes (but in principle users may write their own models, if needed)
Standard models

• Complete set of models for $e^\pm, \gamma, \text{ions, hadrons, } \mu^\pm$
• Tailored to requirements from HEP applications
  – "Cheaper" in terms of CPU
  – Include high-energy corrections (e.g. LPM), assumptions made in the low-energy regime
• Theoretical or phenomenological models
  – Bethe-Bloch, corrected Klein-Nishina, ...  
  – Photoabsorption Ionization (PAI)
    • ionization energy loss of a relativistic charged particle in matter
• Specific high-energy extensions available
  – Extra processes, as $\gamma \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \mu^+\mu^-$
• Dedicated sub-library for optical photons
  – Produced by scintillation or Cherenkov effect
Livermore (& polarized) models

- Based on publicly available evaluated data tables from the Livermore data library: $e^{-}$, $\gamma$
  - Mixture of experiments and theories
  - In principle, tables go down to $\sim 10$ eV
- Applications: medical, underground and rare events, space
- Polarized models
  - Same calculation of the cross section, different way to produce the final state
  - Describe in detail the kinematics of polarized photon interactions
  - Application: space missions for the detection of polarized photons
Penelope models

- Geant4 includes the low-energy models for electrons, positrons and photons from the *Monte Carlo code PENEOLOPE* (PENetration and Energy LOss of Positrons and Electrons)
  - Geant4 implements v2008 of Penelope

- Physics models specifically developed by the group of F. Salvat et al.
  - Great care dedicated to the low-energy description
  - Atomic effects, fluorescence, Doppler broadening...

- Mixed approach: analytical, parameterized and database-driven
  - Applicability energy range: 100 eV – 1 GeV

- Include *positrons*
  - Not described by Livermore models
When/why to use Low Energy Models

• **Use** Low-Energy models (Livermore or Penelope), as an alternative to Standard models, when you:
  
  – need precise treatment of EM showers and interactions at low-energy (keV scale)
  – are interested in atomic effects, as fluorescence x-rays, Doppler broadening, etc.
  – can afford a more CPU-intensive simulation
  – want to cross-check an other simulation (e.g. with a different model)

• **Do not use** when you are interested in EM physics > MeV
  
  – same results as Standard EM models, performance penalty
Example: PhysicsList for $\gamma$-rays

G4ProcessManager* pmanager =
    G4Gamma::GetProcessManager();
pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
pmanager->AddDiscreteProcess(new G4ComptonScattering);
pmanager->AddDiscreteProcess(new G4GammaConversion);
pmanager->AddDiscreteProcess(new G4RayleighScattering);

• Use AddDiscreteProcess because $\gamma$-rays processes have only PostStep actions
EM Physics Constructors for Geant4
10.1 - ready-for-the-use

G4EmStandardPhysics – default
G4EmStandardPhysics_option1 – HEP fast but not precise
G4EmStandardPhysics_option2 – Experimental
G4EmStandardPhysics_option3 – medical, space
G4EmStandardPhysics_option4 – optimal mixture for precision
G4EmLivermorePhysics
G4EmLivermorePolarizedPhysics
G4EmPenelopePhysics
G4EmLowEPPhysics
G4EmDNAPhysics

- Combined Physics
  - Standard > 1 GeV
  - LowEnergy < 1 GeV

- G4INSTALL/source/physics_list/constuctors
- Advantage of using these classes – they are tested on regular basis and are used for regular validation
How to extract Physics?

Possible to retrieve physics quantities via G4EmCalculator or directly from the physics models

- Physics List should be initialized

Example for retrieving the total cross section (cm\(^{-1}\)) of a process with name \textit{procName}: for particle \textit{partName} and material \textit{matName}

```cpp
G4EmCalculator emCalculator;
G4Material* material =
    G4NistManager::Instance()->FindOrBuildMaterial("matName");
G4double massSigma =
    emCalculator.ComputeCrossSectionPerVolume(
        energy, particle, procName, material);
G4cout << G4BestUnit(massSigma, "Surface/Volume") << G4endl;
```

A good example: \$G4INSTALL/examples/extended/electromagnetic/TestEm14\$
Hadronic physics
Hadronic Physics

- Data-driven models
- Parametrised models
- Theory-driven models
Hadronic physics challenge

Three energy regimes

– < 100 MeV
– 100 MeV - 10 GeV, resonance and cascade region
– > 20 GeV (QCD strings)

Within each regime there are several models
Many of these are phenomenological
Reference physics lists for Hadronic interactions

Three families of builders

- **QGS**, or list based on a model that use the Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions and kaons
- **FTF**, based on the FTF (FRITIOF like string model) for protons, neutrons, pions and kaons
- **Other** specialized physics lists
Hadronic processes

- **At rest**
  - Stopped muon, pion, kaon, anti-proton
  - Radioactive decay
  - Particle decay (decay-in-flight is PostStep)

- **Elastic**
  - **Same process** to handle all long-lived hadrons (multiple models available)

- **Inelastic**
  - **Different processes** for each hadron (possibly with multiple models vs. energy)
    - Photo-nuclear, electro-nuclear, mu-nuclear

- **Capture**
  - Pion- and kaon- in flight, neutron

- **Fission**
Cross sections

Default cross section sets are provided for each type of hadronic process:
- Fission, capture, elastic, inelastic

- Low energy neutrons
  - elastic, inelastic, fission and capture (< 20 MeV)
- Neutron and proton inelastic cross sections
  - 20 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections (several models)
  - Good for E/A < 1 GeV
- Isotope production data
  - E < 100 MeV
- Photo-nuclear cross sections
Neutron HP Models

• Transport of **low-energy neutrons** in matter:
  – The energy coverage of these models is from thermal energies to 20 MeV
  – The modeling is based on the data formats of ENDF/B-VI, and all distributions of this standard data format are implemented
  – Includes cross sections and final state information for elastic and inelastic scattering, capture, fission and isotope production
  – The file system is used in order to allow granular access to, and flexibility in, the use of the cross-sections for different isotopes, and channels
  – Code in sub-directory: `/source/processes/hadronic/models/neutron_hp`
Hadronic models match – inelastic interactions

Old picture: LEP models dismissed meanwhile: BERT interfaced directly to QGS/Preco at 9.9 GeV
G4ParticleDefinition* neutron = G4Neutron::NeutronDefinition();
G4ProcessManager* protonProcessManager = proton->GetProcessManager();

// Elastic scattering
G4NeutronHPElastic* neutronElasticModel = new G4NeutronHPElastic();
neutronElasticModel->SetMaxEnergy(20.*MeV);
neutronElasticProcess->RegisterMe(neutronElasticModel);
neutronProcessManager->AddDiscreteProcess(neutronElasticProcess);
Quick overview of validation
EM validation - 1

- Tens of papers and studies available
  - Geant4 Collaboration + User Community
- Results can depend on the specific observable/reference
- Data selection and assessment critical
EM validation – 2

- In general **satisfactory agreement**
- Validation/verification **repository** available on web

http://cern.ch/vnivanch/verification/verification/electromagnetic/

![Graphs showing photon energy vs. intensity for Penelope, Option3, Livermore, and simulations with G4standard.](http://example.com/graphs.png)
EM validation - 3

e- showers, longitudinal profiles

$E_{\text{dep}}$ (MeV$g/cm^2$) vs. depth ($R/R_0$)

- Data
- Opt0
- GS-msc
- WVI-SS
- Opt3
- Single Scat

$^{12}$C ions 62 MeV/n
Hadronic validation

- A website is available to collect relevant information for validation of Geant4 hadronic models (plots, tables, references to data and to models, etc.)
  - [http://geant4.cern.ch/results/validation_plots.htm](http://geant4.cern.ch/results/validation_plots.htm)

- Several physics lists and several use-cases have been considered (e.g. thick target, stopped particles, low-energy)
- Includes final states and cross sections
Some verification: channel cross section

![Graph showing cross sections for different reactions.]
Some verification: secondary energy spectrum
Nuclear fragmentation

Bertini and Binary cascade models: neutron production vs. angle from 1.5 GeV protons on Lead
Neutron production by protons

Binary cascade model: double differential cross-section for neutrons produced by 256 MeV protons impinging on different targets