Electromagnetic and Hadronic physics in Geant4

IX Seminar on software for Nuclear, Subnuclear and Applied physics,
May 28 - June 2, 2012 - Porto Conte, Italy

Outline

- The philosophy of the physics definition
- How to define and activate models
- Electromagnetic physics
- Hadronic physics
- Ongoing models for radiobiology

Philosophy

- Provide a **general model framework** that allows implementation of processes and models

- Separate models and cross sections implement processes

  - **MULTIPLE MODELS FOR THE SAME PROCESS**

- Provide processes containing

  - Many possible models and cross sections

  - Default cross sections for each model

Models under continuous development

G4VUserPhysicsList

- All physics lists must derive from this class
  - and then registered with the Run Manager

- Example

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

- User must implement the following methods:
  - ConstructParticle(), ConstructProces(), SetCuts()

ConstructParticle()

- Choose the particles you need in your simulation and define all of them here
  - G4Electron::ElectronDefinition()
  - .....

- Geant4 has classes that create groups of particles
  - G4BosonConstructor()
  - G4LeptonConstructor()
  - .....

ConstructProcess()

```
void MyPhysicsList::ConstructProcess()
 {
// provided by G4VUserPhysicsList, assign
transportation process to all particles defined in
ConstructParticle();
AddTransportation();
ConstructEM()  //Optional
ConstructGeneral() // Optional
.....
```

SetCuts()

- Define all production cuts for gamma, electrons and positrons
- Recently also for protons

Physics definition

- **Three different way to implement the physics models**

  - Explicitly associating a given model to a given particle for (eventually) a given energy range

    ✓ Error prone

    ✓ At code level

  - Use of BUILDER and REFERENCE PHYSICS LISTS

    ✓ **THE BUILDER** are process related (standard, lowenergy, Bertini, etc.)

      - Defined in the physics lists class

    ✓ **THE REF PHYSICS LISTS** are complete physics lists

      - Can be also called by the macro file

Reference physics lists

- Provide a complete and realistic physics with ALL models of interest

- Provided according to some Use-cases

- Few choices are available for EM physics

- Several possibilities for hadronic

- They are intended as starting point and their builder can be reused

Reference physics lists

- **electromagnetic interactions** for all particles. Different settings are offered
  - Default transport parameters (best performance)
  - Some optimised choice (_EMV extension)
  - Some high precision choice (_EMY extension)
- **Inelastic** interactions
- **Elastic scattering**
- **Capture**
- **Decay** of unstable particles
- Specialised treatment of **low energy neutrons** (< 20 MeV)

Case I - Builders

```
if (name == "standard_opt3") {
    emName = name;
    delete emPhysicsList;
    emPhysicsList = new
G4EmStandardPhysics_option3();

  } else if (name == "LowE_Livermore") {
    emName = name;
    delete emPhysicsList;
    emPhysicsList = new G4EmLivermorePhysics();

  } else if (name == "LowE_Penelope") {
    emName = name;
    delete emPhysicsList;
    emPhysicsList = new G4EmPenelopePhysics();
```

Builders
$G4INSTALL/source/
physics_lists/builders

Case II - Reference Physics Lists

Reference Physics Lists
$G4INSTALL/source/
physics_lists/lists

In your main

```
include <QGSP_BERT.hh>

int main(int,char**)
{
//....
    runManager->SetUserInitialization( new QGSP_BERT );
}

OR

#include <G4PhysListFactory.hh>
int main(int,char**)
{
//....
 G4PhysListFactory factory;
 G4VModularPhysicsList* physList = factory.ReferencePhysList();
 runManager->SetUserInitialization( physList );
}
```

EM concepts I

- 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)

- Different models can be combined, so that the appropriate one is used in each given energy range (␣ performance optimization)

EM concepts II

- 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
  - Refer to the Geant4 manual for the full list of available models

EM physics models

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

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

EM processes for gamma and e+/-

Particle	Process	G4Process
Photons	Gamma Conversion in $e^{\pm}$	`G4GammaConversion`
	Compton scattering	`G4ComptonScattering`
	Photoelectric effect	`G4PhotoElectricEffect`
	Rayleigh scattering	`G4RayleighScattering`
$e^{\pm}$	Ionisation	`G4eIonisation`
	Bremsstrahlung	`G4eBremsstrahlung`
	Multiple scattering	`G4eMultipleScattering`
e^{+}	Annihilation	`G4eplusAnnihilation`

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 at the MeV region
  - same results as Standard EM models, performance penalty

Example: physics list for gamma

```
G4ProcessManager* pmanager
if ( particleName == "gamma"   )
{
   pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
   pmanager->AddDiscreteProcess(new G4ComptonScattering);
   pmanager->AddDiscreteProcess(new G4GammaConversion);
   pmanager->AddDiscreteProcess(new G4RayleighScattering);
 }
```

- For each process a default model is used among all the available ones:
  e.g. the **G4KleinNishinaCompton** for the **G4ComptonStcattering**)

- This default can be changed (e.g. **G4PenelopeComptonModel**)

Ready-to-use Physics Builders

G4EmStandardPhysics – default
G4EmStandardPhysics_option1 – HEP fast but not precise
G4EmStandardPhysics_option2 – Experimental
G4EmStandardPhysics_option3 – medical, space

G4EmLivermorePhysics
G4EmLivermorePolarizedPhysics
G4EmPenelopePhysics
G4EmDNAPhysics

Combined Physics
Standard > 1 GeV
LowEnergy < 1 GeV

- **`$G4INSTALL/source/physics_list/builders`**
- Advantage of using of these classes – they are tested on regular basis and are used for regular validation

How to extract physics

- Possible to retrieve physics quantities via the G4EmCalculator class file

- Example for retrieving total cross section of a process with name procName, for particle partName and for the material matName

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

See $G4INSTALL/examples/extended/electromagnetic/TestEm14

Hadronic Physics

- Data-driven models
- Parametrisation models
- Theory driven models

Hadronic physics challenge

- Three energy regimes
  - < 100 MeV
  - resonance and cascade region (100 MeV - 10 GeV)
  - > 20 GeV (QCD strings)
- Within each regime there are several models
- Many of these are phenomenological

Reference physics lists for Hadronic interaction

- Are part of the Geant4 code
- Four family of lists
  - LHEP or parameterised modelling of hadronic interactions
  - 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 specialised physics lists

The complete lists of Reference Physics List

...../source/physics_lists/lists

```
-rw-r--r--  1 cirrone  staff   4102 16 Aug 09:14 QGSP_BERT_EMV.icc
-rw-r--r--  1 cirrone  staff   2564 11 May  2009 QGSP_BERT_EMX.hh
-rw-r--r--  1 cirrone  staff   4232 16 Aug 09:14 QGSP_BERT_EMX.icc
-rw-r--r--  1 cirrone  staff   2542 31 Oct  2006 QGSP_BERT_HP.hh
-rw-r--r--  1 cirrone  staff   4322 16 Aug 09:14 QGSP_BERT_HP.icc
-rw-r--r--  1 cirrone  staff   2586 17 Oct  2008 QGSP_BERT_NOLEP.hh
-rw-r--r--  1 cirrone  staff   4224 16 Aug 09:14 QGSP_BERT_NOLEP.icc
-rw-r--r--  1 cirrone  staff   2580 26 Apr  2007 QGSP_BERT_NQE.hh
-rw-r--r--  1 cirrone  staff   4240 16 Aug 09:14 QGSP_BERT_NQE.icc
-rw-r--r--  1 cirrone  staff   2557  7 May  2007 QGSP_BERT_TRV.hh
-rw-r--r--  1 cirrone  staff   4236 16 Aug 09:14 QGSP_BERT_TRV.icc
-rw-r--r--  1 cirrone  staff   2496 31 Oct  2006 QGSP_BIC.hh
-rw-r--r--  1 cirrone  staff   4578 16 Aug 09:14 QGSP_BIC.icc
-rw-r--r--  1 cirrone  staff   2552 11 May  2009 QGSP_BIC_EMY.hh
-rw-r--r--  1 cirrone  staff   4176 16 Aug 09:14 QGSP_BIC_EMY.icc
-rw-r--r--  1 cirrone  staff   2550 24 Nov  2006 QGSP_BIC_HP.hh
-rw-r--r--  1 cirrone  staff   4140 16 Aug 09:14 QGSP_BIC_HP.icc
-rw-r--r--  1 cirrone  staff   2563 13 Nov  2007 QGSP_DIF.hh
-rw-r--r--  1 cirrone  staff   4317 16 Aug 09:14 QGSP_DIF.icc
-rw-r--r--  1 cirrone  staff   2502 31 Oct  2006 QGSP_EMV.hh
-rw-r--r--  1 cirrone  staff   4822 16 Aug 09:14 QGSP_EMV.icc
-rw-r--r--  1 cirrone  staff   2541 26 Apr  2007 QGSP_EMV_NQE.hh
-rw-r--r--  1 cirrone  staff   4260 16 Aug 09:14 QGSP_EMV_NQE.icc
-rw-r--r--  1 cirrone  staff   2582 23 Apr  2009 QGSP_FTFP_BERT.hh
-rw-r--r--  1 cirrone  staff   4174 16 Aug 09:14 QGSP_FTFP_BERT.icc
-rw-r--r--  1 cirrone  staff   3499 19 Jul  2009 QGSP_INCL_ABLA.hh
-rw-r--r--  1 cirrone  staff   4262 16 Aug 09:14 QGSP_INCL_ABLA.icc
-rw-r--r--  1 cirrone  staff   2528 26 Apr  2007 QGSP_NQE.hh
-rw-r--r--  1 cirrone  staff   4234 16 Aug 09:14 QGSP_NQE.icc
-rw-r--r--  1 cirrone  staff   2523 28 Nov  2006 QGSP_QEL.hh
-rw-r--r--  1 cirrone  staff   4413 16 Aug 09:14 QGSP_QEL.icc
-rw-r--r--  1 cirrone  staff   2507 13 Nov  2007 QGS_BIC.hh
-rw-r--r--  1 cirrone  staff   4188 16 Aug 09:14 QGS_BIC.icc
-rw-r--r--  1 cirrone  staff   2521  8 Jun 18:05 Shielding.hh
-rw-r--r--  1 cirrone  staff   4113 16 Aug 09:14 Shielding.icc
-rw-r--r--  1 cirrone  staff   3710 31 Oct  2006 SpecialCuts.hh
lists Lavora! >
```

Cross sections

- **Default Cross sections but also specific databases:**
  - Low energy neutrons
    - ✓ G4NDL available as external data files
    - ✓ Available with or without thermal cross section
  - Neutron and proton reaction cross section
    - ✓ 20 MeV < E < 20 GeV
  - Ion-nucleus reaction cross sections
    - ✓ E/A < 1 GeV
  - Isotope production data

Thermal neutron scattering

- At thermal neutron energies, atomic translational motion as well as vibration and rotation of the chemically bound atoms affect the neutron scattering cross section and the energy and angular distribution of secondary neutrons.
- The energy loss or gain of incident neutrons can be different from interactions with nuclei in unbound atoms.
- Only individual Maxwellian motion of the target nucleus (Free Gas Model) was taken into account in the default NeutronHP models.

G4NDL (G4 Neutron Data Library)

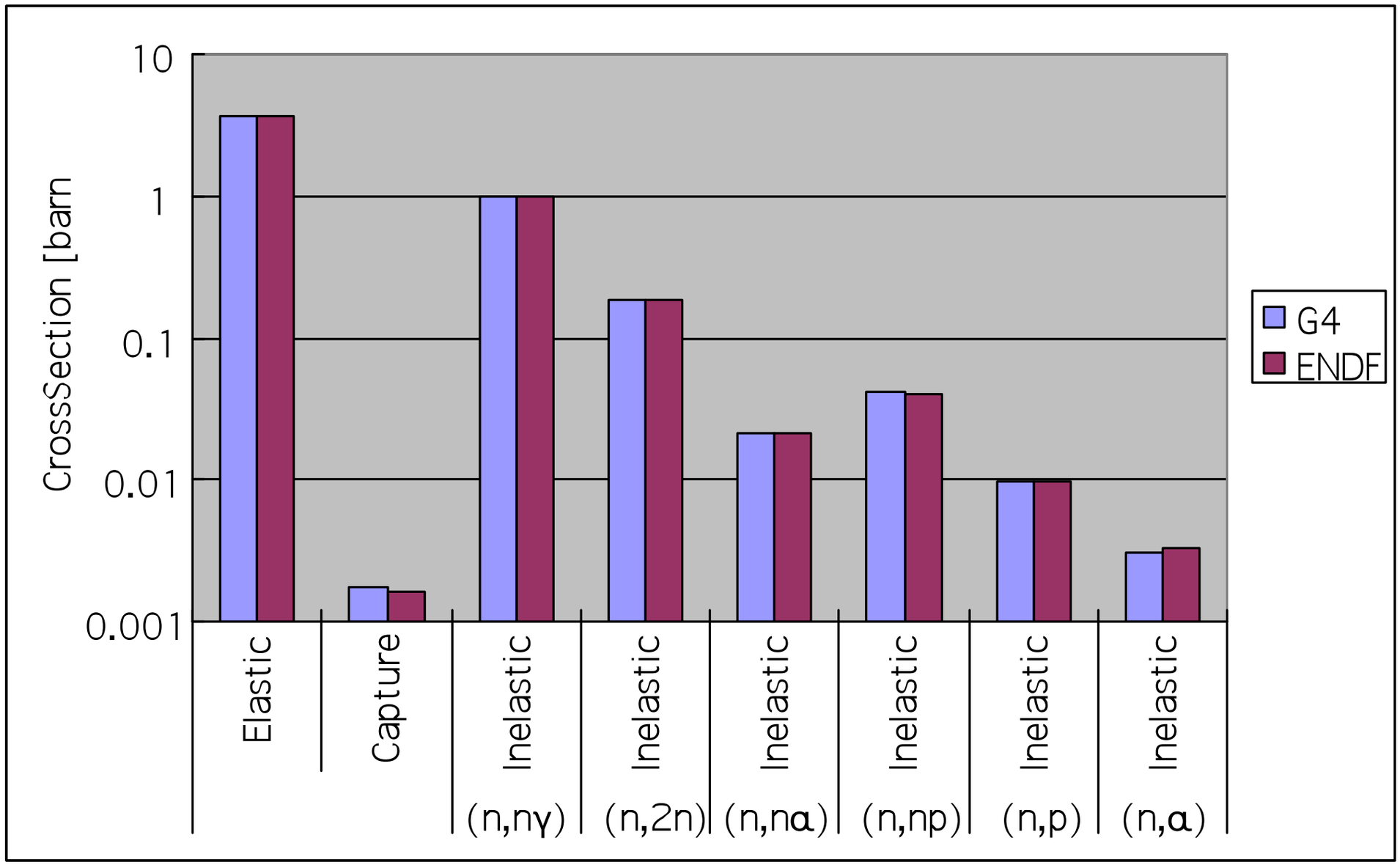
- **Neutron data files for High precision models**
- These data include both cross sections and final states
- These data derived by the following evaluated data libraries
  - Brond-2.1
  - CENDL2.2
  - EFF-3
  - ENDF/B
  - FENDL/E
  - JEF2.2
  - JENDL-FF
  - MENDL

Physics lists for NeutronHPThermalScattering

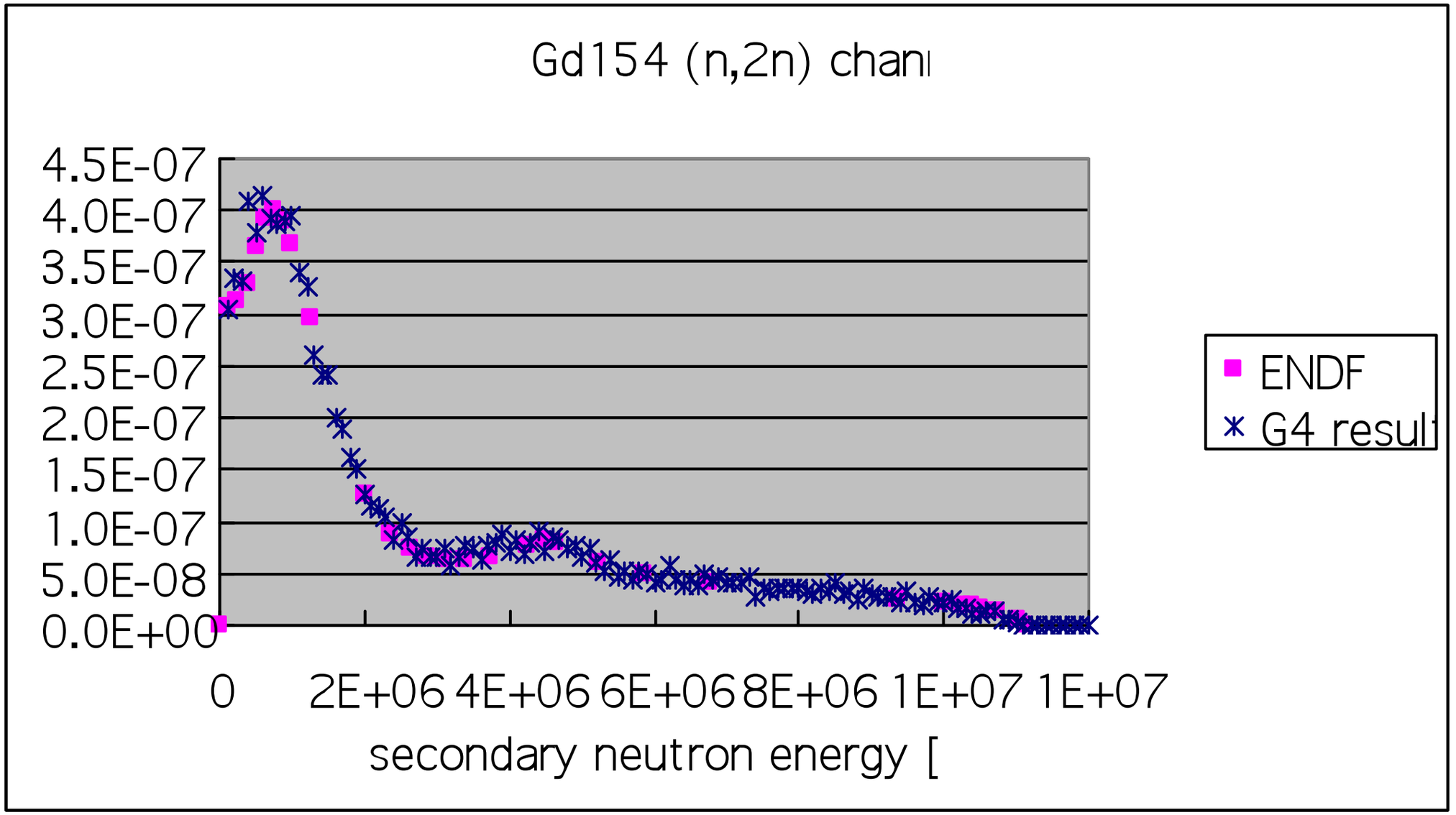
```
// The process
G4HadronElasticProcess*    theNeutronElasticProcess   = new G4HadronElasticProcess();

// Cross Section Data set
G4NeutronHPElasticData* theHPElasticData = new G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theHPElasticData );
G4NeutronHPThermalScatteringData* theHPThermalScatteringData = new G4NeutronHPThermalScatteringData();
theNeutronElasticProcess->AddDataSet( theHPThermalScatteringData );

// The model
G4NeutronHPElastic* theNeutronElasticModel = new G4NeutronHPElastic();
theNeutronElasticModel->SetMinEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel);
G4NeutronHPThermalScattering* theNeutronThermalElasticModel = new
```

```
G4NeutronHPThermalScattering();
theNeutronThermalElasticModel->SetMaxEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronThermalElasticModel);

// Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4Neutron::Neutron()-> GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

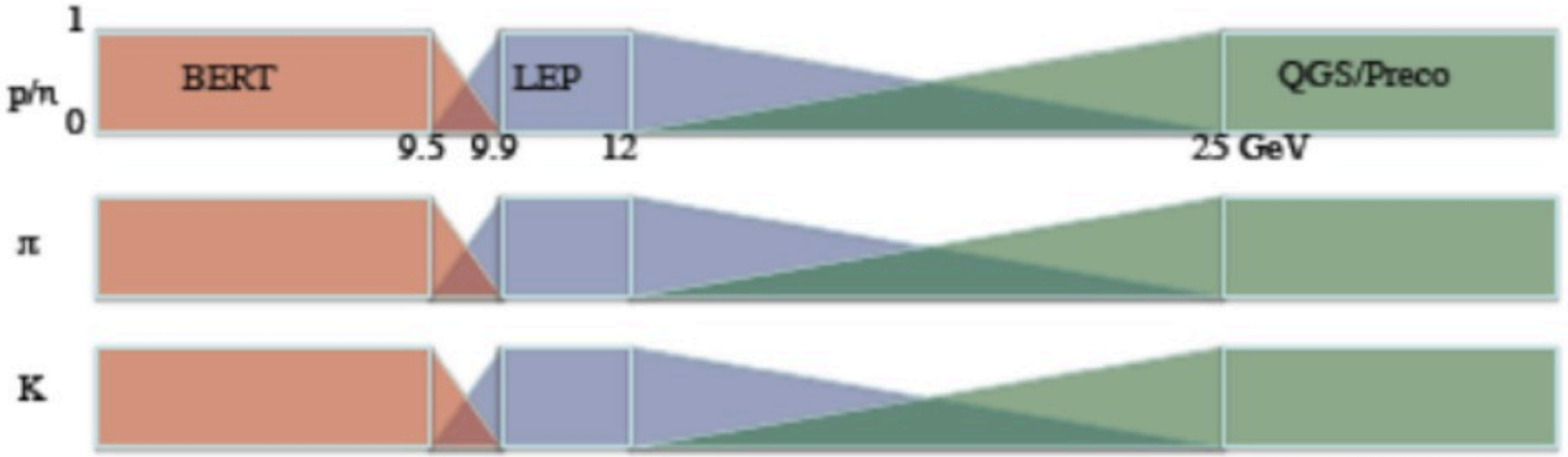
Some verification: channel cross section



Some verification: secondary energy spectrum



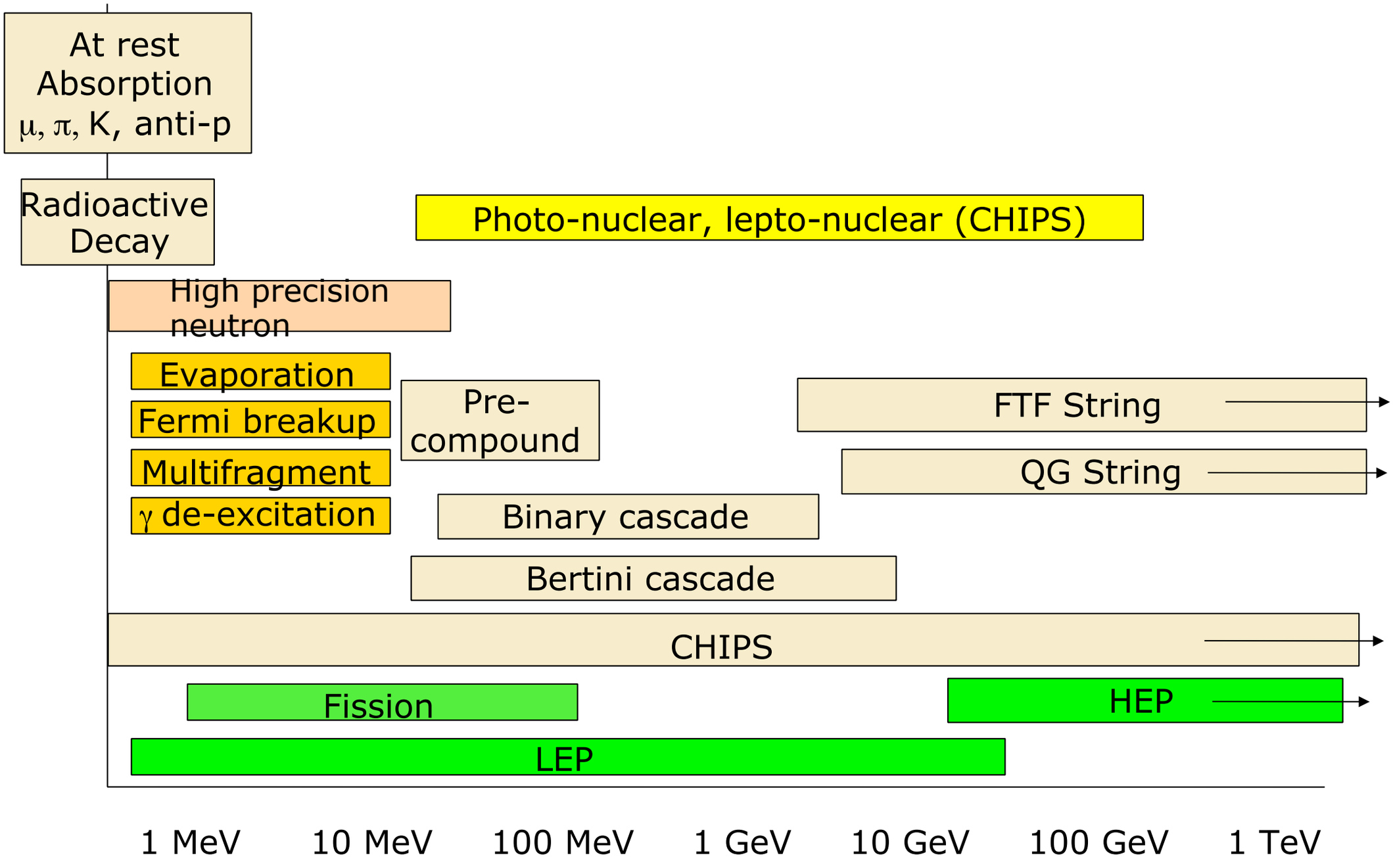
Hadronic models match



Recommended reference physics lists

- A dedicated web page
- Application fields are identified
  - High energy physics
  - LHC neutron fluxes
  - Shielding
  - Medical
  - .....

Hadronic process/Model Inventory



Where to find information?

- Process/model catalog

  - Home/User Support --> Geant4 web site

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
    f. Software Reference Manual
9. Physics lists
    a. Electromagnetic
    b. Hadronic