Version 11.2.1

Geant4 Tutorial Course

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Hadronic Physics I

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Introduction

- Geant4 particles and hadronic processes
- Hadronic physics: cross sections and final state models
- Hadronic physics framework
- Nuclear Capture at rest
- Neutron physics
- Datasets
- Hadronic physics in reference physics lists and extensible factory

… to be followed by Hadronic Physics II at this course

Geant4 particles

In `Geant4` several `G4ParticleDefinitions` exist, i.e. “stable” particles described by their properties (mass, charge, …)

- Leptons: $e^{\pm}$ (`G4Electron`, `G4Positron`), $\mu^{\pm}$ (`G4MuonMinus`, `G4MuonPlus`), …
- Bosons: γ (`G4Gamma`), `G4OpticalPhoton`
- `G4Geantino`, i.e. a particle with no processes except transportation
- “Stable” hadrons: $\pi^{\pm}$ (`G4PionPlus`, `G4PionMinus`), p (`G4Proton`), n (`G4Neutron`), …
- Light ions: deuterium (`G4Deuteron`), tritium (`G4Triton`), …
- Hyper and anti-hyper nuclei, i.e. nuclei with at least one hyperon (baryons with strange quark content): `G4HyperTritium`, `G4HyperAlpha`, …
- Other ions: `G4GenericIon` describes all other ions

Geant4 particles

UI Commands:

```
/particle/select pi+
/particle/property/dump
```

```
/particle/select proton
/particle/property/dump
```

```
--- G4ParticleDefinition ---
 Particle Name : pi+
 PDG particle code : 211 [PDG anti-particle code: -211]
 Mass [GeV/c2] : 0.13957     Width : 2.5284e-17
 Lifetime [nsec] : 26.033
 Charge [e]: 1
 Spin : 0/2
 Parity : -1
 Charge conjugation : 0
 Isospin : (I,Iz): (2/2 , 2/2 )
 GParity : -1
 Quark contents     (d,u,s,c,b,t) : 0, 1, 0, 0, 0, 0
 AntiQuark contents               : 1, 0, 0, 0, 0, 0
 Lepton number : 0 Baryon number : 0
 Particle type : meson [pi]
G4DecayTable:  pi+
0:  BR:  1  [Phase Space]   :   mu+ nu_mu
```

```
--- G4ParticleDefinition ---
 Particle Name : proton
 PDG particle code : 2212 [PDG anti-particle code: -2212]
 Mass [GeV/c2] : 0.938272     Width : 0
 Lifetime [nsec] : -1
 Charge [e]: 1
 Spin : 1/2
 Parity : 1
 Charge conjugation : 0
 Isospin : (I,Iz): (1/2 , 1/2 )
 GParity : 0
 MagneticMoment [MeV/T] : 8.80432e-14
 Quark contents     (d,u,s,c,b,t) : 1, 2, 0, 0, 0, 0
 AntiQuark contents               : 0, 0, 0, 0, 0, 0
 Lepton number : 0 Baryon number : 1
 Particle type : baryon [nucleon]
 Atomic Number : 1  Atomic Mass : 1
 Stable : stable
```

Geant4 particles and hadronic processes

Hadrons are particles interacting with nuclei via the strong interaction.
They play a crucial role in several physics simulation domains as collider physics (e.g. hadronic jets), nuclear physics (e.g. neutron shielding) and atmospheric physics (e.g. cosmic-ray showers).

- In Geant4 with hadronic physics we refer (with few exceptions) to the processes:

hadron + nucleus → X

```
/particle/select proton
/particle/process/verbose 0
/particle/process/dump
```

```
[0]=== process[Transportation :Transportation] Active
[1]=== process[msc :Electromagnetic] Active
[2]=== process[hIoni :Electromagnetic] Active
[3]=== process[hBrems :Electromagnetic] Active
[4]=== process[hPairProd :Electromagnetic] Active
[5]=== process[CoulombScat :Electromagnetic] Active
[6]=== process[hadElastic :Hadronic] Active
[7]=== process[protonInelastic :Hadronic] Active
[8]=== process[StepLimiter :General] Active
[9]=== process[UserSpecialCut :General] Active
```

Hadronic interactions

The most accurate theoretical description of hadronic interactions comes from QCD.

Good example, equation of cross section calculation for proton-proton interaction at the LHC:

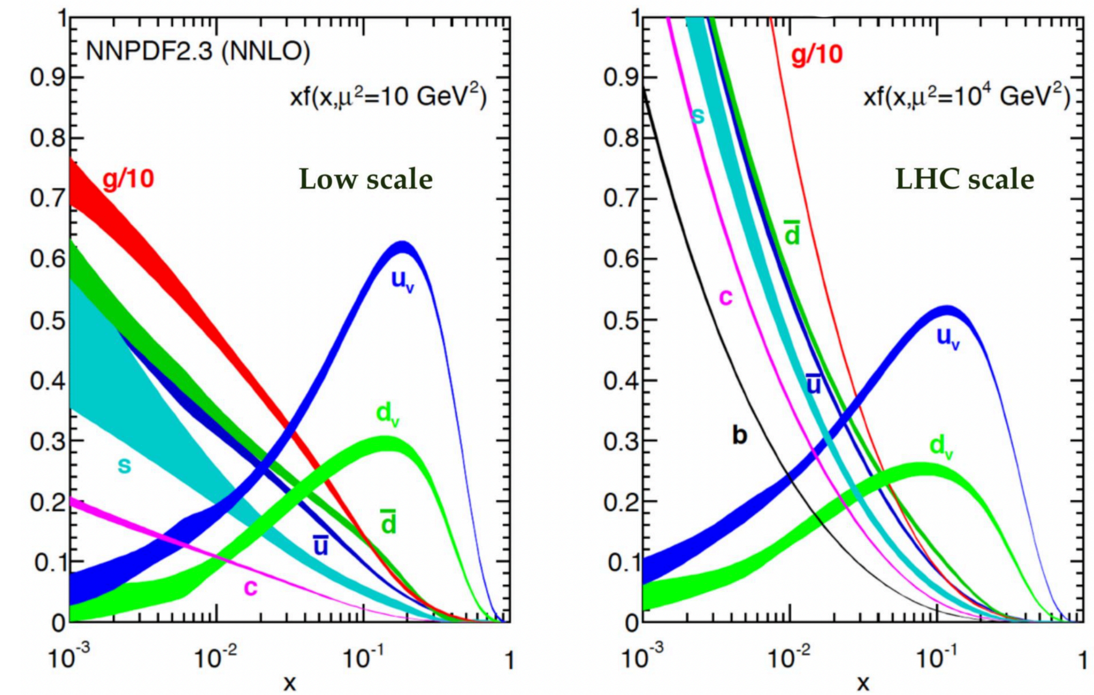
$\hat{\sigma}_{ab \to X}(x_1 x_2 s, Q^2)$:
cross section for partons process (QCD)

$$\sigma_X(s, Q^2) = \sum_{a,b} \int_{x_{min}}^{1} dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{ab \to X}(x_1 x_2 s, Q^2)$$

$f_a(x, Q^2)$:
number of a-type partons with momentum fraction x

$f_b(x, Q^2)$:
number of b-type partons with momentum fraction x

Example of Parton Distribution Functions at different transfer momentum



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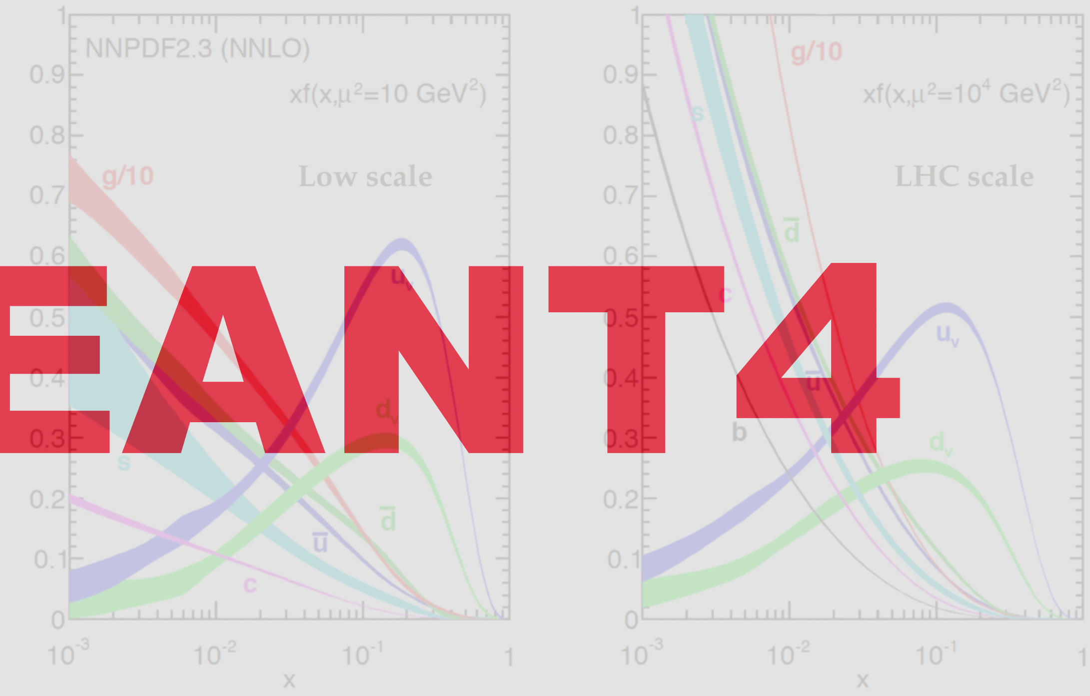
$f_a(x, Q^2)$: number of a-type partons with momentum fraction x

$f_b(x, Q^2)$: number of b-type partons with momentum fraction x

NOT IN GEANT4

Example of Parton Distribution Functions at different transfer momentum



Hadronic interactions

- QCD is only applicable through perturbative calculations of hard-scattering with high transverse momentum
- Equivalently, nucleons parton distribution functions are only valid for high transverse momentum interactions
- Therefore, `Geant4` relies on approximate hadronic models with limited ranges of applicability depending on the particle type, energy and target material

Geant4, in first approximation:

1. Calculates the probability of a hadronic-nucleus interaction using hadronic cross section datasets

2. Determines the properties of the secondaries using hadronic final states models

Hadronic Cross Sections Datasets

- **Hadronic cross section datasets** refer to the total cross section for a hadronic-nucleus interaction (`G4HadronicProcess::GetElementCrossSection()`)
  - Related to the length that a hadron projectile flies in a material before interacting
- In Geant4 there are only 2 types of hadronic cross sections (neutrons are an exception):
  - The elastic cross section describing the process for which the projectile and the target nucleus survive and no additional particles are created
  - The inelastic cross section describing the process for which any other final state is created
  - The hadron elastic process competes with the hadron inelastic one (as with any other process, e.g. ionization, bremsstrahlung, transportation, …)

NOTE: there are no differential cross sections in Geant4 for hadronic interactions. To get the differential cross section for secondaries in a given phase space one has to multiply the total cross section by the fraction of events corresponding to that final state

Hadronic Cross Sections Datasets

`RunAction.cc` - Example: get hadronic inelastic total cross section:

```
#include "G4UnitsTable.hh"
#include "G4Element.hh"
#include "G4Material.hh"
#include "G4NistManager.hh"
#include "G4HadronicProcessStore.hh"

void RunAction::EndOfRunAction(const G4Run * /*run*/) {
  if (isMaster) {
    G4HadronicProcessStore *hadstore = G4HadronicProcessStore::Instance();
    G4Material *matPb = G4NistManager::Instance()->FindOrBuildMaterial("G4_Pb");
    G4Element *element = matPb->GetElement(0);
    G4double InelXS1 = hadstore->GetInelasticCrossSectionPerAtom(
        G4Proton::Proton(), 10. * GeV, element, matPb);
    G4cout << "InelXS 10 GeV p on Pb " << G4BestUnit(InelXS1, ”Surface") << G4endl;
  }
}
```

Notice code modularity

Execution output:

```
InelXS 10 GeV p on Pb 1.83 barn
```

Hadronic Final States Models

- **Hadronic final states models** describe the properties of the secondaries from the hadronic interaction (`G4HadronicProcess::GetHadronicInteraction()`)
  - Related to the number, type and properties of the secondaries produced by the interaction

- When a process is selected against the others, a final state (distribution of secondaries) is produced by one of the hadronic models working in the current energy range

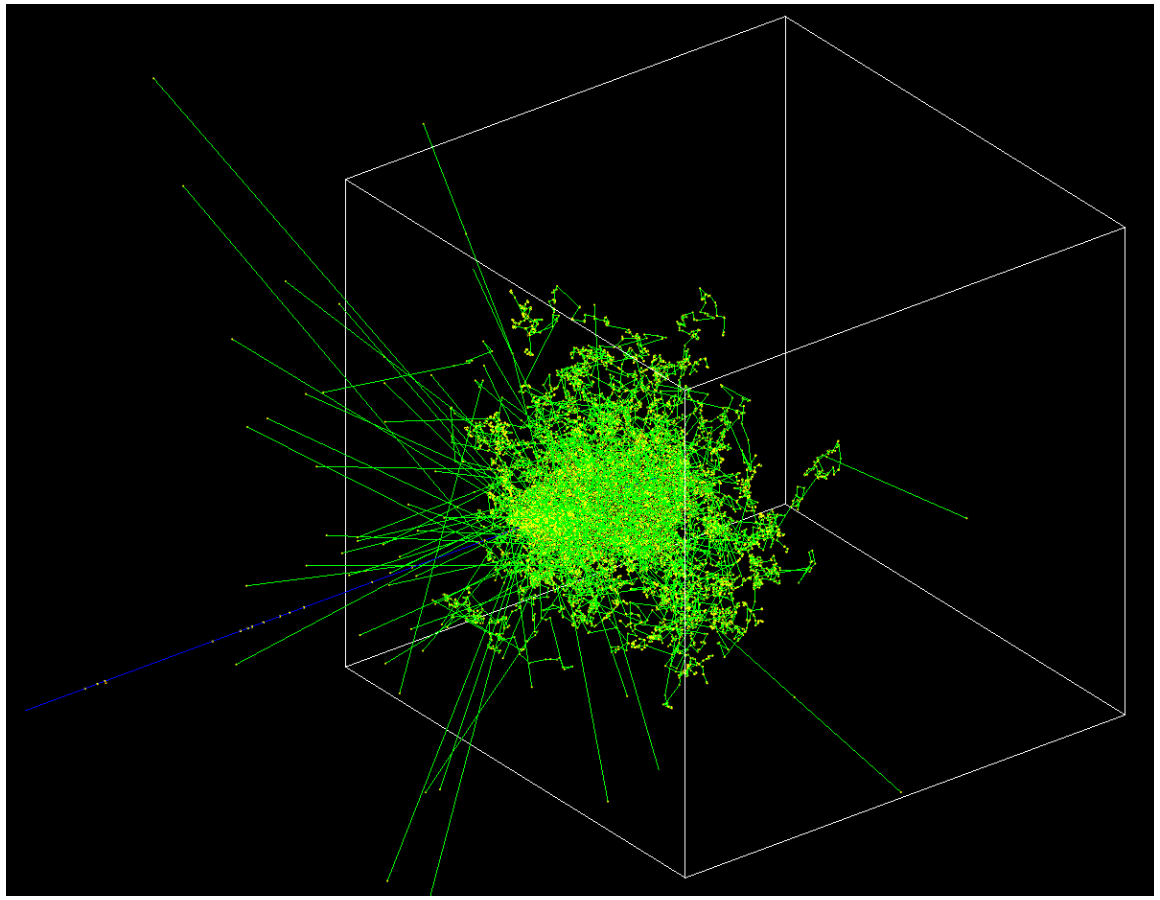
Cross Sections and Models

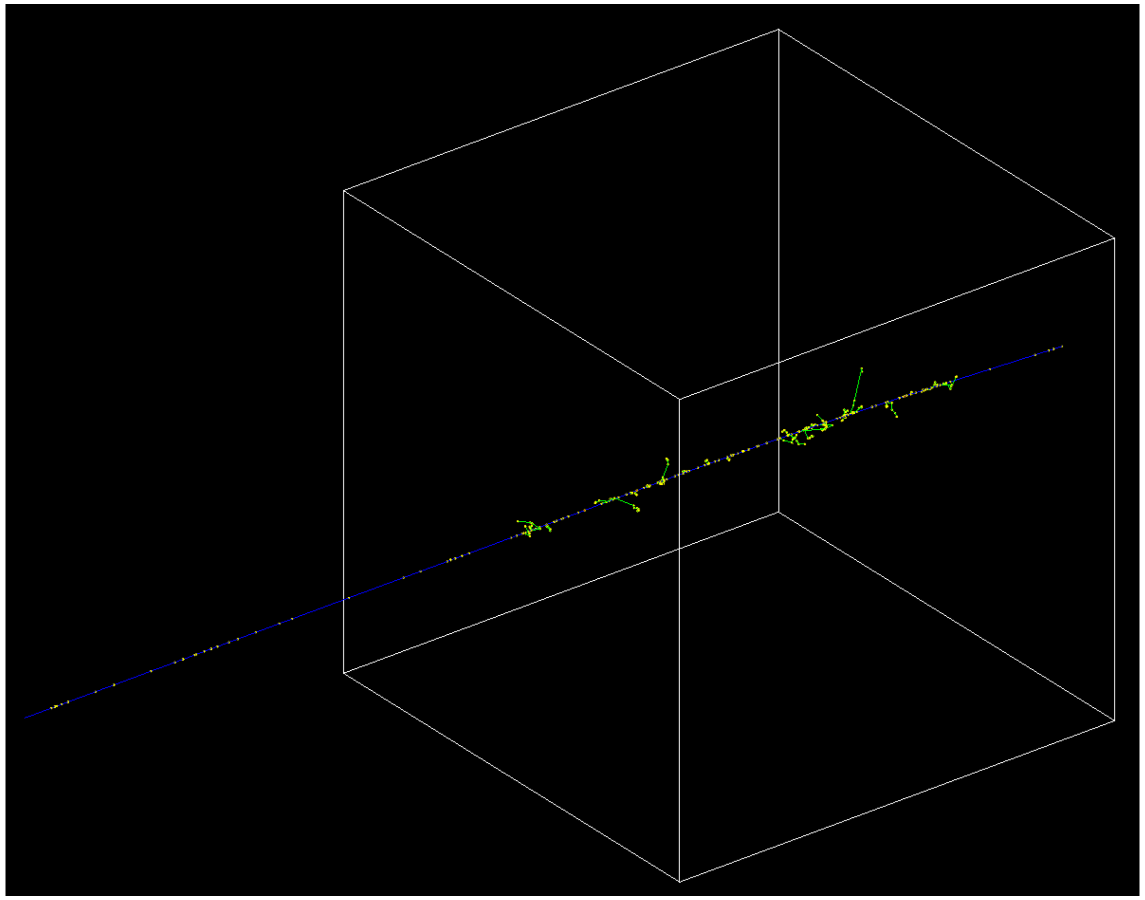
- For each combination of projectile – energy – target:
  - ≥ 1 cross sections must be specified in a physics list
  - 1 or 2 (final-state) models must be specified in a physics list

Example: inactivate hadron inelastic (on Fe)

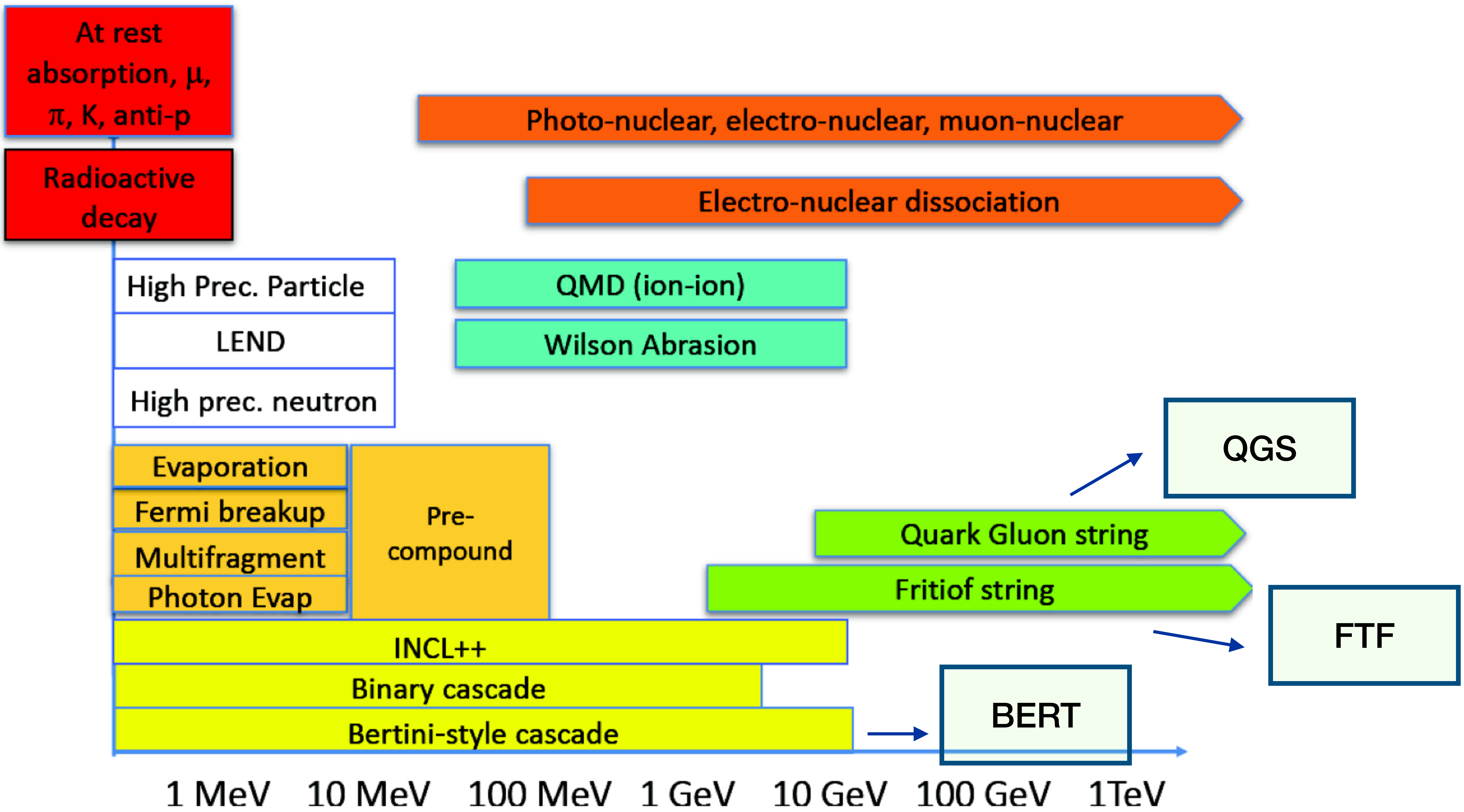
```
/gun/particle proton
/gun/energy 10 GeV
```

```
/gun/particle proton
/gun/energy 10 GeV
/process/inactivate protonInelastic proton
```



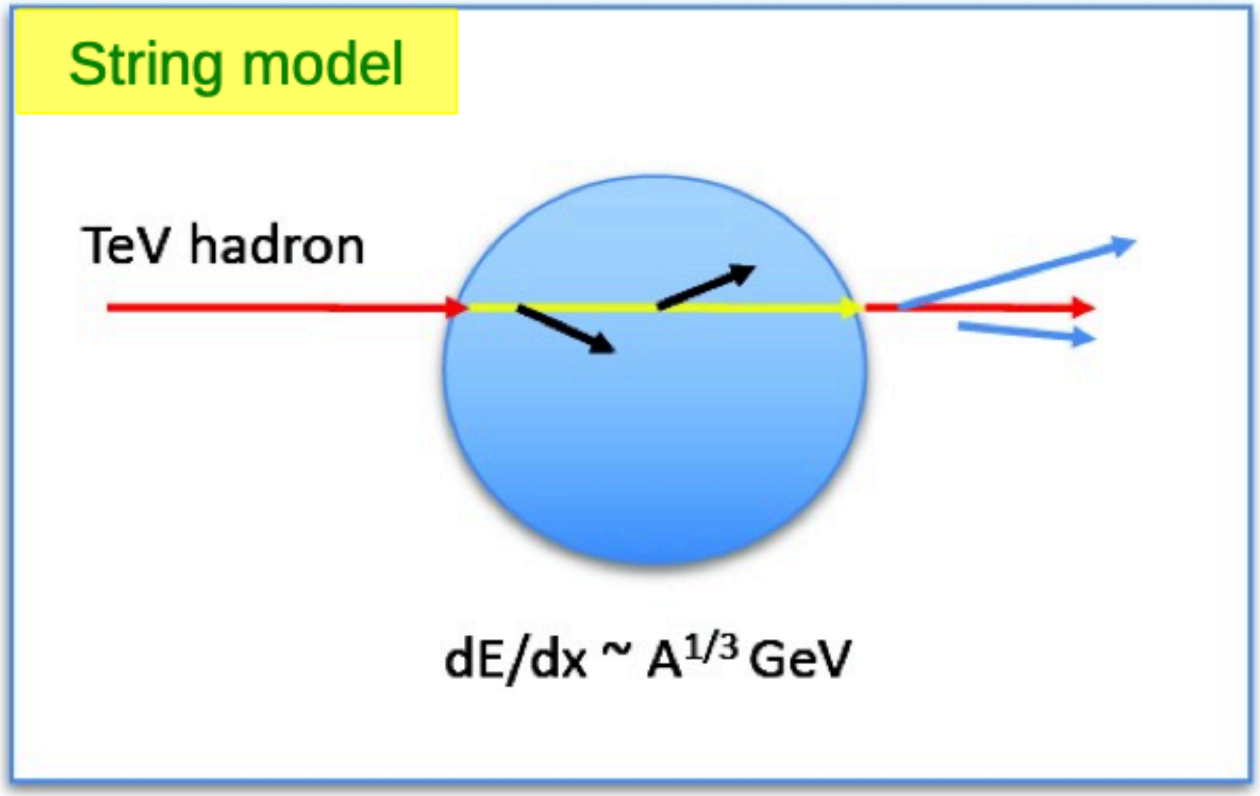


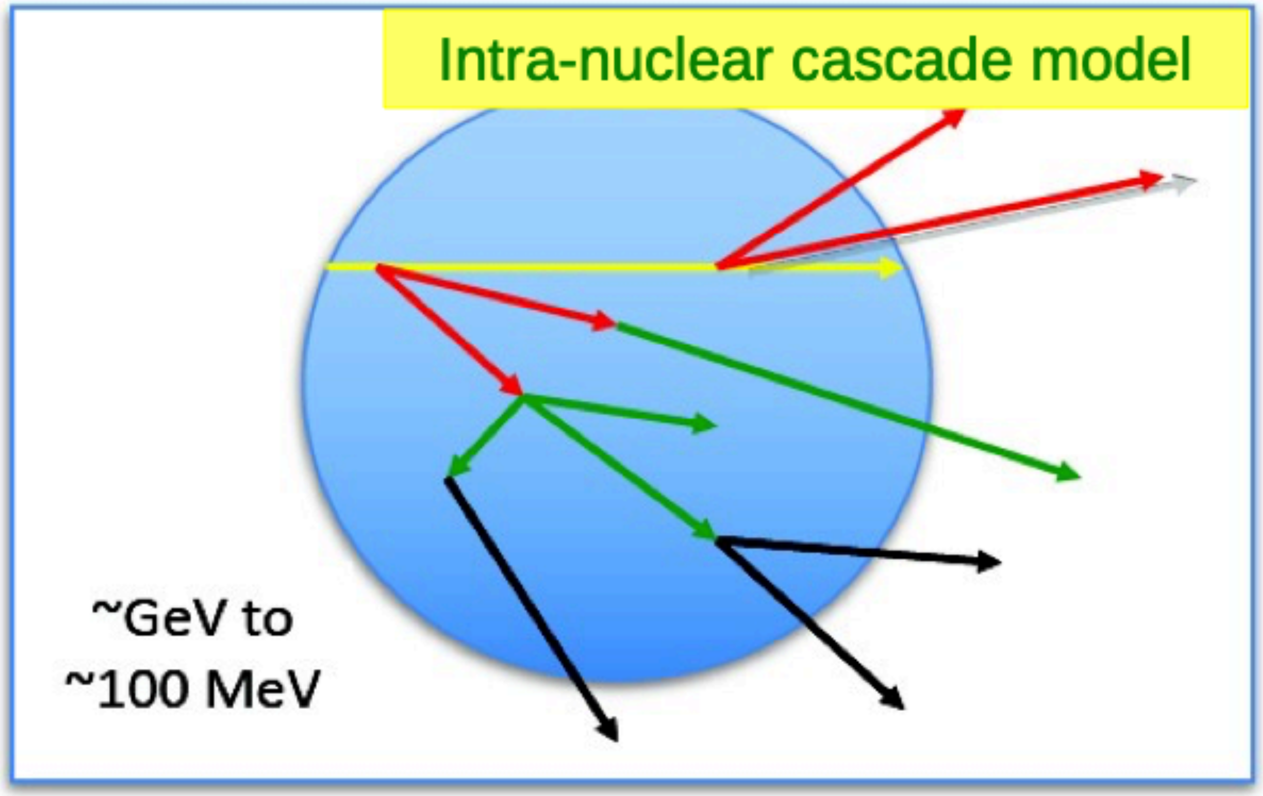
Partial hadronic final states models inventory

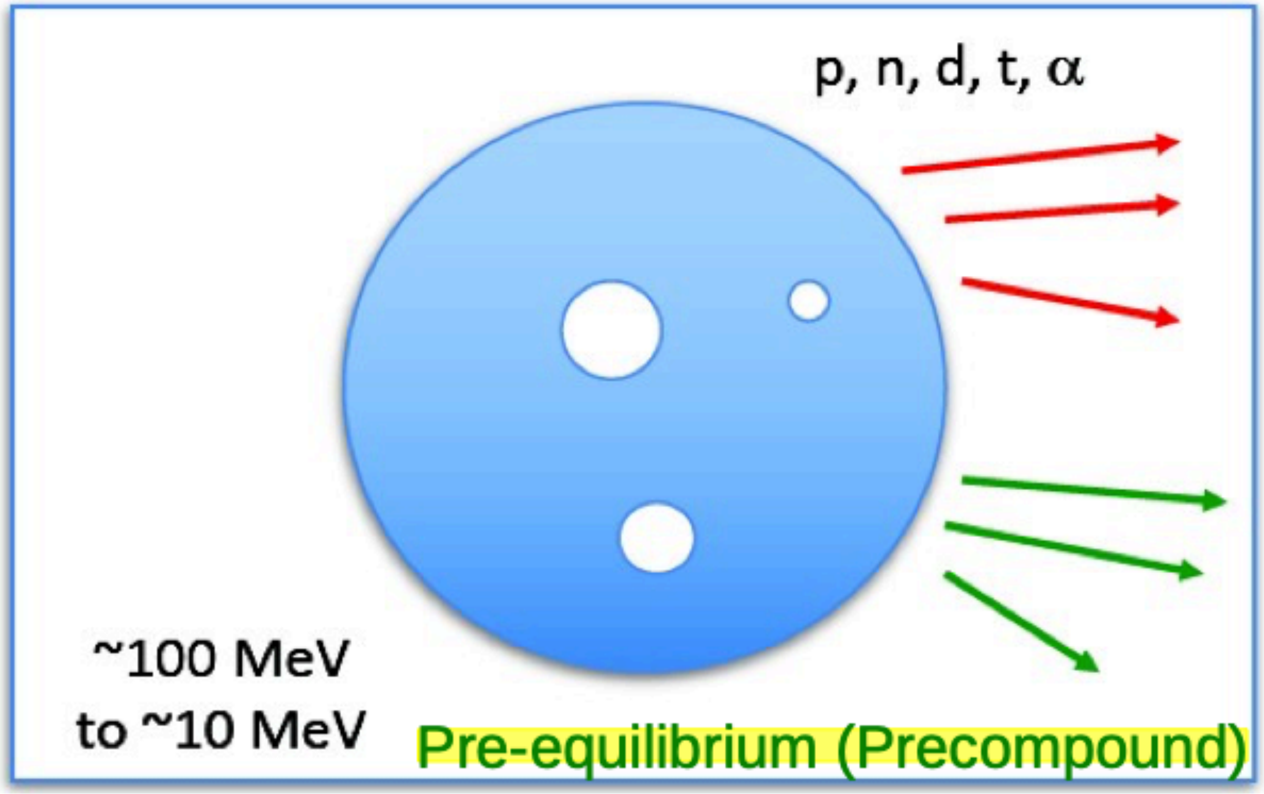


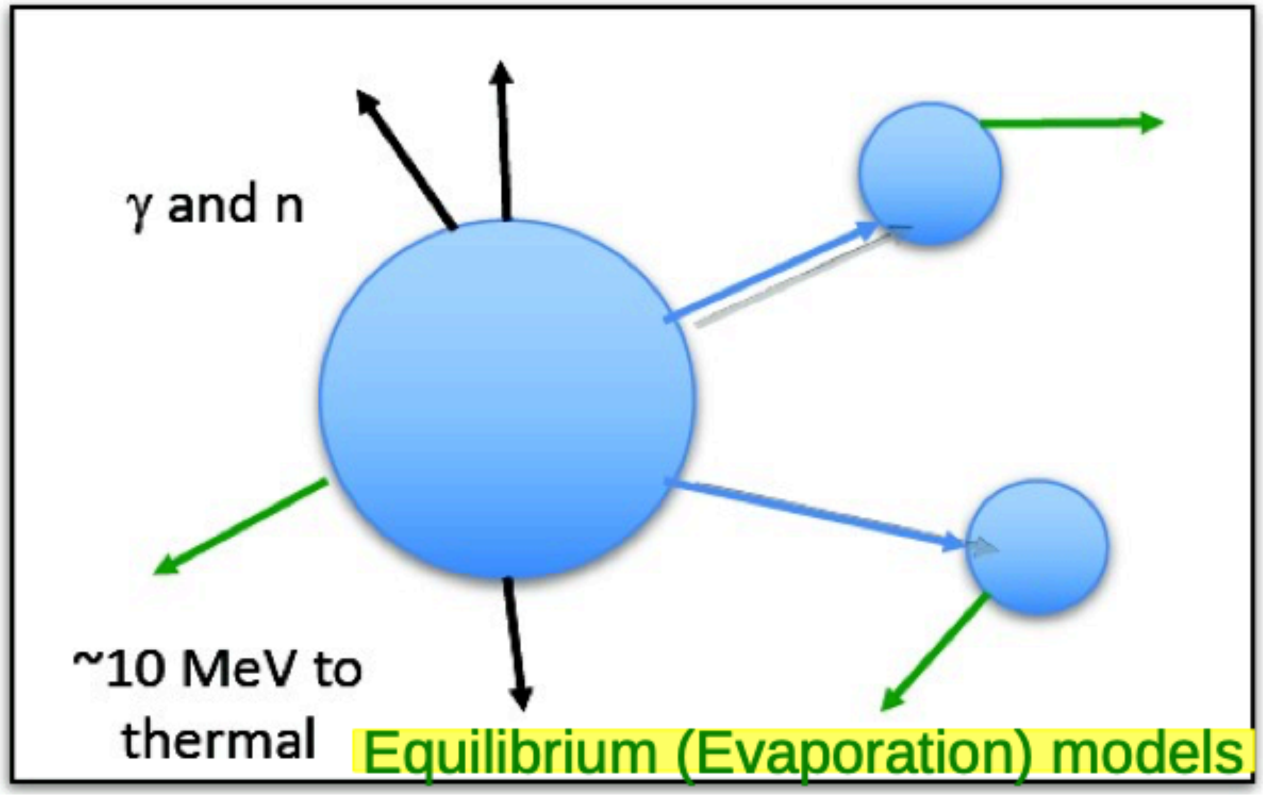
NOTE: Physics list names are derived from the hadronic models used (see lesson *how to choose a physics list*)

Hadronic Interactions from TeV to MeV

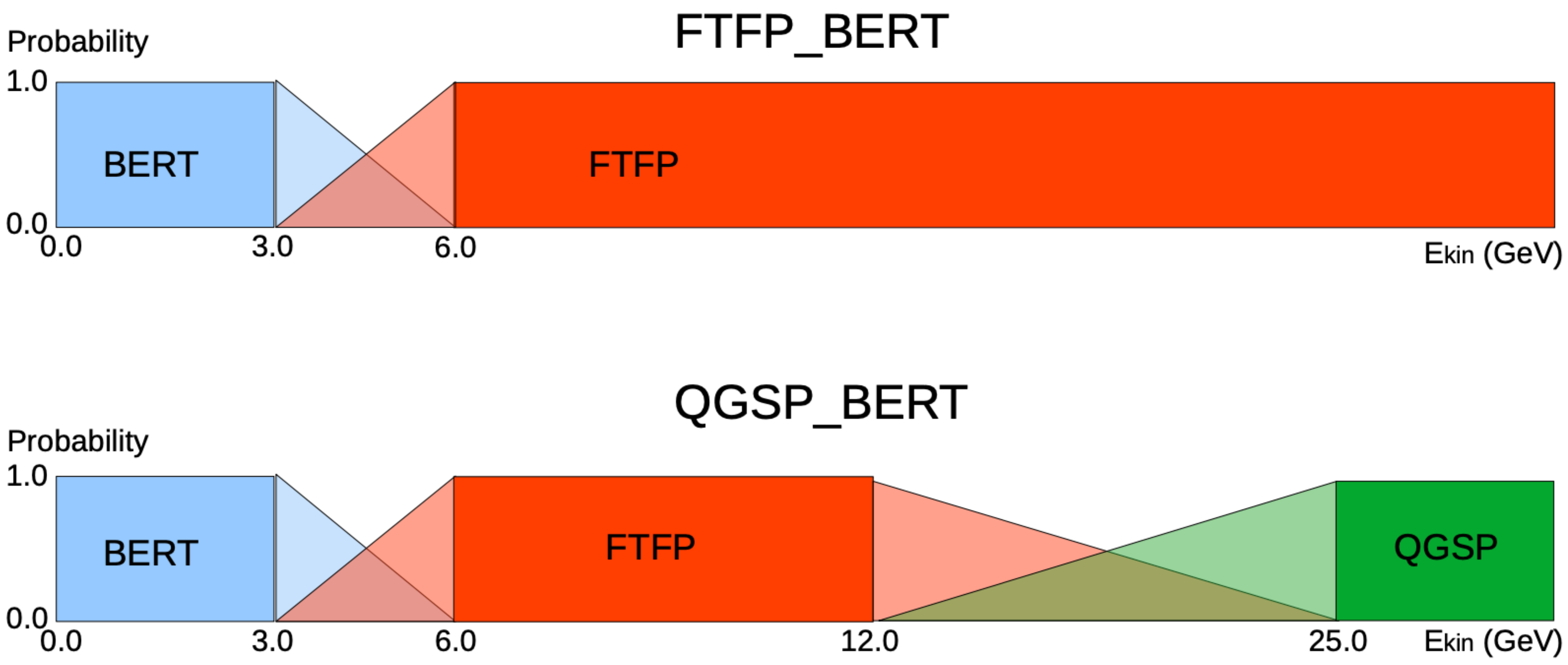






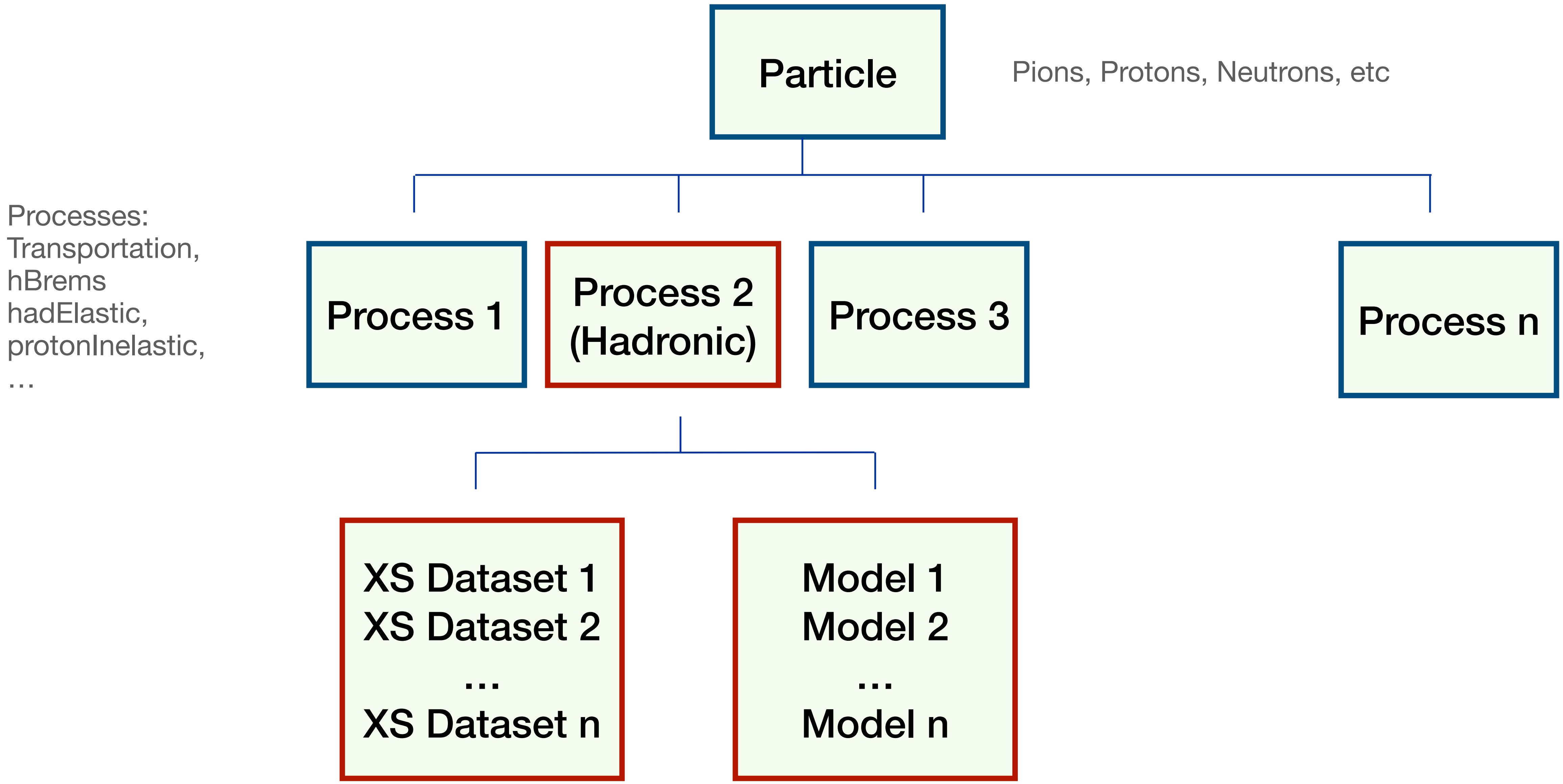


Example of final-state models transition



Hadronic interactions Recap 1

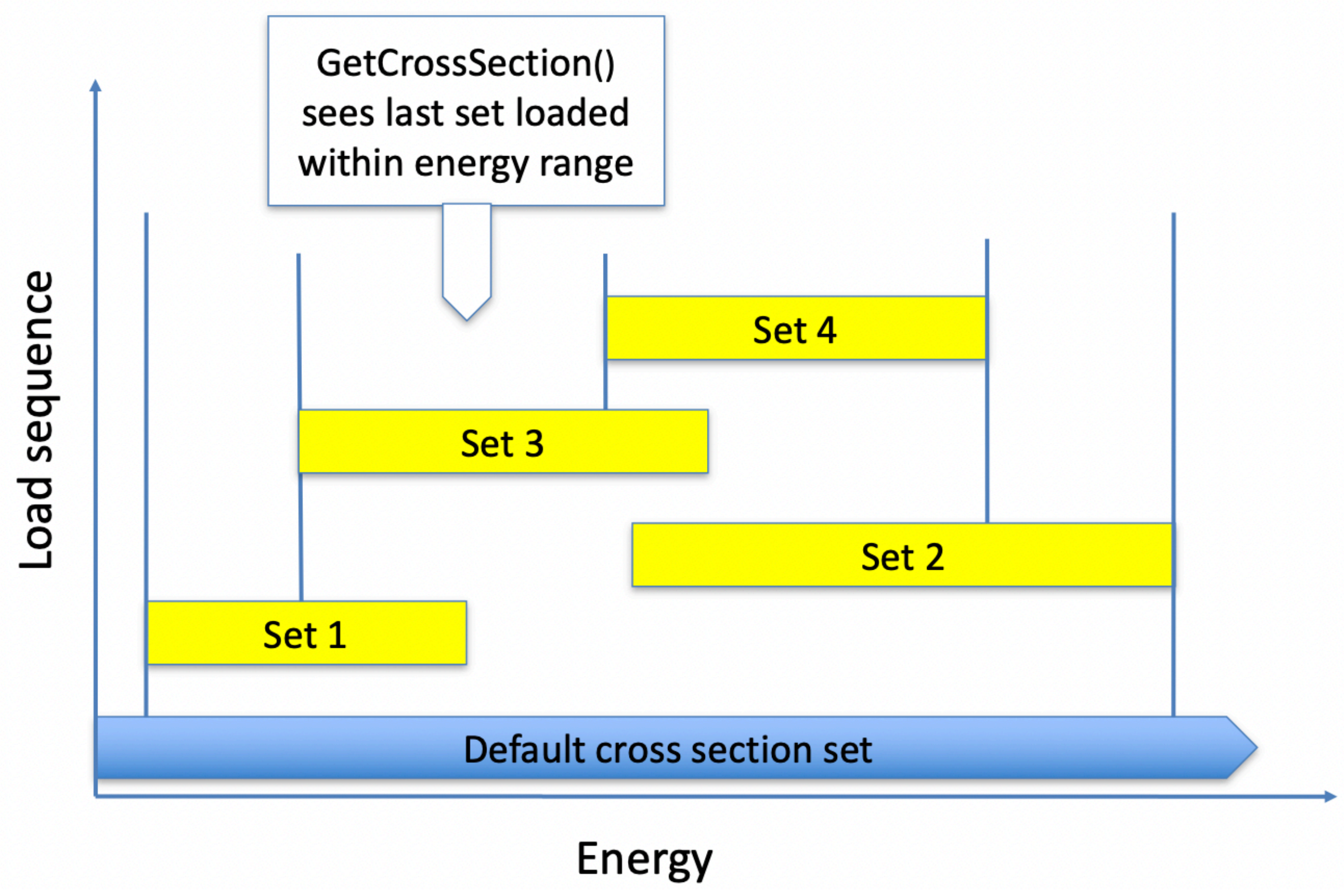
Particles, Associated Processes, Datasets and Models



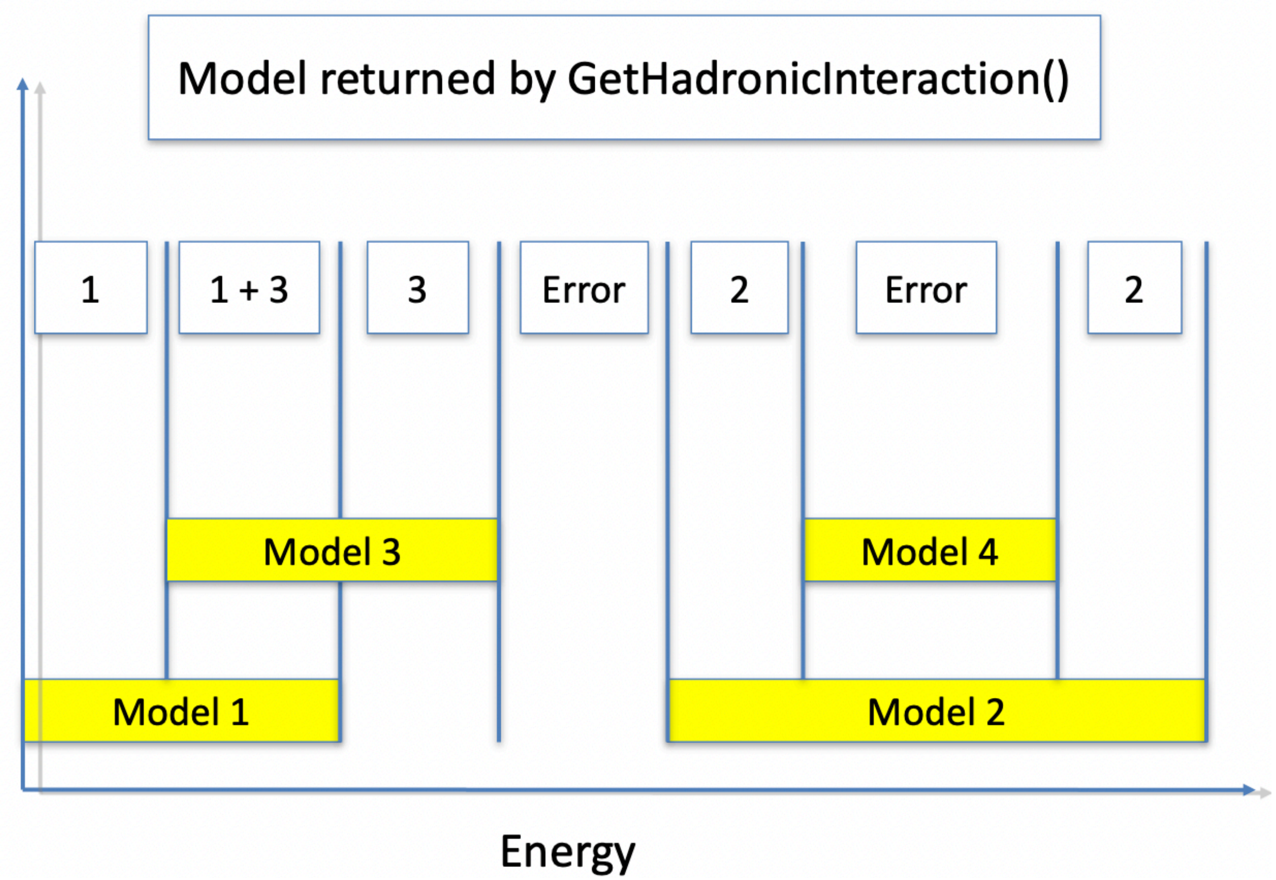
Hadronic interactions Recap 2

Cross section and Final State Model Management

Cross section management



Final state model management



Nuclear capture at rest

Affects negatively charged hadrons and muons at-rest

- In Geant4 charged particles can come at rest (i.e. kinetic energy = 0) due to energy losses by ionization (the simulation is realistic only above few keV)
- Negatively charged hadrons and muons at-rest might undergo an additional process, called (nuclear) capture at rest, for which they are absorbed by a nucleus
- Not to be confused with hadron inelastic process happening in-flight
- The probability for at-rest processes to occur is given by its lifetime (instead of the cross section)
- The nuclear capture at rest processes competes with the decay process

```
/particle/select pi-
/particle/process/verbose 0
/particle/process/dump
```

```
G4ProcessManager: particle[pi-]
[0]=== process[Transportation :Transportation] Active
[1]=== process[msc :Electromagnetic] Active
[2]=== process[hIoni :Electromagnetic] Active
[3]=== process[hBrems :Electromagnetic] Active
[4]=== process[hPairProd :Electromagnetic] Active
[5]=== process[CoulombScat :Electromagnetic] Active
[6]=== process[Decay :Decay] Active
[7]=== process[hadElastic :Hadronic] Active
[8]=== process[pi-Inelastic :Hadronic] Active
[9]=== process[hBertiniCaptureAtRest :Hadronic] Active
[10]=== process[StepLimiter :General] Active
[11]=== process[UserSpecialCut :General] Active
```

Nuclear capture at rest: 10 MeV proton in Iron

```
/gun/particle proton
/gun/energy 10 MeV
/tracking/verbose 2
/run/beamOn 1
```

```
*******************************************************************************************
* G4Track Information:   Particle = proton,   Track ID = 1,   Parent ID = 0
*******************************************************************************************
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0        10        0        0         0       World initStep
    1        0        0    0.182      4.92     5.08    0.182     0.182       World hIoni
    2   0.0104  -0.0106    0.261    0.0609     4.86   0.0805     0.263       World hIoni
    3   0.0104  -0.0108    0.261    0.0125   0.0484 0.000532     0.263       World hIoni
    4   0.0104  -0.0108    0.261         0   0.0125 0.000237     0.263       World hIoni
Run terminated.
```

Nuclear capture at rest: 10 MeV proton in Iron

```
/gun/particle pi-
/gun/energy 10 MeV
/tracking/verbose 2
/run/beamOn 1
```

```
***********************************************************************************************
* G4Track Information:   Particle = pi-,   Track ID = 1,   Parent ID = 0
***********************************************************************************************
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0        10        0        0         0       World initStep
    1        0        0    0.364      7.87     2.13    0.366     0.366       World hIoni
    2   0.0197  0.00231    0.652      6.03     1.84    0.291     0.657       World hIoni
    3   0.0132  -0.0289     0.88      3.92     2.11    0.232     0.889       World hIoni
    4  -0.0101  -0.0447     1.04      1.74     2.18    0.164      1.05       World hIoni
    5  -0.0275  -0.0478     1.09    0.0177     1.72   0.0529      1.11       World hIoni
    6  -0.0275  -0.0478     1.09         0   0.0177 0.000351      1.11       World hIoni
    7  -0.0275  -0.0478     1.09         0        0        0      1.11       World hBertiniCaptureAtRest
    :-- List of 2ndaries - #SpawnInStep= 23(Rest=23,Along= 0,Post= 0), #SpawnTotal= 23 --------------
    :   -0.0275   -0.0478   1.09   0.00968                 e-
```

A special case: neutrons

- Neutrons are crucial particles for every simulation involving hadronic physics (*e.g. hadronic calorimeters, nuclear reactors, shielding, …*)
- Typically several *soft* neutrons are released from nuclei de-excitation after the hadron inelastic process (*notice lepto-nuclear and gamma-nuclear processes release neutrons too*)
- The nCapture (radiative capture) process can happen *in-flight* (differently from the radiative capture at rest for negatively charged hadrons), the neutron is absorbed by a nucleus which emits (see next slide)

Example: inspect neutron processes (FTFP_BERT)

```
/particle/select neutron
/particle/process/verbose 0
/particle/process/dump
```

```
G4ProcessManager: particle[neutron]
[0]=== process[Transportation :Transportation] Active
[1]=== process[Decay :Decay] Active
[2]=== process[hadElastic :Hadronic] Active
[3]=== process[neutronInelastic :Hadronic] Active
[4]=== process[nCapture :Hadronic] Active
[5]=== process[nKiller :General] Active
[6]=== process[UserSpecialCut :General] Active
```

NOTE: In hadronic showers neutrons are typically the third most abundant particles produced, after photons and e-

1 MeV neutron in Iron

```
/gun/particle neutron
/gun/energy 1 MeV
/tracking/verbose 2
/run/beamOn 1
```

```
*********************************************************************************************
* G4Track Information:   Particle = neutron,   Track ID = 1,   Parent ID = 0
*********************************************************************************************
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0         1        0        0         0       World initStep
    1        0        0    0.311     0.962   0.0384    0.311     0.311       World hadElastic
    2    -51.8     34.7    -4.95      0.94   0.0213     62.5      62.9       World hadElastic
    3    -61.4     50.3    -57.5     0.931  0.00918     55.6       118       World hadElastic
...
  170     27.6      242      270         0        0     6.24  3.86e+03       World nCapture
    :----- List of 2ndaries - #SpawnInStep=  2(Rest= 0,Along= 0,Post= 2), #SpawnTotal=  2 -----
    :      27.6       242       270      7.63              gamma
    :      27.6       242       270  0.000503       Fe57[14.413]
    :----------------------------------------------------------------- EndOf2ndaries Info -----
```

A special case: neutrons

- As neutrons do not loose energy by ionization, they usually undergo many elastic collisions (eventually down to thermalization) with nuclei before being killed
- In Geant4 neutrons can be killed by the hadron inelastic process, the decay process, the radiative capture process, the *nKiller* process (default threshold 10 us) or by the Geant4 kernel (*out-of-world killed*)
- Neutron cross sections are wild: they depend, sometimes dramatically and unpredictably, on the neutron energy and the target element/isotope
- The CPU time varies up to one order of magnitude depending on the accuracy of neutron simulation
  - For most high-energy physics and nuclear applications, a simplified and fast description is usually sufficient (FTFP_BERT, QGSP_BERT, …)
  - Where more accuracy is needed, Geant4 offers a more precise, data-driven and isotope-specific treatment for neutrons, for kinetic energies <20 MeV (see lesson *Hadronic Physics II*)

Datasets

Some hadronic models, for both final states and cross sections, are data-driven, i.e. they need as input phenomenological data; similarly, some need as input the result of intensive computation that are performed before the simulation

- The `-DGEANT4_INSTALL_DATA=ON` cmake option sets the datasets automatic download and installation
- The following envs are exported by `/path-to/geant4-install/bin/geant4.sh` and linked to datasets:

Mandatory to all physics list

```
G4LEDATA          = /path-to/geant4-install/data/Geant4-11.2.1/data/G4EMLOW8.5
G4LEVELGAMMADATA  = /path-to/geant4-install/data/Geant4-11.2.1/data/PhotonEvaporation5.7
G4PARTICLEXSDATA  = /path-to/geant4-install/data/Geant4-11.2.1/data/G4PARTICLEXS4.0
G4SAIDXSDATA      = /path-to/geant4-install/data/Geant4-11.2.1/data/G4SAIDDATA2.0
G4ENSDFSTATEDATA  = /path-to/geant4-install/data/Geant4-11.2.1/data/G4ENSDFSTATE2.3
```

```
G4NEUTRONHPDATA   = /path-to/geant4-install/data/Geant4-11.2.1/data/G4NDL4.7
G4RADIOACTIVEDATA = /path-to/geant4-install/data/Geant4-11.2.1/data/RadioactiveDecay5.6
G4PIIDATA         = /path-to/geant4-install/data/Geant4-11.2.1/data/G4PII1.3
G4REALSURFACEDATA = /path-to/geant4-install/data/Geant4-11.2.1/data/RealSurface2.2
G4ABLADATA        = /path-to/geant4-install/data/Geant4-11.2.1/data/G4ABLA3.3
G4INCLDATA        = /path-to/geant4-install/data/Geant4-11.2.1/data/G4INCL1.2
```

Needed only by specific physics list

Datasets

Mandatory to all physics list

- **G4LEDATA** : low-energy electromagnetic data, mostly derived from Livermore data libraries; used in all EM options
- **G4LEVELGAMMADATA** : photon evaporation data, come from the Evaluated Nuclear Structure Data File (ENSDF); used by Precompound/de-excitation models (and RadioactiveDecay if present)
- **G4SAIDXSDATA** : data evaluated from the SAID database for nucleon and pion cross sections below 3 GeV; used in all physics lists
- **G4PARTICLEXSDATA** : evaluated neutron (as well as proton, deuteron, triton, He3, alpha, gamma, neutrino) cross sections derived from G4NDL by averaging in bin of energies; used in all physics lists
- **G4ENSDFSTATEDATA** : nuclear properties, from Evaluated Nuclear Structure Data File (ENSDF); used in all physics lists

Datasets

Needed only by specific physics list

- **G4REALSURFACEDATA** : data for measured optical surface reflectance look-up tables; used only when optical physics is activated

- **G4NEUTRONHPDATA** : evaluated neutron data of cross sections, angular distributions and final-state information; come largely from the JEFF-3.3 library; used only in _HP physics lists (see *Hadronic Physics II* at this course)

- **G4RADIOACTIVEDATA** : radioactive decay data, come from the ENSDF; used only when radioactive decay is activated (see Hadronic Physics II at this course)

- **G4INCLDATA** : data for the intranuclear cascade model INCLXX

- **G4ABLADATA** : data for the ABLA de-excitation model, which is an alternative de-excitation available for INCLXX

Physics Lists

Reminders: See Also Physics Overview I

- A *physics list* is a class that constructs all the particles and the associated processes
- One (and only one) physics list must be present in a `Geant4` simulation
- Users can:
  - Build their own custom physics list
  - Use a reference physics list
  - New: Use extensible factory
- A reference physics list is a pre-packaged collection of physics processes. Using a reference physics list is straightforward, *e.g.* in `main()`
- No default physic list (and no default physics) is provided by `Geant4`, the user is responsible to choose or create a Physics List
- A modular physics list implements a granular approach to physics via *constructors*

How to use a Reference Physics List

Method 1: use it directly

```
#include "FTFP_BERT.hh"
int main( int argc, char** argv ) {
     ...
     auto physicsList = new FTFP_BERT;
     runManager->SetUserInitialization( physicsList );
     ...
}
```

Method 2: modular using extensibleFactory

```
#include "G4PhysListFactoryAlt.hh"
#include "G4VModularPhysicsList.hh"

int main( int argc, char** argv ) {
    ...
    G4PhysListFactory factory;
    const G4String pName = "FTFP_BERT";
    G4VModularPhysicsList*
         phys = factory.GetReferencePhysList(pName);
    runManager->SetUserInitialization(phys);
    ...
}
```

pName can also be: "FTFP_BERT + G4RadioactiveDecayPhysics"

source/source/physics_lists/lists/src/FTFP_BERT.cc

```
FTFP_BERT::FTFP_BERT(G4int ver)
{
  if(ver > 0) {
    G4cout << "<<< Geant4 Physics List simulation
engine: FTFP_BERT"<<G4endl;
    G4cout <<G4endl;
  }
  defaultCutValue = 0.7*CLHEP::mm;
  SetVerboseLevel(ver);

 // EM Physics
  RegisterPhysics( new G4EmStandardPhysics(ver));
  // Synchroton Radiation & GN Physics
  RegisterPhysics( new G4EmExtraPhysics(ver) );
  // Decays
  RegisterPhysics( new G4DecayPhysics(ver) );
   // Hadron Elastic scattering
  RegisterPhysics( new G4HadronElasticPhysics(ver) );
   // Hadron Physics
  RegisterPhysics(  new G4HadronPhysicsFTFP_BERT(ver));
  // Stopping Physics
  RegisterPhysics( new G4StoppingPhysics(ver) );
  // Ion Physics
  RegisterPhysics( new G4IonPhysics(ver));
  // Neutron tracking cut
  RegisterPhysics( new G4NeutronTrackingCut(ver));
}
```

See also examples/extended/physicslists/extensibleFactory

Reference physics lists

Check also naming conventions

The **FTFP_BERT** is the recommended one for high-energy physics simulations. It adopts the models:

- Standard e.m. processes
- **FTF**: (Fritiof) hadronic string model for hadron inelastic process >~ 4 GeV
- **P**: G4Precompound model for nucleus de-excitation + evaporation models
- **BERT**: (Bertini) intra-nuclear cascade model for the hadron inelastic process <~ 6 GeV
- Plus: neutron radiative capture, nuclear capture at rest for negatively charged hadrons, elastic scattering for hadrons, lepto-nuclear and gamma-nuclear processes and standard em physics (*compton, pair-production, photoelectric effect, …*)
- No high-precision treatment of low-energy neutrons (explained in *hadronic physics II*), no radioactive decays (explained in *hadronic physics II*), no optical photons

NOTE: ATLAS, CMS, LHCb and ALICE use mild-variants (tuning) of this physics list
(e.g. the **FTFP_BERT_ATL** physics list used by the ATLAS Experiment)

Reference physics lists

Check also naming conventions

QGSP_BIC_HP

- Standard e.m. processes
- **QGS**: quark-gluon string model for hadron inelastic process > 25 GeV
- **FTF**: (Fritiof) hadronic string model for hadron inelastic process 9.5 - 25 GeV
- **P**: G4Precompound model for nucleus de-excitation + evaporation models
- **BIC**: Binary interaction cascade model for the hadron inelastic process 200 MeV - 9.9 GeV
- Plus: neutron radiative capture, nuclear capture at rest for negatively charged hadrons, elastic scattering for hadrons, lepto-nuclear and gamma-nuclear processes and standard em physics (*compton, pair-production, photoelectric effect, …*)
- **HP** – high precision neutron, proton, d, t, 3He, alpha interaction model (< 20 MeV)

Reference physics lists

Other relevant reference physics lists for hadronic physics are:

- The **FTFP_BERT_HP**: same as FTFP_BERT but using the high-precision neutron treatment for low energy neutrons (< 20 MeV)
- The **QGSP_BERT**: same as FTFP_BERT but uses the QGS (Quark Gluon String) model for the hadron inelastic process with an energy transition range with FTF of [12,25] GeV

  NOTE: Below 12 GeV QGSP_BERT and FTFP_BERT are identical
- The **FTFP_INCLXX**: uses the INCLXX model for the inelastic process of protons, neutrons and charged pions. The INCLXX and the FTF models intersect in the energy range [15,20] GeV
- The **QGSP_BIC**: uses both FTF and QGS models for high-energy interactions and both BERT and BIC (Binary Cascade) models for low-energy interactions, as
  - Protons, neutrons: BIC < 6 GeV, FTFP $[3,25]$ GeV and QGSP > 12 GeV
  - Pions and kaons: BERT < 6 GeV, FTFP $[3,25]$ GeV and QGSP > 12 GeV

Summary

- `Geant4` implements two main hadronic processes, the *hadron elastic* and the *hadron inelastic* processes
- Geant4 covers nearly all particles over energies ranging from 0 to ~TeV
- For negatively charged hadrons the *nuclear capture at rest* process is included as well
- For neutrons the *radiative capture* process is also included
- In `Geant4` cross section datasets and final states models are clearly separated (no differential cross sections available)
- Several final state models are available and applicable to restricted combinations of energies, particles and materials
- Reference physics lists construct hadronic physics by picking up both hadronic final states models and cross section datasets
- Typically reference physics lists are named after the hadronic final state models adopted
- Choosing the appropriate physics list for a given application requires care and validation