

Geant4 Tutorial Course

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Hadronic Physics I

Maurizio Ungaro
Jefferson Lab

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
```

```
--- 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
```

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

```
--- 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:

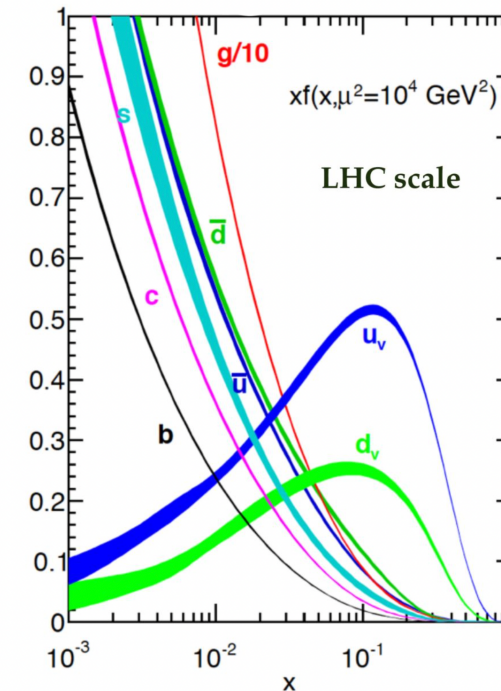
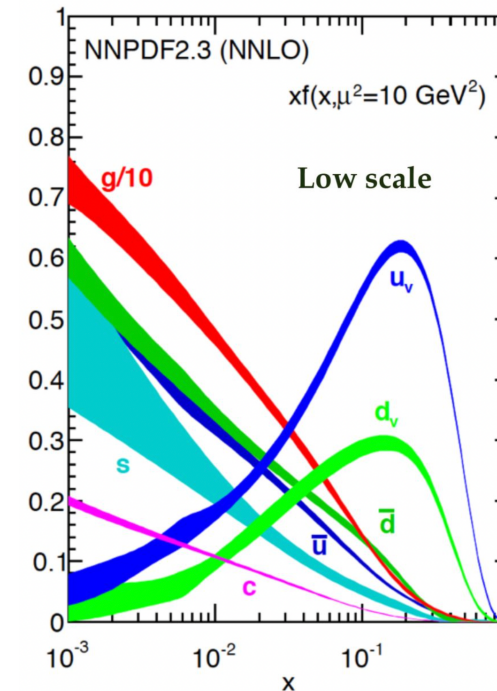
$\hat{\sigma}_{ab \rightarrow X}(x_1 x_2 s, Q^2)$:
cross section for
partons process (QCD)

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

$f_a(x, Q^2)$:
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



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:

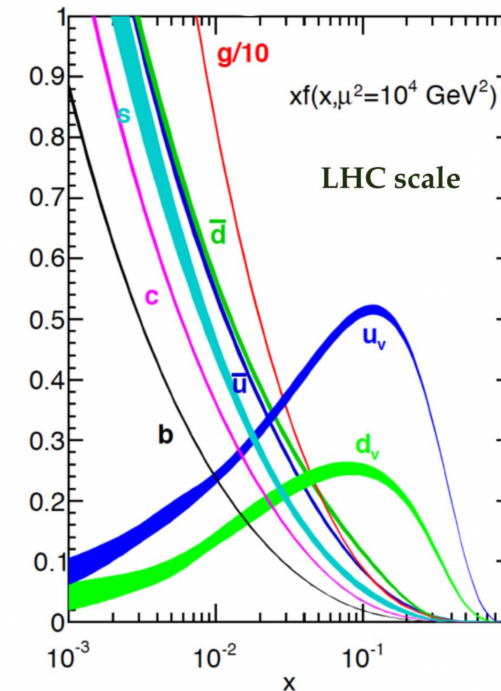
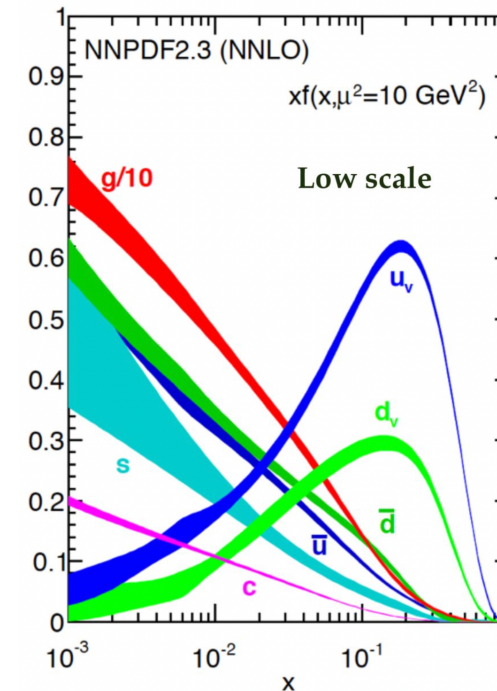
$\hat{\sigma}_{ab \rightarrow X}(x_1 x_2 s, Q^2)$:
cross section for
partons process (QCD)

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

$f_a(x, Q^2)$:
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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



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:

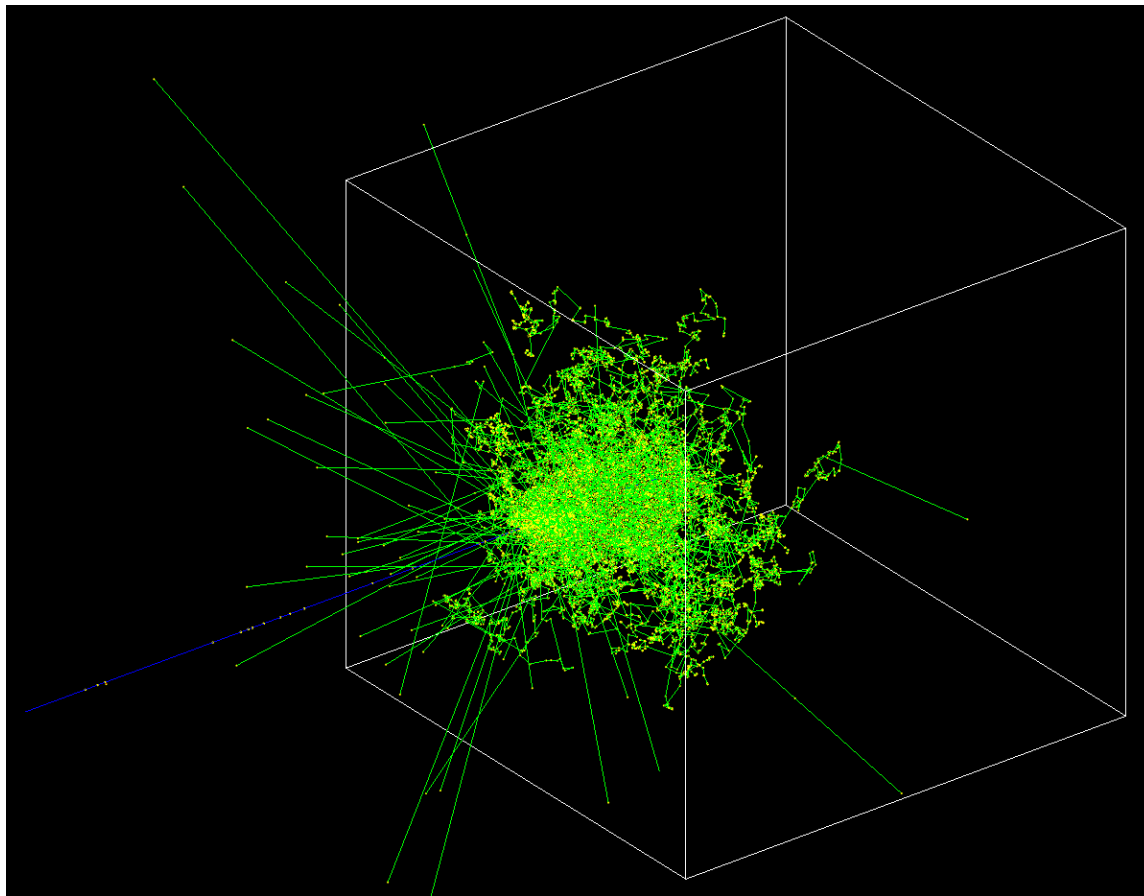
```
InelXS 10 GeV p on Pb 1.83 barn
```

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

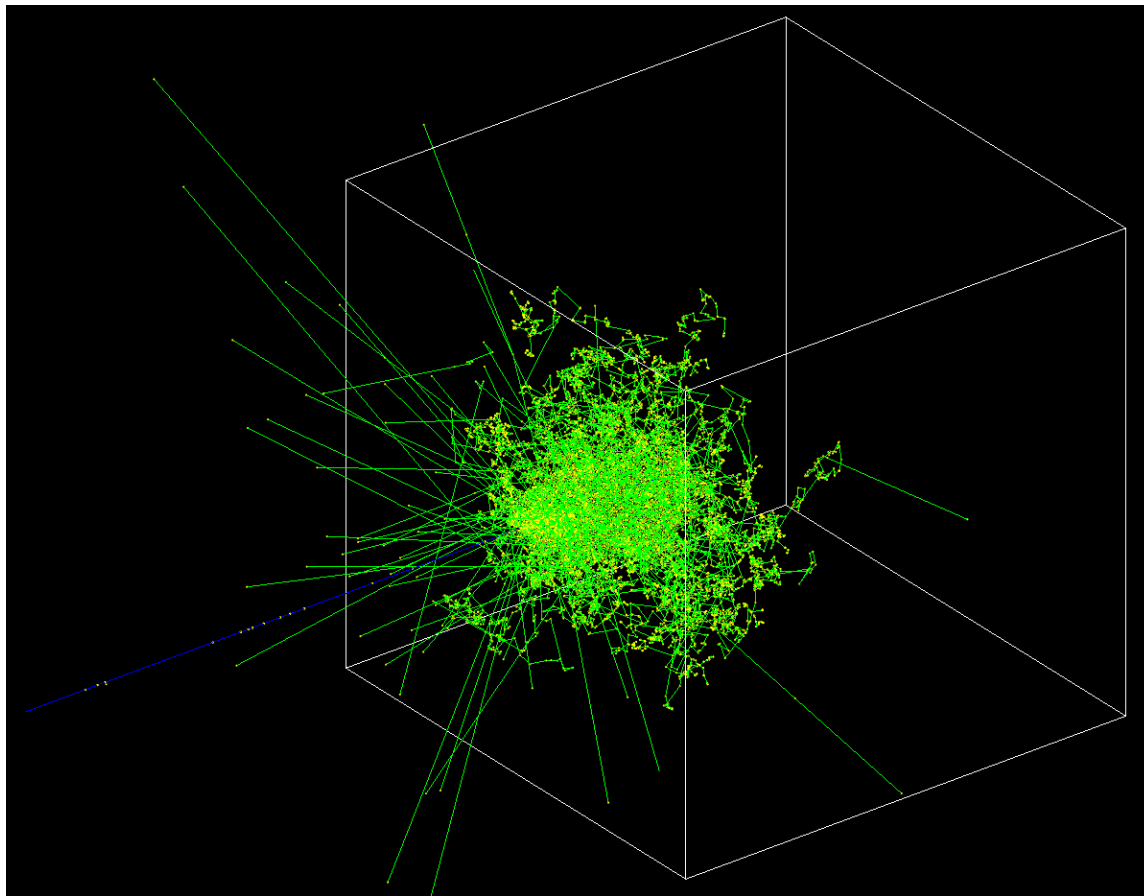
Example: inactivate hadron inelastic (on Fe)

```
/gun/particle proton  
/gun/energy 10 GeV  
/run/beamOn 1
```

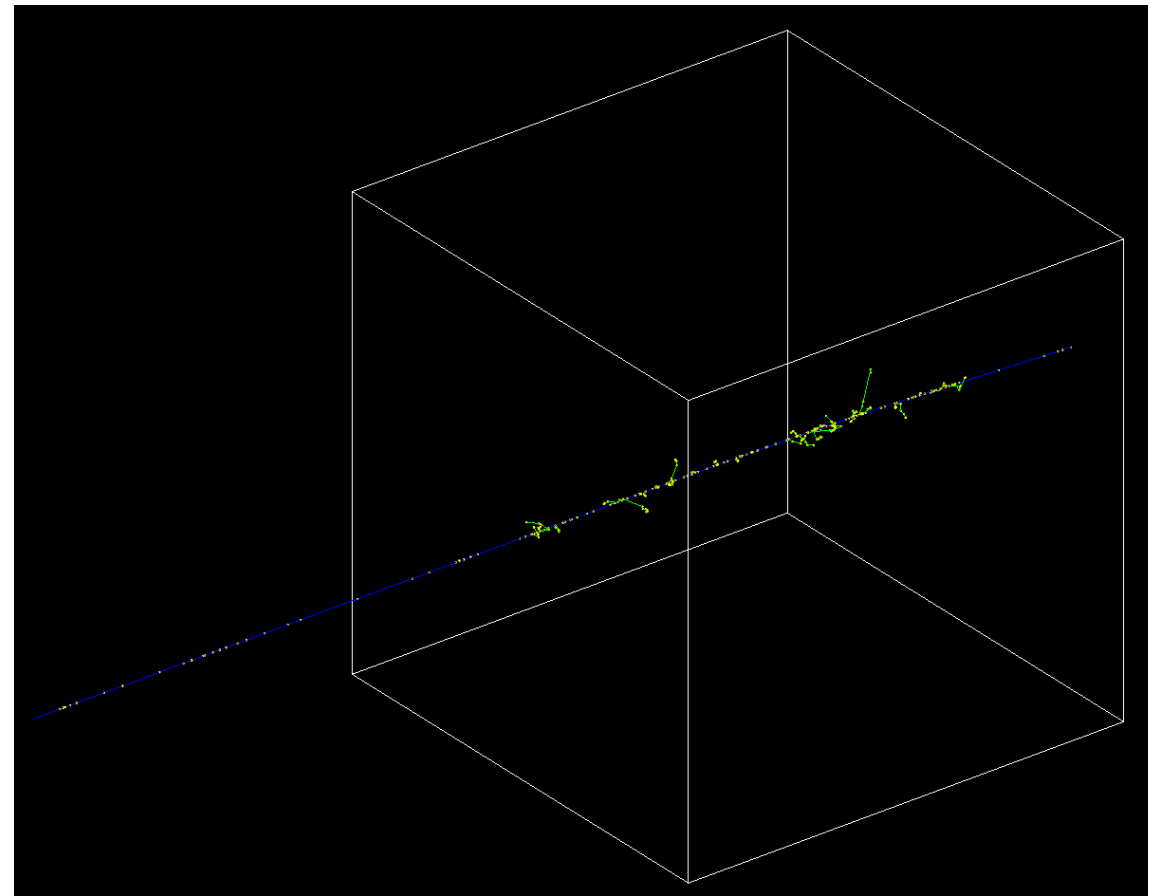


Example: inactivate hadron inelastic (on Fe)

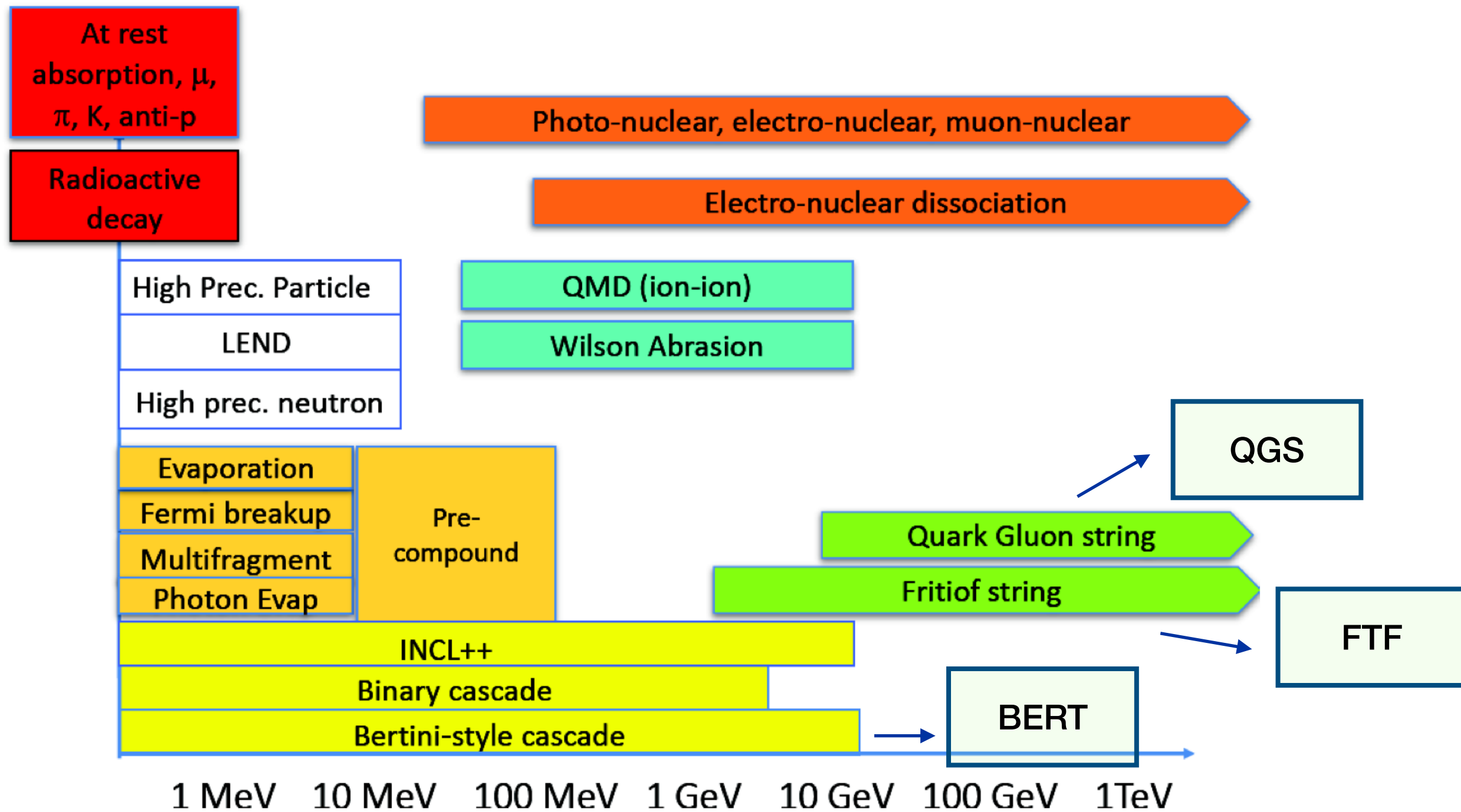
```
/gun/particle proton  
/gun/energy 10 GeV  
/run/beamOn 1
```



```
/process/inactivate protonInelastic proton  
/gun/particle proton  
/gun/energy 10 GeV  
/run/beamOn 1
```



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

String model

TeV hadron

$$dE/dx \sim A^{1/3} \text{ GeV}$$

Intra-nuclear cascade model

$\sim \text{GeV}$ to
 $\sim 100 \text{ MeV}$

p, n, d, t, α

$\sim 100 \text{ MeV}$
to $\sim 10 \text{ MeV}$

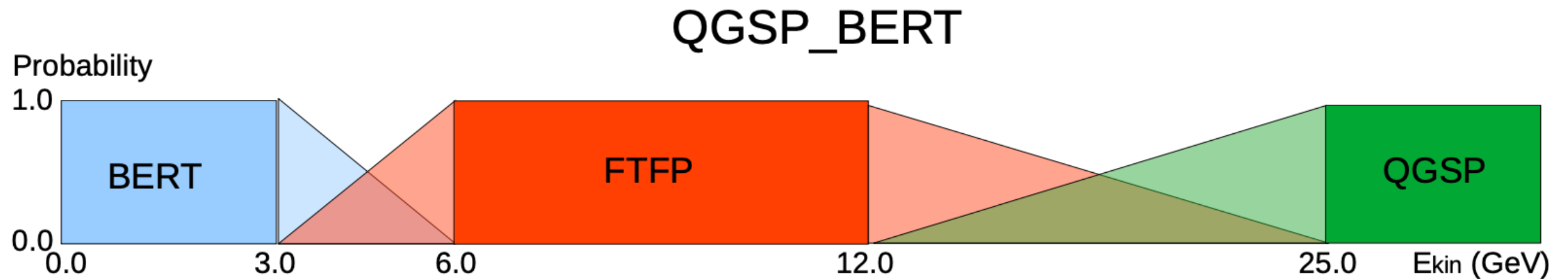
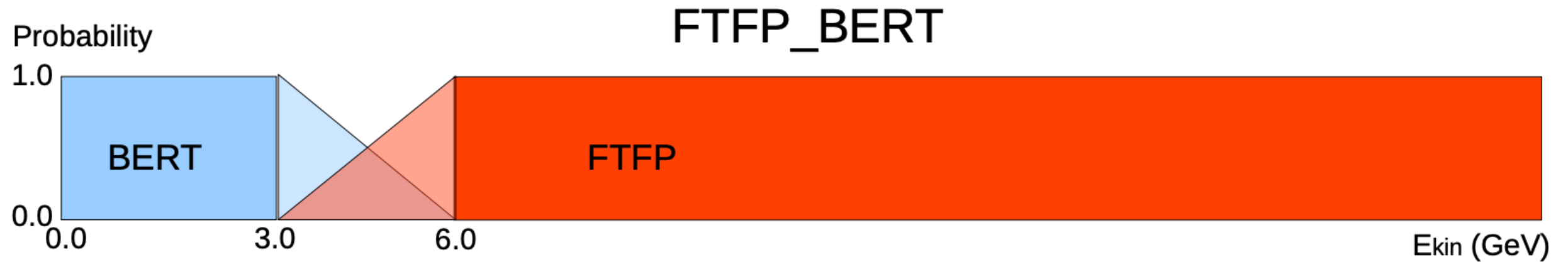
Pre-equilibrium (Precompound)

γ and n

$\sim 10 \text{ MeV}$ to
thermal

Equilibrium (Evaporation) models

Example of final-state models transition



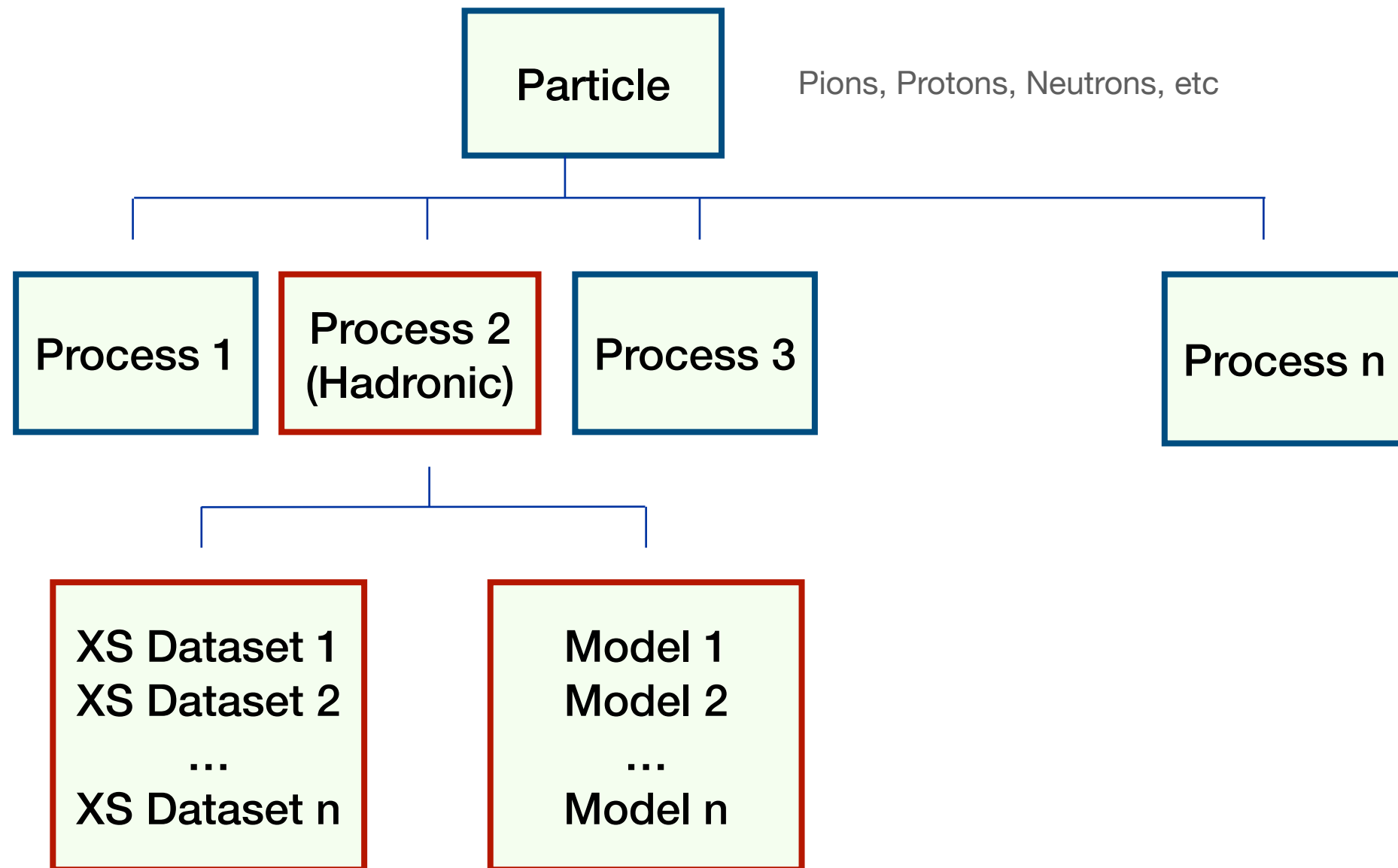
Hadronic Interactions Recap 1

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

Hadronic Interactions Recap 2

Particles, Associated Processes, Datasets and Models

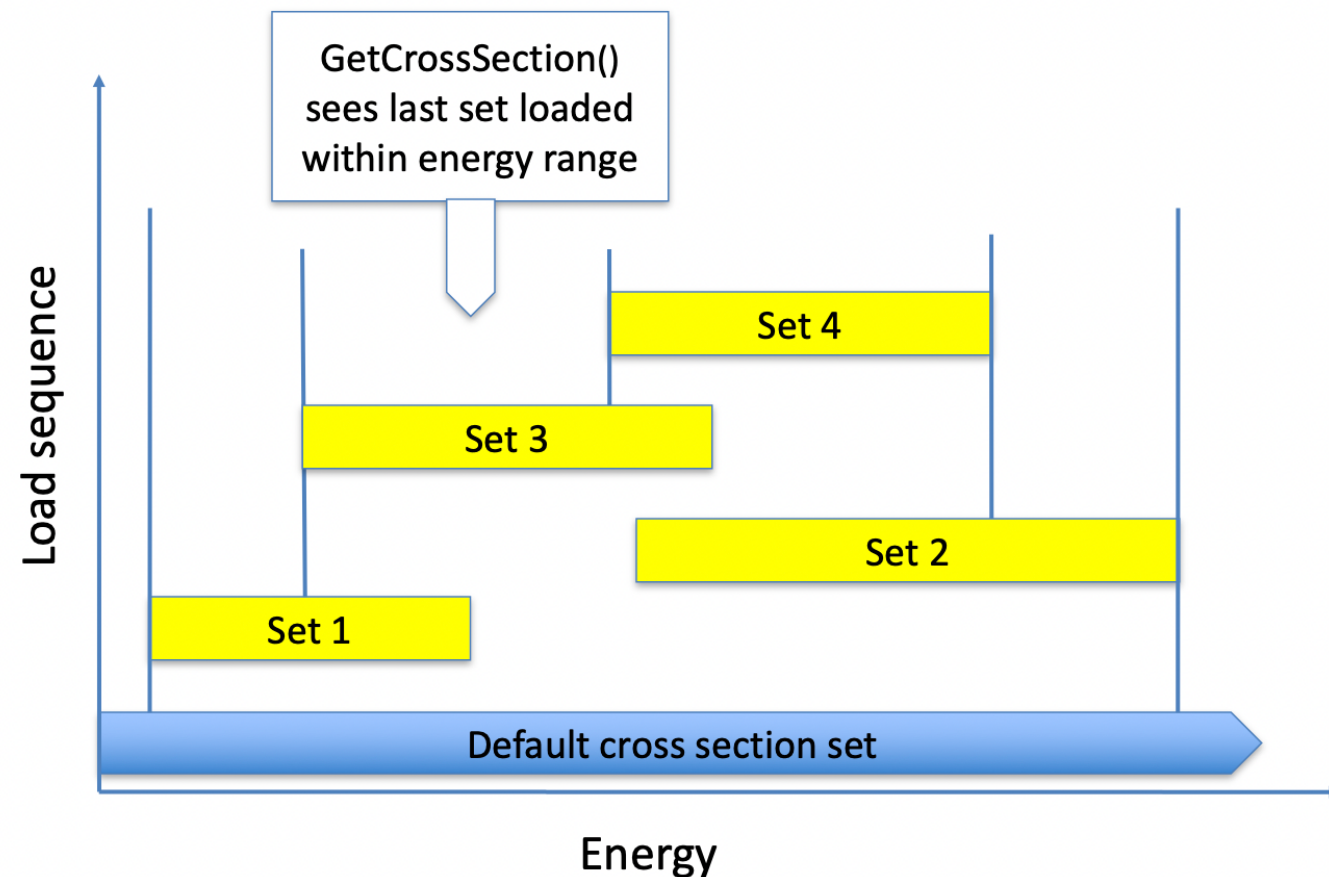
Processes:
Transportation,
hBrems
hadElastic,
protonInelastic,
...



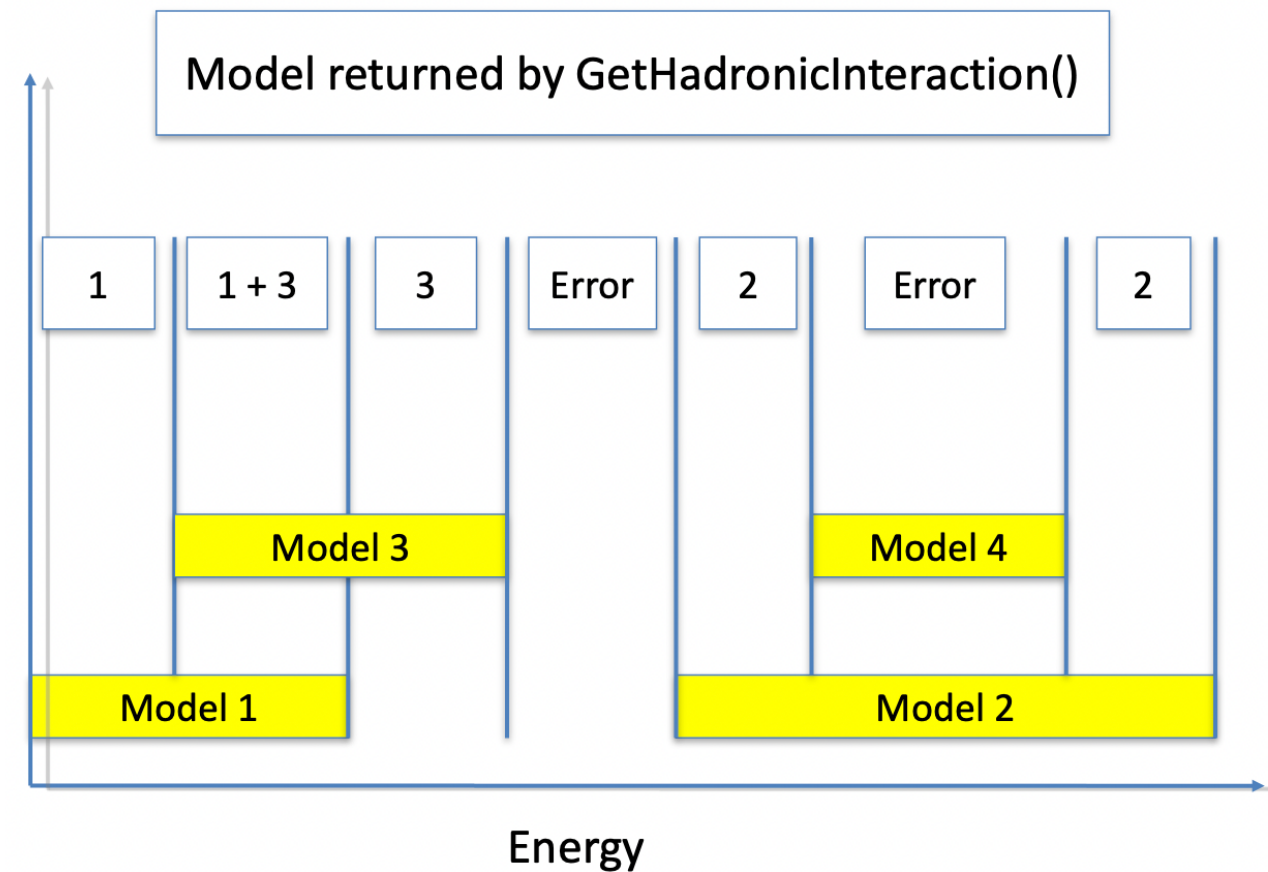
Hadronic Interactions Recap 3

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

Example: inspect neutron processes (FTFP_BERT)

- ◆ 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 secondaries (see next slide)

```
/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 lose 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/G4EML0W8.5
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
G4PII1DATA	=	/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
G4ABLA3DATA	=	/path-to/geant4-install/data/Geant4-11.2.1/data/G4ABLA3.3
G4INCL1DATA	=	/path-to/geant4-install/data/Geant4-11.2.1/data/G4INCL1.2

Needed only by specific physics list

Datasets

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- ◆ 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/Geant4-11.3.2/data/G4EML0W8.6.1
G4LEVELGAMMADATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/PhotonEvaporation6.1
G4PARTICLEXSDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4PARTICLEXS4.1
G4SAIDXSDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4SAIDDATA2.0
G4ENSDFSTATEDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4ENSDFSTATE3.0

G4NEUTRONHPDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4NDL4.7.1
G4RADIOACTIVEDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/RadioactiveDecay6.1.2
G4PIIDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4PII1.3
G4REALSURFACEDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/data/RealSurface2.2
G4ABLAData	=	/path-to/geant4-install/data/Geant4-11.3.2/data/G4ABLA3.3
G4INCLDATA	=	/path-to/geant4-install/data/Geant4-11.3.2/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:

1. Build their own custom physics list

2. Use a reference physics list

3. **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 physics 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 2: use it directly

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

Method 3: 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);
    ...
}
```

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));
    // Synchrotron 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));
}
```

pName can also be: "FTFP_BERT + G4RadioactiveDecayPhysics"



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 $>\sim 4$ GeV
- ◆ **P**: G4Precompound model for nucleus de-excitation + evaporation models
- ◆ **BERT**: (Bertini) intra-nuclear cascade model for the hadron inelastic process $<\sim 6$ 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