



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**:  $\gamma$  (`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:

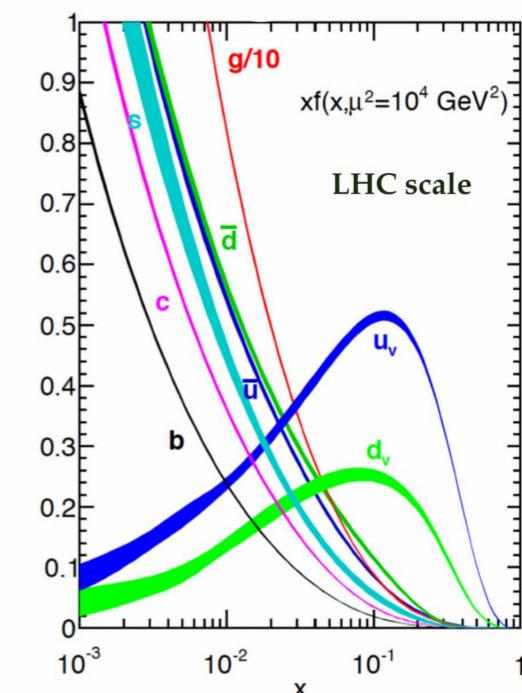
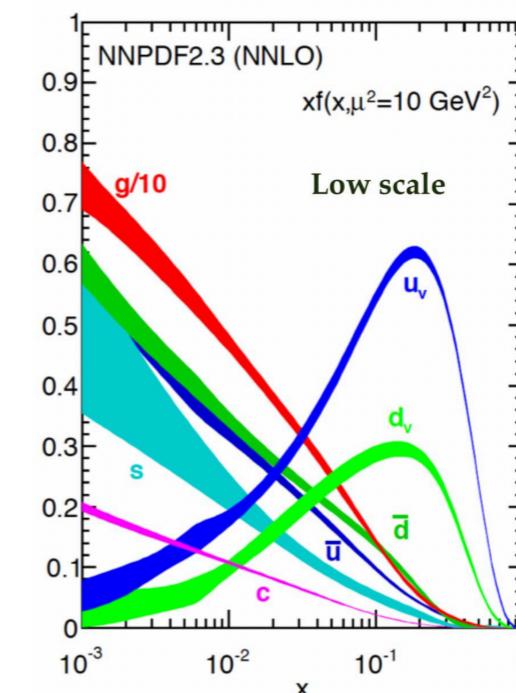
$\hat{\sigma}_{ab \rightarrow X}(x_1 x_2 s, Q^2)$ :  
cross section for  
partons process (QCD)

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

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

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

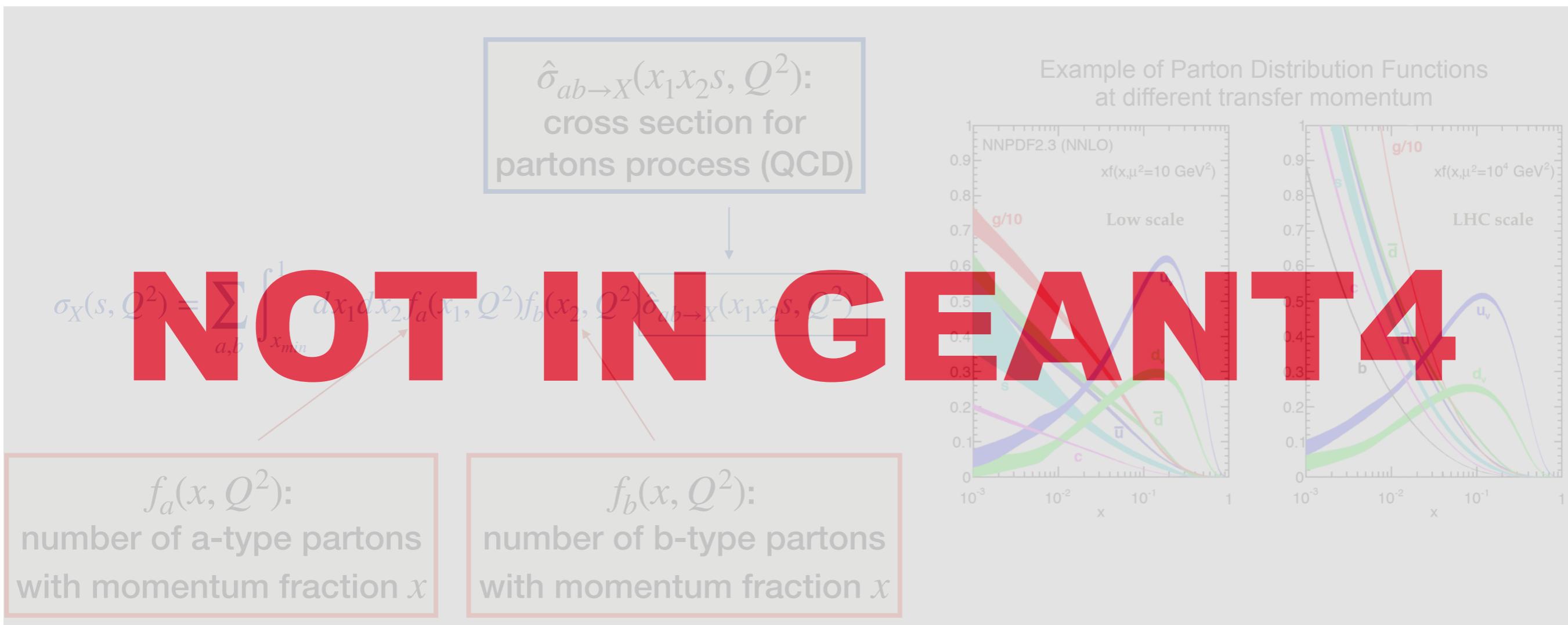
Example of Parton Distribution Functions  
at different transfer momentum



# 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:



# 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

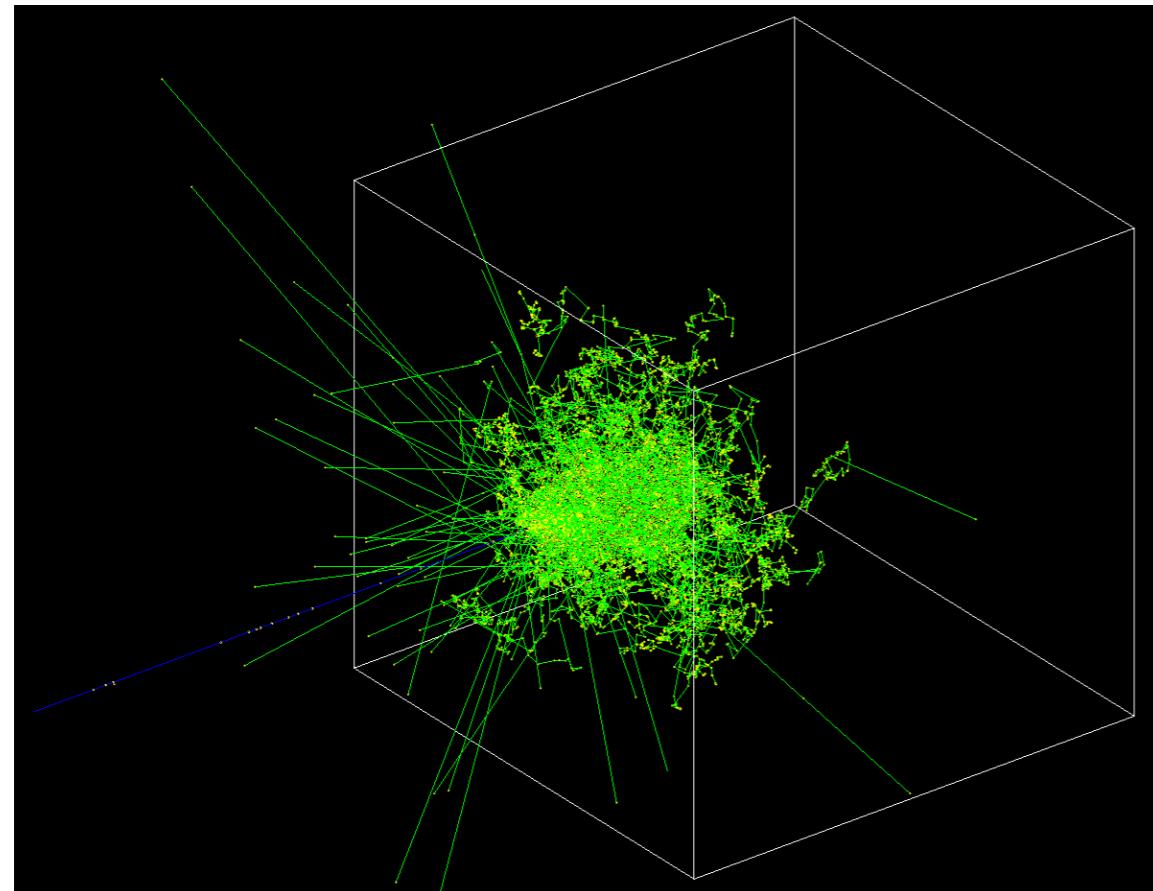
- ◆ **Hadronic final states models** describe the properties of the secondaries from the hadronic interaction (`G4HadronicProcess::GetHadronicInteraction()`)
  - Related to the number, type and properties of the secondaries produced by the interaction
- ◆ When a process is selected against the others, a final state (distribution of secondaries) is produced by one of the hadronic models working in the current energy range

# Cross Sections and Models

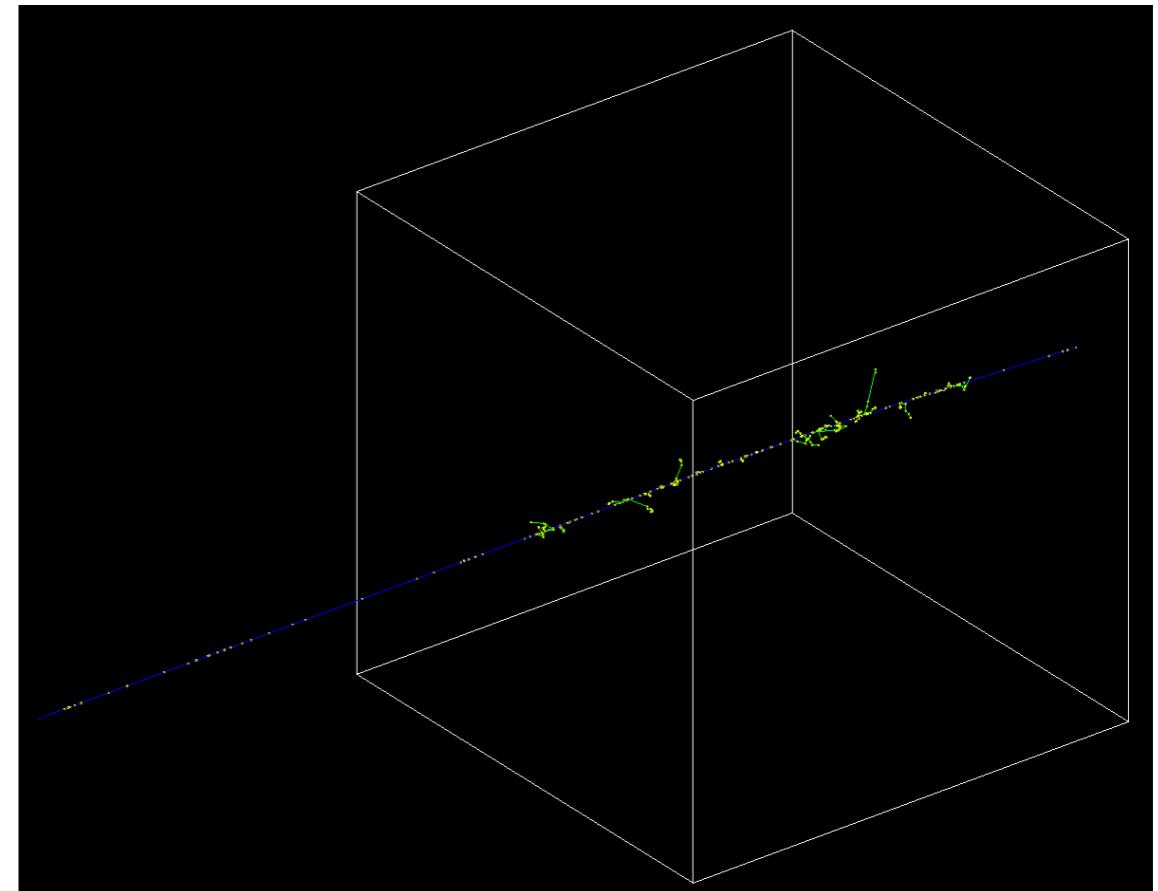
- ◆ For each combination of projectile – energy – target:
  - $\geq 1$  cross sections must be specified in a physics list
  - 1 or 2 (final-state) models must be specified in a physics list

# Example: inactivate hadron inelastic (on Fe)

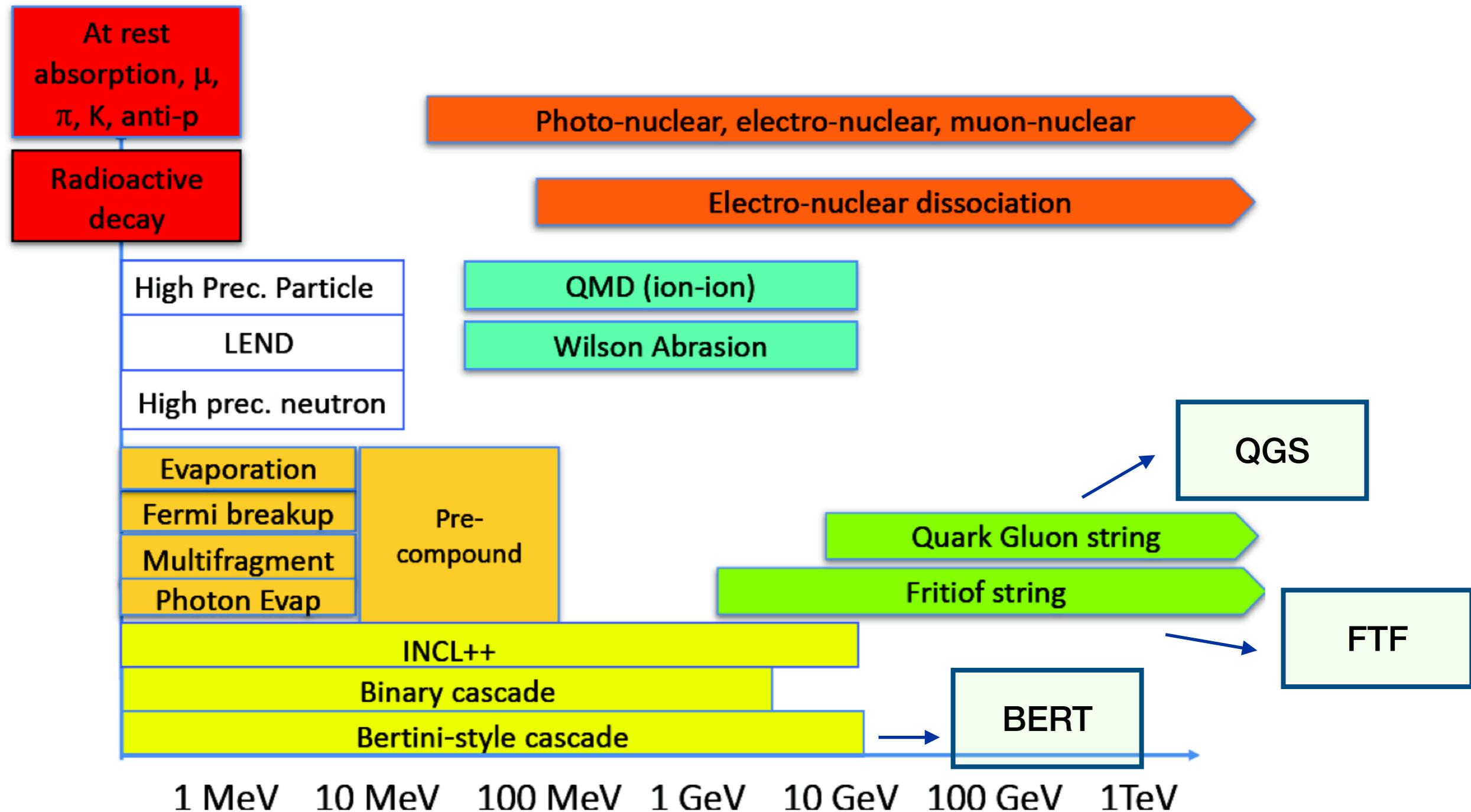
```
/gun/particle proton  
/gun/energy 10 GeV
```



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



# Partial hadronic final states models inventory

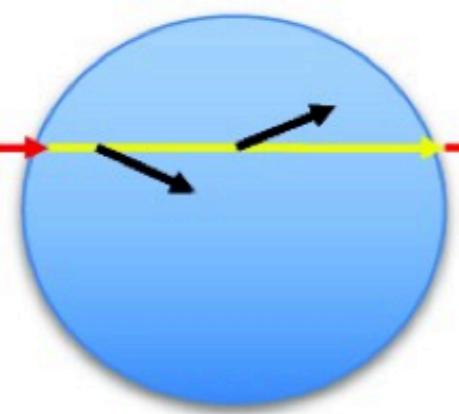


**NOTE:** Physics list names are derived from the hadronic models used  
(see lesson *how to choose a physics list*)

# Hadronic Interactions from TeV to MeV

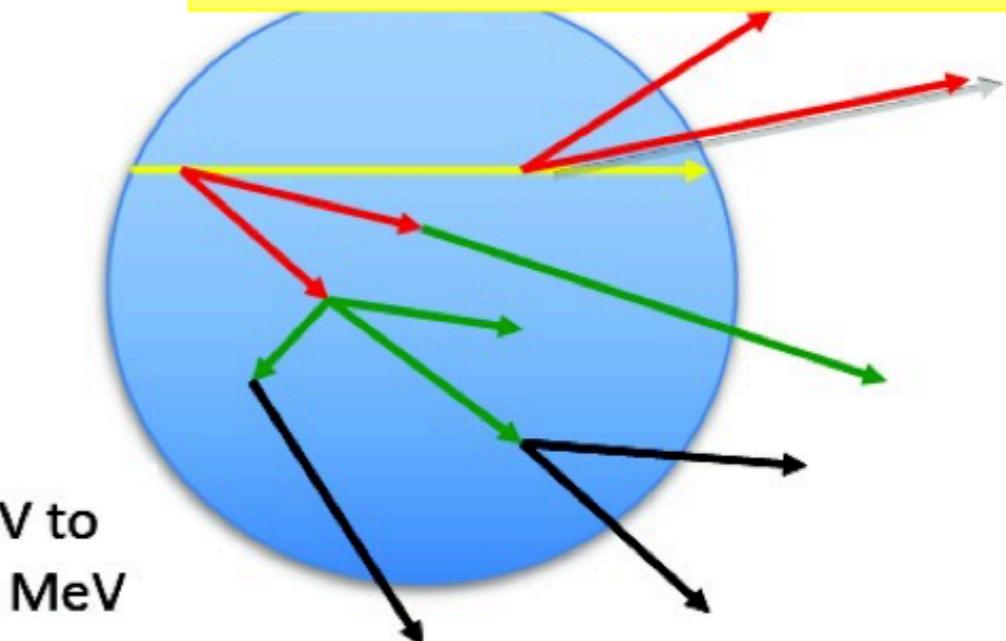
String model

TeV hadron



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

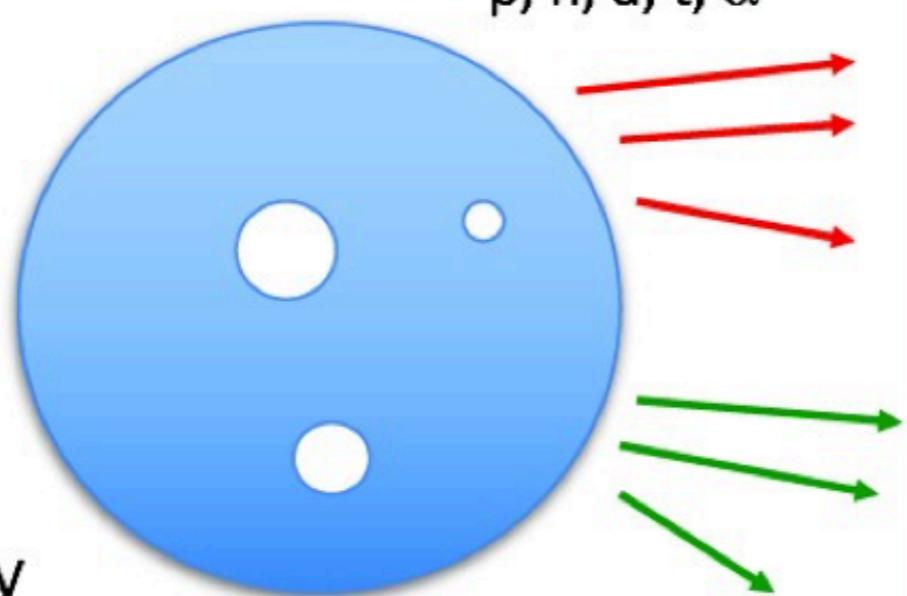
Intra-nuclear cascade model



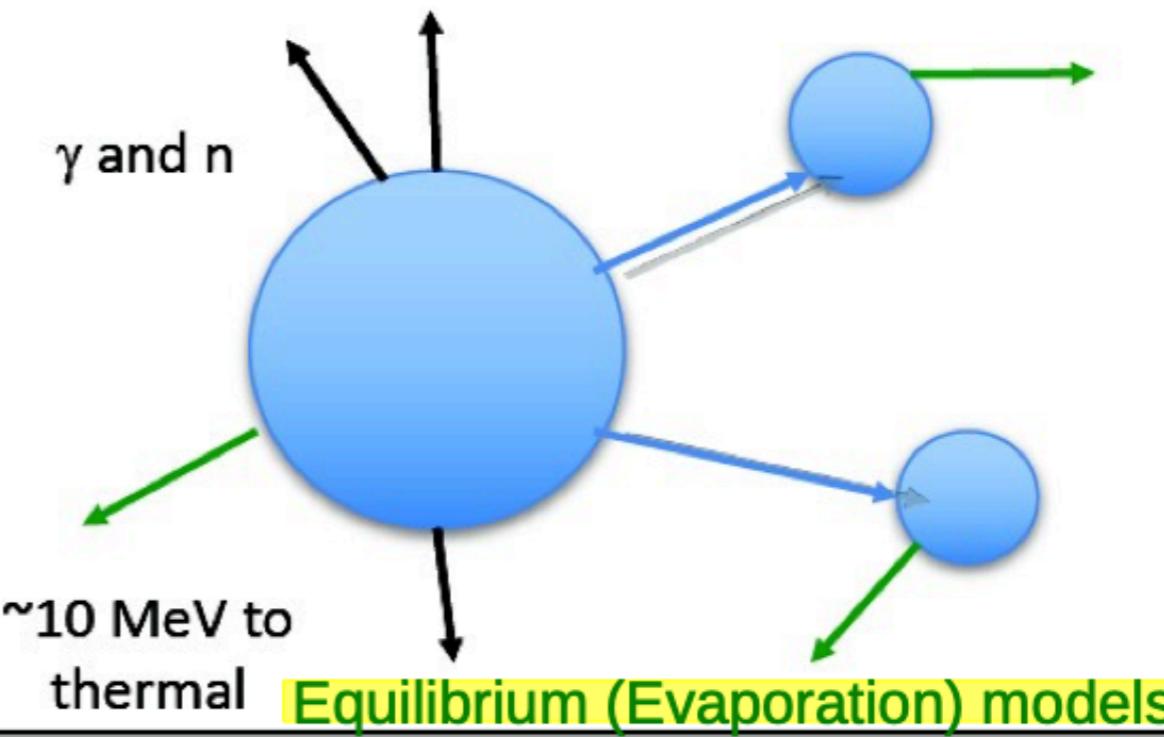
~GeV to  
~100 MeV

p, n, d, t,  $\alpha$

~100 MeV  
to ~10 MeV



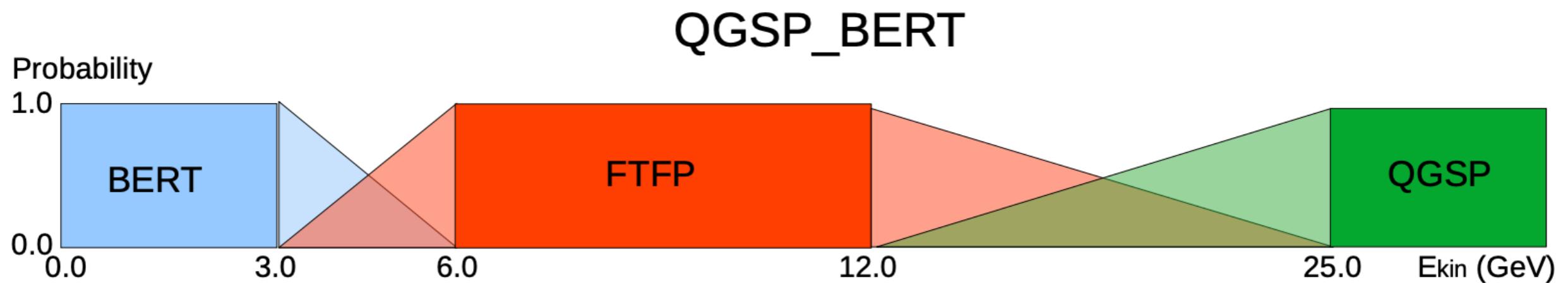
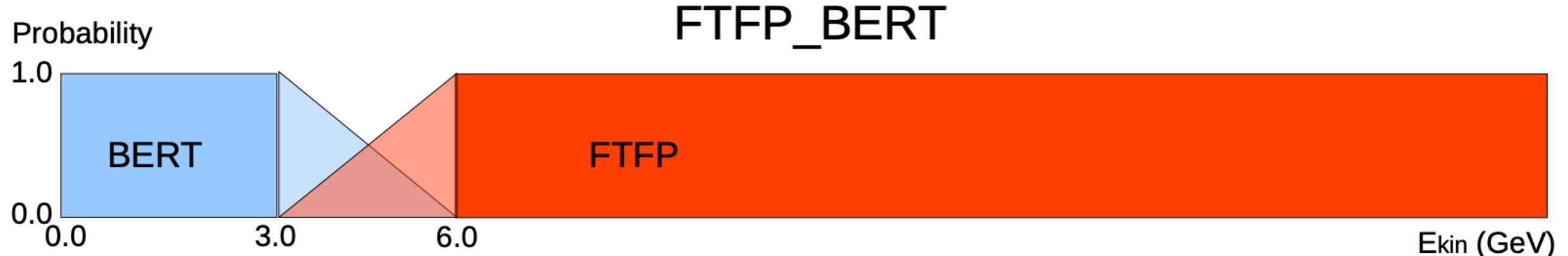
Pre-equilibrium (Precompound)



~10 MeV to  
thermal

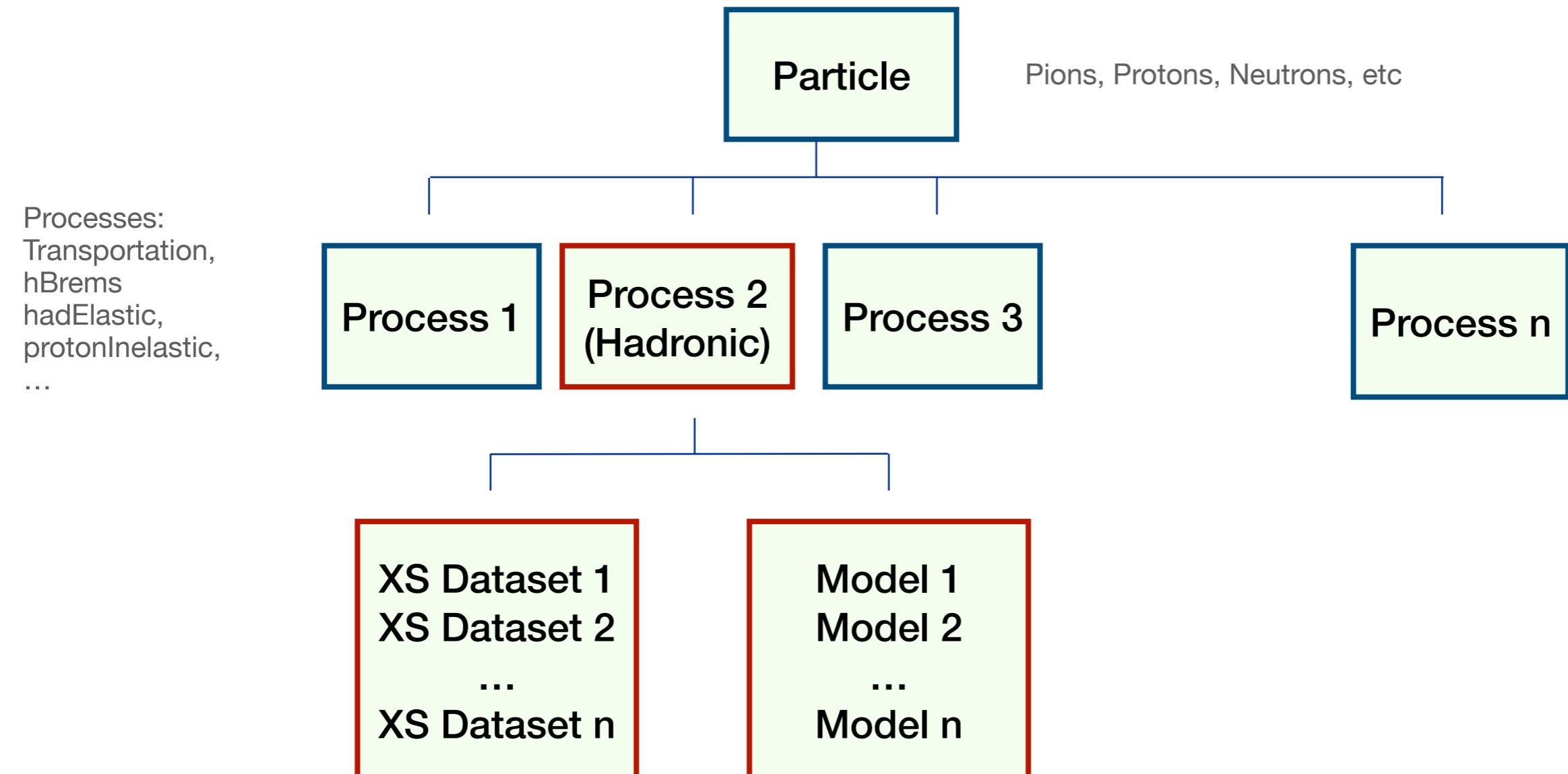
Equilibrium (Evaporation) models

# Example of final-state models transition



# Hadronic interactions Recap 1

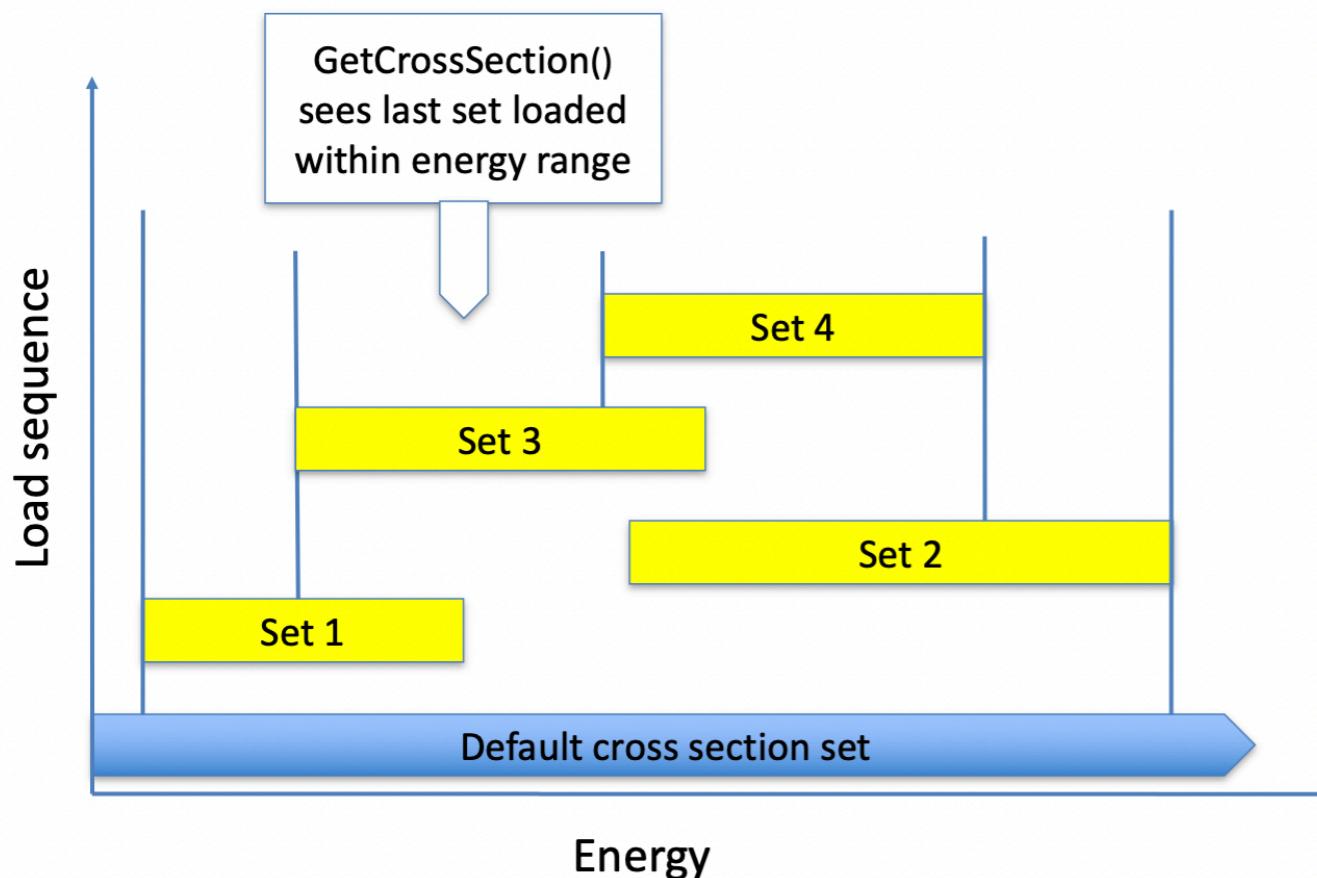
*Particles, Associated Processes, Datasets and Models*



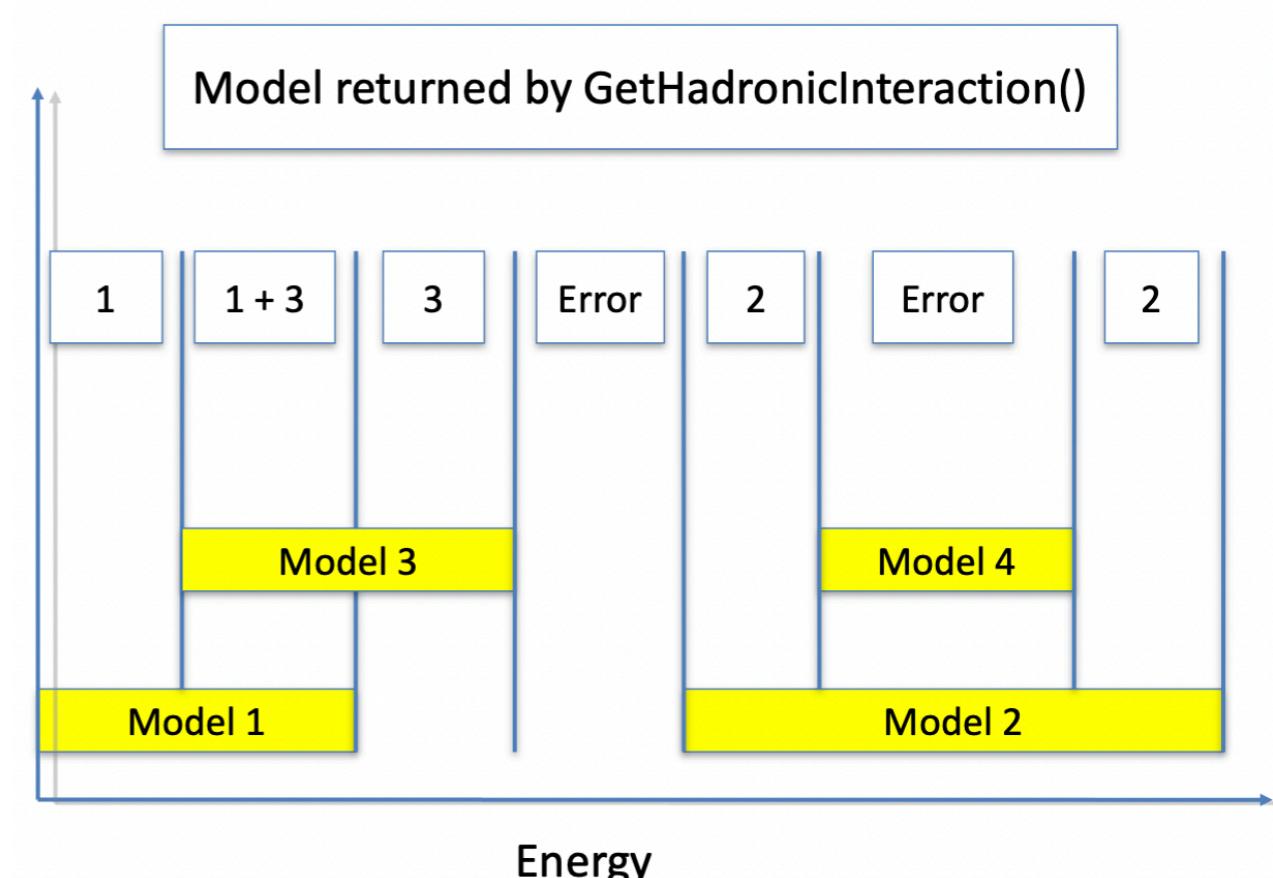
# Hadronic interactions Recap 2

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

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 (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           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

```
G4LEDEDATA      = /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
G4PARTICLEXS DATA = /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
G4ENSDFSTATE DATA = /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

- ◆ **G4LEDETA** : 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);
    ...
}
```

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));
}
```

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,  ${}^3\text{He}$ , 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  $\sim$ 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