

Hadronic Physics I

Geant4-11.1 reference - Based on previous Geant4 courses

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Covered topics

- ◆ **Hadronic physics: final state models vs. cross sections**
- ◆ **Hadronic physics framework**
- ◆ **Capture at rest**
- ◆ **Neutron physics**
- ◆ **Hadronic physics in reference physics lists**

... to be followed by Hadronic Physics II at this course

Geant4 particles and hadrons

(1/3)

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

- ◆ **Leptons:** e^\pm (G4Electron, G4Positron), μ^\pm (G4MuonMinus, G4MuonPlus), ...
- ◆ **Bosons:** γ (G4Gamma), G4OpticalPhoton
- ◆ **G4Geantino**, i.e. a particle with no processes except transportation
- ◆ **“Stable” hadrons:** π^\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 and hadrons

(2/3)

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Bash - Example: inspect π^+ properties

```
/particle/select pi+      # UI Command
/particle/property/dump  # UI Command

--- G4ParticleDefinition ---
Particle Name : pi+
PDG 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
```

Geant4 particles and hadrons

(3/3)

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**

Bash - Example: inspect proton hadronic processes

```
/particle/select proton # UI command
/particle/process/dump # UI command

G4ProcessManager: particle[proton]
[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
```

Hadronic interactions

(1/3)

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:

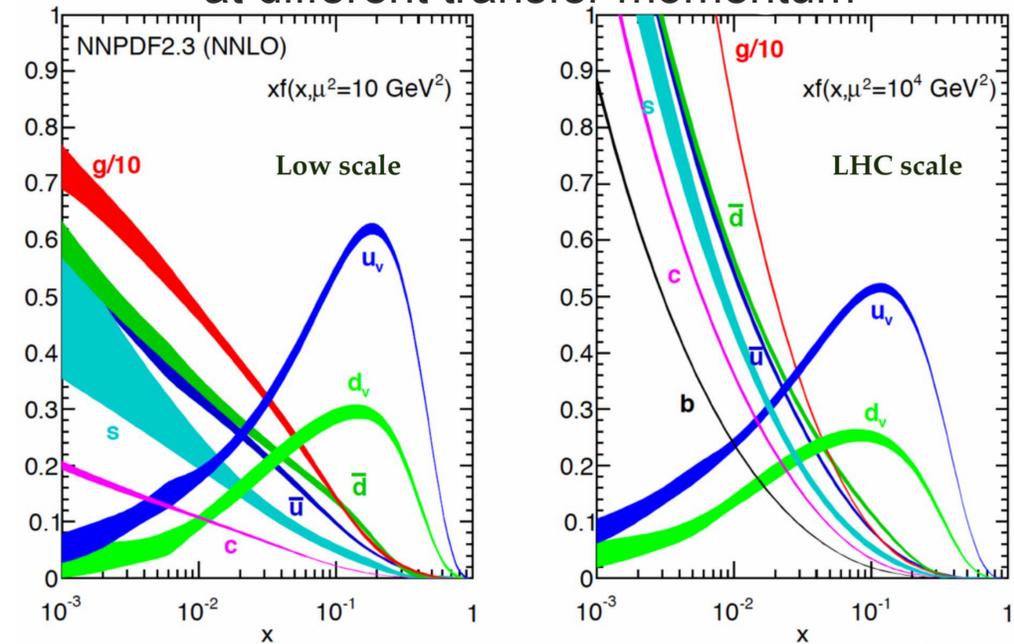
$$\sigma_X(s, Q^2) = \sum_{a,b} \int_{x_{min}}^1 dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(x_1 x_2 s, Q^2)$$

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

$f_a(x, Q^2)$:
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

(2/3)

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

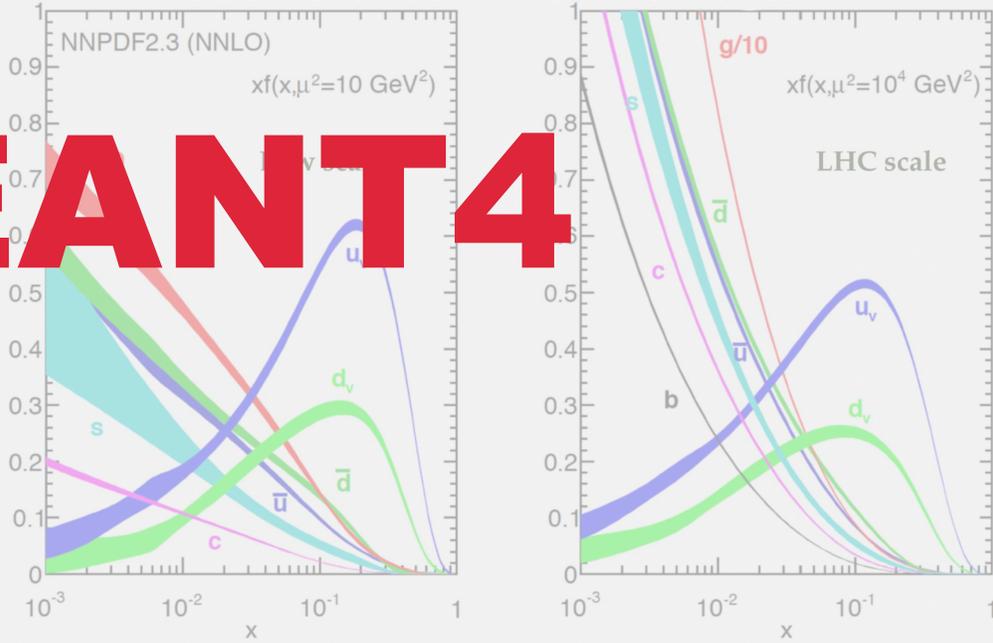
$$\sigma_X(s, Q^2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(x_1 x_2 s, Q^2)$$

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

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

NOT IN GEANT4

Example of Parton Distribution Functions at different transfer momentum



Hadronic interactions

(3/3)

- ◆ 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

Hadronic cross sections

First approximation, **Geant4 separates hadronic cross section datasets from hadronic final states models**

- ◆ **Hadronic cross section datasets** refer to the *total cross section* for a hadronic-nucleus interaction (`G4HadronicProcess::GetElementCrossSection()`)
 - ❖ For each combination of particle, energy and target-material ≥ 1 cross sections must be specified in a physics list (in case more than one is available the last one set is used)
- ◆ 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

NOTE: there are no *differential cross sections* 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

RunAction.cc - Example: get hadronic inelastic cross section (without simulation)

```
#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;
    }
}
```

Bash - execution

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

Good example of code *modularity*: Geant4 is a toolkit, not a software

Available on



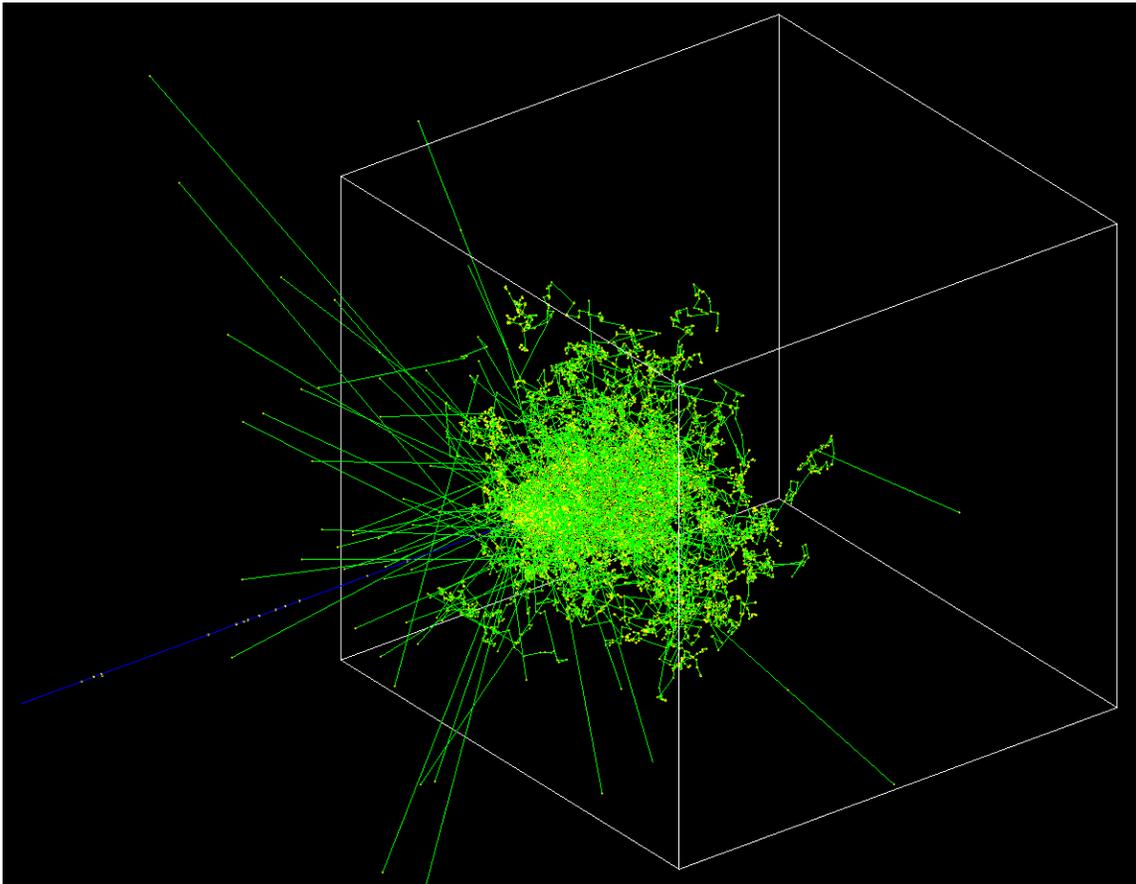
Hadronic final states models

First approximation, **Geant4 separates hadronic cross section datasets from hadronic final states models**

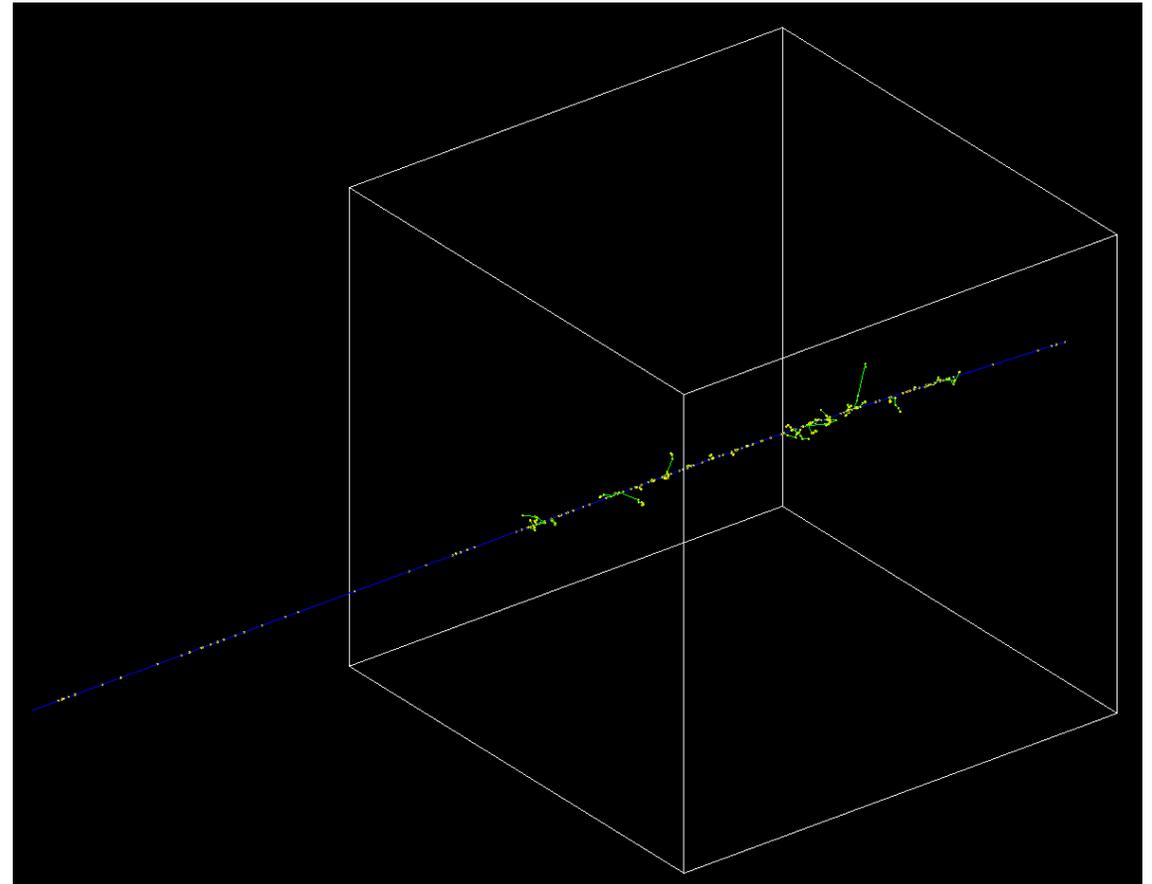
- ◆ **Hadronic final states models** describe the properties of the *secondaries* from the hadronic interaction (`G4HadronicProcess::GetHadronicInteraction()`)
 - ❖ For each combination of particle, energy and target-material, 1 or 2 final states model(s) must be specified in a physics list
(in case two are present in the same energy range, one is selected according to a linear probability interpolation)
- ◆ The **hadron elastic process** competes with the **hadron inelastic one**
(as with any other process, e.g. ionization, bremsstrahlung, transportation, ...)
- ◆ When an inelastic hadronic process occurs, i.e. the 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 (p on Fe)

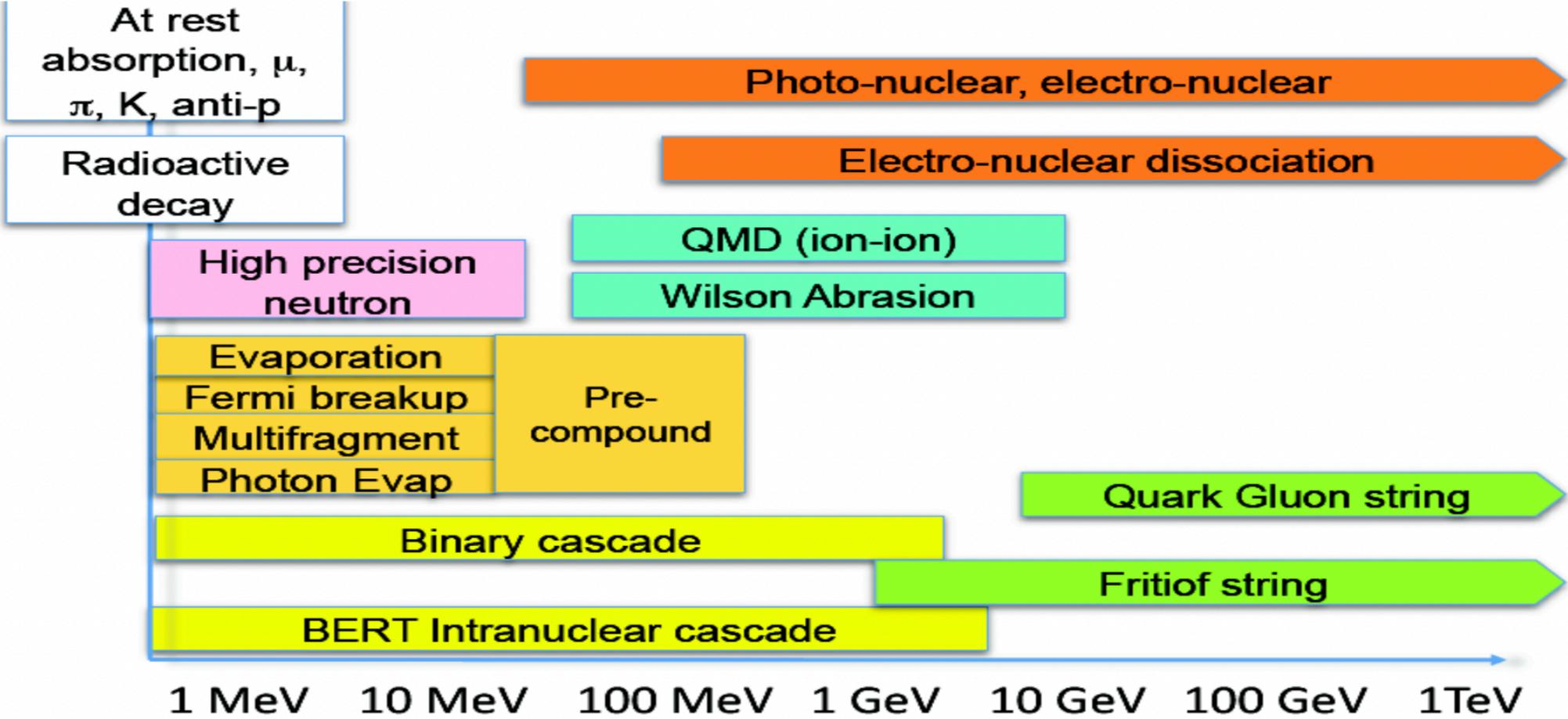
```
/gun/particle proton  
/gun/energy 10 GeV
```



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

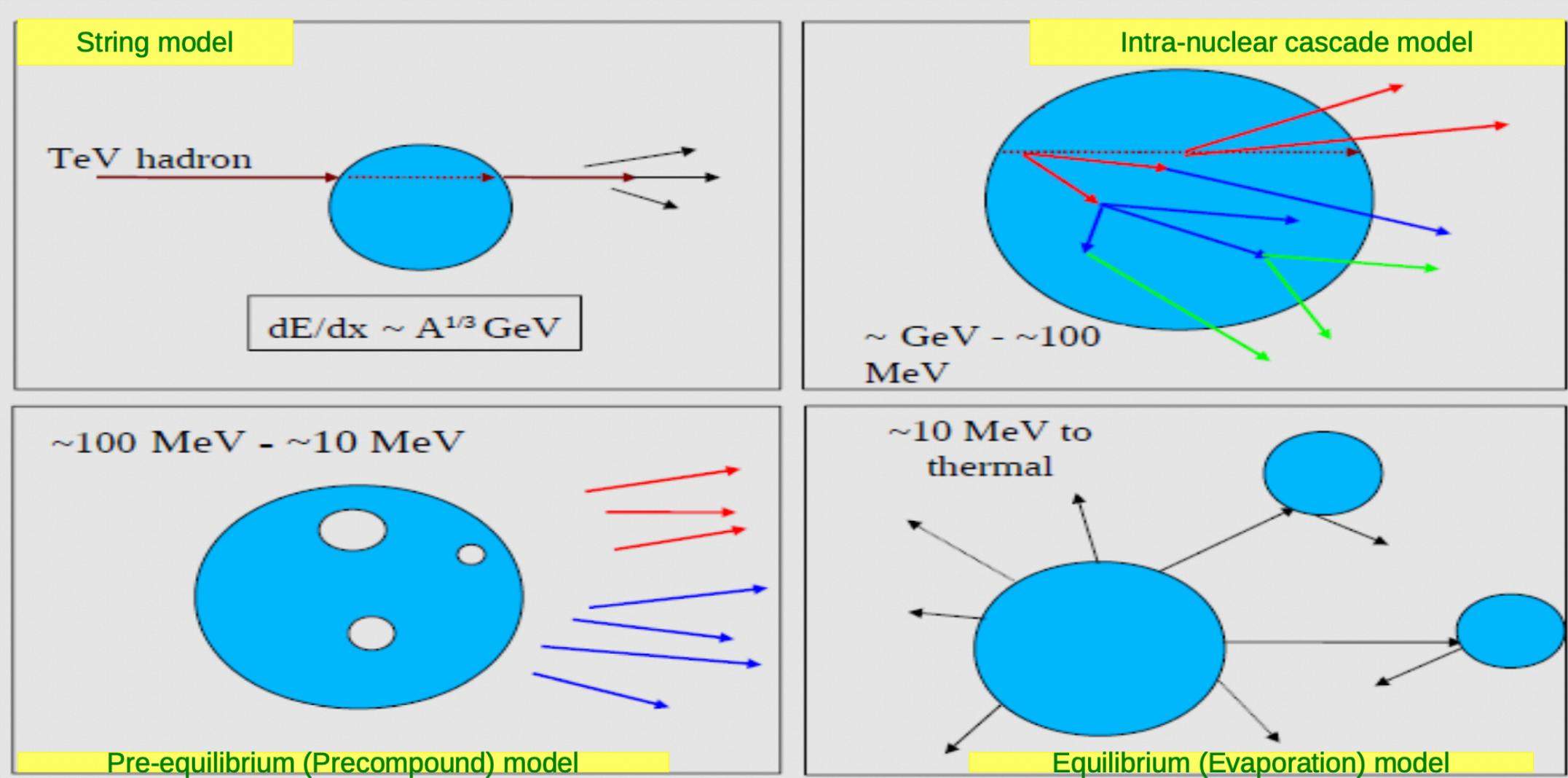


Partial hadronic final states models inventory



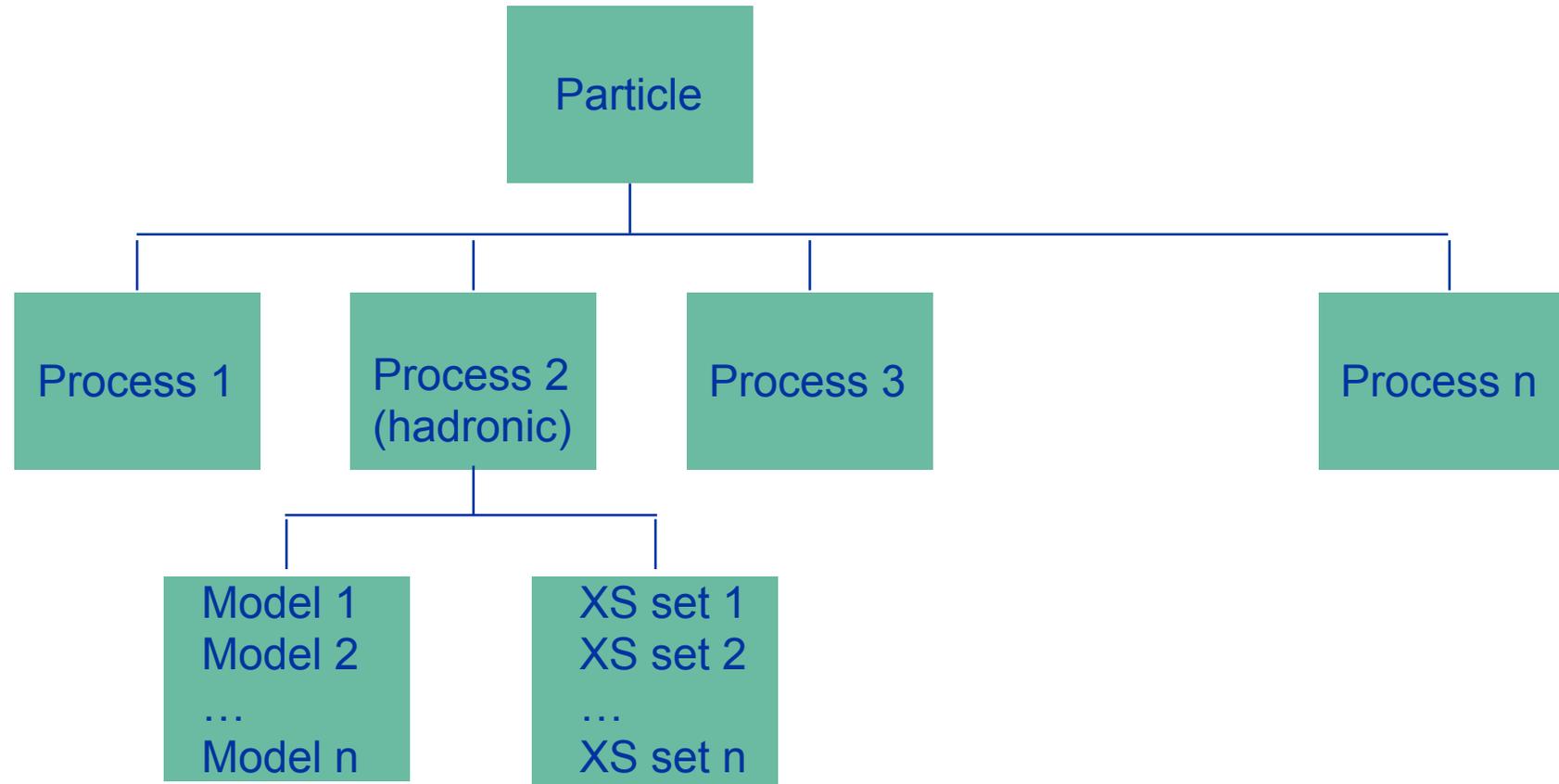
NOTE: Physics list names are derived from the hadronic models used (see lesson *how to choose a physics list*)

Sketch of hadronic final states models



Recap: hadronic physics framework

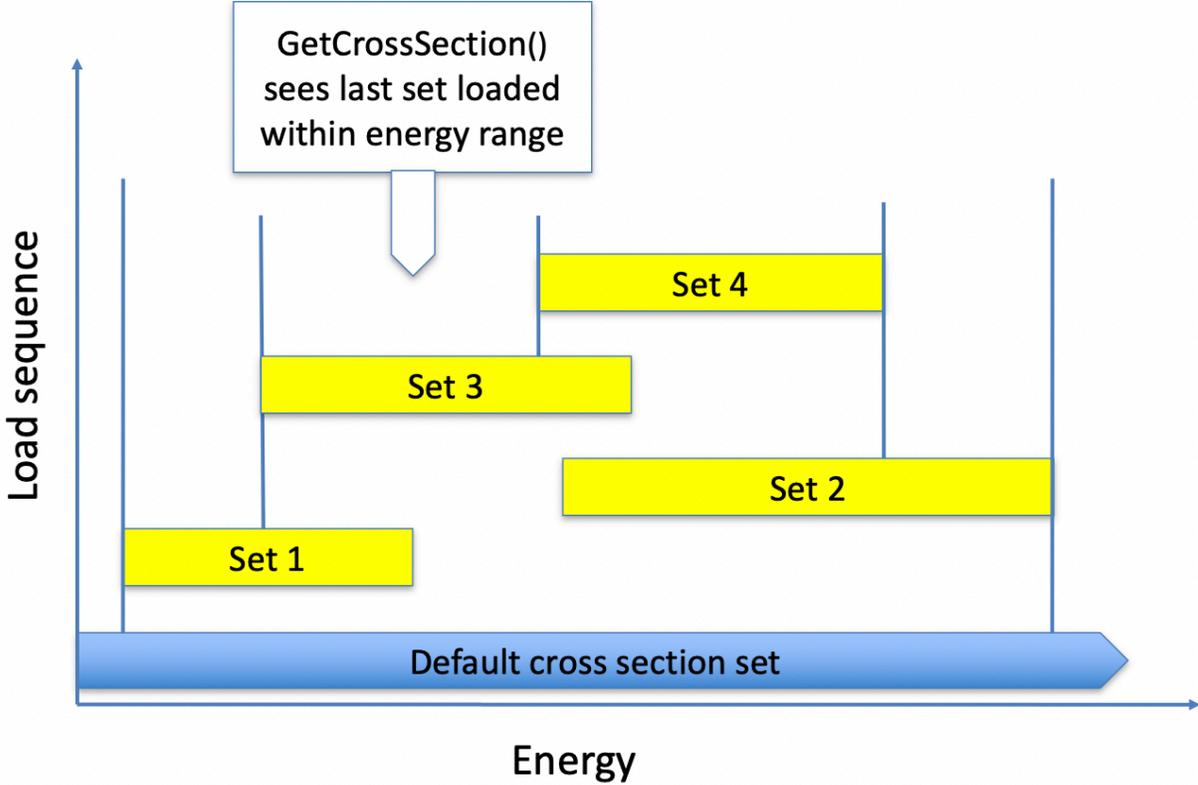
(1/2)



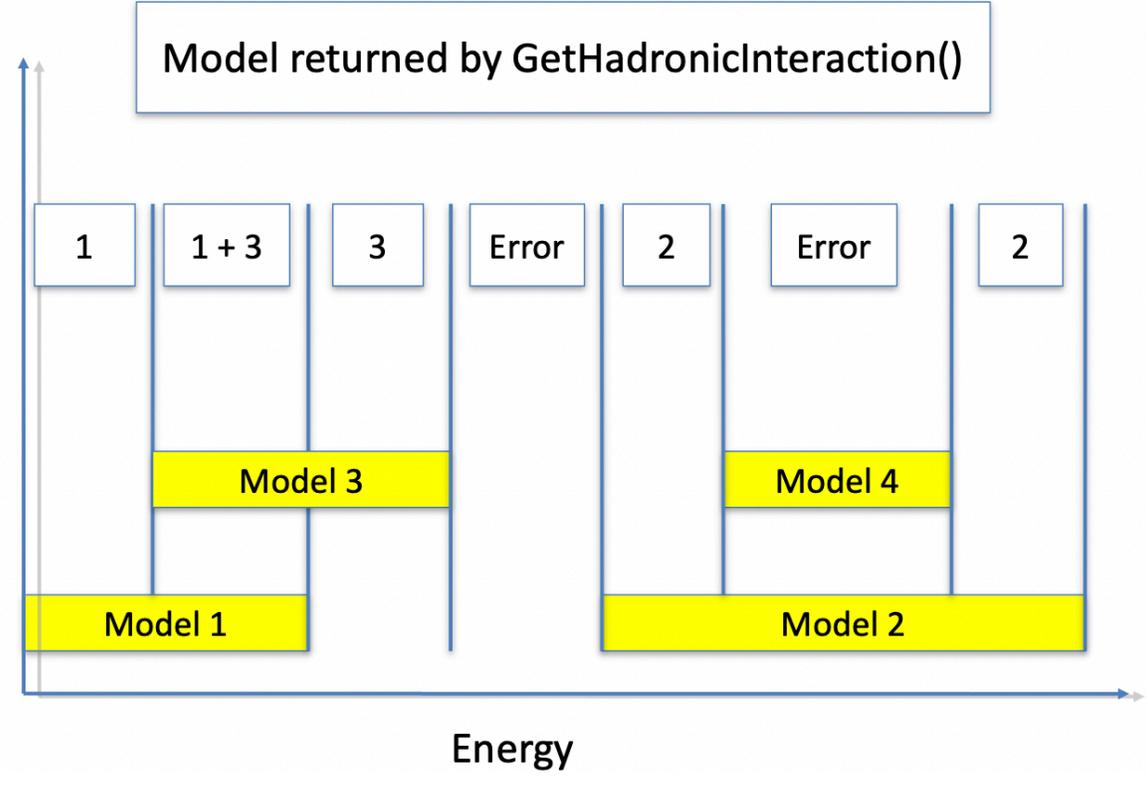
Recap: hadronic physics framework

(2/2)

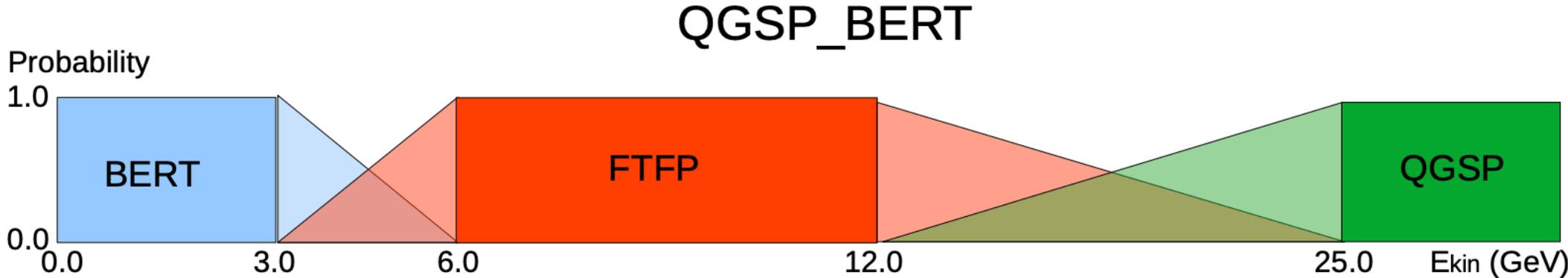
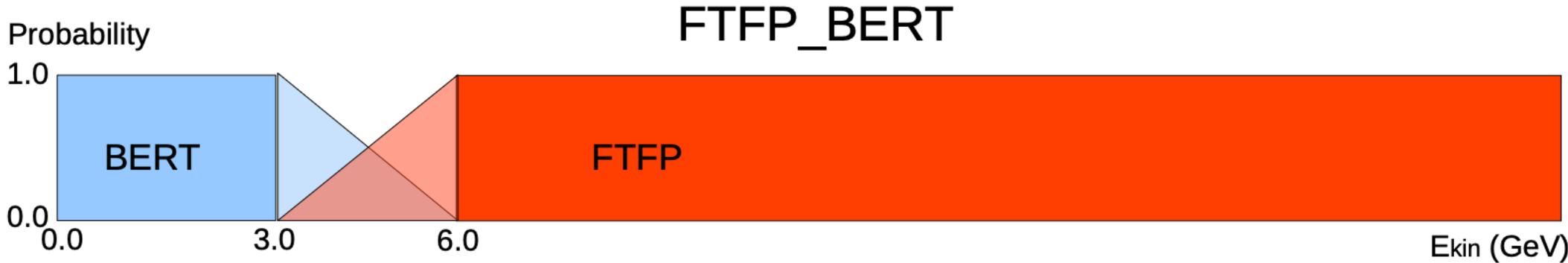
Cross section management



Final state model management



Example of final-state models transition



Nuclear capture 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
 - ❖ It should not be confused with hadron inelastic process happening *in-flight*

Bash - Example: inspect π^- processes

```
/particle/select pi- # UI command
/particle/process/dump # UI command

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
```

- ◆ 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

Example: inspect steps of a 10 MeV proton in iron and compare with π^- (next slide)

```
/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.

Example: inspect steps of a 10 MeV proton (previous slide) in iron and compare with π^-

```
/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

(1/2)

- ◆ 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 (take care *lepto-nuclear* and *gamma-nuclear* processes release neutrons too)

Bash - Example: inspect neutron processes (FTFP_BERT)

```
/particle/select neutron # UI command
/particle/process/dump   # UI command

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
```

- ◆ 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 γ (see next slide)

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

Example: inspect steps of a 1 MeV neutron in iron (FTFP_BERT)

```
/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

(2/2)

- ◆ 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 $10\mu s$) 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*)

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 `geant4.sh` and linked to datasets

`geant4install/bin/geant4.sh` - [Mandatory to every physics list, needed only to specific physics lists]

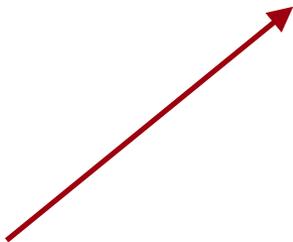
```
# Resource file paths
# - Datasets

export G4NEUTRONHPDATA="/path-to/geant4-install/share/Geant4/data/G4NDL4.7"
export G4LEDATA="/path-to/geant4-install/share/Geant4/data/G4EMLOW8.2"
export G4LEVELGAMMADATA="/path-to/geant4-install/share/Geant4/data/PhotonEvaporation5.7"
export G4RADIOACTIVEDATA="/path-to/geant4-install/share/Geant4/data/RadioactiveDecay5.6"
export G4PARTICLEXSDATA="/path-to/geant4-install/share/Geant4/data/G4PARTICLEXS4.0"
export G4PIIDATA="/path-to/geant4-install/share/Geant4/data/G4PII1.3"
export G4REALSURFACEDATA="/path-to/geant4-install/share/Geant4/data/RealSurface2.2"
export G4SAIDXSDATA="/path-to/geant4-install/share/Geant4/data/G4SAIDDATA2.0"
export G4ABLADATA="/path-to/geant4-install/share/Geant4/data/G4ABLA3.1"
export G4INCLDATA="/path-to/geant4-install/share/Geant4/data/G4INCL1.0"
export G4ENSDFSTATEDATA="/path-to/geant4-install/share/Geant4/data/G4ENSDFSTATE2.3"
```

- ◆ **G4LEDDATA** : 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

- ◆ **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

- ◆ 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
- ◆ Using a reference physics list is straightforward, e.g. in `main()`
`G4VModularPhysicsList* PL = new FTFP_BERT();`
`runManager->SetUserInitialization(PL);`
- ◆ 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*
- ◆ Example of hadronic physics constructors 

geant4/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));
}
```

Reference physics lists

(1/2)

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

- ◆ **FTF**: (Fritiof) hadronic string model for hadron inelastic process > 3 GeV
- ◆ **P**: Precompound 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

(2/2)

Other relevant reference physics lists for hadronic physics are

- ◆ The **FTFP_BERT_HP** PL: same as FTFP_BERT but using the high-precision neutron treatment for low energy neutrons (< 20 MeV)
- ◆ The **QGSP_BERT** PL: 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

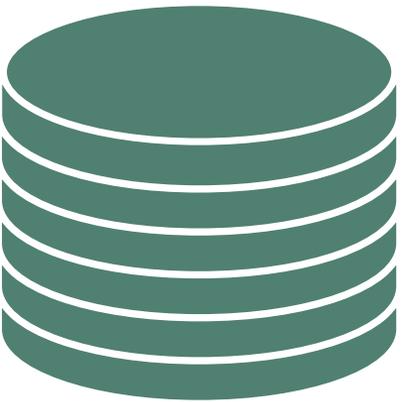
NOTE: Below 12 GeV QGSP_BERT and FTFP_BERT are identical

- ◆ The **FTFP_INCLXX** PL: 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** PL: 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

Recap of *Hadronic Physics I*

- ◆ Geant4 implements two main hadronic processes, the *hadron elastic* and the *hadron inelastic* processes
- ◆ 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

Backup material



The FTF String model algorithm

(1/2)

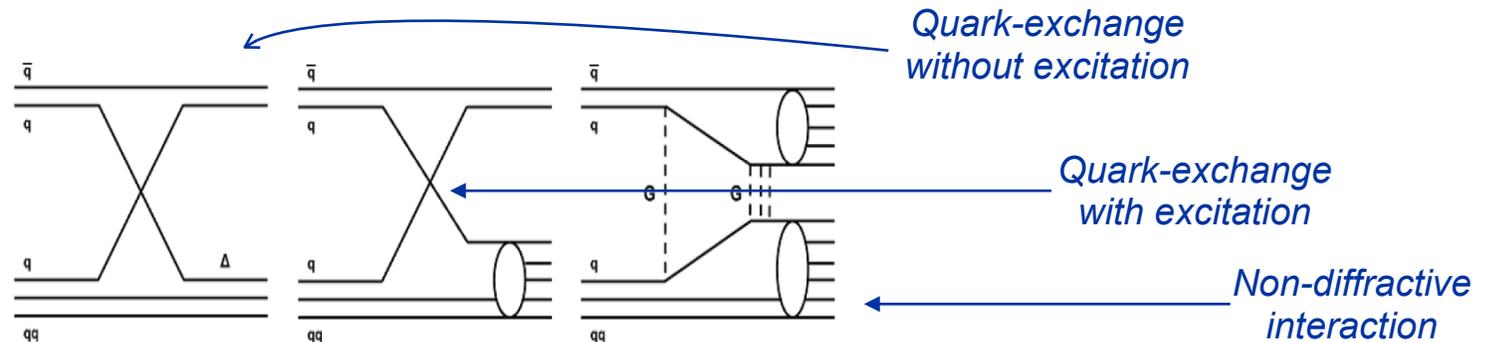
- ◆ Parton string models in Geant4 describe the inelastic interaction of on nucleon/nuclear-target with nucleon, π and k projectiles. The interaction is described in terms of constituent quarks
- ◆ The target nucleus (A nucleons, Z protons) is initialized by selecting r_i coordinates and p_i momenta with $i = 1, \dots, A$
 - ❖ The energy per nucleon is computed as $e = E/A = m_N + B(A, Z)/A$ where m_N is the nucleon mass and $B(A, Z)$ is the nucleon binding energy.
 - ❖ The effective mass of each nucleon is $m_{eff} = \sqrt{(E/A)^2 - p_i^2}$
- ◆ The *impact parameter* of the projectile over the target is randomly chosen
- ◆ The interaction point z_i is sampled according to the total projectile-nucleon cross-section
 - ❖ The closest nucleon is chosen as the interacting one
 - ❖ A choice between elastic and inelastic interaction is implemented

The FTF String model algorithm

(2/2)

- ◆ In case an inelastic collision is chosen a multi-particle process is simulated:
 - ♣ The FTF model assumes that all hadron-nucleon interactions are binary reactions $h_1 + h_2 \rightarrow h'_1 + h'_2$
- ◆ The hadron nucleon interaction can be a quark exchange with excitation, quark exchange without excitation, or a diffractive/non-diffractive interaction

♣ Examples for $\pi^- p$ interaction:



- ◆ For each produced particle new interaction points are sampled
- ◆ Excited hadrons, referred to as *strings*, is decayed into stable particles by the LUND fragmentation model
- ◆ The excitation energy of the residual nucleus is calculated and the nucleus is de-excited with the Precompound and evaporation models