# Hadronic Physics I

Alberto Ribon
CERN EP-SFT

Geant4 Advanced Course, 14 – 18 October 2024

# Outline

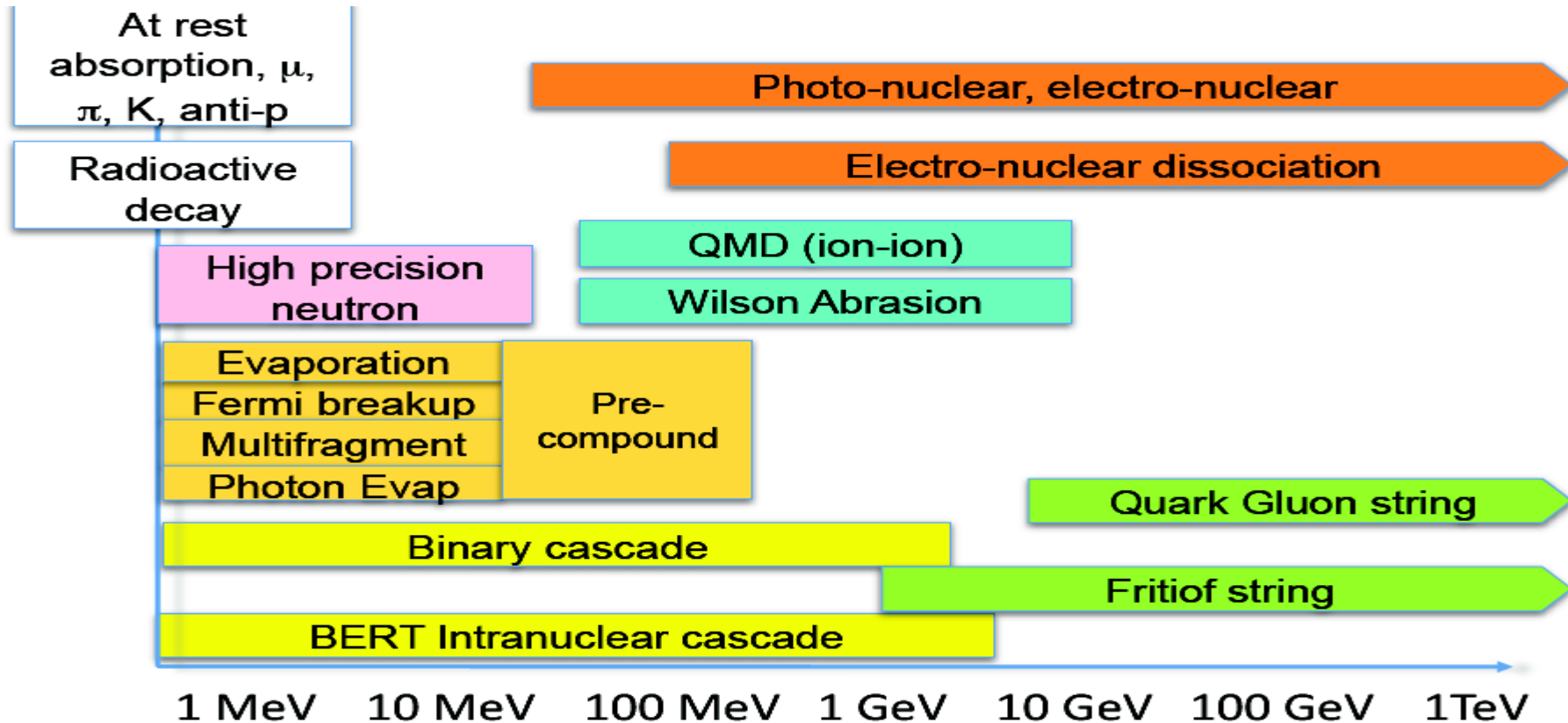- Hadronic Models, Cross Sections and Framework
- Physics Lists
- Validation
- Exercises

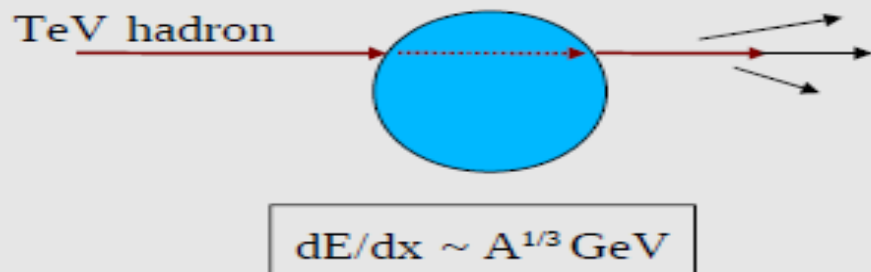# Hadronic Models, Cross Sections and Framework

# Hadronic interactions

- Hadrons ( π± , K± , K°L , p , n , α , *etc.*), produced in jets and decays, travel through the detector ( H , C , Ar , Si , Al , Fe , Cu , W , Pb ...)

- Therefore we need to model hadronic, strong interactions
  **hadron – nucleus -> *anything***

- In principle, QCD is the theory that describes all hadronic interactions in practice, perturbative calculations are applicable only in a tiny (but important!) phase-space region
  the hard scattering at high transverse momentum
  whereas for the rest, *i.e.* most of the phase space
  soft scattering, re-scattering, hadronization, nucleus de-excitation
  only approximate models are available

- Hadronic models are valid for limited combinations of

  **particle type − energy − target material**
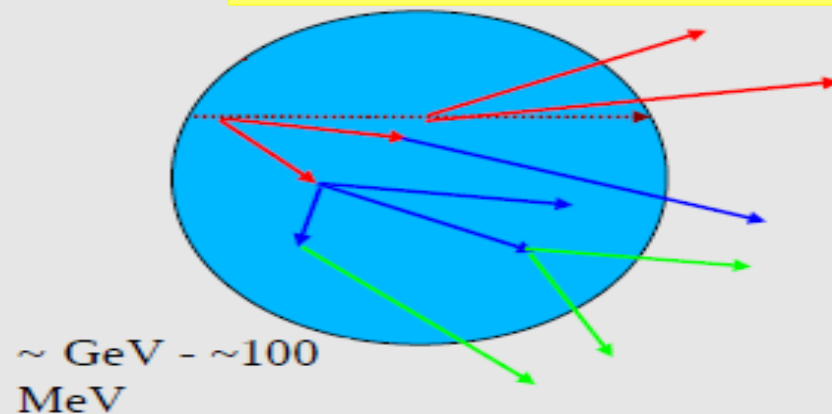
4

# Partial Hadronic Model Inventory

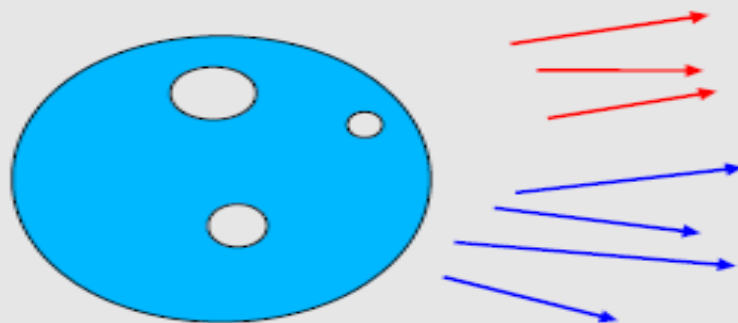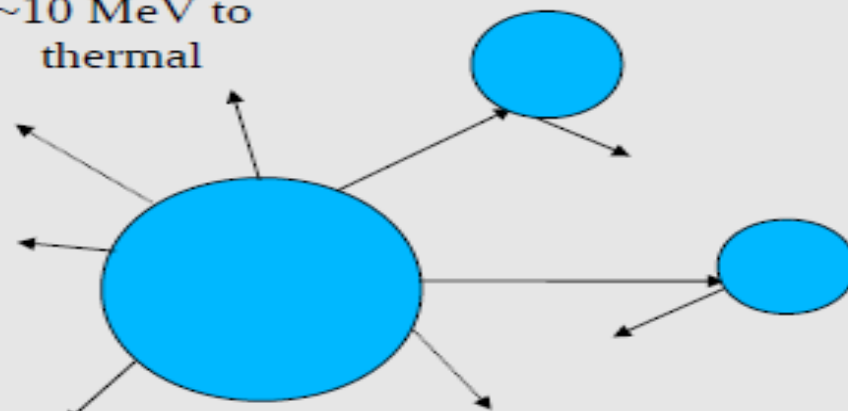# Hadronic Interactions from TeV to meV



String model

TeV hadron

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

Intra-nuclear cascade model

~ GeV - ~100 MeV

~100 MeV - ~10 MeV

Pre-equilibrium (Precompound) model
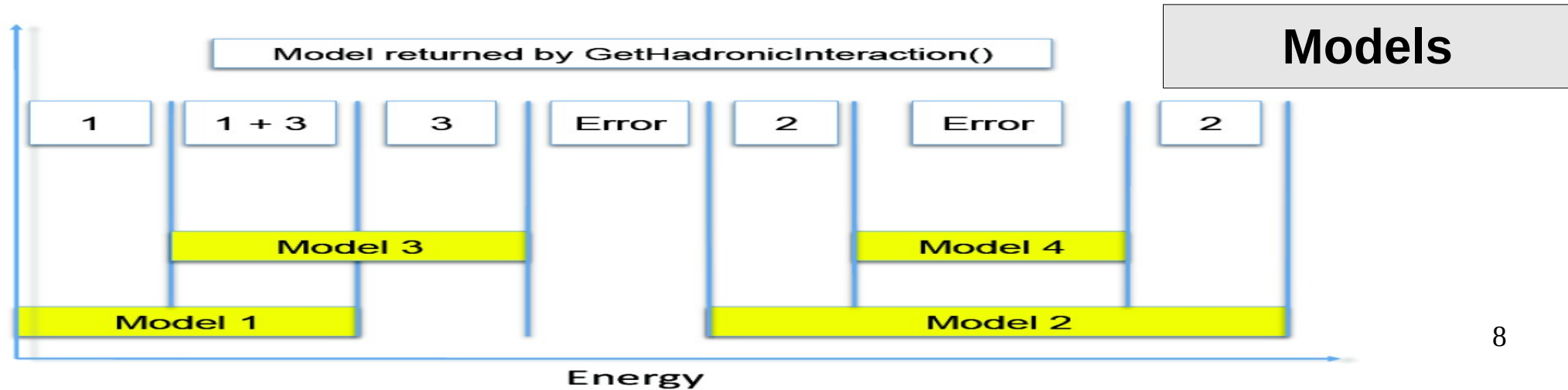
~10 MeV to thermal

Equilibrium (Evaporation) model
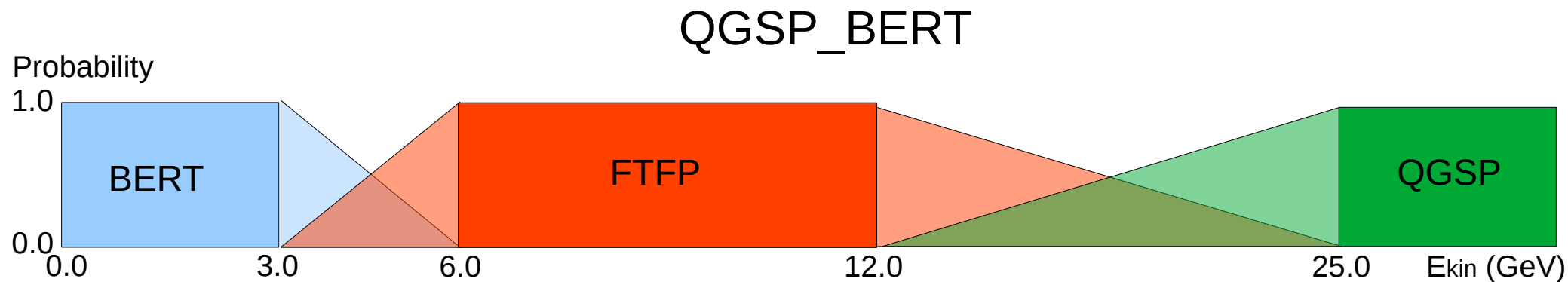
6

# Hadronic Cross Sections and (Final-State) Models

- In Geant4, there is a clear separation between **cross sections** – related to the probability of an elastic or inelastic hadron-nucleus interaction, and therefore to the length that a hadron projectile flies in a material before interacting – and **final-state models** – related to the number, type and properties of the produced secondaries

- For each combination of projectile – energy – target

  - ≥ 1 cross sections must be specified in a physics list : the first available is used

  - 1 or 2 (final-state) models must be specified in a physics list : if two, a random number is thrown to decide which of the two models to use

    – Assumed a linear probability as a function of the energy, over an interval called **transition region**, defined arbitrarily to get smooth observables

7

# Hadronic Framework



**Cross Sections**

GetCrossSection() sees last set loaded within energy range

Load sequence

Set 4

Set 3

Set 2

Set 1

Default cross section set

Energy

**Models**

Model returned by GetHadronicInteraction()

| 1 | 1 + 3 | 3 | Error | 2 | Error | 2 |

Model 3

Model 4

Model 1

Model 2

Energy

8

# Transition between Final-State Models



FTFP_BERT

QGSP_BERT
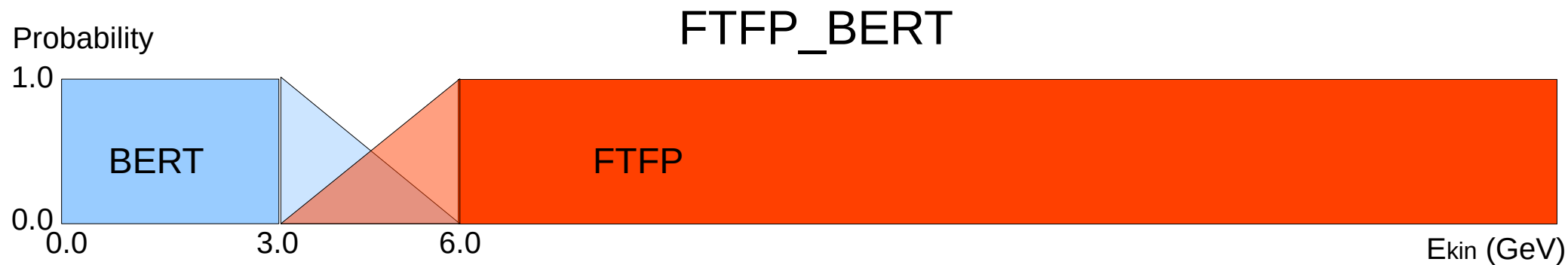
# Inclusive Cross Sections

- In Geant4, in general, for a given hadron projectile type, projectile kinetic energy and target nucleus (*e.g.* 10 GeV p on 56Fe), there are only **2** hadronic cross sections values used by Geant4

  - The **Elastic** cross section

    – Which is the integrated cross section of the process with only two final states, made by the same projectile hadron and ground-state target nucleus

  - The **Inelastic** cross section

    – Which is the integrated cross section for all the "rest" of the processes for any other final-state, with any multiplicity and type of secondaries

Note :  **Elastic + Inelastic** = **Total** cross section

Note : neutron (in particular at low energies) is an exception, because it has also radiative capture  and  fission  *(see later for more...)*

# Inelastic Final States

- In Geant4, for each hadron projectile type (p, π, K, *etc.*), the elastic process and inelastic process are distinct processes which compete with each other

  - As with other physics processes – *e.g.* ionization, decay, *etc.* – (neutrons have also capture and fission) as well as with transportation

- When the inelastic process wins the competition with the other processes, an inelastic final-state is produced by one of the hadronic (inelastic final-state) models assigned to such a process

  - In general, there are **no** "partial" and/or "differential" cross sections used internally by Geant4 to generate specific final states – for choosing either the secondary types of hadrons, or the kinematic properties of these secondaries

  - Some people distinguish between "**quasi-elastic**" and "**production**" in hadronic interactions: both are accounted in Geant4 "**inelastic**" process

# Special case: "Capture At Rest"

- In Nature, particles are never completely "at rest" – *i.e.* with zero kinetic energy in the Lab. frame – however, given the typical simplified treatment in simulations of low-energy (≤ 1 keV) particles, charged particles can come completely at rest in Geant4 !

- In Geant4, **negatively charged hadrons** (and muon as well) have a **nuclear capture at rest** process (independent from their inelastic process, used for "in-flight" interactions)

  - π− , K− , *anti*-p , Σ− , *anti*-Σ+ , Ξ− , *anti*-Ξ+ , Ω− , *anti*-d , *anti*-t , *anti*-He3 , *anti*-α

  - For at-rest processes, the **lifetime** (instead of the cross section as for an in-flight process) is related to the probability that such a process occurs

  - The capture at rest process competes against the **decay** process

12

# G4 Datasets (1/3)

- Some physics models or cross-sections are data-driven, *i.e.* they need as input some phenomenological data; others need as input the results of intensive computations, which are done before the simulation runs

- If you build Geant4 with the CMake option  *GEANT4_INSTALL_DATA=ON* then the data-sets are automatically downloaded & installed

- Else (you want or need to do it manually, *e.g.* for older versions of Geant4) you need to install the data-sets yourself and then inform Geant4 where they are by defining the following environmental variables, *e.g.* for the latest version G4 11.2.2 :

  *export **G4LEDATA**=/dir-path/G4EMLOW8.5*
  *export **G4LEVELGAMMADATA**=/dir-path/PhotonEvaporation5.7*
  *export **G4SAIDXSDATA**=/dir-path/G4SAIDDATA2.0*
  *export **G4PARTICLEXSDATA**=/dir-path/G4PARTICLEXS4.0*
  *export **G4ENSDFSTATEDATA**=/dir-path/G4ENSDFSTATE2.3*
  *export **G4NEUTRONHPDATA**=/dir-path/G4NDL4.7.1*
  *export **G4RADIOACTIVEDATA**=/dir-path/RadioactiveDecay5.6*
  *export **G4REALSURFACEDATA**=/dir-path/RealSurface2.2*
  *export **G4INCLDATA**=/dir-path/G4INCL1.2*
  *export **G4ABLADATA**=/dir-path/G4ABLA3.3*

13

# G4 Datasets (2/3)

- **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

# G4 Datasets (3/3)

- **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

- **G4RADIOACTIVEDATA** : radioactive decay data, come from the ENSDF; used only when radioactive decay is activated

- **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

- **G4PARTICLEHPDATA** : data for ParticleHP (p, d, t, He3, α); used only by QGSP_BIC_AllHP

# An interesting complication: Neutrons

- Neutrons are abundantly produced

  - Mostly "soft" neutrons, produced by the de-excitation of nuclei, after hadron-nucleus interactions

  - It is typically the 3rd most produced particle (after electrons and gammas)

- Before a neutron "disappears" via an inelastic interactions (or decays or exits the world volume), it can have many **elastic scatterings** with nuclei, and eventually can "thermalize" in the environment

- CPU time can vary by an order of magnitude depending on the physical accuracy of the **neutron transportation** simulation

  - For typical high-energy applications, a simple treatment is enough (luckily!)

  - For other applications, a more precise, **data-driven and isotope-specific** treatment is needed, especially for neutrons with kinetic energies below **~ MeV**

# Neutron High Precision (**HP**)

- **H**igh **P**recision treatment of low-energy neutrons

  - $E_{kin}$ **< 20 MeV** , down to thermal energies

  - Includes 4 types of interactions:
    **elastic scattering**, **radiative capture**, **fission**, **inelastic scattering**

  - Based on evaluated neutron scattering data libraries
    (pointed by the environmental variable **G4NEUTRONHPDATA** )

  - It is precise, but slow!

- Not needed for most high-energy applications; useful for:

  - Cavern background, shielding, radiation damage, radio-protection

- Not used in most physics lists

  - If you need it, use one of the _**HP** physics lists:
    FTFP_BERT_**HP** , QGSP_BERT_**HP** , QGSP_BIC_(All)**HP** , Shielding

# Hadronic showers

- A single hadron impinging on a large block of matter (*e.g.* a calorimeter) produces secondary hadrons of lower energies, which in turn can strongly interact and produce other hadrons, and so on: these particles form a **hadronic shower**

  - Electrons, positrons and gammas are also produced copiously because of the decay of π° -> γ γ and the ionization of charged particles (these EM particles form the electromagnetic component of a hadronic shower)

- The development of a hadronic shower involves many energy scales, from hundreds of GeV down to thermal energies, and several different particle types
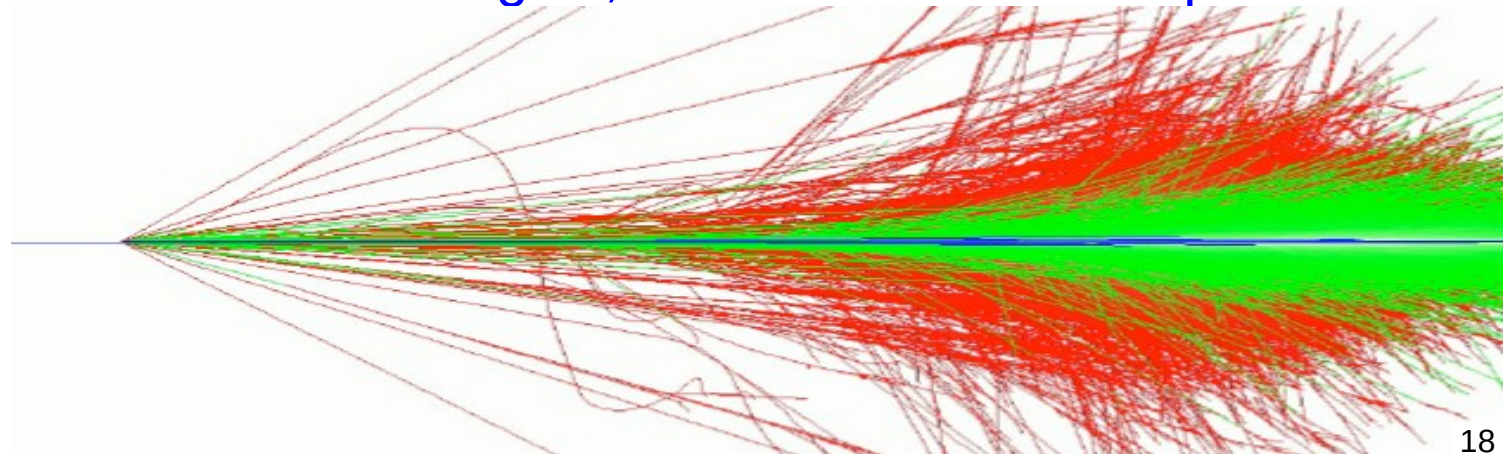
# Jets

The simulation of hadronic showers is an important ingredient for the simulation of **jets**

- The other ingredients are:

  - Monte Carlo event generator

  - Experiment-specific aspects: geometry, digitization, pile-up

- Jets (*i.e.* collimated sprays of hadrons) are produced by strong (QCD) or electroweak (hadronic decays of τ / W / Z / H ) interactions

- Jets can be part of the signal and/or the background

  - Multi-jets in the same event are typical in hadron colliders such as LHC, but they are also frequent in high-energy e+ e- colliders

- For future accelerators (ILC, CLIC, FCC, CEPC, MC, *etc.*) the simulation of jets is essential for the optimal **design** of detectors. For current LHC experiments, the simulation of jets is now important for **physics analysis**

# Physics Lists

# What is a Physics List?

- A class that specifies all the particles, physics processes, and production thresholds needed by your Geant4 application

- One and only one physics list should be present in each application

- There is no default physics list: it should always be explicitly specified

- It is a very flexible way to build a physics environment :

  - Users can pick only the particles they need

  - Users can assign to each selected particle only the processes they are interest in

- But users must have a good understanding of the physics required in their application

  - Omission of particles or physics processes will cause errors or poor simulation

# Why do we need a Physics List?

Nature has just one "physics": so why Geant4 does not provide a complete and unique set of particles and physics processes that everyone can use?

- There are many different physics models, corresponding to a variety of approximations of the real phenomena

  - very much the case for hadronic physics, but also for electromagnetic physics

  According to the application, one can be better than another. Comparing them can give an idea of systematic errors.

- Simulation speed is important

  - Users may prefer a less detailed but faster approximation

- Often all the physics and particles are not needed:

  - *e.g.* most high-energy applications do not need a detailed transportation of low-energy neutrons

# Reference Physics Lists

- Writing a complete and realistic physics list for EM physics and even more for HAD physics is involved, and it depends on the application. To make things easier, pre-packaged **reference physics lists** are provided by Geant4, according to some reference use cases

- Few choices are available for EM physics (different production cuts and/or multiple scattering configurations); several possibilities are available for hadronics physics

  - **FTFP_BERT**, **FTFP_BERT_HP**, **Shielding**, **FTFP_INCLXX**, **QGSP_BERT**, **QGSP_BIC_EMZ**, *etc.*

- These lists are "best guesses" of the physics needed in a given case; they are intended as starting point (and their builders can be re-used); **users are responsible of validating the physics lists for their application**

# FTFP_BERT

Recommended physics list for High-Energy Physics.
Its main components are :

- **FTF** (Fritiof) hadronic string model, used above 3 GeV

- **BERT** (Bertini-like) intra-nuclear cascade model, used below 6 GeV

- Nucleus de-excitation : **P**recompound + evaporation models

- Neutron capture

- Nuclear capture of negatively charged hadrons at rest

- Hadron elastic

- Gamma- , electron- , and muon-nuclear

- Standard electromagnetic physics

- NO : neutron-HP , radioactive decay , optical photons

# A few other Physics Lists

- FTFP_BERT_**HP** : as FTFP_BERT, but with **NeutronHP** for neutrons $E_{kin} < 20$ MeV

  - **Shielding** : similar to FTFP_BERT_HP, but using for ions also the **QMD** (Quantum Molecular Dynamics) model

    – QMD used in the range [100 MeV/A, 10 GeV/A] ;  BIC is used below 90 MeV/A ; FTFP is used above 9.99 GeV/A

- FTFP_**INCLXX** : similar to FTFP_BERT, but using **INCL**XX for some particles

    – Protons, neutrons, charged pions below 20 GeV; FTFP above 15 GeV

- **QGSP**_BERT : similar to FTFP_BERT, but using **QGS** (Quark Gluon String) model at high energies

    – [3, 6] GeV transition BERT − FTFP ; [12, 25] GeV transition FTFP − QGSP

- QGSP_**BIC** : similar to FTFP_BERT but using QGS and BIC (Binary Cascade) instead of FTF and BERT when possible

    – Protons, neutrons :  BIC    < 6 GeV , FTFP in [3, 25] GeV , QGSP > 12 GeV
    Pions & kaons :      BERT < 6 GeV , FTFP in [3, 25] GeV , QGSP > 12 GeV

# How to use a reference Physics List

Let's consider the example of FTFP_BERT :
In your main program:

```
#include "FTFP_BERT.hh"
…
int main( int argc, char** argv ) {
    …
    G4VModularPhysicsList* physicsList = new FTFP_BERT;
    runManager->SetUserInitialization( physicsList );

    …
}
```

# How to add extra physics to a reference P.L.

- To add radioactive decay , in your main program :

```
#include "G4RadioactiveDecayPhysics.hh"
int main( int argc, char** argv ) {
    ...
    G4VModularPhysicsList* physicsList = new FTFP_BERT;
    physicsList->RegisterPhysics( new G4RadioactiveDecayPhysics );
    runManager->SetUserInitialization( physicsList );
    ...
}
```

- To add optical photon and its processes , in your main program:

```
#include "G4OpticalPhysics.hh"
int main( int argc, char** argv ) {
    ...
    G4VModularPhysicsList* physicsList = new FTFP_BERT;
    physicsList->RegisterPhysics( new G4OpticalPhysics );
    runManager->SetUserInitialization( physicsList );
    ...
}
```

# Validation

# Validation & tuning of hadronic models

- The developers of the hadronic models are responsible of the tuning & validation of these models with thin-target (microscopic, single-interaction) measurements
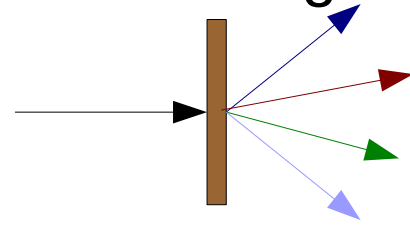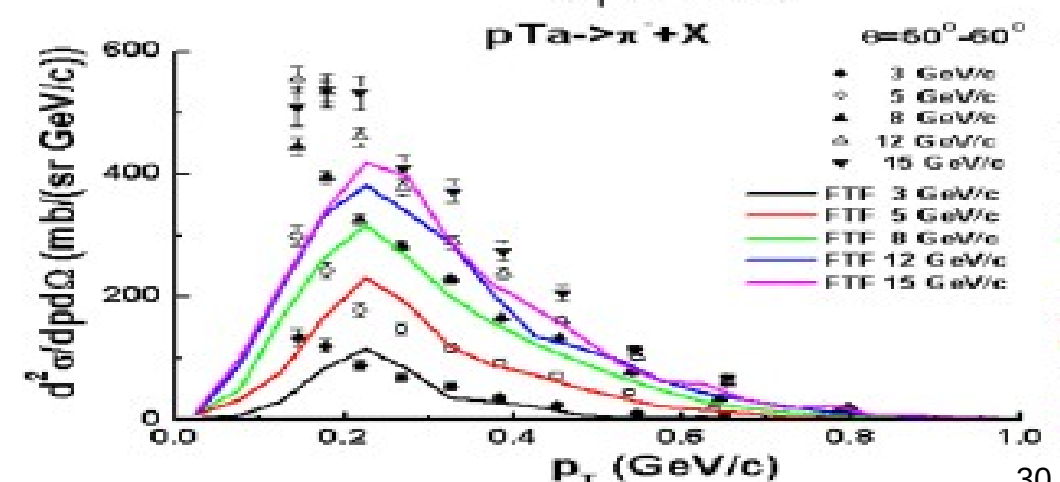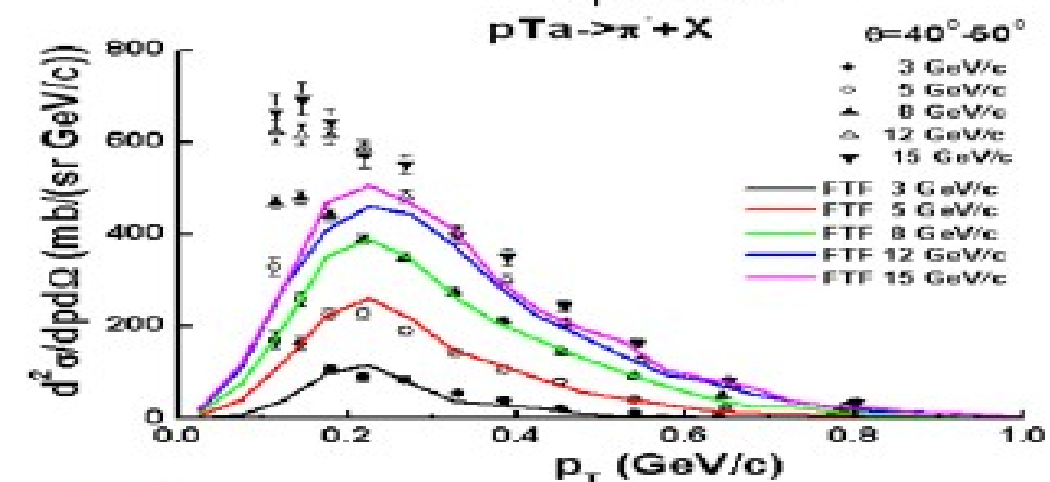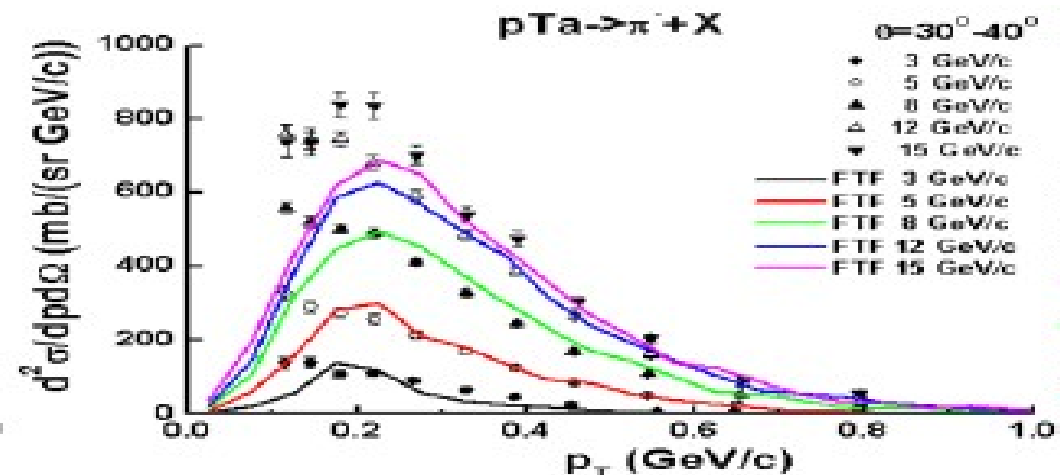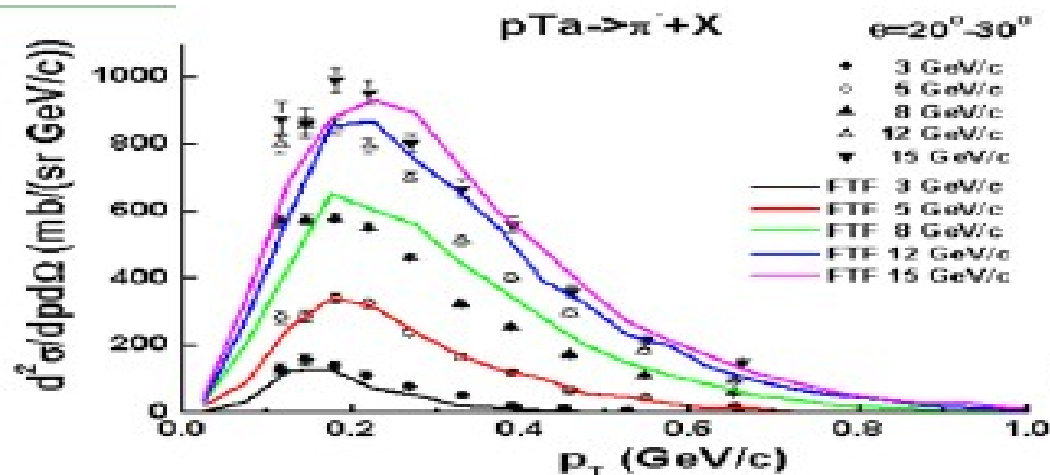
- Validation of complete physics configurations is performed by users mostly via measurements of hadronic showers in calorimeter test-beam set-ups (thick targets)
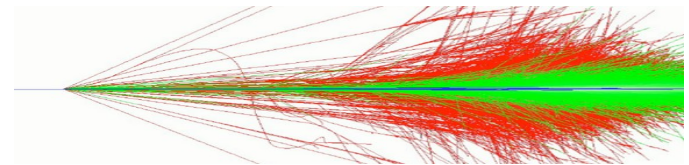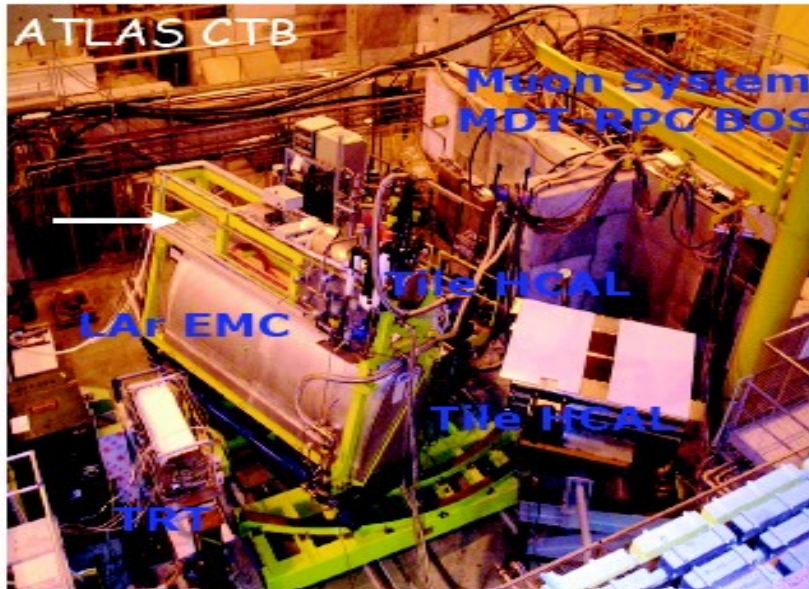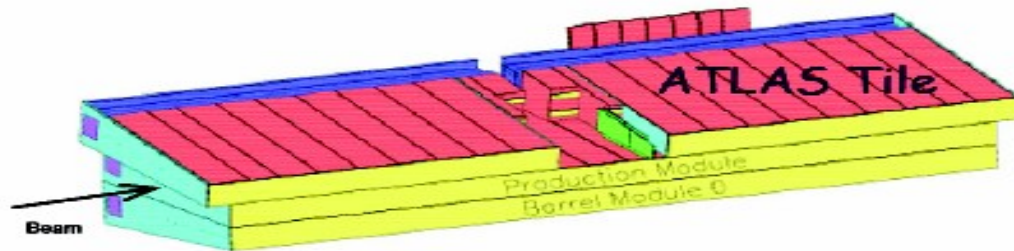
# Model-level thin-target test

# LHC calorimeter test-beams

# Calorimeter observables

- The simulation of hadronic showers can be validated with calorimeter test-beam set-ups, with pion and proton beams of various energies, considering the following observables:

  - Energy response: $\quad\quad\quad\quad\quad\quad$ $E_{rec} / E_{beam}$

  - Energy resolution: $\quad\quad\quad\quad\quad$ $\Delta E_{rec} / E_{rec}$

  - Shower profile:
    - Longitudinal: $\quad\quad\quad\quad\quad$ $E_{rec}(z) / E_{rec}$
    - Lateral (transverse or radial): $\quad$ $E_{rec}(r) / E_{rec}$

- Note that we can test directly only single hadron showers in calorimeter test-beam set-ups, whereas for a collider experiment (*e.g.* ATLAS and CMS) jets are measured

# Energy resolution

## ATLAS HEC test-beam
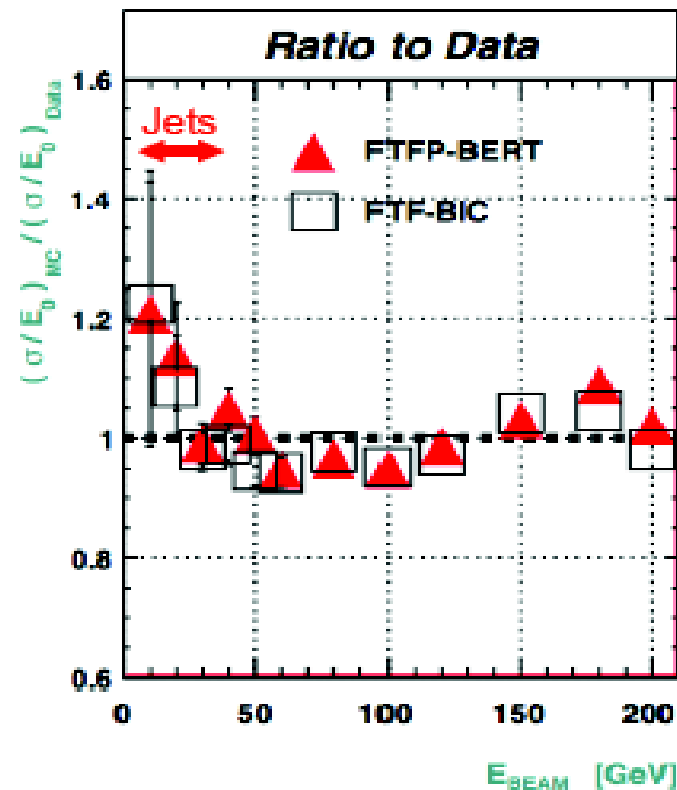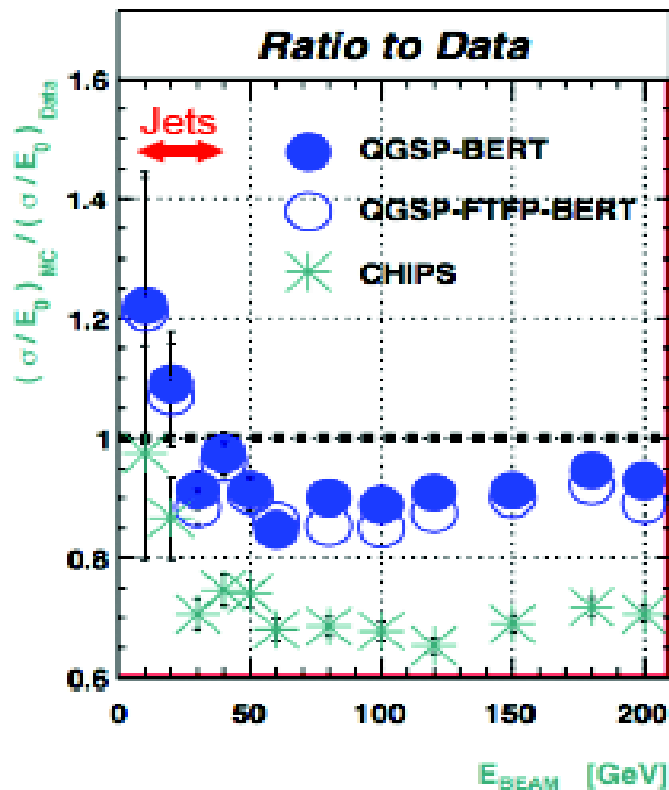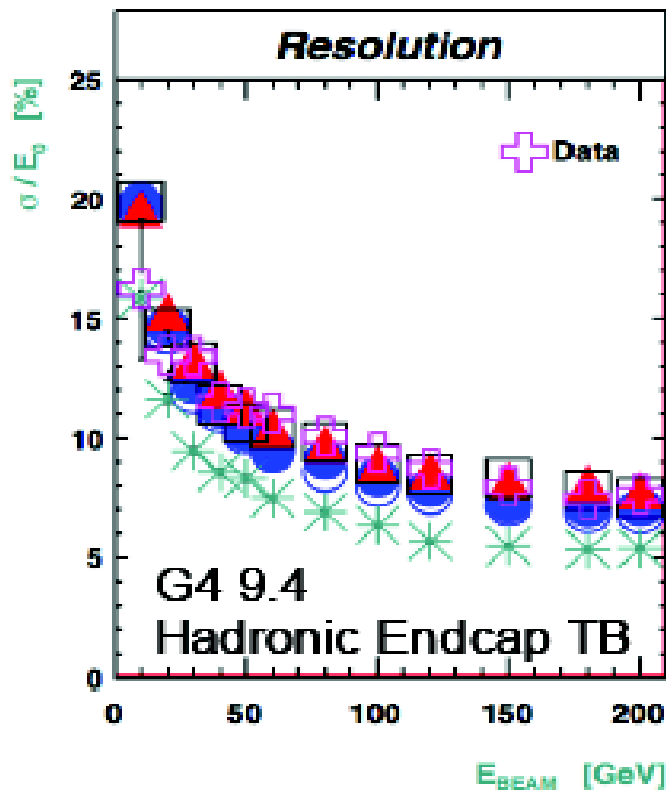
# Summary & Exercises

# Recap: Model, Process, Physics List

- (Hadronic) physics **model** = final-state generator

  - Validated and tuned by Geant4 developers with thin-target data

- (Hadronic) physics **process** = cross section + final-state model

  - Different physics models can share the same cross section

- **Physics list** = list of all particles present in the simulation and all the physics processes associated with these particles

  - Chosen by users: trade-off accuracy *vs.* speed

  - Geant4 offers some reference physics lists ready to be used

  - Validated by users with (test-beam and/or collision) data

# Exercises : general advice

- Take a look at the extended hadronic examples

  *geant4/examples/extended/hadronic*

  - Each of them has a README file with some explanation
  - Start with the example which is the closest to your interest
  - First, try to build and run the example
  - Second, take a look at the code, to learn "how to do things"
  - Third, try to do some simple change
    (*e.g.* particle type, beam energy, material, observable, *etc.*)
  - Fourth, and last, try to adapt / extend / modify the chosen example to do what you are interested in
  - In alternative to the fourth point – or after it – take another example and re-start the learning process…

*Note: there are hundreds of examples in  geant4/examples/ : looking at them is the best way to learn Geant4 and how many applications started!*