



Hadronic Physics I

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GEANT4
A SIMULATION TOOLKIT

Outline

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

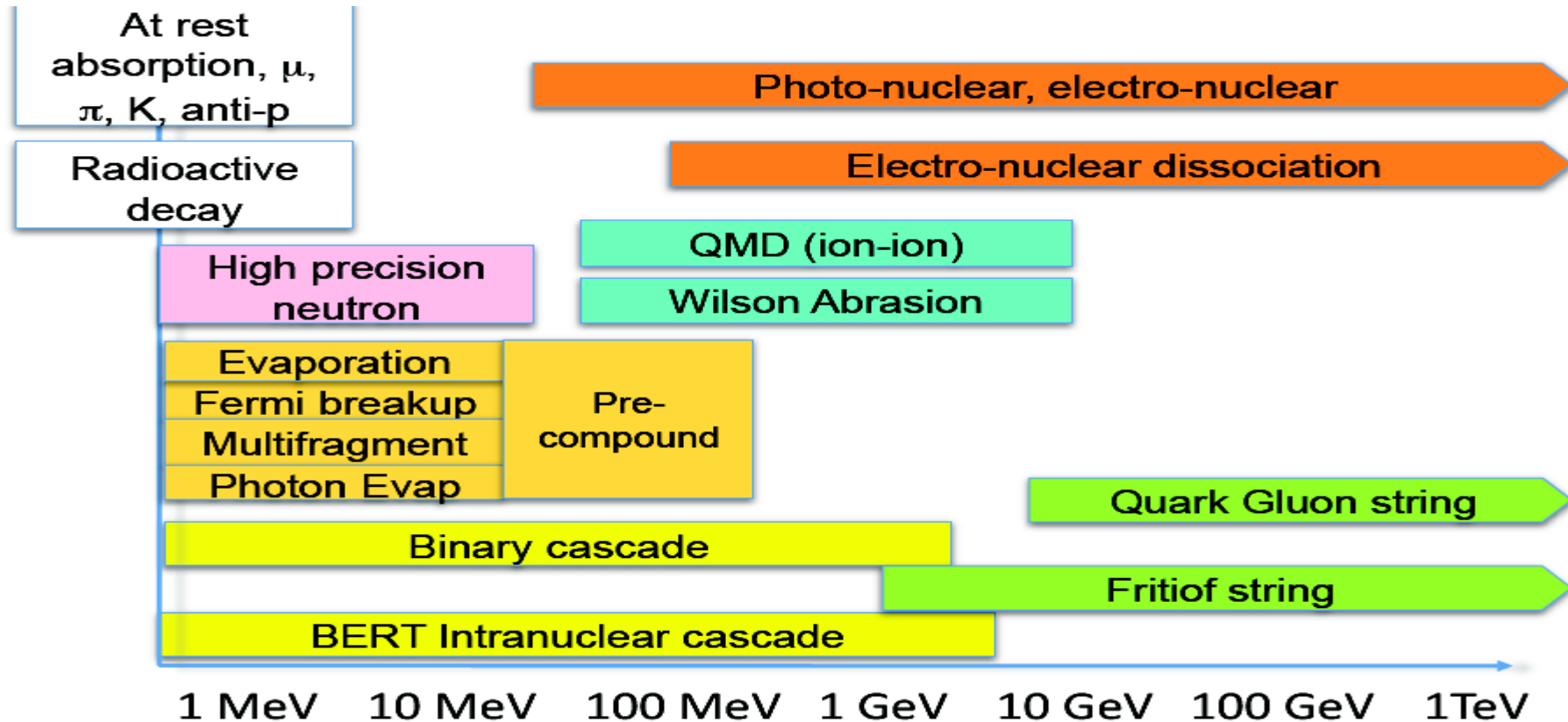


Hadronic Models , Cross Sections and Framework

Hadronic interactions

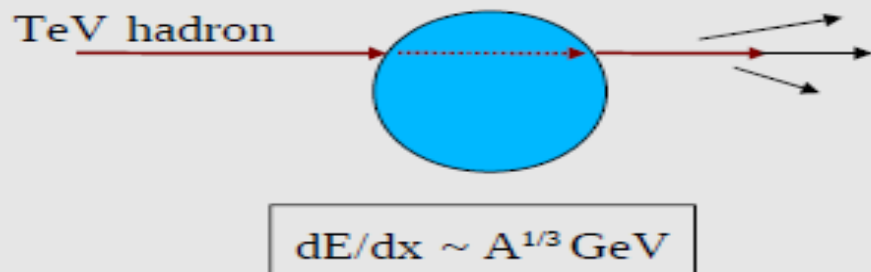
- Hadrons (π^\pm , K^\pm , K^0_L , p , n , α , *etc.*), produced in jets and decays, travel through the detector (H , C , Ar , Si , Al , Fe , Cu , W , Pb ...)
- Therefore we need to model **hadronic interactions**
hadron – nucleus \rightarrow anything
- In principle, QCD is the theory that describes 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

Partial Hadronic Model Inventory

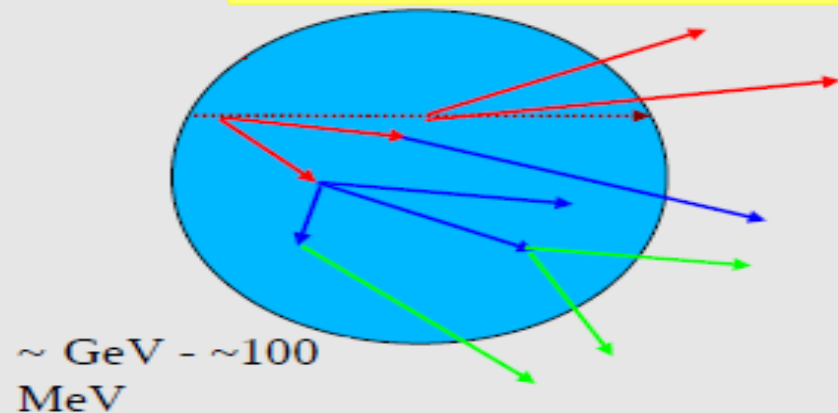


Hadronic Interactions from TeV to meV

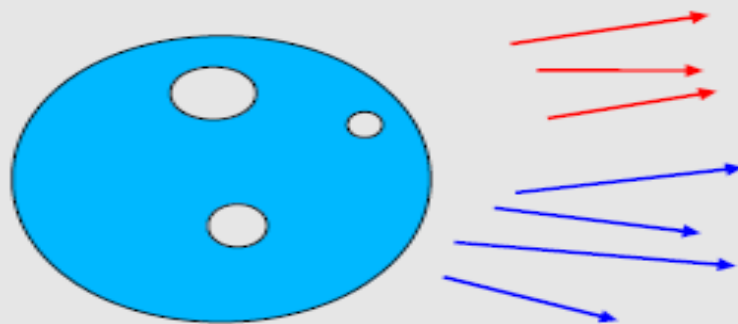
String model



Intra-nuclear cascade model

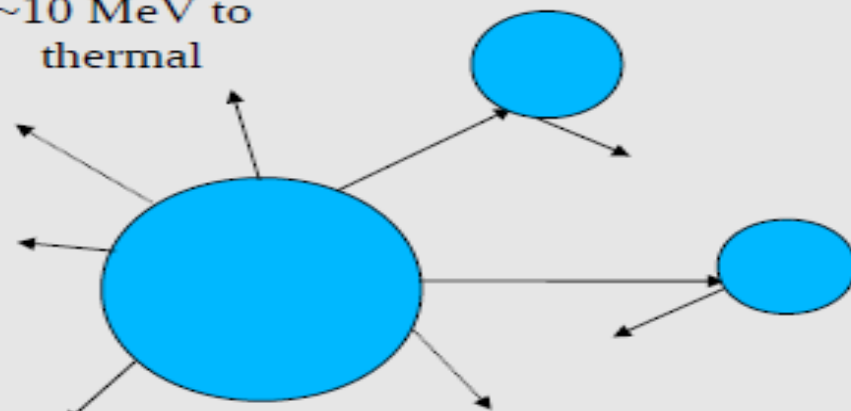


$\sim 100 \text{ MeV} - \sim 10 \text{ MeV}$



Pre-equilibrium (Precompound) model

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

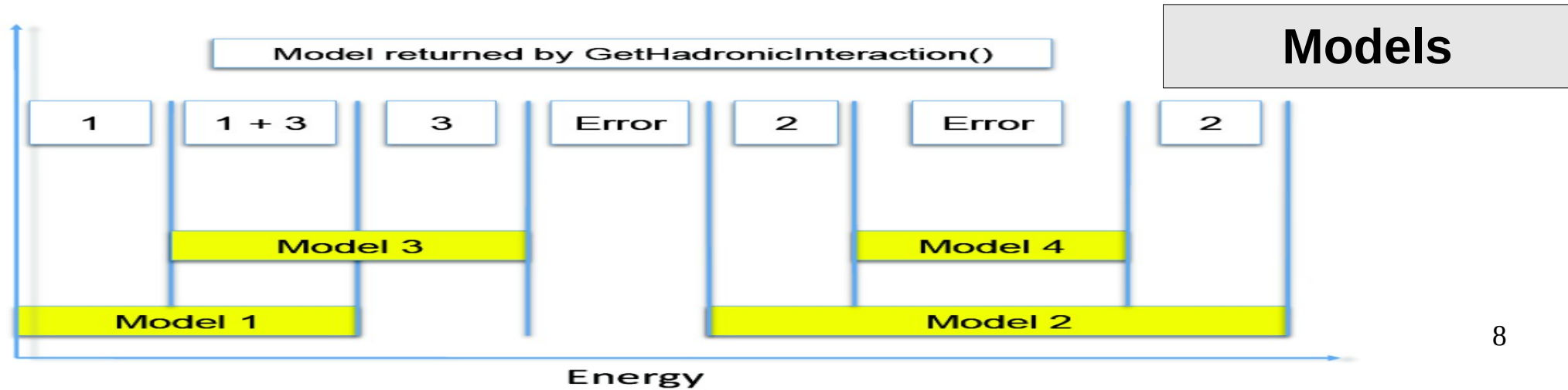


Equilibrium (Evaporation) model

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

Hadronic Framework



Inclusive Cross Sections

- In Geant4, in general, for a given hadron projectile, kinetic energy and target nucleus (e.g. 10 GeV p on ^{56}Fe), 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 or more of the hadronic (inelastic final-state) models
 - In general, there are no “partial” and/or “differential” cross sections used internally by Geant4 to generate specific final states – either specified secondary types of hadrons, or 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 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

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
- If you build G4 with the option **GEANT4_INSTALL_DATA** then the data-sets are automatically downloaded & installed
- Else (you want or need to do it manually, e.g. for older versions of G4) 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 10.7 :

```
export G4LEDATA=/dir-path/G4EMLOW7.13
export G4LEVELGAMMADATA=/dir-path/PhotonEvaporation5.7
export G4SAIDXSDATA=/dir-path/G4SAIDDATA2.0
export G4PARTICLEXSDATA=/dir-path/G4PARTICLEXS3.1.1
export G4ENSDFSTATEDATA=/dir-path/G4ENSDFSTATE2.3
export G4NEUTRONHPDATA=/dir-path/G4NDL4.6
export G4RADIOACTIVEDATA=/dir-path/RadioactiveDecay5.6
export G4REALSURFACEDATA=/dir-path/RealSurface2.2
export G4INCLDATA=/dir-path/G4INCL1.0
export G4ABLADATA=/dir-path/G4ABLA3.1
```

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

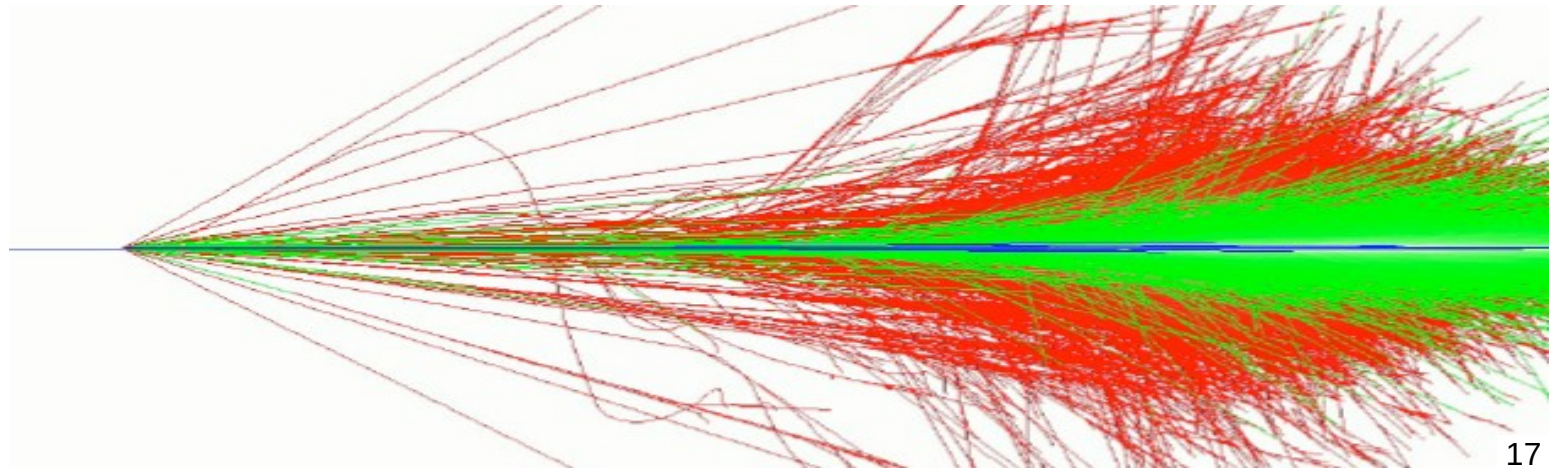
- Neutrons are abundantly produced
 - Mostly “soft” neutrons, produced by the de-excitation of nuclei, after hadron-nucleus interactions
 - It is typically the 3rd most produced particle (after electrons and gammas)
- Before a neutron “disappears” via an inelastic interactions (or decays or exits the 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)

- **High Precision** treatment of low-energy neutrons
 - **$E_{kin} < 20 \text{ MeV}$** , 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 very 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(LEND)**

Hadronic showers

- A single hadron impinging on a large block of matter (e.g. a hadron calorimeter) produces secondary hadrons of lower energies, which in turn can produce other hadrons, and so on: the set of these particles is called a **hadronic shower**
 - $e^-/e^+/\gamma$ (electromagnetic component) are also produced copiously because of $\pi^0 \rightarrow \gamma \gamma$ and ionization of charged particles
- The development of a hadronic shower involves **many energy scales, from hundreds of GeV down to thermal energies**



Jets

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

- The other ingredients are:
 - the Monte Carlo event generator
 - the experiment-specific aspects: geometry, digitization, pile-up
- Jets (= **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 as LHC, but they are also frequent in high-energy e⁺-e⁻ colliders
- For future accelerators (e.g. ILC, CLIC, FCC, CEPC), the simulation of jets is essential for the optimal **design** of the detector.
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, 10 GeV] : below BIC, above FTFP
- **FTFP_INCLXX** : similar to FTFP_BERT, but using **INCLXX** 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:

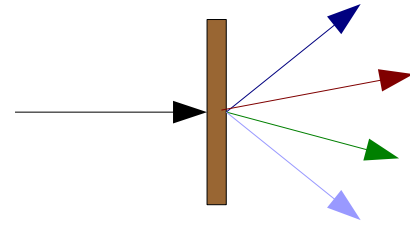
```
#include "G4OpticalPhysics.hh"  
int main( int argc, char** argv ) {  
    ...  
    G4VModularPhysicsList* physicsList = new FTFP_BERT;  
    physicsList->RegisterPhysics( new G4OpticalPhysics );  
    runManager->SetUserInitialization( physicsList );  
    ...  
}
```



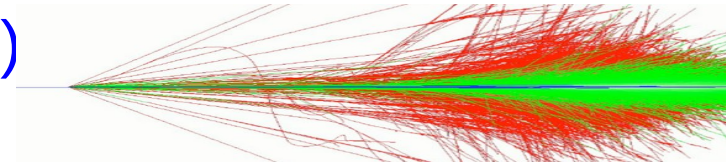
Validation

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



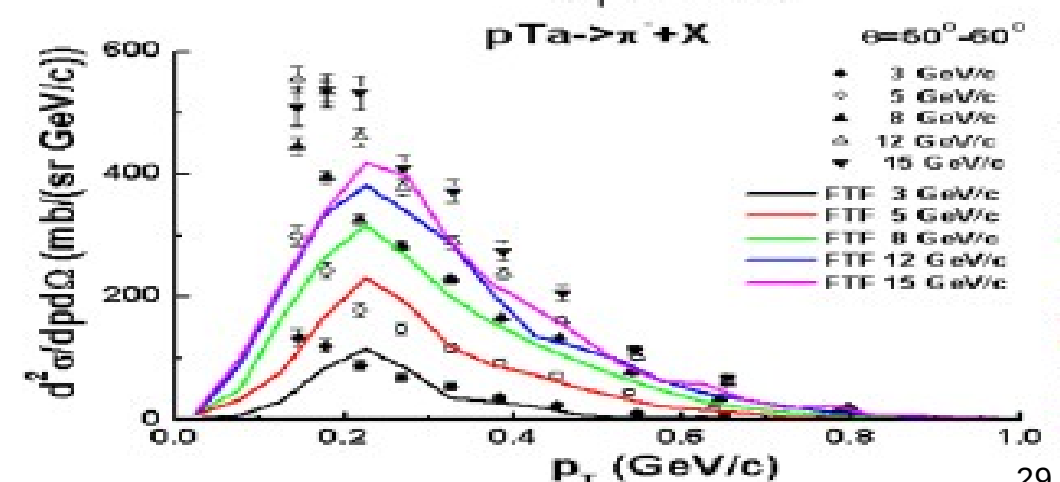
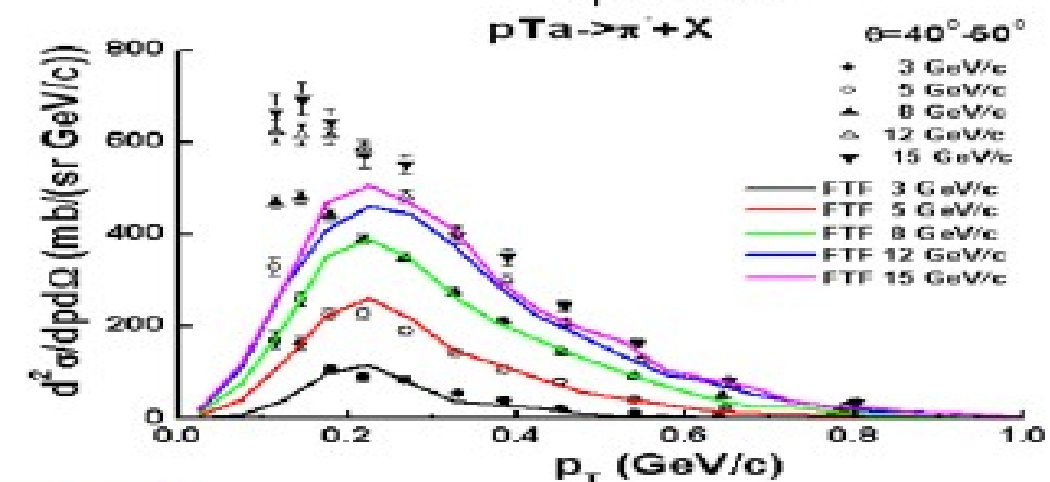
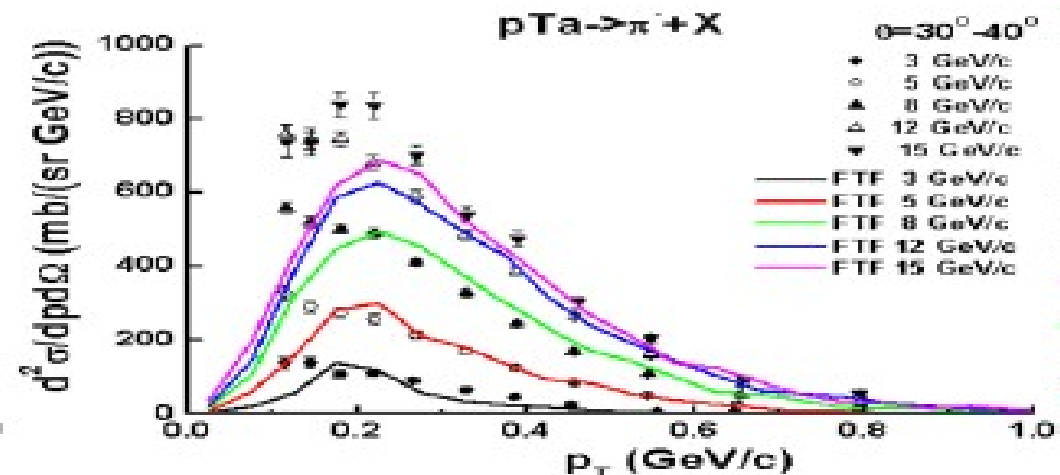
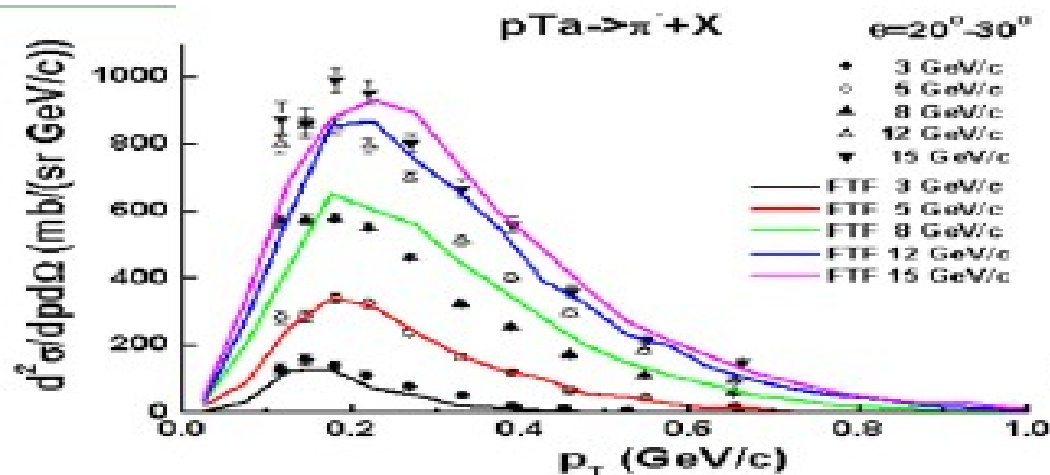
- Validation of complete physics configurations is performed by users mostly via measurements of **hadronic showers in calorimeter test-beam setups (thick targets)**



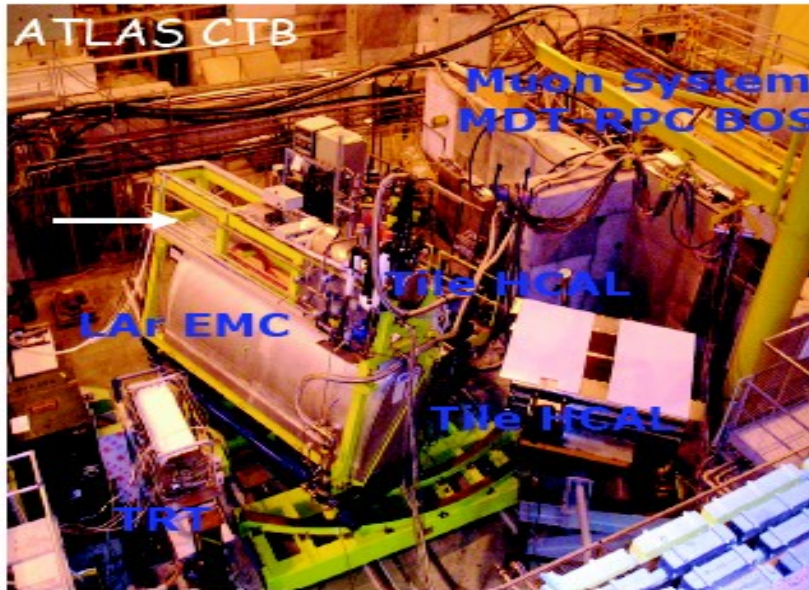
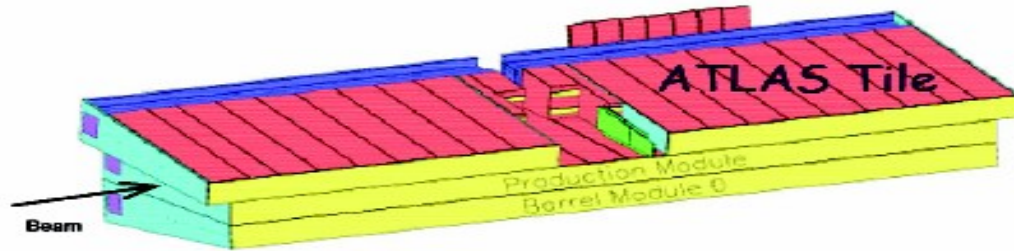
- The most important application of the hadronic models for collider experiments is the **simulation of jets**, which involves:
 1. the Monte Carlo event generator
 2. the convolution of the showers for each constituent hadron
 3. experiment specific: geometry & materials, digitization, *etc.*

Model-level thin-target test

FTF validation, HARP-CDP data



LHC calorimeter test-beams

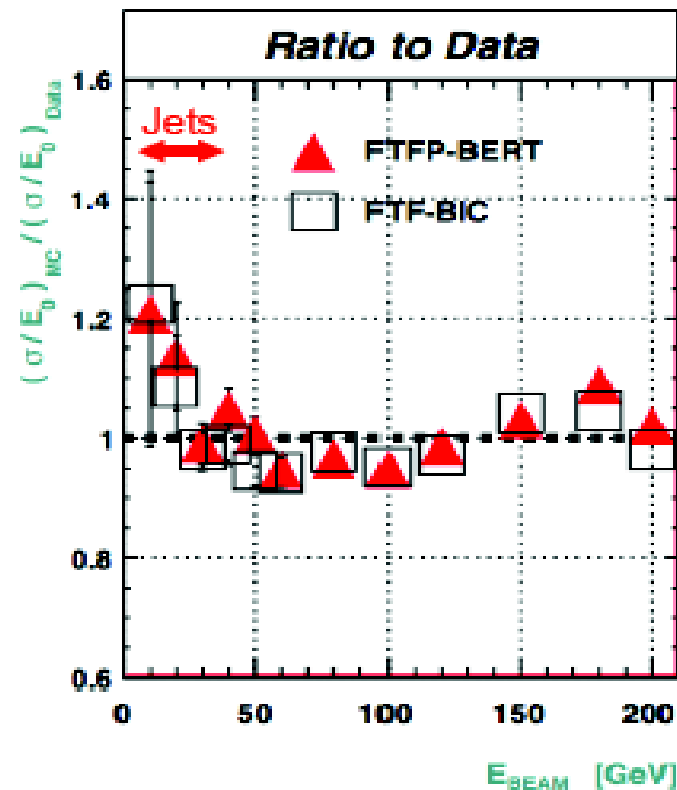
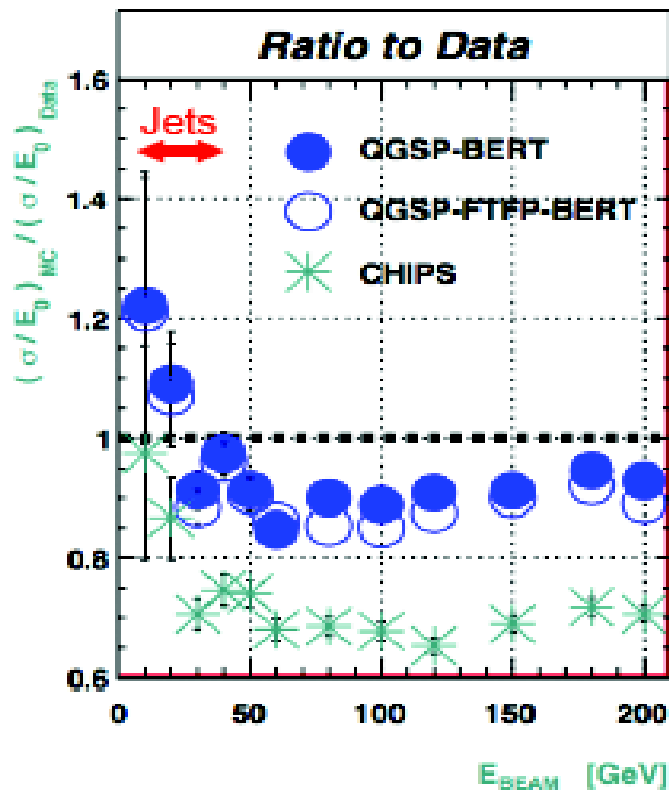
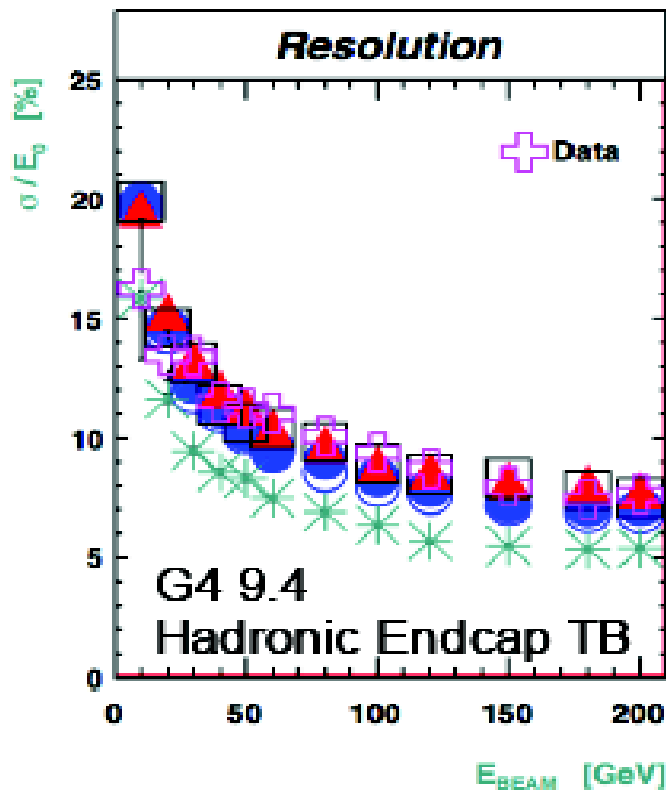


Calorimeter observables

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



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 the 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