Hadronic Physics

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Outline

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

Hadronic
Models , Cross Sections and Framework

Hadronic interactions

- Hadrons ($\pi\pm$, $K\pm$, K°_{L} , p, n, α, *etc.*), produced in jets and decays, traverse the detectors (H,C,Ar,Si,Al,Fe,Cu,W,Pb...)
- Therefore we need to model hadronic interactions

  hadron – nucleus -> *anything*

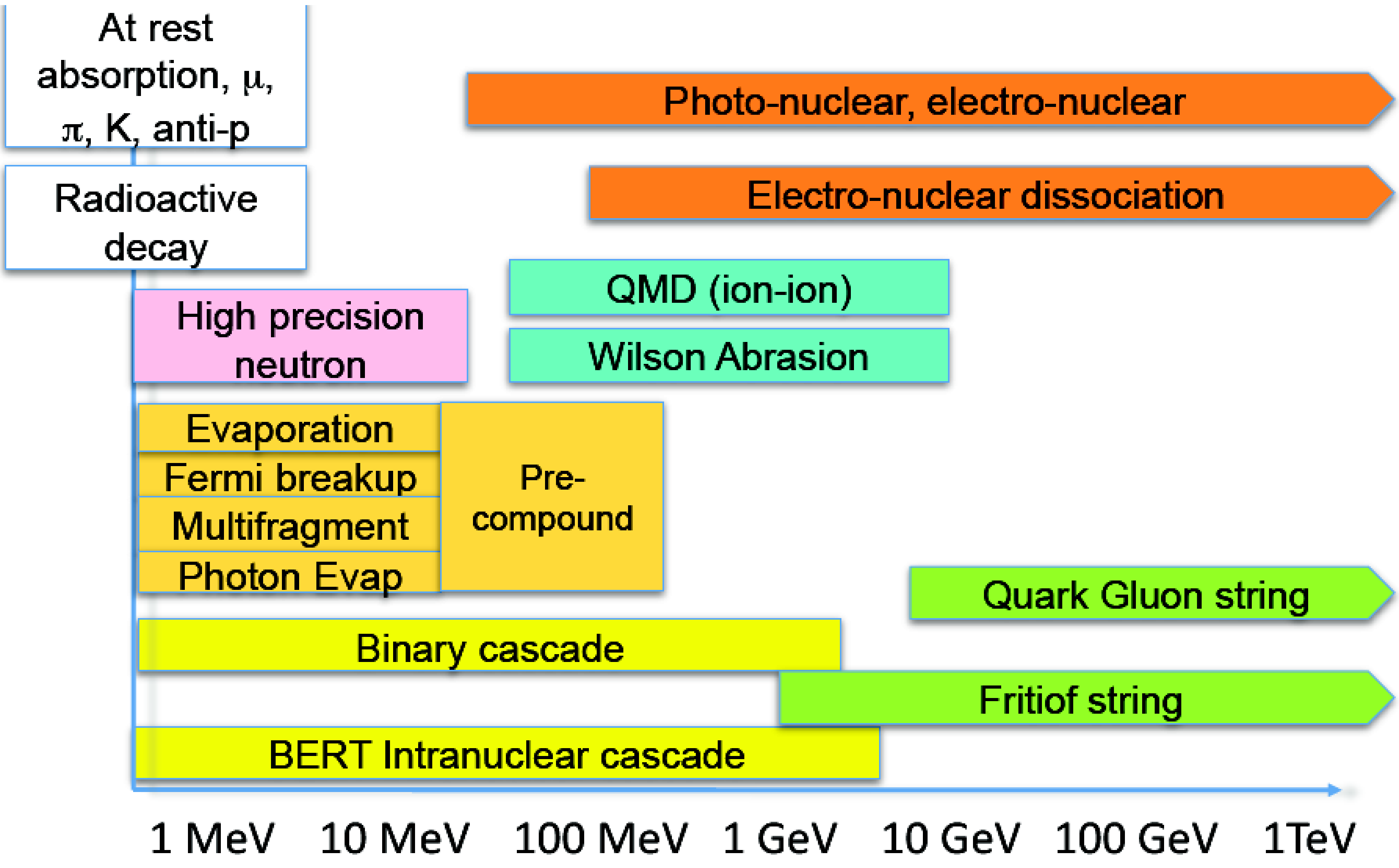
  in our detector simulations
- In principle, QCD is the theory that describes all hadronic interactions; in practice, perturbative calculations are applicable only in a tiny (but important!) phase-space region
  - the hard scattering at high transverse momentum

  whereas for the rest, i.e. most of the phase space
  - soft scattering, re-scattering, hadronization, nucleus de-excitation

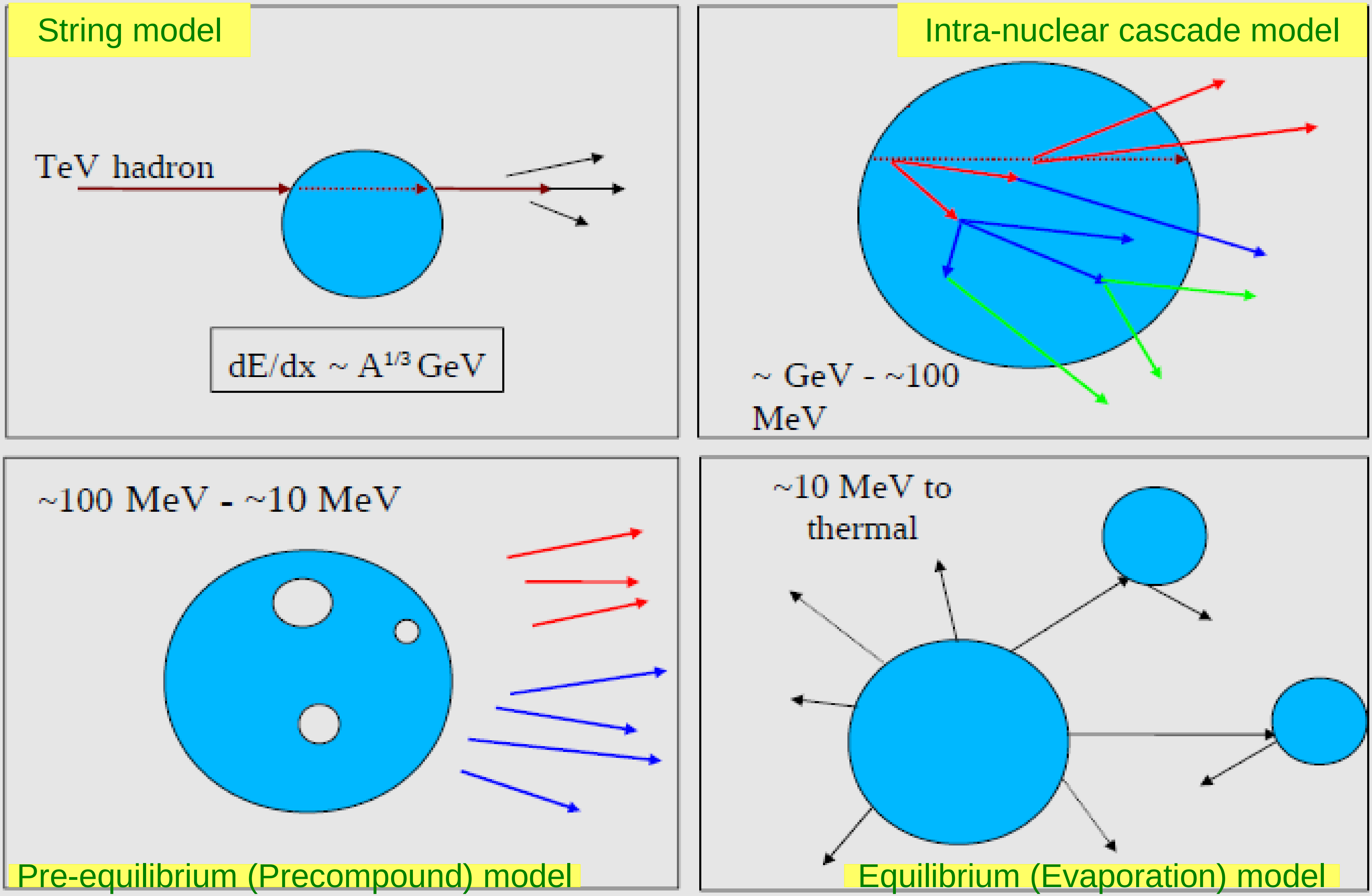
  only approximated models are available
- Hadronic models are valid for limited combinations of

  particle type – energy – target material

Partial Hadronic Model Inventory



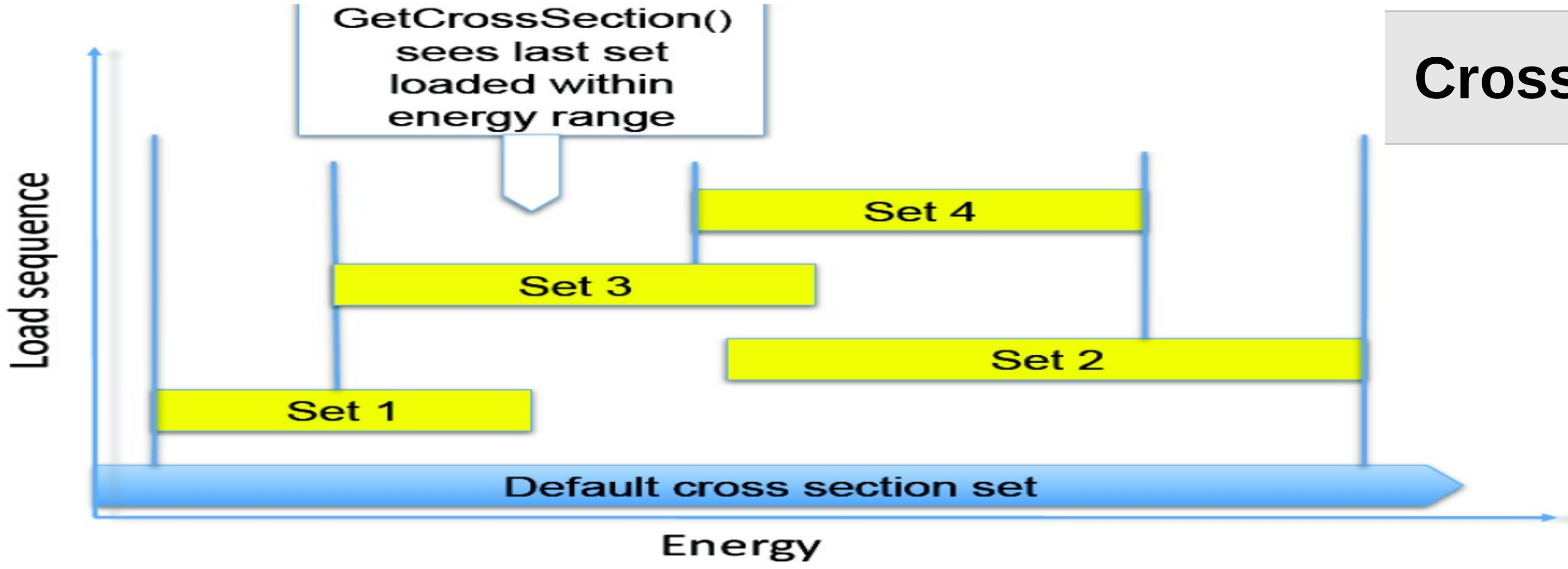
Hadronic Interactions from TeV to meV



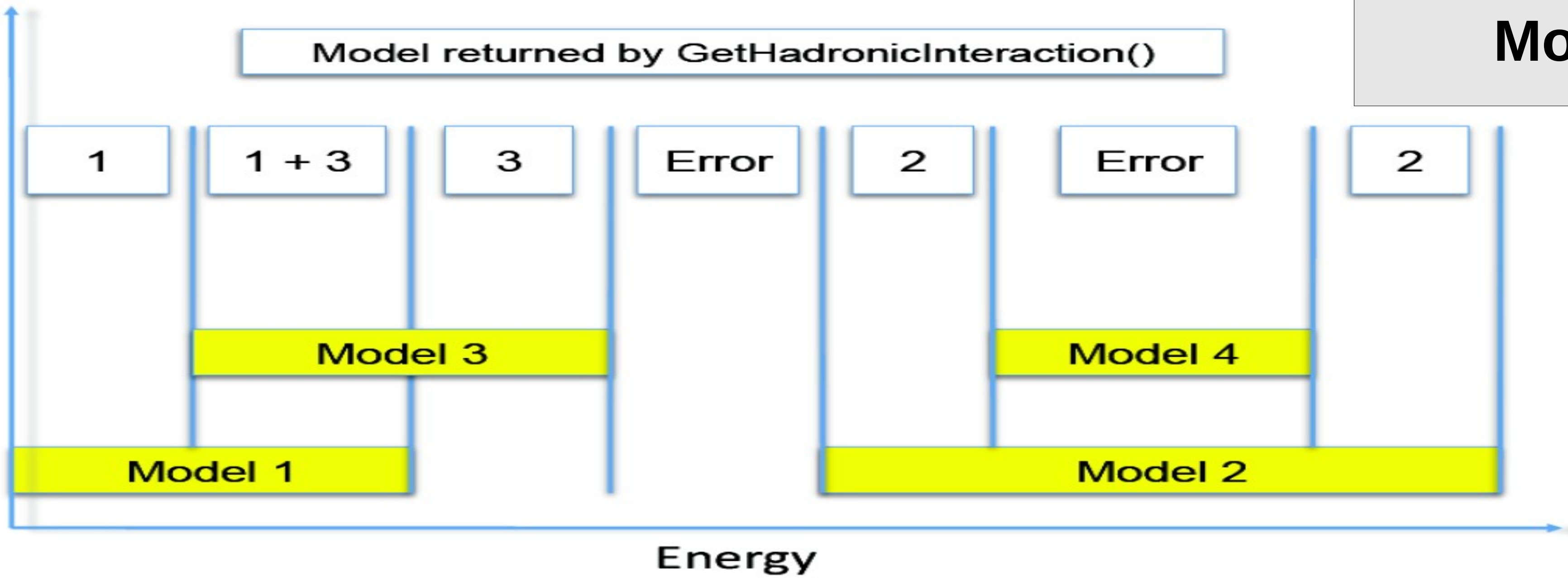
Hadronic Cross Sections and (Final-State) Models

- 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 secondaries produced by the interaction
- 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



Cross Sections



Models

G4 Datasets (1/3)

- Some physics models or cross-sections are data-driven, i.e. they need as input some phenomenogical data; others need as input the results of intensive computations, which are done before the simulation
- If you build Geant4 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, or to use your own data libraries) 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 10.5 :

```
export G4LEDATA=/dir-path/G4EMLOW7.7
export G4LEVELGAMMADATA=/dir-path/PhotonEvaporation5.3
export G4SAIDXSDATA=/dir-path/G4SAIDDATA2.0
export G4PARTICLEXSDATA=/dir-path/G4PARTICLEXS1.1
export G4ENSDFSTATEDATA=/dir-path/G4ENSDFSTATE2.2
export G4NEUTRONHPDATA=/dir-path/G4NDL4.5
export G4RADIOACTIVEDATA=/dir-path/RadioactiveDecay5.3
export G4REALSURFACEDATA=/dir-path/RealSurface2.1.1
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 and alpha) cross sections derived from G4NDL (G4PARTICLEHPDATA) 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 ENDF/B-VII 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 e-, γ)
- Before a neutron “disappears” via an inelastic interaction, it can have many elastic scatterings with nuclei, and eventually it can “thermalize” in the environment
- The CPU time of the detector simulation can vary by an order of magnitude according to the physical accuracy of the neutron transportation simulation
  - For typical high-energy applications, a simple treatment is enough (luckily!)
  - For activation and radiation damage studies, a more precise, **data-driven and isotope-specific** treatment is needed, especially for neutrons of kinetic energy below **~ MeV**

Neutron-HP

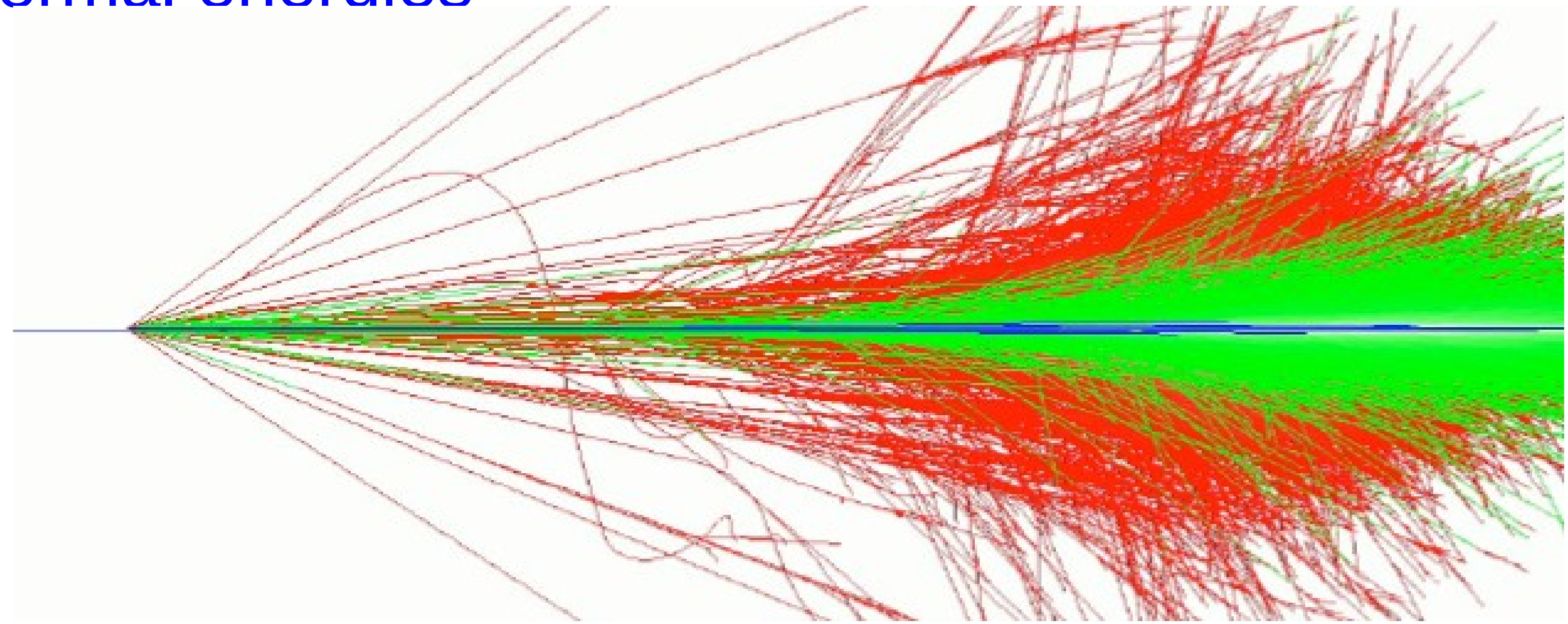
- **H**igh **P**recision treatment of low-energy neutrons
  - **E_{kin} < 20 MeV** , down to thermal energies
  - Includes 4 types of interactions:
    radiative capture, elastic scattering, fission, inelastic scattering
  - Based on evaluated neutron scattering data libraries
    (pointed by the environmental variable **G4NEUTRONHPDATA**)
  - It is precise, but very slow!

- It is 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+/γ (electromagnetic component) are also produced copiously because of **$\pi^\circ \rightarrow \gamma\,\gamma$** 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 it is also frequent in high-energy e+ e- linear colliders as ILC/CLIC
- For future accelerators (e.g. LC (ILC/CLIC), FCC), the simulation of jets is essential for the optimal design of the detector
- For ATLAS and CMS, the simulation of jets is now important for physics analyses

Physics Lists

Recap: Model, Process, Physics List

- Physics model = final-state generator
  - Validated and tuned by Geant4 developers with thin-target data

- Physics process = cross section + final-state model
  - Different physics models can share the same cross section

- Physics list = a list of physics processes associated to each particle present in the simulation
  - Chosen by users: trade-off accuracy vs. speed
  - Geant4 offers some reference physics lists ready to be used
  - Validated by the users with (test-beam and/or collision) data

Reference Physics Lists

- Writing a complete and realistic physics list for EM physics and even more for hadronic 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 use cases
- Few choices are available for EM physics (different production cuts and/or multiple scattering configurations); several possibilities are available for hadronics physics: *e.g.* **FTFP_BERT**, **FTFP_BERT_HP**, **Shielding, FTFP_INCLXX, QGSP_FTFP_BERT**, **QGSP_BIC**, *etc.*
- These lists are "best guess" 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 list used in their application**

FTFP_BERT

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

- **FTF** (Fritiof string) model, used above 3 GeV
- **BERT** (Bertini cascade) model, used below 12 GeV
- Nucleus de-excitation: **P**recompound + evaporation
- Neutron capture
- Nuclear capture of negatively charged hadrons at rest
- Gamma- and electron-nuclear interactions
- Hadron elastic
- 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 of kinetic energy below 20 MeV
  - **Shielding** : similar to FTFP_BERT_HP, but with **Radioactive Decay** and **QMD** (Quantum Molecular Dynamics) for ions
    - QMD used in the range [100 MeV, 10 GeV] : below BIC, above FTFP
- FTFP_**INCLXX** : similar to FTFP_BERT, but using **INCL**XX instead of BERT for some particles
  - Protons, neutrons, charged pions below 20 GeV; FTFP above 15 GeV
- **QGSP**_FTFP_BERT : similar to FTFP_BERT, but using **QGS** (Quark Gluon String) model at high energies
  - [6, 8] 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 < 9.9 GeV , FTFP in [9.5, 25] GeV , QGSP > 12 GeV
    Pions & kaons : BERT < 5 GeV , FTFP in [4, 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.

- Adding 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 );
  ...
}
```

- Adding optical photon and its processes :
  In your main program:

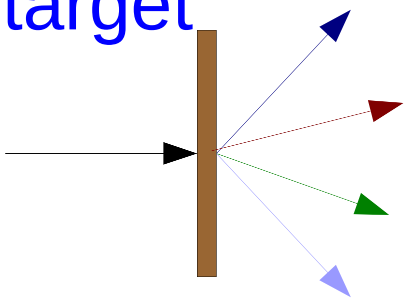
```
#include "G4OpticalPhysics.hh"
int main( int argc, char** argv ) {
  ...
  G4VModularPhysicsList* physicsList = new FTFP_BERT;
  physicsList->RegisterPhysics( new G4OpticalPhysics );
  runManager->SetUserInitialization( physicsList );
  ...
}
```

GEANT4
A SIMULATION TOOLKIT

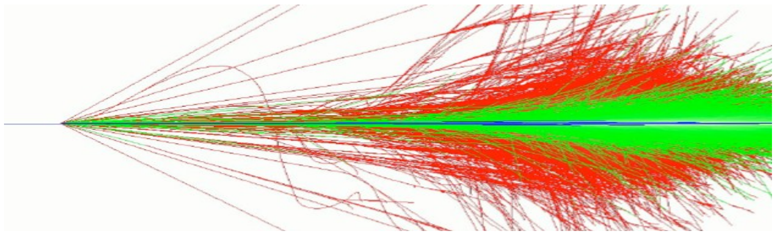
Validation

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:

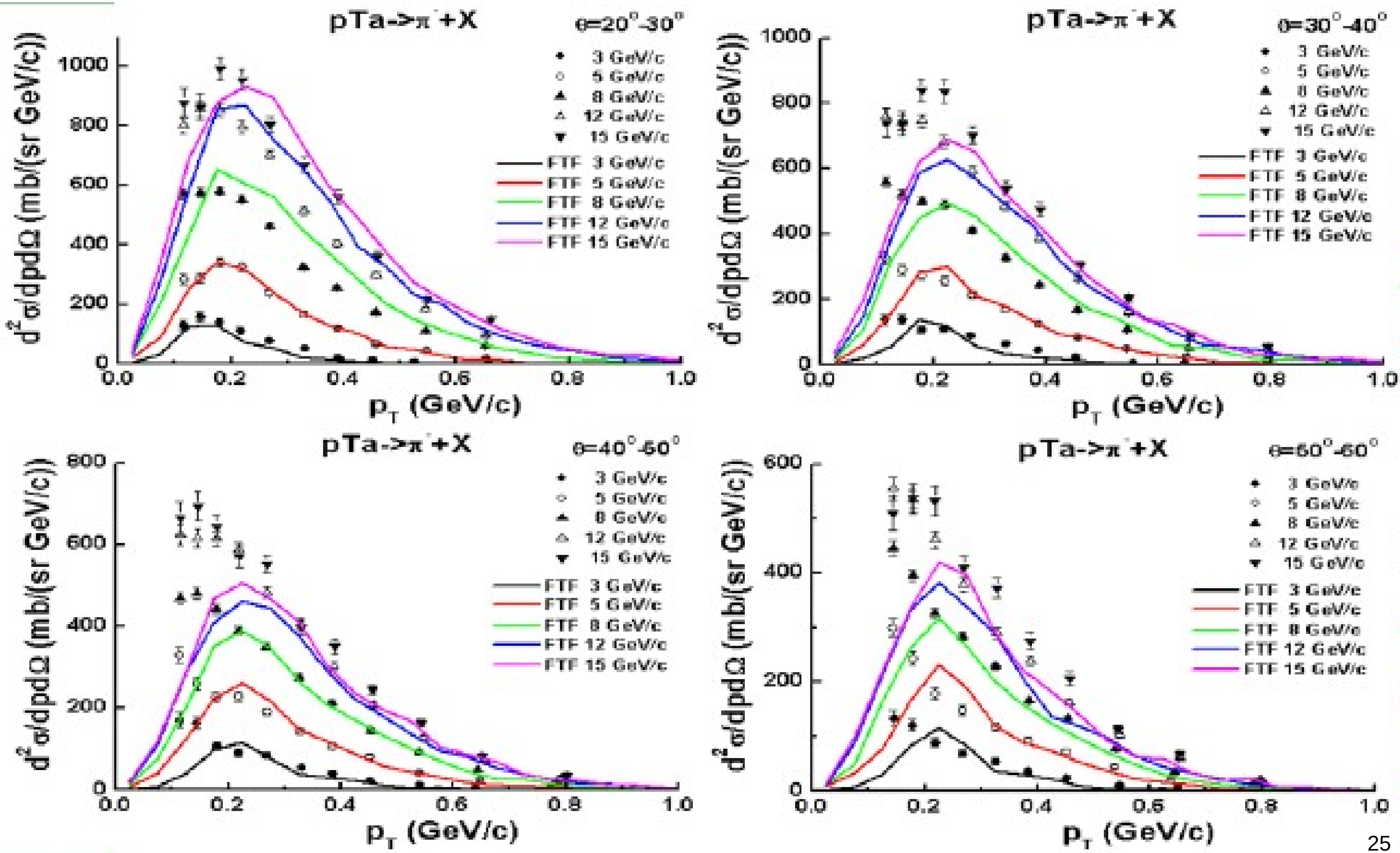
  1. the Monte Carlo event generator

  2. the convolution of the showers for each constituent hadron

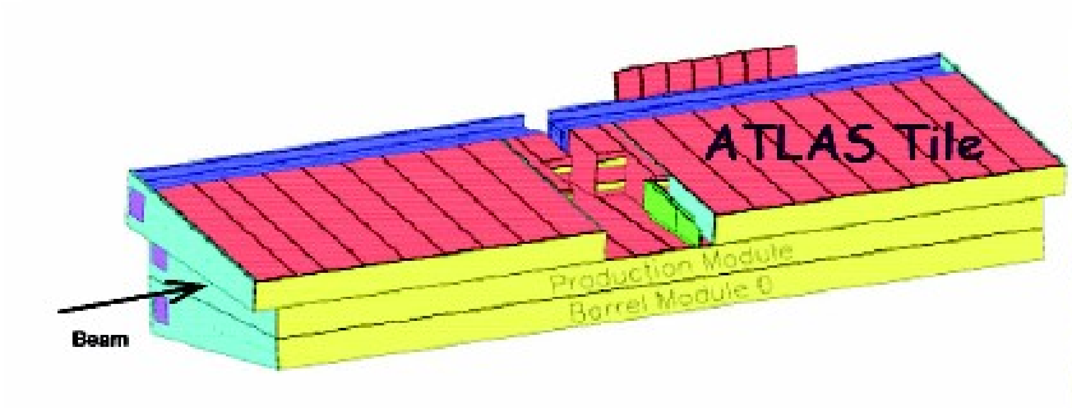
  3. experiment specific: geometry & materials, digitization, *etc.*

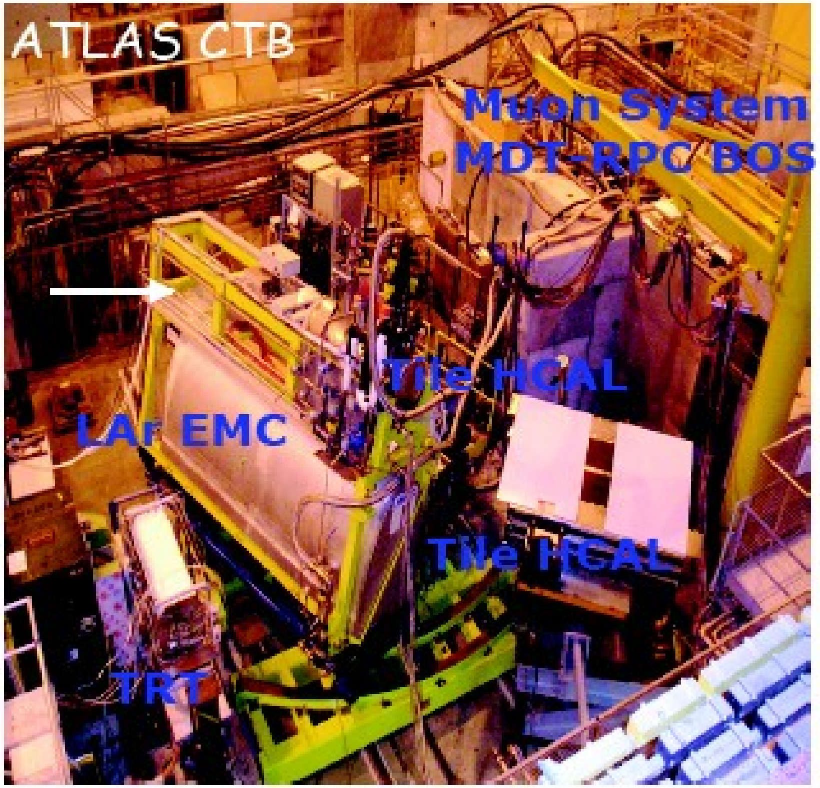
Model-level thin-target test

FTF validation, HARP-CDP data



LHC calorimeter test-beams





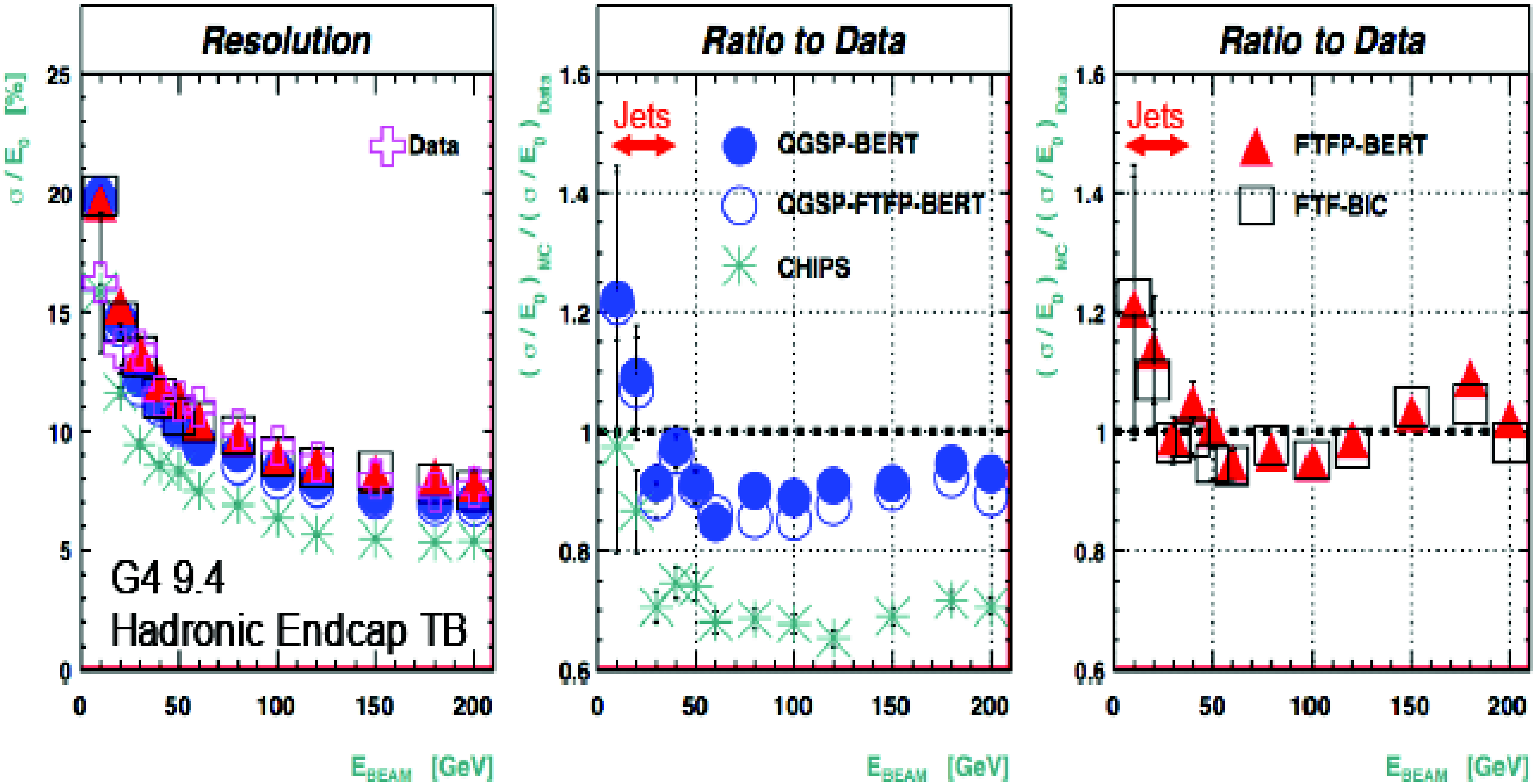
Calorimeter observables

- 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.
  The simulation of jets involves:
  1. the Monte Carlo Event Generator
  2. the convolution of the showers for each constituent hadron

Energy resolution

ATLAS HEC test-beam



Exercise

Exercise : “offline”

Some suggestions to get familiar with Geant4 and hadronic physics aspects relevant for high-energy physics:

- Build a simplified, hadronic sampling calorimeter
  - Or use/modify an already existing calorimeter example
- Using the user actions, plot and/or print some of the properties of hadronic showers
  - Like the visible energy, energy resolution, shower shapes
- Study how the properties of hadronic showers change
  - From one “event” (= shower) to another
  - On average, by changing the beam particle type ($\pi^\pm$, $K^\pm$, K°_L , p , n , *etc.*) and the beam energy (GeV – TeV)
  - By changing the sampling calorimeter (materials, dimensions)
  - By changing the physics list
  - By changing the version of Geant4

Exercise : for today

- Consider the same example you are already familiar with:
  - ***examples/basic/B4/B4a***
- Visualize the shower and consider the visible energy
  - *E.g.* the sum of the deposited energy in the gap (liquid-argon)
- Enlarge the calorimeter (from a typical EM to a typical HAD)
  - In the method ***B4DetectorConstruction::DefineVolumes*** increase both ***nofLayers*** and ***calorSizeXY*** by a factor of ***10***
- Observe how the properties of showers change
  - From one "event" (= shower) to another (and on average)
  - Between ***e−*** and ***pi−*** of the same energy, *e.g.* ***10 GeV***
  - Between different beam energies, *e.g.* *10 GeV* *vs.* ***100 GeV***
  - By changing the physics list, *e.g.* *FTFP_BERT* *vs.* ***QGSP_BIC_HP***
    - Look also at the printout list of hadronic models and their energy ranges