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European School of Instrumentation in Particle & Astroparticle Physics

Physics

Witold Pokorski, Alberto Ribon
CERN PH/SFT

GEANT4
A SIMULATION TOOLKIT

ESIPAP, Archamps, 11-12 February 2019

G4 Datasets (1)

- 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 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 10.5 :

```
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)

- **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)

- **G4REALSURFACEDATA** : data for measured optical surface reflectance look-up tables; used only when optical physics is activated

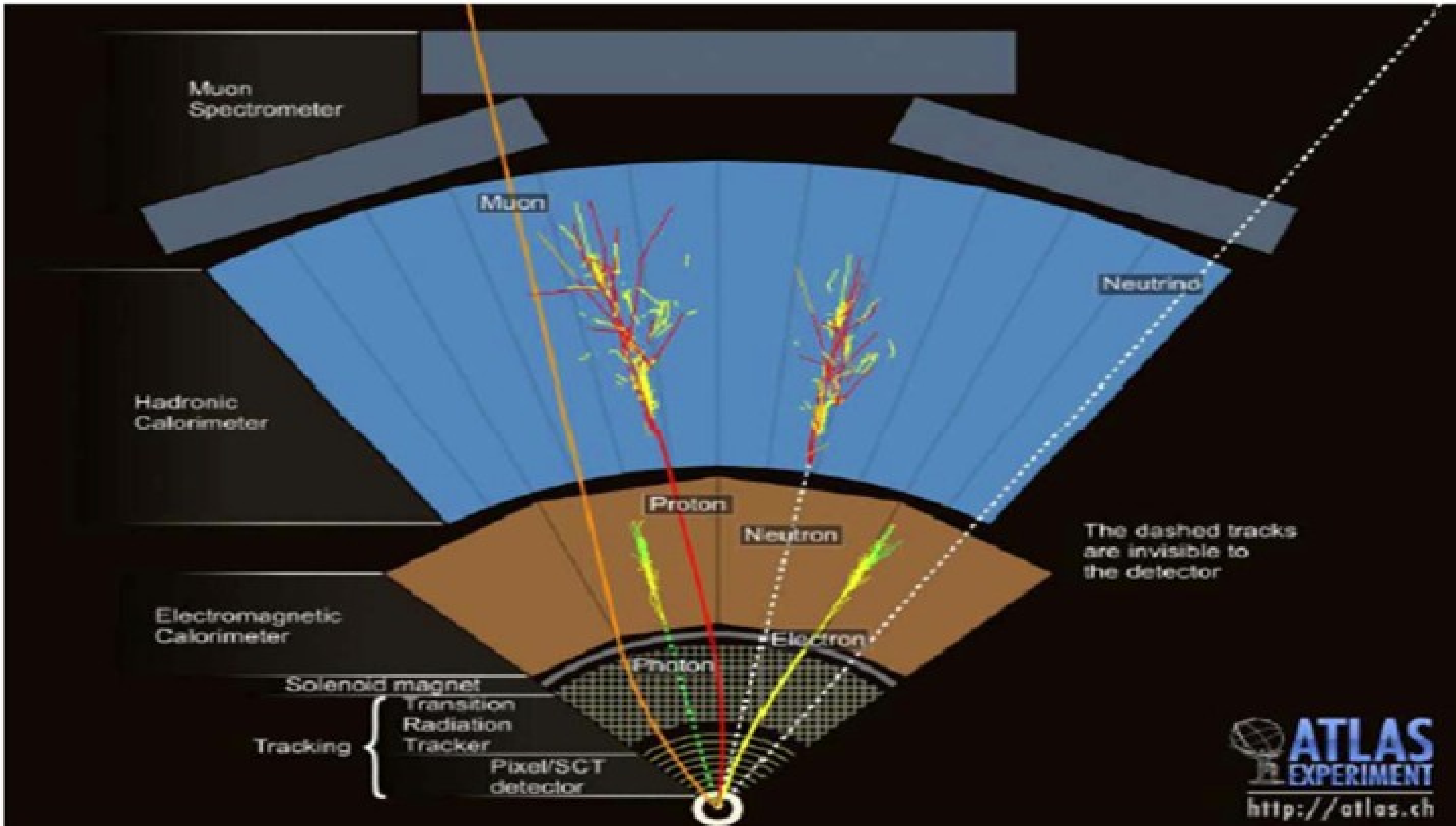
- **G4NEUTRONHPDATA** : evaluated neutron data of cross sections, angular distributions and final-state information; come largely from the ENDF/B-VII library; used only in _HP physics lists
- **G4RADIOACTIVEDATA** : radioactive decay data, come from the ENSDF; used only when radioactive decay is activated
- **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

Electromagnetic physics (EM)

Particle interactions

Each particle type has its own set of physics processes.
Only electromagnetic effects are directly measurable



Main electromagnetic processes

Gamma

- Conversion :
  γ -> e+ e- , μ+ μ-
- Compton scattering :
  γ *(atomic)*e- -> γ *(free)*e-
- Photo-electric
  γ material -> *(free)*e-
- Rayleigh scattering
  γ atom -> γ atom

Muon

- Pair production
  μ- atom -> μ- e+ e-
- Bremsstrahlung
  μ- (atom) -> μ- γ
- MSC (Coulomb scattering) :
  μ- atom -> μ- atom
- Ionization :
  μ- atom -> μ- ion+ e-

Total cross section:
step length

Differential & partial cross sections :
final state
(multiplicity & spectra)

Electron, Positron

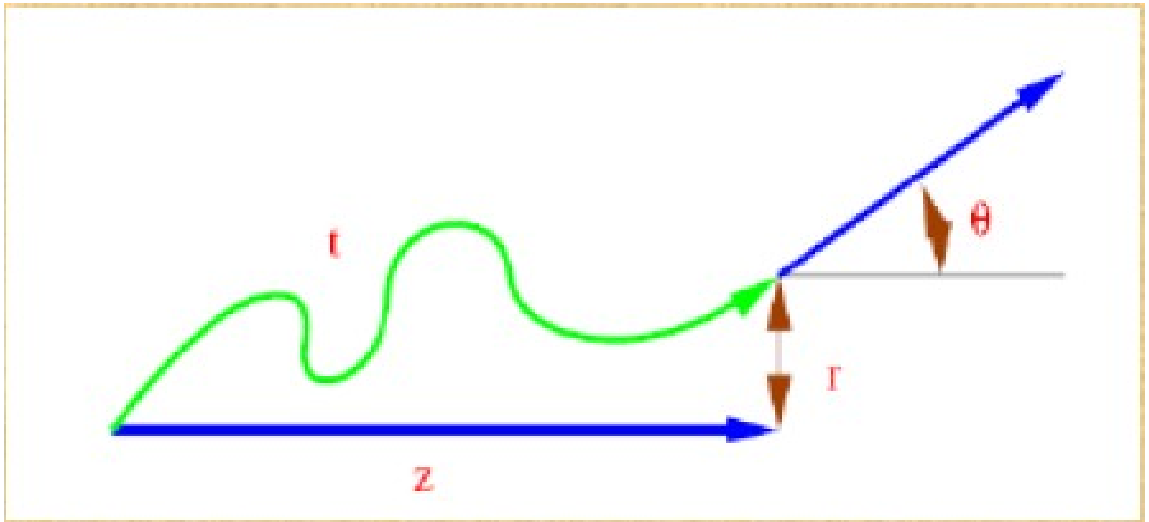
- Bremsstrahlung
  e- (atom) -> e- γ
- MSC (Coulomb scattering):
  e- atom -> e- atom
- Ionization :
  e- atom -> e- ion+ e-
- Positron annihilation
  e+ e- -> γ γ

Charged hadron, ion

- (Bremsstrahlung
  h- (atom) -> h- γ)
- MSC (Coulomb scattering):
  h- atom -> h- atom
- Ionization :
  h- atom -> h- ion+ e-

Multiple (Coulomb) scattering (MSC)

- Charged particles traversing a finite thickness of matter suffer a huge number (millions) of elastic Coulomb scatterings
- The cumulative effect of these small angle scatterings is mainly a net deflection from the original particle direction
- In most cases, to save CPU time, these multiple scatterings are not simulated individually, but in a “condensed” form
- Various algorithms exist, and new ones under development. One of the main differences between codes



Electromagnetic physics

- Typical validity of electromagnetic physics **≥ 1 keV** ;
  for a few processes, extensions to lower energies
- CPU performance of electromagnetic physics is critical : significant effort to improve it
- Detailed validation of electromagnetic physics is necessary before the validation of hadronic physics
- Typical precision in electromagnetic physics is **~1%**
  - QED is extremely precise for elementary processes,
    but atomic and medium effects, important for detector simulations, bring larger uncertainties...
  - Moreover, the “condensed” description of multiple scattering introduces further approximations...
  - Major effort to improve the models

EM options

- **Baseline** (default, *a.k.a.* Opt0)
  - Used in production by ATLAS
  - Available in all reference physics lists, e.g. **FTFP_BERT**
- Fast (EMV, *a.k.a.* Opt1)
  - Used in production by CMS: good for crystals, not for sampling calo
  - Available in _**EMV** variants of physics lists
- Accurate (EMZ, *a.k.a.* Opt4)
  - Used in medical and space science applications
  - Available in _**EMZ** variants of physics lists
- Other options are available:
  - _**EMX** (*a.k.a.* Opt2) : experimental, used by LHCb
  - _**EMY** (*a.k.a.* Opt3) : as Opt0 but with more restricted stepping
  - _**LIV** : models based on the Livermore database
  - _**PEN** : Penelope models implemented in Geant4

Optical Photons

- A photon is considered to be optical when its wavelength is greater than the typical inter-atomic distance
- In Geant4, for convenience, optical photons are treated as a separated particle class, **G4OpticalPhoton**, distinct from the class of high-energy photons, **G4Gamma**
- Three processes in Geant4 can produce optical photons: Cerenkov effect, scintillation, and transition radiation
- Geant4 processes that can be associated to optical photons: refraction, reflection, absorption, scattering, wavelength shifting
- Optical properties of media (reflectivity, transmission, etc.) should be specified (in G4MaterialPropertiesTable linked to G4Material)
- For some examples, see: ***examples/extended/optical/***

Hadronic physics (HAD)

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

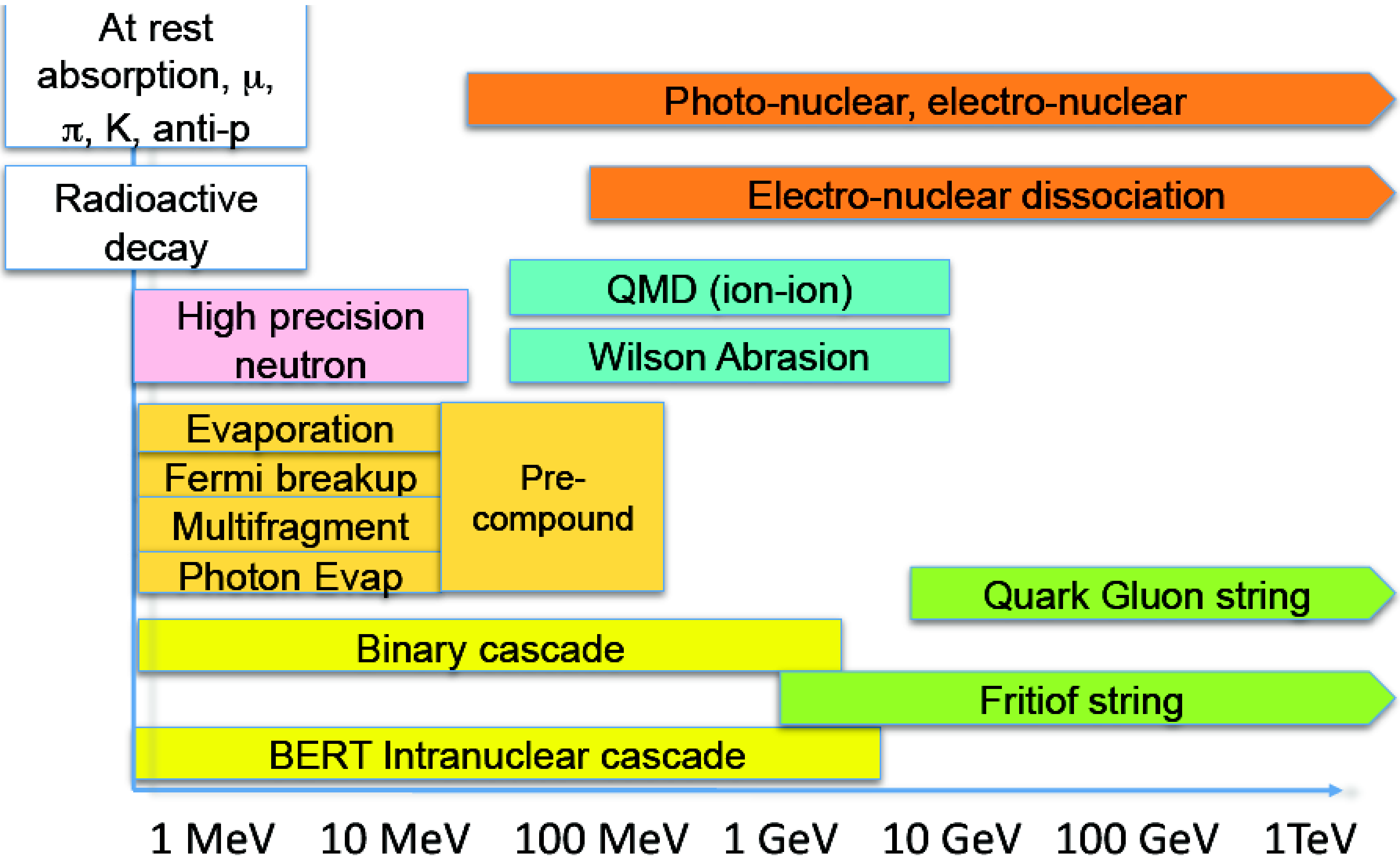
  hadron – nucleus -> *anything*

  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

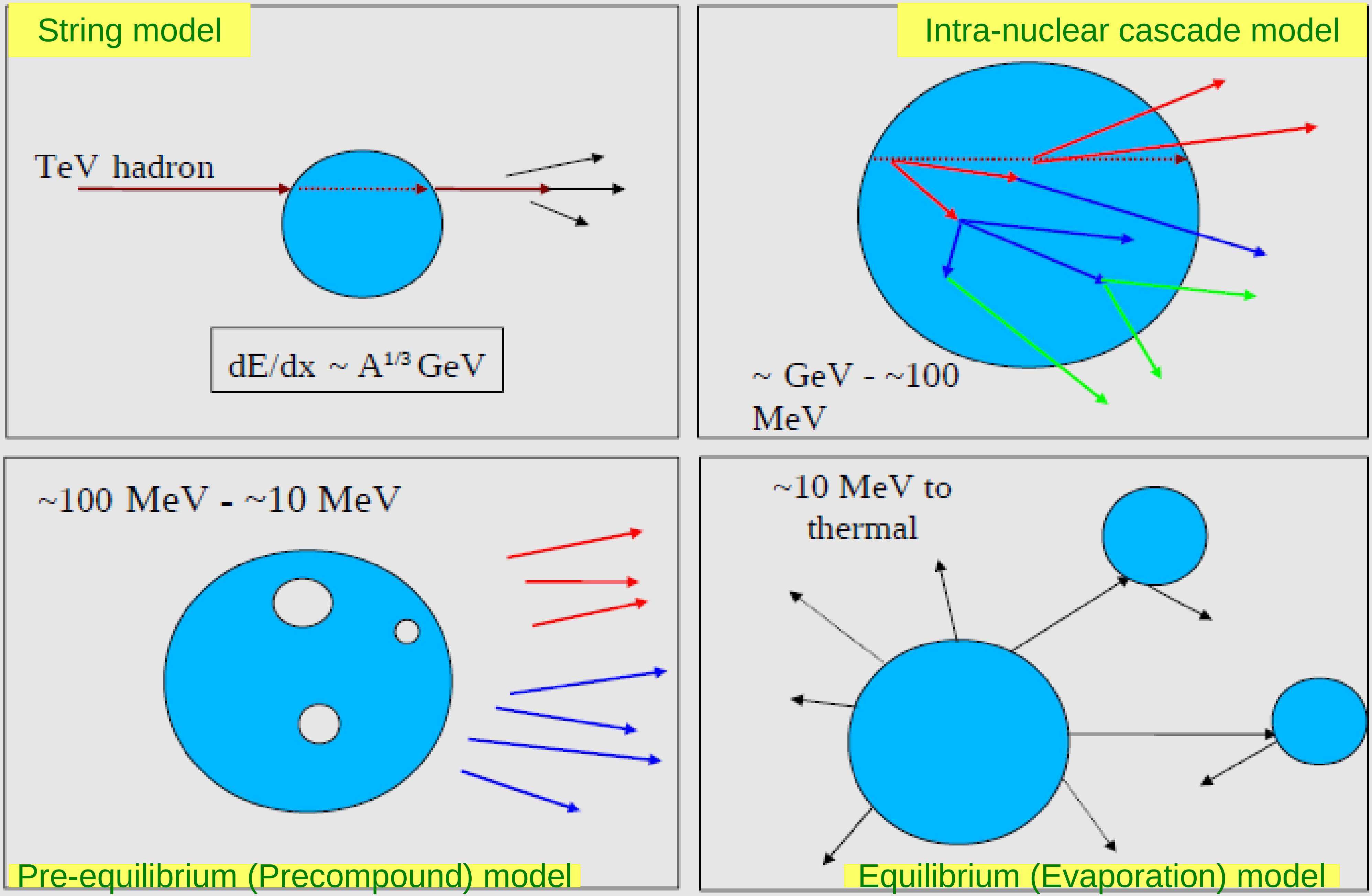
  whereas for the rest, i.e. most of the phase space
  - soft scattering, re-scattering, hadronization, nucleus de-excitation

  only 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



An interesting complication: Neutrons

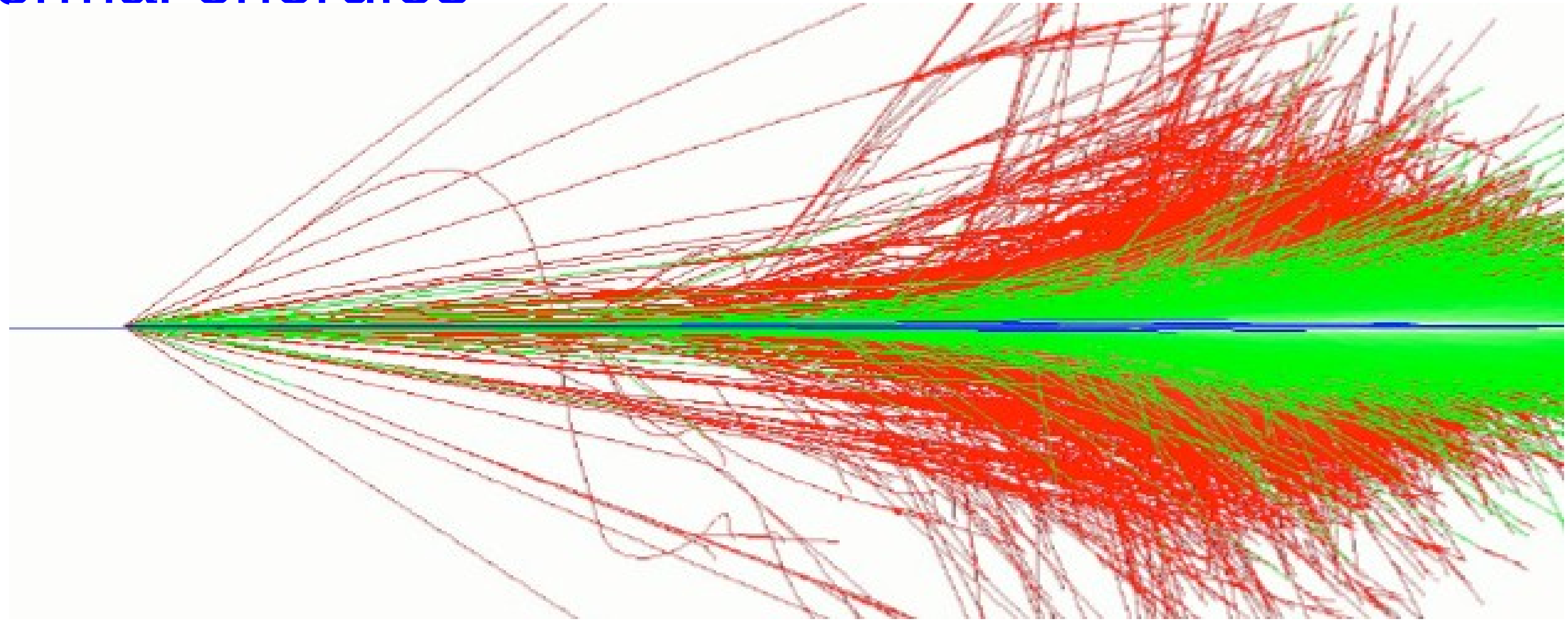
- Neutrons are abundantly produced
  - Mostly “soft” neutrons, produced by the de-excitation of nuclei, after hadron-nucleus interactions
  - It is typically the 3rd most produced particle (after e-, γ)
- Before a neutron “disappears” via an inelastic interaction, it can have many elastic scatterings 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 analysis

Physics Lists

What is a Physics List ?

- A class that collects all the particles, physics processes, and production thresholds needed by your application
- One and only one physics list should be present in each Geant4 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 interested 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 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 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: e.g. **FTFP_BERT**, **FTFP_BERT_HP**, **Shielding**, **FTFP_INCLXX**, **QGSP_FTFP_BERT**, **QGSP_BIC_EMY**, *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 lists for their application**

FTFP_BERT

Recommended physics list for High-Energy Physics.

Its main components are the following:

- **FTF** (Fritiof string) model, above 3 GeV
- **BERT** (Bertini cascade) model, below 12 GeV
- Nucleus de-excitation: **P**recompound + evaporation
- Neutron capture
- Nuclear capture of negatively charged hadrons at rest
- Hadron elastic
- Gamma- and electro-nuclear
- Standard electromagnetics

- 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 );
  ...
}
```

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