Physics

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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 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
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
```

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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 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

Electromagnetic physics (EM)

Particle interactions

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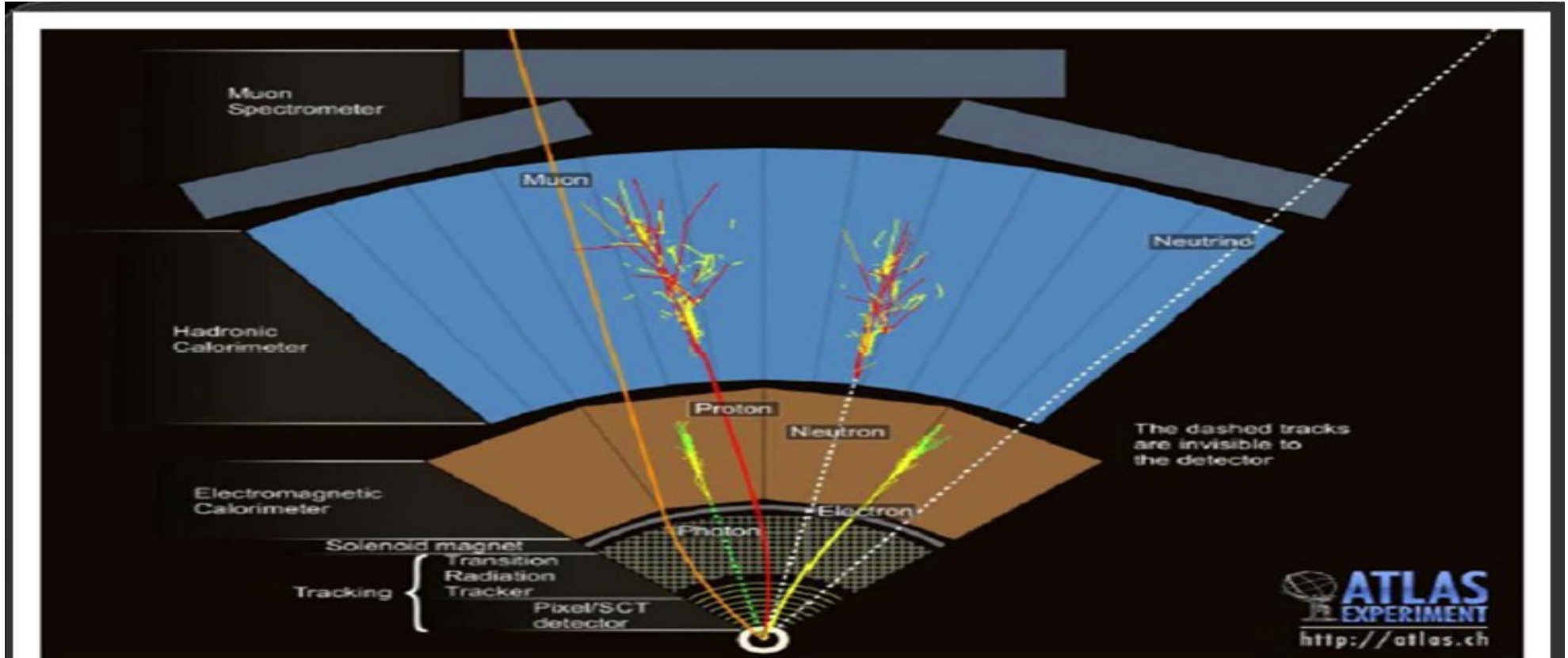
Main electromagnetic processes

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-

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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
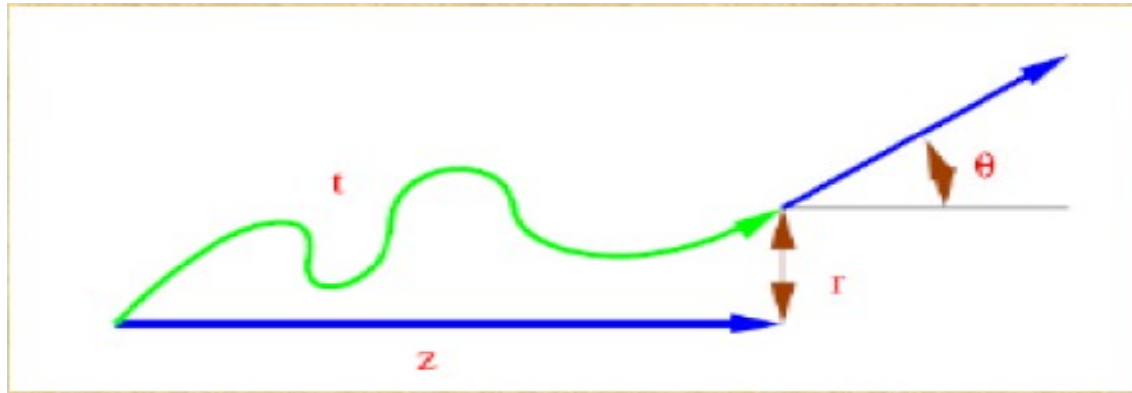
Electromagnetic physics

- 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.* Opt**0**)
  - Used in production by ATLAS
  - Available in all reference physics lists, e.g. **FTFP_BERT**

- Fast (*a.k.a.* Opt**1**)
  - Used in production by CMS: good for crystals, not for sampling calorimeters
  - Available in **_EMV** variants of physics lists

- Accurate (*a.k.a.* Opt**4**)
  - Used in medical and space science applications
  - Available in **_EMZ** variants of physics lists

- Other options are available:

  - **_EMX** (*a.k.a.* Opt**2**) : experimental, used by LHCb

  - **_EMY** (*a.k.a.* Opt**3**) : similar to Opt**0** but with more restricted stepping

  - **_LIV** : models based on the Livermore database

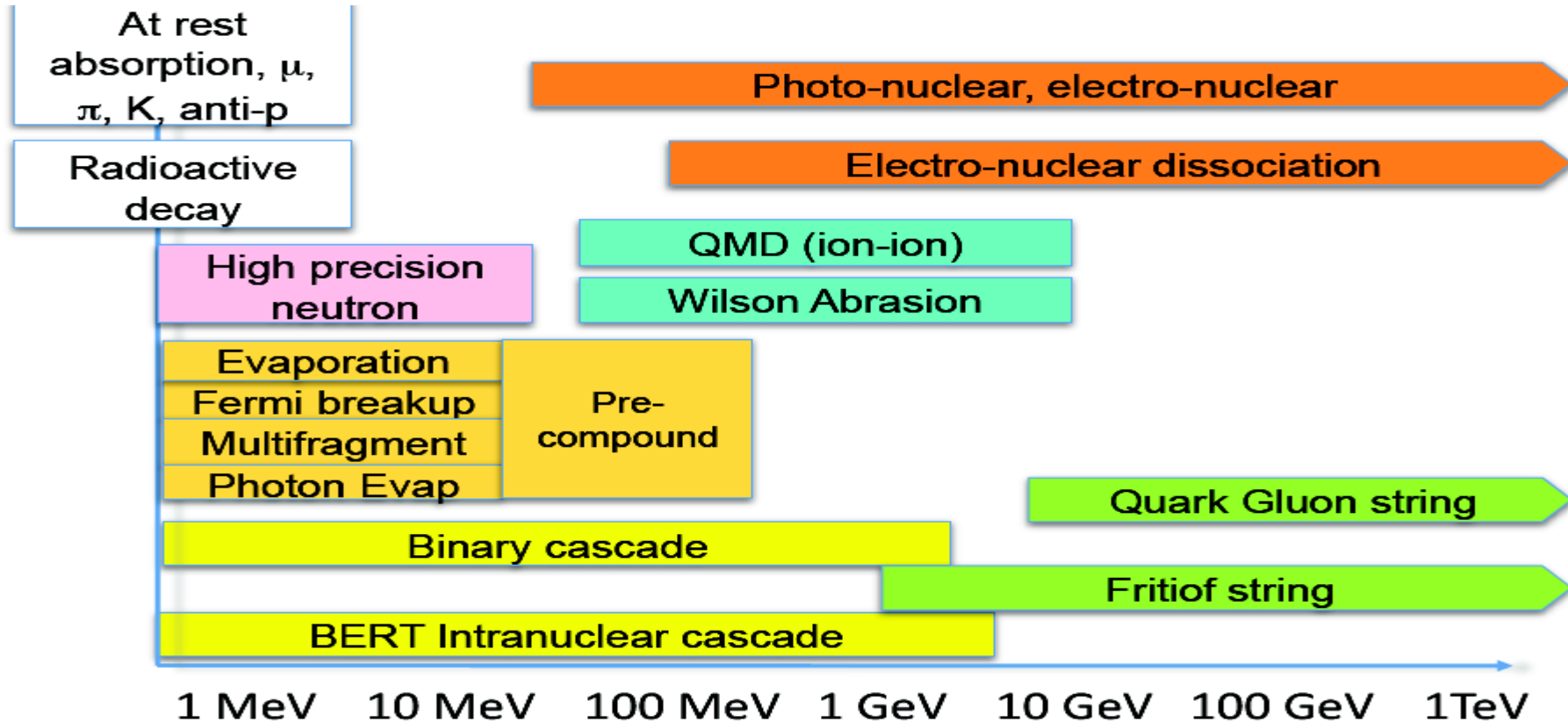 - **_PEN** : Penelope models implemented in Geant4

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 , scintillation , 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/***

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Hadronic physics (HAD)
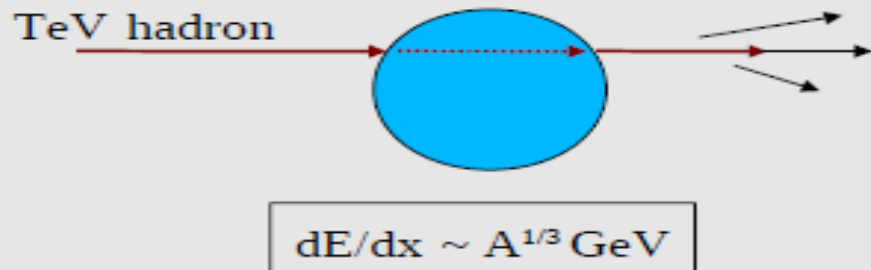
Hadronic interactions

- 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 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**
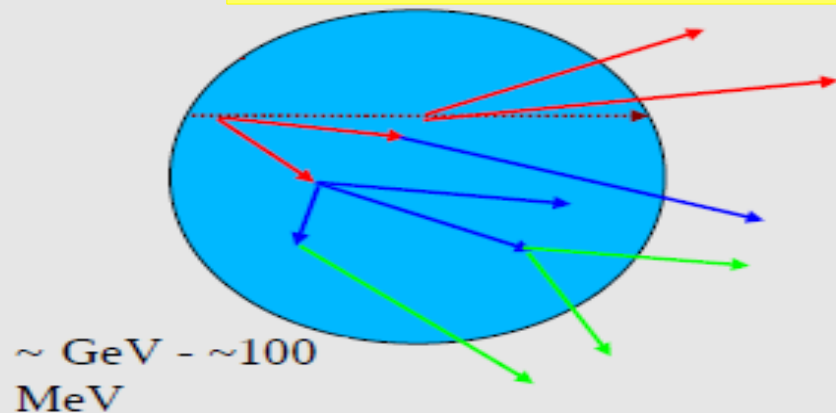
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Partial Hadronic Model Inventory

At rest absorption, μ, π, K, anti-p

Radioactive decay

Photo-nuclear, electro-nuclear

Electro-nuclear dissociation

QMD (ion-ion)

High precision neutron

Wilson Abrasion

Evaporation

Fermi breakup

Multifragment

Photon Evap

Pre-compound

Quark Gluon string

Binary cascade

Fritiof string

BERT Intranuclear cascade

1 MeV   10 MeV   100 MeV   1 GeV   10 GeV   100 GeV   1TeV

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Hadronic Interactions from TeV to meV

String model

TeV hadron

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

Intra-nuclear cascade model

$\sim$ GeV - $\sim$100 MeV

$\sim$100 MeV - $\sim$10 MeV
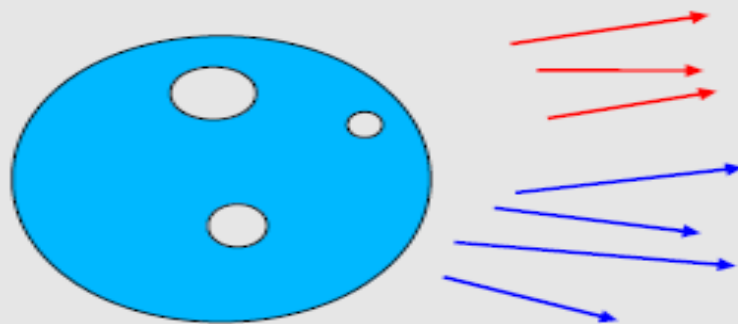
Pre-equilibrium (Precompound) model

$\sim$10 MeV to thermal
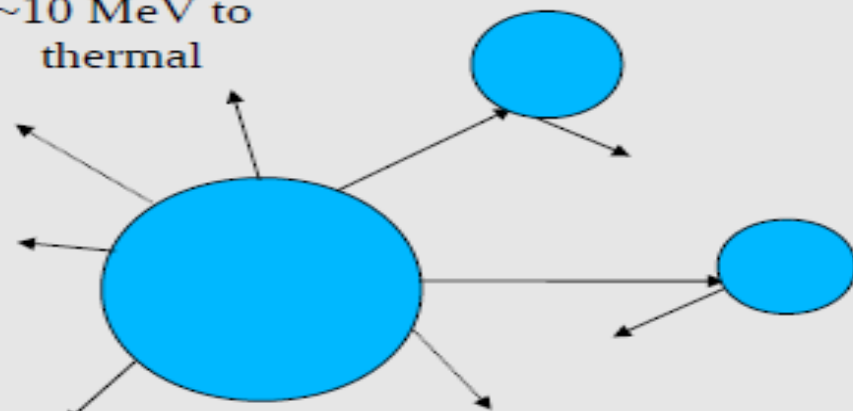
Equilibrium (Evaporation) models

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**

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Neutron-HP

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

  - **Ekin < 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)

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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 **π° -> γ γ** and ionization of charged particles

- The development of a hadronic shower involves many energy scales, from hundreds of GeV down to thermal energies
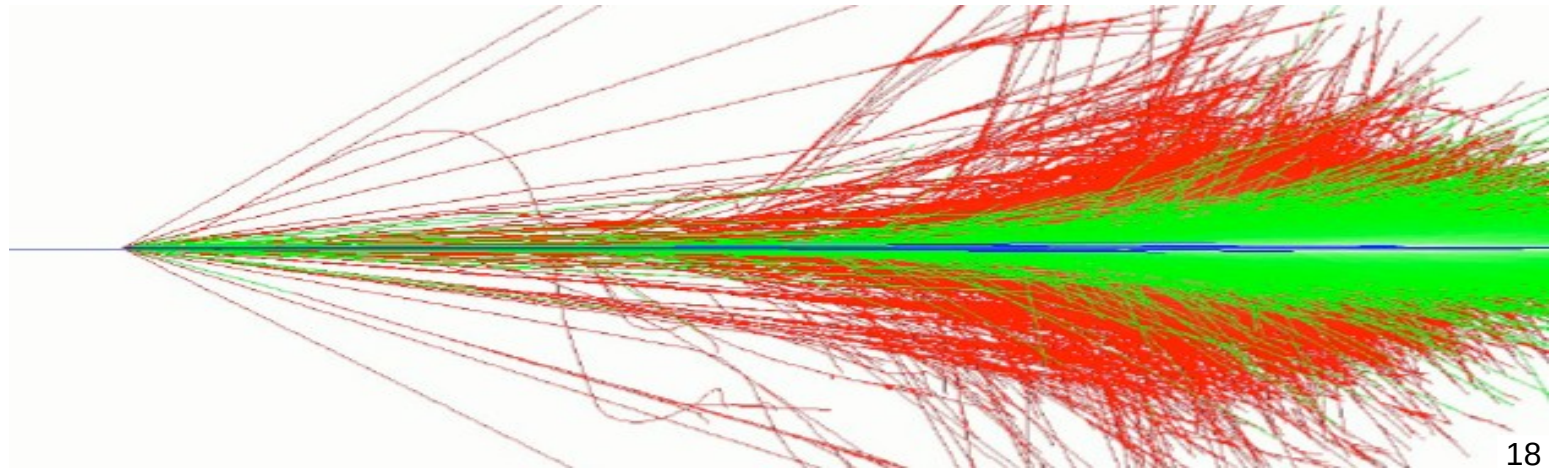
Jets

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), the simulation of jets is essential for the optimal design of the detector. For LHC experiments, the simulation of jets is now important for physics analysis

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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

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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_EMY**, *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**

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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 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 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 );
    ...
}
```

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