European Scientific Institute

European School of Instrumentation in Particle & Astroparticle Physics

Physics

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G4 Datasets (1)

- Some physics models are data-driven, i.e. they are phenomenological models that need some input data (either experimental or computed from theory)
- 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 G4 where they are by defining the following environmental variables (e.g. for the latest version G4 10.4):

```
export G4LEDATA=/dir-path/G4EMLOW7.3
export G4LEVELGAMMADATA=/dir-path/PhotonEvaporation5.2
export G4SAIDXSDATA=/dir-path/G4SAIDDATA1.1
export G4NEUTRONXSDATA=/dir-path/G4NEUTRONXS1.4
export G4ENSDFSTATEDATA=/dir-path/G4ENSDFSTATE2.2
export G4NEUTRONHPDATA=/dir-path/G4NDL4.5
export G4RADIOACTIVEDATA=/dir-path/RadioactiveDecay5.2
export G4REALSURFACEDATA=/dir-path/RealSurface2.1
```

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
- **G4NEUTRONXSDATA** : evaluated neutron 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)

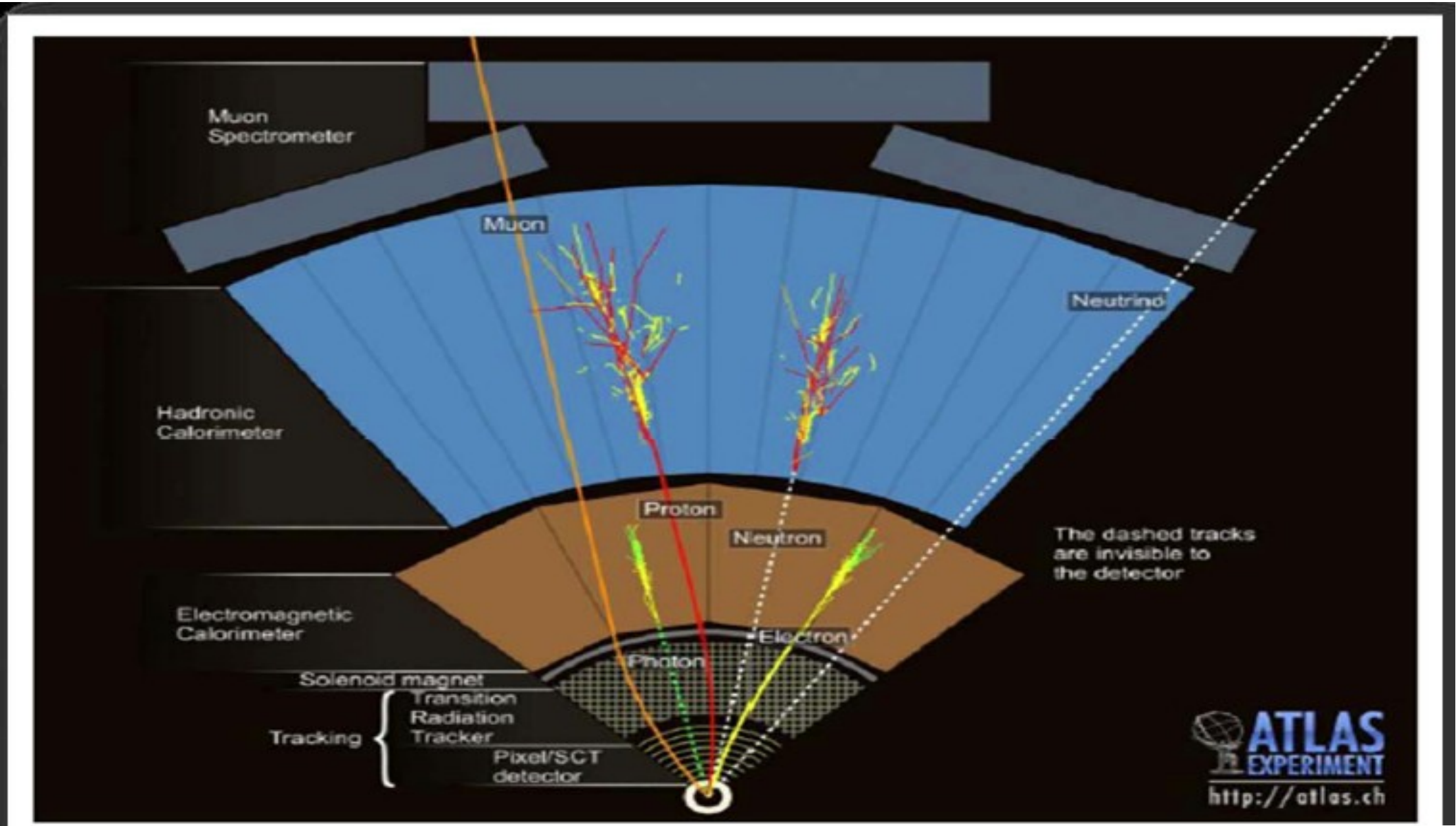
- **G4NEUTRONHPDATA** : evaluated neutron data of cross sections, angular distributions and final-state information; come largely from the ENDF/B-VII library; used only in _HP physics lists
- **G4RADIOACTIVEDATA** : radioactive decay data, come from the ENSDF; used only when radioactive decay is activated
- **G4REALSURFACEDATA** : data for measured optical surface reflectance look-up tables; used only when optical physics is activated

- **G4PARTICLEHPDATA** : data for ParticleHP (p, d, t, He3, α)

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

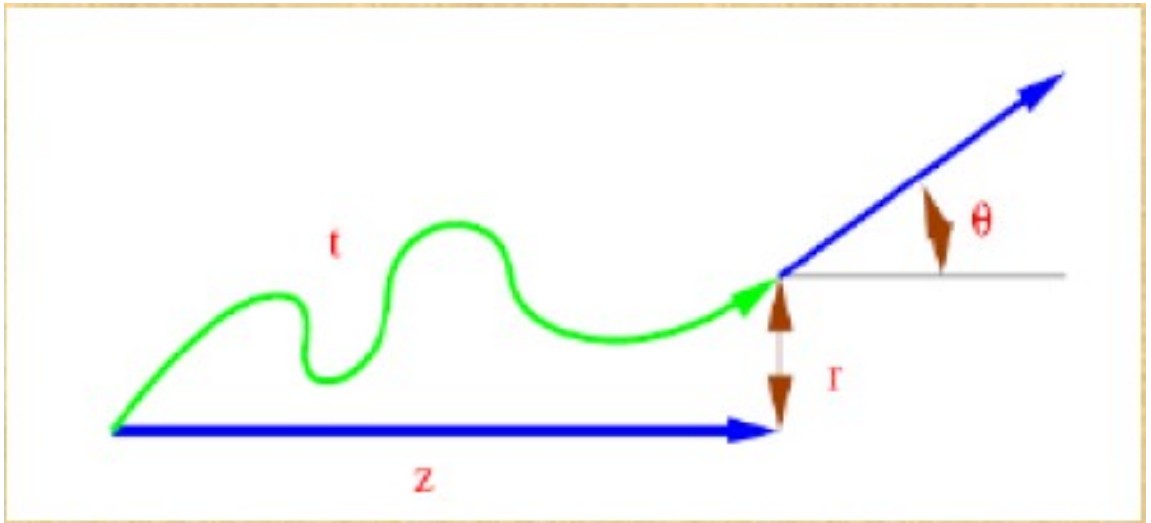
- Bremsstrahlung
  e- (atom) -> e- γ
- MSC (Coulomb scattering):
  e- atom -> e- atom
- Ionization :
  e- atom -> e- ion+ e-
- Positron annihilation
  e+ e- -> γ γ

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 (EMY, *a.k.a.* Opt3)
  - Used in medical and space science applications
  - Available in _**EMY** variants of physics lists
- Other options are available:
  - _**EMX** (*a.k.a.* Opt2) : experimental, used by LHCb
  - _**EMZ** (*a.k.a.* Opt4) : the most precise EM available in G4
  - _**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)

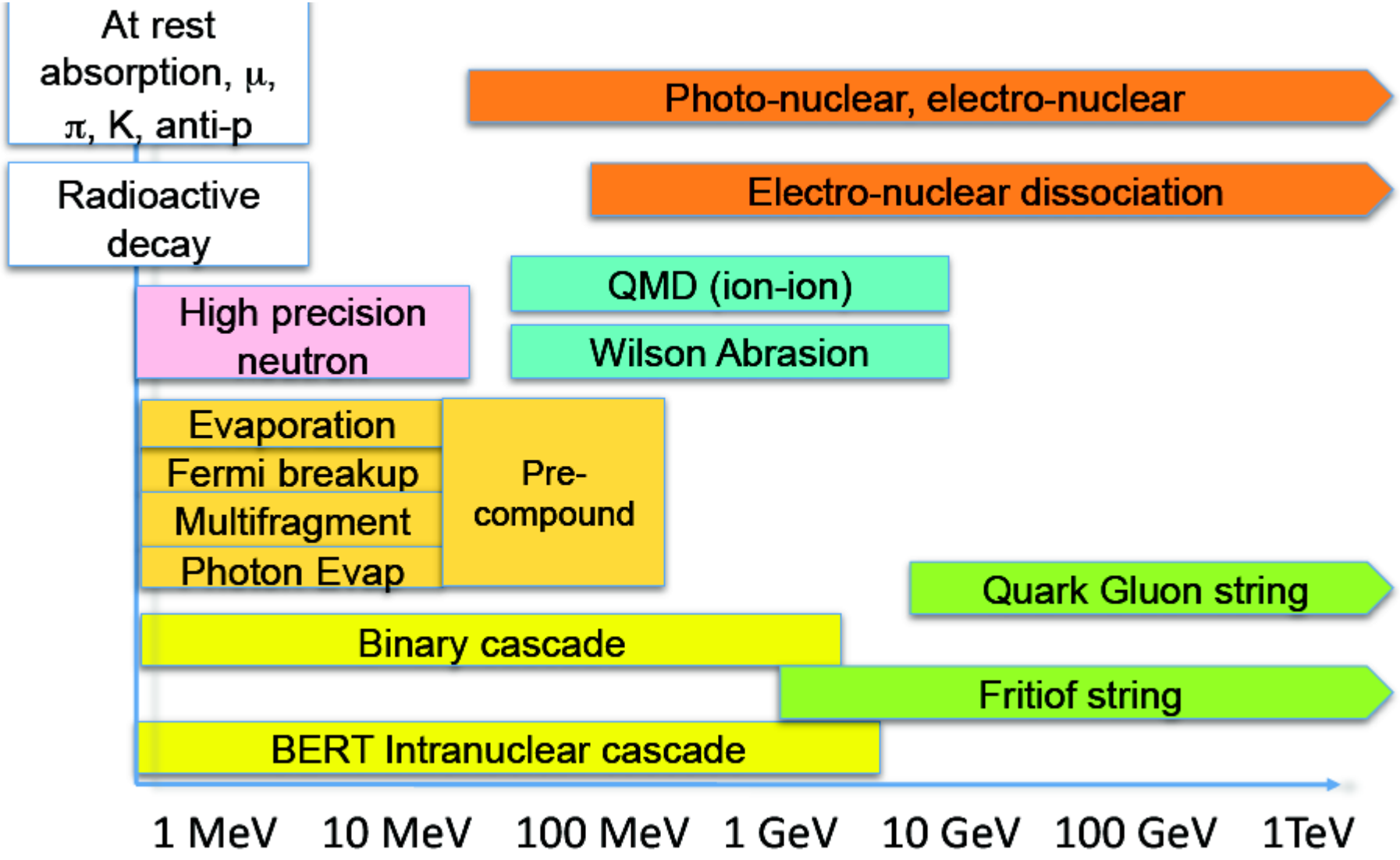
Hadronic interactions

- Hadrons (π±, K±, 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

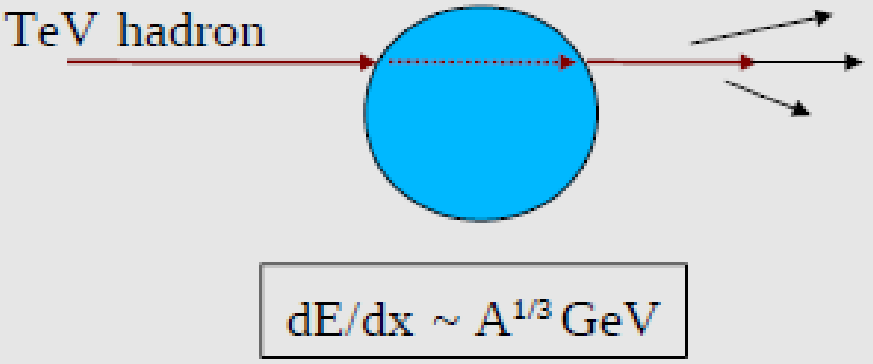
  only approximate models are available
- Hadronic models are valid for limited combinations of
  - **particle type - energy - target material**

Partial Hadronic Model Inventory

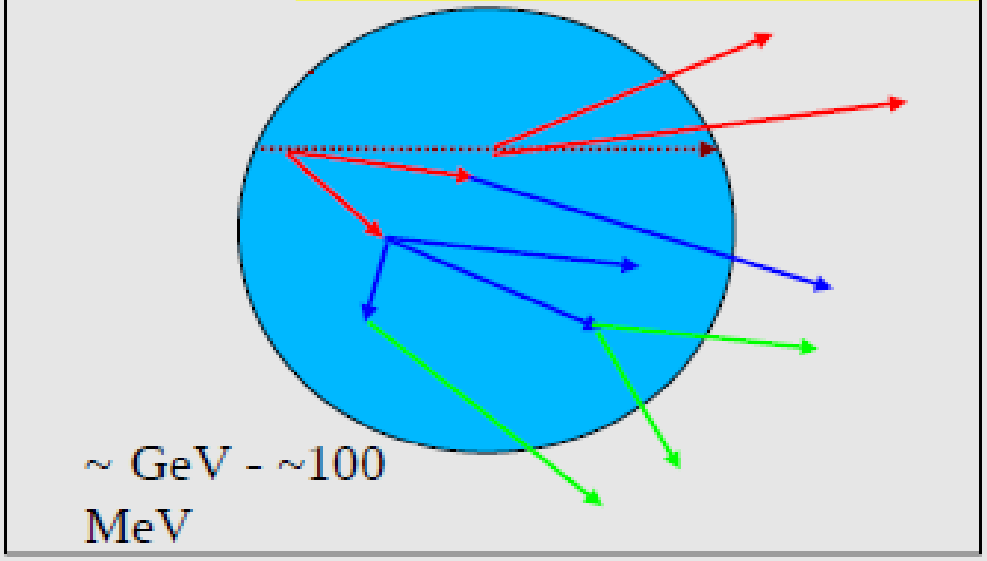


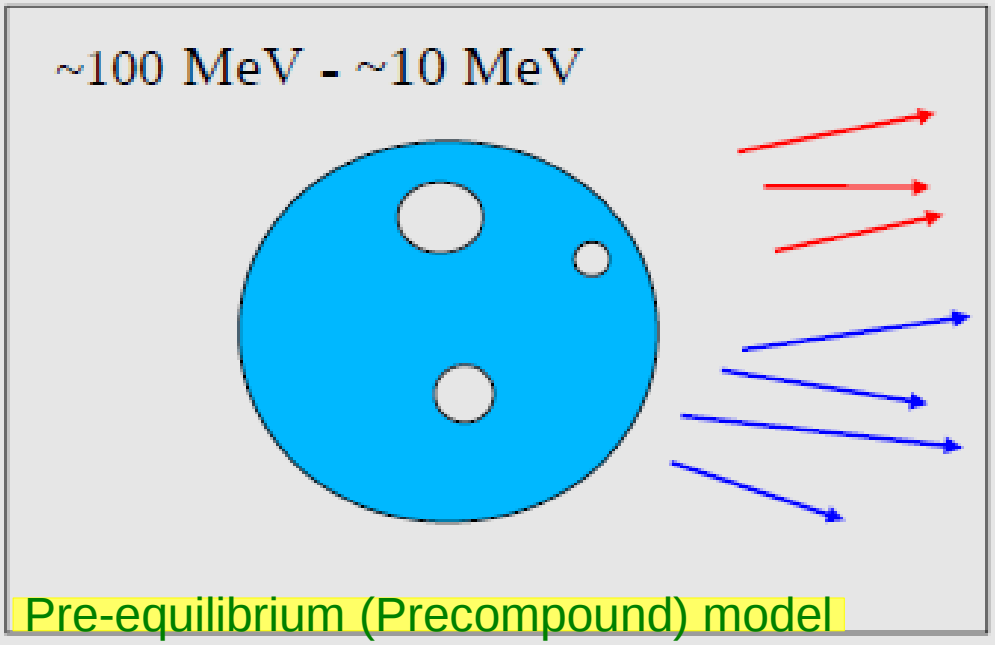
Hadronic Interactions from TeV to meV

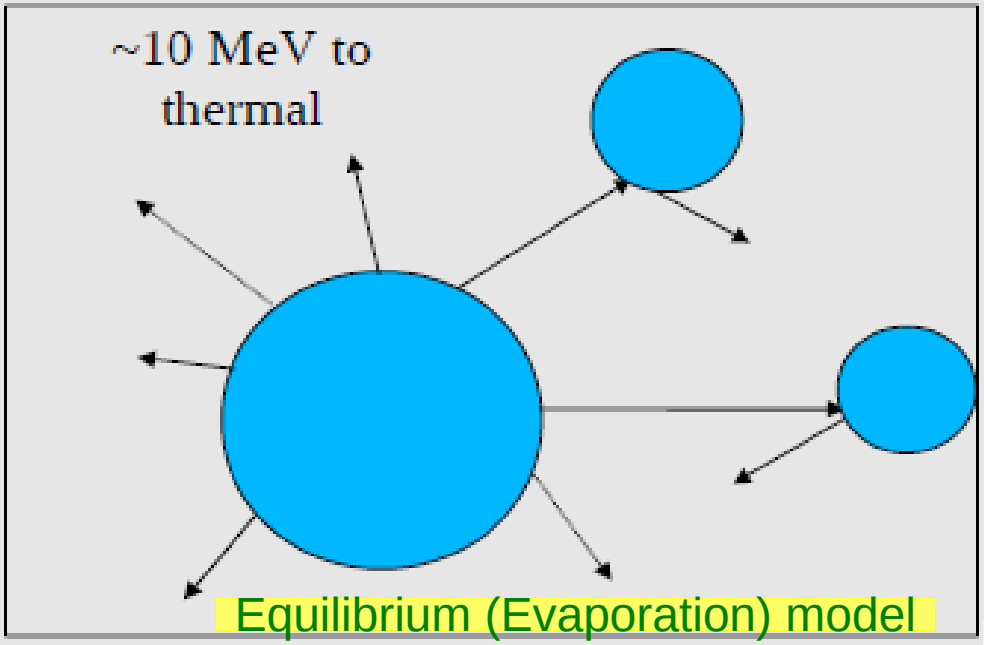
String model



Intra-nuclear cascade model







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

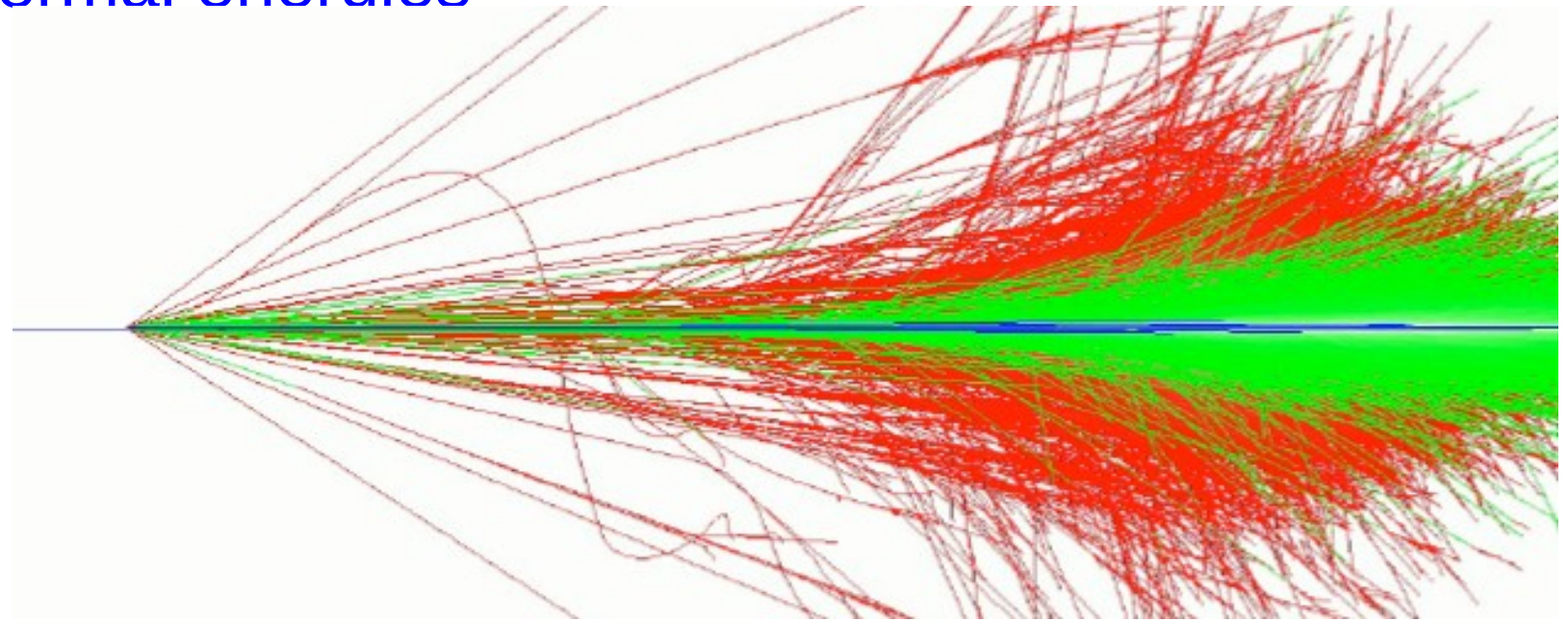
- **H**igh **P**recision treatment of low-energy neutrons
  - **E_{kin} < 20 MeV** , down to thermal energies
  - Includes 4 types of interactions:
    radiative capture, elastic scattering, fission, inelastic scattering
  - Based on evaluated neutron scattering data libraries
    (pointed by the environmental 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_**HP** , Shielding

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 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
  - a user 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** **QGSP_FTFP_BERT**, **QGSP_BIC_EMY**
- 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
- Gamma- and electro-nuclear
- Standard electromagnetics

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

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

Backup

Optical Photons (1)

- A **photon** is considered to be optical when its wavelength is greater than the typical inter-atomic distance
- In Geant4, optical photons are treated as a separated particle class, **G4OpticalPhoton**, distinct from the class of high-energy photons, **G4Gamma**
  - This allows to incorporate some of the wave-like properties of electromagnetic radiation into the optical photon processes
  - But there is no smooth transition as a function of energy between optical photons and gammas
- Optical photons in G4 must always have linear polarization
  - This is guaranteed by the processes that can create them
  - For primary particle, the linear polarization should be set by the user: in the case of an unpolarized source, the linear polarization should be sampled randomly for each new primary photon

Optical Photons (2)

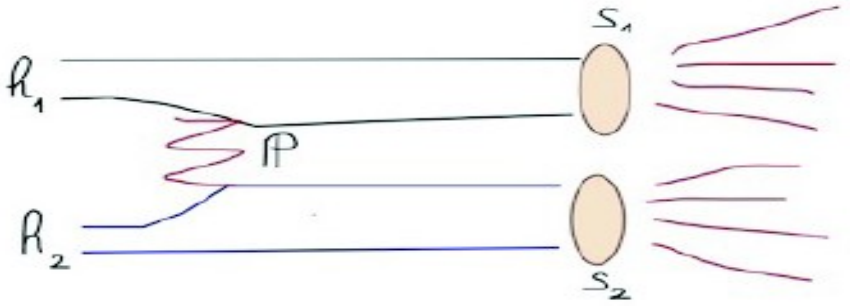
- Three processes in Geant4 can produce optical photons: Cerenkov effect, scintillation, and transition radiation
  - optical photons are generated without energy conservation
- Geant4 processes that can be associated to optical photons:
  - refraction and reflection at medium boundaries
  - bulk absorption
  - Mie and Rayleigh scattering
  - wavelength shifting (WLS)
- Optical properties of media:
  - the processes associated to optical photons require some optical properties of media: reflectivity, transmission efficiency, dielectric constants, surface properties
  - these properties are stored as entries in G4MaterialPropertiesTable which is linked to G4Material

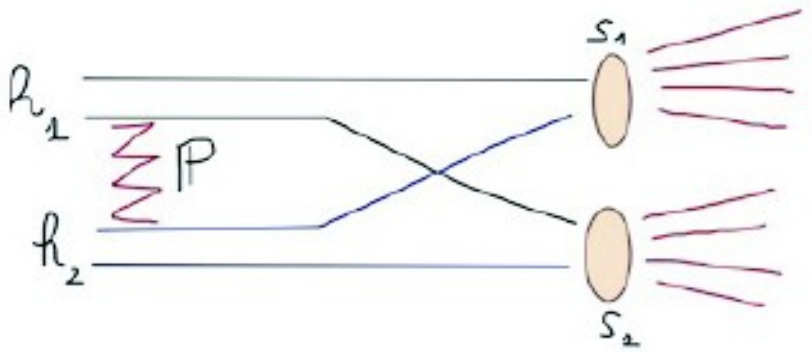
Optical Photons (3)

- For some examples, see: ***examples/extended/optical/***
  - ***OpNovice/*** : simulation of optical photons generation and transport
  - ***LXe/*** : scintillation inside a bulk scintillator with PMT
  - ***wls/*** : propagation of photons inside a Wave Length Shifting (WLS) fiber
- In practice, optical photons are not used frequently
  - Substantial slow down of the simulation
  - Very difficult to model accurately all properties (and imperfections!) of real, experimental set-ups
  - Easier to treat the effects of optical photons at the level of "digitization", i.e. applying a factor (determined from data) to the deposited energy obtained from Geant4
  - Most of the physics lists do not include optical photons, and their related processes, by default

Fritiof (FTF) model (1)

- High-energy string model valid for any hadron projectile with kinetic energy between ~ 3 GeV and ~ 1 TeV
- Selection of collision partners: projectile, nucleon
- Splitting of nucleons into quarks and diquarks
- Formation and excitation of strings (between constituents)
- String hadronization/fragmentation
  - Insert q-q pair , u : d : s : qq = 1 : 1 : 0.27 : 0.1
  - At break: new string plus hadron
    - gets $P_{||}$ from sampling fragmentation functions
    - gets P_T from sampling a Gaussian





FTF (2)

- Build up 3D model of nucleus
- Calculate impact parameter with all nucleons
  - Calculate hadron-nucleon collision probabilities
  - Multiple collisions are allowed
  - Use gaussian density distributions for hadrons and nucleons
- Sample number of strings exchanged in each collision
- String formation and then fragmentation into hadrons
- Remnant nucleus
  - After the HE interaction is performed an excited nucleus remains
  - De-excitation via precompound model
- Recently extended to nucleus-nucleus collision
  - Applicable for kinetic energies above ~2 GeV/nucleon
- Under developing/testing: re-scattering
  - Use Binary Cascade or Bertini to propagate string fragments in nuclear media

Bertini-like intra-nuclear cascade model (BERT)

- The Geant4 implementation started as the original Bertini (1960), but it was then extended and modified significantly
- Valid for p, n , π, K, hyperons with E_{kin} ~< 15 GeV
- The incident hadron penetrates the nucleus, and propagates in a density-dependent nuclear potential
- All hadron-nucleon interactions are based on free-space cross sections, angular distributions, etc., but the Pauli exclusion principle is taken into account
- Each secondary is propagated in the nuclear potential until re-interacts or leaves the nucleus
- Particle-hole excitons are created during the cascade

Preco: pre-equilibrium

Native pre-equilibrium de-excitation model in Geant4 is a version of the standard exciton model. Key ingredients:

- Internal transition rates:
  - CEM (Cascade Exciton Model): default
  - Blann-Machner's parameterization
- Emission rates:
  – Nucleon emission in standard exciton formulation
  – Complex particle emission (d , t , 3He , α) from CEM

The pre-equilibrium phase continues until:

number of excitons ≤ number of excitons in equilibrium

then transition to equilibrium

Preco: equilibrium

Five processes are considered:

Alternates:

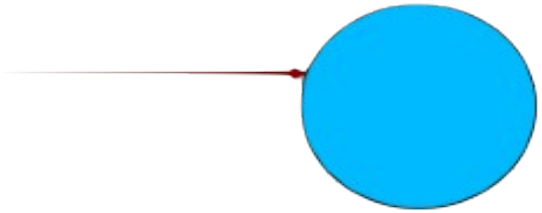
- Fermi Breakup, for Z < 9 and A < 17 (Botvina et al)
- Statistical Multifragmentation, for E*/A > 3 MeV (Botvina et al)

Competitors:

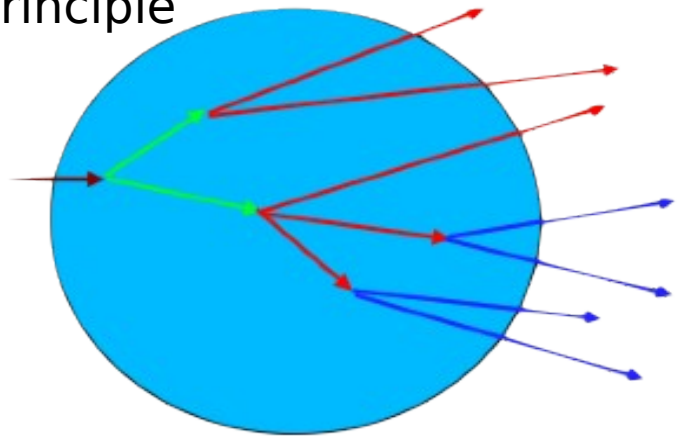
- Fission (Bohr-Wheeler model + Amelin prescript.)
- Particle Evaporation :
  - Evaporation Model WE (Weisskopf-Ewing) (evaporation of: n , p , d , t , 3He , α)
  - Generalized Evaporation Model GEM (Furihata) (heavier ejected fragments: Z < 13 and A < 29)
- Photon Evaporation :
  - Discrete (tabulated E1, M1, E2)
  - Continuum (GDR strength)

BERT + Preco (1)

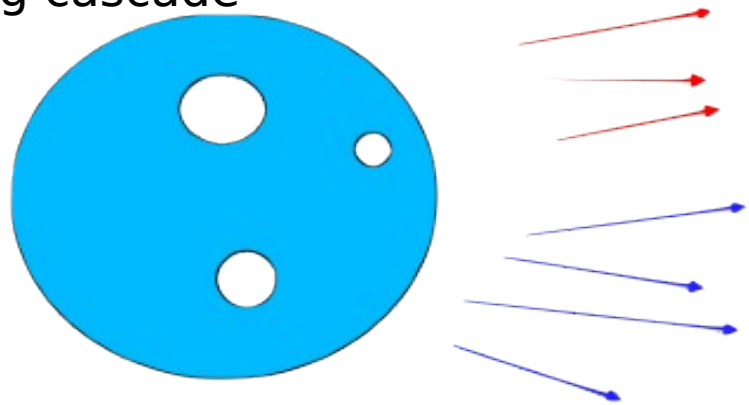
Hadron penetrates nucleus
Nucleus: density-dependent potential



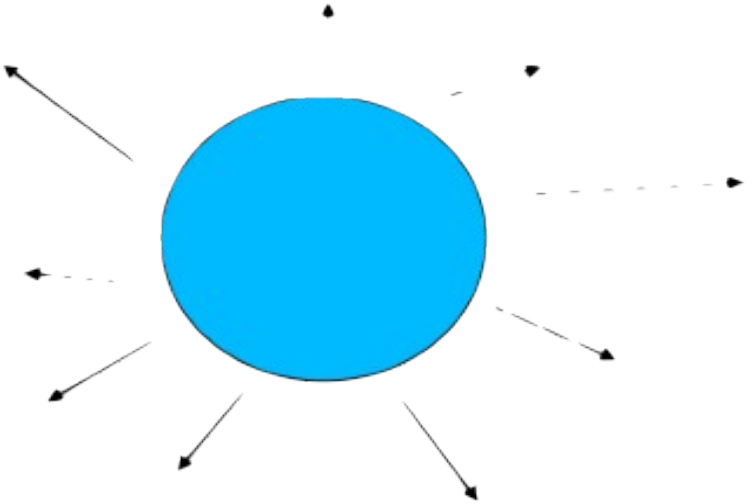
Free-space σ and angular distributions
Pauli principle



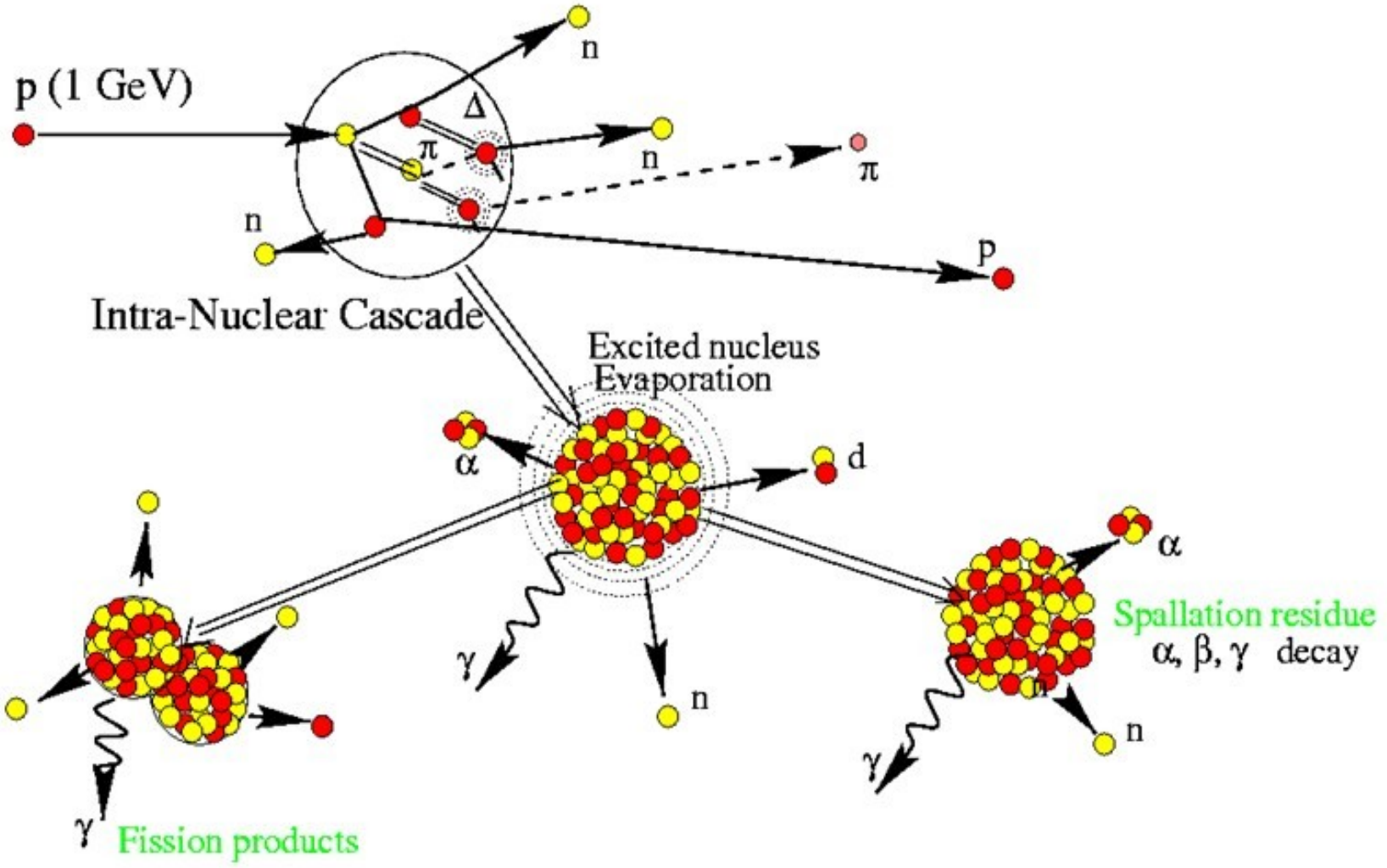
Particle-hole excitations are created during cascade



Nucleus is de-excited



BERT + Preco (2)


p (1 GeV)
n
Δ
π
n
π
n
p
Intra-Nuclear Cascade
Excited nucleus
Evaporation
α
d
γ
n
α
Spallation residue
α, β, γ decay
n
γ
γ
Fission products

Component-based approach to physics

Geant4 takes a component-based approach to physics:

- Provide many physics components (processes) which are decoupled from one another
- User selects these components in custom-designed physics lists in much the same way as a detector geometry is built
- Exceptions:
  - A few electromagnetic processes must be used together
  - Future processes involving interference of electromagnetic and strong interactions may require coupling as well

G4VUserPhysicsList

- All physics lists must derive from this class
  - and then be registered with the Run Manager
- Example:

```
class MyPhysicsList: public G4VUserPhysicsList {
  public:
    MyPhysicsList();
    ~MyPhysicsList();
    void ConstructParticle();
    void ConstructProcess();
    void SetCuts();
}
```

- User must implement the methods: **ConstructParticle** , **ConstructProcess** , and **SetCuts**

ConstructParticle()

- Choose the particles you need in your simulation and define all of them here. Example:

```
void MyPhysicsList::ConstructParticle() {
  G4Electron::ElectronDefinition();
  G4Positron::PositronDefinition();
  G4Gamma::GammaDefinition();
  G4Proton::ProtonDefinition();
  G4Neutron::NeutronDefinition();
  …
}
```

- It is possible to use Geant4 classes that create group of particles (instead of individual ones):
  G4BosonConstructor , G4LeptonConstructor , G4MesonConstructor , G4BaryonConstructor , G4IonConstructor

ConstructProcess()

For each particle defined in ConstructParticle() assign all the physics processes that you want to consider in your simulation

```
void MyPhysicsList::ConstructProcess() {

    AddTransportation();
    // method provided by G4VUserPhysicsList , assign transportation process
    // to all particles defined in ConstructParticle()

    ConstructEM();
    // convenience method that user may define; put electromagnetic physics here

    ConstructGeneral();
    // convenience method that user may define
}
```

ConstructEM()

```
void MyPhysicsList::ConstructEM() {
  theParticleIterator->reset();
  while ( (*theParticleIterator)() ) {
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager =
                                        particle->GetProcessManager();
    G4String particleName = particle->GetParticleName();

    if ( particleName == "gamma" ) {
      pmanager->AddDiscreteProcess(
                          new G4GammaConversion()  );
      …
    }
    …
  }
}
```

ConstructGeneral()

```
void MyPhysicsList::ConstructGeneral() {
  G4Decay* theDecayProcess = new G4Decay();
  theParticleIterator->reset();
  while ( (*theParticleIterator)() ) {
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager =
                                        particle->GetProcessManager();
    if ( theDecayProcess->IsApplicable( *particle ) ) {
      pmanager->AddProcess( theDecayProcess );
      pmanager->SetProcessOrdering( theDecayProcess,
                                          idxPostStep );
      pmanager->SetProcessOrdering( theDecayProcess,
                                          idxAtRest );
    }
  }
}
```

SetCuts()

```
void MyPhysicsList::SetCuts() {
   defaultCutValue = 1.0*mm;

   SetCutValue( defaultCutValue, “gamma” );
   SetCutValue( defaultCutValue, “e-” );
   SetCutValue( defaultCutValue, “e+” );
}
```

A simple G4VModularPhysicsList

- Constructor

```
MyModPhysList::MyModPhysList() : G4VModularPhysicsList() {
   defaultCutValue = 1.0*mm;
   RegisterPhysics( new ProtonPhysics() );
   // all physics processes having to do with protons

   RegisterPhysics( new ElectronPhysics() );
   // all physics processes having to do with electrons

   RegisterPhysics( new DecayPhysics() );
   // decay of unstable particles
}
```

- SetCuts

```
void MyModPhysList::SetCuts() {
   SetCutsWithDefault();
}
```

G4VModularPhysicsList

Use G4ModularPhysicsList to build a realistic physics list which would be too long, complicated and hard to maintain with the previous approach.
Its features are:

- Derived from **G4VUserPhysicsList**
- AddTransportation() automatically called for all registered particles
- Allows to define "physics modules":
  - electromagnetic physics
  - hadronic physics
  - decay physics
  - ion physics
  - radioactive physics
  - optical physics
  - etc.

Physics Constructors

Allow you to group particle and process construction according to physics domains

```
class ProtonPhysics : public G4VPhysicsConstructor {
  public:
    ProtonPhysics( const G4String& name = "proton" );
    virtual ~ProtonPhysics();

    virtual void ConstructParticle();
    // easy – only one particle to build in this case

    virtual void ConstructProcess();
    // put here all the processes a proton can have
}
```