Detector Simulation — Geant4

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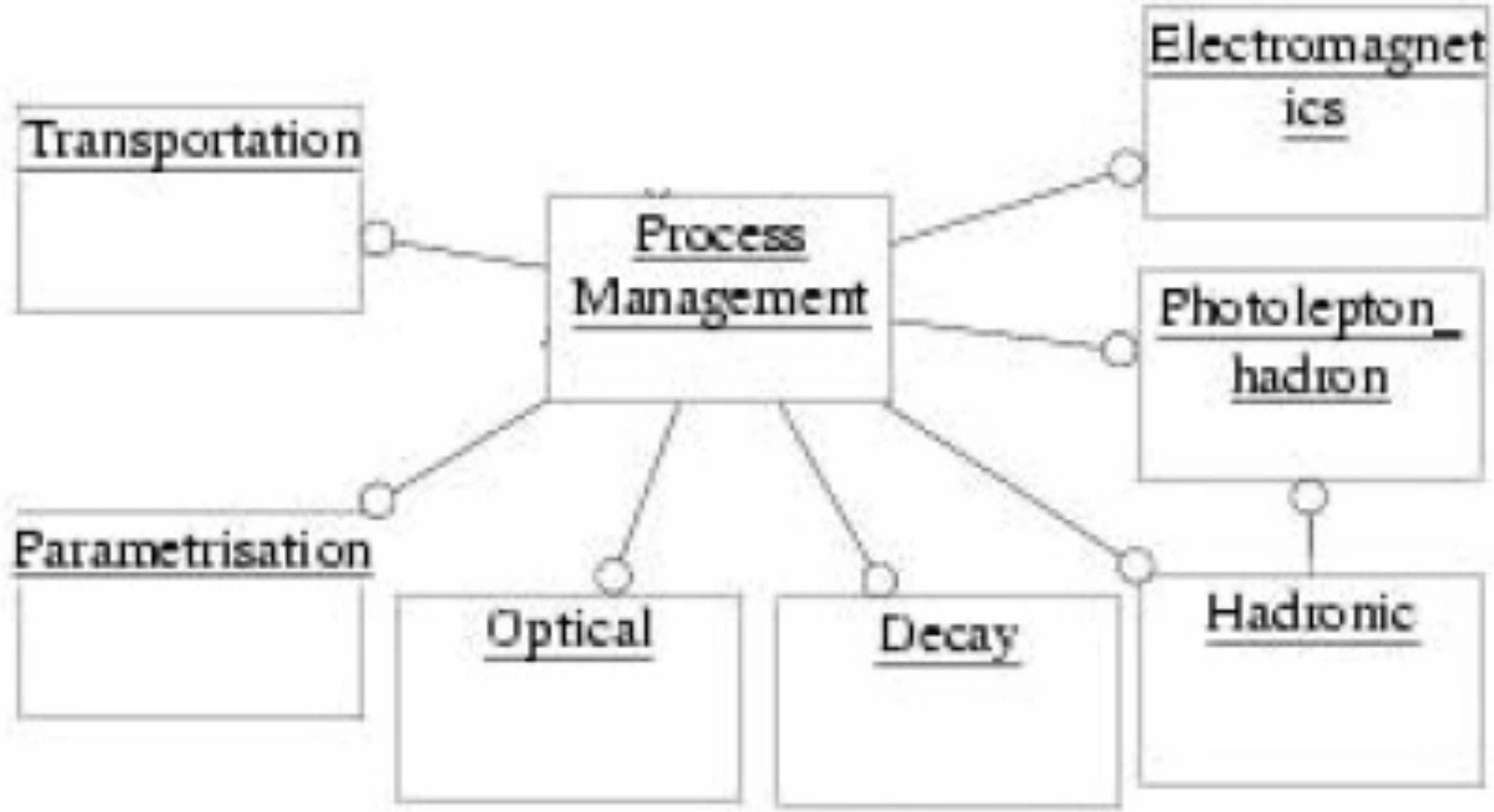
GEANT4: Physics Process & List

Physics Lists

- Geant4 provides the possibility of simulating the physics processes of a variety of particles
  - each such particle can have interactions of different types: strong, electromagnetic or weak and each such interaction can be described by different models
  - unlike many other simulation tools, Geant4 leaves it to the user to decide on which particles, which interactions and which models are to be used during the simulation step
  - declaration of the list of particles and the choice of models is done using the physics list
  - the toolkit provides handles for a few well-defined physics lists which are suitable for certain specific types of application

Processes in Geant4



- Processes describe how particles interact with material or with a volume

- Three basic types:
  - At rest process (e.g. decay at rest)
  - Continuous process (e.g. ionisation)
  - Discrete process (e.g. Compton scattering)

- Transportation is also a process
  - Interacting with the volume boundary

- A process which requires the shortest interaction length limits the step

Types of Processes

- There are several types of modules which can be combined to define the physics list
  - electromagnetic physics
  - extra physics processes for photons and leptons
  - decays
  - hadronic elastic
  - hadronic inelastic
  - stopping particles and capture processes
  - ion nuclear interactions
  - step limits
  - others

- The others category includes optical photons, exotic physics processes, thermal neutron transport models, ….

- The user needs to define the physics list through the 3 handles:
  - RegisterPhysics
  - ReplacePhysics
  - RemovePhysics

An Example of Making a Physics List

```
// EM Physics
RegisterPhysics(new G4EmStandardPhysics(verbosity));

// Synchroton Radiation & GN Physics
G4EmExtraPhysics* gn = new G4EmExtraPhysics(verbosity);
RegisterPhysics(gn);

// Decays
this->RegisterPhysics(new G4DecayPhysics(verbosity));

// Hadron Elastic scattering
RegisterPhysics(new G4HadronElasticPhysics(verbosity));

// Hadron Physics
RegisterPhysics(new G4HadronPhysicsFTF_BIC(verbosity));

// Stopping Physics
RegisterPhysics(new G4StoppingPhysics(verbosity));

// Ion Physics
RegisterPhysics(new G4IonPhysics(verbosity));

// Neutron tracking cut
RegisterPhysics(new G4NeutronTrackingCut(verbosity));
```

Electromagnetic Physics

- Applicable to
  - electrons and positrons
  - γ, X-ray and optical photons
  - muons
  - charged hadrons
  - ions

- Several physics models are available. Standard EM physics is extended to low energies using many data-driven techniques to improve the quality of simulation at low energies

- *All obey the same abstract Process interface*: transparent to tracking

Models available for

- Multiple scattering
- Bremsstrahlung
- Ionization
- Annihilation
- Photoelectric effect
- Compton scattering
- Pair production
- Rayleigh scattering
- γ conversion
- Synchrotron radiation
- Transition radiation
- Reflection, refraction
- Cherenkov radiation
- Scintillation
- ....

Geant4 Options for EM Physics

- There are 10+ options for EM physics
  - opt1 (EMV): a fast but less precise version used in HE physics lists
  - opt2 (EMX): also a fast and less precise version for HE physics lists
  - opt3 (EMY): provides a more accurate simulation of photons and charged hadrons
  - opt4 (EMZ): most precise but slow description of EM physics for HE applications
  - LIV: similar to opt3 but models for photos and electrons make use of Livermore set of models
  - PEN: similar to opt3 with models for photons and electrons making use of Penelope set of models
  - _GS: substitute Urban multiple scattering models with the Goudschmidt-Sanderson model
  - _LE: low energy WentzelVI model is used for multiple scattering
  - WVI: WentzelVI model and ATIMA ion ionisation models are used for a better description of multiple scattering
  - _SS: single scattering models used on top of standard EM configuration

- Please note that the same model describes EM physics over the entire energy region

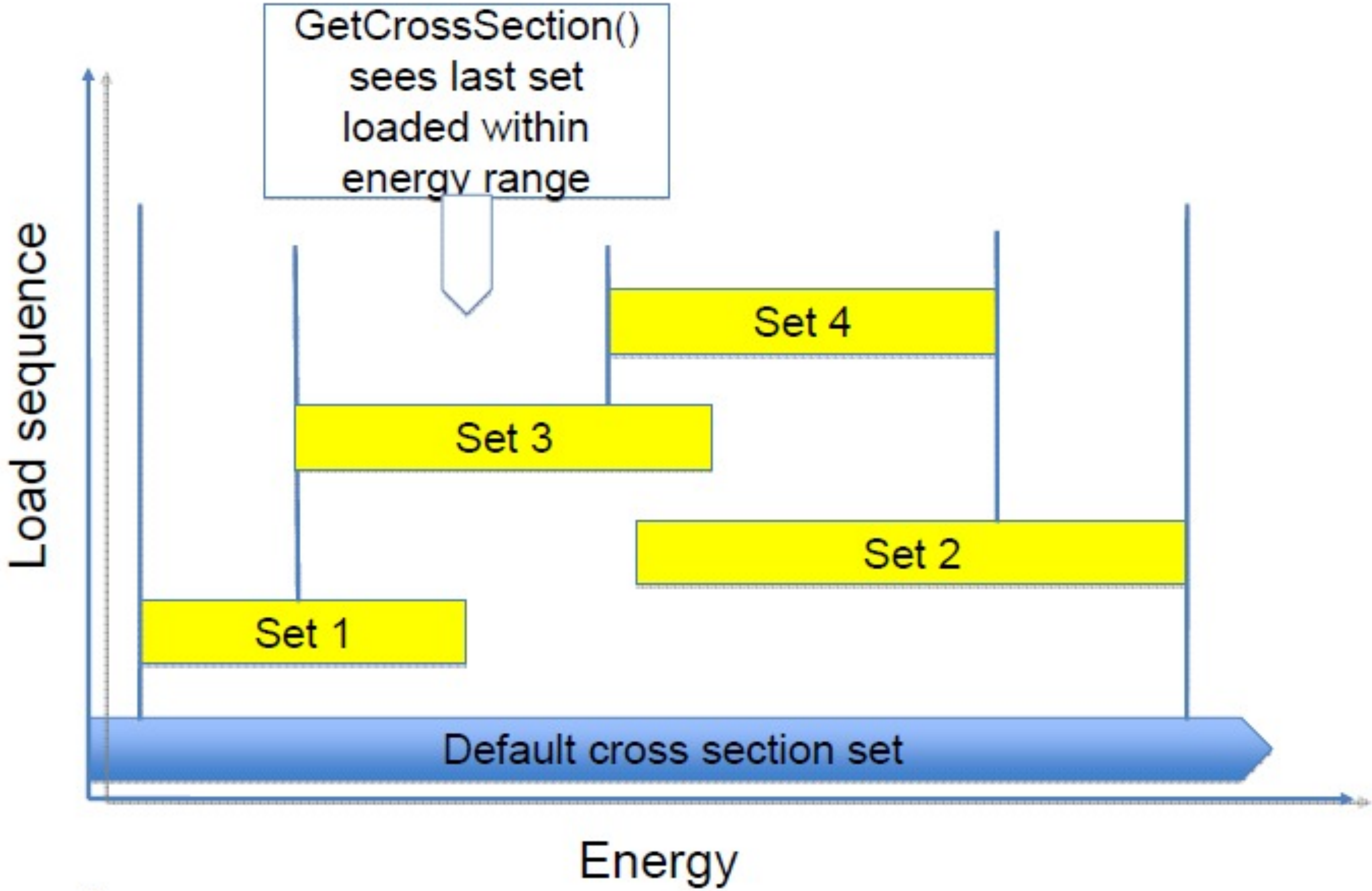
Hadronic Processes

- Hadronic processes are often implemented in terms of a model class
- There are usually several models for a given process
  - user must choose
  - can, and sometimes must, have more than one per process
- A process must also have cross sections assigned
  - here too, there are options
- Default cross-section sets are provided for each type of hadronic process
  - fission, capture, elastic, inelastic
  - can be overridden or completely replaced
- Different types of cross-section sets exist
  - some contain a few numbers to parametric the cross-section as a function of energy
  - some represent large databases
  - some are purely theoretical (equation driven)

Alternative Cross Sections

- Cross-section databases are available for low-energy neutrons
  - G4NDL available among the Geant4 distribution files
  - Livermore database (LEND) is also available
  - these are available with or without thermal cross-sections
- Cross section table is available for medium energy neutrons and protons
  - 14 MeV < E < 20 MeV
- Several alternatives exist for ion-nucleus cross-section
  - these are empirical and parametrised cross-section formulae with some theoretical insight
  - these are good for E/A < 10 GeV
- Alternative cross-sections also exist for pion cross-section

Cross Section Management



Models in Hadronic Interactions

- Data-driven models: When sufficient data are available with sufficient coverage over the phase space, a data-driven approach is the optimal way
  - neutron transport, photon evaporation, absorption at rest, isotope production, inclusive cross section, ……

- Parametrised models: Extrapolation of cross sections and parametrisation of multiplicity distributions and final state kinematics
  - adaptation of GHEISHA in some earlier versions of Geant4

- Theory-based models: These include a set of theoretical models describing hadronic interactions depending on the addressed energy range
  - diffractive string excitation, dual parton model or quark-gluon string model at medium to high energies
  - intra-nuclear cascade models air medium to low energies
  - nuclear evaporation, fission models, …… at very low energies

Data Driven Hadronic Models

- These are characterised by lots of data on
  - cross sections
  - angular distributions
  - multiplicities, etc.

- To get interaction length and final state, these models depend on interpolation of data
  - cross sections, Legendre coefficients, ..

- Examples:
  - neutrons with $E < 20$ MeV
  - coherent elastic scattering (pp, np, nn)
  - radioactive decays

Theory Driven Hadronic Models

- These are dominated by theoretical arguments (QCD, Glauber theory, exciton model, …)
- Final states (number and type of particles in the final sate with their energy and angular distributions) are determined by sampling theoretically calculated distributions
- This type of models is preferred as they are the most predictive
- Examples:
  - quark-gluon string models (projectiles with E > 20 GeV)
  - intra-nuclear cascade models (intermediate energies)
  - nuclear de-excitation and break-up

Parametrised Hadronic Models

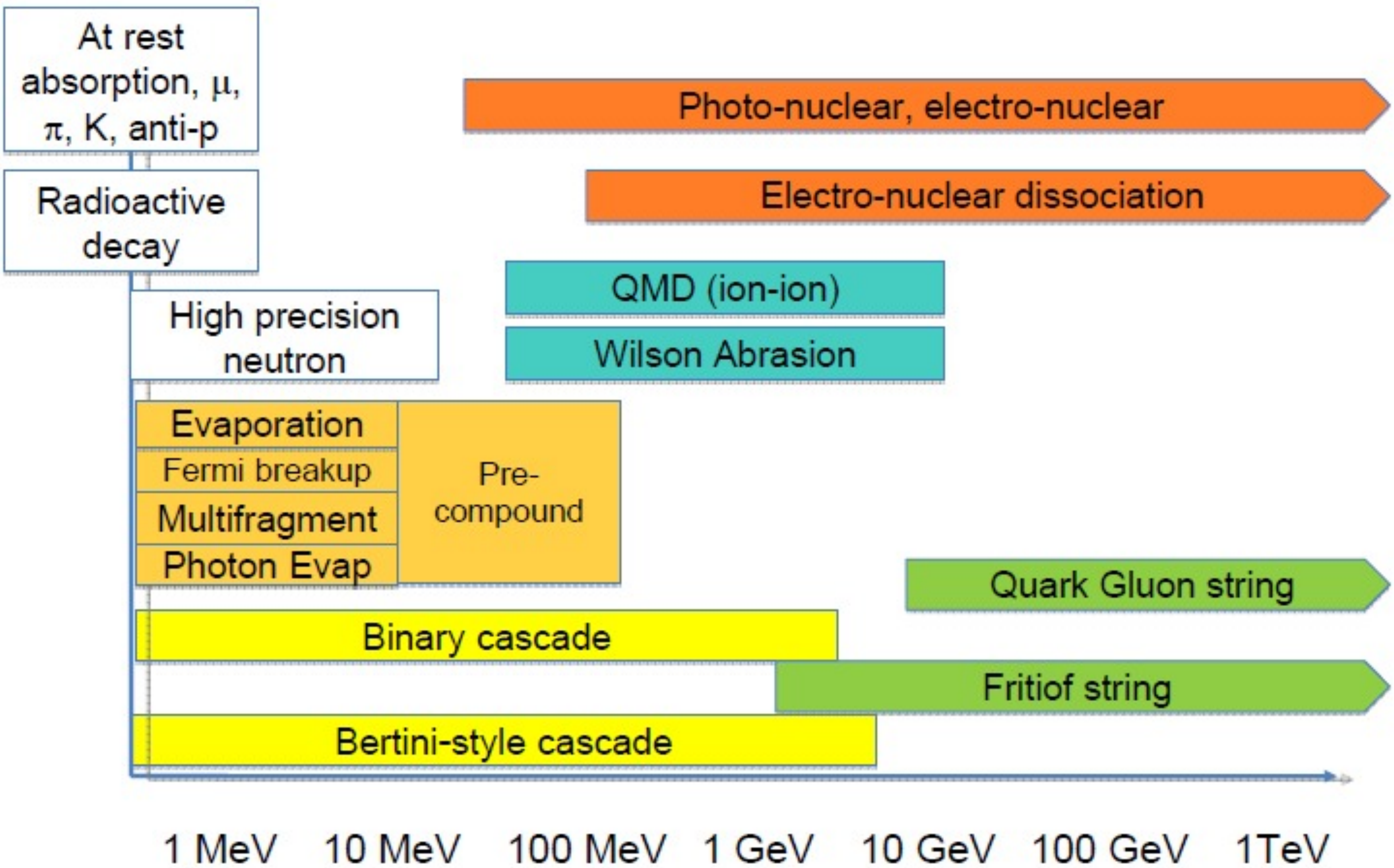
- Current versions do not contain any parametrised version. In versions preceding Geant4 10.0, two models existed. They were re-engineered versions of the Fortran Gheisha code used in Geant3

- These models depended mostly on fits to data with some theoretical guidance

- Two such models existed:
  - Low Energy Parametrised (LEP) for $E < 20$ GeV
  - High Energy Parametrised (HEP) for $E > 20$ GeV
  - each type referred to a collection of models (one for each type of hadron)

- These codes were fast and existed for all types of particles. But they were not detailed enough and there was no-one to maintain these codes

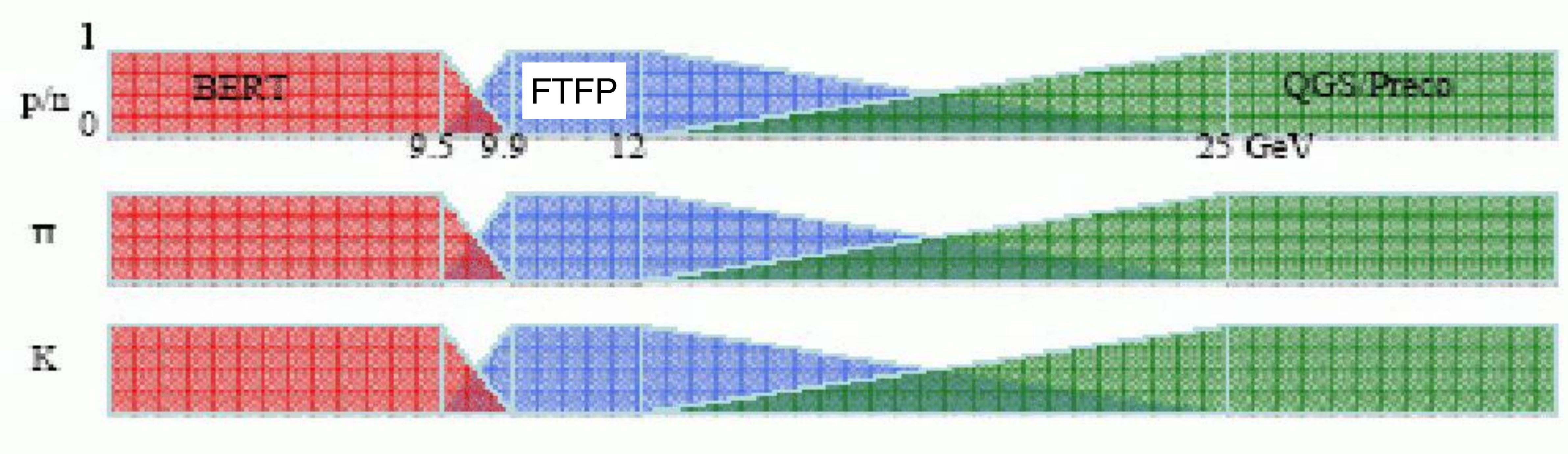
Partial Hadronic Model Inventory



Inelastic Hadronic Interactions

- No single model for hadron inelastic process can cover the entire energy region required in a high-energy physics experiment
  - Quark-gluon string models are good at high energies
  - Nuclear cascade models are good at medium and low energies
  - At very low energies, models for fission and pre-combination are required

- So all physics lists for inelastic hadronic interaction combine a number of models



Physics List Library

- There are a number of Physics Lists available in the Geant4 library which can be directly incorporated into the user code
  - FTFP_BERT High Energy Experiments
  - FTFP_BERT_ATL
  - FTFP_BERT_HP
  - FTFP_BERT_TRV
  - FTFP_INCLXX
  - FTFQGSP_BERT
  - FTF_BIC
  - QBBC Medical and Space Physics Applications
  - QGSP_BERT Former default for High Energy Experiments
  - QGSP_BERT_HP
  - QGSP_BIC Cosmic Ray applications
  - QGSP_BIC_AllHP
  - QGSP_BIC_HIP
  - QGSP_FTFP_BERT
  - QGSP_INCLXX
  - QGS_BIC
  - Shielding Recommended for shielding studies
  - ShieldingLEND
  - LBE
  - NuBeam

Main Program

- Simple example of the main program:

```
#include "G4RunManager.hh"
#include "G4UImanager.hh"
#include "Randomize.hh"
#include "time.h"
#include "MyDetectorConstruction.hh"
#include "MyEventAction.hh"
#include "MyPrimaryGeneratorAction.hh"
#include "G4PhysListFactory.hh"
#include "QGSP_BERT.hh"

int main(int argc,char** argv) {
  // Choose the Random engine
  CLHEP::HepRandom::setTheEngine(new CLHEP::RanecuEngine);
  // Set random seed with system time
  G4long seed = time(NULL);
  CLHEP::HepRandom::setTheSeed(seed);

  // Construct the default run manager, which manages start and stop simulation
  G4RunManager * runManager = new G4RunManager;

  // Set mandatory initialization classes:
  // =====================================
  // Initilization detector construction class
  MyDetectorConstruction* detector = new MyDetectorConstruction;
  runManager->SetUserInitialization(detector);

  G4PhysListFactory factory;
  runManager->SetUserInitialization(factory.GetReferencePhysList("QGSP_BERT"));
```

Main Program (cont)

```
// Set user generator action class
MyPrimaryGeneratorAction* genAction = new MyPrimaryGeneratorAction();
runManager->SetUserAction(genAction);

// Set user event-action class
MyEventAction* eventAction = new MyEventAction(detector);
runManager->SetUserAction(eventAction);

// Initialize G4 kernel
runManager->Initialize();

// Get the pointer to the User Interface manager
G4UImanager* UI = G4UImanager::GetUIpointer();

G4String command = "/control/execute ";
G4String fileName = argv[1];
UI->ApplyCommand(command+fileName);

// Job termination
// Free the store: user actions, physics_list and detector_description are
//                 owned and deleted by the run manager, so they should not
//                 be deleted in the main() program !
delete runManager;

return 0;
```

Hit Class

```
#include "G4VHit.hh"
#include "G4THitsCollection.hh"
#include "G4Allocator.hh"

class G4AttDef;

class MyHit : public G4VHit {

public:
  MyHit();
  MyHit(G4int id, G4double e, G4double t);
  ~MyHit() = default;
  MyHit(const MyHit &right);
  const MyHit& operator=(const MyHit &right);
  G4int operator=(const MyHit &right) const;

  inline void *operator new(size_t);
  inline void operator delete(void *aHit);
  void Draw() {}
  void Print() {}

private:
  G4int           cellID_;
  G4double        edep_, time_;

  ...
```

```
public:
  inline void setCellID(G4int id) { cellID_ = id; }
  inline G4int cellID() const { return cellID_; }
  inline void setEdep(G4double de) { edep_ = de; }
  inline void addEdep(G4double de) { edep_ += de; }
  inline G4double getEdep() const { return edep_; }
  inline void setTime(G4double t) { time_ = t; }
  inline G4double time() const { return time_; }

};

typedef G4THitsCollection<MyHit> MyHitsCollection;
extern G4Allocator<MyHit> MyHitAllocator;

inline void* MyHit::operator new(size_t) {
  void *aHit;
  aHit = (void *) MyHitAllocator.MallocSingle();
  return aHit;
}

inline void MyHit::operator delete(void *aHit) {
  MyHitAllocator.FreeSingle((MyHit*) aHit);
}
```

Detector Construction

```
#include "G4VUserDetectorConstruction.hh"

#include "G4RunManager.hh"
#include "G4LogicalVolume.hh"
#include "G4PVPlacement.hh"
#include "G4SystemOfUnits.hh"
#include "G4VPhysicalVolume.hh"
#include "G4LogicalVolume.hh"

class MyDetectorConstruction : public G4VUserDetectorConstruction {
public:
  MyDetectorConstruction() {}
  ~MyDetectorConstruction() override = default;
  G4VPhysicalVolume* Construct();

  void setSensitive();

private:
  G4LogicalVolume   *logSens;
};
```

Sensitive Detector

```
#include "G4VSensitiveDetector.hh"
#include "MyHit.hh"

class MyDetectorConstruction;
class G4Step;
class G4HCofThisEvent;
class G4TouchableHistory;

class MySensitiveDetector : public G4VSensitiveDetector {
public:
  MySensitiveDetector(MyDetectorConstruction*, G4String);
  ~MySensitiveDetector();

  void      Initialize(G4HCofThisEvent*HCE);
  G4bool    ProcessHits(G4Step*aStep, G4TouchableHistory*ROhist);
  void      EndOfEvent(G4HCofThisEvent*HCE);
  void      clear();
  void      DrawAll();
  void      PrintAll();

private:
  const MyDetectorConstruction *detector_;
  MyHitsCollection *calCollection_;
  G4int hcID_;

};
```

Primary Generator Action

```
#include "G4VUserPrimaryGeneratorAction.hh"
#include "globals.hh"
#include "G4ParticleGun.hh"
#include "G4ThreeVector.hh"

class G4Event;

class PrimaryGeneratorAction : public G4VUserPrimaryGeneratorAction {

public:
  PrimaryGeneratorAction();
  virtual ~PrimaryGeneratorAction();

  void GeneratePrimaries(G4Event*);
  G4ParticleGun* GetParticleGun() {return particleGun;};
private:
  G4ParticleGun*                particleGun;      //pointer a to G4  class
  G4double                      xVertex, yVertex, zVertex;
};
```

EventAction

```
#include <iostream>
#include <vector>
#include "TFile.h"
#include "TTree.h"
#include "G4UserEventAction.hh"
#include "globals.hh"

#include "MyDetectorConstruction.hh"

class MyEventAction : public G4UserEventAction {

public:

  MyEventAction(MyDetectorConstruction *det);
  virtual ~MyEventAction();

  void  BeginOfEventAction(const G4Event*);
  void    EndOfEventAction(const G4Event*);

private:
  const MyDetectorConstruction *detCon;

  ///tree variables
  std::vector<int> *cellX, *cellY, *layer;

  G4double gunPx, gunPy, gunPz, gunP, gunPt, gunE;
  G4double distX, distY, gunX, gunY, gunZ;

  TFile *file;
  TTree *tree;
};
```

Additional Slides