

Hadronic Physics I

Geant4 Tutorial at Chalk River

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Dennis Wright



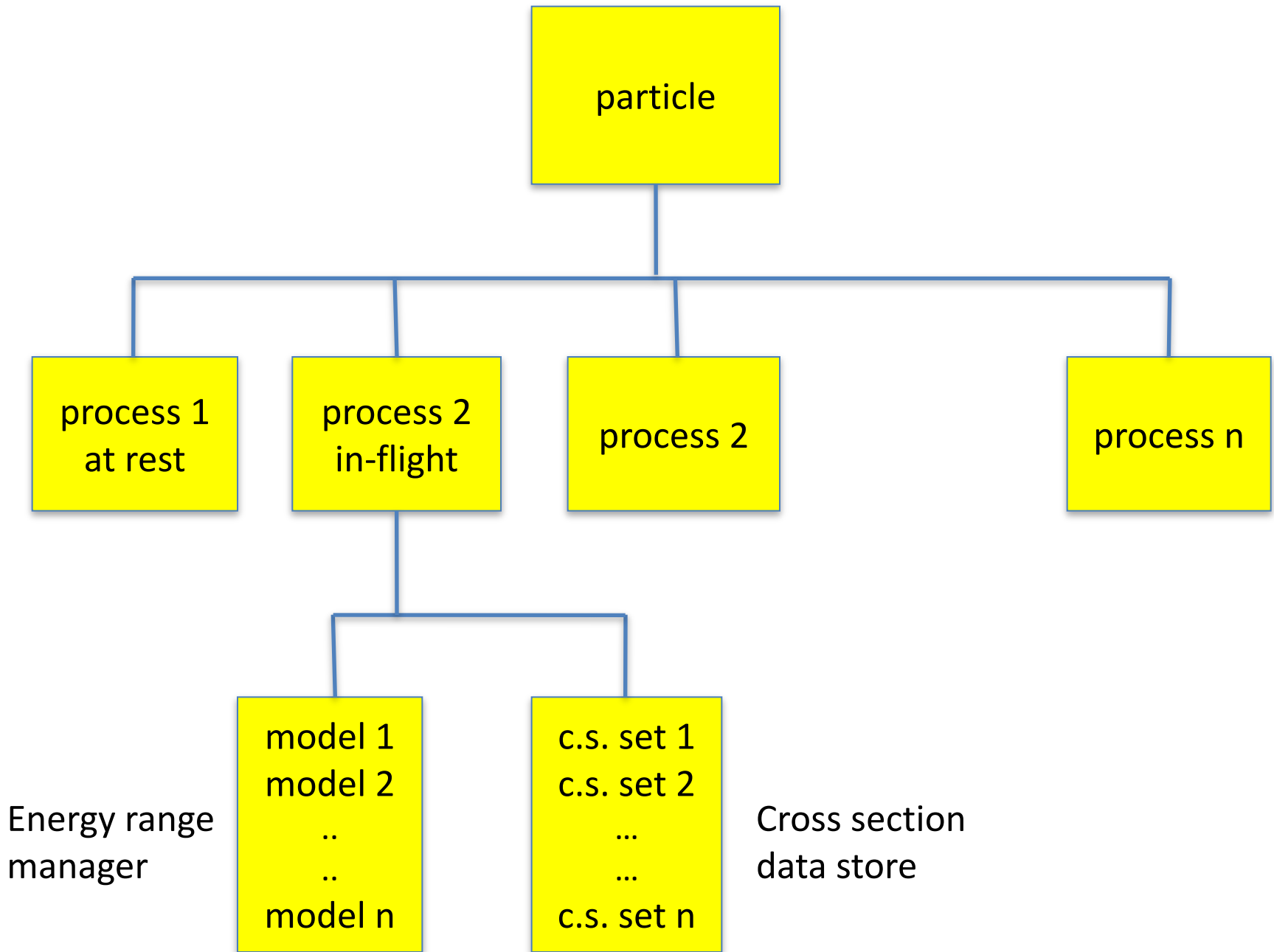
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Outline

- Overview of hadronic physics
- Precompound and de-excitation models
- Cascade models

Hadronic Processes, Models and Cross Sections

- In Geant4 physics is assigned to a particle through **processes**
- Each process may be implemented
 - directly, as part of the process, or
 - in terms of a **model** class
- Geant4 often provides 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



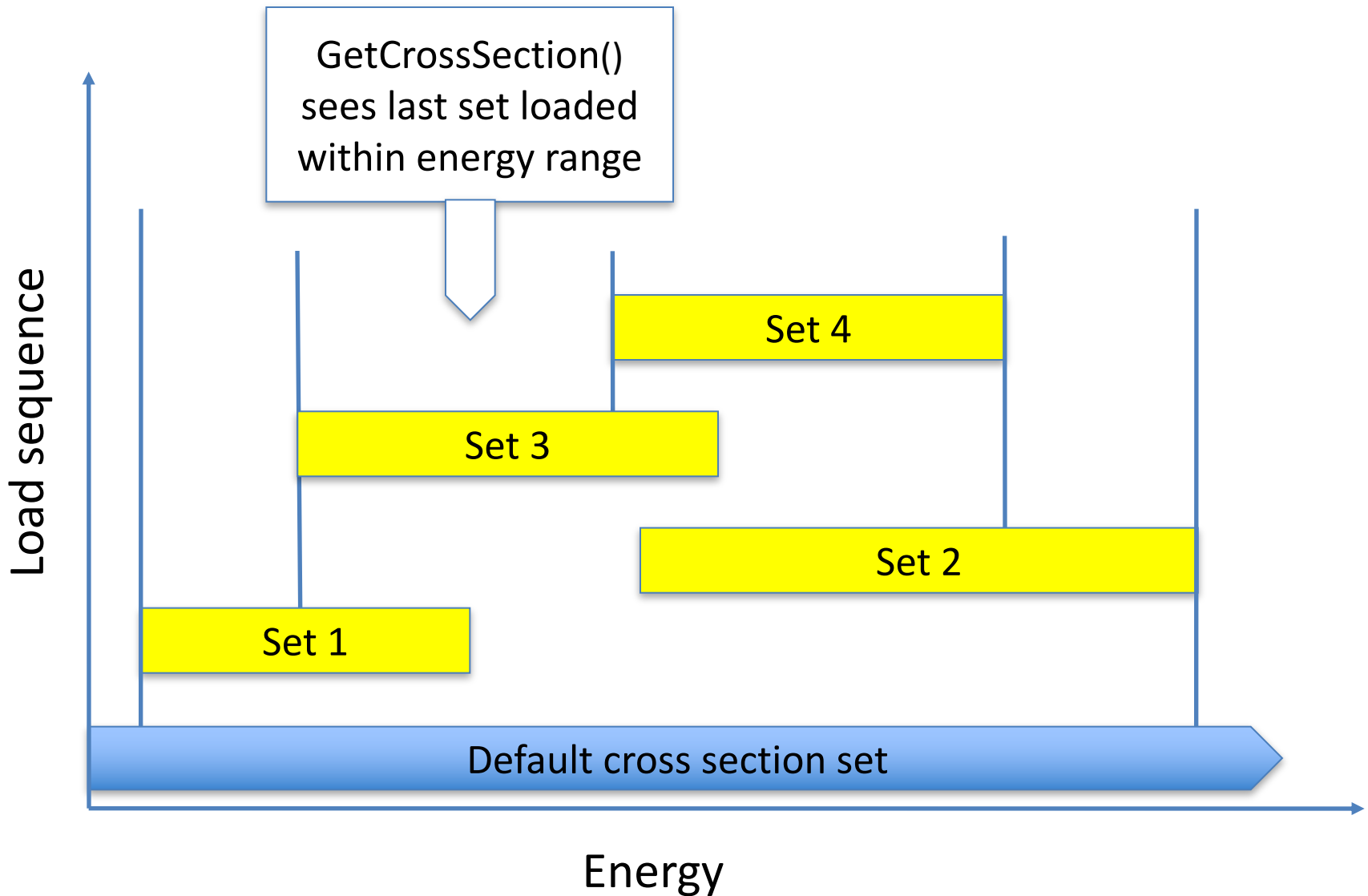
Cross Sections

- 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
 - some contain only a few numbers to parameterize the c.s.
 - some represent large databases
 - some are purely theoretical (equation-driven)

Alternative Cross Sections

- Low energy neutrons
 - G4NDL available as Geant4 distribution files
 - Livermore database (GND) also available
 - available with or without thermal cross sections
- Medium energy neutron and proton reaction cross sections
 - $14 \text{ MeV} < E < 20 \text{ GeV}$
- Ion-nucleus reaction cross sections
 - Tripathi, Shen, Kox
 - good for $E/A < 10 \text{ GeV}$
- Pion reaction cross sections

Cross Section Management



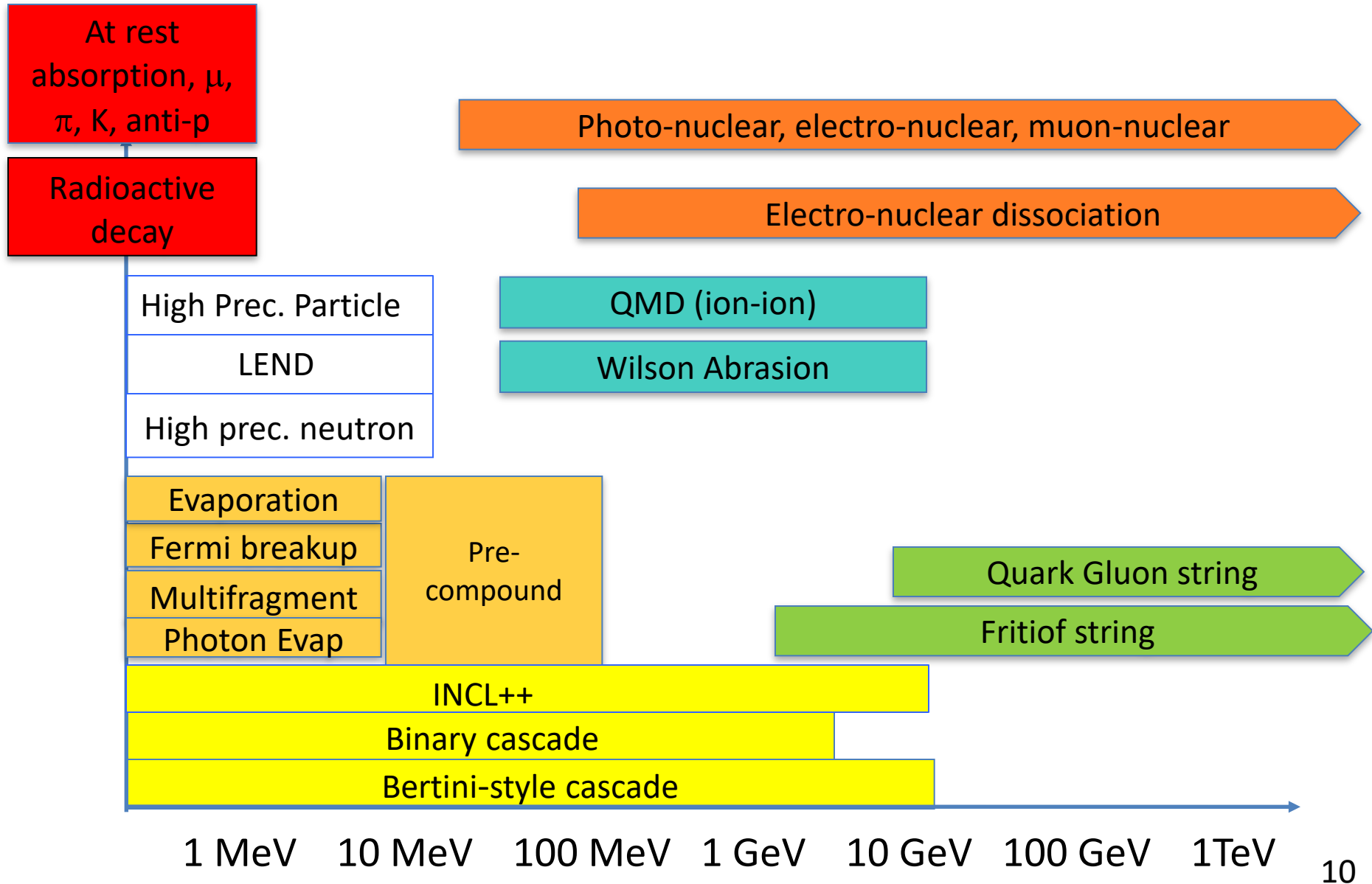
Data-driven Hadronic Models

- Characterized by lots of data
 - cross sections
 - angular distributions
 - multiplicities, etc.
- To get interaction length and final state, models depend on interpolation of data
 - cross sections, Legendre coefficients
- Examples
 - neutrons ($E < 20$ MeV)
 - coherent elastic scattering (pp, np, nn)
 - radioactive decay

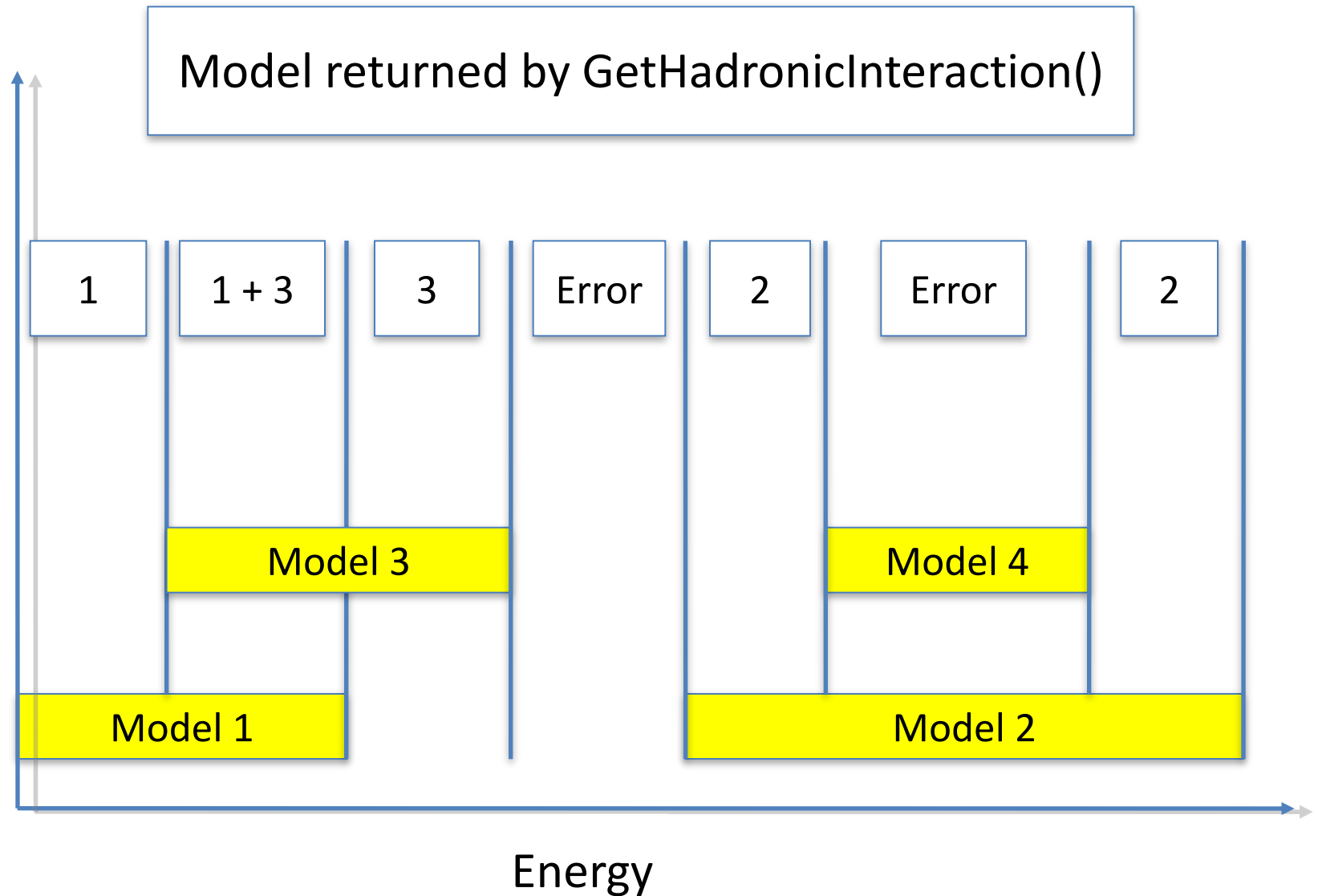
Theory-driven Hadronic Models

- Dominated by theoretical arguments (QCD, Glauber theory, exciton theory...)
- Final states (number and type of particles and their energy and angular distributions) determined by sampling theoretically calculated distributions
- This type of model is preferred, as it is the most predictive
- Examples
 - quark-gluon string (projectiles with $E > 20$ GeV)
 - intra-nuclear cascade (intermediate energies)
 - nuclear de-excitation and break-up

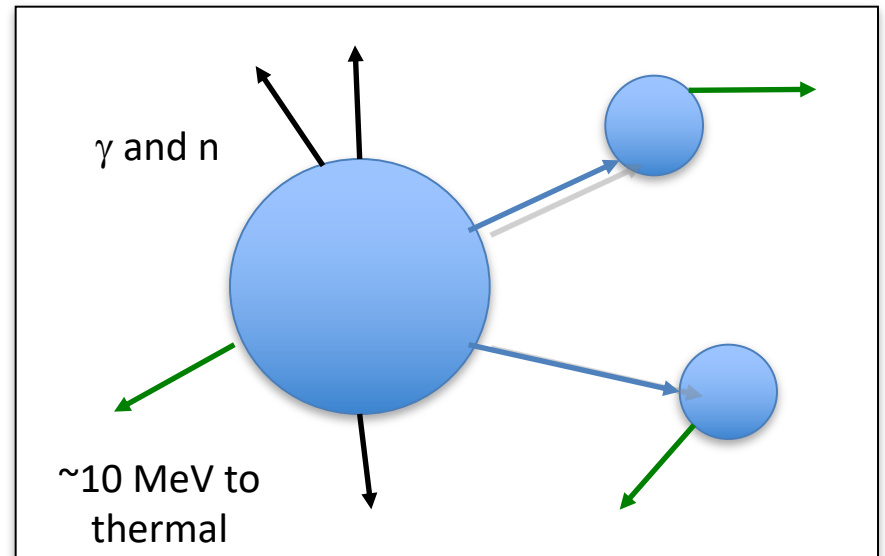
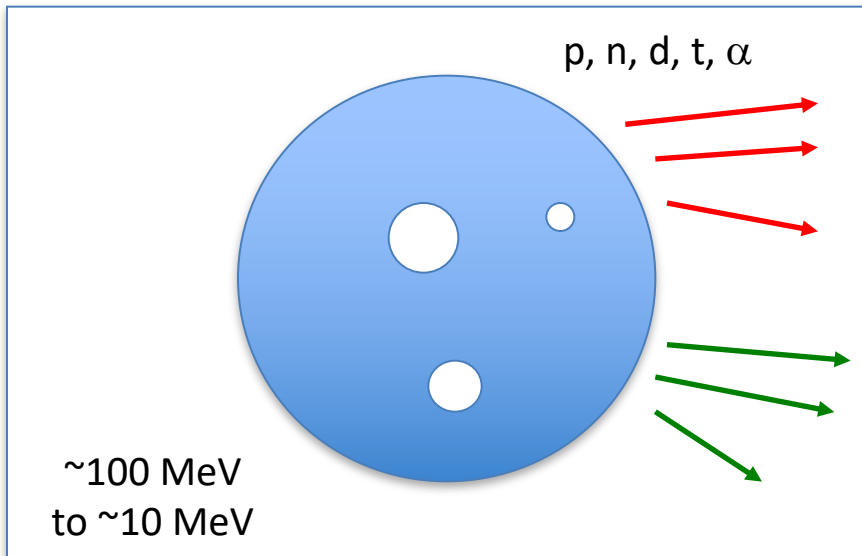
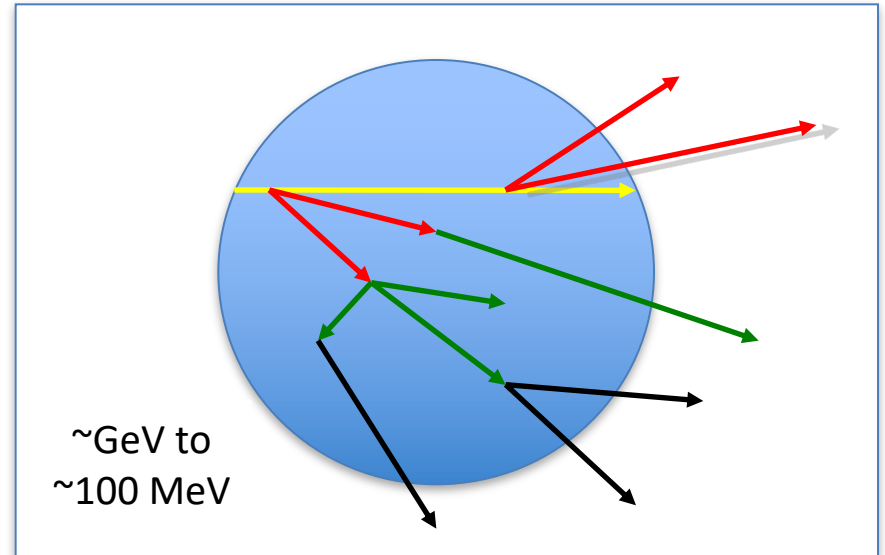
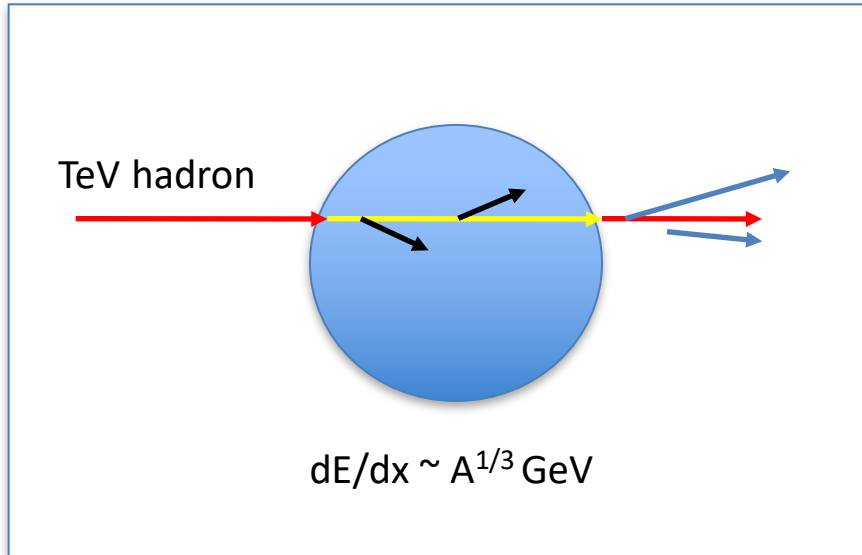
Partial Hadronic Model Inventory



Model Management



Hadronic Interactions from TeV to meV



Precompound Models

- G4PrecompoundModel is used for nucleon-nucleus interactions at low energy and as a nuclear de-excitation model within higher-energy codes
 - valid for incident p, n from 0 to 170 MeV
 - takes a nucleus from a highly excited set of particle-hole states down to equilibrium energy by emitting p, n, d, t, ^3He and α
 - once equilibrium is reached, four sub-models are called to take care of nuclear evaporation and break-up
 - these 4 models not currently callable by users
- Two Geant4 cascade models have their own version of nuclear de-excitation models embedded in them

De-excitation Models

- Four sub-models typically used to de-excite a remnant nucleus
 - Fermi break-up
 - photon evaporation
 - multi-fragmentation
 - fission
- These models are not intended to be assigned directly to a process
 - instead they are meant to be linked together and then assigned to the G4Precompound model through the class G4ExcitationHandler

De-excitation Model Details

- Fermi break-up
 - remnant nucleus is destroyed – nothing left but p, n, t, a
 - valid only for $A < 17$ and high excitation energies
- Fission
 - splits excited nucleus and emits fission fragments + n
 - valid only for $A > 65$
- Multi-fragmentation
 - statistical breakup model with propagation of fragments in Coulomb field
 - for excitation energies $E/A > 3$ MeV

De-excitation Model Details

- Photon evaporation
 - usually final stage of nuclear de-excitation
 - data-driven: uses ENSDF database
 - currently have up to hundreds of gamma levels for 2071 nuclides in PhotonEvaporation3.1
 - handles gamma cascades, does electron emission in case of internal conversion
 - currently no correlation when more than one gamma emitted (but that's coming)

Precompound Models

- Invocation of Precompound model:

```
G4ExcitationHandler* handler = new G4ExcitationHandler;  
G4PrecompoundModel* preco = new G4PrecompoundModel(handler);  
// Create de-excitation models and assign them to precompound model
```

```
G4NeutronInelasticProcess* nproc = new G4NeutronInelasticProcess;  
nproc->RegisterMe(preco);  
neutronManager->AddDiscreteProcess(nproc);  
// Register model to process, process to particle
```

- Here the model is invoked in isolation, but usually it is used in combination with high energy or cascade models
 - a standard interface exists for this

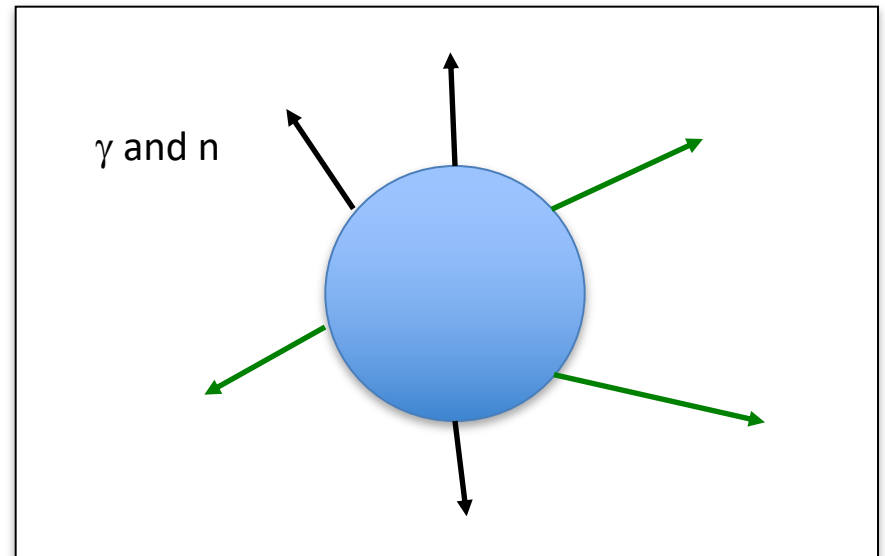
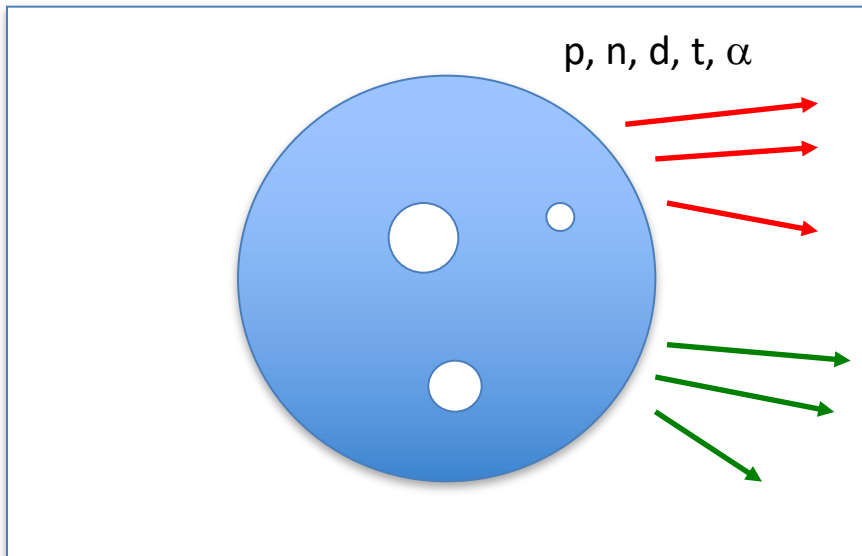
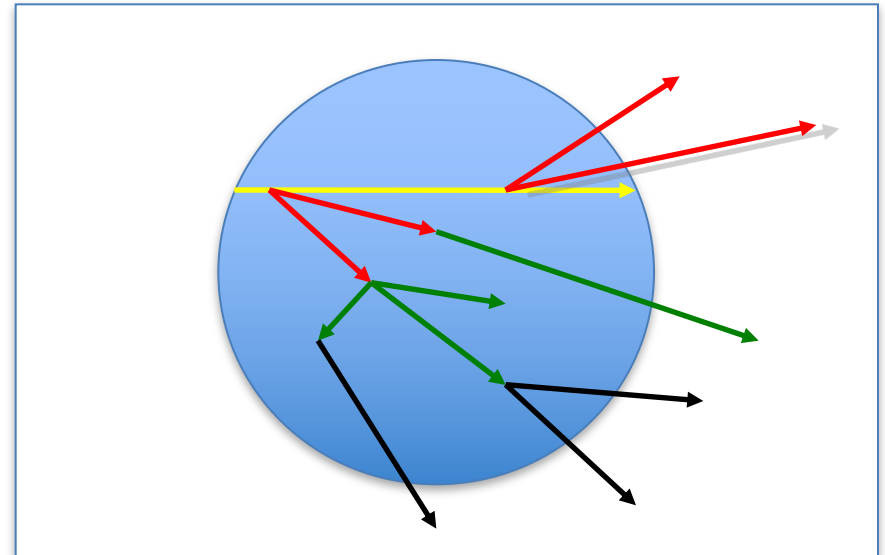
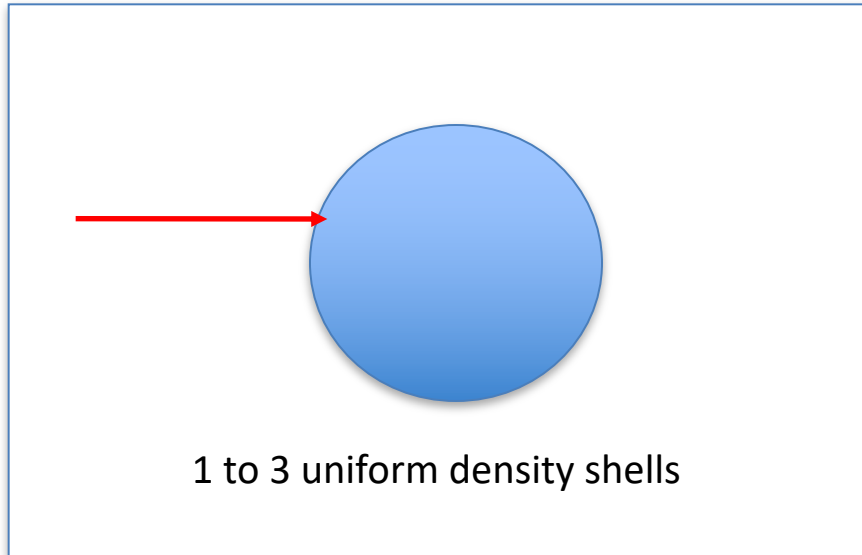
Intra-nuclear Cascade Models

- Typical intra-nuclear cascade energies are inconvenient
 - too high for nuclear physics treatments
 - too low for QCD
- Must use Monte Carlo techniques to propagate hadrons within the target nucleus in order to produce a final state
 - “Monte Carlo within a Monte Carlo”
 - one of the first applications of Monte Carlo methods to nuclear interactions
 - time-consuming
- Specific channels not produced
 - do not use data to produce, for example $^{14}\text{N}(p,n)^{14}\text{O}$

Bertini-style Cascade Model

- A classical (non-quantum mechanical) cascade
 - average solution of a particle traveling through a medium (Boltzmann equation)
 - no scattering matrix calculated
 - can be traced back to some of the earliest codes (1960s)
- Core code:
 - elementary particle collisions with individual protons and neutrons: free space cross sections used to generate secondaries
 - cascade in nuclear medium
 - pre-equilibrium and equilibrium decay of residual nucleus
 - target nucleus built of three concentric shells

Bertini Cascade ($0 < E < 10$ GeV)



Using the Bertini Cascade

- In Geant4 the Bertini cascade is used for p , n , π^+ , π^- , K^+ , K^- , K^0_L , K^0_S , Λ , Σ^0 , Σ^+ , Σ^- , Ξ^0 , Ξ^- , Ω^-
 - valid for incident energies of 0 – 15 GeV
 - can also be used for gammas

- Invocation sequence

```
G4CascadeInterface* bert = new G4CascadeInterface;
```

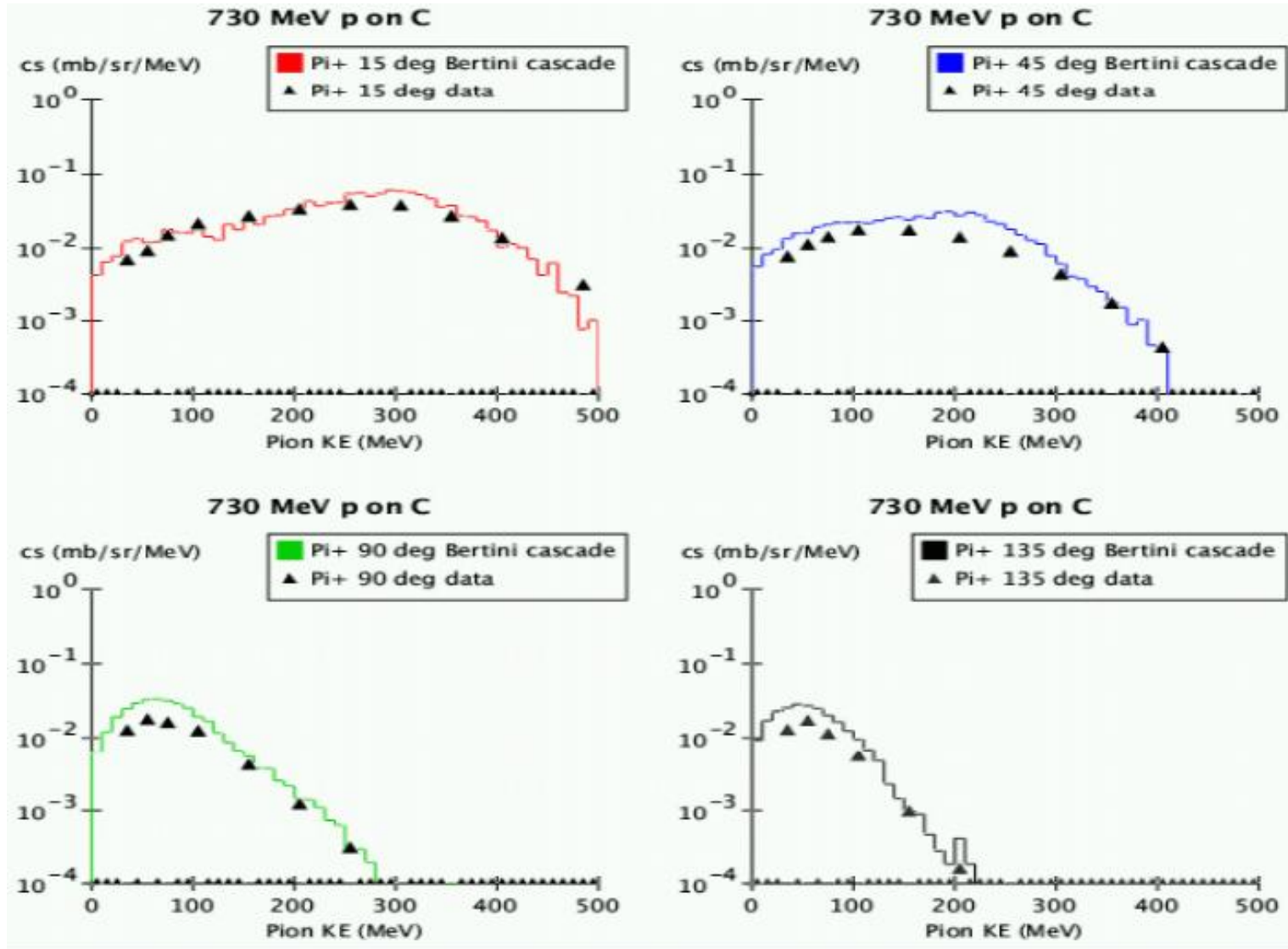
```
G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess;
```

```
pproc->RegisterMe(bert);
```

```
protonManager->AddDiscreteProcess(pproc);
```

```
// same sequence for all other hadrons and gamma
```

Validation of Bertini Cascade



Binary Cascade Model

- Modeling sequence similar to Bertini, except
 - it's a time-dependent model
 - hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
 - particles follow curved trajectories in smooth nuclear potential
- Binary cascade is currently used for incident p, n and π
 - valid for incident p, n from 0 to 10 GeV
 - valid for incident π^+ , π^- from 0 to 1.3 GeV
- A variant of the model, G4BinaryLightIonReaction, is valid for incident ions up to $A = 12$ (or higher if target has $A < 12$)

Using the Binary Cascade

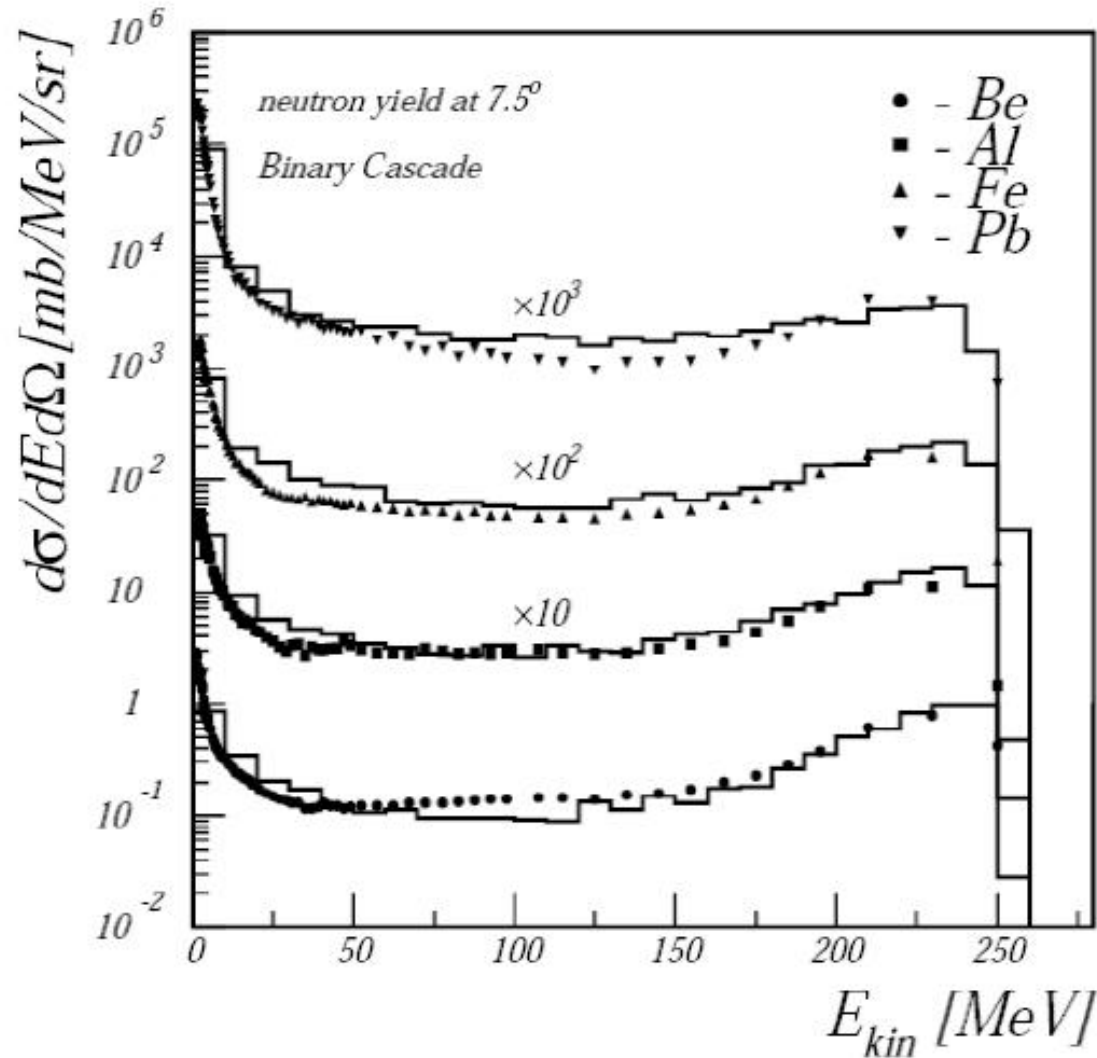
- Invocation sequence:

```
G4BinaryCascade* binary = new G4BinaryCascade();  
G4PionPlusInelasticProcess* piproc =  
    new G4PionPlusInelasticProcess();  
piproc->RegisterMe(binary);  
piplus_Manager->AddDiscreteProcess(piproc);
```

- Invoking BinaryLightIonReaction

```
G4BinaryLightIonReaction* ionBinary =  
    new G4BinaryLightIonReaction();  
G4IonInelasticProcess* ionProc = new G4IonInelasticProcess();  
ionProc->RegisterMe(ionBinary);  
genericIonManager->AddDiscreteProcess(ionProc);
```


Validation of Binary Cascade 256 MeV protons

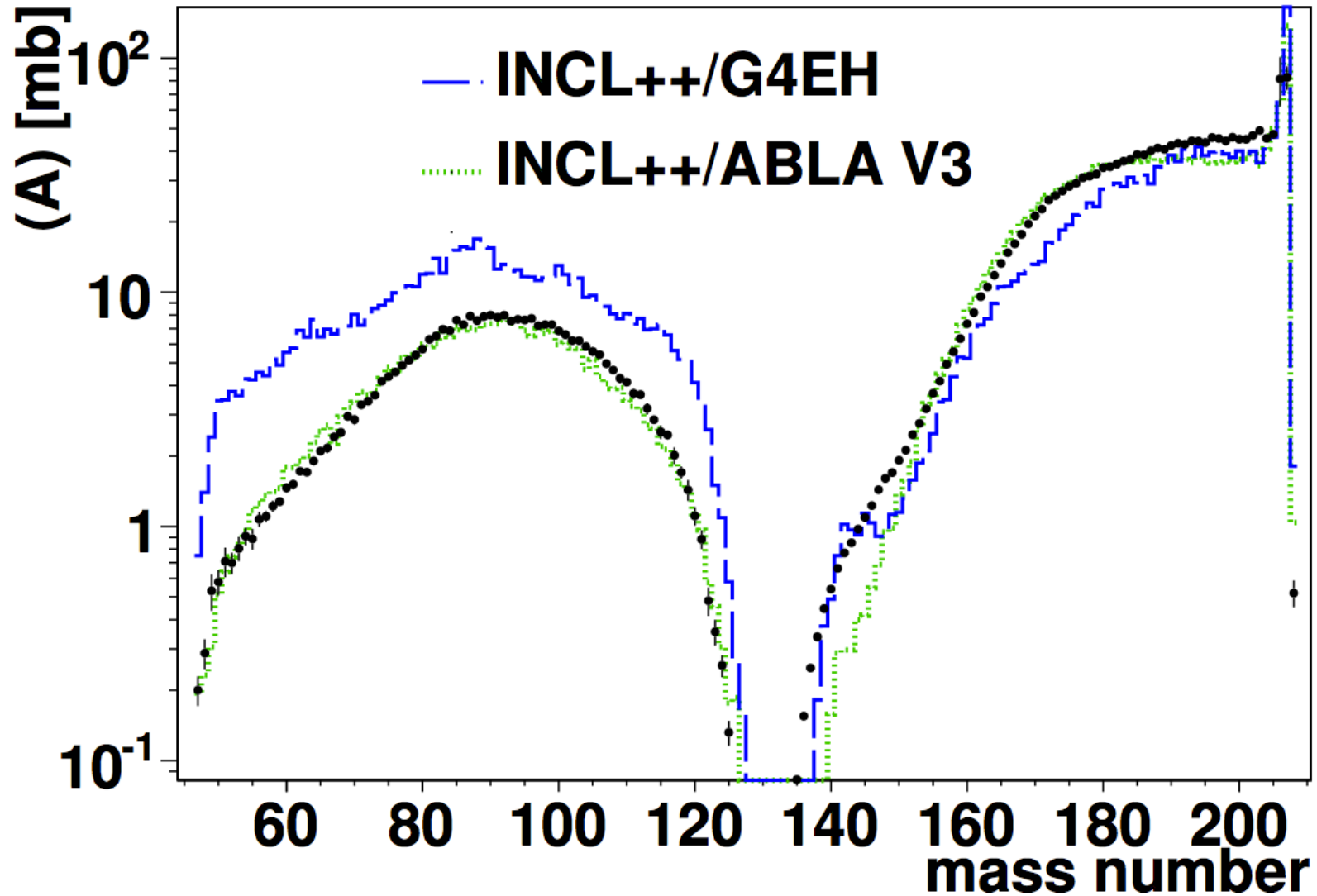


INCL++ Cascade Model

- Model elements
 - time-dependent model
 - smooth Woods-Saxon or harmonic oscillator potential
 - particles travel in straight lines through potential
 - delta resonance formation and decay (like Binary cascade)
- Valid for incident p, n and π , d, t, ^3He , α from 150 MeV to 10 GeV
 - also works for projectiles up to $A = 12$
 - targets must be $11 < A < 239$
 - ablation model (ABLA) can be used to de-excite nucleus
- Used successfully in spallation studies
 - also expected to be good in medical applications

Validation of INCL++ Model

Spallation residues from $p + {}^{208}\text{Pb}$



Summary (1)

- Geant4 hadronic physics allows user to choose how a physics process should be implemented
 - cross sections
 - models
- Many processes, models and cross sections to choose from
 - hadronic framework makes it easier for users to add more
- Precompound models are available for low energy nucleon projectiles and nuclear de-excitation
 - de-excitation sub-models handle the decay after the precompound stage

Summary (2)

- Three intra-nuclear cascade models available to cover medium energies (up to 10 GeV)
 - Bertini-style
 - Binary cascade
 - INCL++