Hadronic Physics I

Geant4 School at IFIN-HH, Bucharest

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Dennis Wright

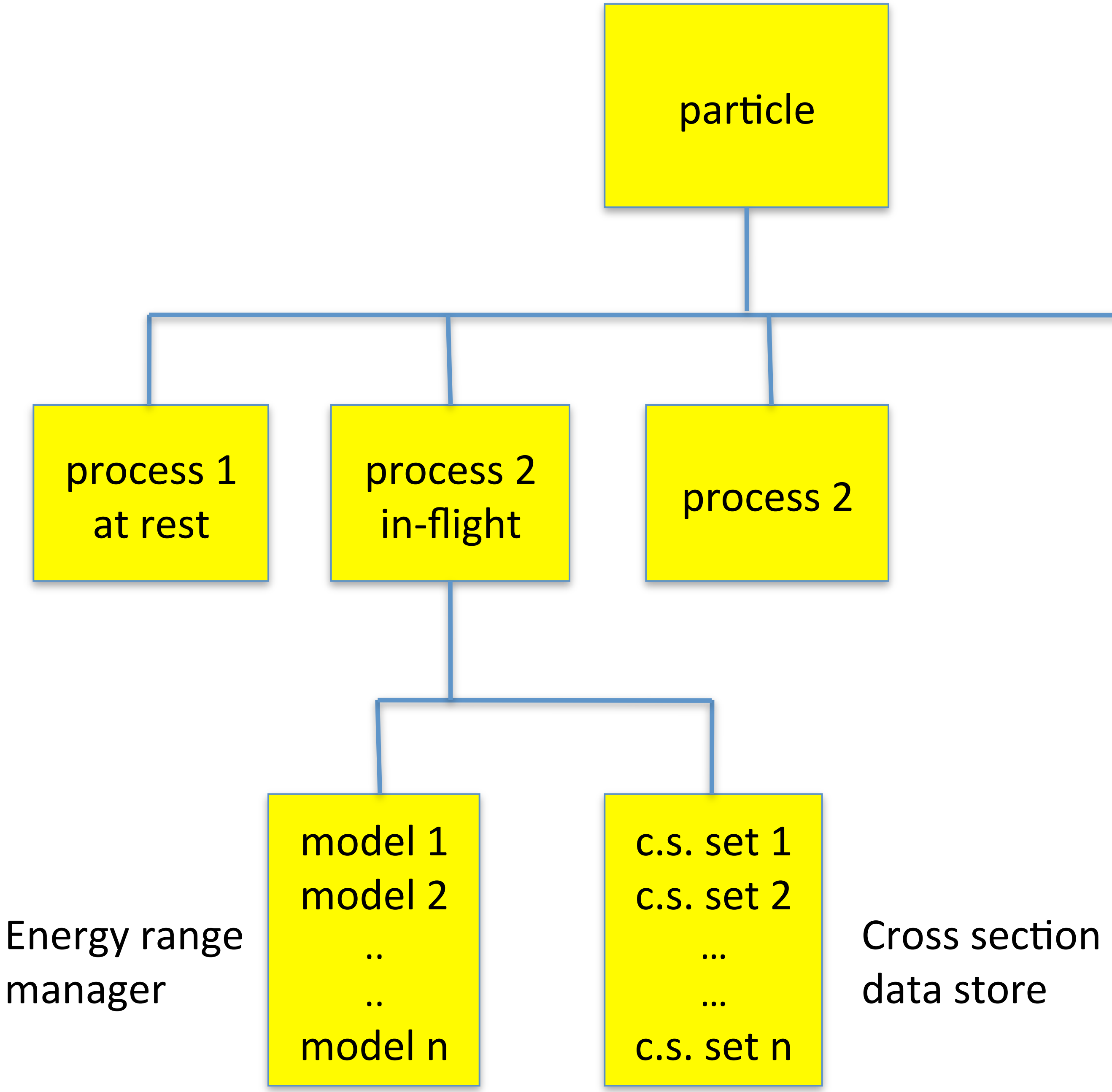
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Overview of hadronic physics
  - processes, cross sections, models
  - hadronic framework and organization
- Precompound models
  - and de-excitation models
- Cascade models
  - Bertini-style, binary, INCL++

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


particle
process 1
at rest
process 2
in-flight
process 2
process n
Energy range
manager
model 1
model 2
..
..
model n
c.s. set 1
c.s. set 2
…
…
c.s. set n
Cross section
data store

Cross Sections

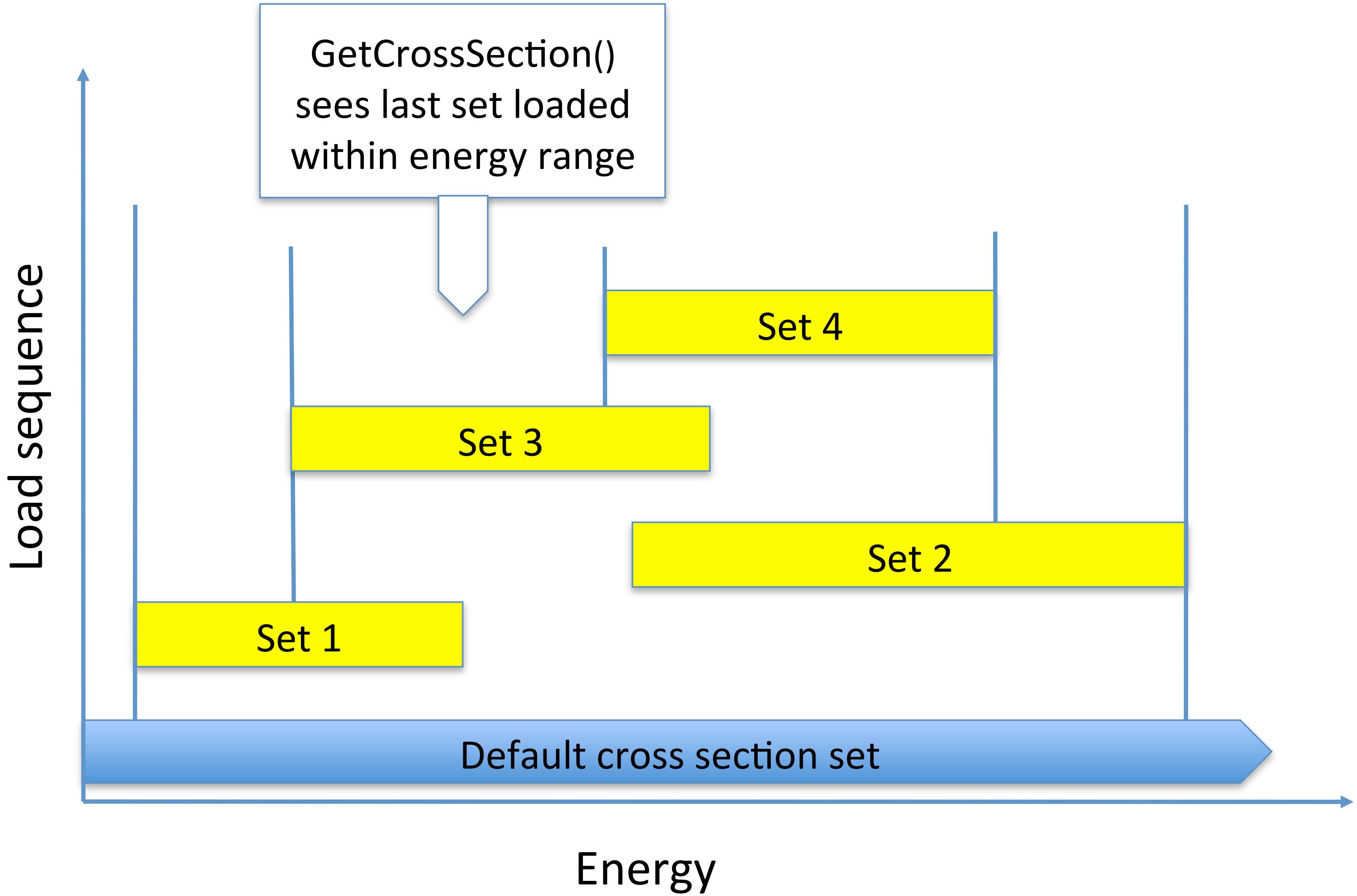
- Default cross section sets are provided for each type of hadronic process
  - fission, capture, elastic, inelastic
  - can be overridden or completely replaced

- 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 (LEND) also available
  - available with or without thermal cross sections
- Medium energy neutron and proton reaction cross sections
  - 14 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections
  - Tripathi, Shen, Kox
  - good for E/A < 10 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

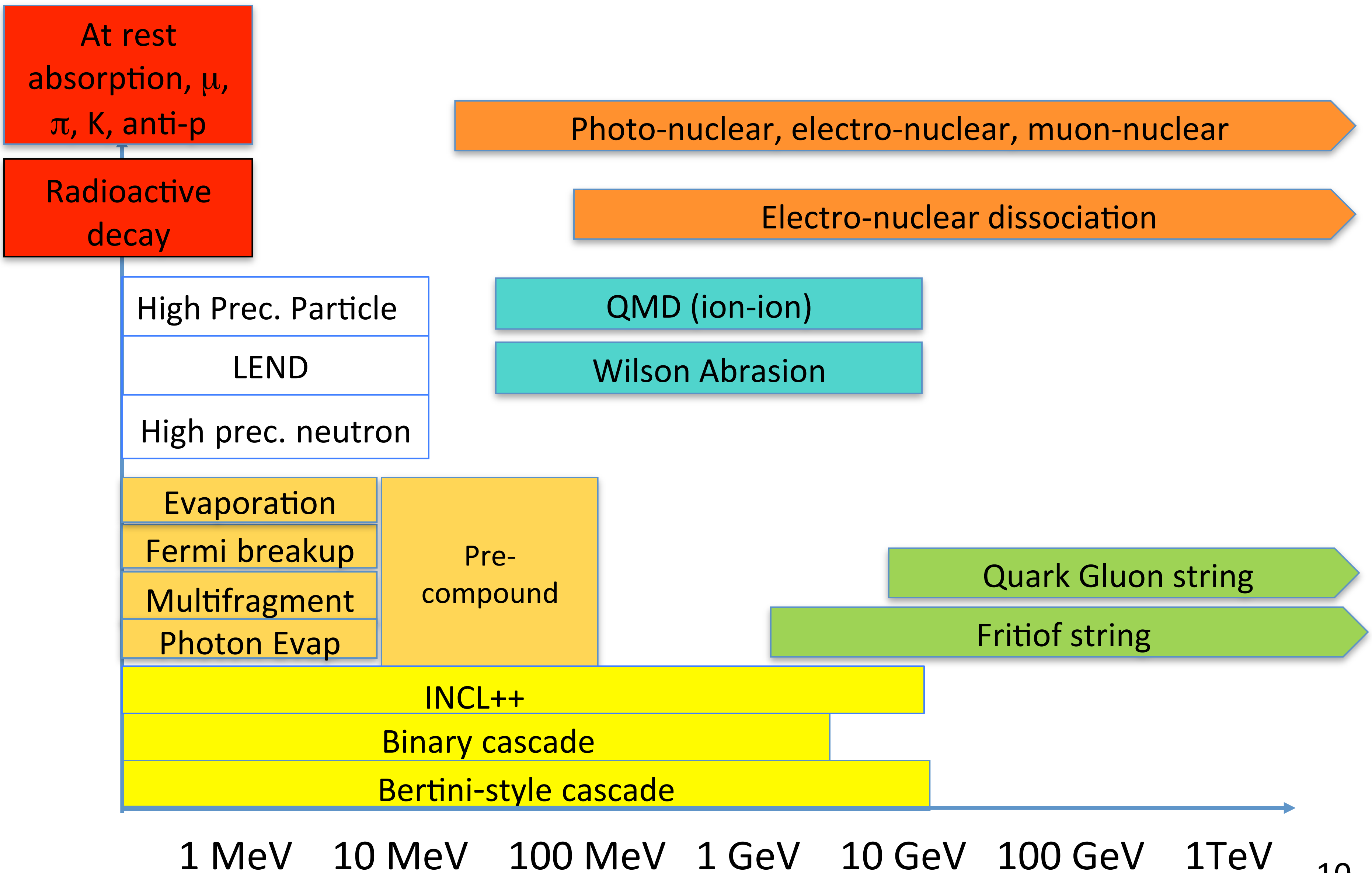
- Dominated by theoretical arguments (QCD, Glauber theory, exciton theory…)

- Final states (number and type of particles and their energy and angular distributions) determined by sampling theoretically calculated distributions

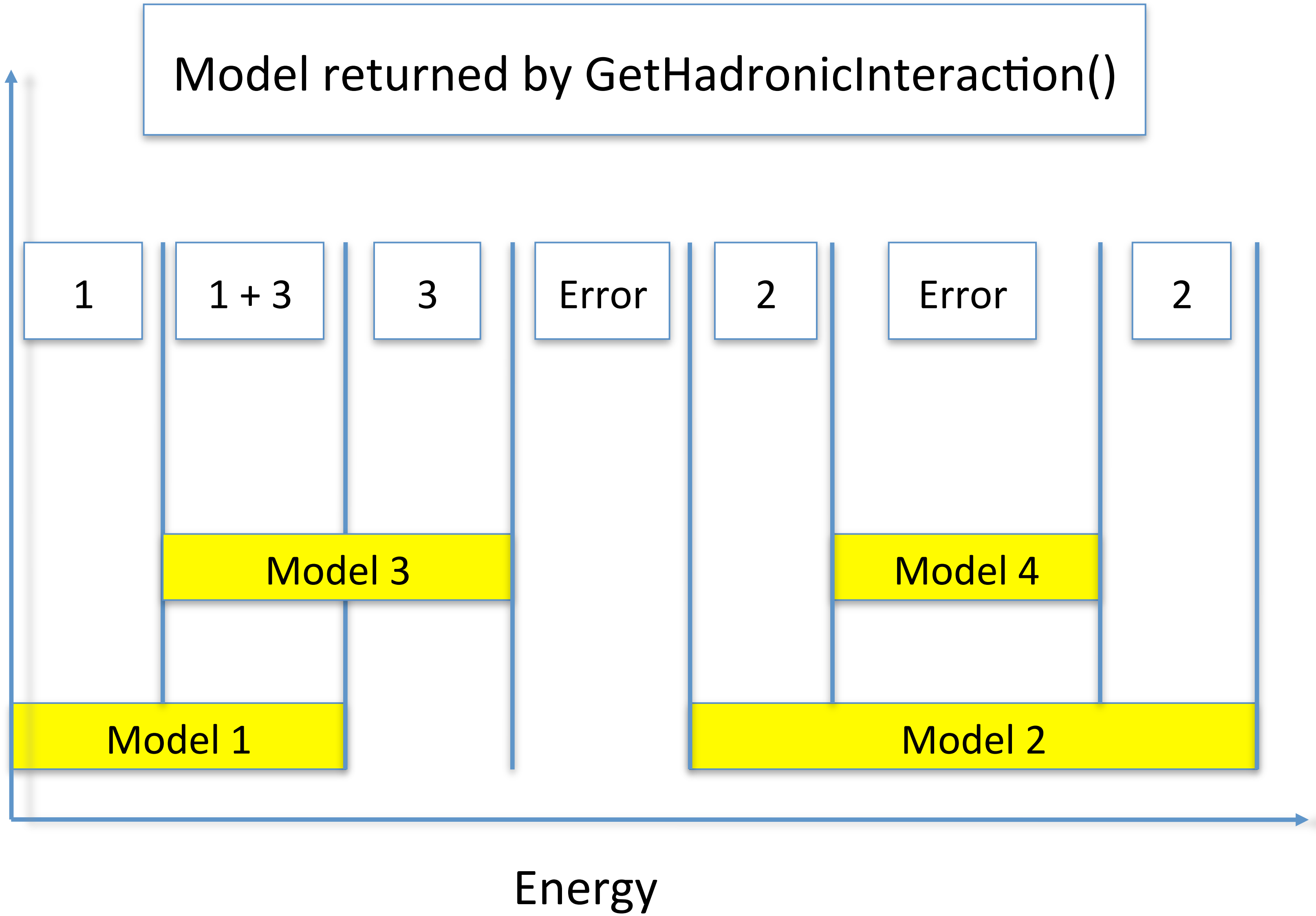
- This type of model is preferred, as it is the most predictive

- Examples
  - quark-gluon string (projectiles with E > 20 GeV)
  - intra-nuclear cascade (intermediate energies)
  - nuclear de-excitation and break-up

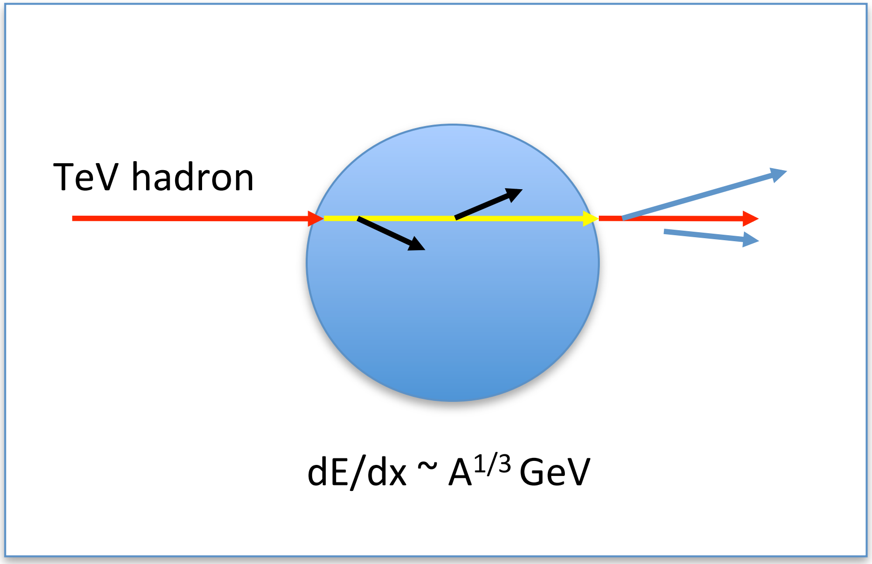
Partial Hadronic Model Inventory

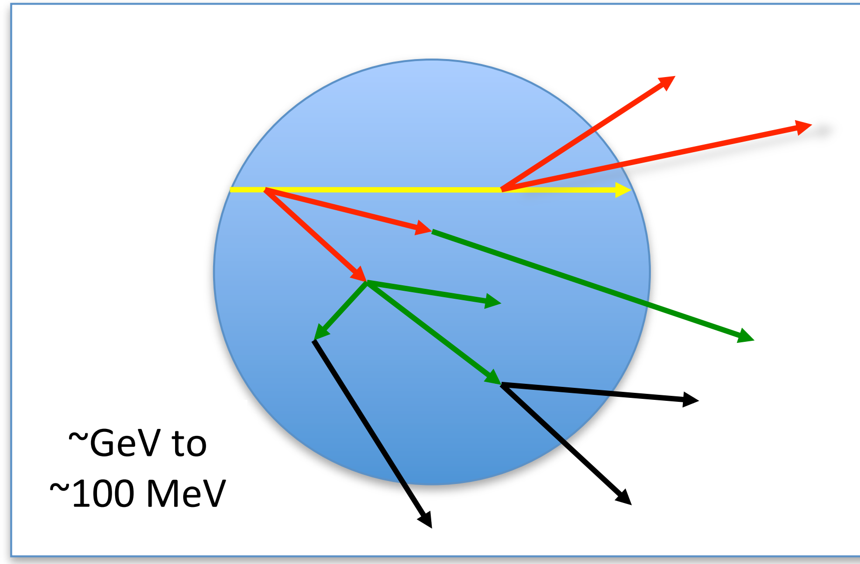


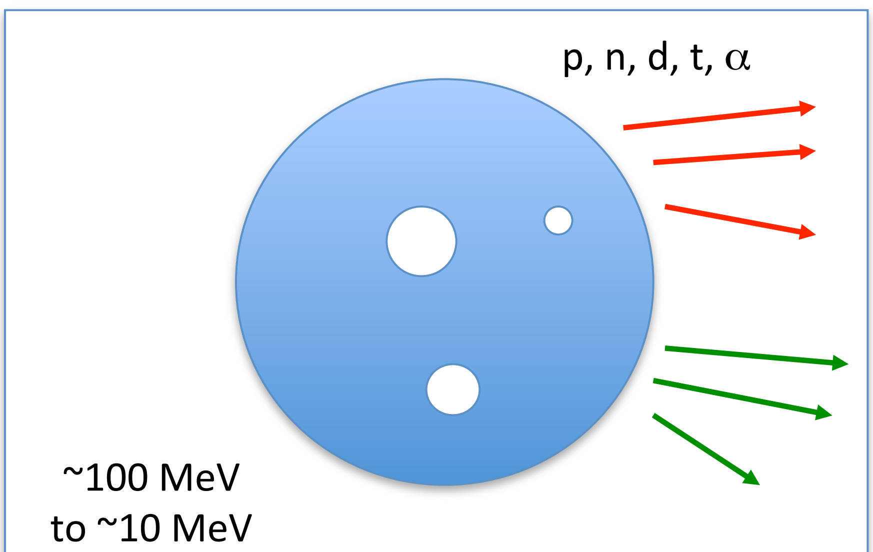
Model Management

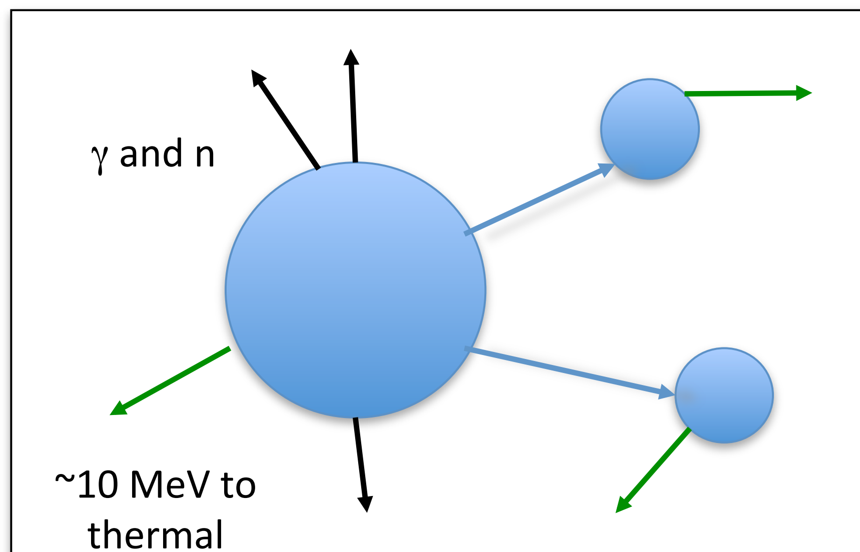


Hadronic Interactions from TeV to meV









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, ^{3}He 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

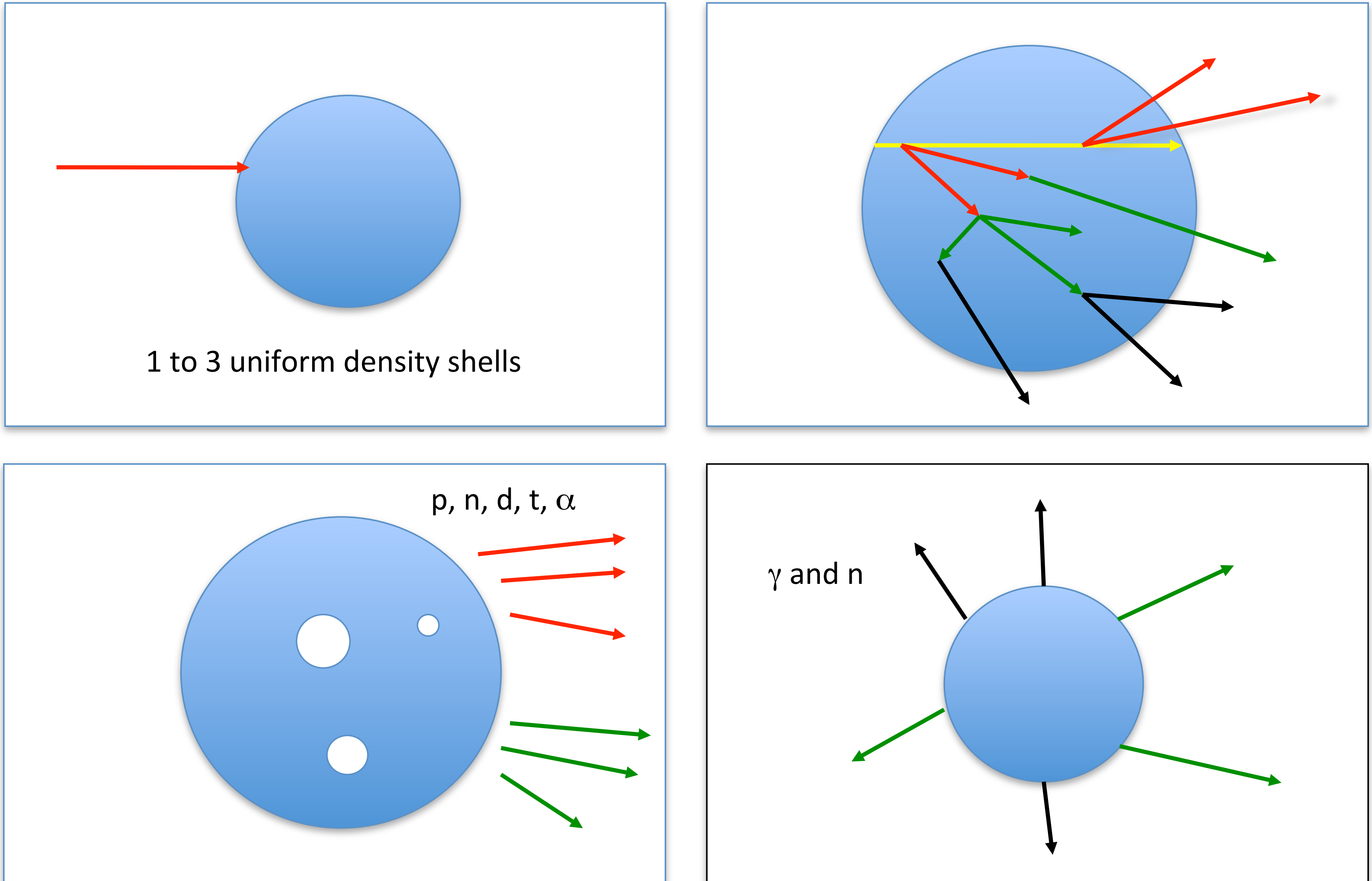
Intra-nuclear Cascade Models

- 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 $^{14}N(p,n)^{14}O$

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)



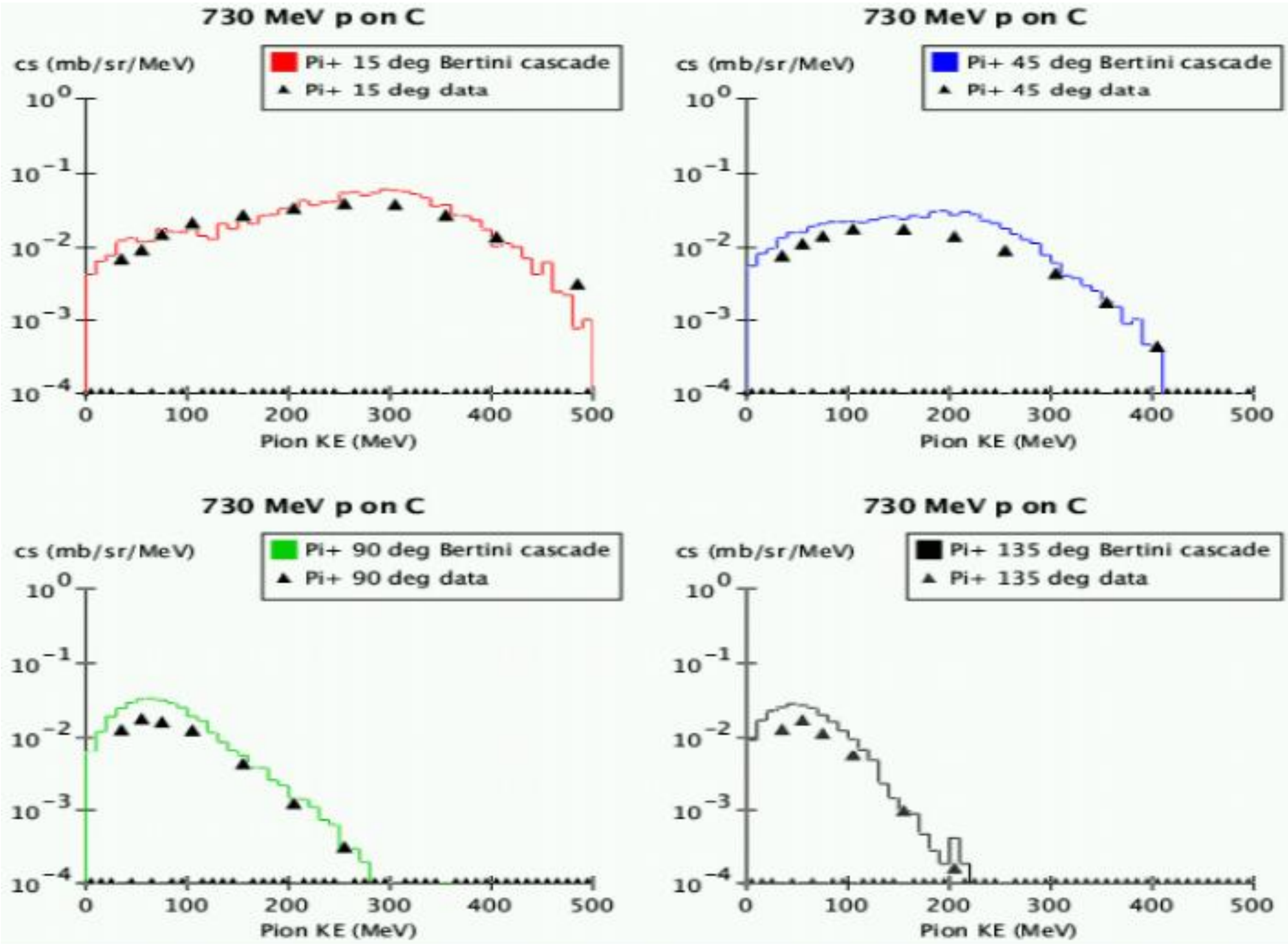
Using the Bertini Cascade

- 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 – 10 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

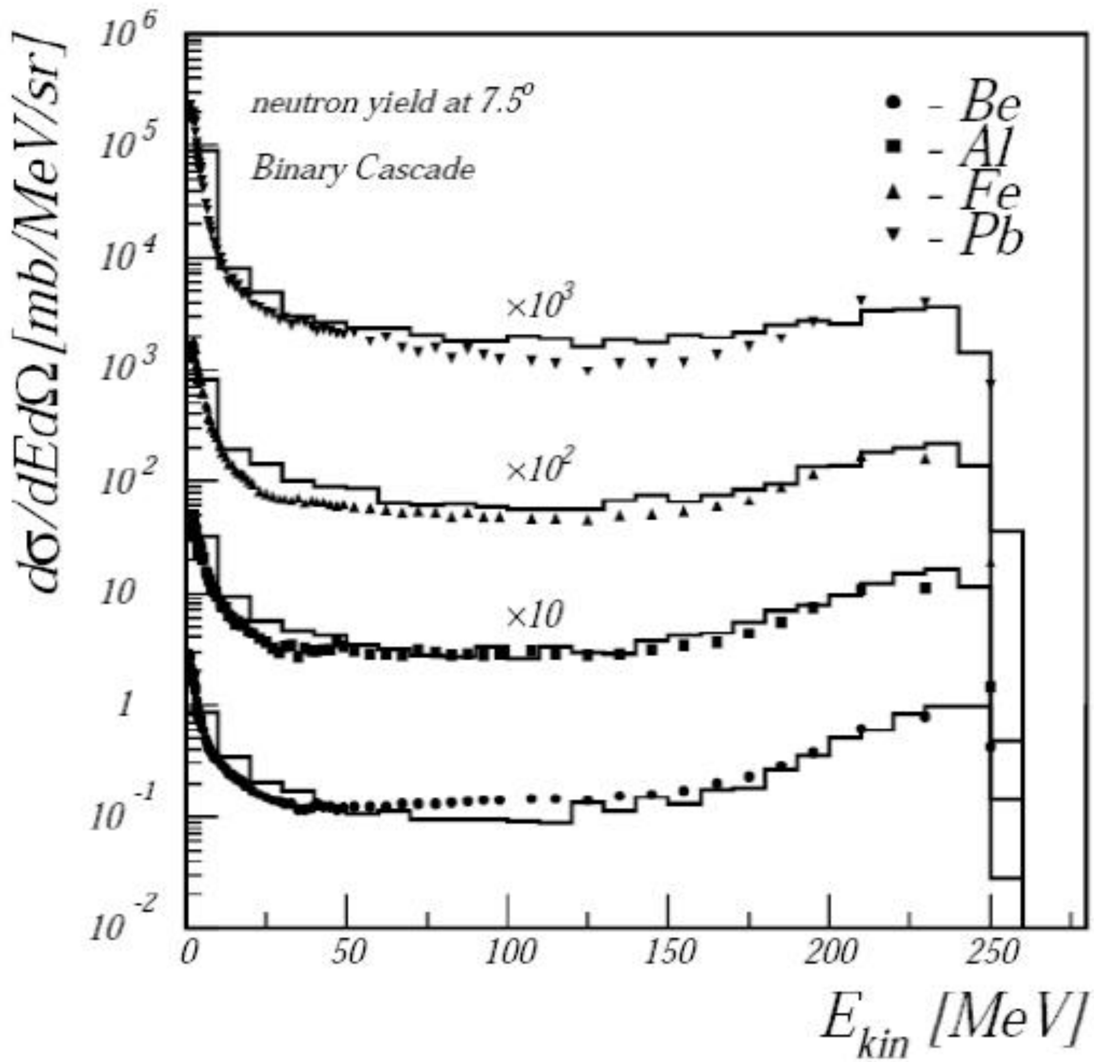
- Invocation sequence:

```
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

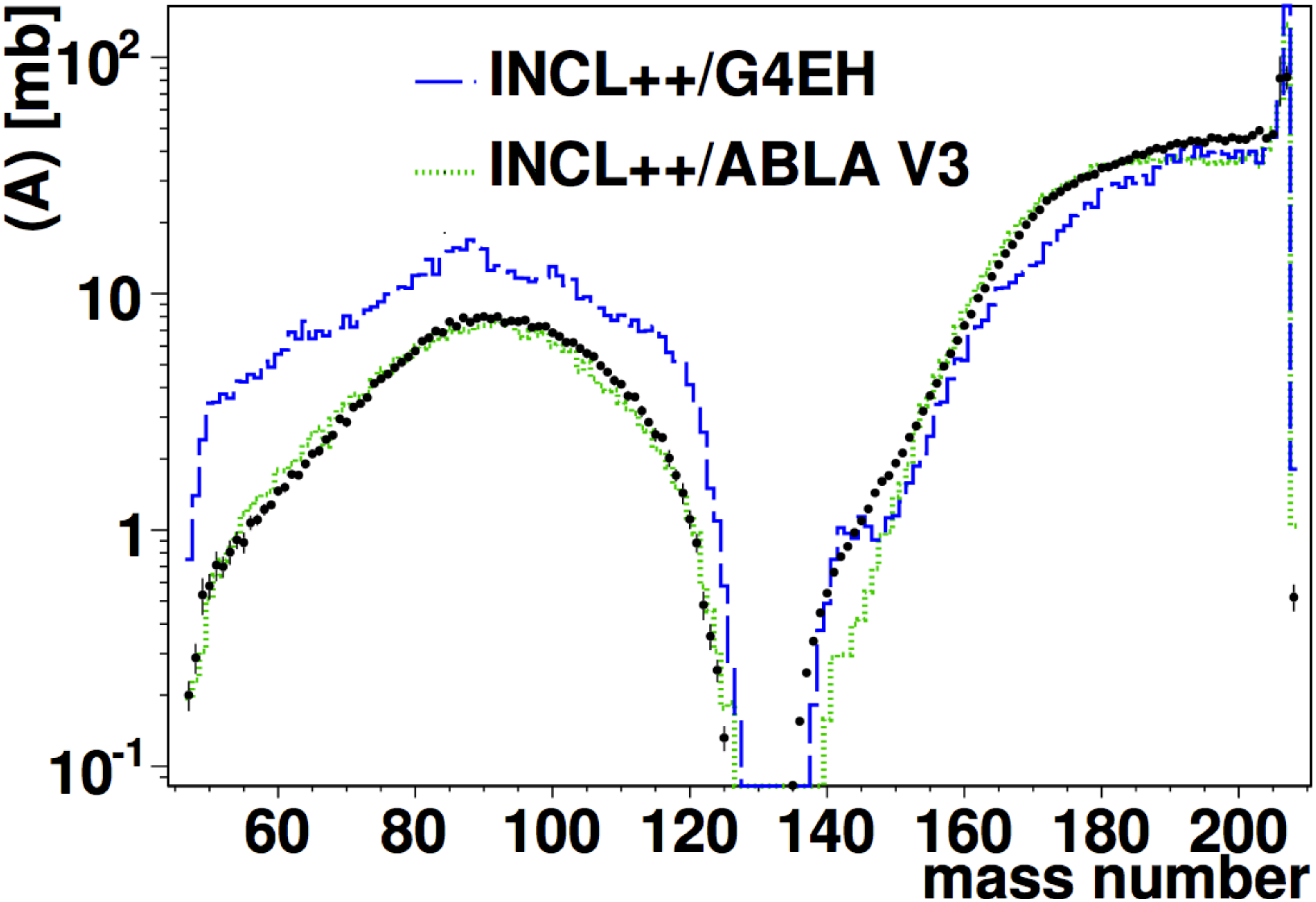


INCL++ Cascade Model

- 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, ^{3}He, 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}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++