Hadronic Physics I

Geant4 Tutorial, KIRAMS, Seoul, 9-13 July 2018

Mihaly Novak
based on Dennis Wright's lectures

Outline

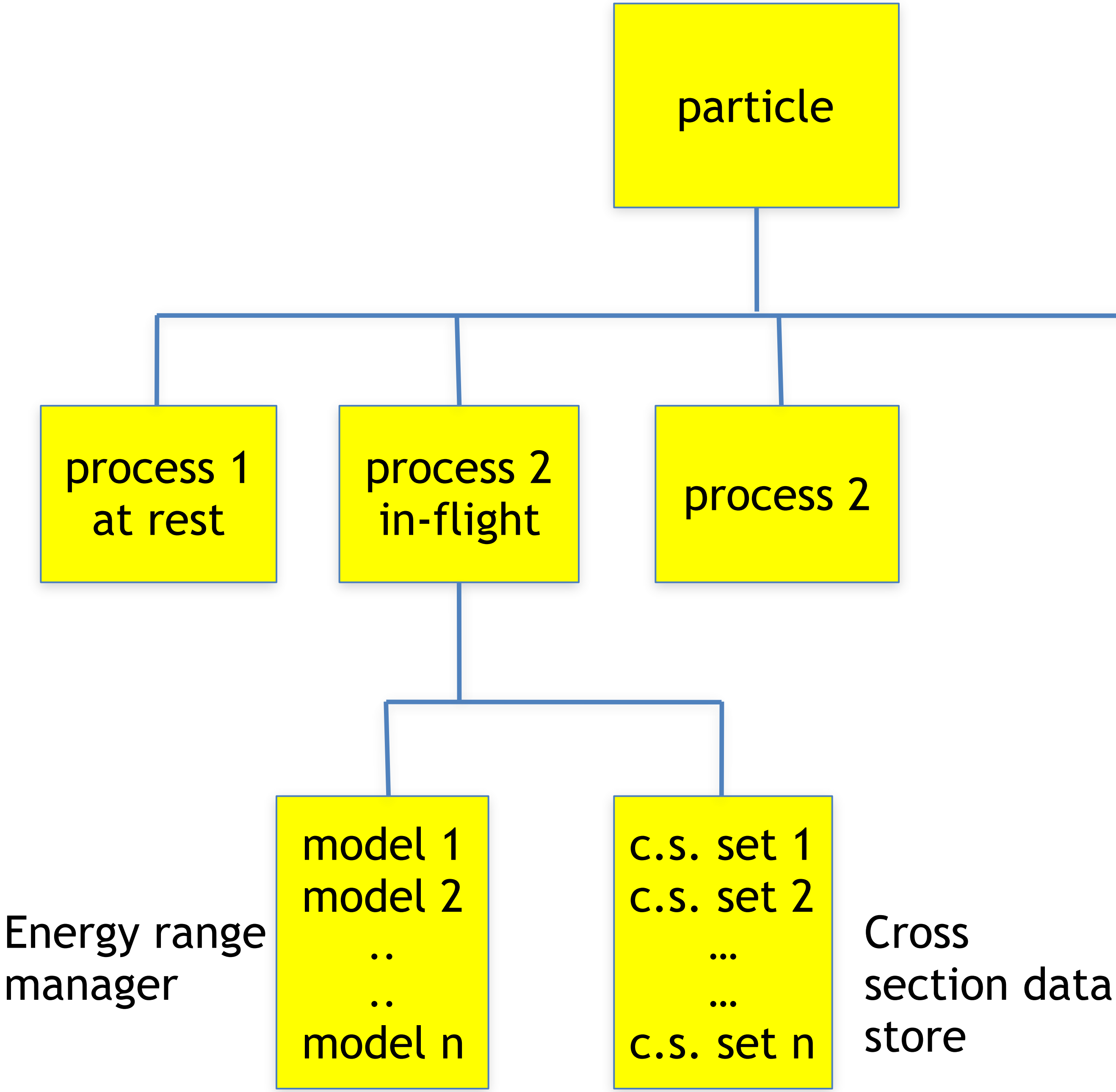
- Overview of hadronic physics
  - processes, cross sections, models
  - hadronic framework and organization
- Precompound models
  - and de-excitation models
- Intra-nuclear cascade models
  - Bertini-style, binary, INCL++

Introduction

- Simulation of interaction of hadrons with atomic nuclei from 0 up to 100 TeV
- Different that EM
  - EM interactions are at the level and scale of the atom
  - hadronic interaction scale ranging from the level of quarks (~100 TeV) to the level of the nucleus (thermal energies)
  - EM interactions (both cross section and final state) are described by the corresponding DCS
  - in case of hadronic interactions, the cross sections and final states are independent
- There is no unified model that could describe the interactions (cross section, final state) over the whole energy range
- Hadronic cross sections, final states are valid for a limited combination of particle type - energy - target

Hadronic Processes, Models and Cross Sections

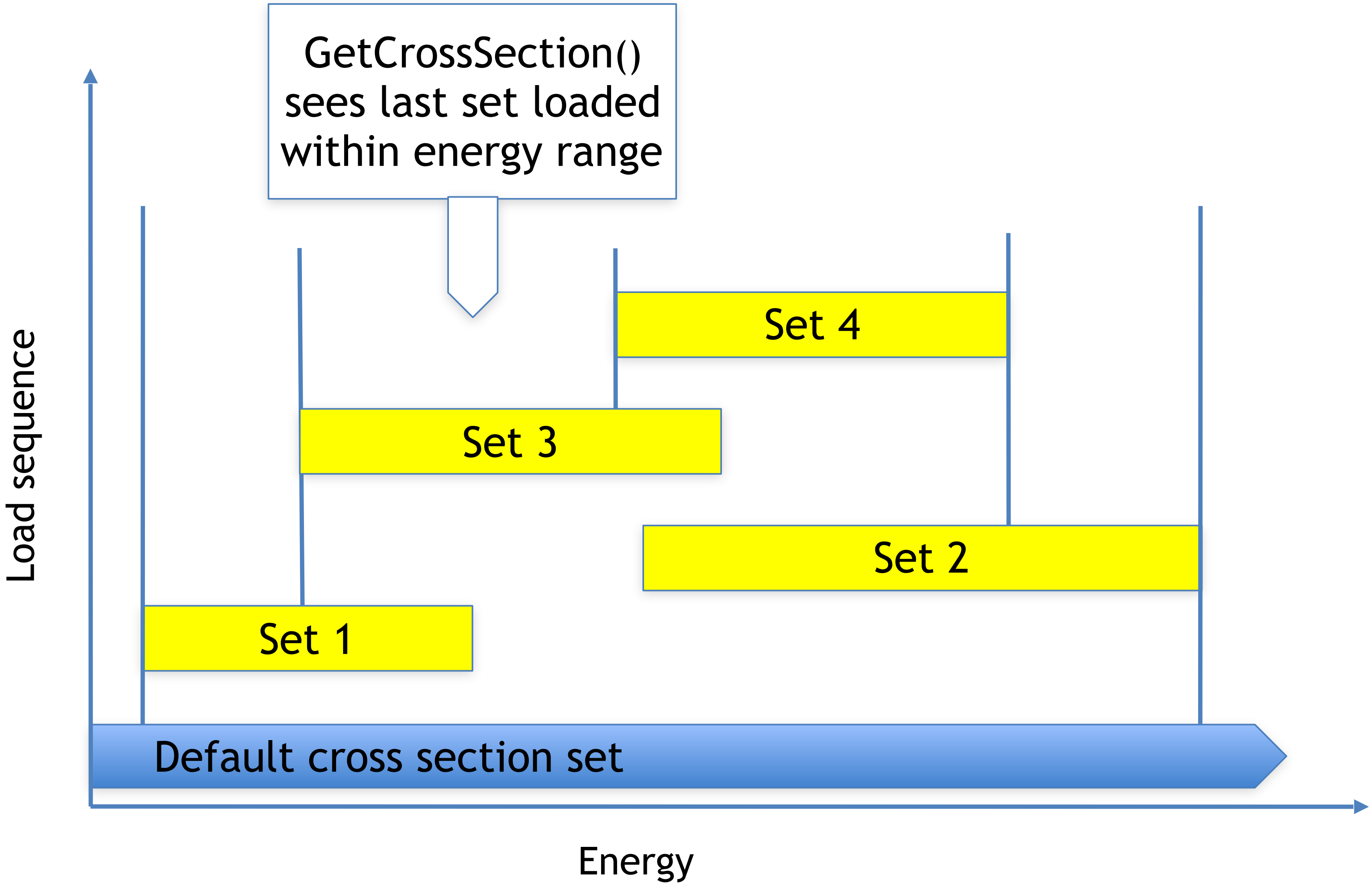
- In Geant4 physics is assigned to a particle through **processes**
- Each process may be implemented
  - directly, as part of the process, or
  - in terms of a **model** class
- Geant4 often provides several **models** for a given **process**
  - user must choose
  - can, and sometimes must, have more 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)

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**

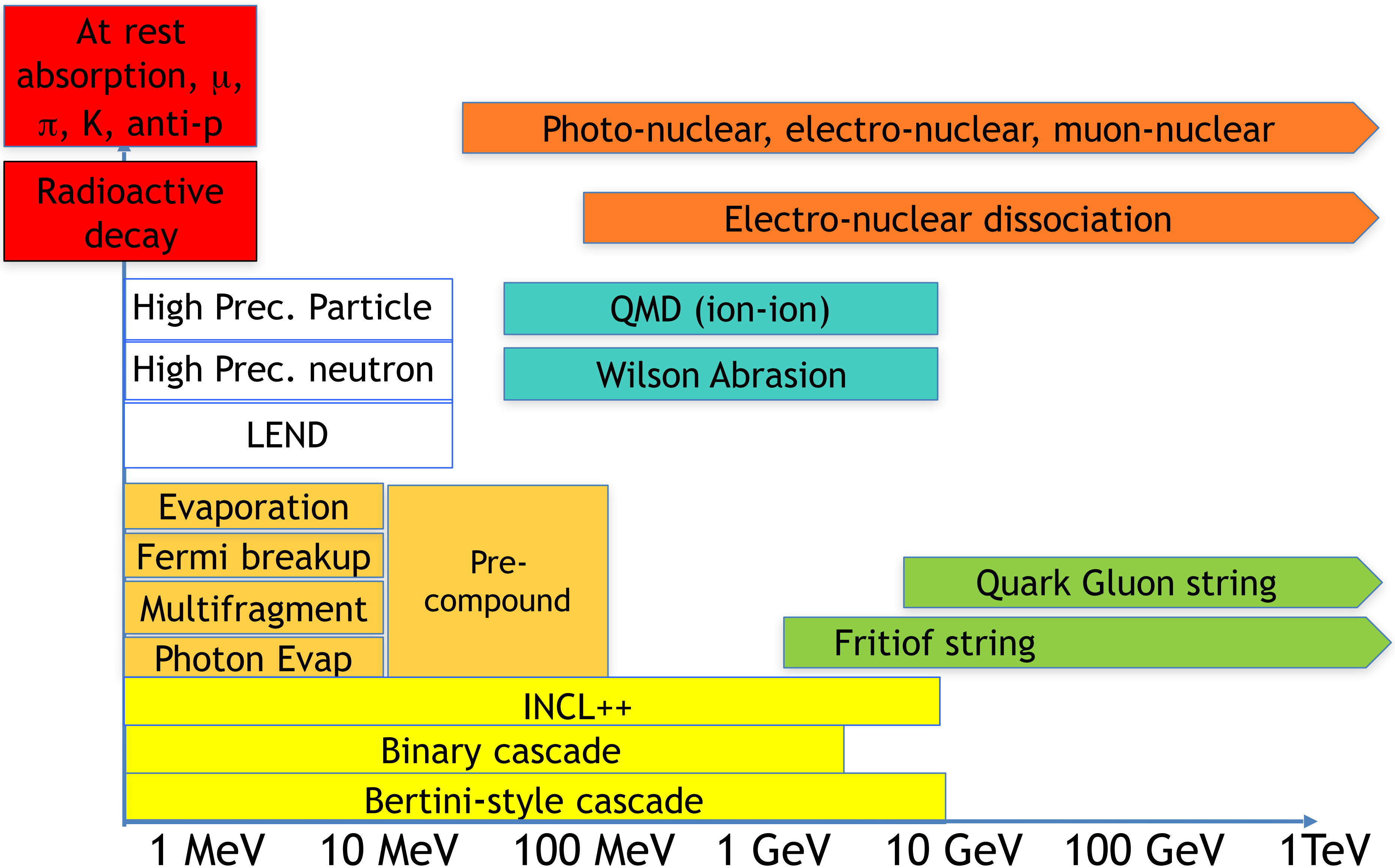
- Dominated by theoretical arguments (QCD, Glauber theory, exciton theory…)

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

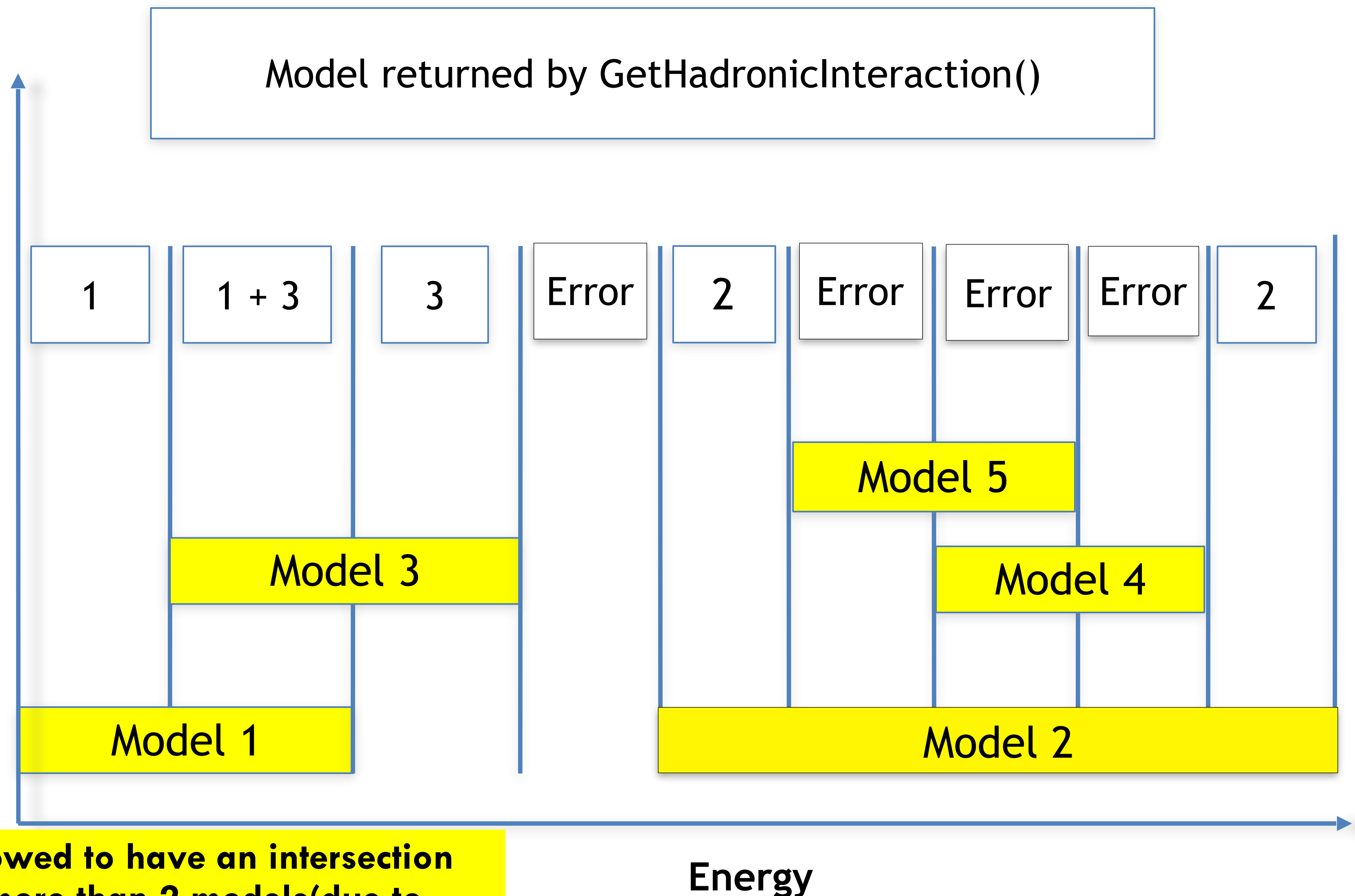
- This type of model is preferred, as it is the most predictive

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

Partial Hadronic Model Inventory

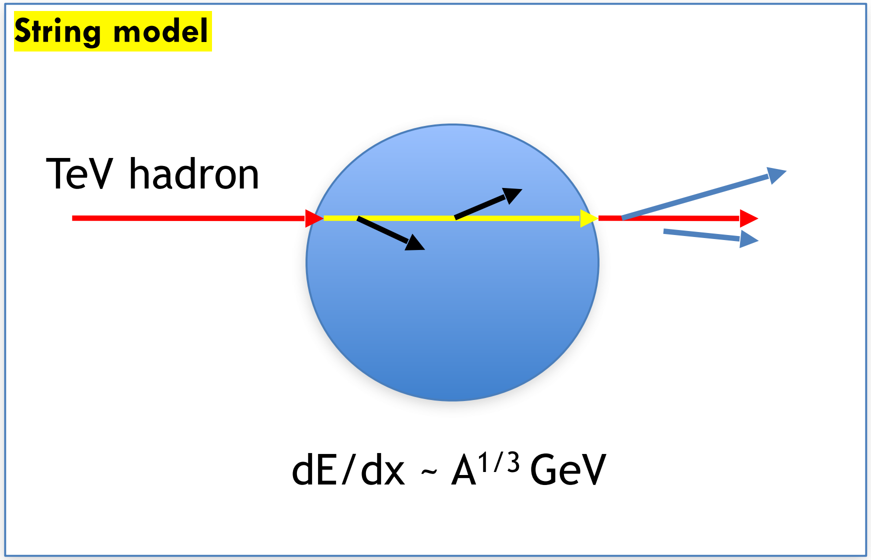


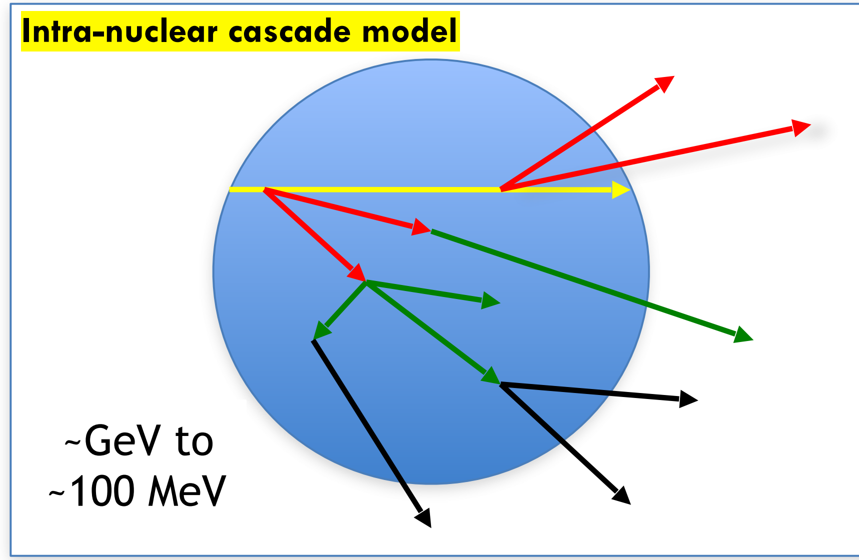
Model Management

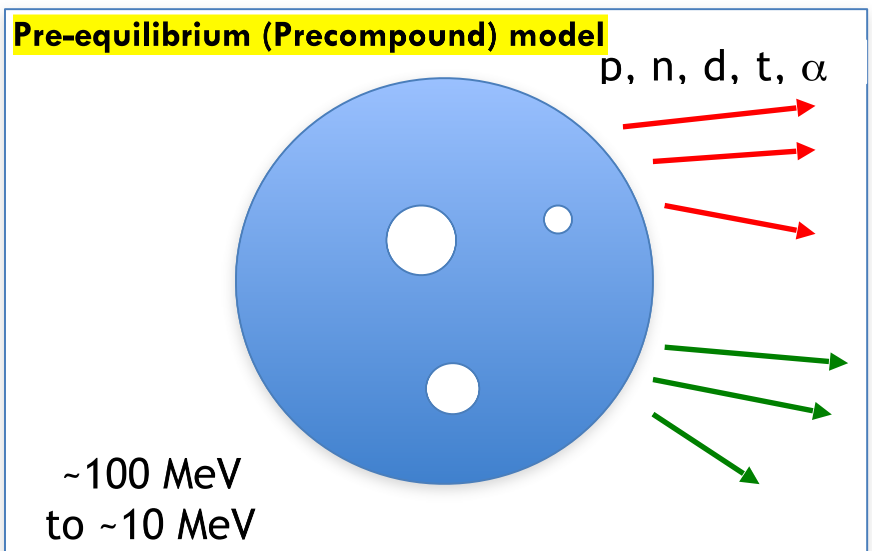


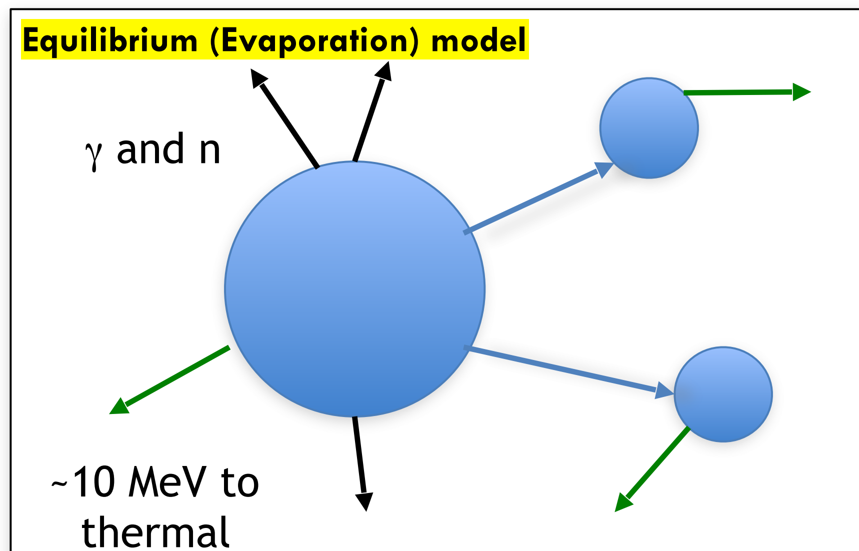
It is allowed to have an intersection of not more than 2 models(due to the way in which a model is selected)

Hadronic Interactions from TeV to meV









Precompound Models

- G4PrecompoundModel(i.e. pre-equilibrium, pre-fission) 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, 4 sub-models are called to take care of nuclear **break-up and evaporation**
    - these 4 models not currently callable by users

- Two Geant4 cascade models (Bertini, Binary) 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(Evaluated Nuclear Structure Data File) 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)

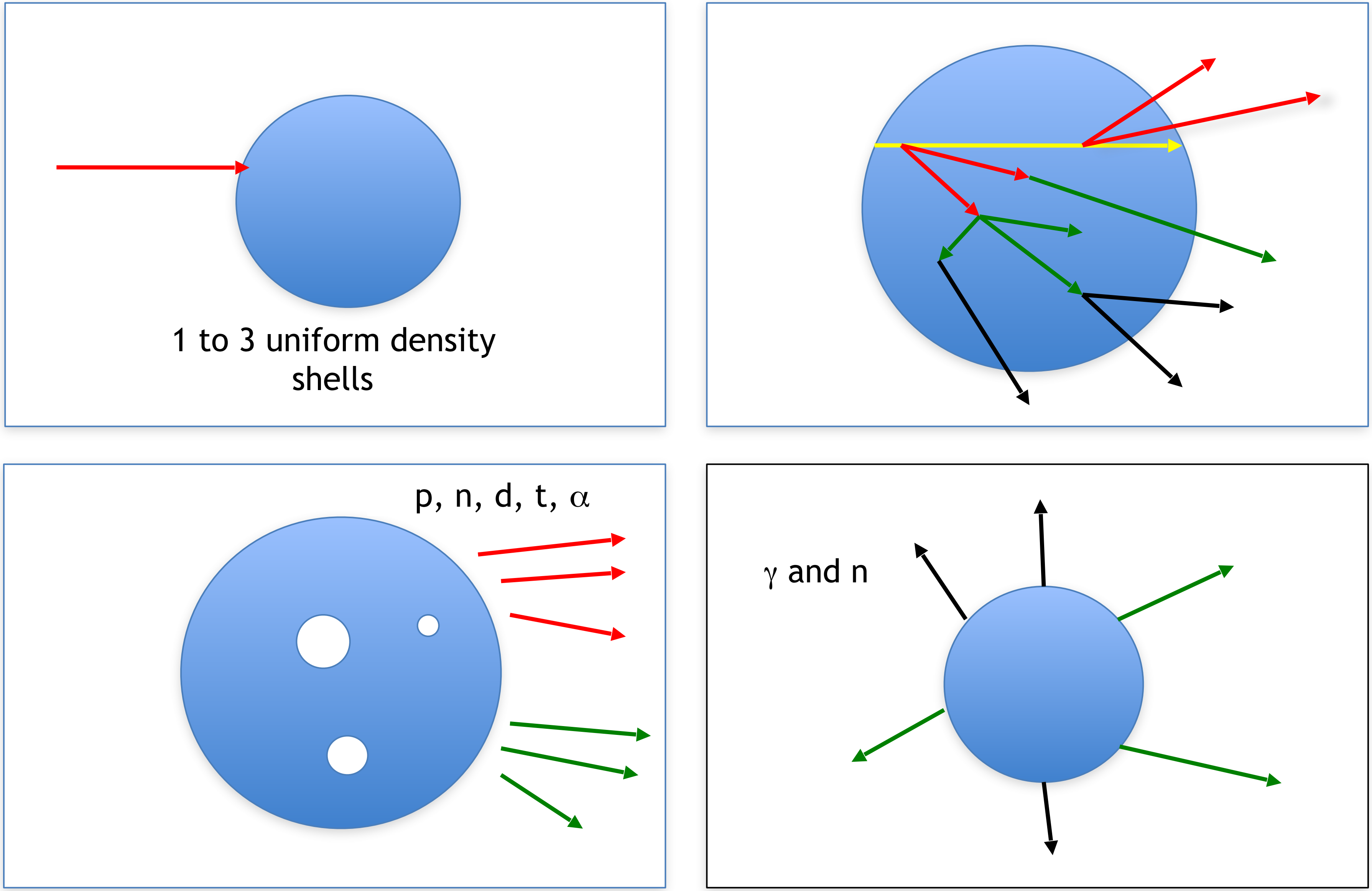
Intra-nuclear Cascade Models

- Typical intra-nuclear cascade energies are inconvenient
  - too high for nuclear physics treatments (nucleus level)
  - too low for QCD (parton level)
- Serber(1947): in particle-nuclear collisions
  - the wave length of the incident particle is comparable to the average intra-nucleon distance
  - interaction can be described in terms of particle-particle collisions
- 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
- Geant4 models for intra-nuclear cascade:
  - Bertini-style, Binary, INCL++

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)



Binary Cascade Model

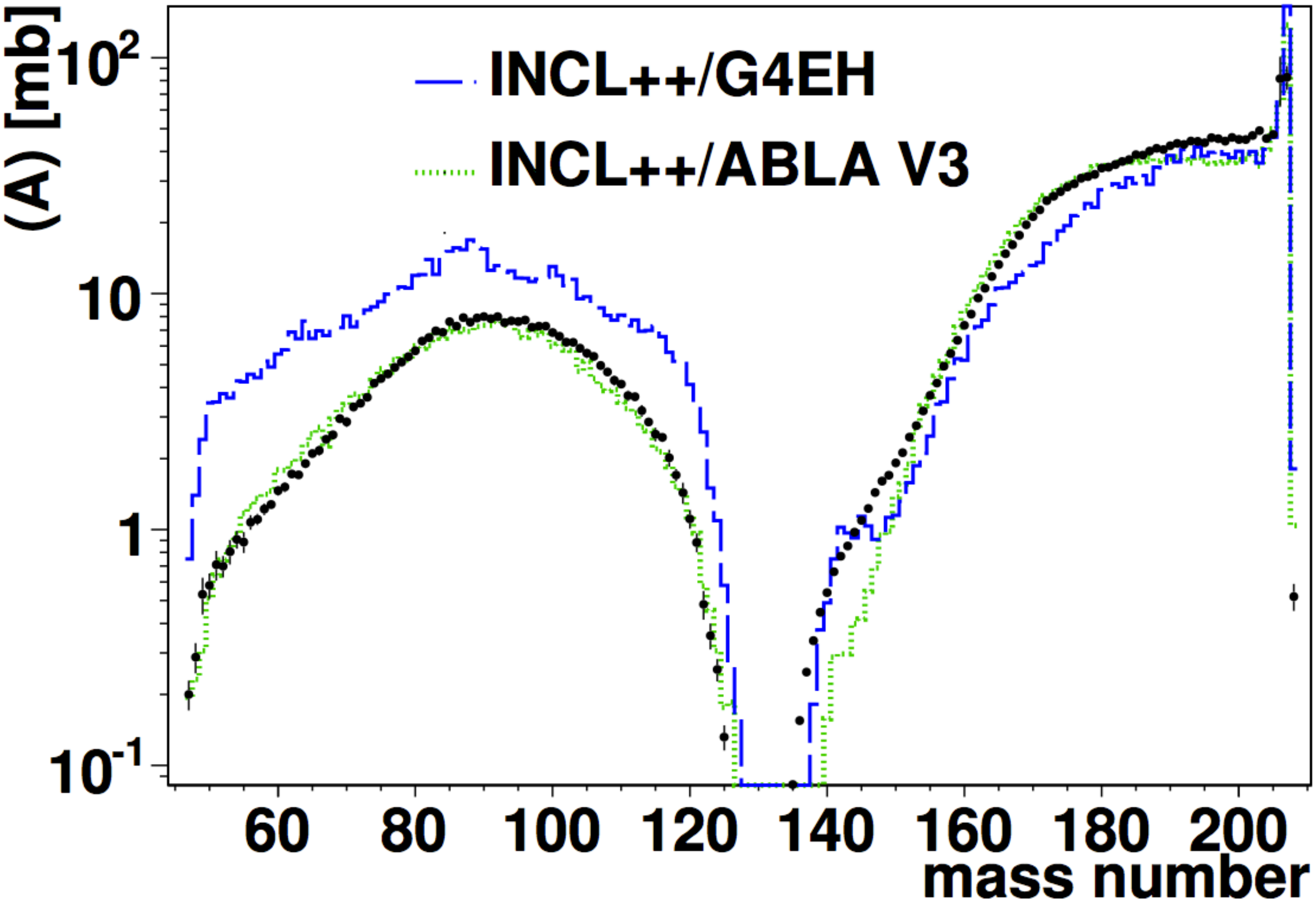
- Modelling sequence similar to Bertini, except
  - it's a time-dependent model
  - hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
  - particles follow curved trajectories in smooth nuclear potential
- Binary cascade is currently used for incident 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)

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, 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

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