Hadronic Physics I

Geant4 Tutorial: version 10.0.p01

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Hadronic Physics I

- What is Hadronic Physics?

- The Hadronic Framework
  - Processes vs. Models
  - Cross sections and process selection
  - Energy ranges and model selection

- Precompound and De-excitation Models

- Cascade Models

What is Hadronic Physics?

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- Interactions with atomic nuclei
- Projectile is a hadron
- or produced secondary particles are hadrons

Hadronic physics always involve QCD processes, using models with varying levels of detail, parametrization, or data library dependence.

Differential outcomes (angular, energy dependence) are model dependent, not tabulated cross-sections.

Hadronic Framework: Processes and Models

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- In Geant4 physics interactions (between a particle and material) occur through processes

- Each process may be implemented

  - directly, as part of the process, or

  - in terms of a model class linked to the process

- Geant4 often provides several models for a given process

  - user must choose during physics list setup

  - may have more than one per process

- A process must also have cross sections assigned

  - multiple data tables available, select during physics list setup

Hadronic Framework: Processes and Models
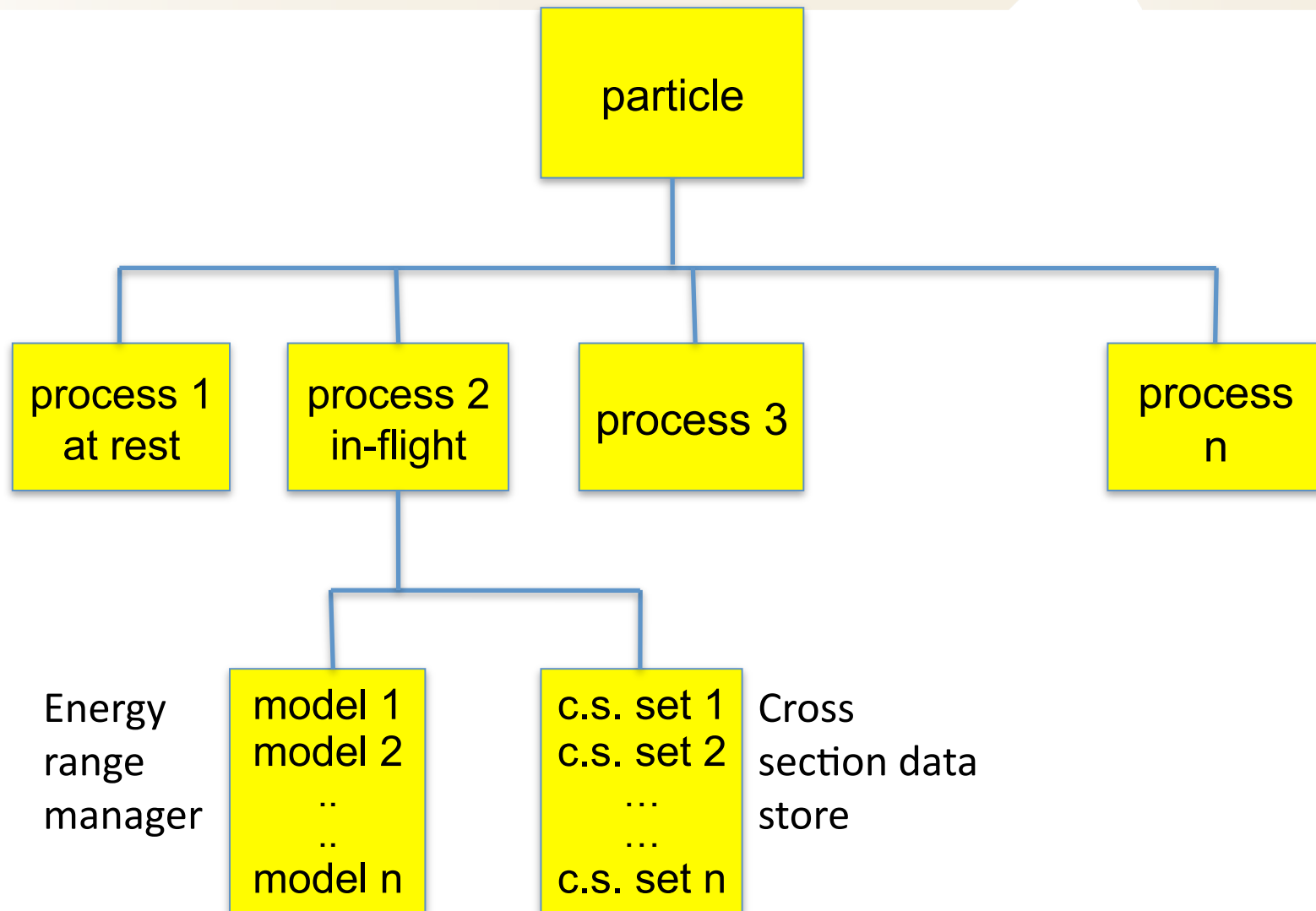
Hadronic Model Organization
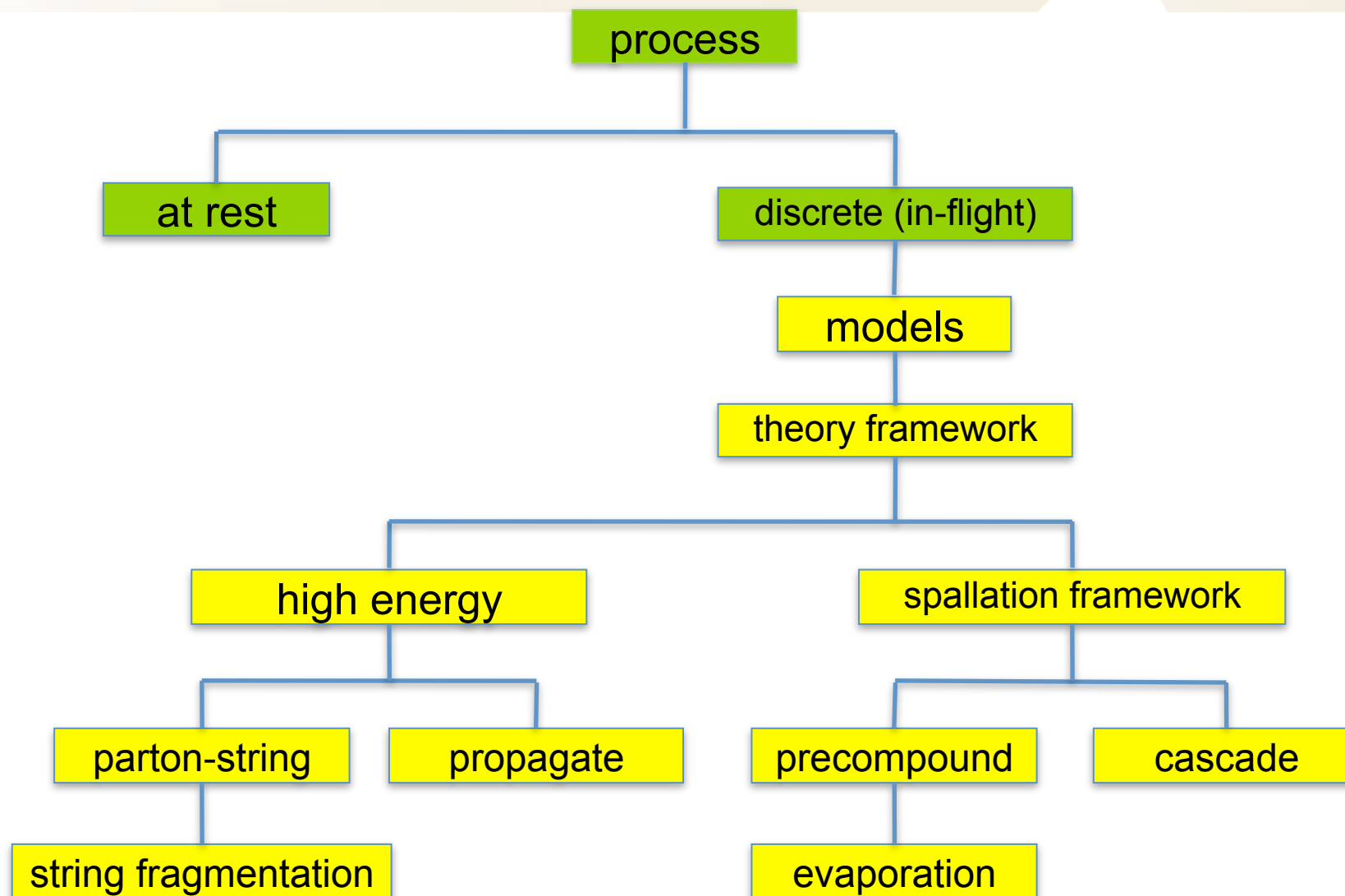
Hadronic Framework: Cross Sections

- 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 few parameters with "fitted" functions

  - some represent large databases

  - some are purely theoretical (equation-driven)

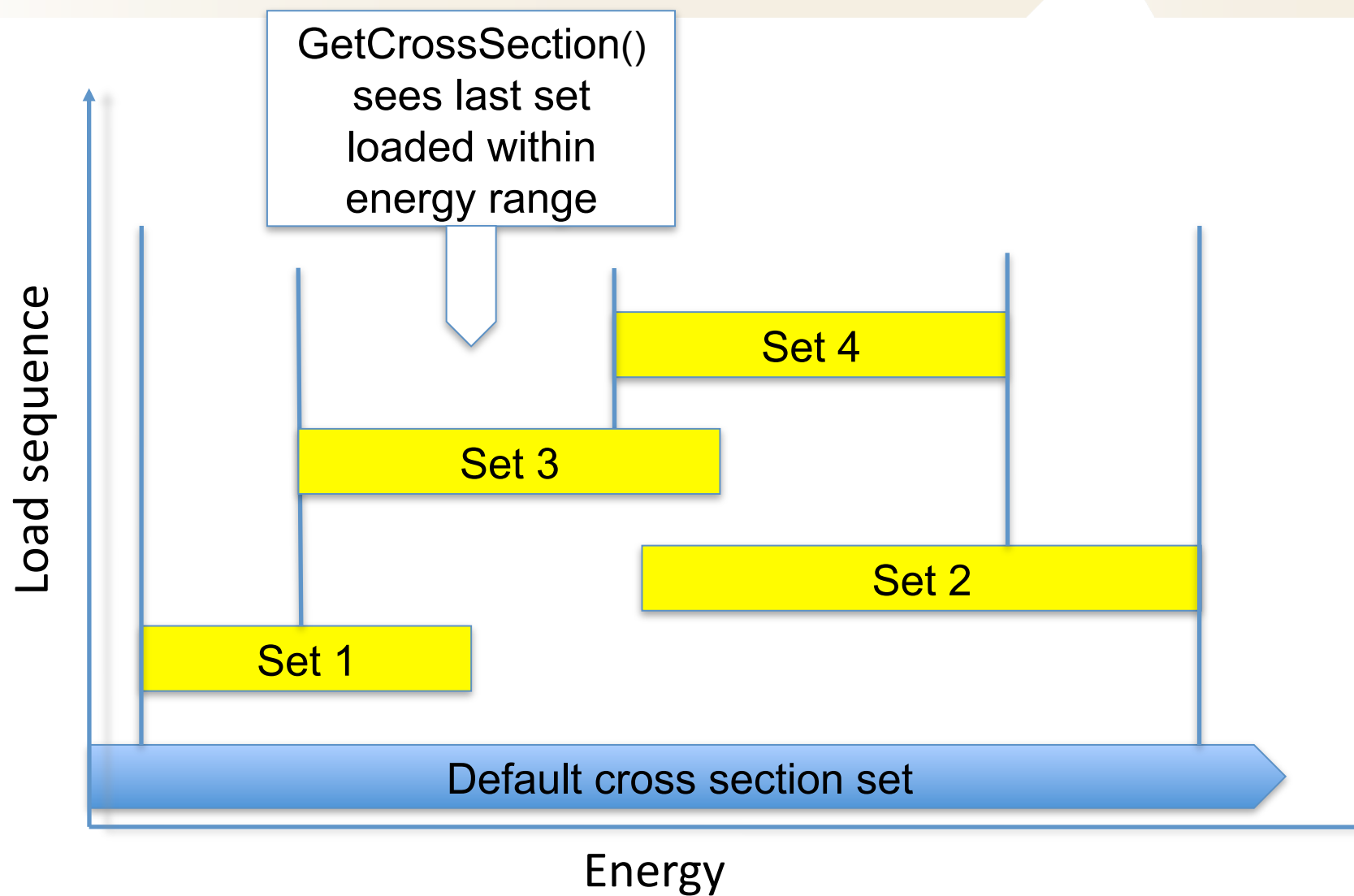- Cross section sets are inclusive, not differential

Available Cross Section Data Sets

- 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 Validity Ranges

GetCrossSection() sees last set loaded within energy range

Load sequence

Set 4

Set 3

Set 2

Set 1

Default cross section set

Energy

Hadronic Model Validity Ranges

Processes may have one or more models registered to them [`G4HadronicProcess::RegisterMe()`]

Each model has an associated energy range; default values can be changed in physics list setup.

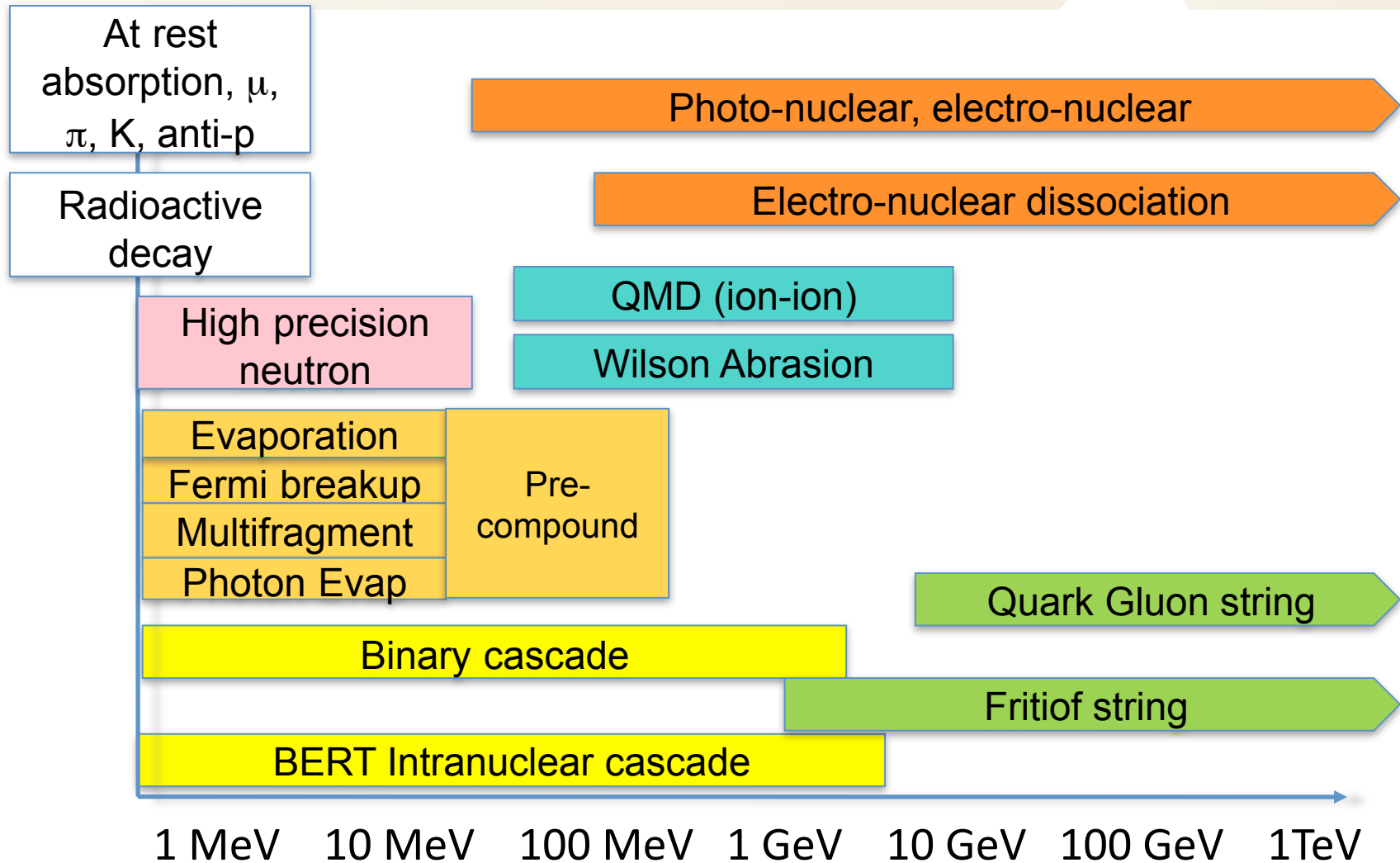For each process, whole energy range (zero to "infinity") must be covered by models

- Model ranges may overlap at ends
- Ranges must not be "enclosed" (duplicated)
- No energies may be excluded

Overlaps are "interpolated" with linear random selection at each interaction

Hadronic Model Validity Ranges
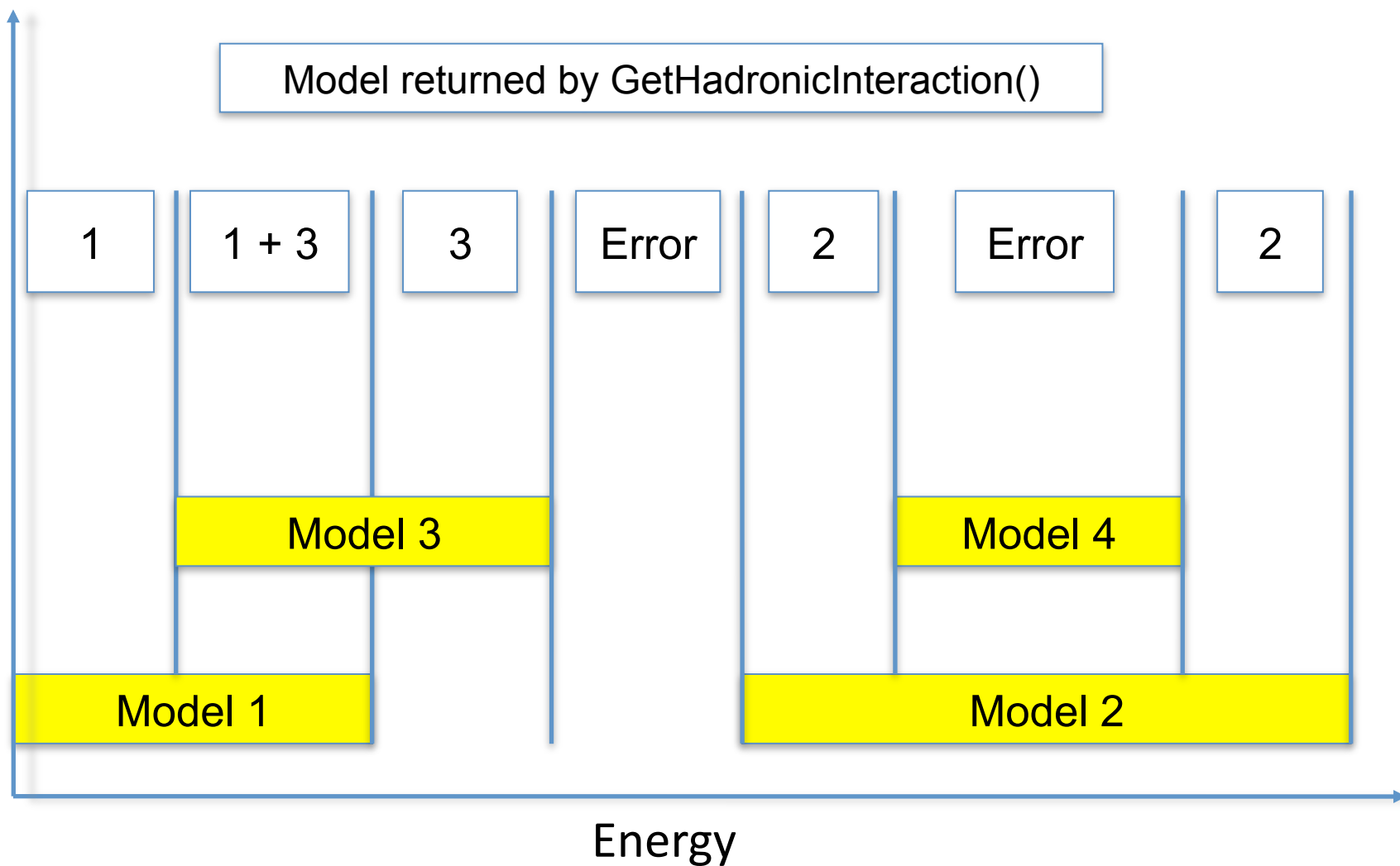
Available Hadronic Models

Precompound and De-excitation Models

Pre-compound model handles

- Nucleon or pion absorption at low energies (roughly below pion emission threshold)
- Nuclear fragments resulting from higher energy interactions
- "Wounded nucleus" with set of excited particle-hole states
- Resolves to equilibrium, emitting p, n, d, t, ^{3}He, **α**

Closer to equilibrium, *De-excitation* model resolves excess energy in nucleus

- Nuclear evaporation and break-up
- Continuum gamma emission

Cascade Models

Up to a few GeV, hadron-nucleus interactions may be modeled as a series of hadron-nucleon collisions within the nuclear potential.

Secondaries from each collision react in turn against nearby nucleons, in a "cascade," until the initial energy is partitioned.

Ultimately, some final state of mesons, nucleons, and one or more nuclear fragments is produced.

Geant4 includes three different cascade models
- Binary Cascade
- BERT (Bertini-inspired) intranuclear cascade
- INCL++/ABLA++ (Liege Model)

Cascade Models: Binary Cascade

Time-dependent model (ordered interactions)

- Hadron-nucleon collisions form resonances
- Decayed according to their quantum numbers
- Particles follow curved trajectories in smooth nuclear potential

Binary cascade currently used for incident p, n, $\pi^{\pm}$

- Valid for incident p, n up to 10 GeV
- Valid for incident $\pi^{\pm}$ up to 1.3 GeV

Nucleus-nucleus: `G4BinaryLightIonReaction`

- Valid for incident ions up to A = 12
- Higher if target A < 12

Adding Binary Cascade to the physics list

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Using BinaryCascade

```
G4BinaryCascade* binary = new G4BinaryCascade();

G4PionPlusInelasticProcess* piproc = new
G4PionPlusInelasticProcess();

piproc->RegisterMe(binary);

piplus_Manager->AddDiscreteProcess(piproc);
```

Using BinaryLightIonReaction

```
G4BinaryLightIonReaction* ionBinary = new
G4BinaryLightIonReaction();

G4IonInelasticProcess* ionProc = new
G4IonInelasticProcess();

ionProc->RegisterMe(ionBinary);

genericIonManager->AddDiscreteProcess(ionProc);
```

Binary Cascade Validation with 256 MeV protons
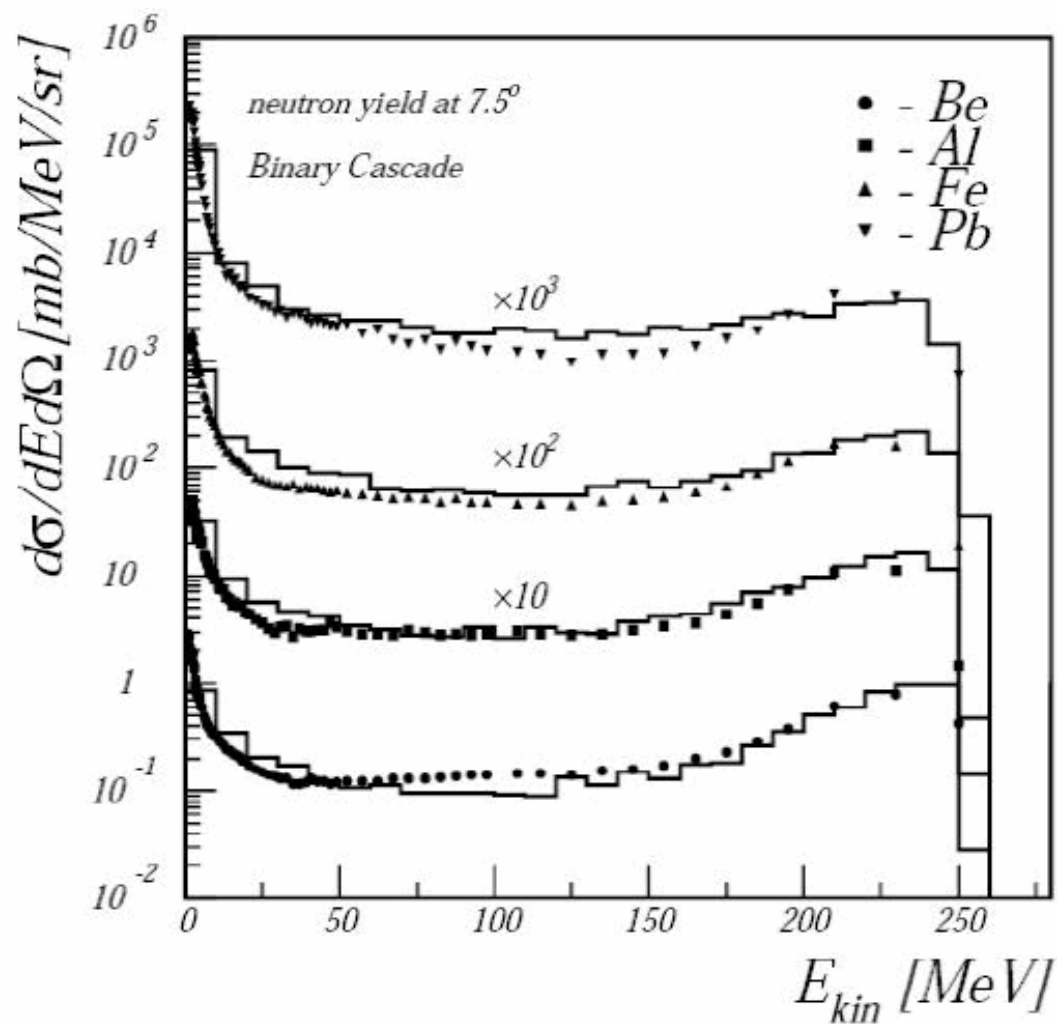
Cascade Models: BERT Intranuclear Cascade

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"Classical" (non-quantum) cascade

- Average solution of particle in medium (Boltzmann equation)
- No scattering matrix calculated
- Traces back to some of earliest codes (1960s)

Single-particle collisions with individual nucleons

- Free space cross sections used to generate secondaries
- Cascade in "continuous" nuclear medium
- Pre-equilibrium and equilibrium decay of residual nucleus
- Nuclear potential integrated in up to six concentric shells

BERT Intranuclear Cascade

1 to 3 uniform density shells

p, n, d, t, α

γ and n
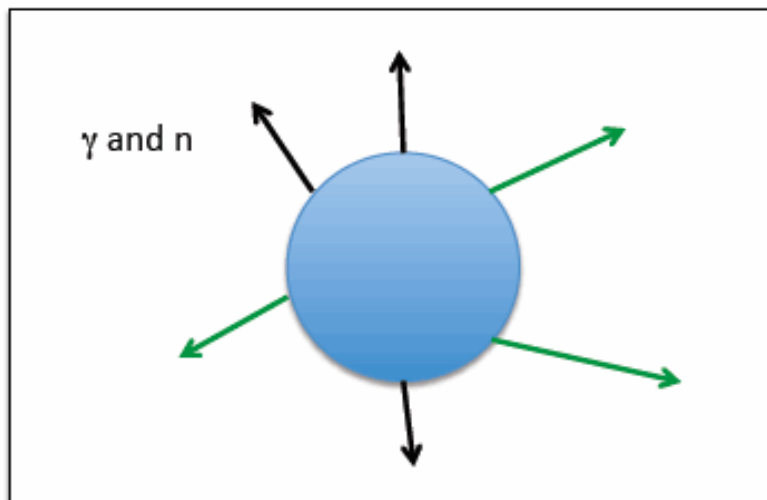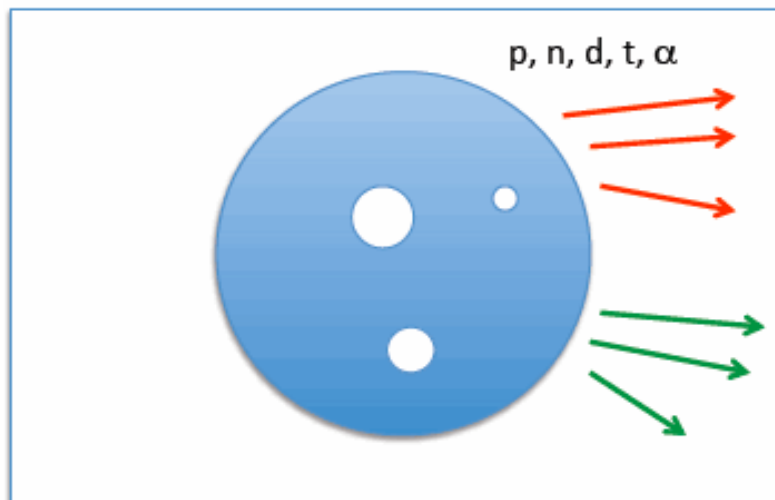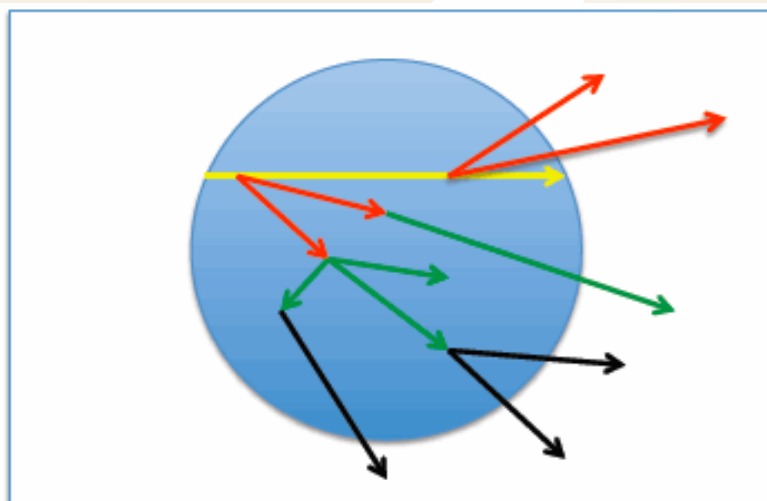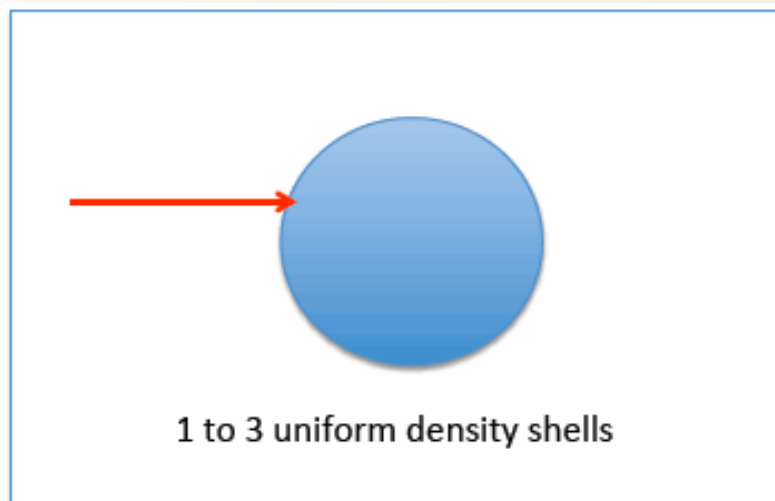
BERT Intranuclear Cascade

Extensions in Geant4 move beyond original Bertini codes

- Support for kaon and hyperon projectiles and secondaries
- γ-(p,n) photonuclear interactions
- μ-(p,n) leptonuclear interactions (muon capture)
- "Trailing effect" to approximate time-dependence
- Clustering (making light ions) of collinear outgoing nucleons

Model development continues to improve angular distributions, nuclear structure model to match low and intermediate energy data

BERT Intranuclear Cascade

Used for γ, μ^-, p, n, $\pi^\pm$, π^0, $K^\pm$, $K^0_{L,S}$, Λ, $\Sigma^{\pm,0}$, $\Xi^{-,0}$

- Validated for incident energies up to 10 GeV
- Usable for capture of hadrons on "large" nuclei (A > 4)
- Usable for photonuclear and muon-nuclear interactions
- No additional photons produced in h-N collisions

Code includes interface to handle incident nuclei, but very primitively

- All constituent nucleons are collided
- No impact parameter, incident nuclear potential
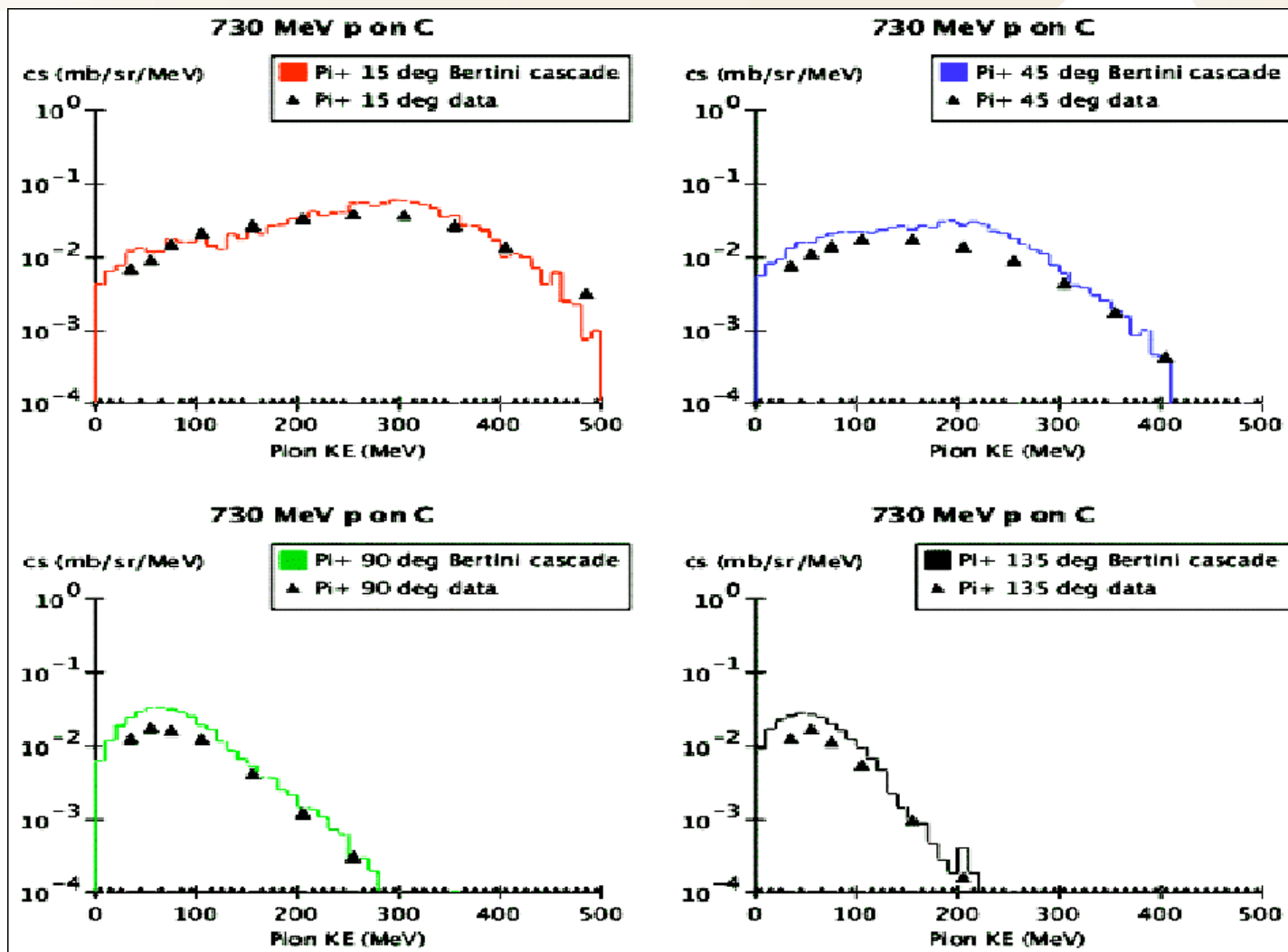- INCL++ or BinaryLightIon should be used

Using BERT Intranuclear Cascade

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```
G4CascadeInterface* bert = new G4CascadeInterface;

G4ProtonInelasticProcess* pproc = new

G4ProtonInelasticProcess;

pproc->RegisterMe(bert);

protonManager->AddDiscreteProcess(pproc);
```

Repeat as necessary for other hadrons

BERT Intranuclear Cascade Validation

Cascade Models: Leige INCL++

Time-dependent model (ordered interactions)

- Smooth Woods-Saxon or harmonic oscillator potential
- Particles travel in straight lines through potential
- Resonance formation and decay (like Binary cascade)

Valid for incident *p, n, π, d, t*, ^{3}He, *α*

- From 150 MeV to 3 GeV
- Also works for projectile nuclei up to A = 12
- Targets must be 11 < A < 239

Ablation model (ABLA) used to de-excite nucleus

- Used successfully in spallation studies
- Also expected to be good in medical applications

INCL++ Validation with Cl-C Collisions

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Green: INCL 4.3   Red: INCL 4.2   Blue: Binary Cascade