Hadronic Physics I

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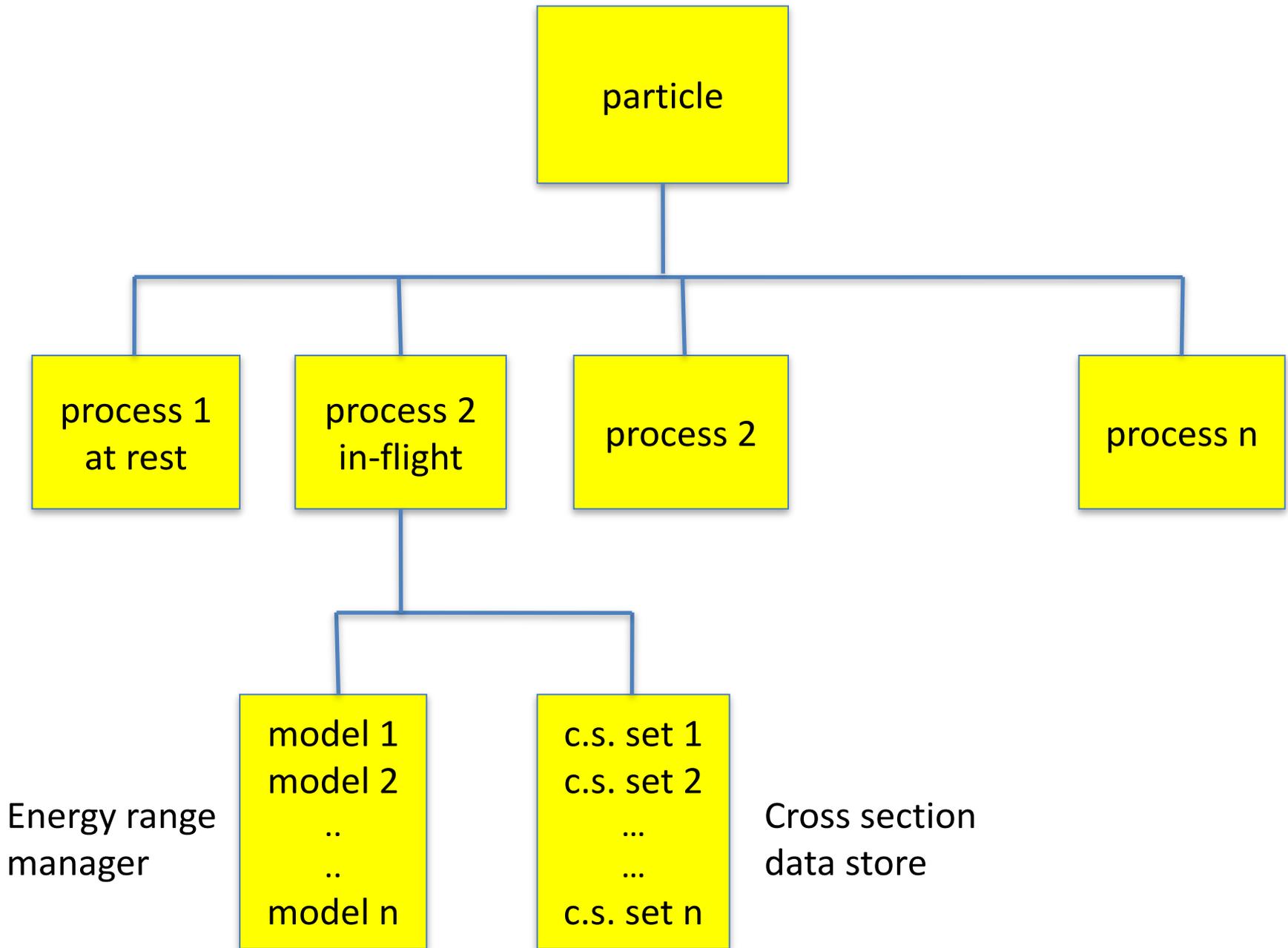
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Overview of hadronic physics

- Hadron elastic scattering

- 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

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

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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 MeV < E < 20 GeV

- Ion-nucleus reaction cross sections
  - Tripathi, Shen, Kox
  - good for E/A < 10 GeV

- Pion reaction cross sections

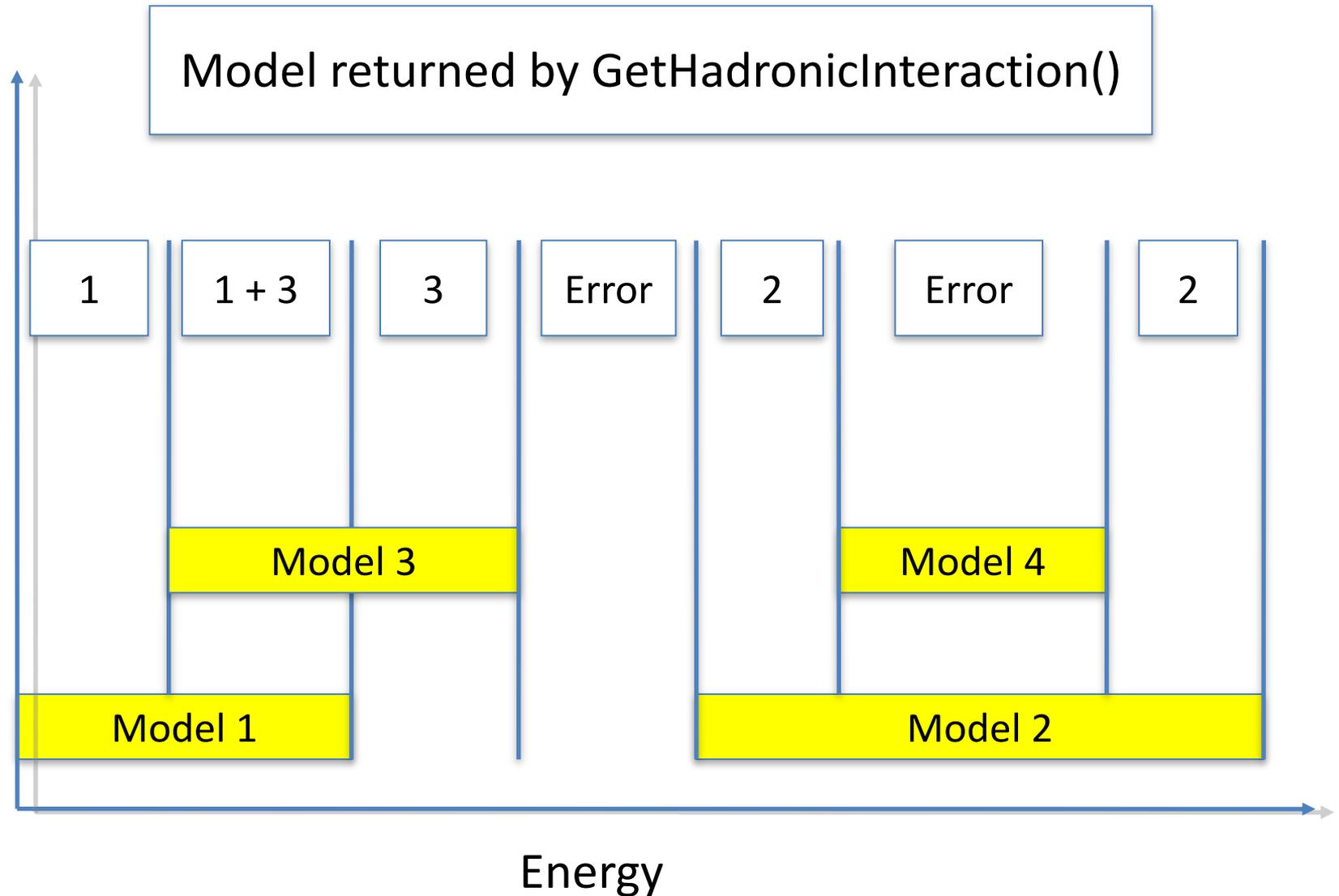# Cross Section Management
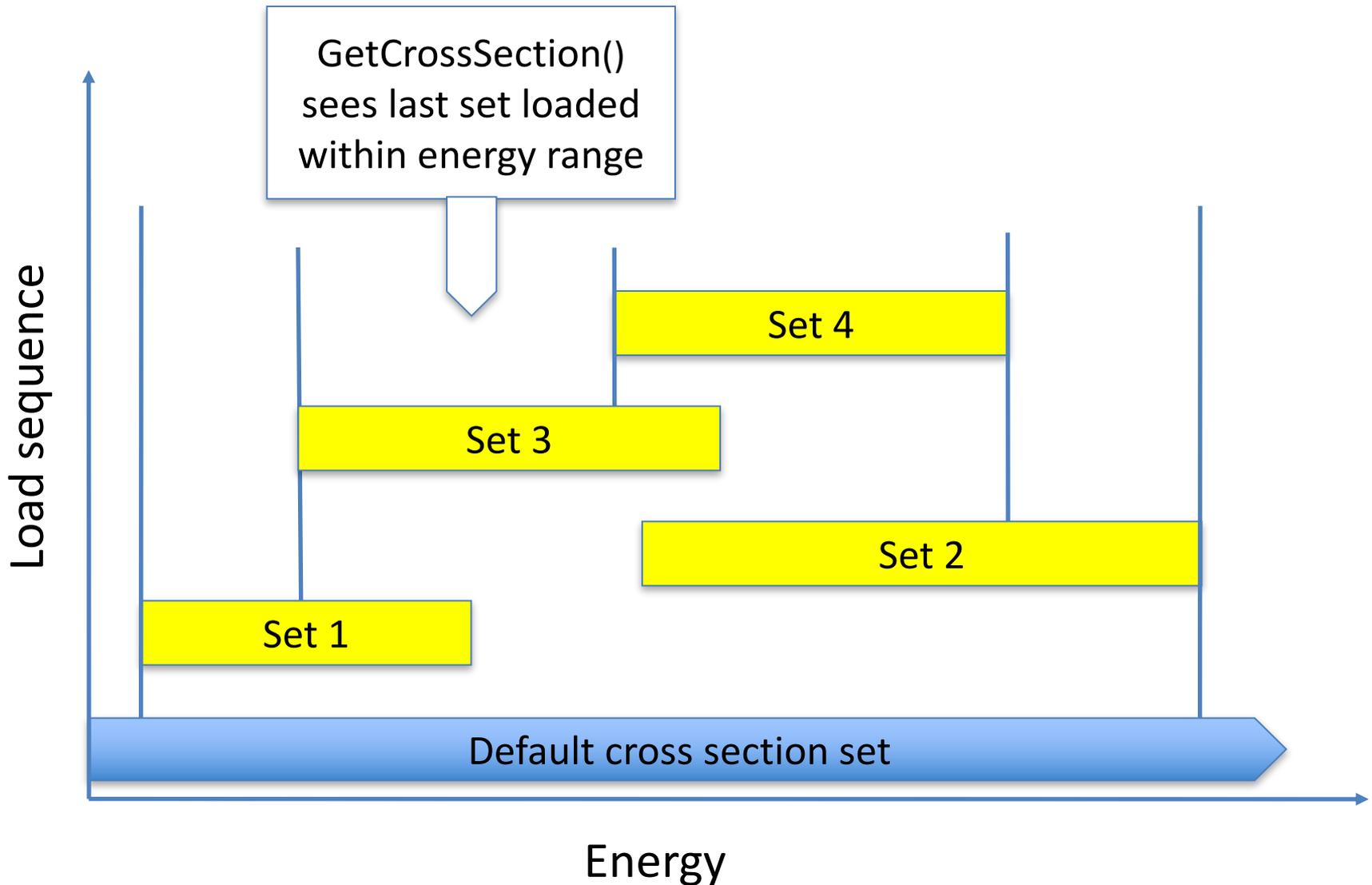
Data-driven Hadronic Models

- 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)
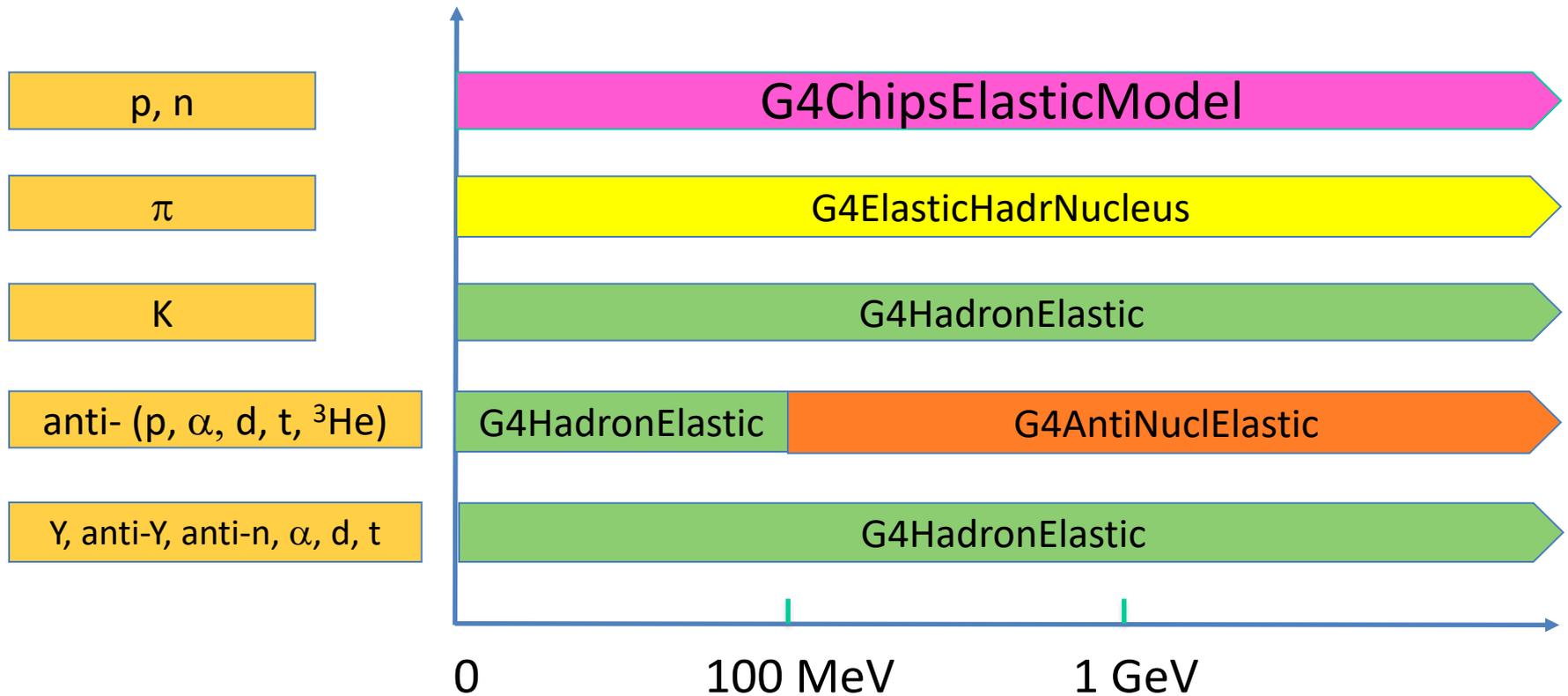 - nuclear de-excitation and break-up

Model Management

Model returned by GetHadronicInteraction()

| 1 | 1 + 3 | 3 | Error | 2 | Error | 2 |

Model 3

Model 4

Model 1

Model 2

Energy

Hadron Elastic Scattering

- G4HadronElasticProcess: general elastic scattering
  - valid for all energies, all projectiles
  - includes p, n, π , K, hyperons, anti-nucleons, anti-hyperons, …
  - uses proton cut values (scaled by Z) for recoil nucleus generation

- Implemented by
  - elastic cross section data sets
  - elastic models

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# Hadron Elastic Cross Sections

- G4HadronElasticDataSet (from Geant4/Gheisha)

- G4ComponentAntiNuclNuclearXS

  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach

- G4BGGPionElasticXS

  - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above

- G4ChipsNeutron(Proton)ElasticXS

  - elastic cross sections extracted from CHIPS framework

Hadronic Models Implementing G4HadronElasticProcess

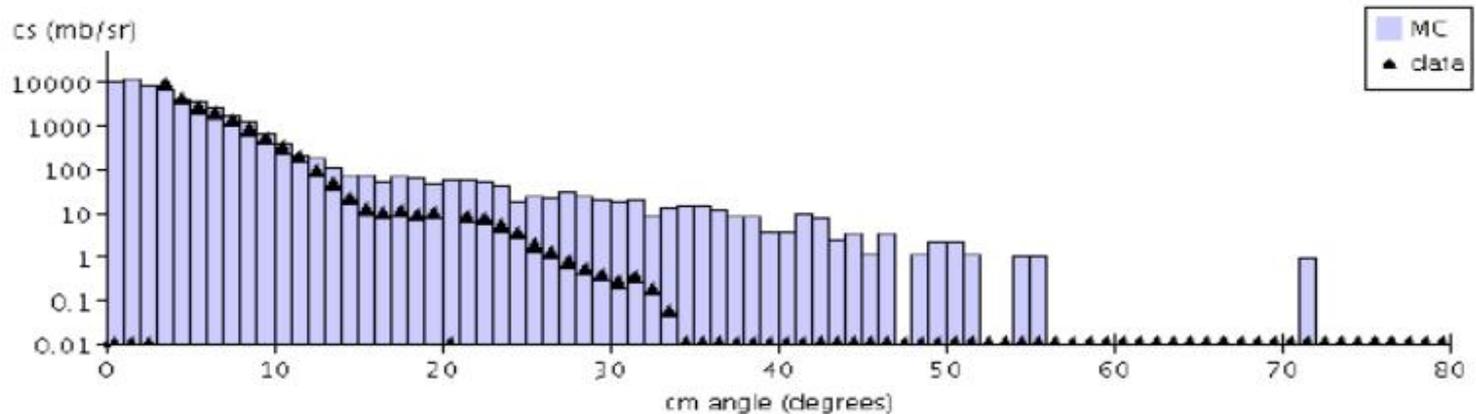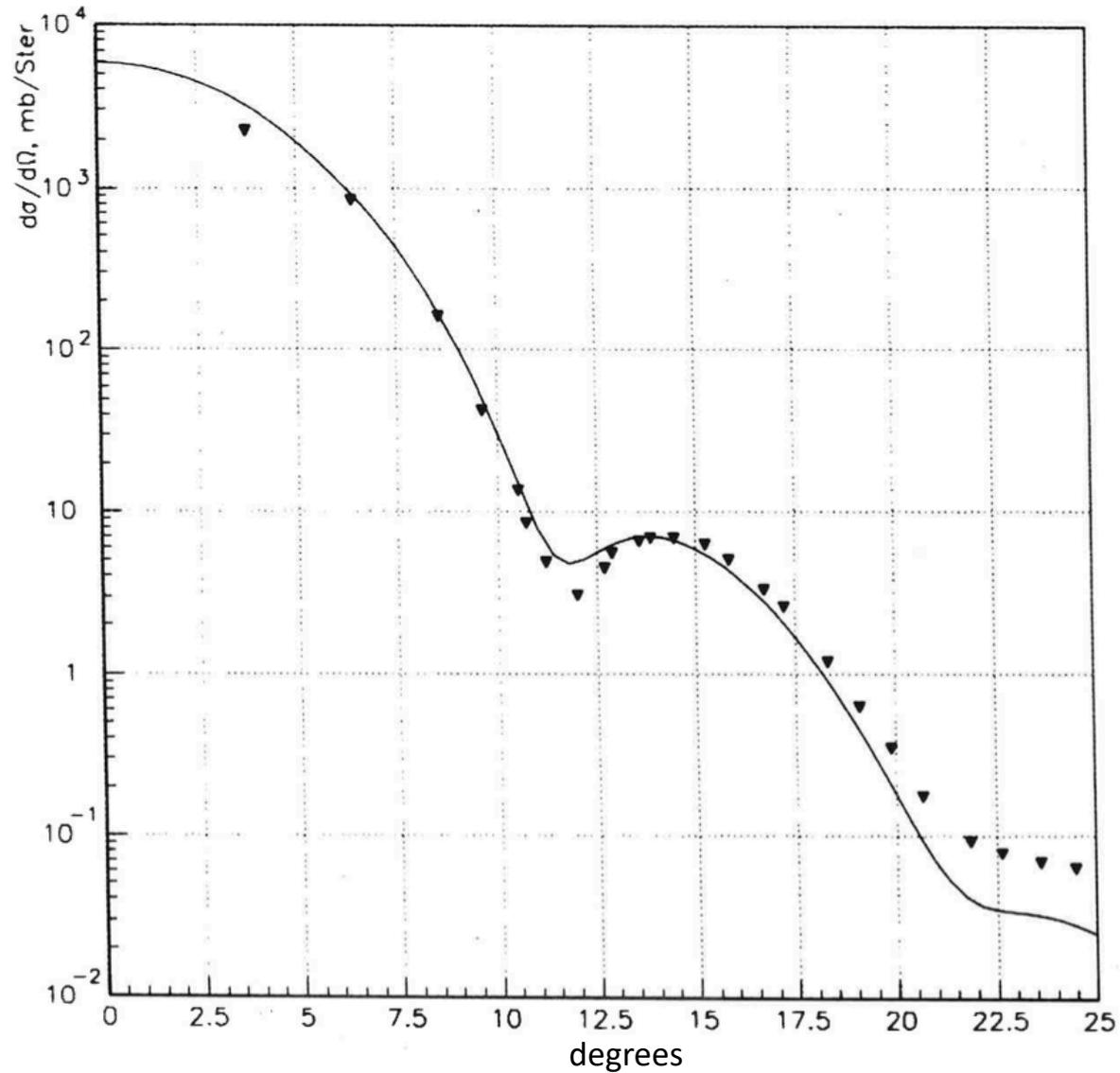|	0	100 MeV	1 GeV
p, n	G4ChipsElasticModel		
π	G4ElasticHadrNucleus		
K	G4HadronElastic		
anti- (p, α, d, t, ³He)	G4HadronElastic	G4AntiNuclElastic	
Y, anti-Y, anti-n, α, d, t	G4HadronElastic		

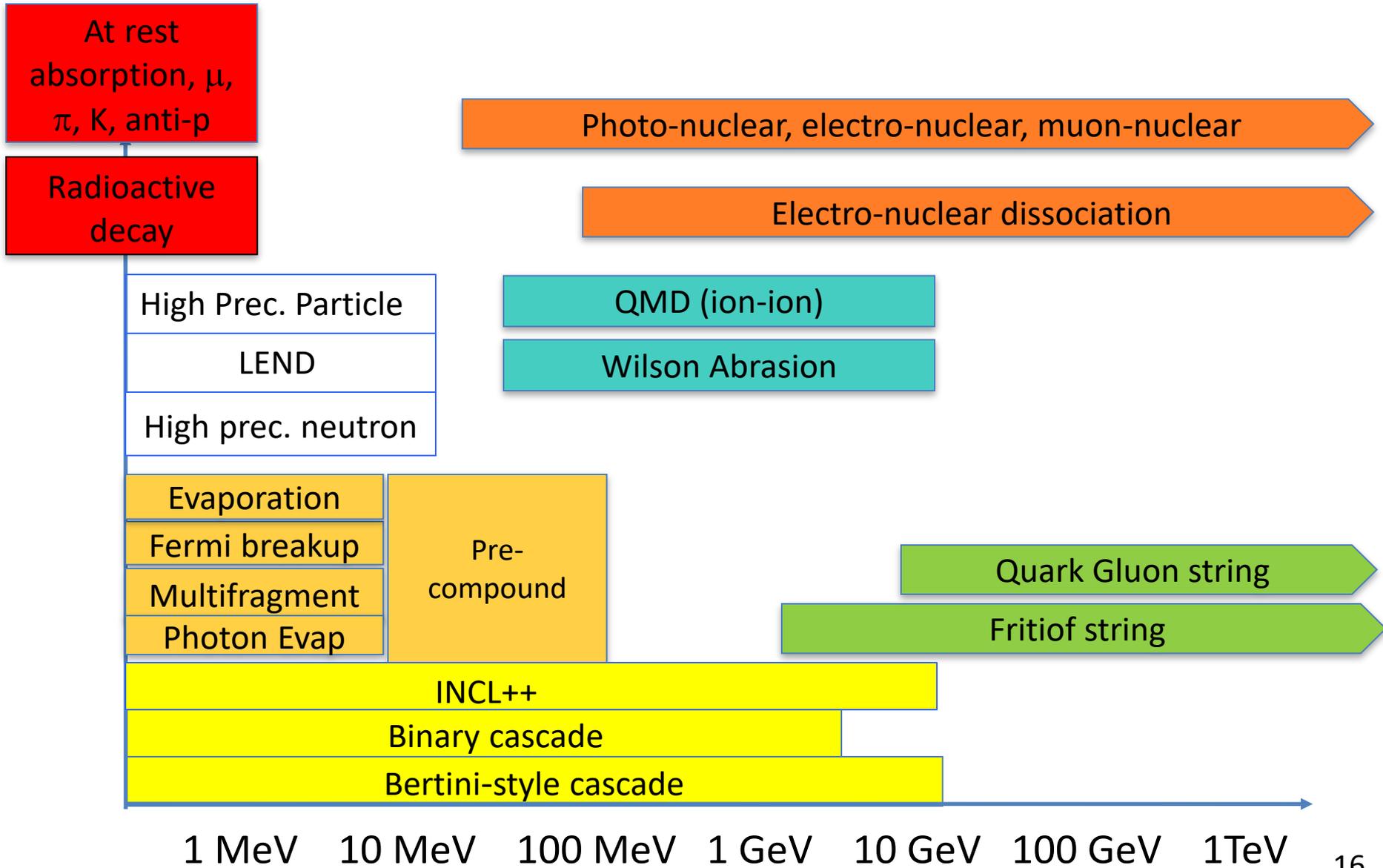# Elastic Scattering Validation (G4HadronElastic)

Elastic K+ scattering from C at 800 MeV/c
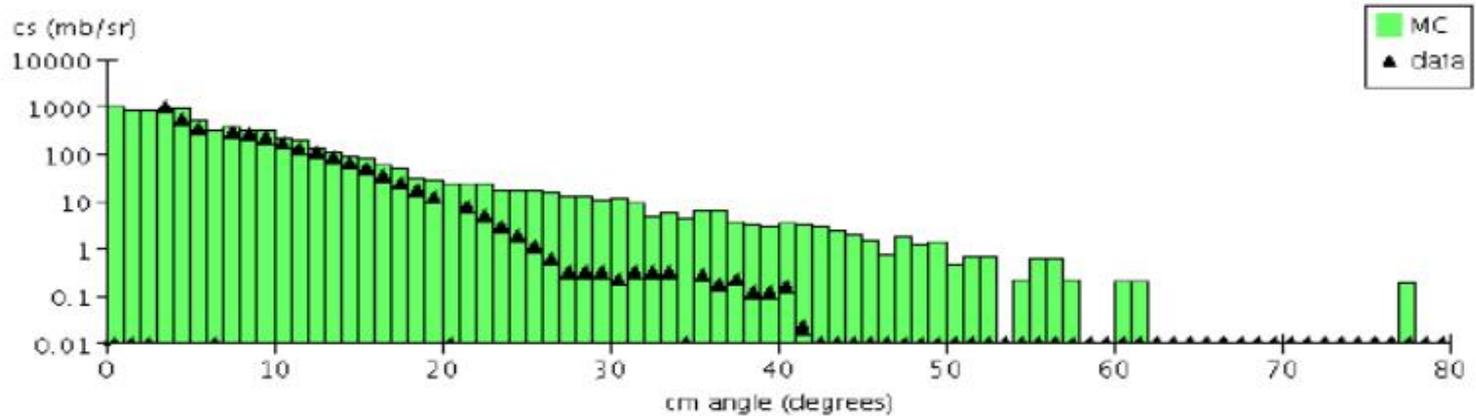
Elastic K+ scattering from Ca at 800 MeV/c

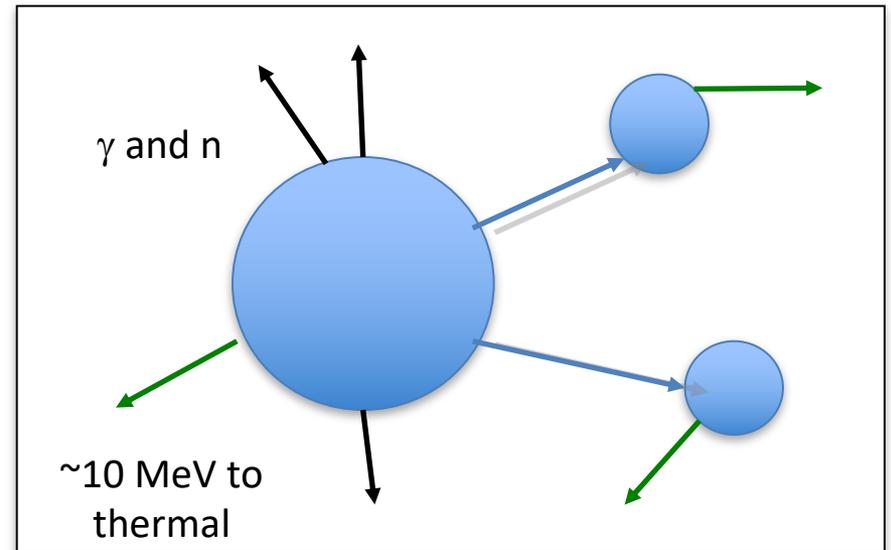# G4ElasticHadrNucleus (1 GeV π^+ on C)

Partial Inelastic Hadronic Model Inventory

At rest absorption, μ, π, K, anti-p

Radioactive decay

Photo-nuclear, electro-nuclear, muon-nuclear

Electro-nuclear dissociation

High Prec. Particle

LEND

High prec. neutron

QMD (ion-ion)

Wilson Abrasion

Evaporation

Fermi breakup

Multifragment

Photon Evap

Pre-compound

Quark Gluon string

Fritiof string

INCL++

Binary cascade

Bertini-style cascade

1 MeV   10 MeV   100 MeV   1 GeV   10 GeV   100 GeV   1TeV

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Hadronic Interactions from TeV to meV

TeV hadron

$dE/dx \sim A^{1/3}$ GeV

~GeV to ~100 MeV

p, n, d, t, α

~100 MeV to ~10 MeV

γ and n

~10 MeV to thermal

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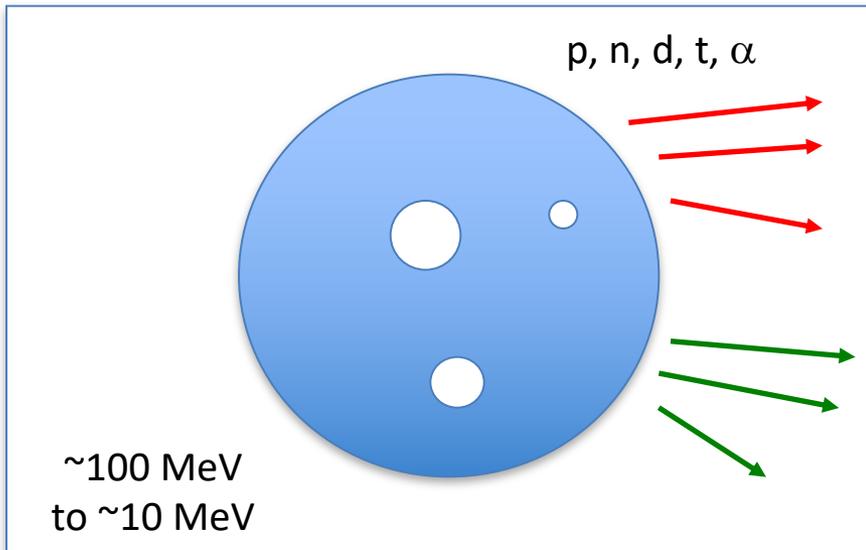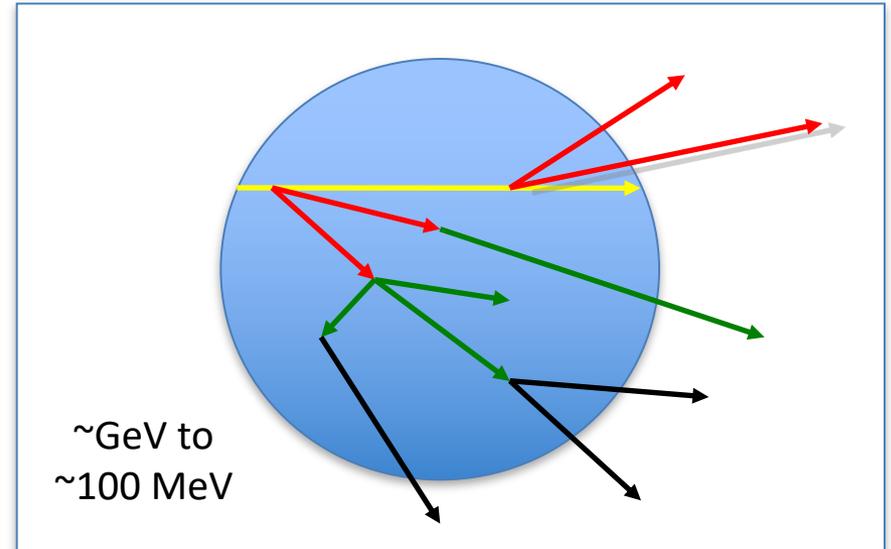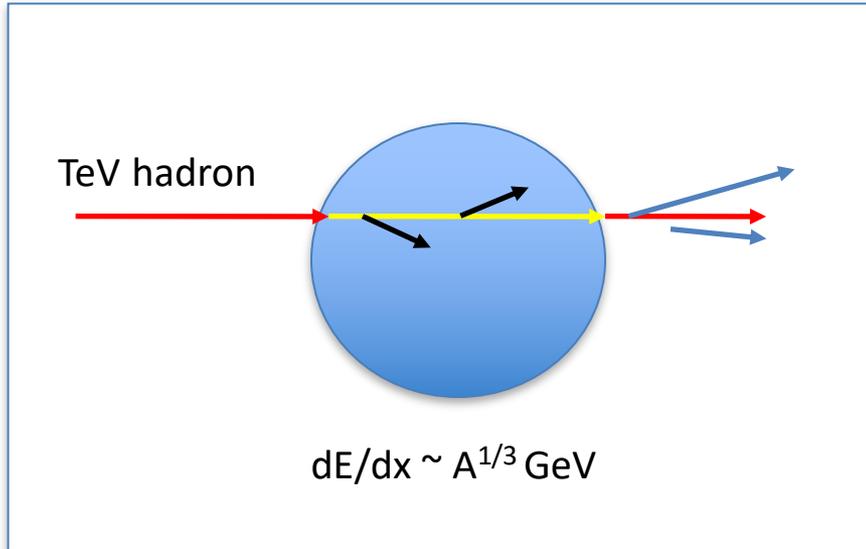
Precompound Models

- 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

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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

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Bertini Cascade (0 < E < 10 GeV)

1 to 3 uniform density shells

p, n, d, t, α

γ and n
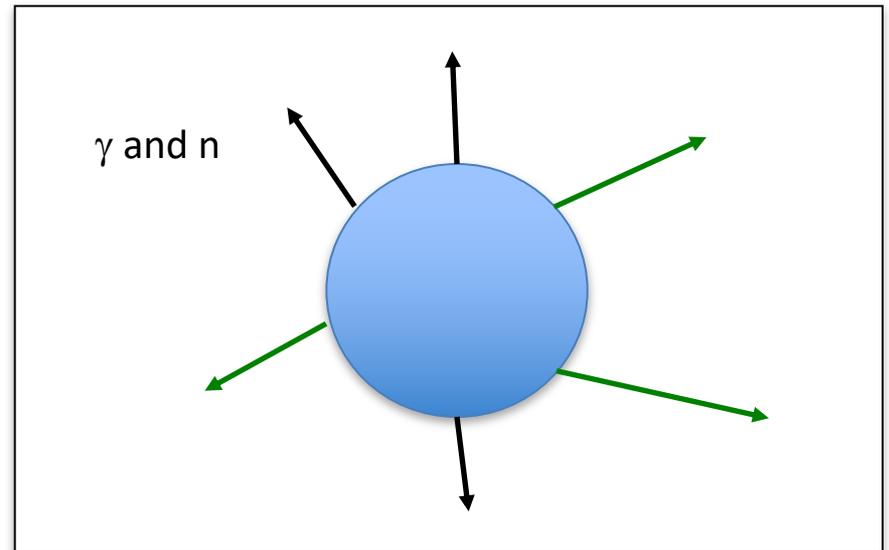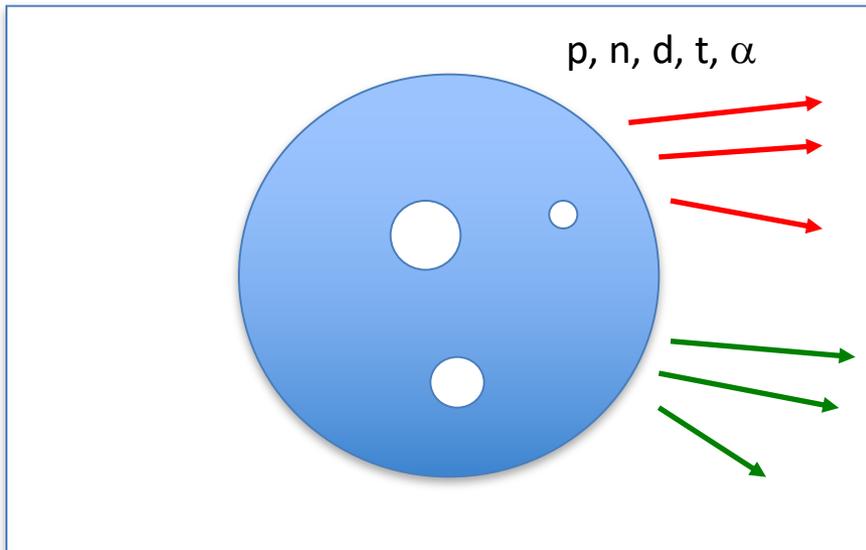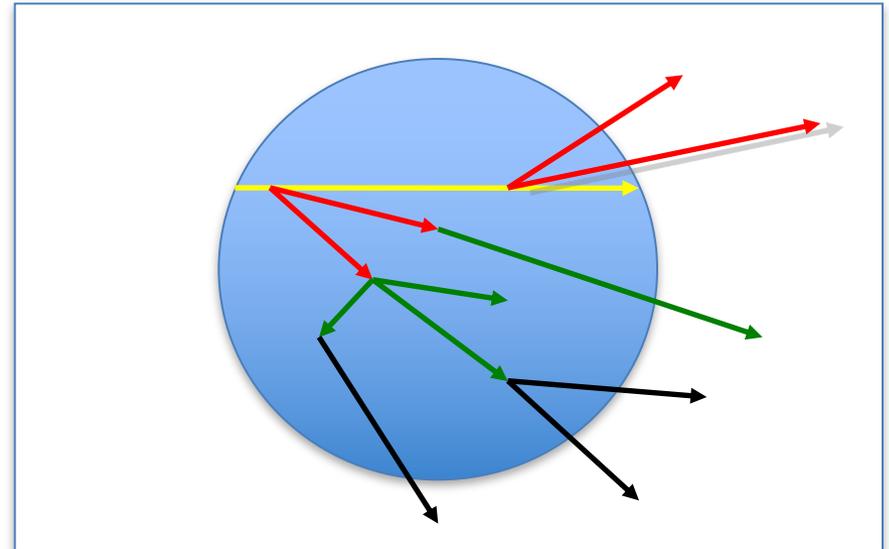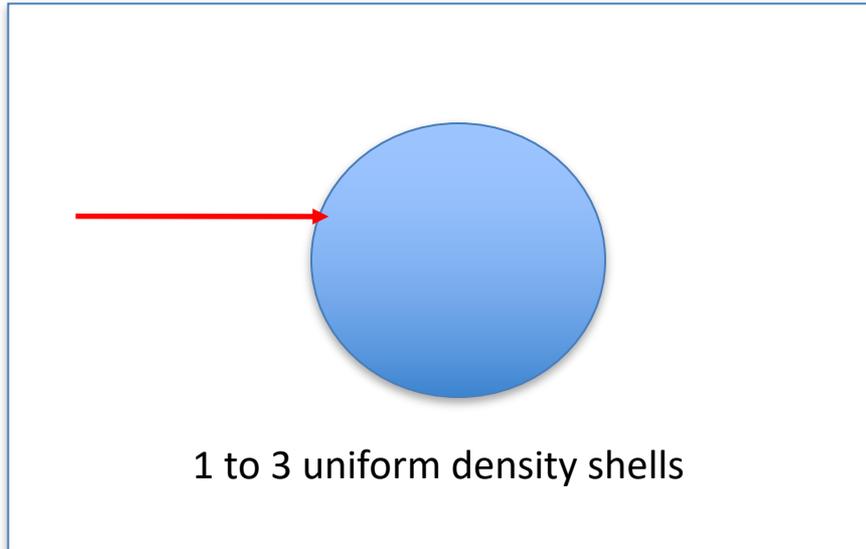
Using the Bertini Cascade

- 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
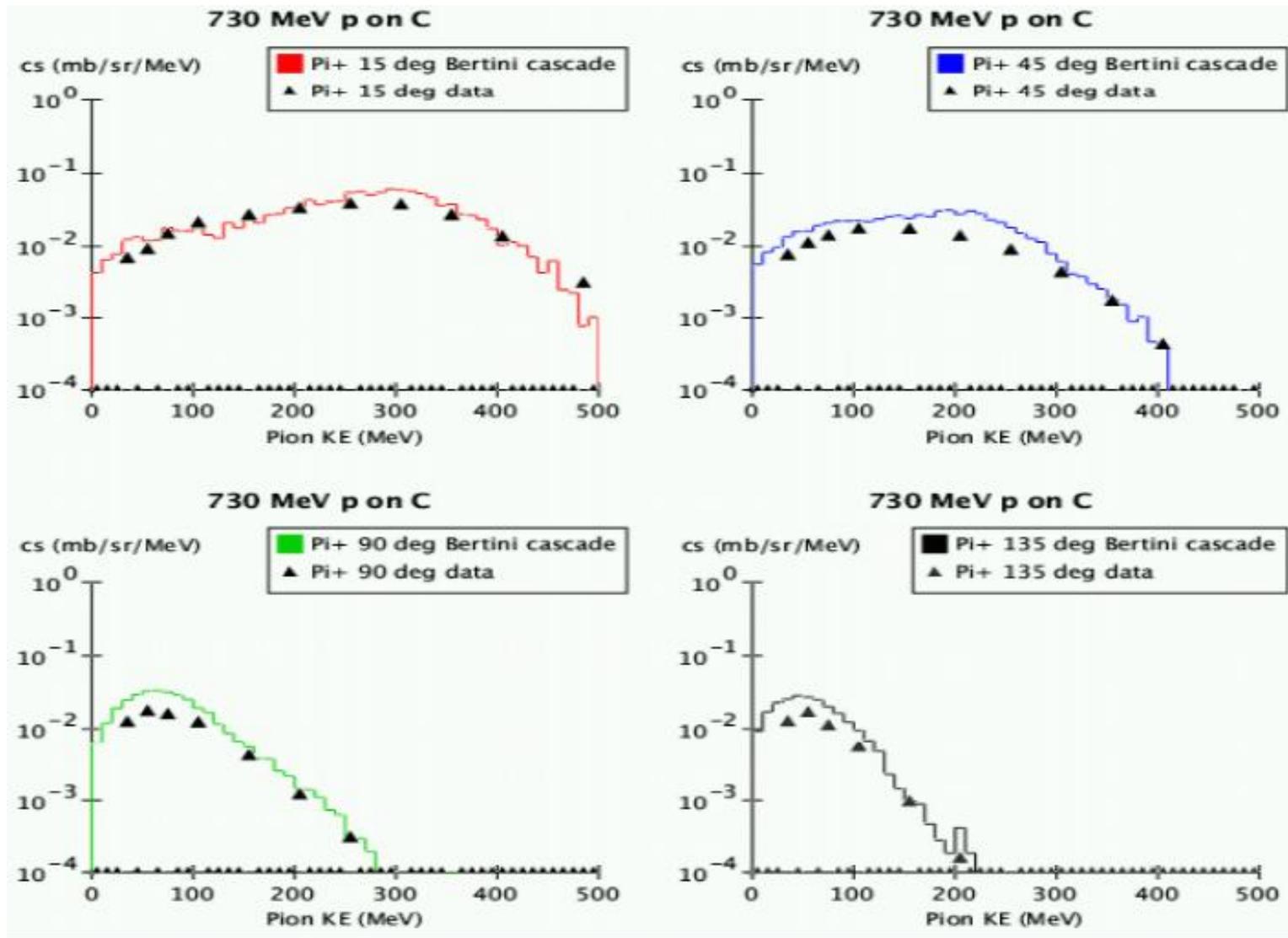
G4CascadeInterface* bert = new G4CascadeInterface;

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)
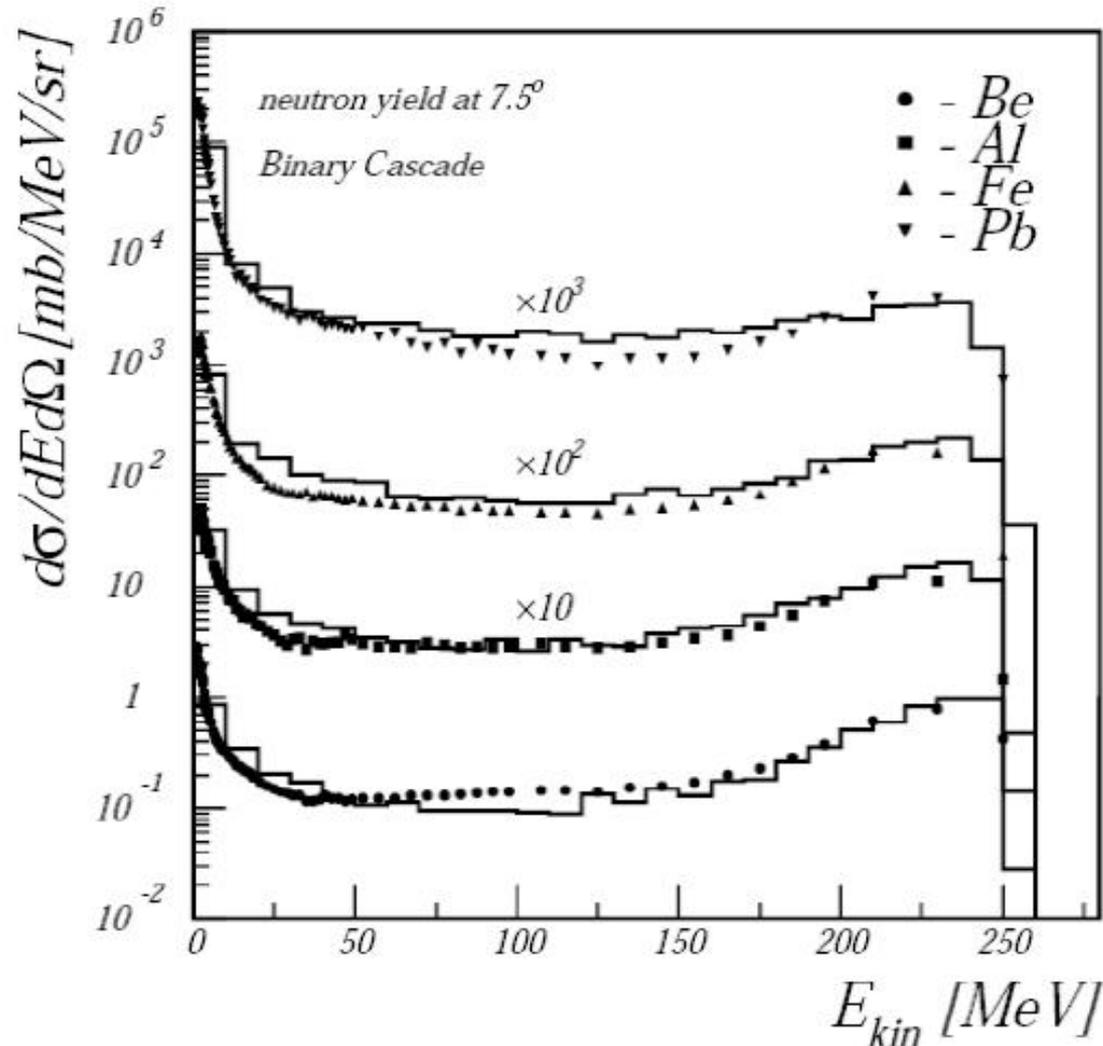
Using the Binary Cascade

- 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, ^{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
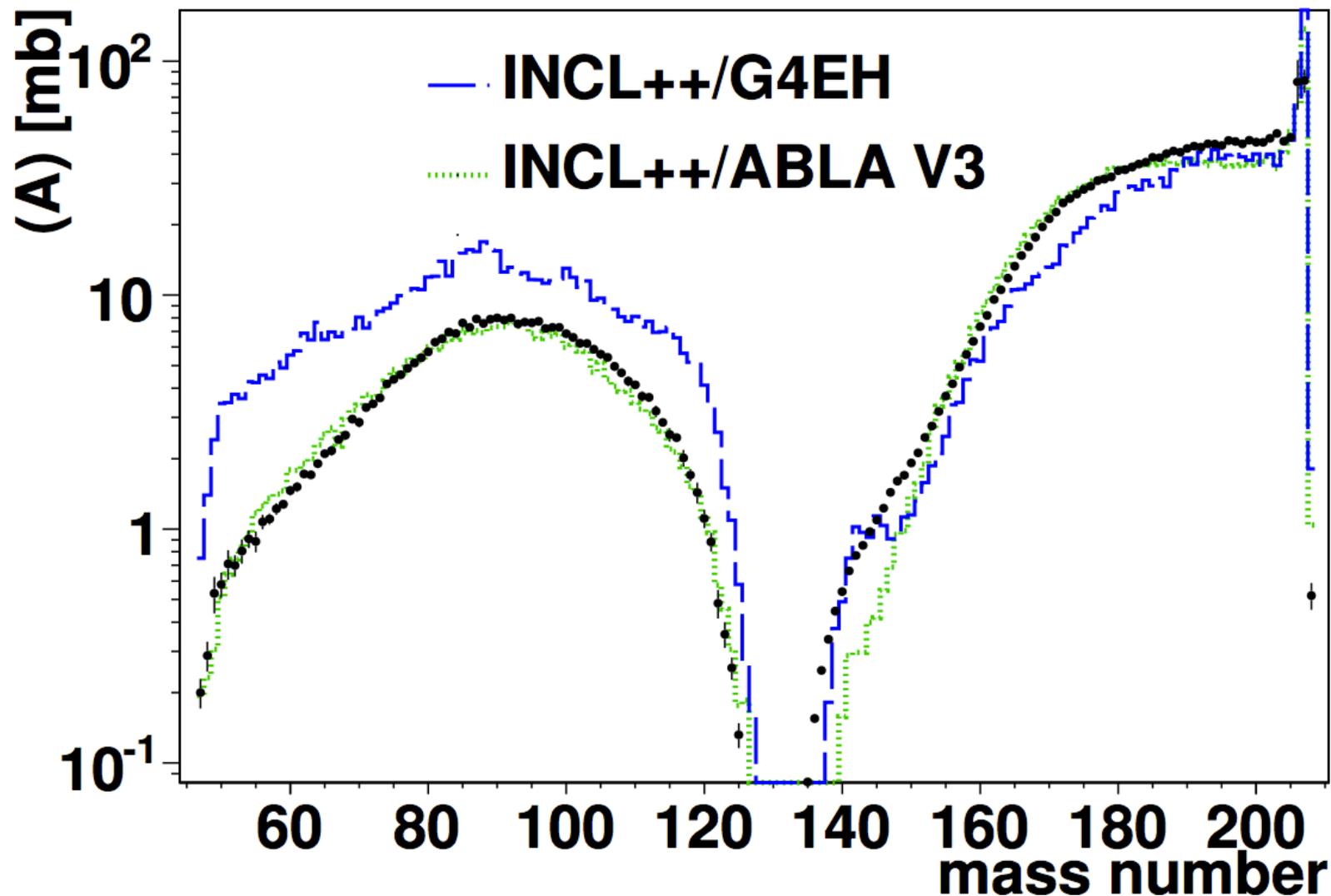
Summary (1)

- 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

- Hadron elastic scattering has only one process for all hadrons at all energies
  - however, several different models implement it

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Summary (2)

- 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 cascade

  - INCL++