Hadronic Physics

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Slides courtesy of SLAC GEANT4 Team

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Outline

- Overview of hadronic physics
  - processes, cross sections, models
  - hadronic framework and organization
- The cascade models
  - Bertini, binary
- Parameterized models
  - high energy, low energy

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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
- In Geant4 hadronic physics there are sometimes many models for a given process
  - user must choose
  - can have more than one per process
- A process must also have cross sections assigned
  - here too, there are options

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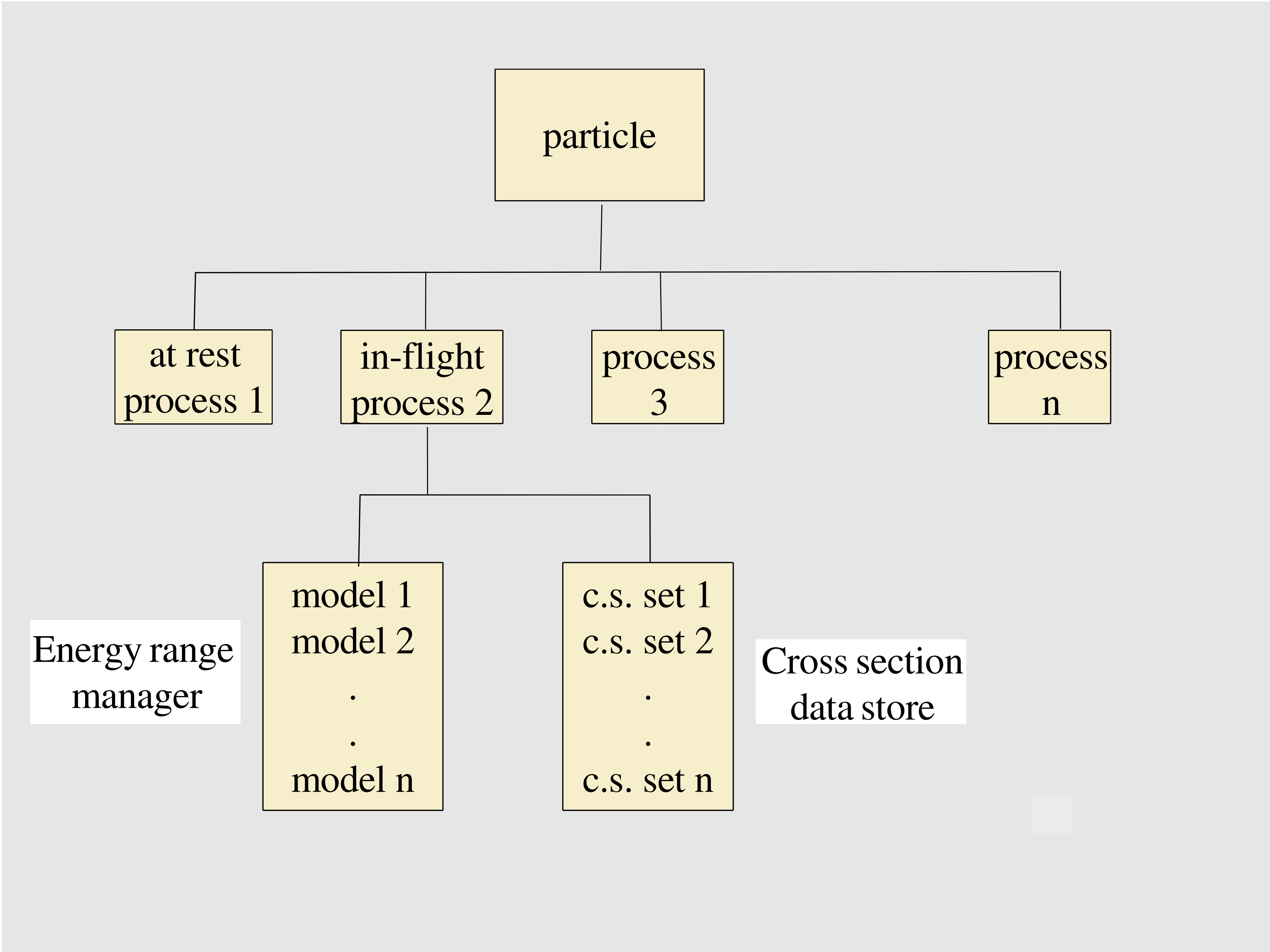

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Cross Sections

- 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 c.s.
  - some represent large databases
  - some are purely theoretical

Alternative Cross Sections

- Low energy neutrons
  - G4NDL available as Geant4 distribution data files
  - Available with or without thermal cross sections
- "High energy" neutron and proton reaction σ
  - 14 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections
  - Good for E/A < 10 GeV
- Pion reaction cross sections

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Hadronic Models – Data Driven

- Characterized by lots of data
  - cross section
  - angular distribution
  - multiplicity
  - etc.
- To get interaction length and final state, models interpolate data
  - cross section, coef of Legendre polynomials
- Examples
  - neutrons (E < 20 MeV)
  - coherent elastic scattering (pp, np, nn)
  - Radioactive decay

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Hadronic Models – Theory Driven

- Dominated by theory (quark-gluon strings, chiral perturbation theory, ...)
  - not as much data to tie things down
- Final states determined by sampling theoretical distributions
- Examples:
  - quark-gluon string (projectiles with E > 20 GeV)
  - intra-nuclear cascade (intermediate energies)
  - nuclear de-excitation and breakup
  - chiral invariant phase space (up to a few GeV)

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Hadronic Models - Parameterized

- Depend mostly on fits to data and some theoretical distributions
- Two models available:
  - Low Energy Parameterized (LEP) for < 20 GeV
  - High Energy Parameterized (HEP) for > 20 GeV
  - Each type refers to a collection of models
- Both derived from GHEISHA model used in Geant3
- Core code:
  - hadron fragmentation
  - cluster formation and fragmentation
  - nuclear de-excitation

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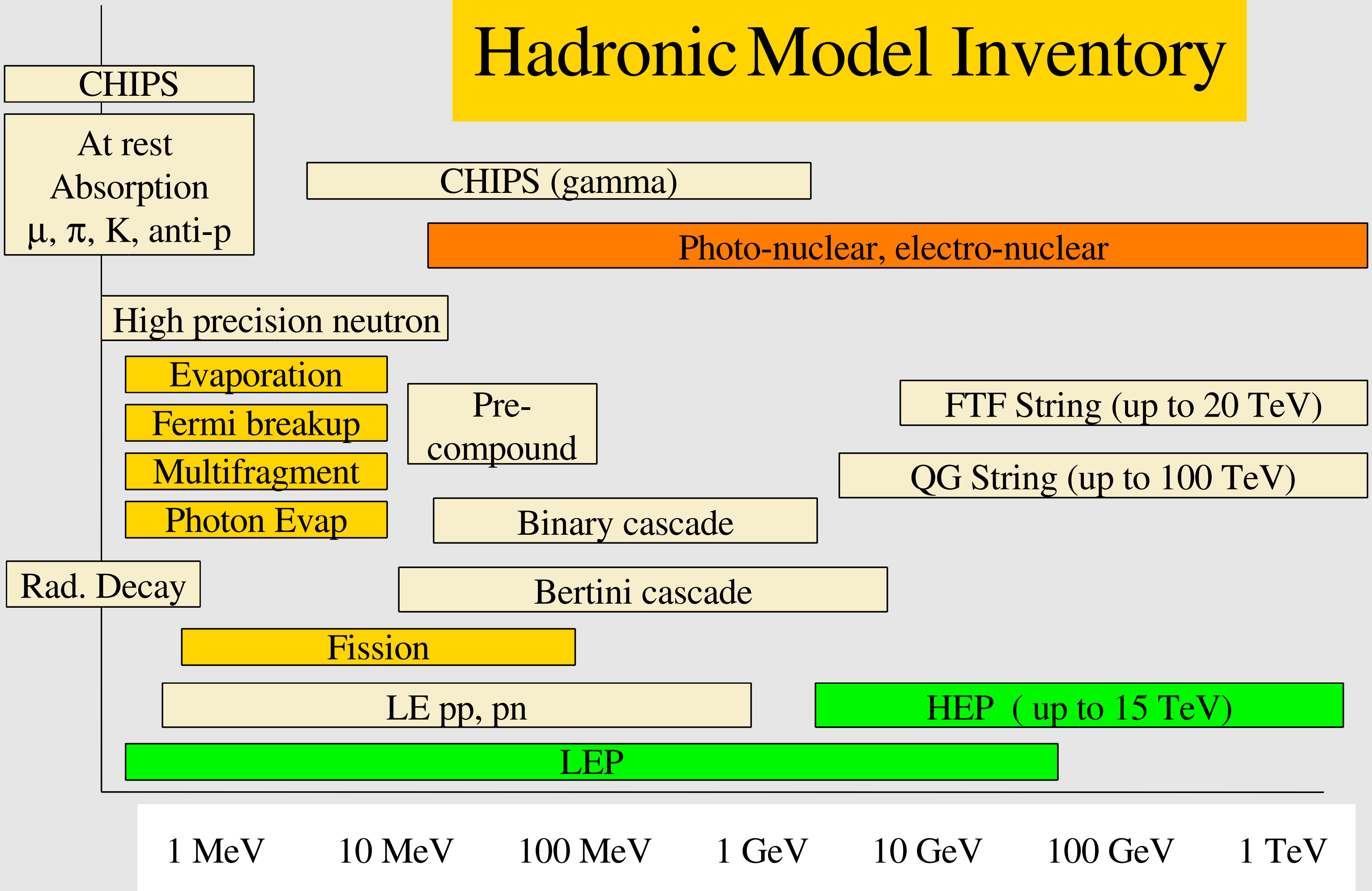
Hadronic Model Inventory



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Using the LEP and HEP models

- The LEP and HEP models are valid for p, n, π, K, Λ, Σ, Ξ, Ω, α, t, d
  - LEP valid for incident energies of 0 – ~30 GeV
  - HEP valid for incident energies of ~10 GeV – 15 TeV
- Invocation sequence
  -
```
G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess();
G4LEProtonInelastic* LEproton = new G4LEProtonInelastic();
pproc -> RegisterMe(LEproton);
G4HEProtonInelastic* HEproton = new G4HEProtonInelastic();
HEproton -> SetMinEnergy(20*GeV);
pproc -> RegisterMe(HEproton);
proton_manager -> AddDiscreteProcess(pproc);
```

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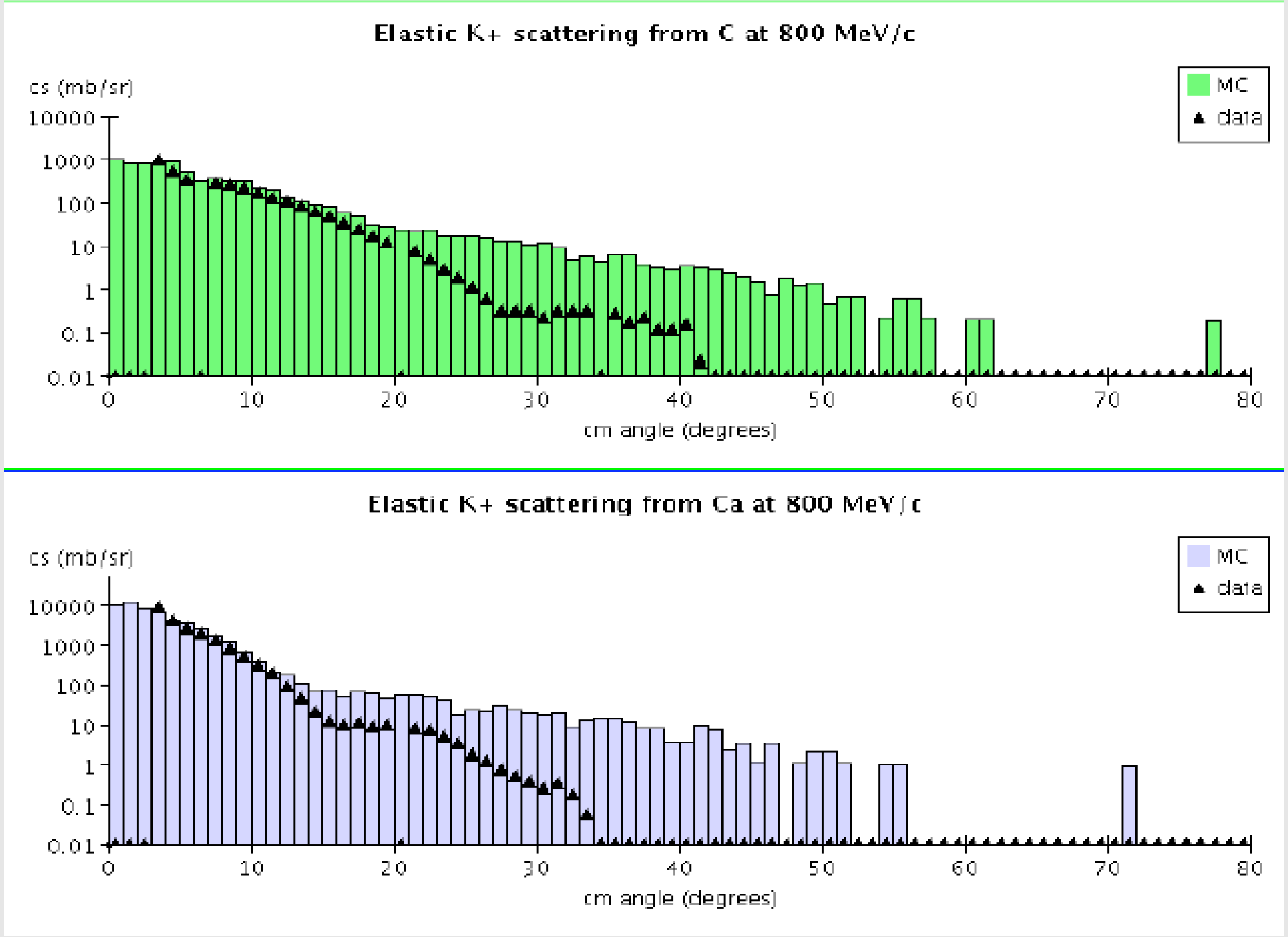
Validation of LEP, HEP Models



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Using the Bertini Cascade

- In Geant4 the Bertini model is currently used for p, n, π, K^+, K^-, K^0_L, K^0_S, Λ, Σ^+, Σ^-, Ξ^-, Ξ^0, Ω^-
  - valid for incident energies of 0 – 10 GeV
  - may be extended to 15 GeV when new validation data are available
  - currently being extended to kaons and hyperons
- Invocation sequence
  - ```
    G4CascadeInterface* bertini = new G4CascadeInterface();
    G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess();
    pproc -> RegisterMe(bertini);
    proton_manager -> AddDiscreteProcess(pproc);
    ```

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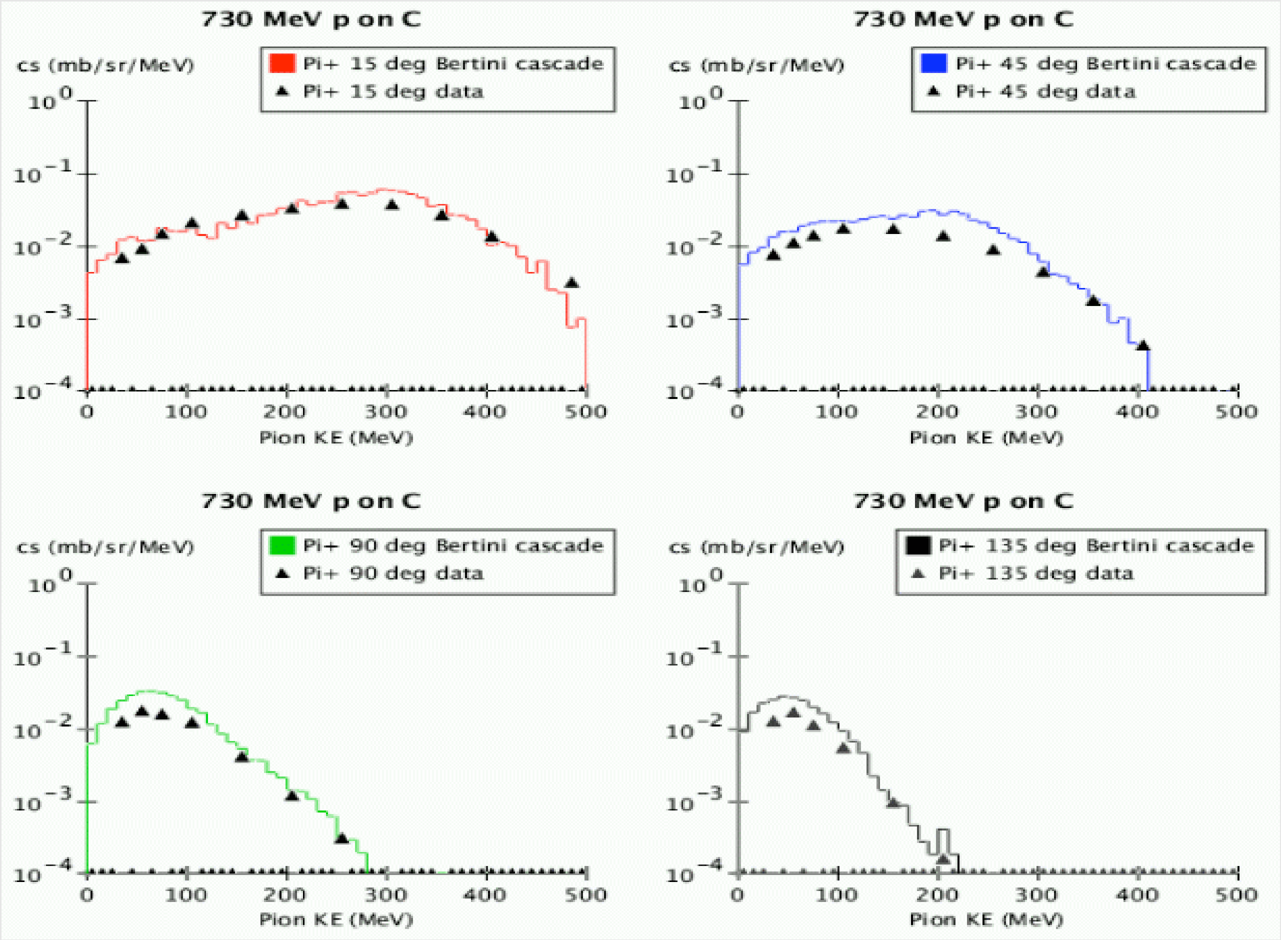
    ```

Validation of the Bertini Cascade



Pion production from 730MeV proton on Carbon

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Binary Cascade

- Modeling sequence similar to Bertini, except that
  - hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
  - particles follow curved trajectories in nuclear potential
- In Geant4 the Binary cascade model 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)

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Using the Binary Cascade

- Invocation sequence Binary cascade
  - G4BinaryCascade* binary = new G4BinaryCascade();
    G4PionPlusInelasticProcess* pproc = new G4PionPlusInelasticProcess();
    pproc -> RegisterMe(binary);
    piplus_manager -> AddDiscreteProcess(pproc);

- Invocation sequence BinaryLightIonReaction
  - G4BinaryLightIonReaction* ionBinary = new G4BinaryLightIonReaction;
    G4IonInelasticProcess* ionProc = new G4IonInelasticProcess;
    ionProc->RegisterMe(ionBinary);
    genericIonManager->AddDiscreteProcess(ionProc);

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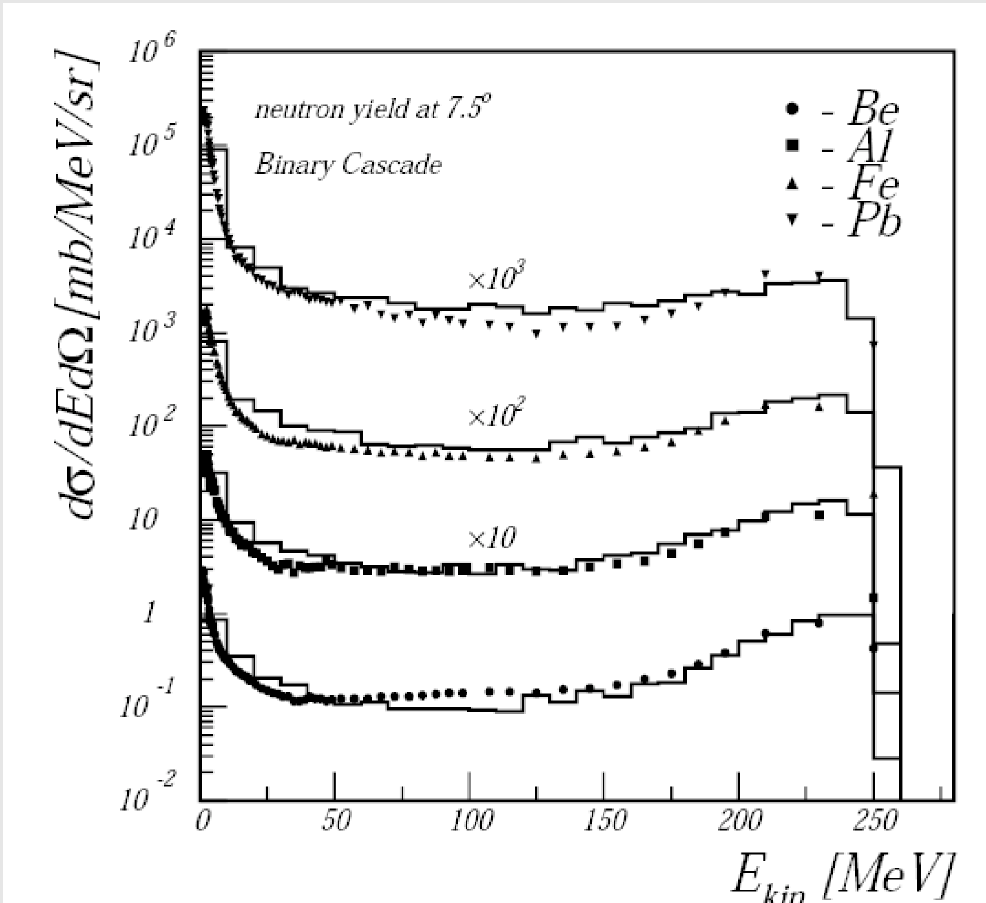
Validation of the Binary Cascade
256 MeV protons



Double-differential cross section for neutrons produced by 256 MeV protons

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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

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Summary (2)

- Parameterized models (LEP, HEP) handle the most particle types over the largest energy range
  - based on fits to data and some theory
  - not very detailed
  - fast
- Cascade models (Bertini, Binary) are valid for fewer particles over a smaller energy range
  - more theory-based
  - more detailed
  - slower

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Next ...

Overview

- Low Energy Neutron Physics
  - High Precision Neutron Models
- Ion Physics
  - Inelastic
  - Radio Active Decay

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Low energy (< 20MeV) neutrons physics

- High Precision Neutron Models (and Cross Section Data Sets)
  - G4NDL
    - ENDF
  - Elastic
  - Inelastic
  - Capture
  - Fission
- NeutronHPorLEModel(s)

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G4NDL
(Geant4 Neutron Data Library)

- The neutron data files for High Precision Neutron models
- The data are including both cross sections and final states.
- The data are derived evaluations based on the following evaluated data libraries (in alphabetic order)
  - Brond-2.1
  - CENDL2.2
  - EFF-3
  - ENDF/B-VI.0, 1, 4
  - FENDL/E2.0
  - JEF2.2
  - JENDL-FF
  - JENDL-3.1,2
  - MENDL-2
- The data format is similar ENDF, however it is not equal to.

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Cross Sections

- Many cross section formulae for NN collisions are included in Geant4
  - Tripathi, Shen, Kox and Sihver
- These are empirical and parameterized formulae with theoretical insights.
- G4GeneralSpaceNNCrossSection was prepared to assist users in selecting the appropriate cross section formula.

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References to NN Cross Section Formulae implemented in Geant4

- Tripathi Formula
  - NASA Technical Paper TP-3621 (1997)
- Tripathi Light System
  - NASA Technical Paper TP-209726 (1999)
- Kox Formula
  - Phys. Rev. C 35 1678 (1987)
- Shen Formula
  - Nuclear Physics. A 49 1130 (1989)
- Sihver Formula
  - Phys. Rev. C 47 1225 (1993)

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Ion Physics
Radio Active Decay

- To simulate the decay of radioactive nuclei
- Empirical and data-driven model
- α, β^+, β^- decay electron capture (EC) are implemented
- Data (RadioactiveDecay) derived from Evaluated Nuclear Structure Data File (ENSDF)
  - nuclear half-lives
  - nuclear level structure for the parent or daughter nuclide
  - decay branching ratios
  - the energy of the decay process.
- If the daughter of a nuclear decay is an excited isomer, its prompt nuclear de-excitation is treated using the G4PhotonEvapolation

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