Geant4 11.2.p01

Hadronic Physics II

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Outline

- Elastic processes and models
- Low energy neutron and proton physics
- Ion-ion physics
- Capture, stopping and fission reactions

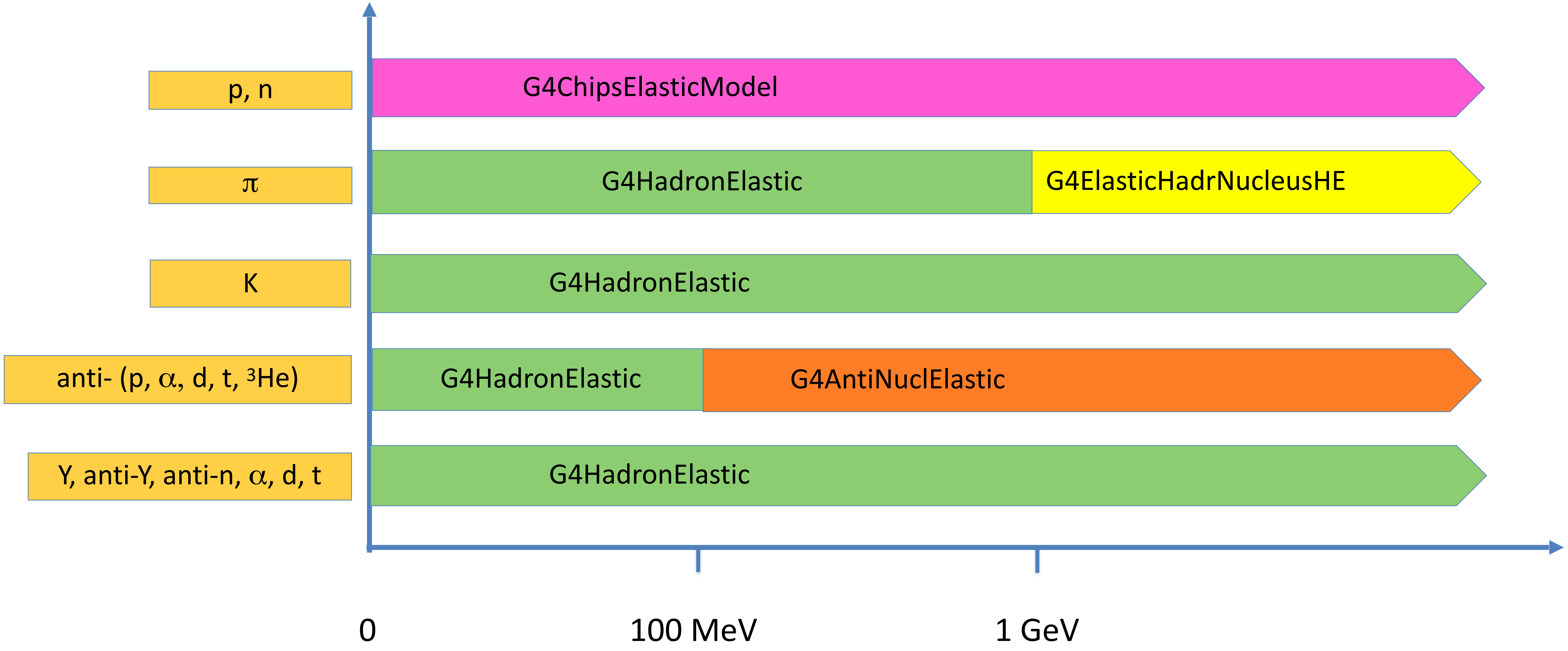
Hadron Elastic Scattering

- 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

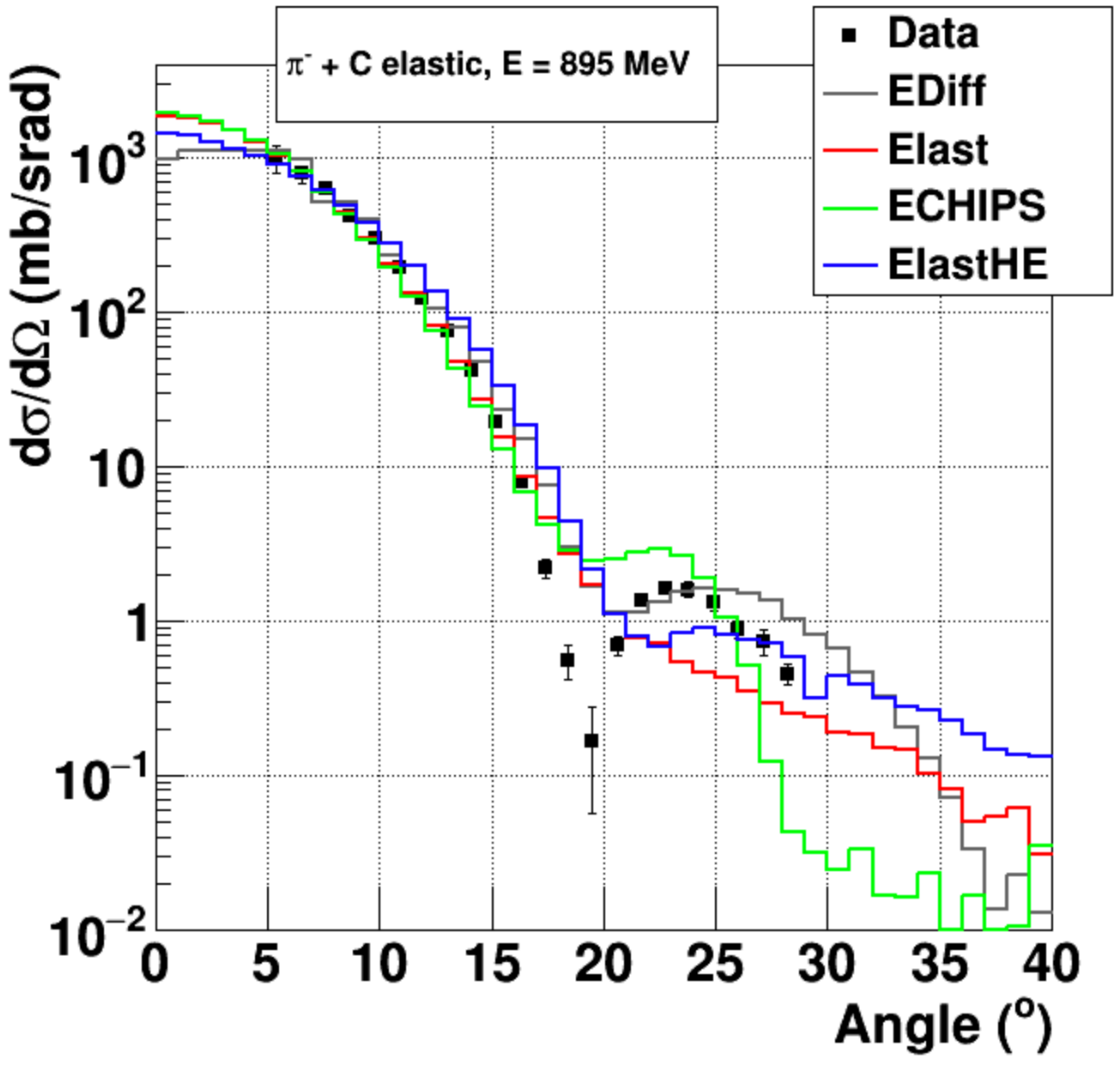
Hadron Elastic Cross Sections

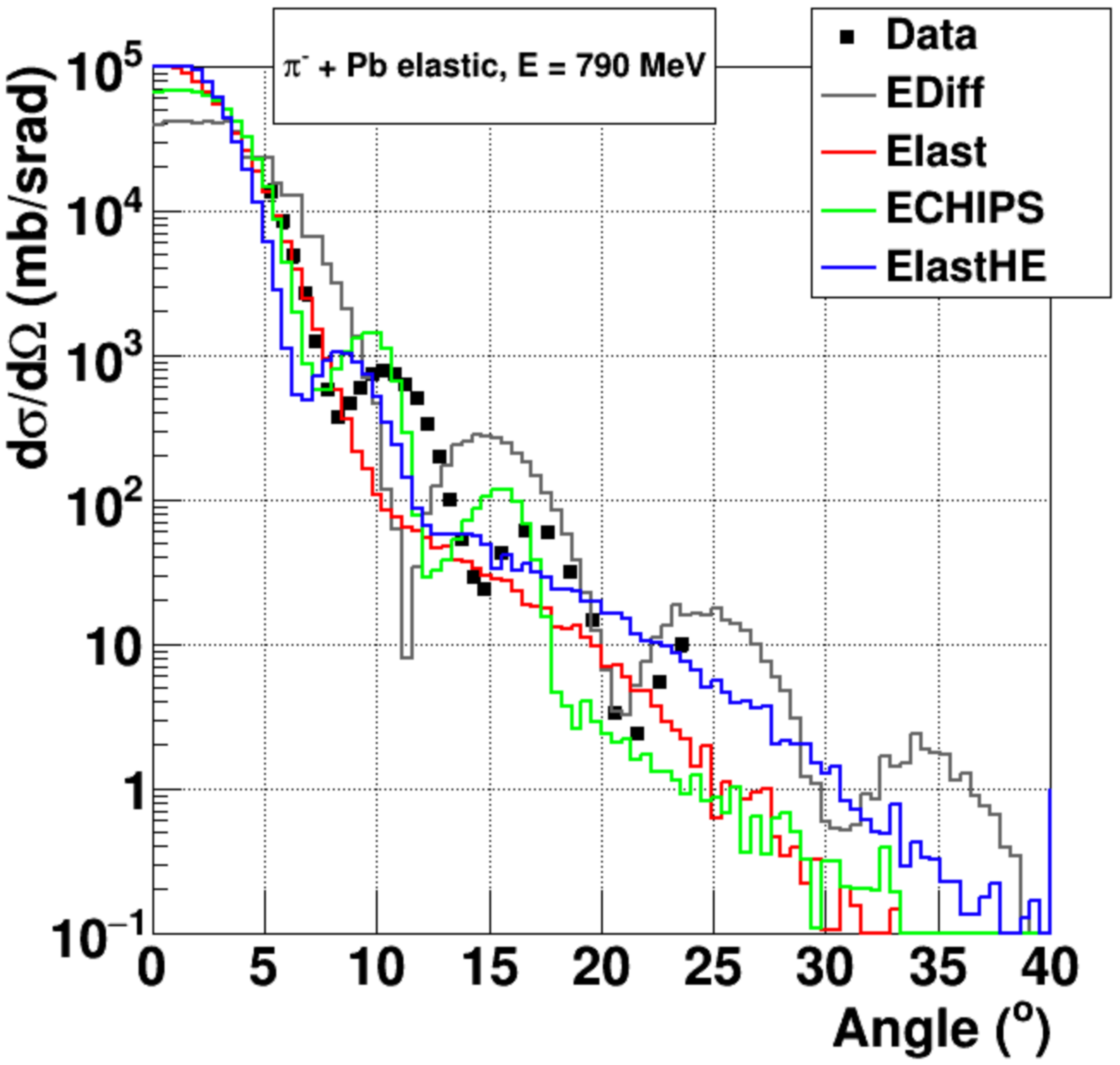
- G4BGGNucleonElasticXS (BGG = Barashenkov-Glauber-Gribov)
  - protons
- G4NeutronElasticXS
  - neutrons
- G4BGGPionElasticXS
  - BGG elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above
- G4ComponentGGNuclNuclXsc
  - kaons, hyperons, anti-hyperons and light ions
- G4ComponentAntiNuclNuclearXS
  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach
- No elastic cross sections available for A > 4

Hadronic Models Implementing G4HadronElasticProcess



Elastic Model Validation





Low Energy Hadron Physics

- Below about 20 MeV incident energy, Geant4 provides several models for treating n, p, d, t, ^{3}He and α interactions in detail

- The high precision models (ParticleHP) are data-driven and depend on a large database of cross sections, etc.
  - the G4NDL database is available for download from the Geant4 web site
  - TENDL optional database is also available
  - elastic, inelastic, capture and fission models all use this isotope-dependent data

- There are also models to handle thermal scattering from chemically bound atoms

High Precision Particle Transport

- ParticleHP models provide elastic, inelastic, capture and fission for incident n, p, d, t, ^{3}He, α below 20 MeV for n
    - from sub-eV to ~20 MeV for neutrons
    - 0 < E < 200 MeV for charged particles
    - depend on large database (JEFF)
    - alternative databases available: TENDL, IAEA medical
- Note: these models and database not originally designed for event-by-event energy conservation
    - much of the data were taken and parameterized in spectrum mode -> energy conserved when averaged over events
    - environment variable added in Geant4 to force event-by-event energy conservation, but this can distort original spectrum

Geant4 Neutron Data Library (G4NDL)

- Contains the data files for the high precision particle models
  - includes both cross sections and final states
  - current version: G4NDL4.7
  - download from Geant4 web page
- Based on JEFF-3.3 since Geant4 10.6
  - JEFF: Joint Evaluated Fission and Fusion Library
  - ENDF/B-VII used from Geant4 9.5 to 10.6
- Data and final states from JEFF converted to G4NDL format
  - using PREPRO-2017 (standard public conversion code from IAEA)
- Other evaluated neutron cross section libraries in G4NDL format available
  - https://www.oecd-nea.org/geant4

G4ParticleHPElastic

- Handles elastic scattering of n, p, d, t, ^{3}He, α by sampling differential cross section data
  - interpolates between points in the cross section tables as a function of energy
  - interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
  - scattered particle and recoil nucleus generated as final state

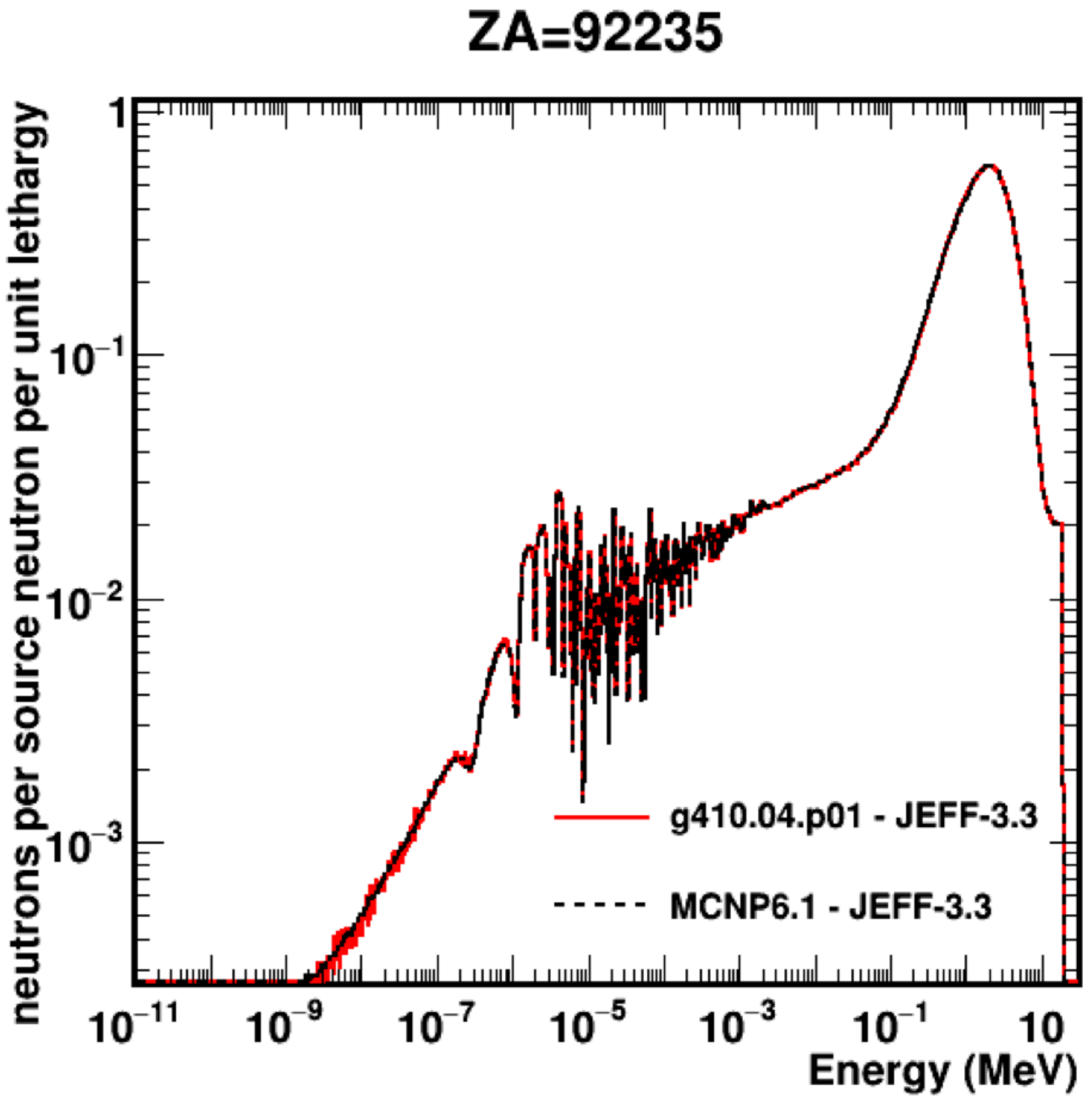
- Note that because look-up tables are based on binned data, there will always be a small energy non-conservation
  - true for HP inelastic, capture and fission processes as well

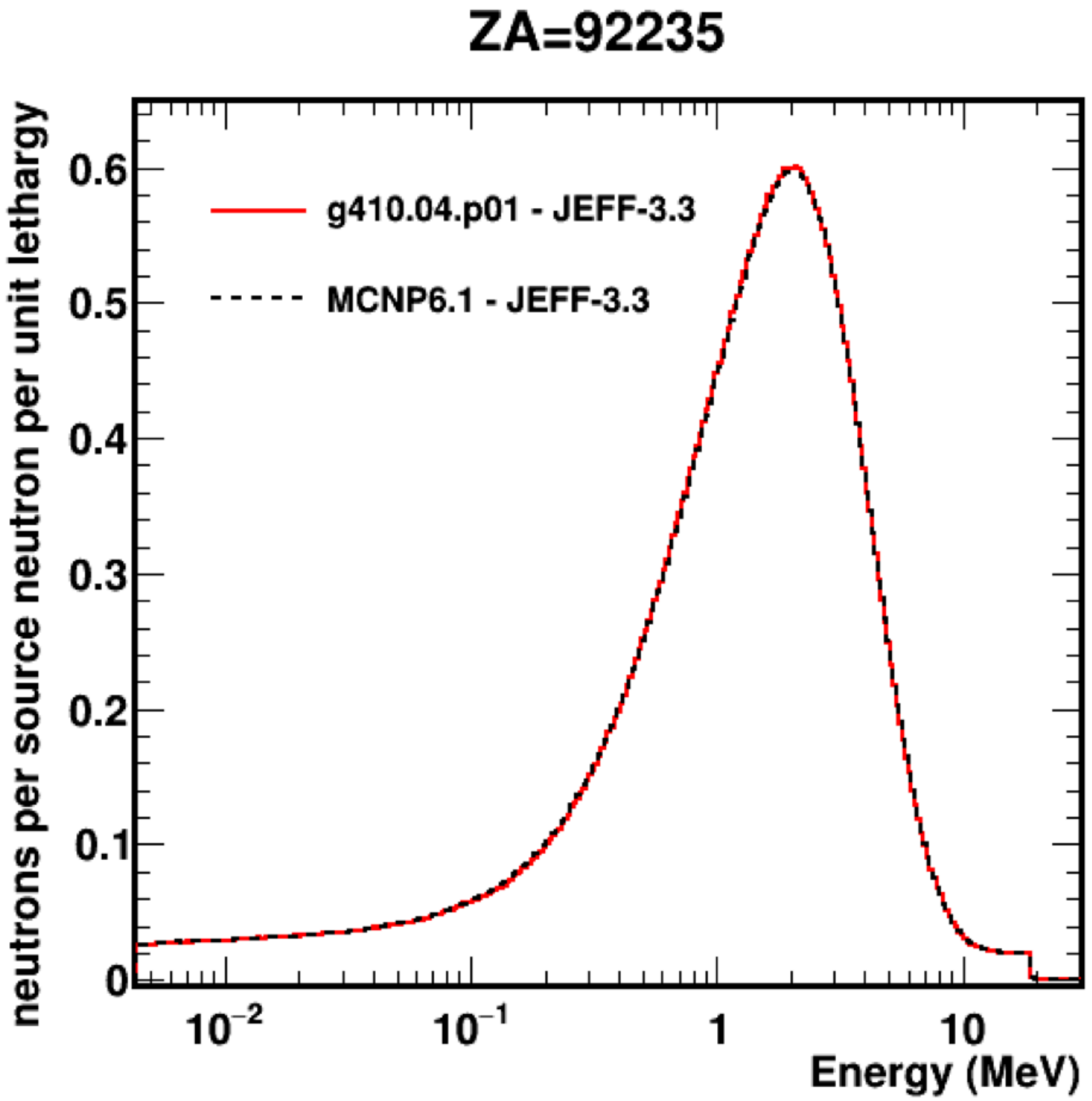
G4ParticleHPInelastic

- Currently supports many inelastic final states (discrete and continuum)
  - n (A,Z) -> (A, Z) n γ
  - n (A,Z) -> (A-1, Z-1) n p
  - n (A,Z) -> (A-3, Z) n n n n
  - n (A,Z) -> (A-4, Z-2) d t
  - …

- Secondary distribution probabilities
  - isotropic emission
  - discrete two-body kinematics
  - N-body phase space
  - continuum energy-angle distributions (in lab and CM)

Secondary Neutrons from (n, ^{235}U) integrated over all angles





Lethargy $u = \ln(\frac{E_0}{E})$

GIDI-LEND

- GIDI+ : collection of packages for reading and sampling GNDS data as needed by transport codes
  - developed by Livermore

- GNDS database
  - data for neutron and gamma reactions
  - modern format, more general and easier to understand than ENDF
  - not yet as extensive, but growing

- LEND : collection of Geant4 models that use GIDI+
  - an alternative to the HP models
  - corresponding model to each one in HP (elastic, inelastic, capture, fission)

- Invocation in physics list:
  - use model names G4LENDElastic, G4LENDInelastic, G4LENDCapture, G4LENDFission, and cross sections G4LENDElasticCrossSection, G4LENDInelasticCrossSection, G4LENDCaptureCrossSection, G4LENDFissionCrossSection

- Note: the above is the new version (ready soon); current version of GIGI-LEND in Geant4 is old and buggy but usable
  - to get database go to ftp://gdo-nuclear.ucllnl.org/pub/ and select G4LEND, then ENDF-B-VII.0.tar.gz
  - new version will have library downloadable from Geant4 web page

Ion-ion Inelastic Scattering

- Up to now we've considered only hadron-nucleus interactions, but Geant4 has six different nucleus-nucleus collision models
  - G4BinaryLightIon
  - G4WilsonAbrasion/G4WilsonAblation
  - G4EMDissociationModel
  - G4QMD
  - G4Incl
  - FTF
- Also provided are several ion-ion cross section data sets
- Currently no ion-ion elastic scattering models provided

G4BinaryLightIonReaction

- This model is an extension of the G4BinaryCascade model (discussed earlier)
- The hadron-nuclear interaction part is identical, but the nucleus-nucleus part involves:
  - preparation of two 3D nuclei with Woods-Saxon or harmonic oscillator potentials
  - lighter nucleus always assumed to be the projectile
  - nucleons in the projectile are entered with their positions and momenta into the initial collision state
  - nucleons are interacted one-by-one with the target nucleus, using the original Binary cascade model

G4WilsonAbrasion and G4WilsonAblation

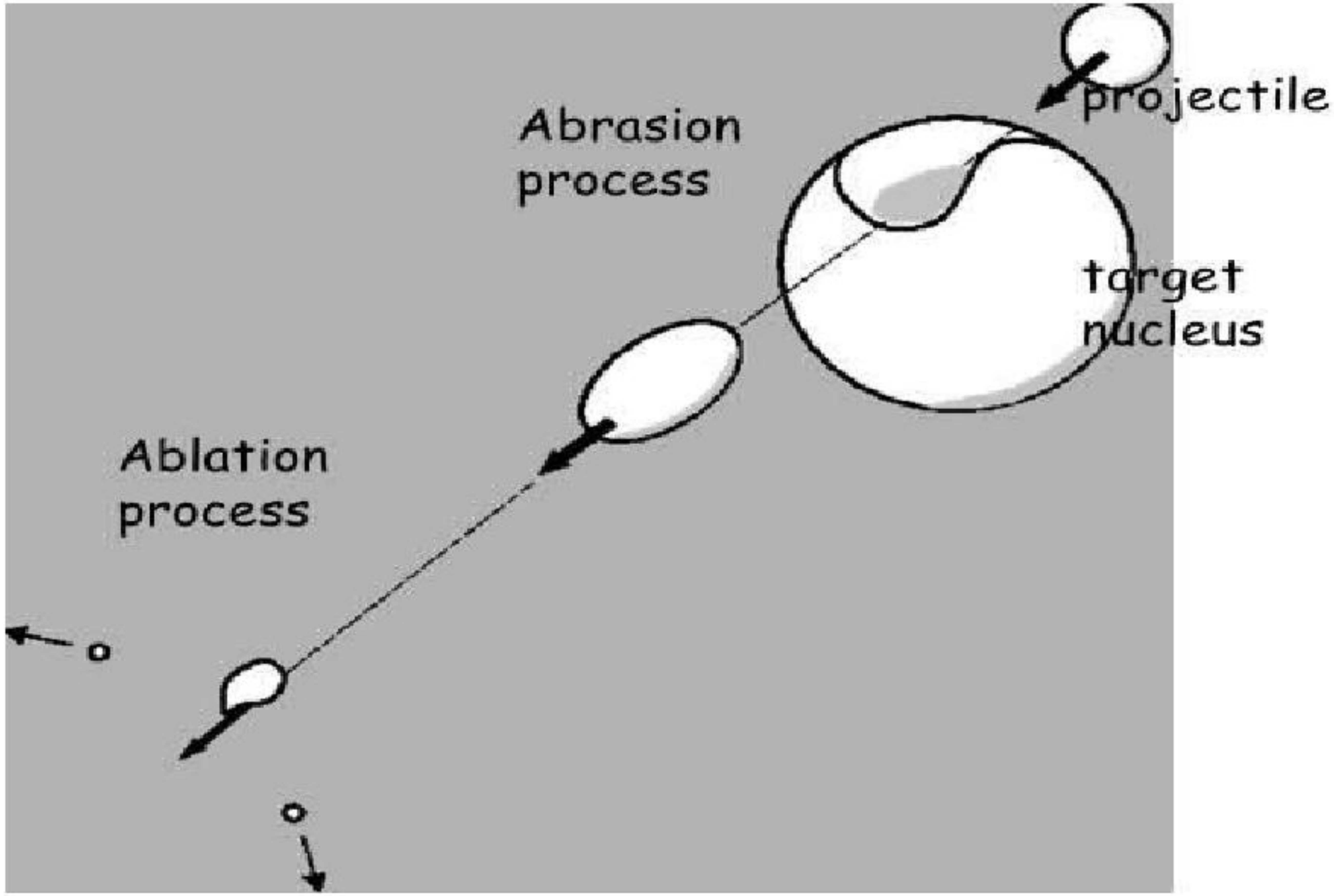
- A simplified macroscopic model of nucleus-nucleus collisions
  - based largely on geometric arguments
  - faster than Binary cascade or QMD models, but less detailed

- The two models are used together
  - G4WilsonAbrasion handles the initial collision in which a chunk of the target nucleus is gouged out by the projectile nucleus
  - G4WilsonAblation handles the de-excitation of the resulting fragments

- Based on the NUCFRG2 model (NASA TP 3533)

- Can be used up to 10 GeV/n

Wilson Abrasion/Ablation



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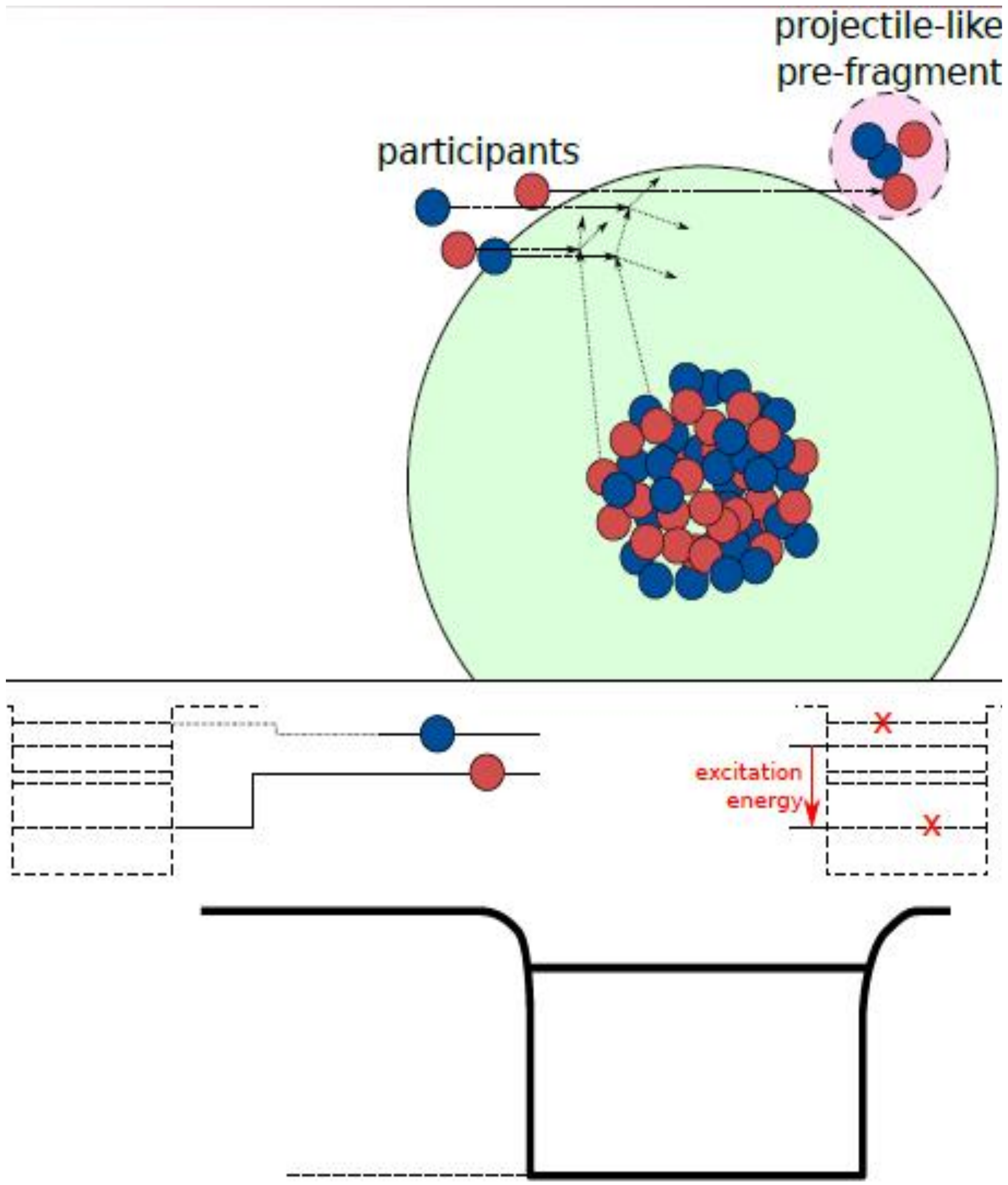
G4EMDissociation Model

- Electromagnetic dissociation is the liberation of nucleons or nuclear fragments as a result of strong EM fields
  - as when two high-Z nuclei approach one another
  - exchange of virtual photons instead of nuclear force
- Useful for relativistic nucleus-nucleus collisions where the Z of the nucleus is large
- Model and cross sections are an implementation of the NUCFRG2 model (NASA TP 3533)
- Can be used up to 100 TeV

INCL Nucleus-Nucleus

- Uses INCL hadron-nucleus model
- Projectile nucleus treated as a collection of nucleons without a nuclear potential, but with binding energy taken into account
- True potential is used for target nucleus
- Projectile nucleons can pass through to form fragments or interact with nucleus

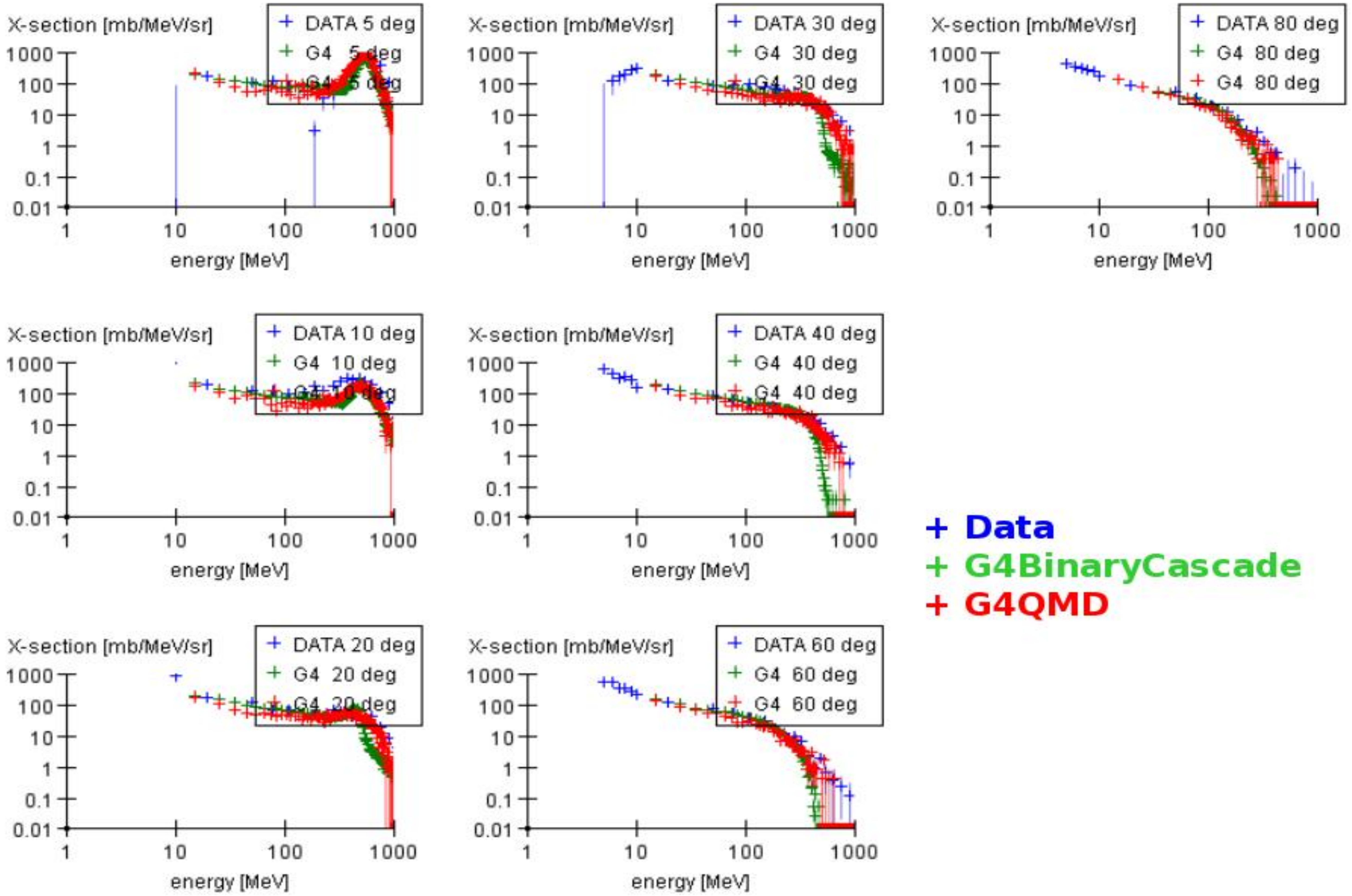


G4QMD Model

- BinaryLightIonReaction has some limitations
    - neglects participant-participant scattering
    - uses simple time-independent nuclear potential
    - imposes small A limitation for target or projectile
    - Binary cascade base model can only go to 5-10 GeV
- Solution is QMD (quantum molecular dynamics) model
    - an extension of the classical molecular dynamics model
    - treats each nucleon as a gaussian wave packet
    - propagation with scattering which takes Pauli principal into account
    - can be used for high energy, high Z collisions

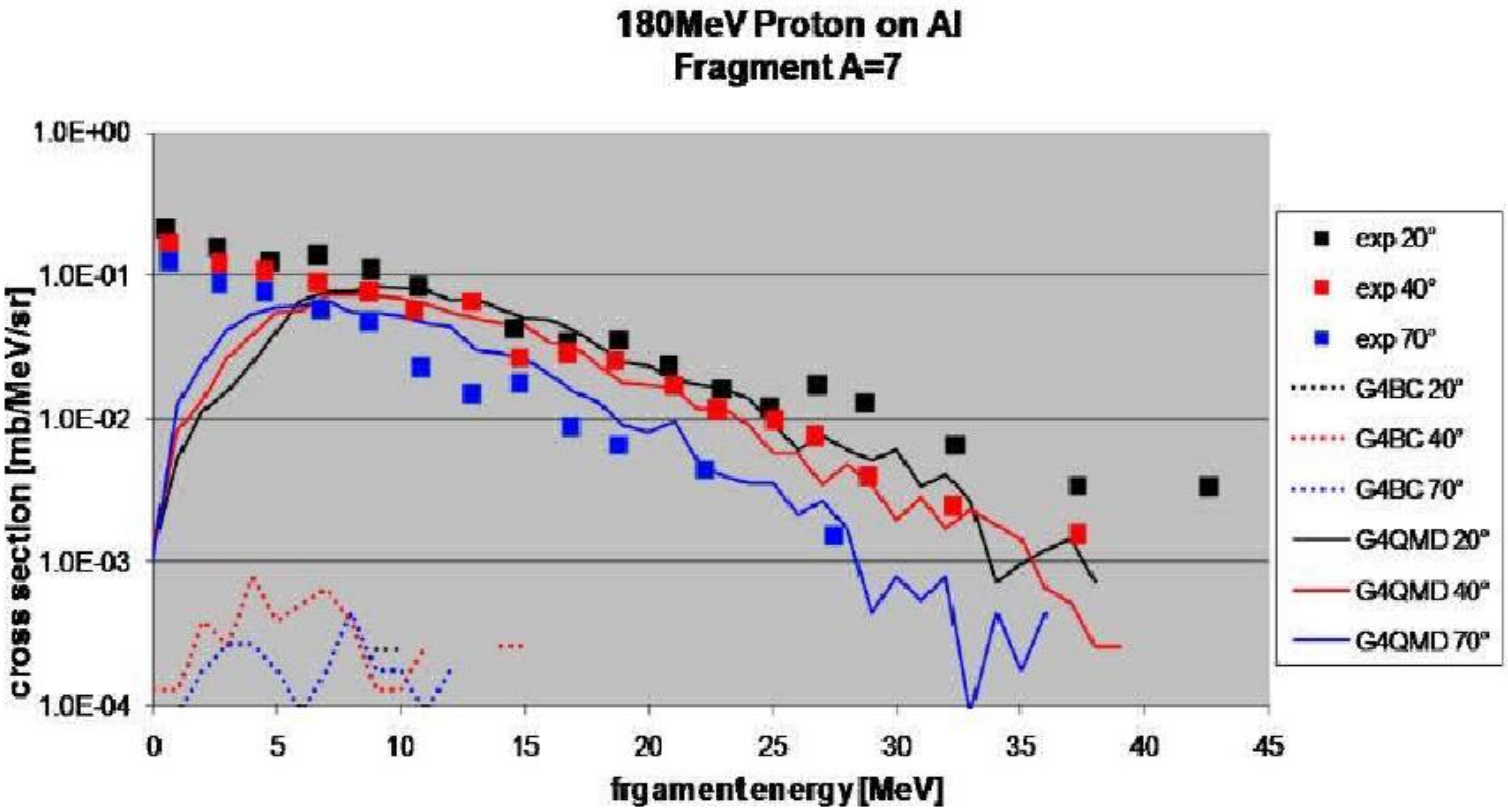
QMD Validation (1)

Ar40 560MeV/n on Lead



+ Data
+ G4BinaryCascade
+ G4QMD

QMD Validation (2)



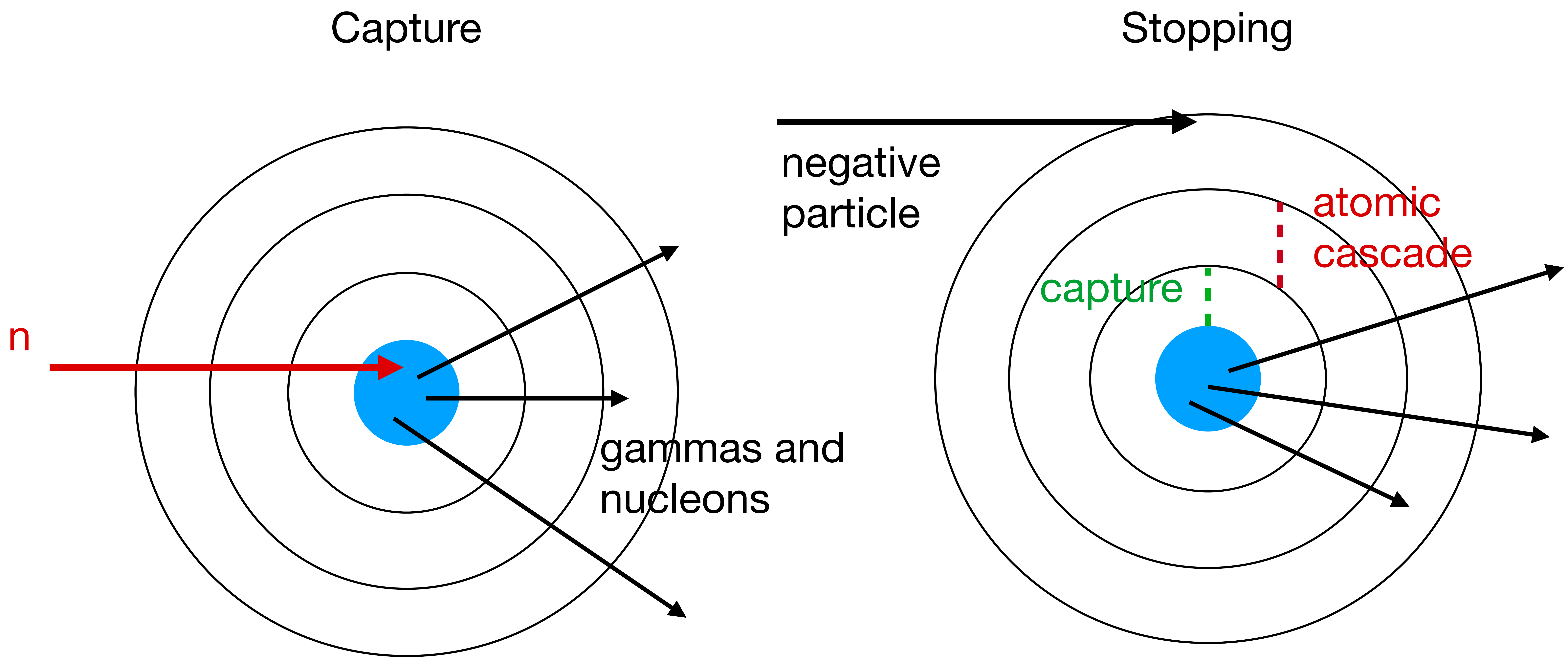
Nucleus-nucleus Cross Sections

- G4ComponentGGNuclNuclXsc
  - Total, elastic and inelastic nucleus-nucleus cross sections using Glauber model with Gribov corrections

- G4ComponentAntiNuclNucleusXS
  - Total, elastic and inelastic cross sections for anti-nucleon and anti-nucleus scattering from nuclei

- G4IonsShenCrossSection
  - for incident ion energies between 10 MeV/n to 10 GeV/n
  - parameterized from data and theory

Capture and Stopping Models



Stopped Hadron Models

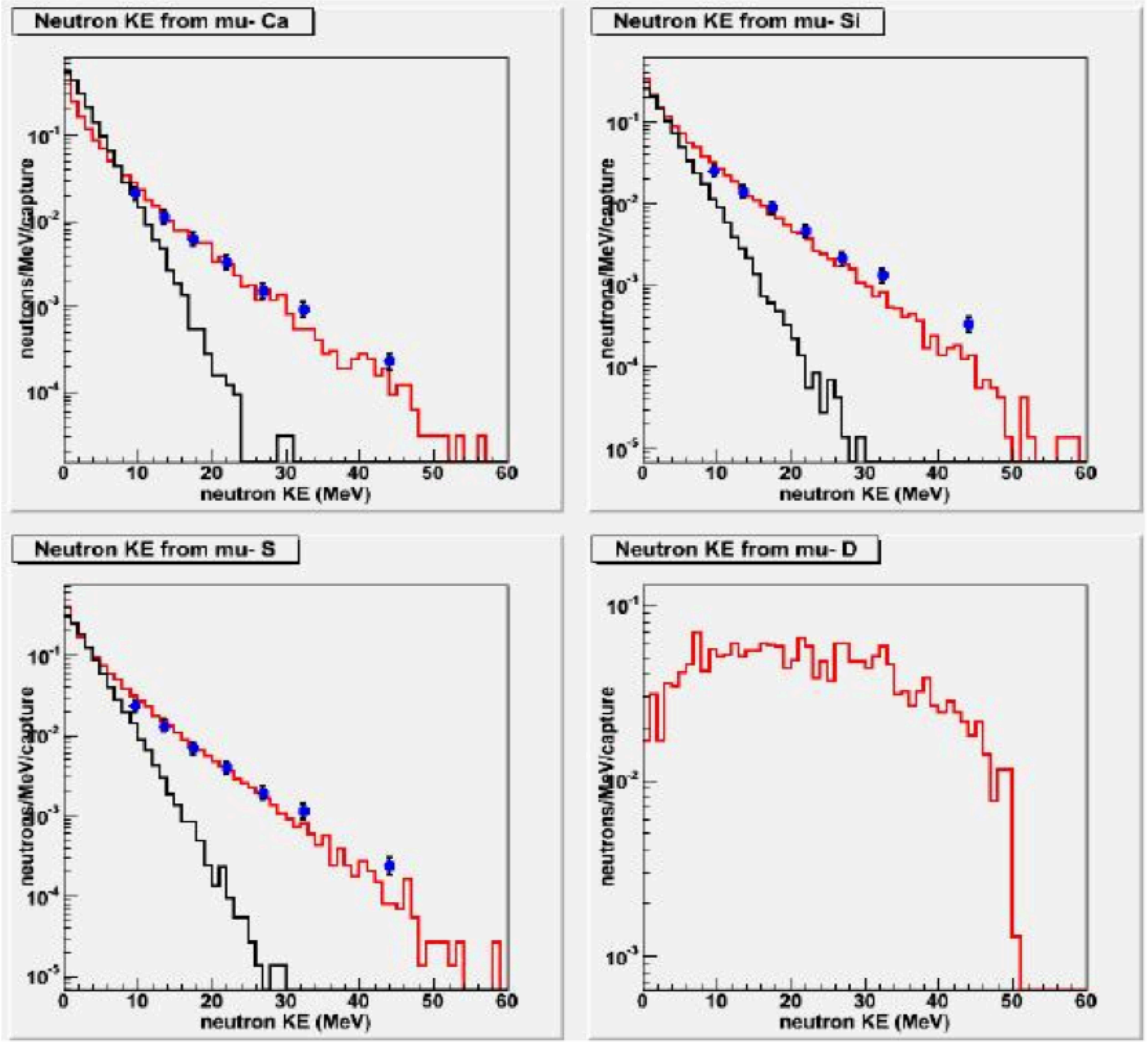
- Derived from class G4HadronStoppingProcess

- G4HadronicAbsorptionBertini
  - at rest process implemented with Bertini cascade model
  - absorption of π^-, K^- and Σ^- with subsequent cascade
  - G4Precompound model used for de-excitation of nucleus
  - includes atomic cascade but not decay in orbit

- G4HadronicAbsorptionFritiof
  - absorption of $\overline{p}$ and $\overline{\Sigma^+}$
  - FTF model used because > 2 GeV available in reaction
  - G4Precompound model used for de-excitation of nucleus
  - includes atomic cascade but not decay in orbit

- G4HadronicAbsorptionINCLXX
  - absorption of $\overline{p}$
  - INCL cascade followed by G4Precompound de-excitation of nucleus

Muon Capture using Bertini Model (red) Old model (black)



Stopped Muon Models

- Muon can decay in orbit, $\mu^- \rightarrow e^- \overline{\nu_e} \nu_\mu$ or be captured in the nucleus, $\mu^- p \rightarrow n \nu_\mu$, depending on nuclear (A, Z) then nuclear de-excitation

- G4MuonMinusCapture
  - also derived from G4HadronStoppingProcess
  - atomic cascade, with decay in orbit enabled
  - K-shell capture and nuclear de-excitation implemented with Bertini cascade model
  - used in most physics lists

- G4MuMinusCapturePrecompound
  - atomic cascade, with decay in orbit enabled
  - K-shell capture uses simple particle-hole model
  - nuclear de-excitation handled by G4Precompound model

Capture Process and Models

- Neutrons, anti-neutrons never really stop, they just slow down from elastic scattering or are absorbed
    - kinetic energy must be taken into account

- G4NeutronCaptureProcess
    - in-flight capture of neutral hadrons (neutrons, anti-neutrons)

- Models
    - G4ParticleHPCapture (below 20 MeV)
    - G4NeutronRadCapture (all energies)
    - G4NeutronRadCaptureHP (below 20 MeV)

Fission Process and Models

- Many hadronic models include fission implicitly
  - nuclear de-excitation code, for example
  - In that case, don't add fission process to physics -> double counting
  - dedicated fission models usually needed only in special cases (reactor studies)

- G4NeutronFissionProcess
- Models
  - G4ParticleHPFission
    - for incident neutrons below 20 MeV
    - fission fragments produced if desired
    - G4WendtFissionFragmentGenerator
  - G4FissLib: Livermore Spontaneous Fission
    - handles spontaneous fission as an inelastic process
    - no fission fragments produced, just neutrons

Summary (1)

- All hadron elastic scattering is handled by one process
  - but implemented by several models depending on energy and particle type
- Specialized high precision models (n, p, d, t, ^{3}He, α)
  - HP models which use G4NDL, now based entirely on JEFF-3.3
  - alternative LEND (Livermore) models are faster but currently less extensive - new ones coming soon
- Several models for nucleus-nucleus collisions
  - Wilson models fast, but not so detailed
  - cascade models more detailed but slower
  - QMD model very detailed but not so fast

Summary (2)

- Stopping processes for selected particle types
  - negative hadrons and muons
- Capture for neutrons
- Several fission models available
  - some implicitly included in other models
  - some must be explicitly added by users
  - make sure not to double-count !