2ND GEANT4 International school and ROOT analysis concepts

Hadronic Physics

J. M. Quesada, University of Sevilla
Based on lectures developed by V. Ivanchenko (CERN), M. Kelsey, T. Koi and D. Wright (SLAC)

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What is Geant4 Hadronic Physics?

- Interactions with atomic nuclei
- Projectile is a hadron
- and/or produced secondary particles are hadrons
- Energy range from zero up to 100 TeV

The hadronic *challenge*

- The theory of inelastic hadronic interactions is not fully established from 1st principles, therefore phenomenology and parameterisations must be used at some level.
- Even though there is an underlying theory (QCD), applying it is much more difficult than applying QED for EM physics

The Geant4 Philosofy of Hadronics

- We must deal with several energy regimes
  - QCD strings (> 20 GeV)
  - Cascade region (100 MeV – 20 GeV)
  - Preequilibrium+deexcitation region (< 100 MeV)
- Geant4 provides several cross section sets and models in each region
- Some of these are phenomenological, some have more theoretical content
- **It is user's responsability which physics is the best**
- Which ones to use? Which ones are correct?
- Geant4 provides a general model framework that allows the implementation of more processes and models at many levels
- The new models are validated as data become available

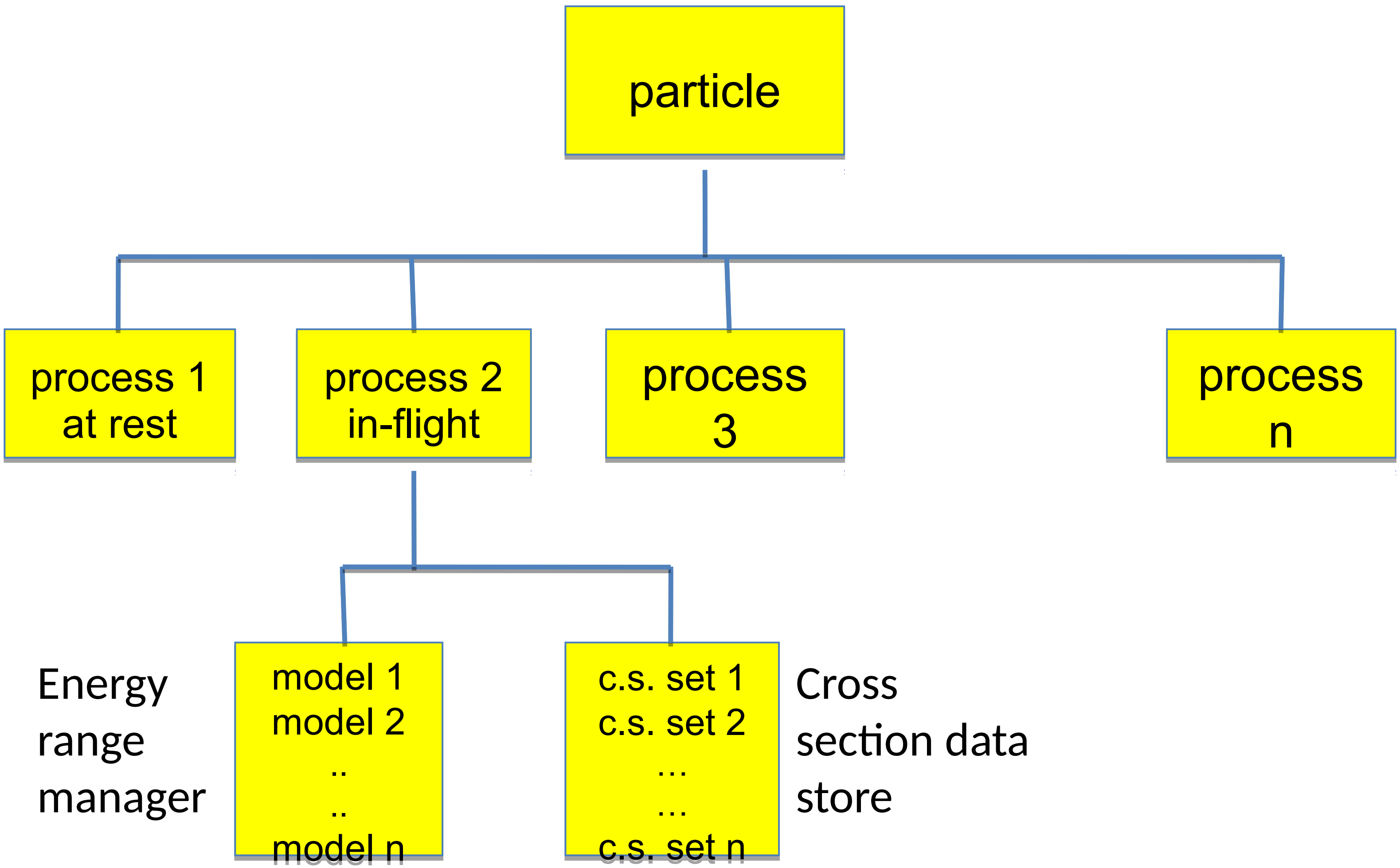
Hadronic Processes

- At rest
  - Capture of stopped μ,π , K, anti-proton
  - Radioactive decay
- Elastic
  - same process for all long-lived hadrons
- Inelastic
  - Different process for each hadron
  - Photo-nuclear
  - electro-nuclear
- Capture
  - π, K in flight
- Fission

Hadronic framework:
processes, cross sections and models

- In Geant4 physics interactions between a particle and material occur through processes
- A process has two ingredients, which are independent :
  - **Cross sections** to decide when and where an interaction will occur (i.e. also for process selection)
    - GetPhysicalInteractionLength()
  - **Models** (final state generators):
    - DoIt()
- A process must have **cross sections** assigned
  - multiple data tables available, selecedt during physics list setup
- Geant4 often provides also several **models** for a given process
  - different models for different energy ranges and particle types
  - may have more than one per process
  - user must choose during physics list setup

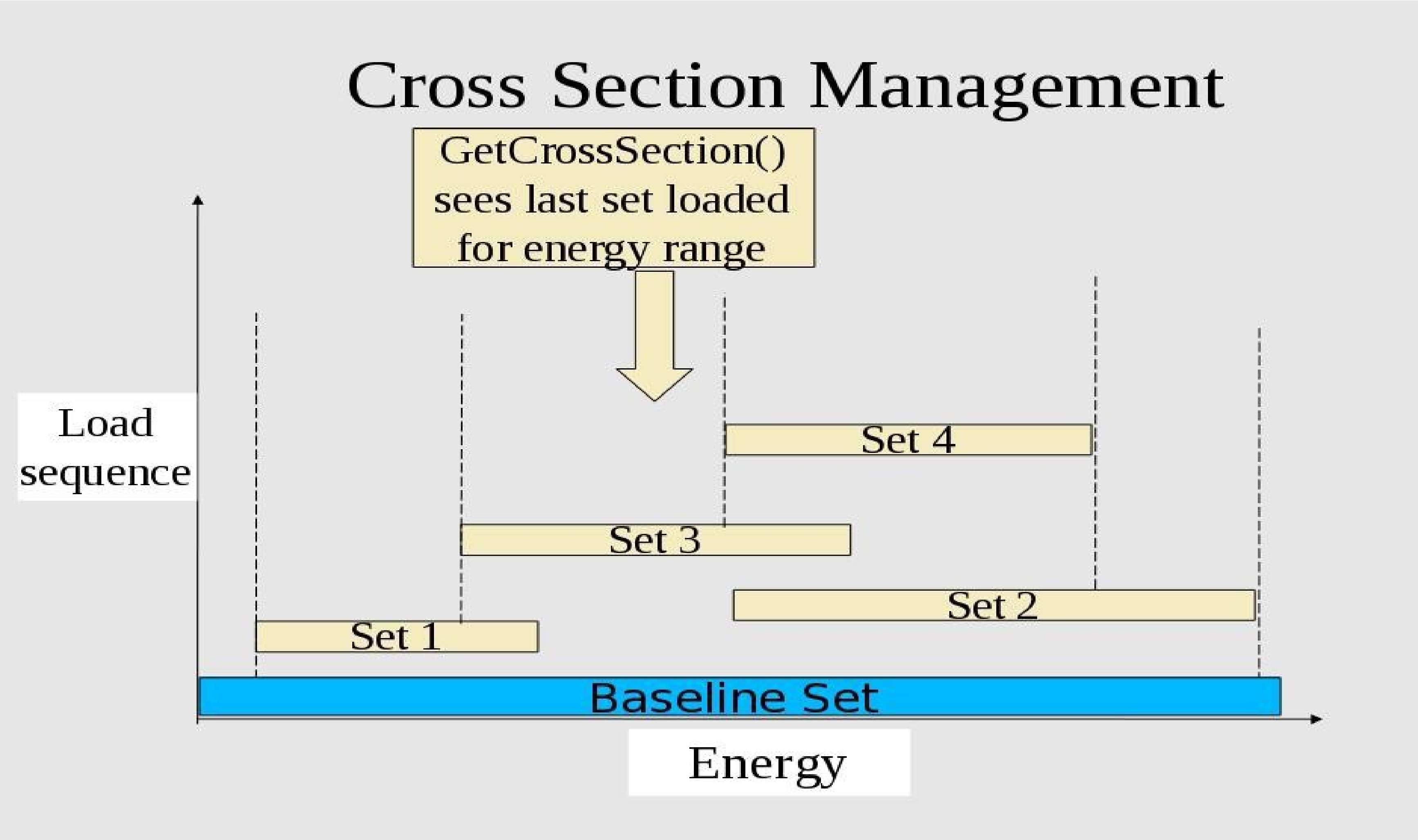
Hadronic framework: processes, cross sections and models



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**

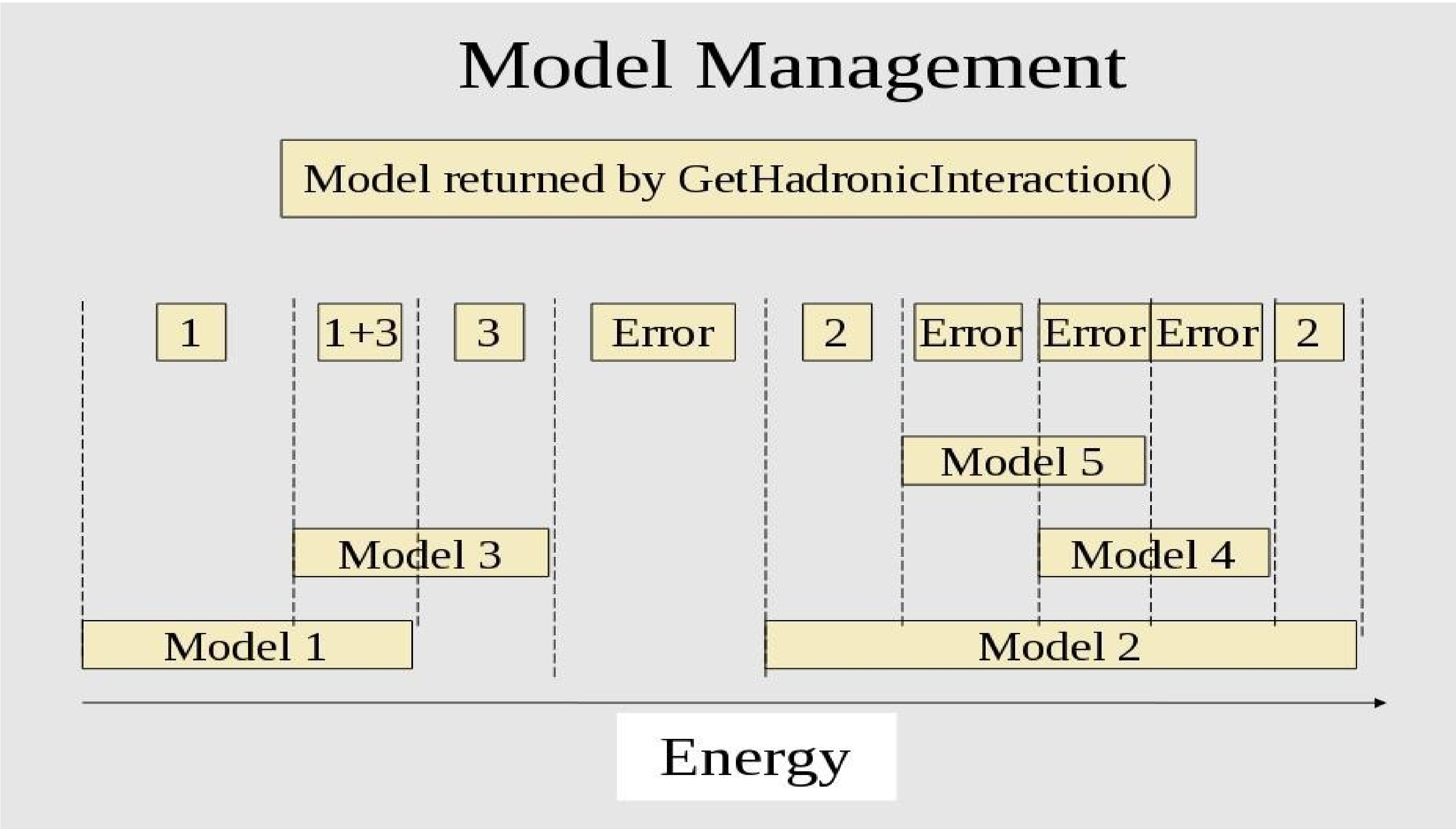
Hadronic process should have set of cross sections for required energy range



Hadronic Models 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 “energy gaps” are allowed
- Overlaps are “interpolated” with linear random selection at each interaction

Hadronic processes should have set of models covering the required energy range



Elastic Process

G4HadronElasticProcess :

- “hadElastic” is the name of this process
- Having **cross sections** to calculate mean free path and **models** for final states.

Elastic cross sections

G4HadronElasticDataSet

- Cross sections from the Geant3/Gheisha routine GHESIG.

G4ChipsNeutron(Proton)ElasticXS

- Cross sections extracted from CHIPS framework

G4ComponentAntiNuclNuclearXS

- elastic cross sections of anti-nucleons and light anti-nucleus interactions with nuclei using Glauber's approach.

G4BGGNucleonElasticXS

- Barashenkov-Glauber-Gribov cross section handles elastic scattering of protons and neutrons from nuclei using the Barashenkov parameterization below 91 GeV and the Glauber-Gribov parameterization above 91 GeV.

G4GGNuclNuclCrossSection

- elastic cross sections for nucleus-nucleus collisions using the Glauber model with Gribov corrections

Elastic Models

G4HadronElastic

- from the Geant3/Gheisha

G4ChipsElasticModel

- from CHIPS framework

G4ElasticHadrNucleusHE

- high energy hadron-nucleus elastic scattering for the kinetic energy T > 1 GeV

G4AntiNuclElastic

- for AntiNuclear Nuclear Elastic Scattering

G4NuclNuclDiffuseElastic

- Final state production model for nucleus-nucleus elastic scattering

Inelastic Processes

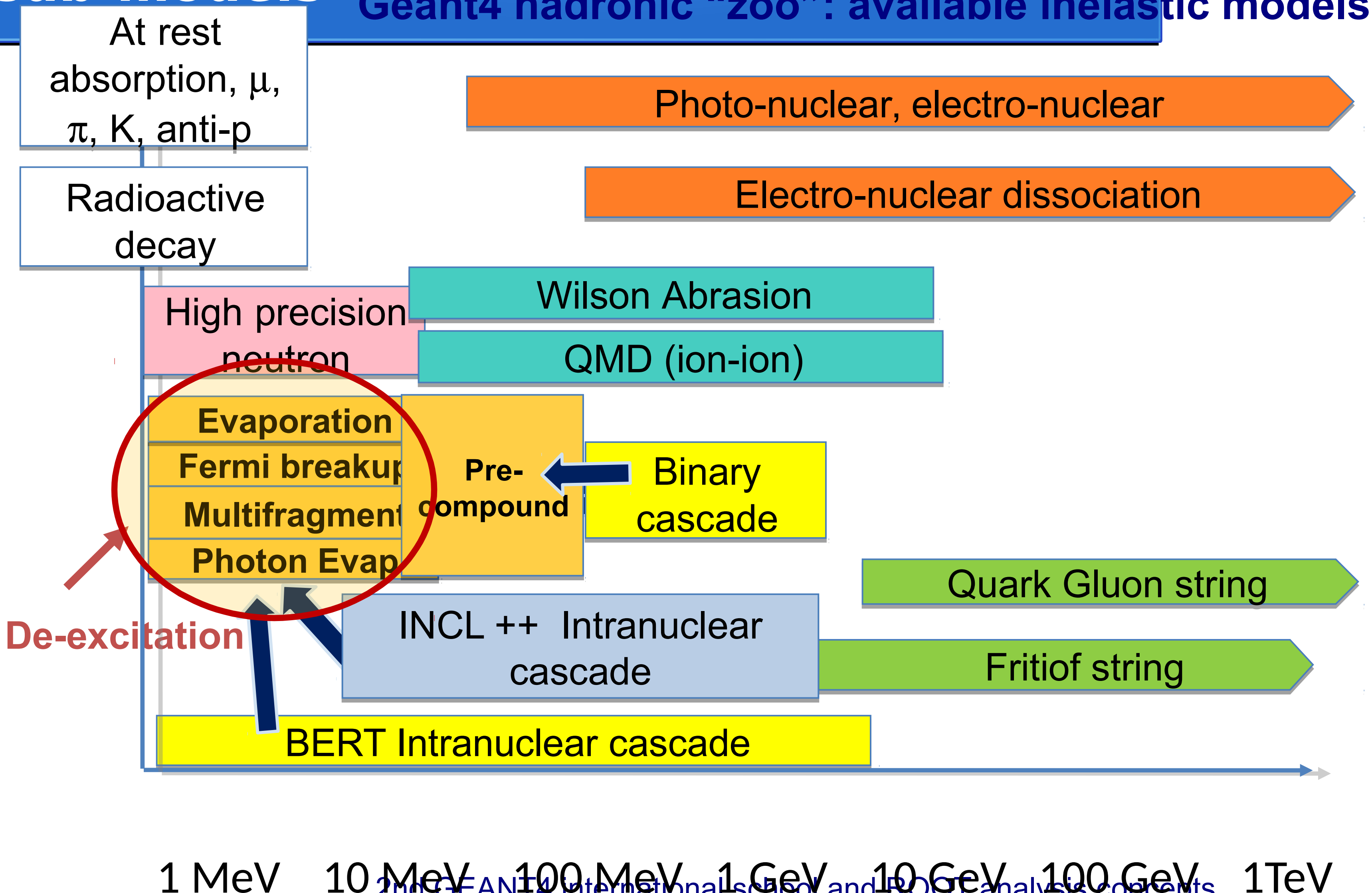
- One for each hadron (G4ProtonInelasticProcess, G4PionPlusInelasticProces, ..)
- Many choices for cross sections and models

Inelastic cross sections

- CHIPS elastic and inelastic cross-sections for protons, neutrons, pions, kaons, hyperons and anti-baryons
- Axen-Wellisch for proton-nucleus
- Laidlaw-Wellisch for neutron-nucleus
- Barashenkov-Glauber-Gribov for nucleon-nucleus inelastic cross sections are now used in most physics lists
- Ion-Ion physics (see later)

Hadronic inelastic interaction includes several stages using different sub-models

Geant4 hadronic "zoo": available inelastic models



Main choice for hadronic physics:

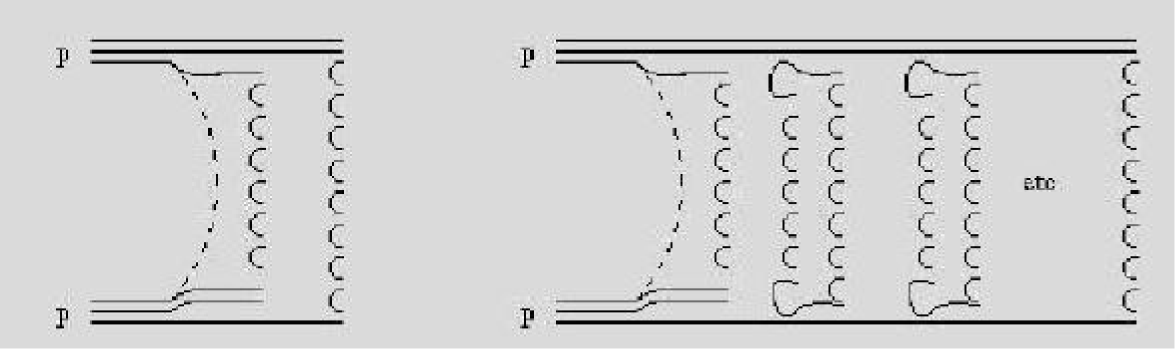
- When starting hadronic physics simulation one needs to choose a combination of models and cross sections
- User should ask himself:
  - What string model?
  - What cascade model?
  - What pre-compound/de-excitation model?
  - Are high precision neutron models needed?
- Geant4 include number of professionals with 10-30 years of expertise in specific hadronic models
  - They usually are responsible for their own models

High energy QCD non cascade models

- Quark Gluon String Model (QGS)
- Fritiof Model

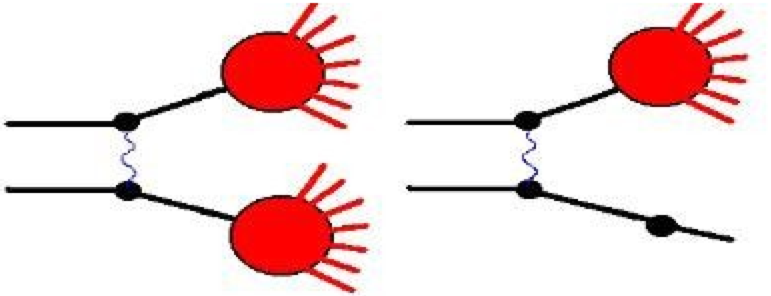
Quark-Gluon String

- One of the Geant4 QCD string models
- valid from 20 GeV - 1TeV
- In this model, two or more strings are stretched between the partons (quarks or gluons) within the hadrons



Fritiof Fragmentation Model

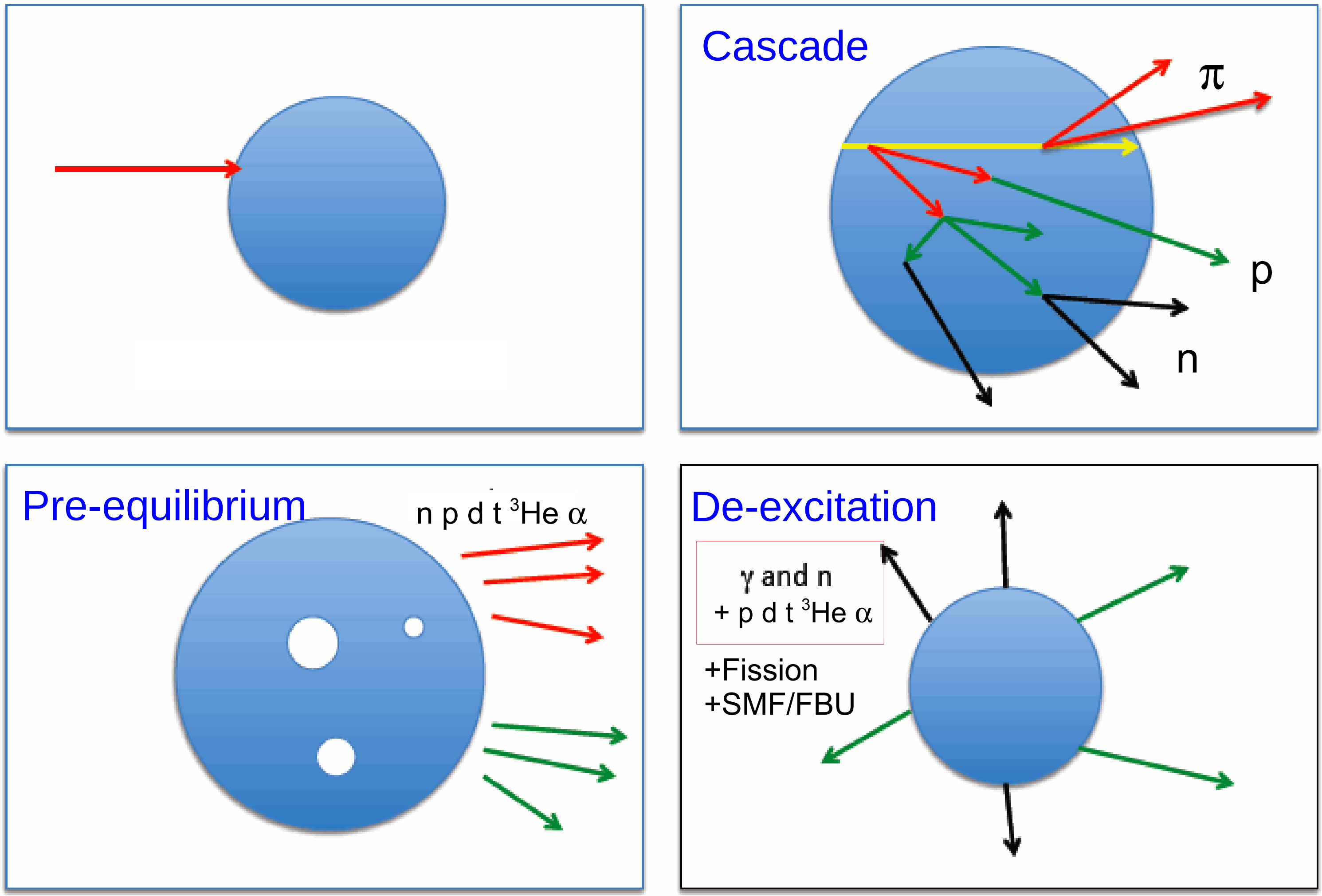
- Alternative QCD string fragmentation model
  - valid from 3 GeV - 1TeV
- This model applies at much lower energies due to
  - ability to handle lower string masses
  - Reggeon cascade
  - Natural introduction of diffraction processes
  - Since release 10.0 it is applicable for all hadrons and ions
- The model uses a different set of fragmentation functions and relies more on fitted parameters than QGS model



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 photons, nucleons, and one or more nuclear fragments are produced.
- Geant4 includes three different cascade models
  - Binary Cascade
  - BERT (Bertini-inspired) intranuclear cascade
  - INCL++/ABLA++ (Liege Model)

Intranuclear Cascade



BERT Intranuclear Cascade (I)

- “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
  - Modified free space cross sections used to generate secondaries
  - Cascade in “continuous” nuclear medium
  - 3-D model of nucleus consisting of up to 6 concentric shells of different nuclear density.
  - Pre-equilibrium and equilibrium decay of residual nucleus

BERT Intranuclear Cascade (II)

- 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 (III)

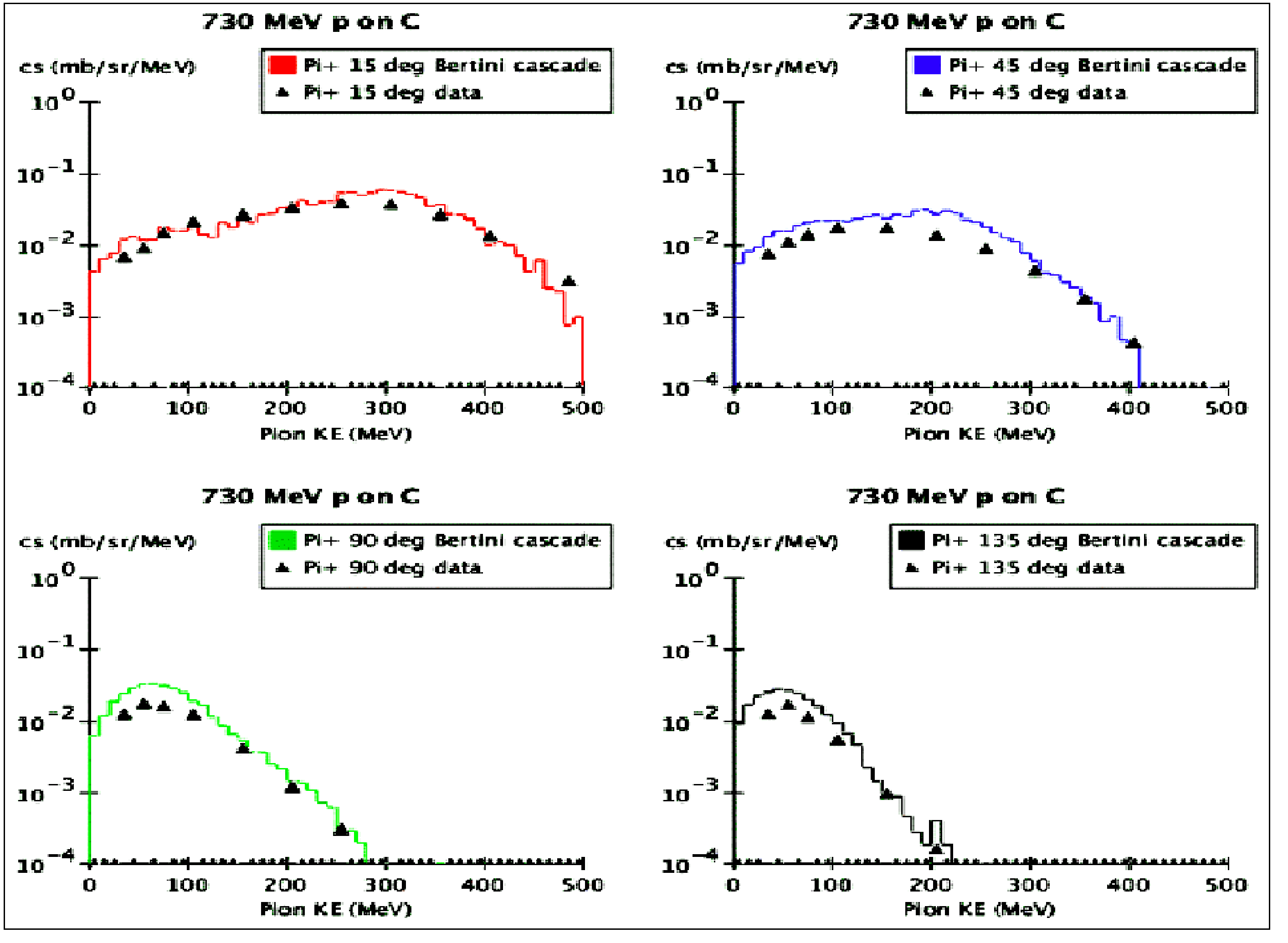
- Used for γ, μ^-, p, n, $\pi^\pm$, π^0, $K^\pm$, $K^0_{L,S}$, Λ, $\Sigma^{\pm,0}$, $\Xi^{-,0}$
  - Validated for incident energies up to 10 GeV
  - Usable for capture of hadrons on A > 4 nuclei
  - Usable for photonuclear and muon-nuclear interactions
  - No additional photons produced in h-N collisions

- 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

```
// Model:
G4CascadeInterface* bert = new G4CascadeInterface;
// Process:
G4ProtonInelasticProcess* pproc = new
G4ProtonInelasticProcess;
//Register model to process:
pproc->RegisterMe(bert);
//Add process:
protonManager->AddDiscreteProcess(pproc);
```

BERT Intranuclear Cascade Validation



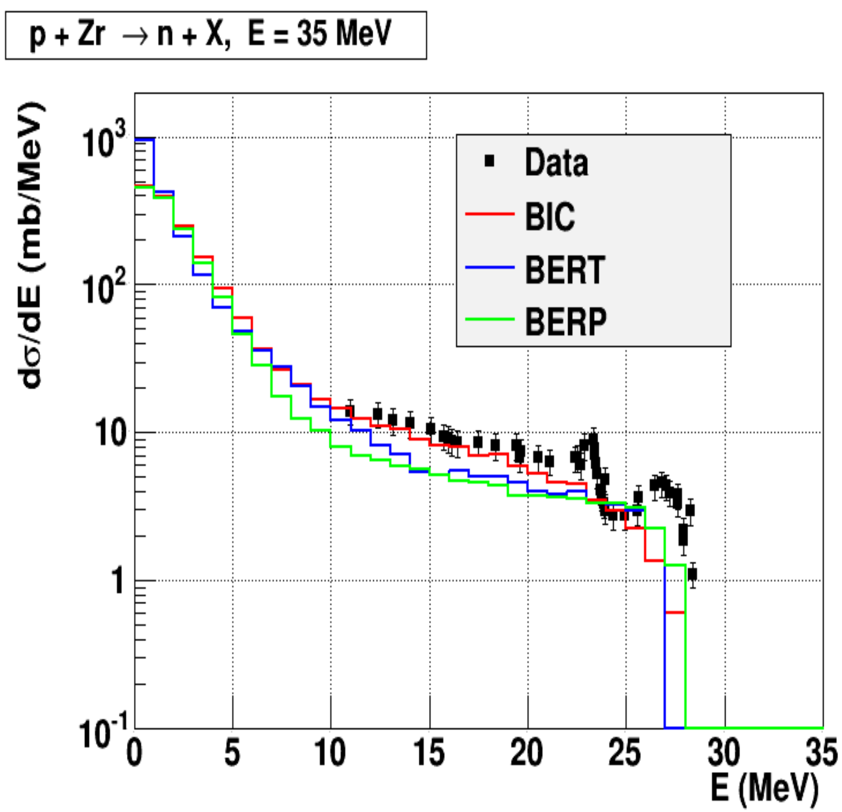
Binary Cascade (I)

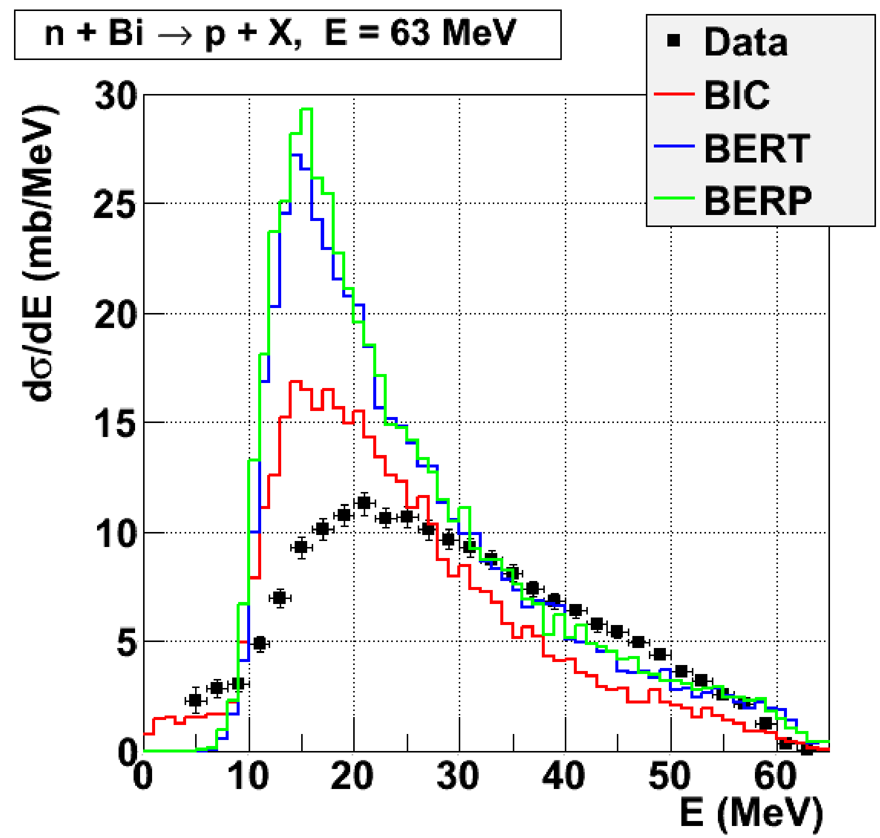
- Time-dependent model (ordered interactions)
  - Hadron-nucleon collisions form resonances
  - Decayed according to their quantum numbers
  - Particles follow curved trajectories in smooth nuclear potential
  - Geant4 native PreCompound model after cascading phase
- Binary cascade currently used for incident *p*, *n*, $\pi^{\pm}$
  - Valid for incident *p*, *n* up to 10 GeV
  - Valid for incident $\pi^{\pm}$ up to 1.3 GeV

Binary Cascade (II) & Binary Light Ion

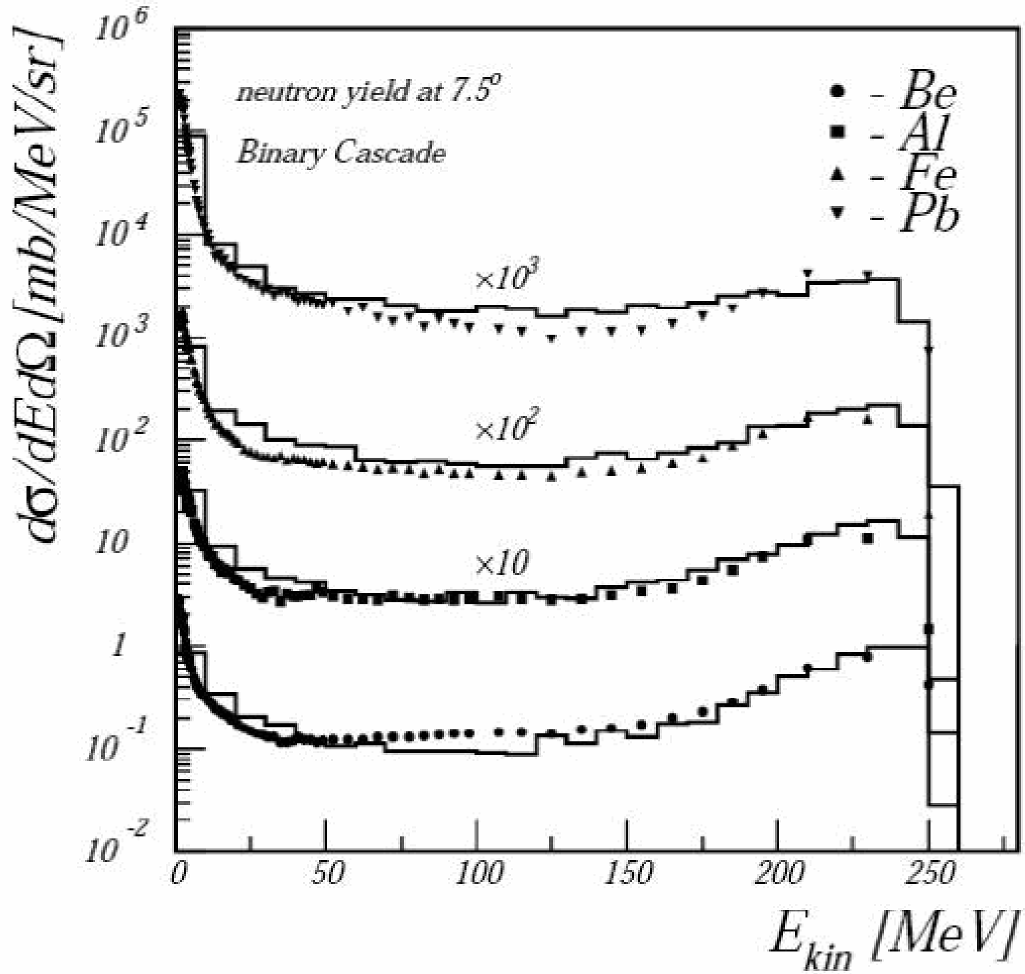
- In Binary Cascade, each participating **nucleon is seen as a gaussian wave packet,** (like QMD)
- Total wave function of the nucleus is assumed to be direct product of these. (no anti-symmetrization)
- The centroid of this wave packet follows the classical Hamilton equations, which can be solved numerically.
- The Hamiltonian is calculated using simple time independent **nuclear optical potential** (unlike QMD), 3 dimensional model of the nucleus constructed from A and Z. Nucleon distribution follows
  - A>16 Woods-Saxon model
  - Light nuclei harmonic-oscillator shell model
  - Nucleon momenta are sampled from 0 to Fermi momentum and sum of these momenta is set to 0
- Nucleus-nucleus: **G4BinaryLightIonReaction**
- Alternative : QMD model.

Binary – BERT cascades validation: proton and neutron production @ low proton energies





Binary Cascade Validation with 256 MeV protons



Using Binary Cascade

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);
```

Precompound and De-excitation Models

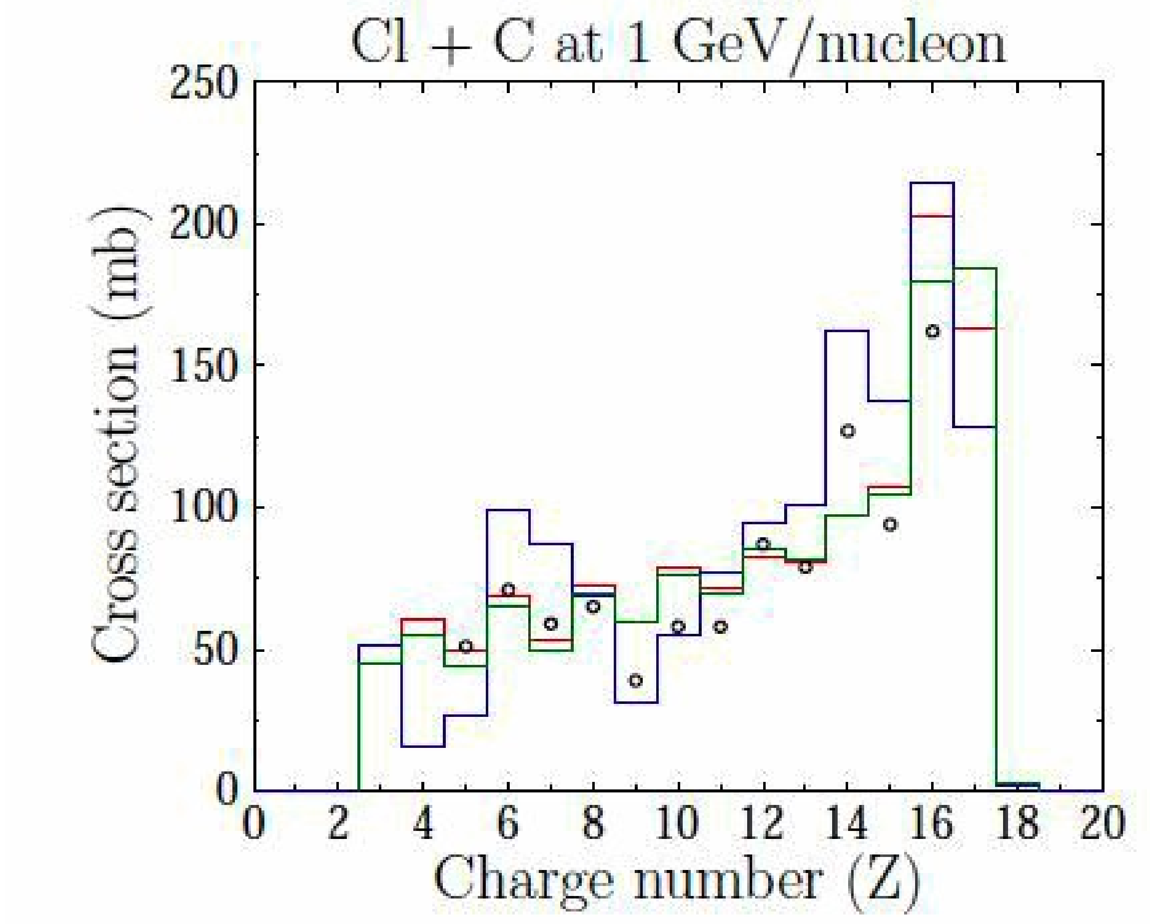
- ***Pre-compound* model handles**
  - Nucleon absorption at low energies (roughly below pion emission threshold)
  - Nuclear fragments resulting from higher energy interactions
  - “Wounded nucleus” with set of excited particle-hole states
  - Resolves to equilibrium, emitting *p*, *n*, *d*, *t*, ^{3}He, α
- Closer to equilibrium, ***De-excitation*** model resolves excess energy in nucleus
  - Nuclear evaporation, statistical multifragmentation and break-up and fission
  - Continuum and discrete gamma emission

Liege INCL++

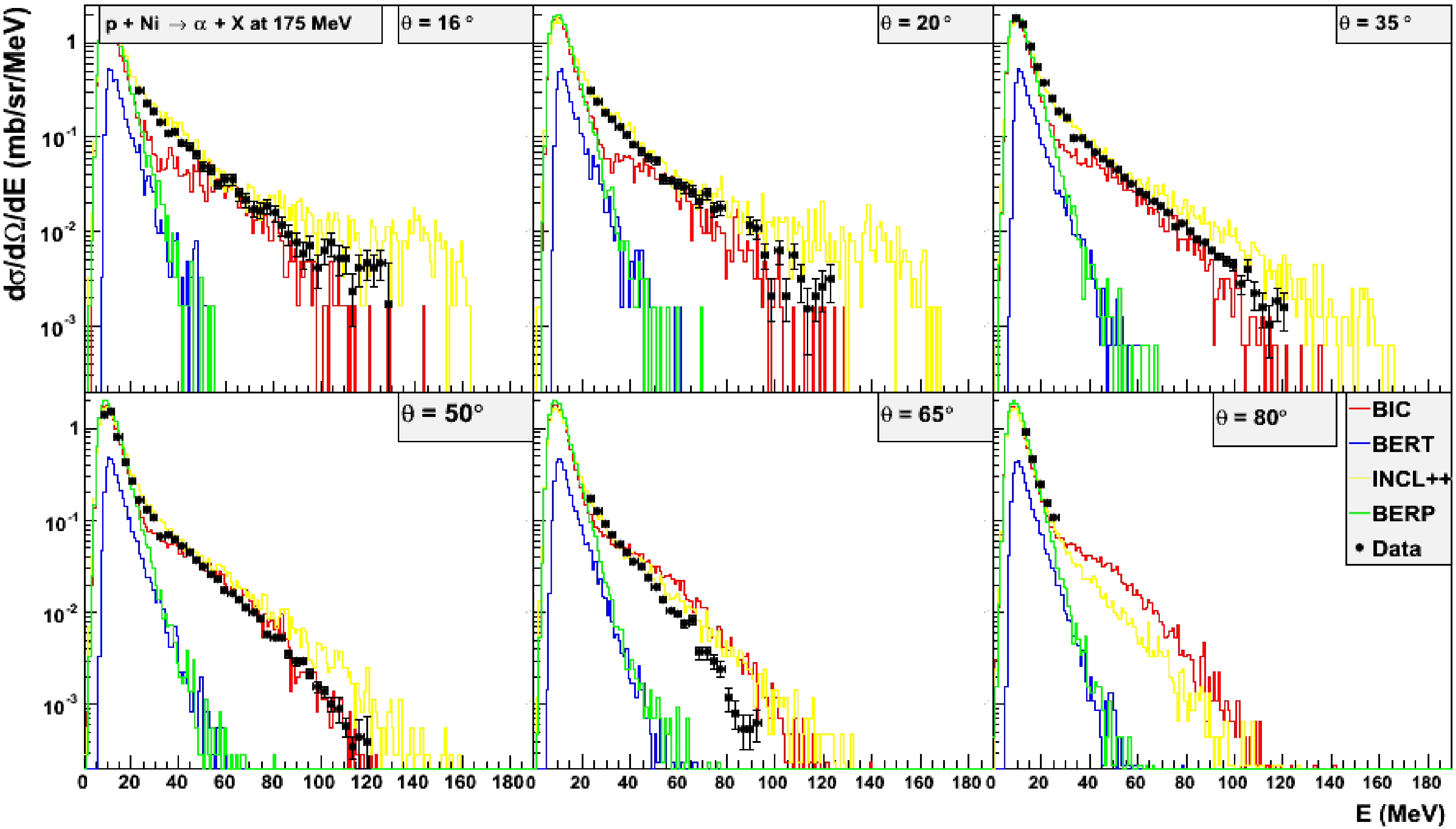
- FORTRAN -> C++, completely redesigned OO version in Geant4
- Time-dependent model (ordered interactions)
  - Smooth Woods-Saxon or harmonic oscillator potential
  - Resonance formation and decay (like Binary cascade)
- Valid for incident *p, n, π, d, t*, ^{3}He, *α*
  - From 150 MeV to 3 GeV
  - Also 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
- Now also interfaced to native Geant4 de-excitation

INCL++ Validation with Cl-C Collisions

Green: INCL 4.3 Red: INCL 4.2 Blue: Binary Light Ion



Hadronic validation: ^{4}He ion emission in proton induced nuclear reaction



Low energy (< 20MeV) neutron physics

- **G4NDL database: High Precision Neutron Models and Cross Sections**
  - **G4NEUTRONHPDATA** (env. var.)**:** the neutron data files for high precision neutron model
  - Most data were converted from **ENDF/B-VII database** with **NJOY** for resonance reconstruction
  - Point-wise cross section data
  - More than 400 isotopes data were converted.
  - Data files for heavier than U are omitted from public release.
- **Elastic, Inelastic, Capture and Fission** models and cross sections
  - **Register** them to Elastic, Inelastic Capture and Fission processes
- **G4NDL data format** is similar **ENDF-6 format**, however it is not equal to

Evaluated Nuclear Data File (ENDF)

“ENDF” is used with two meanings :

- One is a name of Data Formats and Procedures
  - How to write Nuclear Data files
  - How to use the Nuclear Data files
  - **ENDF-6** is the latest version
  - Usually use numerical number to represent its version

- The other is a name of recommended libraries of USA nuclear data projects.
    - **ENDF-VII.r1** is the latest (by 2012)
      - Usually use Roman numerals as the version number

Some features of NeutronHP

- **G4NeutronHP does not guarantee energy and momentum conservation**
- Description of ENDF data file is not complete in many reactions
  - The worst case, only channel cross section is provided
  - In such cases, neutronHP uses other Geant4 models in producing final states
- **Target thermal motions** including Doppler broadening of the resonances can be simulated
  - They are calculated on-the fly. Very CPU intensive
  - Very low-energy processes taking into account molecular effects
  - ThermalScatteringModels S(α,β) (and Cross Section data Sets)
- Ultra cold neutrons (<<10^{-5} eV) may have trouble in transportation
  - This is basically caused by the numerical precision of floating number of double (64bit)
- Gravity is not included in default
  –

Thermal neutron scattering from chemically bound atoms

- At thermal neutron energies, atomic translational motion as well as vibration and rotation of the chemically bound atoms affect the neutron scattering cross section and the energy and angular distribution of secondary neutrons.
- The energy loss or gain of incident neutrons can be different from interactions with nuclei in unbound atoms.
- Only individual Maxwellian motion of the target nucleus (Free Gas Model) was taken into account the default NeutronHP models.

$$\text{Scattering cross section}: \sigma(E \rightarrow E', \mu) = \frac{\sigma_b}{2kT}\sqrt{\frac{E'}{E}}S(\alpha,\beta);$$

$$\text{momentum transfer}: \alpha = \frac{E' + E - 2\sqrt{E'E}\mu}{AkT}, \text{ energy transfer}: \beta = \frac{E' - E}{kT}$$

Physics List for NeutronHPThermalScattering

```
G4HadronElasticProcess*    theNeutronElasticProcess   = new G4HadronElasticProcess();
// Cross Section Data set
G4NeutronHPElasticData* theHPElasticData = new G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theHPElasticData );
G4NeutronHPThermalScatteringData* theHPThermalScatteringData = new G4NeutronHPThermalScatteringData();
theNeutronElasticProcess->AddDataSet( theHPThermalScatteringData );
// Models
G4NeutronHPElastic* theNeutronElasticModel = new G4NeutronHPElastic();
theNeutronElasticModel->SetMinEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel);
G4NeutronHPThermalScattering* theNeutronThermalElasticModel = new G4NeutronHPThermalScattering();
theNeutronThermalElasticModel->SetMaxEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronThermalElasticModel);

// Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4Neutron::Neutron()-> GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

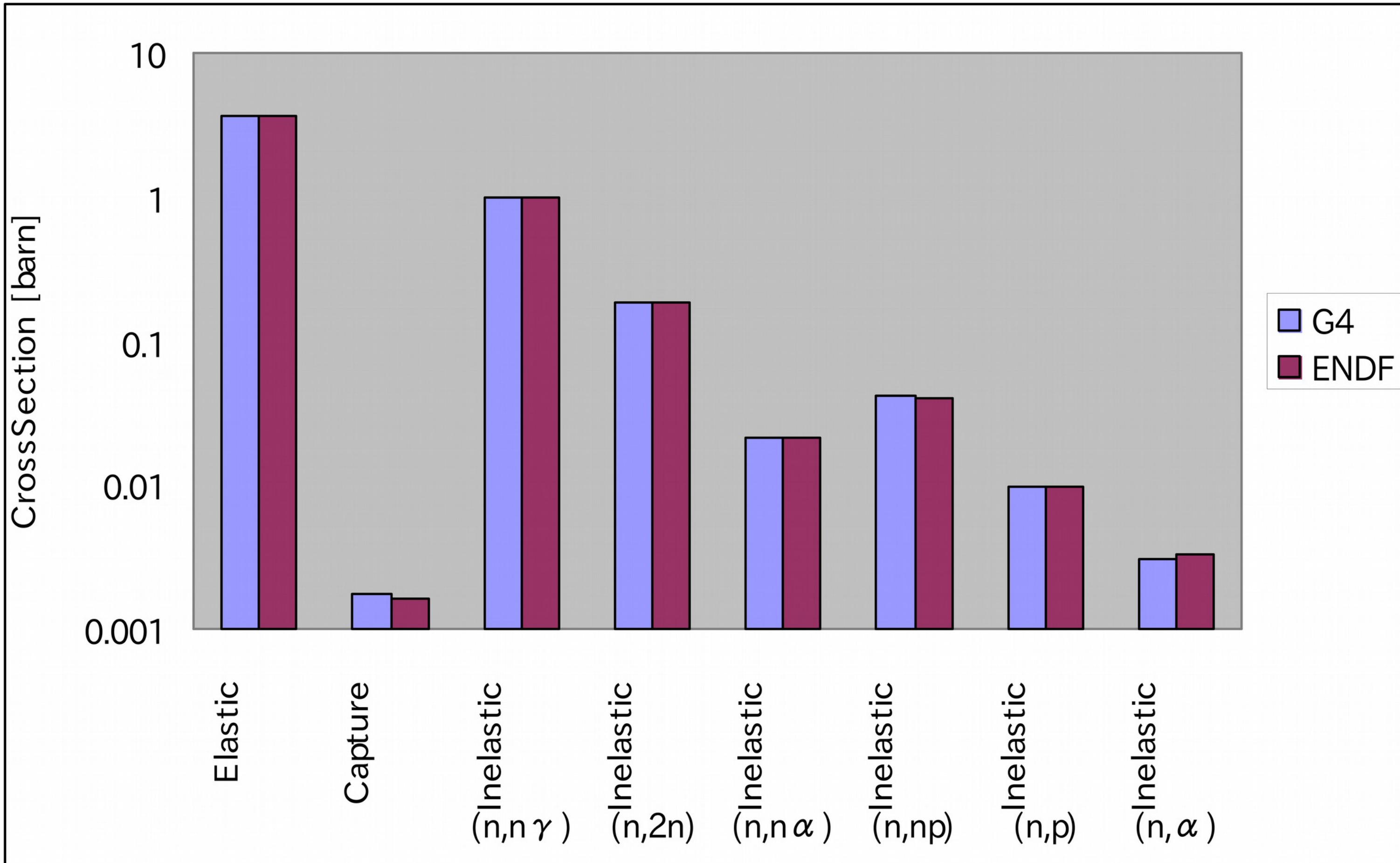
Material Definitions for NeutronHPThermalScattering

- Thermal neutron scattering files from ENDF/B-VII thermal data (ENDF-6 File 7) are converted into G4NDL by NJOY
  - There are about 20 materials in ENDF-VII thermal scattering
- To activate NeutronHPThermalScattering, a volume must be made from elements having specific names like "TS_H_of_Water".
  - G4NeutronHPThermalScatteringNames
- It's possible to to use a predefined material like G4_WATER.
  - However not all TS supported materials are in predefined material database.

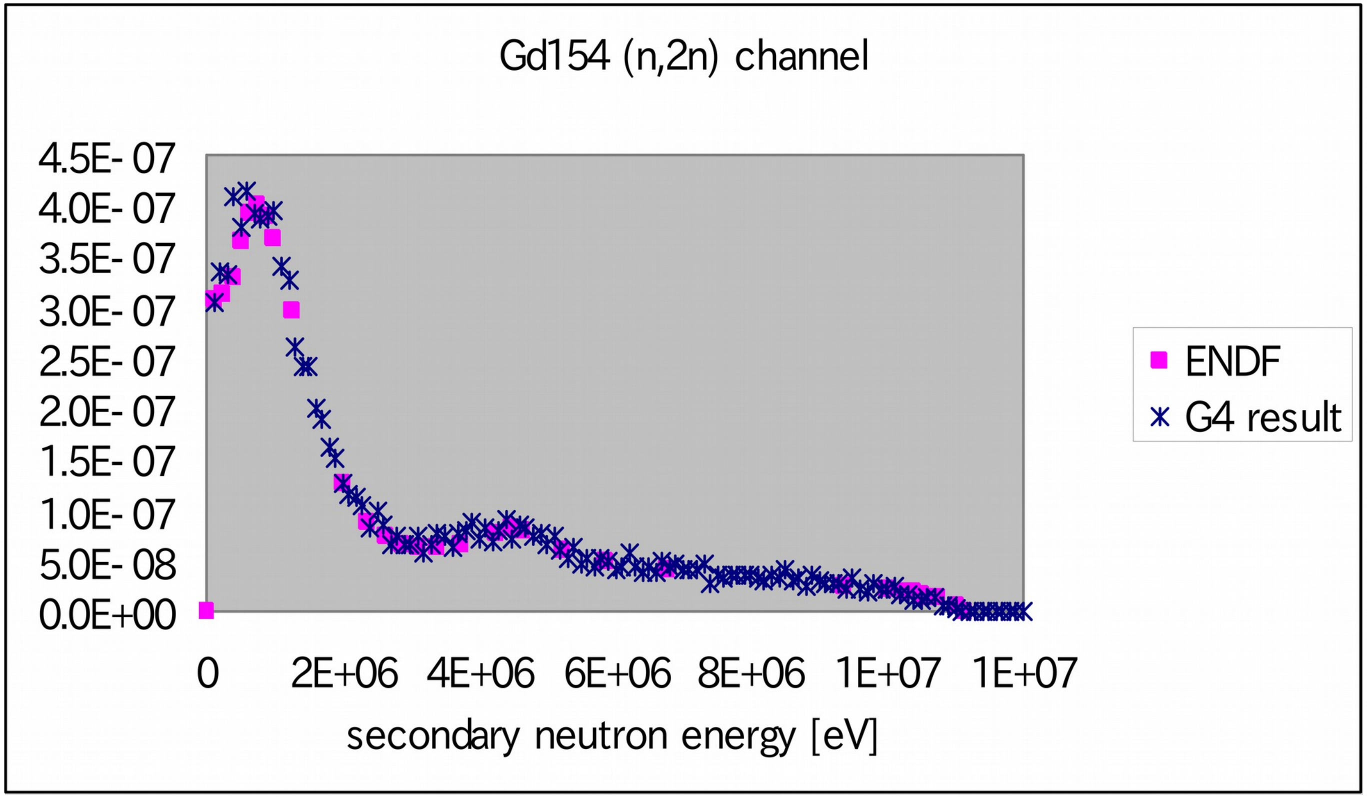
Material Definitions for NeutronHPThermalScattering

```
// Create Element for Thermal Scattering

G4Element* elTSHW = new G4Element( "TS_H_of_Water" , "H_WATER" , 1.0 , 1.0079*g/mole );

G4Element* elTSH = new G4Element( "TS_H_of_Polyethylene" , "H_POLYETHYLENE" , 1.0 ,
1.0079*g/mole );

// Create Materials from the elements

 G4Material* matH2O_TS = new G4Material( "Water_TS" , density = 1.0*g/cm3 , ncomponents = 2 );
        matH2O_TS -> AddElement(elTSHW,natoms=2);
        matH2O_TS -> AddElement(elO,natoms=1);

G4Material* matCH2_TS = new G4Material( "Polyethylene_TS" , density = 0.94*g/cm3 , ncomponents = 2 );
matCH2_TS -> AddElement(elTSH,natoms=2);
matCH2_TS -> AddElement(elC,natoms=1);
```

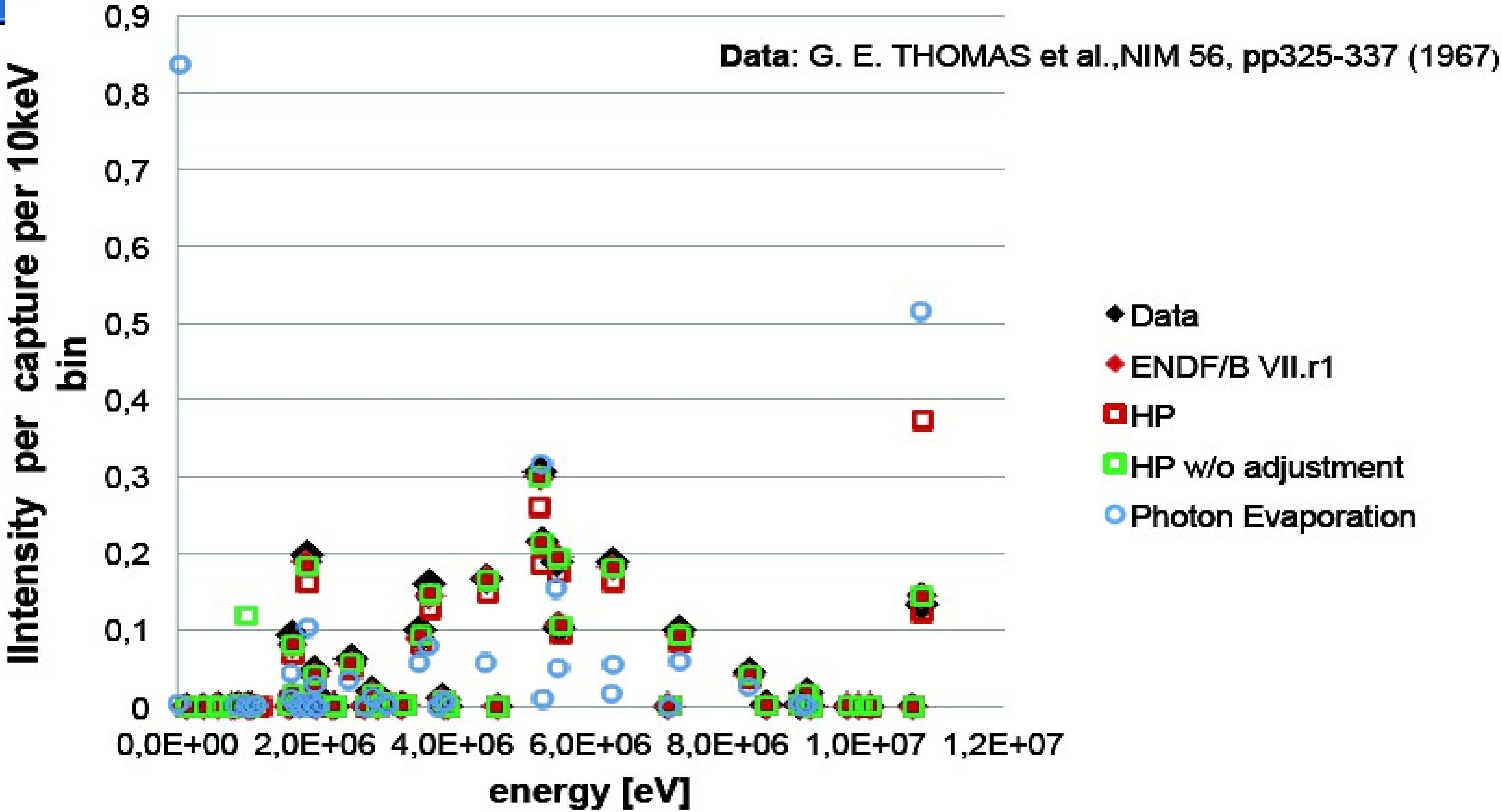
Verification of High Precision Neutron cross sections



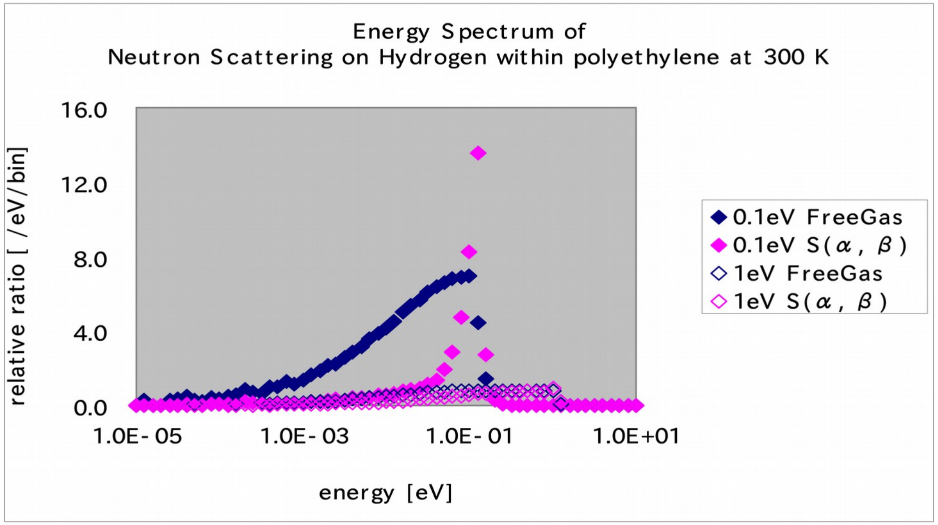
Verification of High Precision Neutron models: energy spectrum of secondary particles

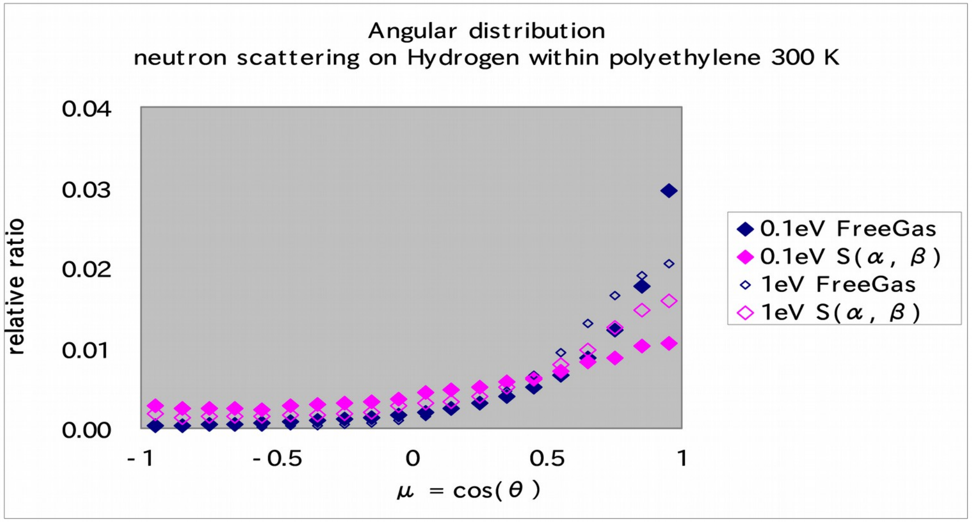


Validation of gamma emission after neutron capture by nitrogen



Cross section and Secondary Neutron Distributions using S(α, β) model





Ion Physics
Inelastic Reactions

- Cross Sections
- Models:
  - Binary Light Ion
  - QMD
  - INCL++

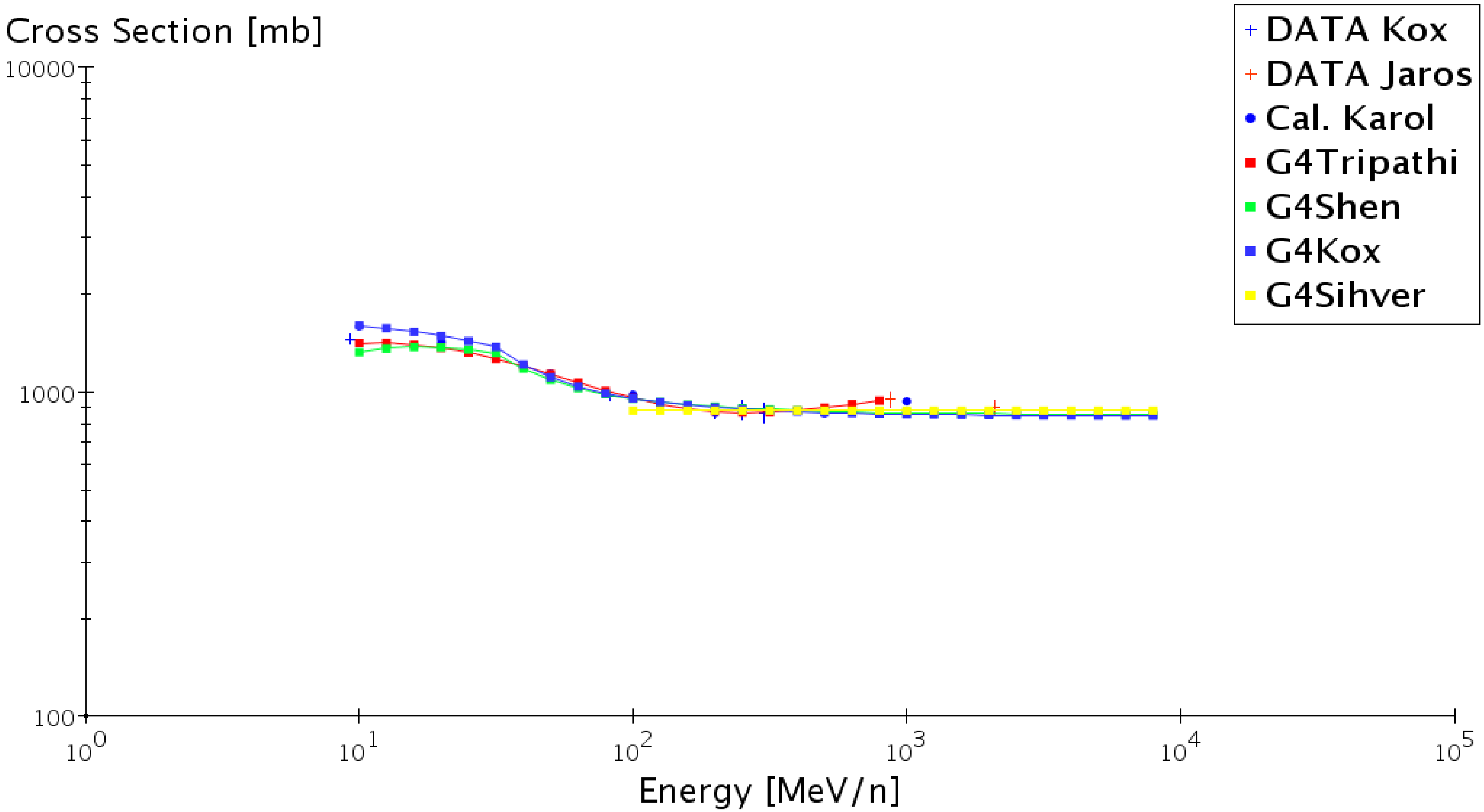
Cross Sections

- 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.

References to nucleus-nucleus 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)

Inelastic Cross Sections C12 on C12



Glauber-Gribov nucleus-nucleus cross sections

- Calculates total and inelastic cross section
- Derives elastic as total – inelastic, according to Glauber model with Gribov correction.
- Most reference physics lists recently switch to this cross section for nucleus-nucleus interactions

Models

- Binary Light Ion
- QMD
- INCL++

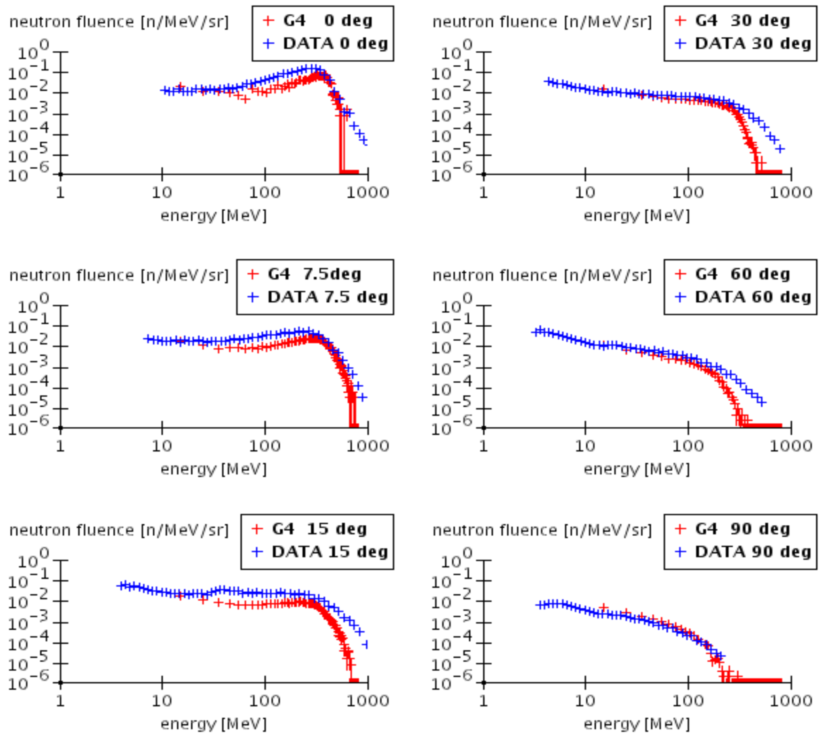
Binary Light Ion Cascade

- *Natural* extension of Binary Cascade to incident light ions
- Concept of participant & expectator incident nucleons

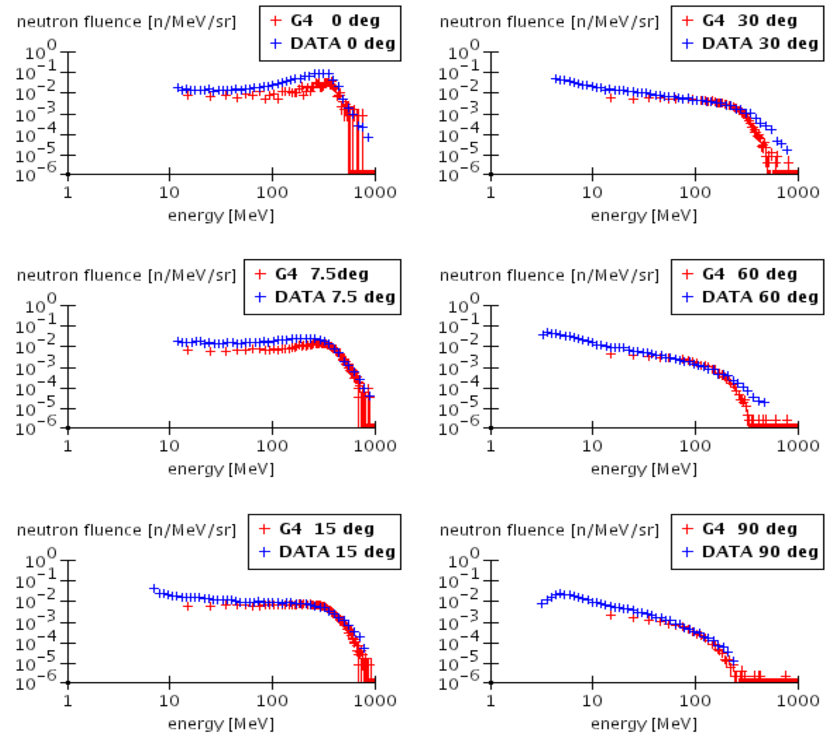
Physics List for Binary Light Ion

```
//Process
G4HadronInelasticProcess* theIPGenericIon =         new
G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() );
// Cross Section Data Set
G4TripathiCrossSection * TripathiCrossSection= new G4TripathiCrossSection;
G4IonsShenCrossSection * aShen = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(aShen);
theIPGenericIon->AddDataSet(TripathiCrossSection);
// Model
G4BinaryLightIonReaction * theGenIonBC= new G4BinaryLightIonReaction;
theIPGenericIon->RegisterMe(theGenIonBC);
//Apply Processes to Process Manager of GenericIon
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Neutron Yield
Fe 400 MeV/n beams



Copper Thick Target



Lead Thick Target

T. Kurosawa et al.,
Phys. Rev. **C62**
pp. 04461501 (2000)

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
- An altenative 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 Principle into account
  - can be used for high energy, high Z collisions
- **LIMITATION : CPU time consumption**

Physics List for QMD

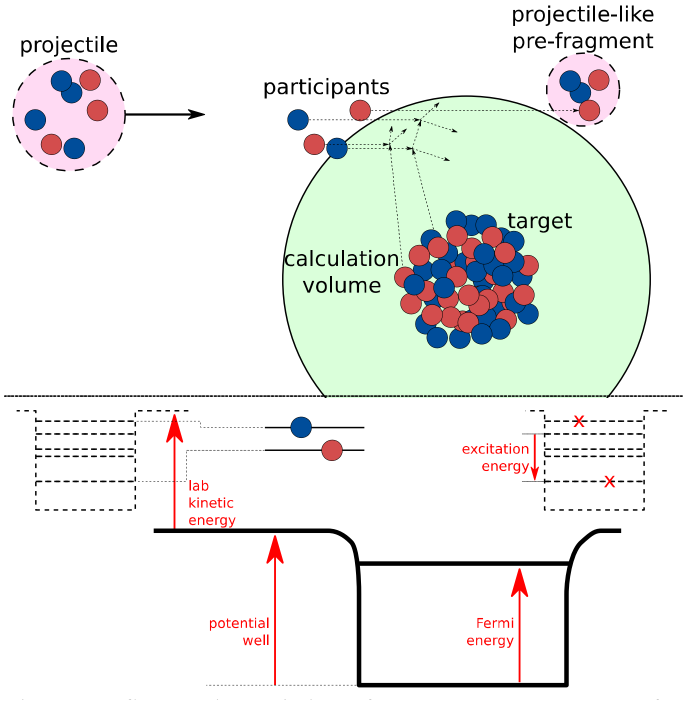
```
//Process
G4HadronInelasticProcess* theIPGenericIon =        new
G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() );
// Cross Section Data Set
G4TripathiCrossSection * TripathiCrossSection= new G4TripathiCrossSection;
G4IonsShenCrossSection * aShen = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(aShen);
theIPGenericIon->AddDataSet(TripathiCrossSection);
// Model
G4QMDReaction * theGenIonQMD= new G4QMDReaction;
theIPGenericIon->RegisterMe(theGenIonQMD);
//Apply Processes to Process Manager of GenericIon
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

INCL++

- Liège intranuclear-cascade model (INCL), jointly developed by CEA-Saclay (France) and the University of Liège (Belgium)
  - Nucleon- and pion-induced reactions on nuclei between ~100 MeV and ~3 GeV
  - Coupled to a suitable nuclear de-excitation model, it can reliably reproduce several observables such as emission spectra of particles and light ions, residual mass and charge distributions and residual recoil- velocity distributions
  - Original model written in Fortran
- **INCL++** is a completely redesigned version of the INCL model in C++ for Geant4
  - Better performance than original!
  - Extension to light projectiles is already available

Schematic depiction of the preparatory phase of a nucleus-nucleus reaction in INCL++

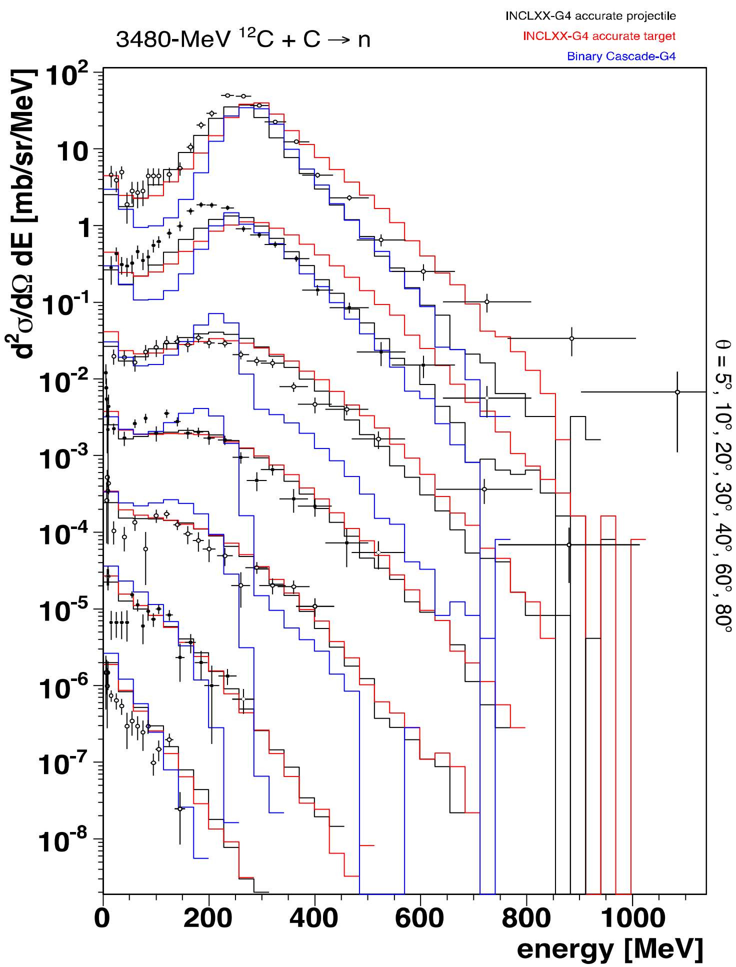
- INCL hadron-nucleus model used to interact projectile nucleons with target
- True potential is not used for projectile nucleus, but binding energy is taken into account
- True potential is used for target
- Projectile nucleons can pass through to form fragment or interact with nucleus



Physics List for INCL++

- Included in reference physics lists QGSP_INCLXX and FTFP_INCLXX
- INCL++ is used in ions reactions that one of the nucleus is equal to or lighter than carbon, otherwise Binary light ion cascade or G4QMD will handle these reactions.
- G4IonINCLXXPhysics constructor in the physics list.
  - RegisterPhysics(new G4IonINCLXXPhysics(ver));

Double-differential cross section for neutron produc- tion from a 290 AMeV 12C+C reaction.



INCLXX-G4 projectile

INCLXX-G4 target

Binary Cascade

Y. Iwata et al., *Phys. Rev. C*, 64, 054609 (2001).


Grazie mille per vostra attenzione
Thanks for your attention