GeantV – Hadronic and Neutron Physics

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Outline

- Plan for GeantV Hadronic Physics
- Design of GeantV Hadronic Physics Interface
- Neutron Physics

Plan for GeantV Hadronic Physics

Vectorization of Physics

To achieve significant speed-up of the simulation from the vectorization & locality of the physics is very challenging

- Semi-classical approach, no quantum-mechanical evolution of a wave function → plenty of “if-then-else” branches to emulate the richness of the physics naturally embedded in the wave-function
- The electromagnetic physics sector is the most critical for CPU performance
  - most particles are low-energy electrons and gammas; hadronic showers have a electromagnetic component
- Hadronic physics is less important, with the detailed transportation of low-energy neutrons as the most promising for vectorization

Geant4 Evolution in the Simulation of Hadronic Showers

LHEP	Gheisha parameterized model
↓	
QGSP	Theory models (string + precompound/excitation) at high energies
↓	
QGSP_BERT	Added intra-nuclear cascade model
↓	
FTFP_BERT	Low-energy extension of string model → no parameterized model any longer
↓ ?	
QGSP_BERT	More theory-based string model

Basic Ingredients for Hadronics in HEP

Worth to make a thorough review – theoretical basis, simplified approximations, algorithms - for both G4 & GV

- **Hadronic cross sections**
  - Glauber-Gribov approach
- **Elastic scattering**
  - Diffuse model
- **Precompound/de-excitation models**
- **Bertini-like intra-nuclear cascade model**
  - On-going interesting, but not yet successful, attempts to replace it with very low-energy extensions of string models…
- **QGS string model**

- *Precise transportation of low-energy neutrons*

GeantV Plan for Hadronic Physics Development

- Design of the Hadronic Physics Framework
- **Review & implementation** of the main hadronic **models** needed for simulating **hadronic showers**
  - Cross sections & elastic scattering : ~ 1.5 FTE yrs
  - Precompound/de-excitation : ~ 3 FTE yrs
  - Intranuclear cascade model (BERT-like) : ~ 3 FTE yrs
  - String model (QGS) : ~ 3 FTE yrs
- Start with **high-energy** applications, but with low-energy extensions in mind
  - e.g. low-energy neutrons already considered...

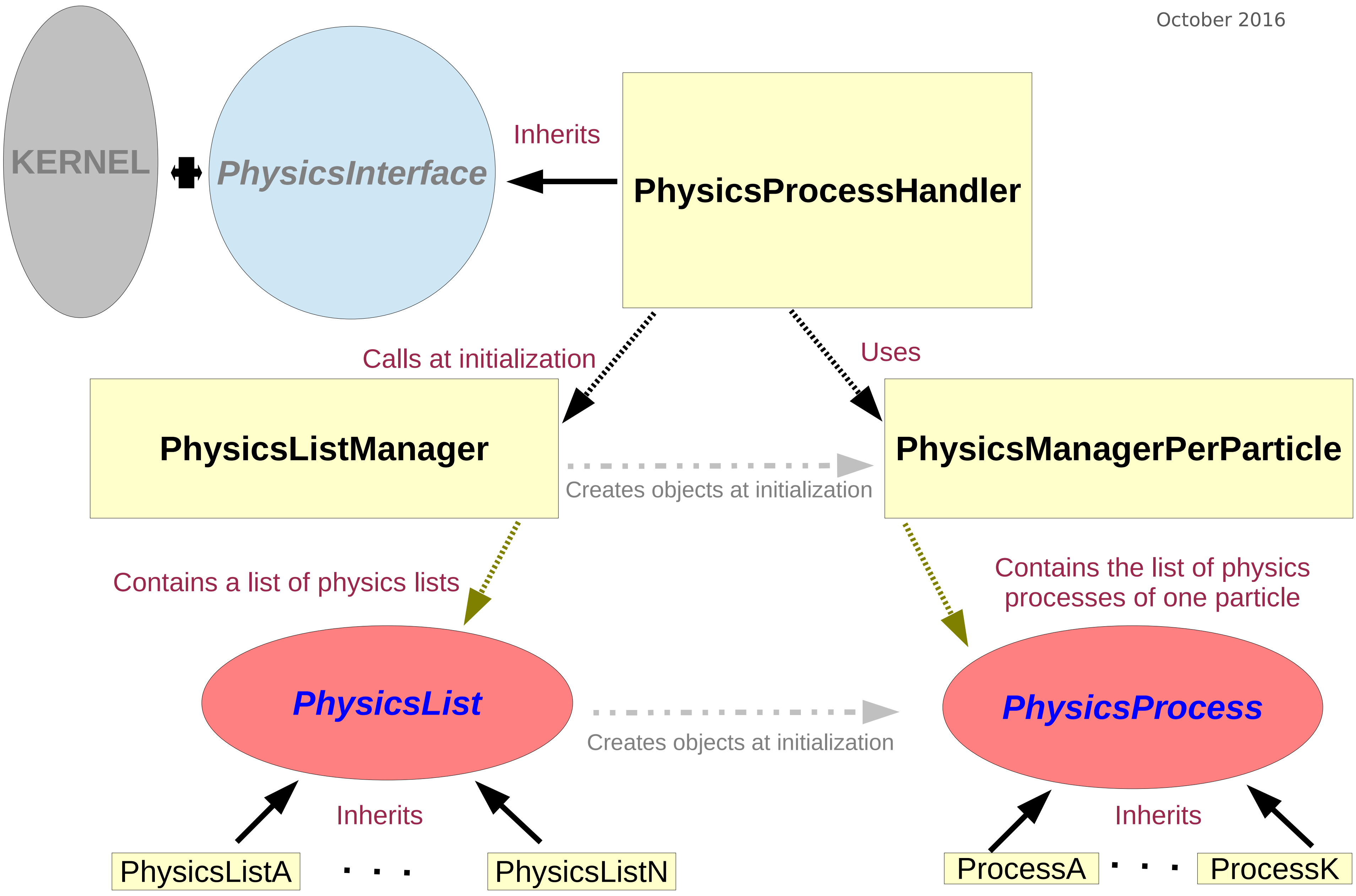
A Few Notes

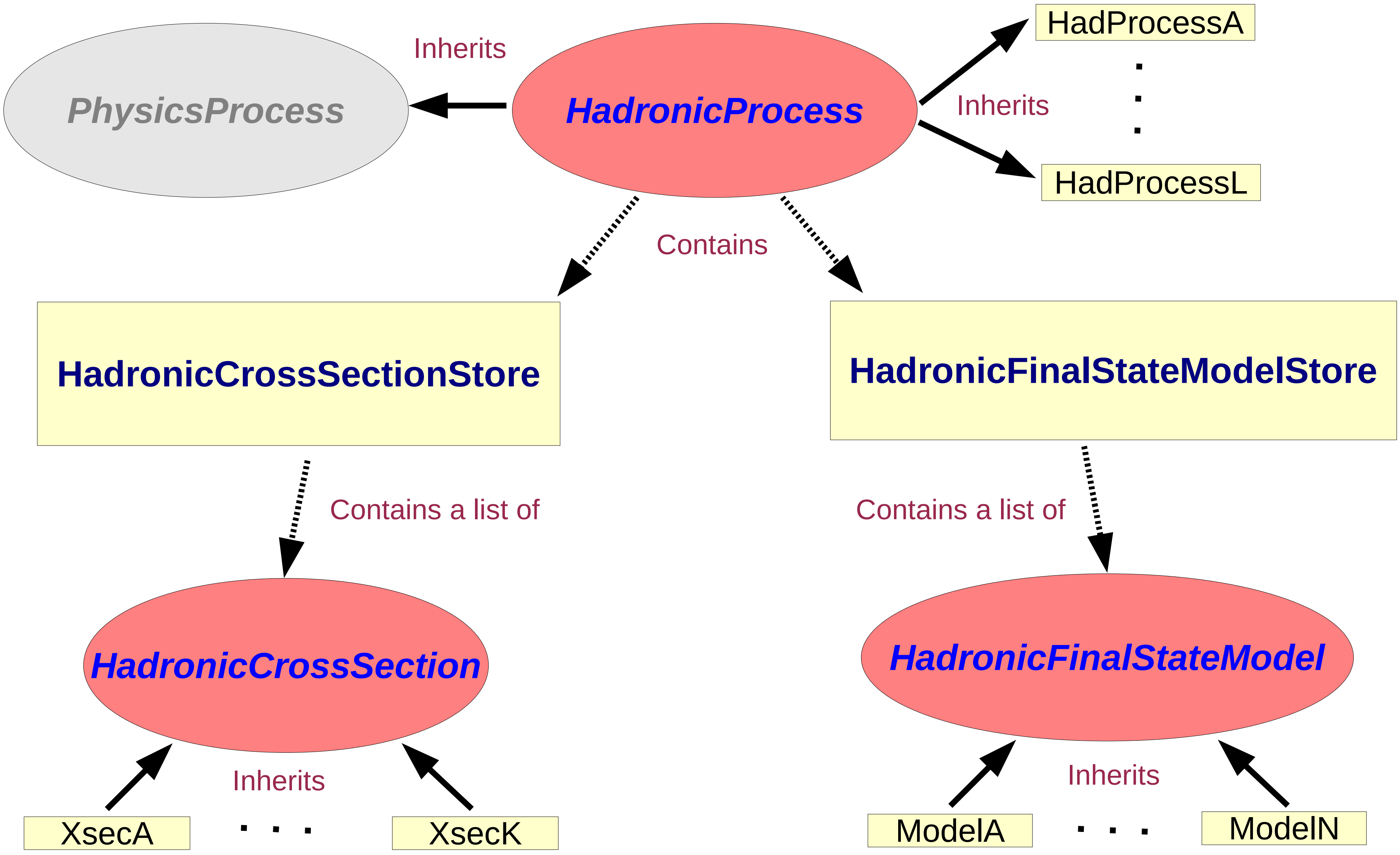
- Estimated efforts (in Full Time Equivalent) include:
  - review of theoretical papers
  - design and code implementation
  - development of validation tests
  - tuning of models parameters
  - Documentation
- For evaluation of systematic errors
  - Variation of models' parameters (ideal)
  - Development of alternative models (man-power issue)
  - Quick wrap/import of alternative models from Geant4
  - Run Geant4 with alternative models

Design of GeantV Hadronic Physics Interface

Goals of the Hadronic Physics Interface

- Create the basic infrastructure to fit hadronic physics in the existing physics interface of GeantV
- Leverage on key ideas of the design of Geant4 hadronic physics, but with a **bottom-up** approach
  - simplest interfaces to **cross sections** and **final-state models**, and on top of it the minimal structure needed to either **couple or mix** hadronic models
  - focus on scalar case but with vectorization in mind


KERNEL
PhysicsInterface
Inherits
PhysicsProcessHandler
Calls at initialization
Uses
PhysicsListManager
PhysicsManagerPerParticle
Creates objects at initialization
Contains a list of physics lists
Contains the list of physics processes of one particle
PhysicsList
PhysicsProcess
Creates objects at initialization
Inherits
Inherits
PhysicsListA
. . .
PhysicsListN
ProcessA
. . .
ProcessK

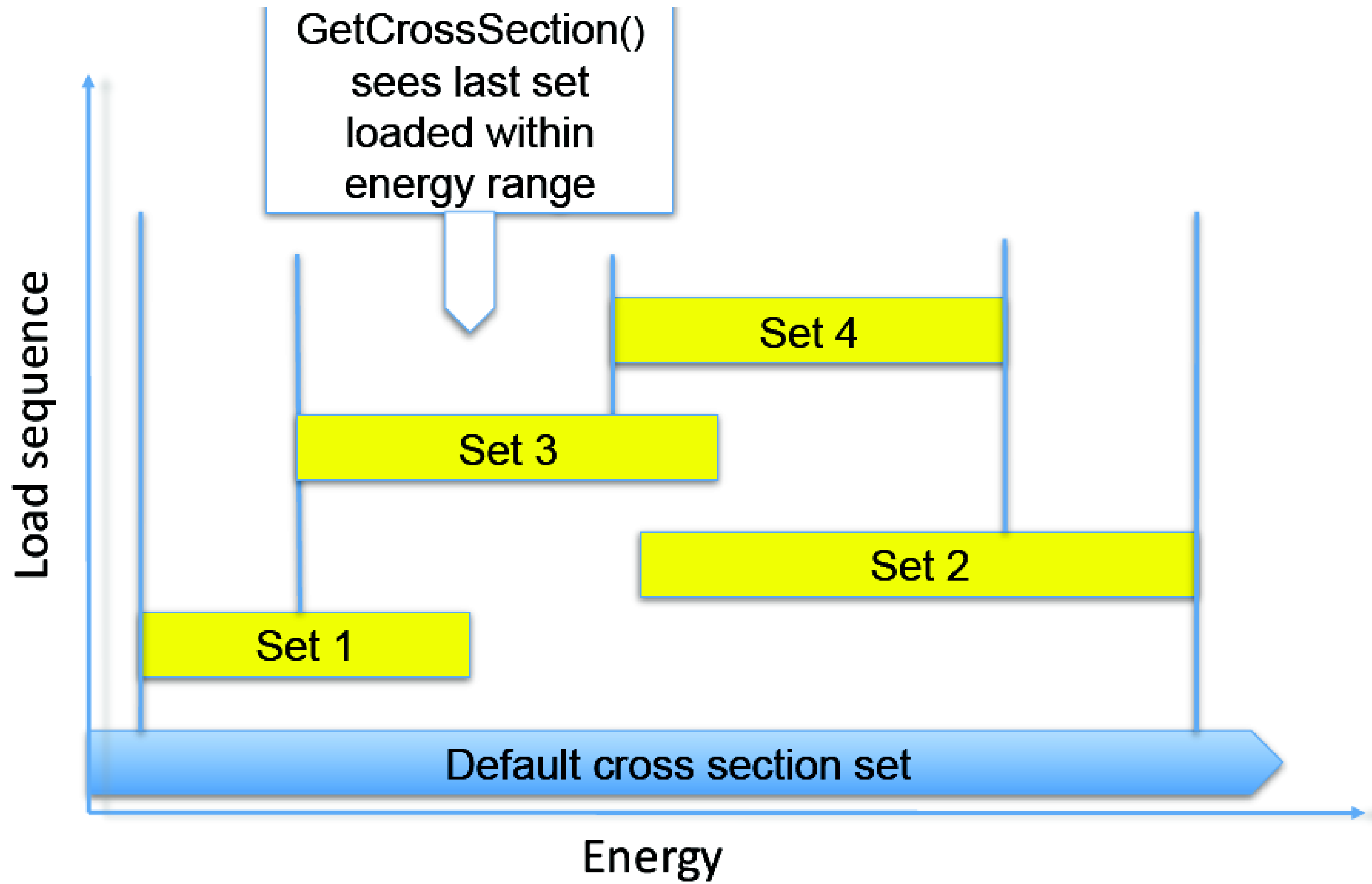

PhysicsProcess
Inherits
HadronicProcess
HadProcessA
Inherits
HadProcessL
Contains
HadronicCrossSectionStore
HadronicFinalStateModelStore
Contains a list of
Contains a list of
HadronicCrossSection
HadronicFinalStateModel
Inherits
XsecA
XsecK
Inherits
ModelA
ModelN

HadronicCrossSection

- Abstract base class for all microscopic hadronic cross sections
  - Per-element (in most cases) and per-isotope (for low-energy high-precision transportation) elastic or inelastic cross sections
  - For one or more projectile hadron type(s)
  - Similar to *G4VCrossSectionDataSet*

HadronicCrossSectionStore

- Class for all (microscopic & macroscopic) hadronic cross sections
  - Per-isotope, per-element, per-material (macroscopic, i.e. times the number of atoms for unit of volume) elastic or inelastic cross sections, for one or more projectile hadron type(s)
  - List of (pointers to) HadronicCrossSection objects
    - last-in-first-out or with ordering-priorities
  - Similar to *G4CrossSectionDataStor*e

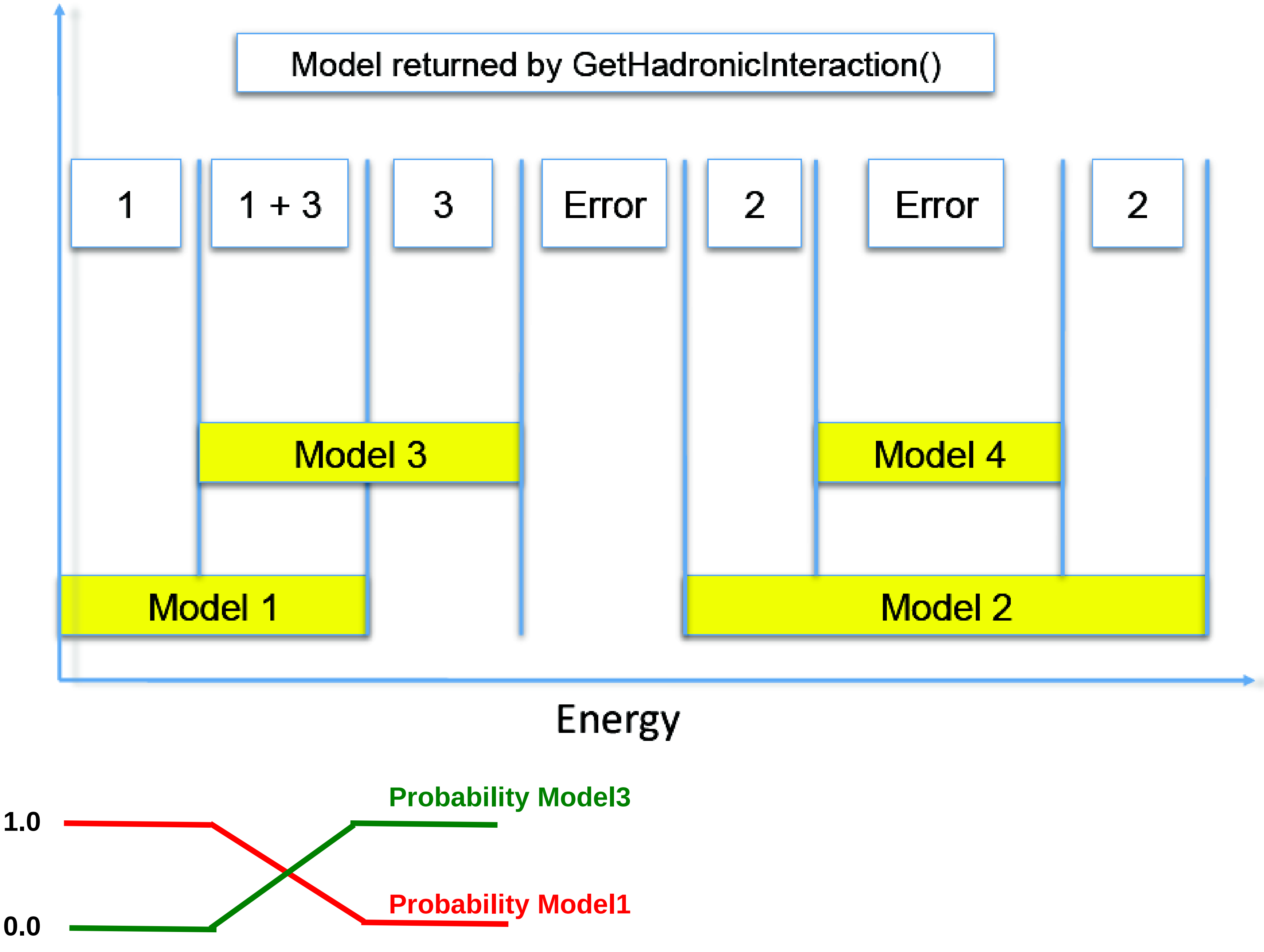

GetCrossSection()
sees last set
loaded within
energy range
Set 4
Set 3
Set 2
Set 1
Default cross section set
Load sequence
Energy

HadronicFinalStateModel

- Abstract base class for all hadronic final-state models
  - Elastic and inelastic final-state models
  - For one or more projectile hadron type(s)
  - Similar to *G4HadronicInteraction*

HadronicFinalStateModelStore

- Class for all hadronic final-state models
  - List of (pointers to) elastic or inelastic final-state model objects (derived from HadronicFinalStateModel), for one or more projectile hadron type(s)
    - Order of registration of models does not matter
  - Overlapping in the projectile energy between models is allowed, but with the “usual” two restrictions:
    - Not more than 2 models can overlap in the same interval
    - Two models cannot fully overlap
  - When two models overlap in an energy interval, at each interaction one model is chosen randomly with the “usual” rule of linear probability...



Model returned by GetHadronicInteraction()
1
1 + 3
3
Error
2
Error
2
Model 3
Model 4
Model 1
Model 2
Energy
Probability Model3
1.0
Probability Model1
0.0

HadronicProcess

- Abstract base class for all hadronic physics processes
  - Elastic or inelastic
  - For one or more projectile hadron type(s)
  - Inherits from *PhysicsProcess*
  - Contains (a pointer to) *HadronicCrossSectionStore* and *HadronicFinalStateModelStore* objects
  - Similar to *G4HadronicProcess*

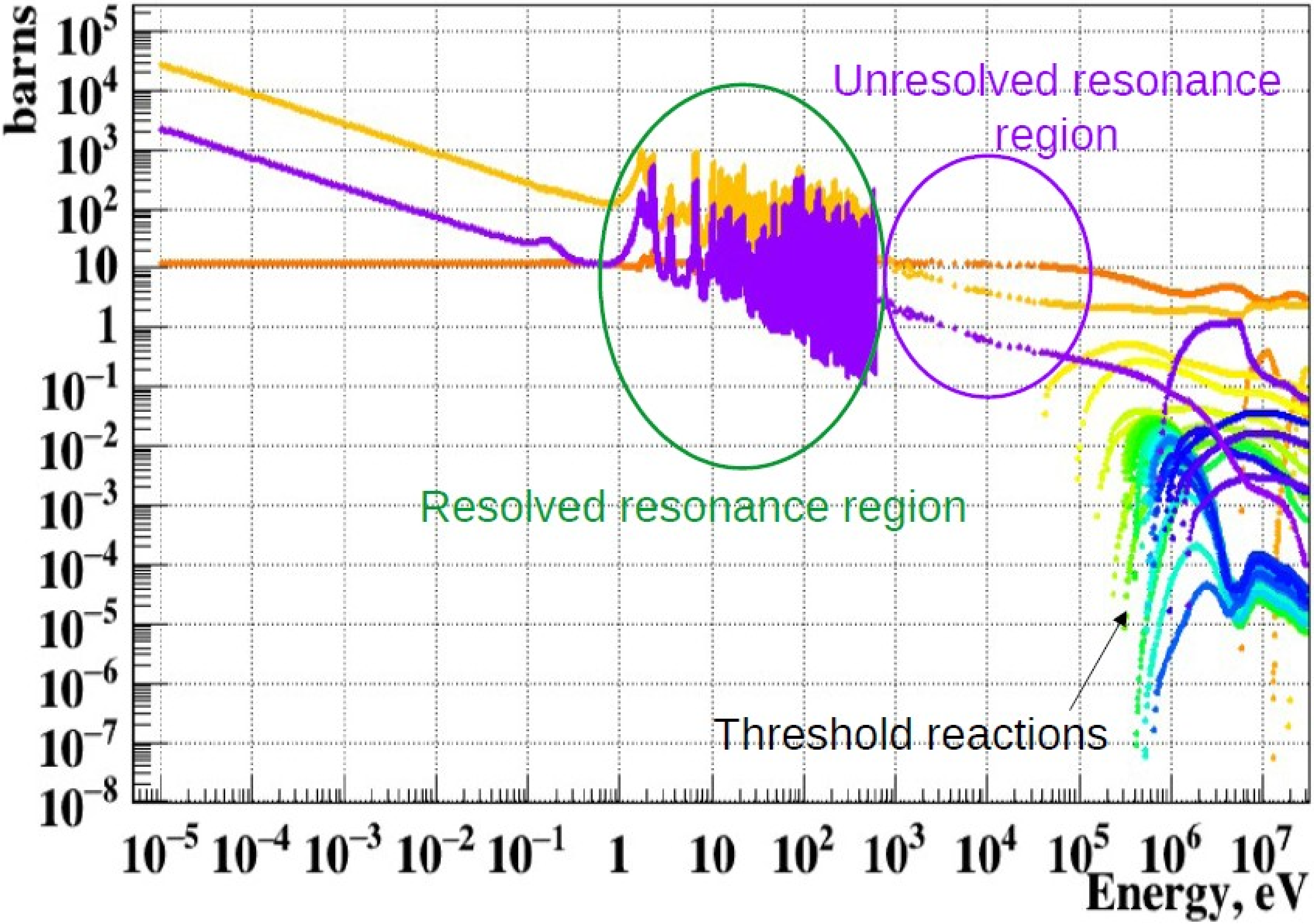
Neutron Physics

Introduction

- Neutrons are abundantly produced in hadron-nucleus collisions
  - Mostly “soft” neutrons, produced by the de-excitation of nuclei
  - It is typically the third most produced particle type (after e^- , γ)
- Before a neutron “disappears” via an inelastic interaction (or decay), it can have many **elastic scatterings** with nuclei, and eventually can “thermalize” in the environment
- The CPU time of a detector simulation can vary by an order of magnitude according to the physical accuracy of the neutron transportation simulation
  - For typical HEP applications, a simple and fast treatment is sufficient (luckily!)
  - For activation and radiation damage studies, a more precise, **data-driven isotope-specific** treatment is needed, especially for neutrons of kinetic energies **below ~ MeV**

High-Precision Transportation of Low-Energy Neutrons

- No theoretical model can work well for all isotopes: a data-driven approach is therefore necessary!
- **Evaluated neutron scattering data libraries** available for neutron kinetic energies below ~20 MeV (200 MeV in few cases) , down to thermal energies
- Includes 4 types of interactions
  - **Elastic scattering**
  - **Radiative capture**
  - **Fission**
  - **Inelastic scattering**
- The large number of neutrons, having several similar interactions, most of which relatively simple and with only neutrons and/or gammas as final state, makes the treatment of low-energy neutron transportation potentially promising for vectorization and GPUs



barns
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
Unresolved resonance region
Resolved resonance region
Threshold reactions
10^-5 10^-4 10^-3 10^-2 10^-1 1 10 10^2 10^3 10^4 10^5 10^6 10^7
Energy, eV

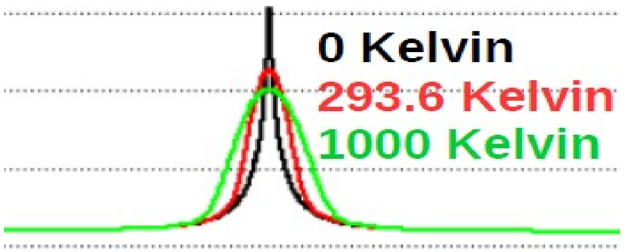
Reconstruction of Neutron Cross Sections

- The data are given as resonance parameters from which is possible to compute the cross sections for all reactions
- This is quite complex and CPU time consuming, and must be done with a dedicated pre-processing tool whose output files are then used by the simulation
  - NJOY and PREPRO are the standard packages
    - e.g. Geant4 use them to produce the G4NDL libraries
- For GeantV, a ROOT stand-alone application has been developed from scratch
  - Open source, easy to use and understand
  - Benefit of ROOT capabilities (fitting, graphics, etc.)

BARC : H.Kumawat, *et al.*

Some Details

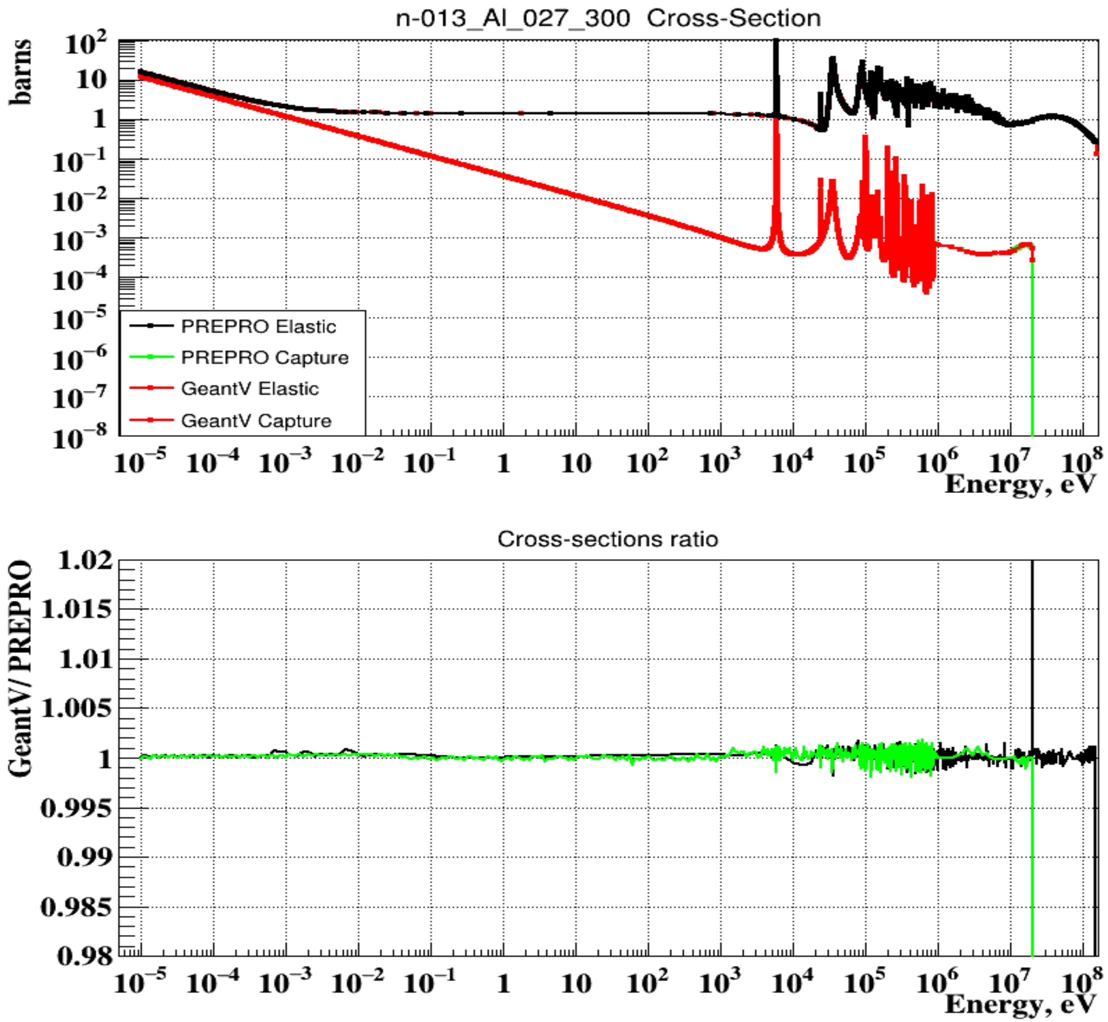
- Linearization
  - 4 formats: log-log, log-lin, lin-log, lin-lin
- "Unionization"
  - Union of all energy points from different reactions and calculate xsec for all of these energy points
- Doppler broadening
  - From 0 K to 293.6 K



- Construct total cross sections
  - Resonance energy points, widths, types
    - Single-level Breit-Wigner, Multi-level Breit-Wigner, Reich-Moore, Adler-Adler

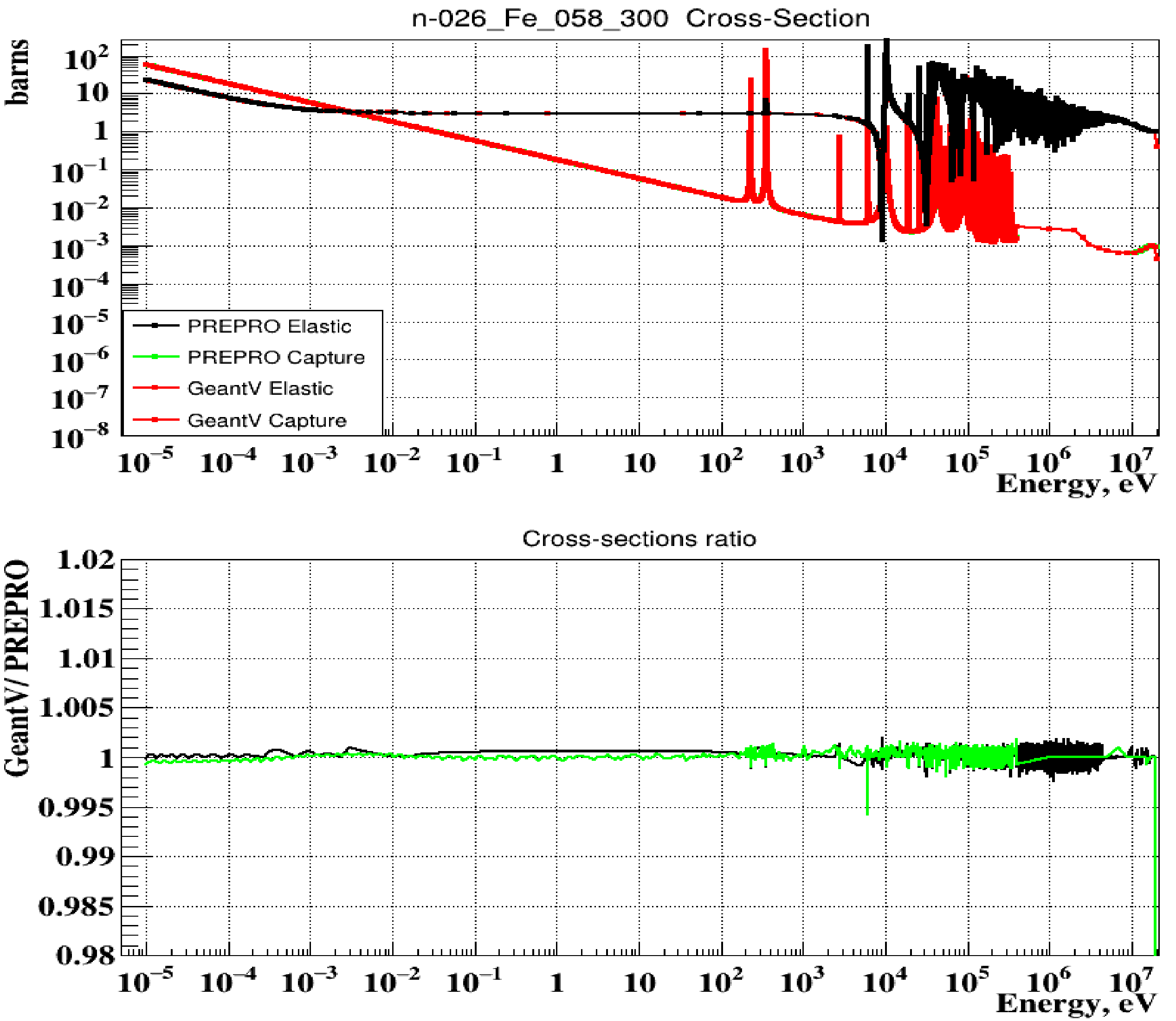
BARC : H.Kumawat, *et al.*

Reconstruction: **Al27** cross sections



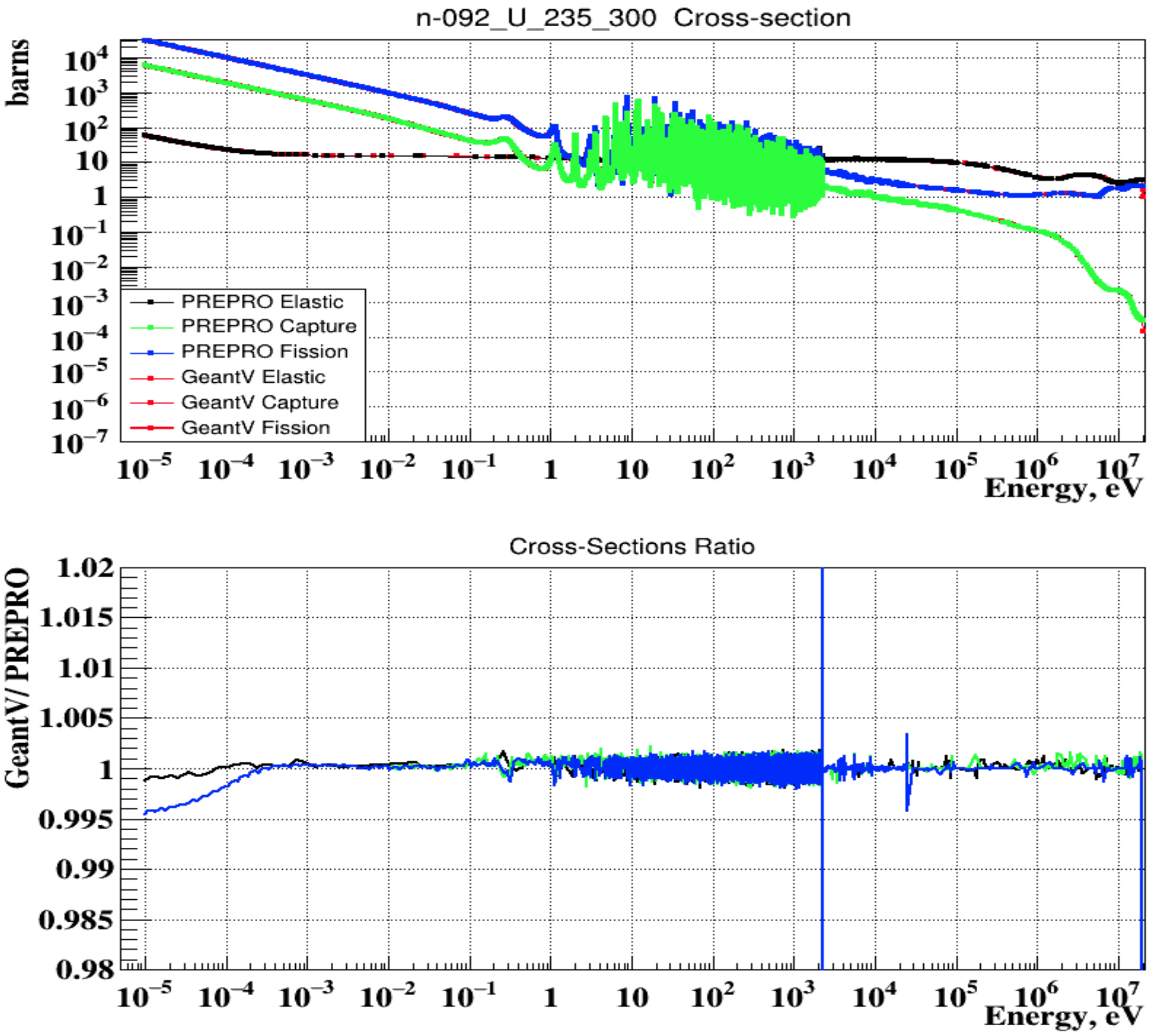
BARC : H.Kumawat, *et al.*

Reconstruction: **Fe58** cross sections



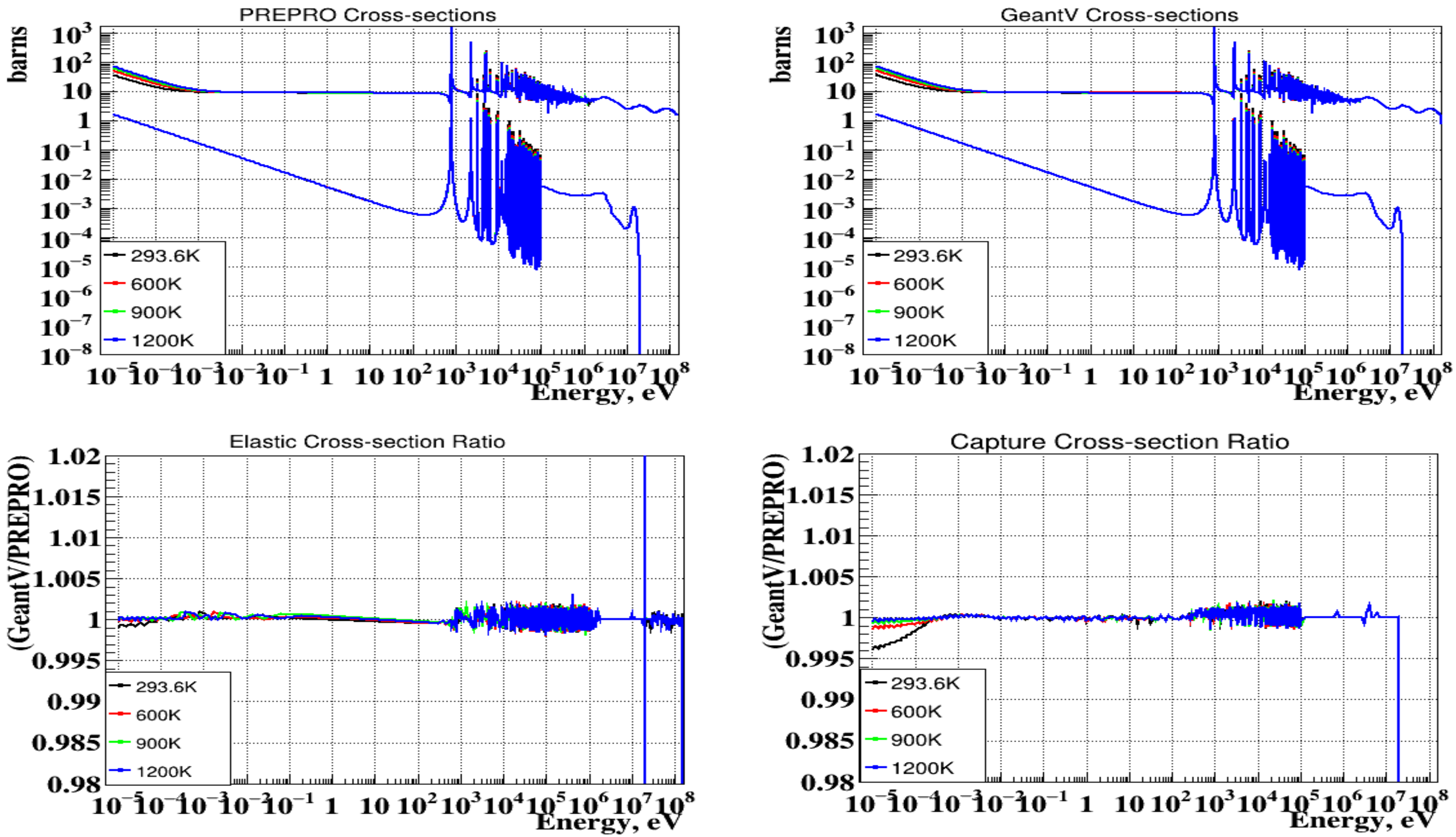
BARC : H.Kumawat, *et al.*

Reconstruction: **U235** cross sections



BARC : H.Kumawat, *et al.*

Doppler Broadening: **Bi209** cross section



BARC : H.Kumawat, *et al.*

Other Information

- Independent angular distributions
- Independent energy distributions
- Correlated angular-energy distributions
- Thermal neutron scattering data
- Decay data and fission products
- Production cross sections and multiplicities for radioactive nuclide production
- Photon production cross sections and multiplicities, and angular distributions

BARC : H.Kumawat, *et al.*

SLAC Proposal

M. Asai, A. Dotti, **T. Koi**

Develop a stand-alone, GPU friendly, neutron specific physics simulation library:
- outside of any specific "toolkit", but with integration into Geant4 and GeantV in mind
- specialized code to deal with (low Energy) neutron interactions