Electromagnetic and Hadronic physics in Geant4

Partially based on presentations by A. Lechner, M.G. Pia, V. Ivanchenko, S. Incerti, M. Maire and A. Howard and L.Pandola

Date

Outline

- The philosophy of the physics definition
- How to define and activate models
- Electromagnetic physics
- Hadronic physics

Philosophy

- Provide a general model framework that allows implementation of processes and models
- Separate models and cross sections implement processes
  - MULTIPLE MODELS FOR THE SAME PROCESS
- Provide processes containing
  - Many possible models and cross sections
  - Default cross sections for each model

Models under continuous development

G4VUserPhysicsList

- All physics lists must derive from this class
  - and then registered with the Run Manager
- Example

```
class MyPhysicsList: public G4VUserPhysicsList {
public:
MyPhysicsList();
~MyPhysicsList();
void ConstructParticle();
void ConstructProcess();
void SetCuts();
}
```

- User must implement the following methods:
  - ConstructParticle(), ConstructProces(), SetCuts()

ConstructParticle()

- Choose the particles you need in your simulation and define all of them here
  - G4Electron::ElectronDefinition()
  - ....
- It is possible use Geant4 classes that create groups of particles
  - G4BosonConstructor()
  - G4LeptonConstructor()
  - ....

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ConstructProcess()

- For each particle defined in ConstructParticle() assign all the physics processes that you want to consider

```
void MyPhysicsList::ConstructProcess()
 {
// provided by G4VUserPhysicsList, assign transportation
process to all particles defined in ConstructParticle()
AddTransportation();
ConstructEM()  //Optional
ConstructGeneral() // Optional
```

SetCuts()

- Define all production cuts for gamma, electrons and positrons
- Recently also for protons

Physics definition

- Three different way to implement the physics models
  - Explicitly associating a given model to a given particle for (eventually) a given energy range
    - Error prone
      - At code level
      - At physics level
  - Use of BUILDER and REFERENCE PHYSICS LISTS
    - Process related (standard, lowenergy, Bertini, etc.)
      - Defined in the physics lists class
    - Complete physics lists
      - Called by the macro file

G4VModularPhysicsList

- It is used to build a realistic physics list which would be to long and complicated with the previous approach
- It is derived from G4VUserPhysicsList
- AddTransportation automatically called
- Usage of the Builder
- Allows the definition of “physics modules”
  - Electromagnetic
  - hadronic
  - decay
  - ion physics
  - optical physics

Example of modular physics

```
G4eMultipleScattering* msc = new G4eMultipleScattering();
pmanager->AddProcess(msc,-1, 1, 1);
```

Reference physics lists

- Provide a complete and realistic physics with ALL models of interest
- Provided according to some Use-cases
- Few choices are available for EM physics
- Several possibilities for hadronic
- They are intended as starting point and their builder can be reused

Reference physics lists

- These families share components to attach certain types of processes to groups of particles. These components are:
  - electromagnetic interactions for all particles. Three different settings are offered
    - Default transport parameters (best performance)
    - Some optimised choice (_EMV extension)
    - Some experimental parameter (_EMX extension)
  - Inelastic interactions
  - Elastic scattering
  - Capture
  - Decay of unstable particles
  - Specialised treatment of low energy neutrons (< 20 MeV)

Case I - Explicit definition

```
else if (particleName == "e-")
  {
     //electron
     // process ordering: AddProcess(name, at rest, along step, post step)
     // Multiple scattering
     G4eMultipleScattering* msc = new G4eMultipleScattering();
     msc->SetStepLimitType(fUseDistanceToBoundary);
     pmanager->AddProcess(msc,-1, 1, 1);

     // Ionisation
     G4eIonisation* eIonisation = new G4eIonisation();
     eIonisation->SetEmModel(new G4LivermoreIonisationModel());
     eIonisation->SetStepFunction(0.2, 100*um); //improved precision in tracking
     pmanager->AddProcess(eIonisation,-1, 2, 2);

     // Bremsstrahlung
     G4eBremsstrahlung* eBremsstrahlung = new G4eBremsstrahlung();
     eBremsstrahlung->SetEmModel(new G4LivermoreBremsstrahlungModel());
     pmanager->AddProcess(eBremsstrahlung, -1,-3, 3);
```

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Case II - Builders

```
if (name == "standard_opt3") {
   emName = name;
   delete emPhysicsList;
   emPhysicsList = new G4EmStandardPhysics_option3();

 } else if (name == "LowE_Livermore") {
   emName = name;
   delete emPhysicsList;
   emPhysicsList = new G4EmLivermorePhysics();

 } else if (name == "LowE_Penelope") {
   emName = name;
   delete emPhysicsList;
   emPhysicsList = new G4EmPenelopePhysics();
```

Builders
$G4INSTALL/source/physics_lists/builders

Case III - Reference Physics Lists

In your main

```
include <QGSP_BERT.hh>

int main(int,char**)
{
//....
      runManager->SetUserInitialization( new QGSP_BERT );
}

OR

#include <G4PhysListFactory.hh>
int main(int,char**)
{
//....
 G4PhysListFactory factory;
 G4VModularPhysicsList* physList = factory.ReferencePhysList();
 runManager->SetUserInitialization( physList );
}
```

Reference Physics Lists
$G4INSTALL/source/physics_lists/lists

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EM concepts I

- The same physics processes (e.g. Compton scattering) can be described by different models, that can be alternative or complementary in a given energy range
- For instance: Compton scattering can be described by
  - G4KleinNishinaCompton
  - G4LivermoreComptonModel (specialized low-energy, based on the Livermore database)
  - G4PenelopeComptonModel (specialized low-energy, based on the Penelope analytical model)
  - G4LivermorePolarizedComptonModel (specialized low-energy, Livermore database with polarization)
  - G4PolarizedComptonModel (Klein-Nishina with polarization)
- Different models can be combined, so that the appropriate one is used in each given energy range (␣ performance optimization)

EM concepts II

- A physical interaction or process is described by a process class
  - Naming scheme : « G4ProcessName »
  - Eg. : « G4Compton » for photon Compton scattering
- A physical process can be simulated according to several models, each model being described by a model class
  - The usual naming scheme is: « G4ModelNameProcessNameModel »
  - Eg. : « G4LivermoreComptonModel » for the Livermore Compton model
  - Models can be alternative and/or complementary on certain energy ranges
  - Refer to the Geant4 manual for the full list of available models

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EM physics models

- Models and processes for the description of the EM interactions in Geant4 have been grouped in several packages

Package	Description
Standard	γ-rays, $e^{\pm}$ up to 100 TeV, Hadrons, ions up to 100 TeV
Muons	Muons up to 1 PeV
X-rays	X-rays and optical photon production
Optical	Optical photons interactions
High-Energy	Processes at high energy (> 10 GeV). Physics for exotic particles
Low-Energy	Specialized processes for low-energy (down to 250 eV), including atomic effects
Polarization	Simulation of polarized beams

EM processes for gamma and e+/-

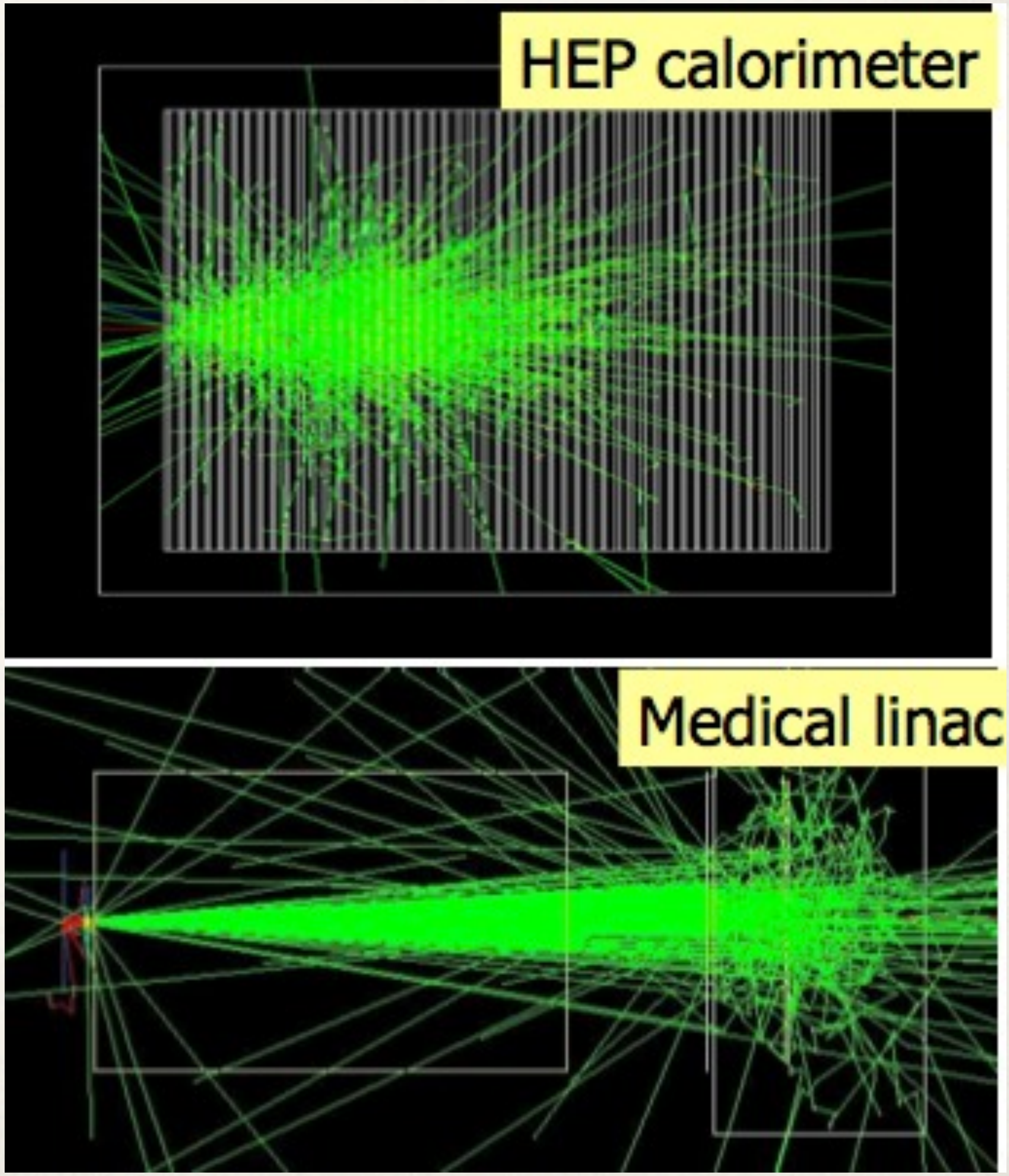
Particle	Process	G4Process
Photons	Gamma Conversion in $e^{\pm}$	G4GammaConversion
	Compton scattering	G4ComptonScattering
	Photoelectric effect	G4PhotoElectricEffect
	Rayleigh scattering	G4RayleighScattering
$e^{\pm}$	Ionisation	G4eIonisation
	Bremsstrahlung	G4eBremsstrahlung
	Multiple scattering	G4eMultipleScattering
e^{+}	Annihilation	G4eplusAnnihilation

Standard EM package

- Standard
  - Gamma, electrons up to 100 TeV
  - Hadrons up to 100 TeV
  - Ions up to 100 TeV
- Muons
  - Up to 1 PeV
- X rays
  - X-ray and optical photons
- Optical
  - Optical photon interaction
- Polarisation
  - New package for simulation of polarized beams

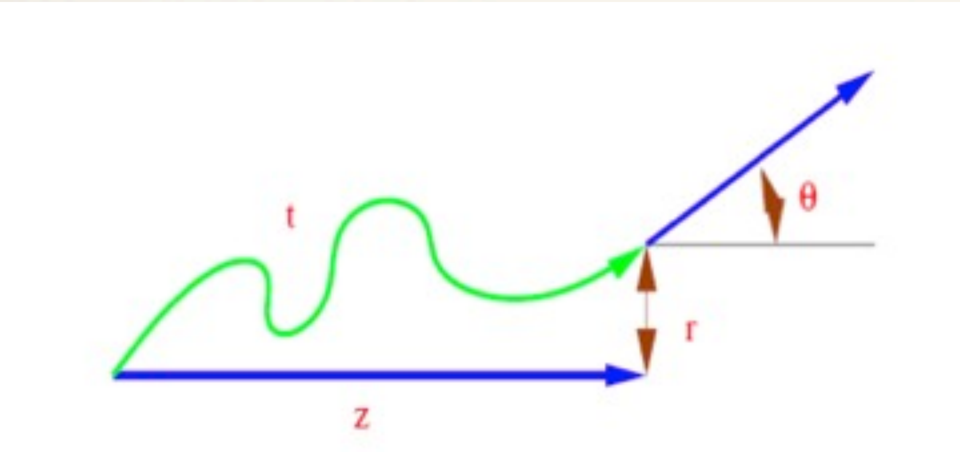
Gamma/electron transport examples

- Photon processes:
  - Gamma conversion into e−/e+ pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering (in the LowE package)
- e−/+ processes
  - Ionisation
  - Coulomb scattering
  - Bremsstrahlung
  - Nuclear interaction (in the CHIP sub-package)
- Positron annihilation



Multiple scattering

- Charged particles traversing a medium suffer repeated elastic Coulomb scattering
- The cumulative effects of these is a net deflection from the original particle direction
- Lewis theory
- See details in the Physics Reference manual



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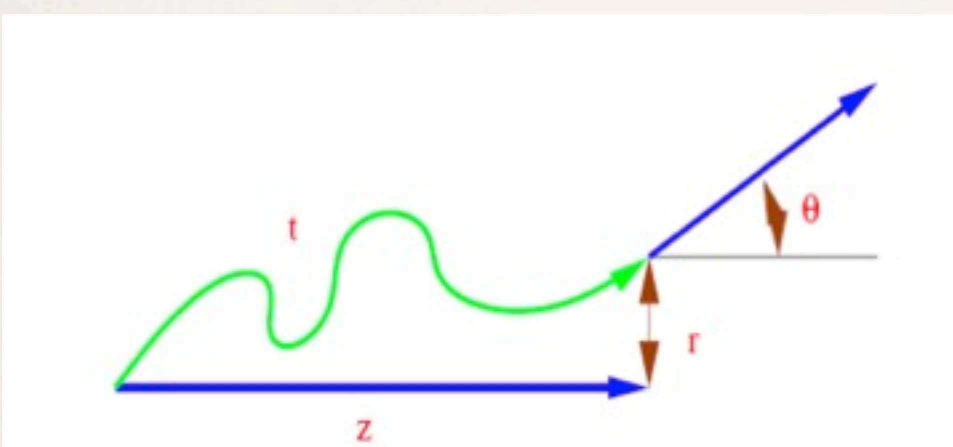
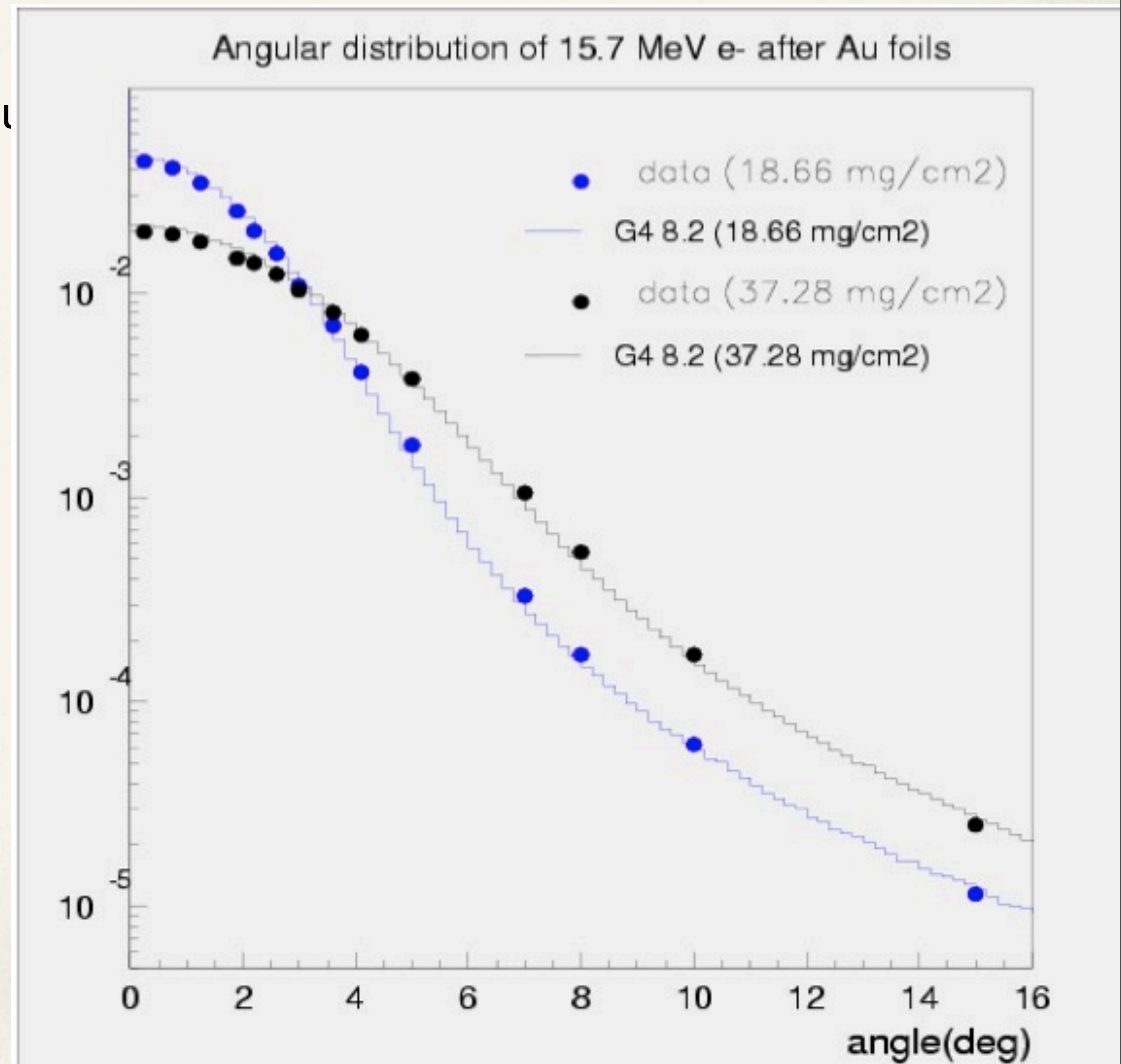


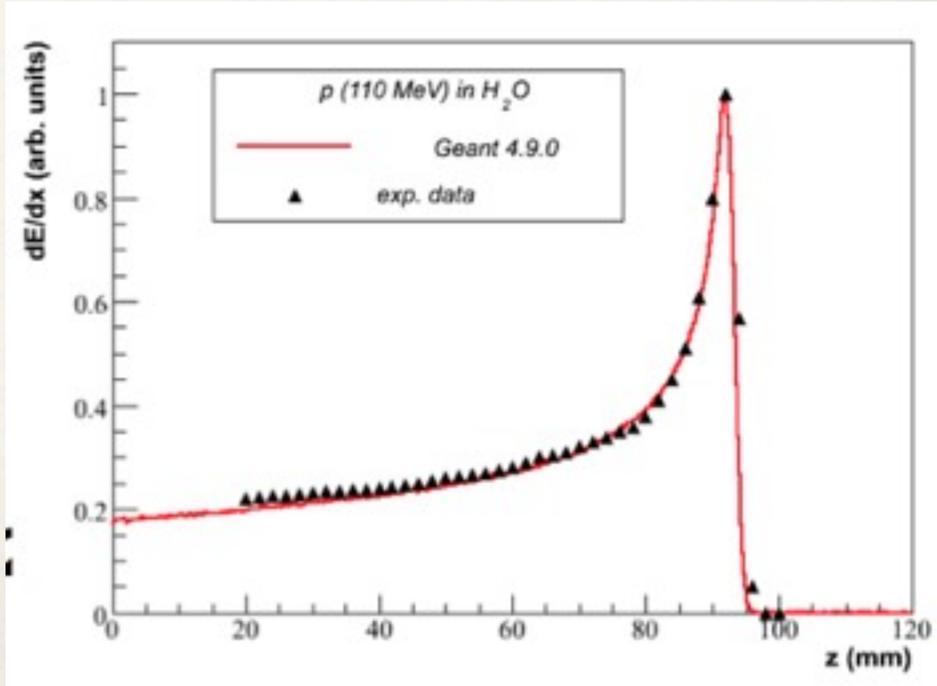


Hadron and Ion physics

- Coulomb scattering
- Bethe-Bloch formula with corrections for energy > 2 MeV

$$-\frac{dE}{dx} = 4\pi N_e r_0^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \frac{\beta^2}{2}\left(1-\frac{T_c}{T_{max}}\right) - \frac{C}{Z} + \frac{G-\delta-F}{2} + zL_1 + z^2 L_2\right)$$

- Bragg peak parameterisation for E < 2 MeV
- ICRU49, ICRU73, NIST database



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Using ICRU73 Tables

- ICRU 73 stopping powers are available for a range of elemental and compound materials:
  - To use ICRU73 tables only the Geant4 NIST material must be used (or must have the same name!)
  - ICRU73 stopping powers are not available for all NIST materials
  - Available stopping powers can be looked in the following classes ($G4INSTALL/source/materials):
  - G4SimpleMaterialStoppingICRU73(ions up to Ar)

Optical photons

- Optical photons are created by
  - Cherenkov effect **(G4Cherenkov)**
  - Transition radiation **(G4TransitionRadiation)**
  - Scintillation **(G4Scintillation)**
- Optical photon are hence managed by
  - Reflection and refraction at boundary **(G4OpBoundaryProcess)**
  - Absorption **(G4OpAbsorption)**
  - Rayleigh scattering **(G4OpRayleigh)**
  - Wavelength shifting **(G4OpWLS)**

LowEnergy (or Livermore) Models

- **Full set of models** in Geant4 for electrons, γ-rays and ions based on the **Livermore data libraries** (cross sections and final states)
- Energy range down to 250 eV. They include atomic effects, like fluorescence, Auger emission, etc.
- `G4LivemorePolarizedXXXXModel`

Particles	Processes	
Cross sections (probability to interact)	Evaluated Photon Data Library	: EPDL97
	Evaluated Electron Data Library	: EEDL
	Evaluated Atomic Data Library	: EADL
	International Commission on radiation Units	: ICRU49
	Binding energies	: Scofield

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Penelope models

- Geant4 includes the low-energy models for **e±** and γ**-rays** from the Monte Carlo code **PENELOPE** (PENetration and Energy LOss of Positrons and Electrons)
  Nucl. Instrum. Meth. B 207 (2003) 107
- The physics models have been specifically developed by the Barcelona group (F. Salvat et al.) and a great care was dedicated to the low-energy description (atomic effects, fluorescence, Doppler broadening, etc.)
- Mixed approach: analytical, parametrized & database-driven ␣
  applicabilityenergyrange:**250eV␣1GeV**
- Includes also **positrons** (not described by Livermore models**)**
- `G4PenelopeXXXXModel` (e.g. `G4PenelopeComptonModel`)

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When/why to use Low Energy models

- **Use** Low-Energy models (Livermore or Penelope), as an alternative to Standard models, when you:
  - need precise treatment of EM showers and interactions at low-energy (keV scale)
  - are interested in atomic effects, as fluorescence x-rays, Doppler broadening, etc.
  - can afford a more CPU-intensive simulation
  - want to cross-check an other simulation (e.g. with a different model)
- Do **not** use when you are interested in EM physics MeV
  - same results as Standard EM models, performance penalty

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Example: physics list for gamma

```
G4ProcessManager* pmanager
if ( particleName == "gamma"  )
{
   pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
   pmanager->AddDiscreteProcess(new G4ComptonScattering);
   pmanager->AddDiscreteProcess(new G4GammaConversion);
   pmanager->AddDiscreteProcess(new G4RayleighScattering);
}
```

- For each process a default model is used among all the available ones:
  e.g. the **G4KleinNishinaCompton** for the **G4ComptonStcattering**)
- This default can be changed (e.g. **G4PenelopeComptonModel**)

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Physics List

- Physics Lists represents the way to make a general interface between physics and Geant4 kernel
  - It should include the list of particles
  - The G4ProcessManager of each particle maintains a list of processes
- Geant4 provides a set of different configuration of EM physics in the physics_list library
- These constructors can be also included into Modular Physics List User application

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Ready-to-use Physics Constructor

G4EmStandardPhysics – default
G4EmStandardPhysics_option1 – HEP fast but not precise
G4EmStandardPhysics_option2 – Experimental
G4EmStandardPhysics_option3 – medical, space

G4EmLivermorePhysics
G4EmLivermorePolarizedPhysics
G4EmPenelopePhysics
G4EmDNAPhysics

Combined Physics
Standard > 1 GeV
LowEnergy < 1 GeV

- **$G4INSTALL/source/physics_list/builders**
- Advantage of using of these classes – they are tested on regular basis and are used for regular validation

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How to extract physics

- Possible to retrieve physics quantities via the G4EmCalculator class file

- Example for retrieving total cross section of a process with name procName, for particle partName and for the material matName

```
G4EmCalculator emCalculator;
G4Material* material =
  G4NistManager::Instance()->FindOrBuildMaterial("matName);
G4double massSigma = emCalculator.ComputeCrossSectionPerVolume
   (energy,particle,procName,material);
G4cout << G4BestUnit(massSigma, "Surface/Volume") << G4endl;
```

See $G4INSTALL/examples/extended/electromagnetic/TestEm14

Hadronic Physics

- Data-driven models
- Parametrisation models
- Theory driven models

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Hadronic physics challenge

- Three energy regimes
  - < 100 MeV
  - resonance and cascade region (100 MeV – 10 GeV)
  - > 20 GeV (QCD strings)
- Within each regime there are several models
- Many of these are phenomenological

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Reference physics lists for Hadronic interaction

- Are part of the Geant4 code
- Four family of lists
  - LHEP or parameterised modelling of hadronic interactions
  - QGS, or list based on a model that use the Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions and kaons
  - FTF, based on the FTF (FRITIOF like string model) for protons, neutrons, pions and kaons
  - Other specialised physics lists

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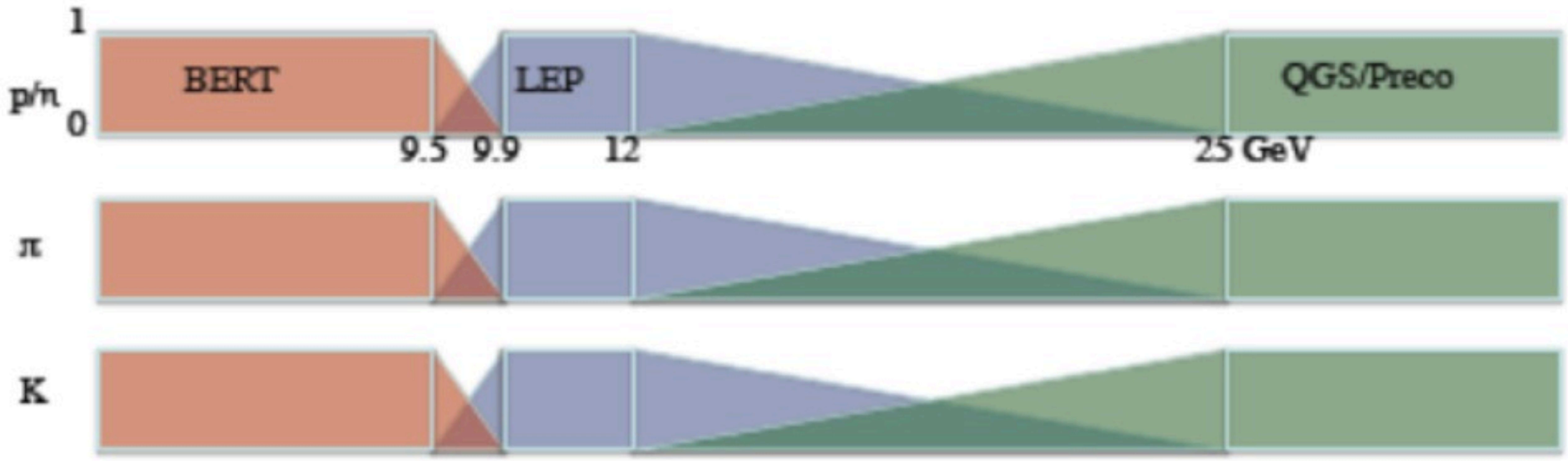
Reference physics lists: the QGS case

- Protons, neutrons, pions and kaons in 5-25 GeV range
- Interactions at lower energies are modelled with the LEP
- For some particles the LEP is replaced by a cascade models below 10 GeV
- Nuclear capture of negative particles and neutrons at rest are modelled using the CHIPS model
- Proton and neutron elastic scattering use CHIPS
- You can use this physics list calling the string “QGSP”

Reference physics lists: the QGS case

- **QGSP**: the created excited nucleus is passed to the Precompound model for the de-excitation
- **QGSP_EMV** optimized electromagnetic processes
- **QGSC**: the nuclear de-excitation is performed with CHIPS
- **QGSP_BERT**: like QGSP but using the Geant4 Bertini cascade for primary protons, neutrons and pions below 10 GeV
  - Better than QGSP that uses the LEP for low energy
- **QGSP_BERT_HP** : uses the data driven high precision neutron package (NeutronHP) to transport neutrons below 20 MeV down to thermal energies

Hadronic models match



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The complete lists of Reference Physics List

......./source/physics_lists/lists

```
-rw-r--r--  1 cirrone  staff   4102 16 Aug 09:14 QGSP_BERT_EMV.icc
-rw-r--r--  1 cirrone  staff   2564 11 May  2009 QGSP_BERT_EMX.hh
-rw-r--r--  1 cirrone  staff   4232 16 Aug 09:14 QGSP_BERT_EMX.icc
-rw-r--r--  1 cirrone  staff   2542 31 Oct  2006 QGSP_BERT_HP.hh
-rw-r--r--  1 cirrone  staff   4322 16 Aug 09:14 QGSP_BERT_HP.icc
-rw-r--r--  1 cirrone  staff   2586 17 Oct  2008 QGSP_BERT_NOLEP.hh
-rw-r--r--  1 cirrone  staff   4224 16 Aug 09:14 QGSP_BERT_NOLEP.icc
-rw-r--r--  1 cirrone  staff   2580 26 Apr  2007 QGSP_BERT_NQE.hh
-rw-r--r--  1 cirrone  staff   4240 16 Aug 09:14 QGSP_BERT_NQE.icc
-rw-r--r--  1 cirrone  staff   2557  7 May  2007 QGSP_BERT_TRV.hh
-rw-r--r--  1 cirrone  staff   4236 16 Aug 09:14 QGSP_BERT_TRV.icc
-rw-r--r--  1 cirrone  staff   2496 31 Oct  2006 QGSP_BIC.hh
-rw-r--r--  1 cirrone  staff   4578 16 Aug 09:14 QGSP_BIC.icc
-rw-r--r--  1 cirrone  staff   2552 11 May  2009 QGSP_BIC_EMY.hh
-rw-r--r--  1 cirrone  staff   4176 16 Aug 09:14 QGSP_BIC_EMY.icc
-rw-r--r--  1 cirrone  staff   2550 24 Nov  2006 QGSP_BIC_HP.hh
-rw-r--r--  1 cirrone  staff   4140 16 Aug 09:14 QGSP_BIC_HP.icc
-rw-r--r--  1 cirrone  staff   2563 13 Nov  2007 QGSP_DIF.hh
-rw-r--r--  1 cirrone  staff   4317 16 Aug 09:14 QGSP_DIF.icc
-rw-r--r--  1 cirrone  staff   2502 31 Oct  2006 QGSP_EMV.hh
-rw-r--r--  1 cirrone  staff   4822 16 Aug 09:14 QGSP_EMV.icc
-rw-r--r--  1 cirrone  staff   2541 26 Apr  2007 QGSP_EMV_NQE.hh
-rw-r--r--  1 cirrone  staff   4260 16 Aug 09:14 QGSP_EMV_NQE.icc
-rw-r--r--  1 cirrone  staff   2582 23 Apr  2009 QGSP_FTFP_BERT.hh
-rw-r--r--  1 cirrone  staff   4174 16 Aug 09:14 QGSP_FTFP_BERT.icc
-rw-r--r--  1 cirrone  staff   3499 19 Jul  2009 QGSP_INCL_ABLA.hh
-rw-r--r--  1 cirrone  staff   4262 16 Aug 09:14 QGSP_INCL_ABLA.icc
-rw-r--r--  1 cirrone  staff   2528 26 Apr  2007 QGSP_NQE.hh
-rw-r--r--  1 cirrone  staff   4234 16 Aug 09:14 QGSP_NQE.icc
-rw-r--r--  1 cirrone  staff   2523 28 Nov  2006 QGSP_QEL.hh
-rw-r--r--  1 cirrone  staff   4413 16 Aug 09:14 QGSP_QEL.icc
-rw-r--r--  1 cirrone  staff   2507 13 Nov  2007 QGS_BIC.hh
-rw-r--r--  1 cirrone  staff   4188 16 Aug 09:14 QGS_BIC.icc
-rw-r--r--  1 cirrone  staff   2521  8 Jun 18:05 Shielding.hh
-rw-r--r--  1 cirrone  staff   4113 16 Aug 09:14 Shielding.icc
-rw-r--r--  1 cirrone  staff   3710 31 Oct  2006 SpecialCuts.hh
lists Lavora! > _
```

Recommended reference physics lists

- A dedicated web page
- Application fields are identified
  - High energy physics
  - LHC neutron fluxes
  - Shielding
  - Medical
  - ....

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Where to find information?

- Process/model catalog
  - Home/User Support --> Geant4 web site

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Where to find information?

User Support

1. Getting started
2. Training courses and materials
3. Source code
   a. Download page
   b. LXR code browser -or- draft doxygen documentation
4. Frequently Asked Questions (FAQ)
5. Bug reports and fixes
6. User requirements tracker
7. User Forum
8. Documentation
   a. Introduction to Geant4
   b. Installation Guide
   c. Application Developers Guide
   d. Toolkit Developers Guide
   e. Physics Reference Manual
   f. Software Reference Manual
9. Physics lists
   a. Electromagnetic
   b. Hadronic

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Hadronic processes

- At rest
  - Stopped muon, pion, ...
  - Radioactive decay
- Elastic scattering
- Inelastic
  - Different process for each hadron
  - Photo-nuclear
  - Electro-nuclear
- Capture
- Fission

.... and some corresponding models

- Hadron Elastic scattering
  - G4LElastic
  - G4QElastic
  - G4HElastic
- Hadron inelastic interactions
  - String models
  - cascade models
    - Bertini, Binary, INCL/ABLA

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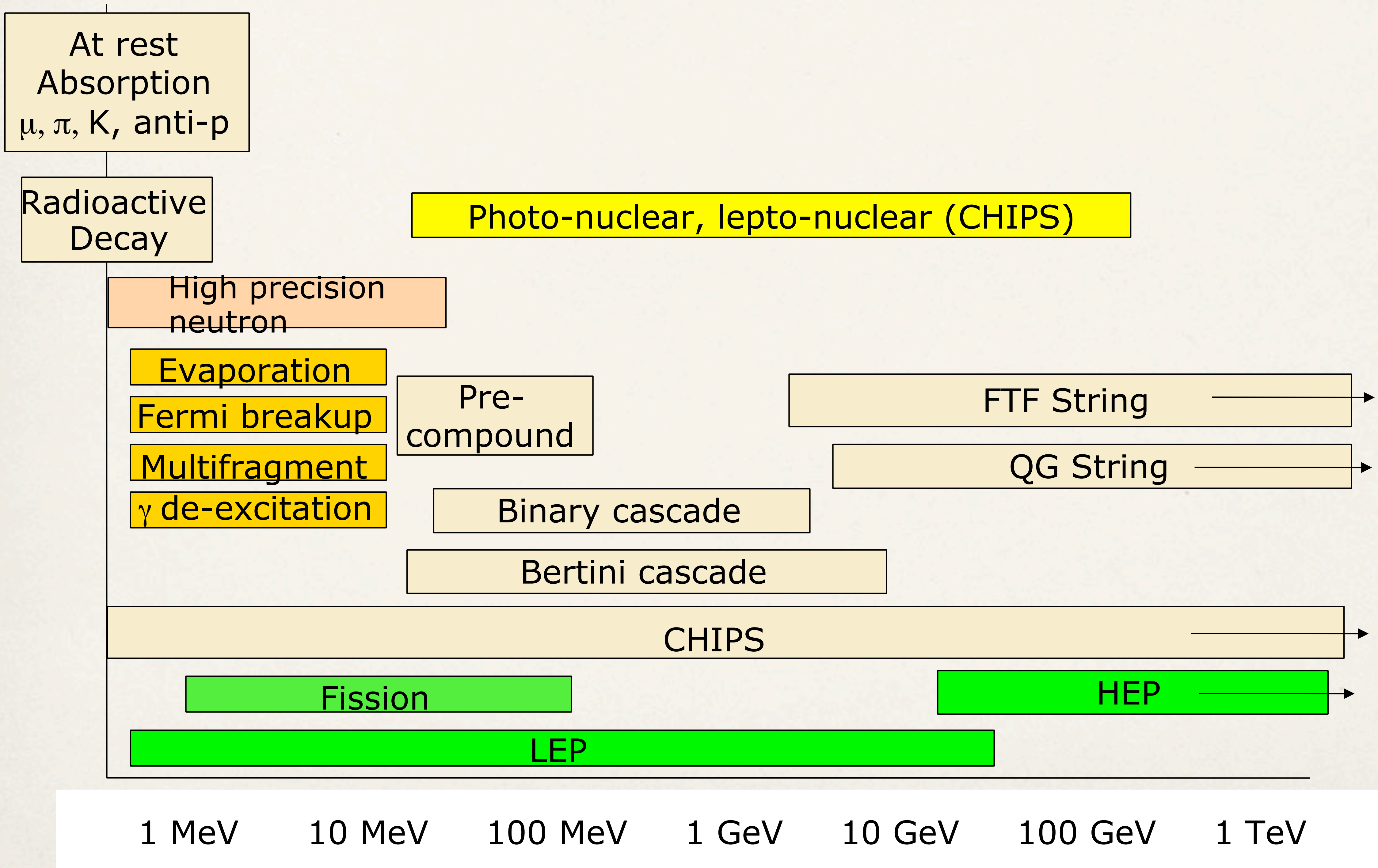
Hadronic process/Model Inventory



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Cross sections

- Default cross section sets are provided for each type of hadronic process
  - Fission, capture, elastic, inelastic
- Different type of cross section sets
  - Some contains only a few numbers of parameterized cross section
  - Some represent a large database (data driven model)

Alternative cross sections

- Low energy neutrons
  - G4NDL available as external data files
  - Available with or without thermal cross section
- Neutron and proton reaction cross section
  - 20 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections
  - E/A < 1 GeV
- Isotope production data

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The cascade scheme

- Incident particle penetrates nucleus, is propagated in a density-dependent nuclear potential
- Each secondary from initial interaction is propagated in nuclear potential until it interacts or leaves nucleus
- Pre-equilibrium decay occurs using exciton states
- Next, nuclear breakup, evaporation, or fission models

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i.e.: the Binary cascade

- Only valid for incident p, n, and pi
    - For p and n from 0 to 10 GeV
    - for pi+ and pi- from 0 to 1.3 GeV
- A variant is the **`G4BinaryLigthtIonReaction`**

How to use the Binary Cascade

```
G4BinaryCascade* binary = new
 G4BinaryCascade();
G4PionPlusInelasticProcess* pproc = new
G4PionPlusInelasticProcess();
pproc -> Register(binary);
piplus_manager -> AddDiscreteProcess(pproc);
```

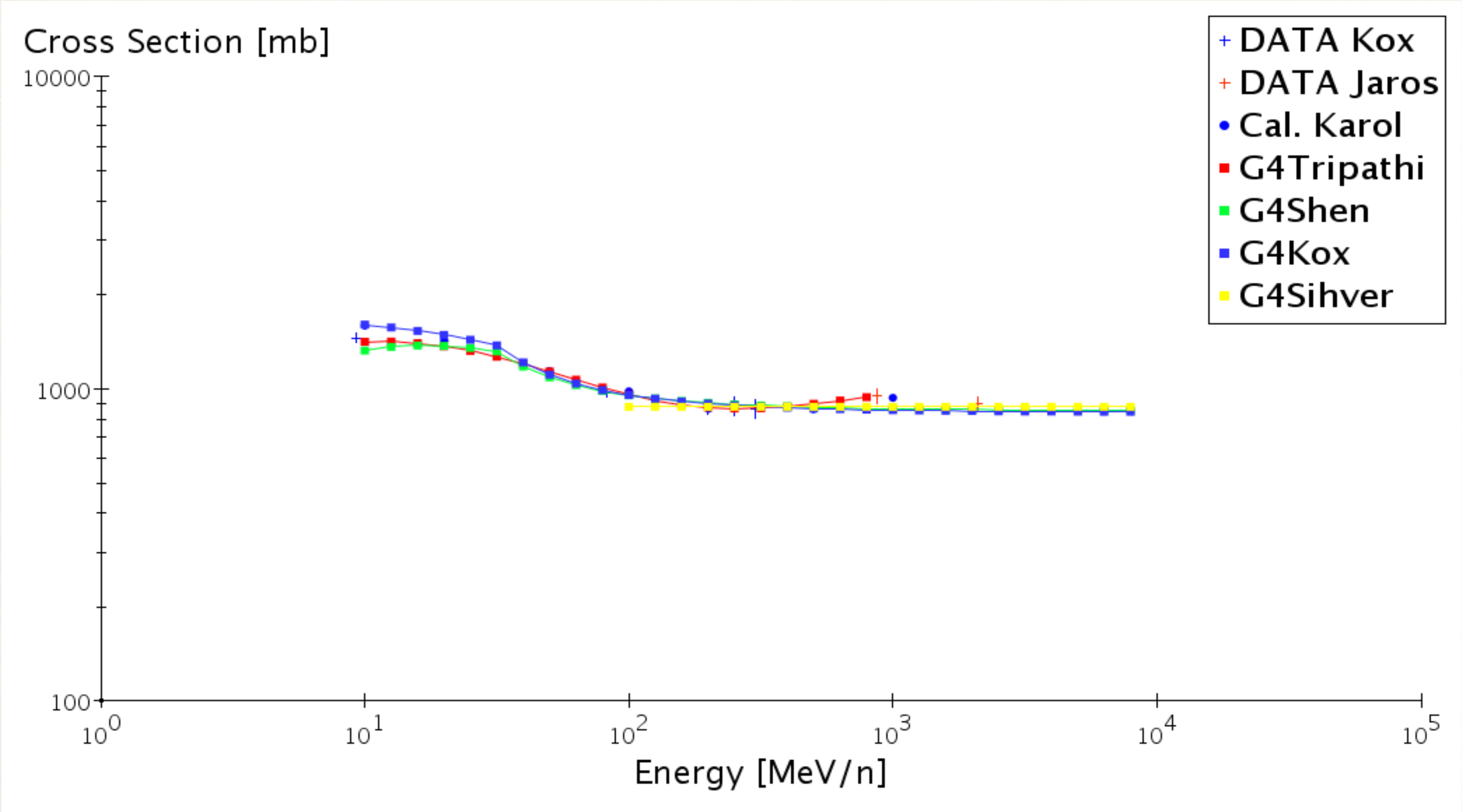
Something on ions physics

- Total production cross sections
  - Tripathi NASA technical paper TP-3621 (1997)
  - Shen, Nuclear physics A 49 1130 (1989)
  - Kox, Phys. Rev C 35 1678 (1987)
- Model
  - G4BinaryLigthIon
  - G4WilsonAbrasion
  - QMD
  - INCL/ABLA

Ion physics: cross sections

- Many cross section formulas for NN collision are included in Geant4
- Empirical and parameterised formulas with some theoretical approach
- G4GeneralSpaceNNCrossSection can be called to choose the appropriate one

Ion physics: cross sections



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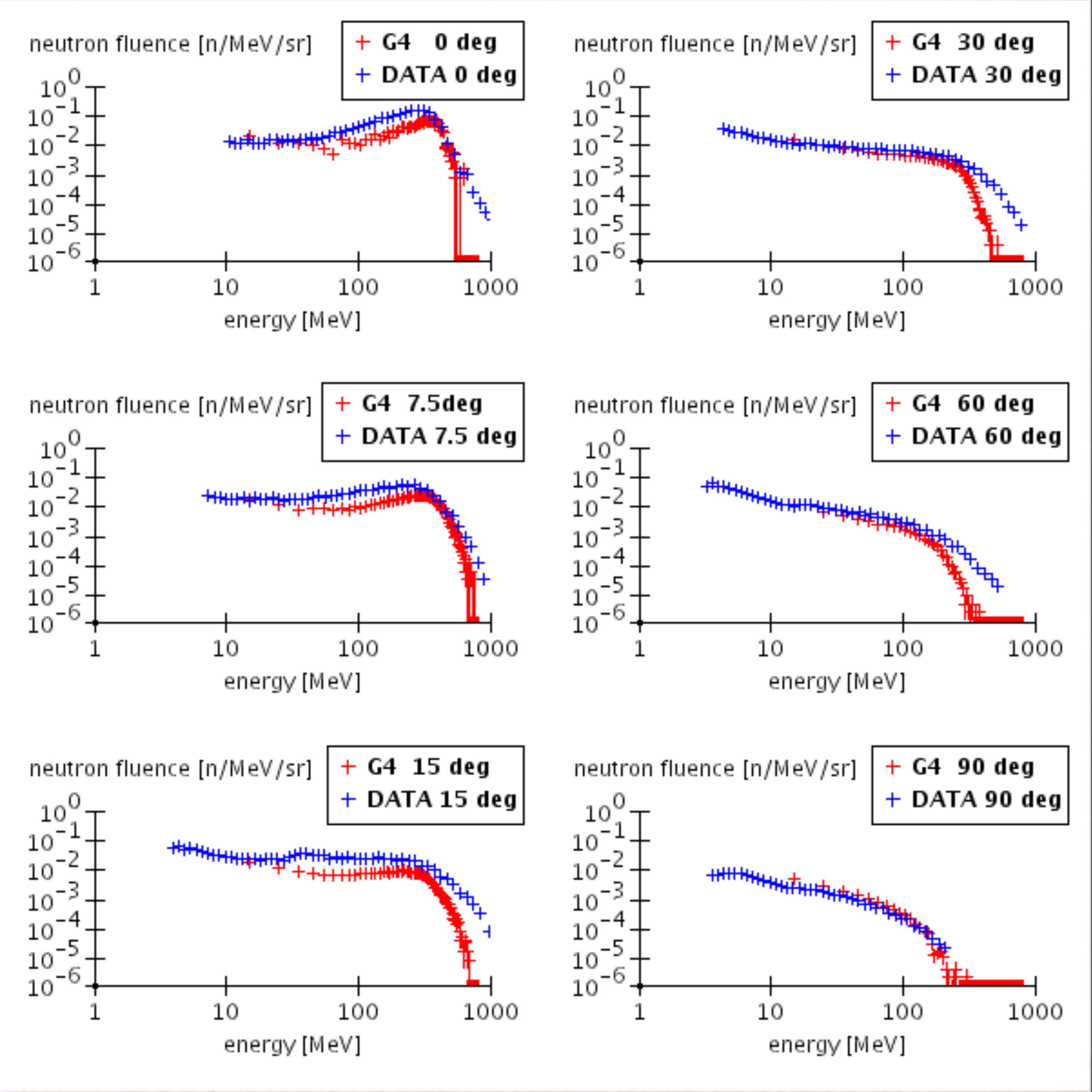
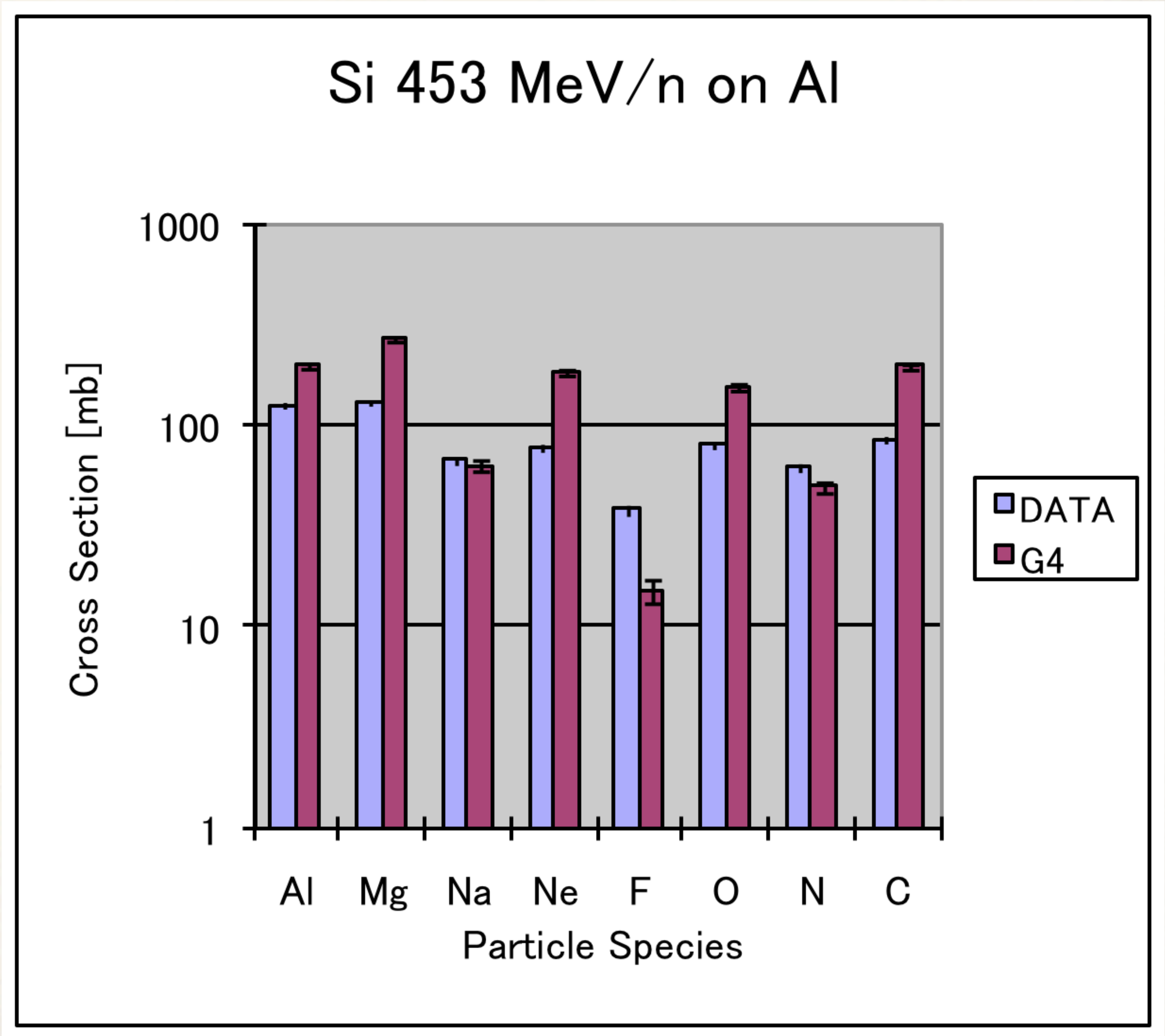
Binary Light Ion model

Neutrons yield of 400 AMeV Fe on Copper thick target



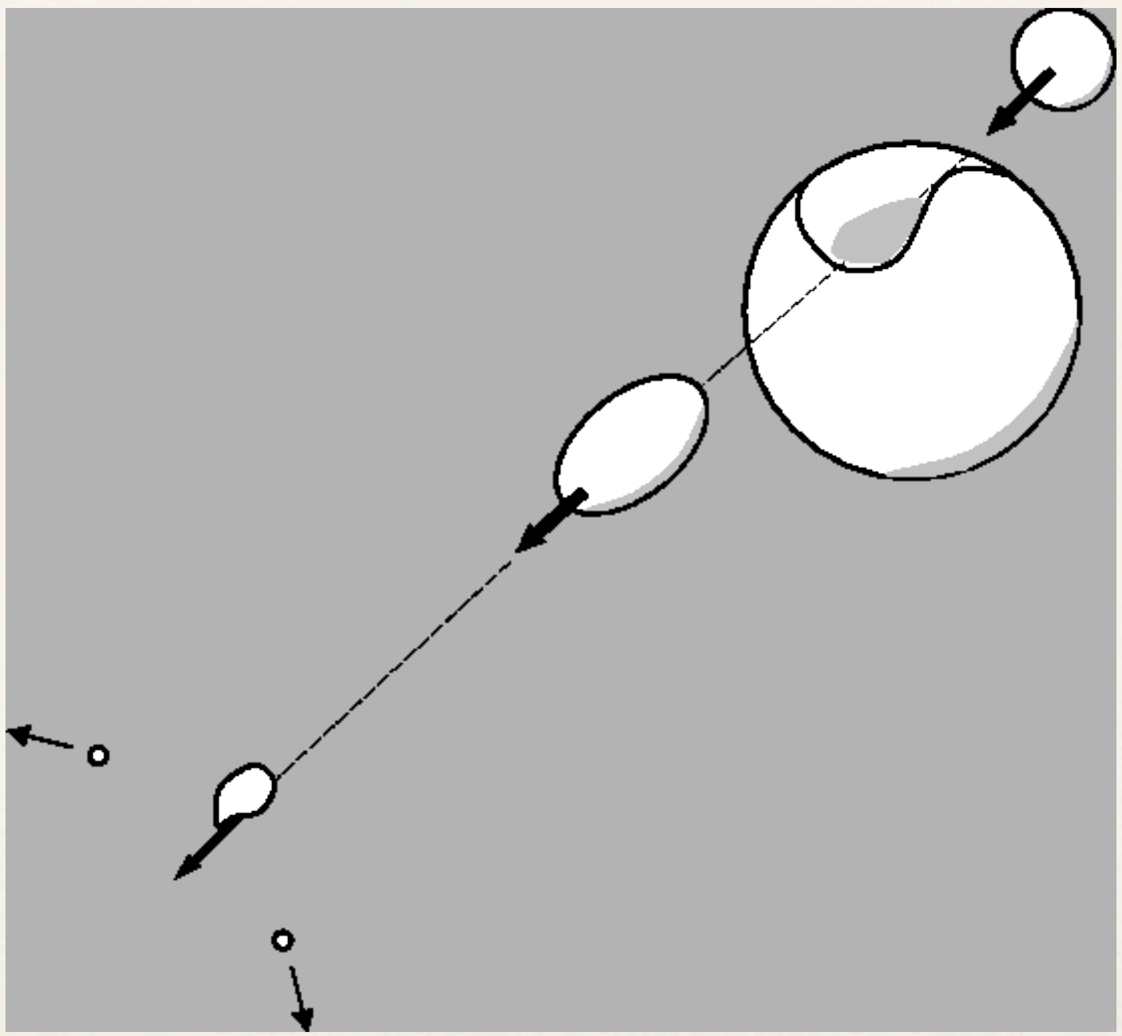
Binary Light Ion model



F. Flesch et al.,
J, RM, 34 237 2001

Wilson Abrasion/Ablation

Abrasion process

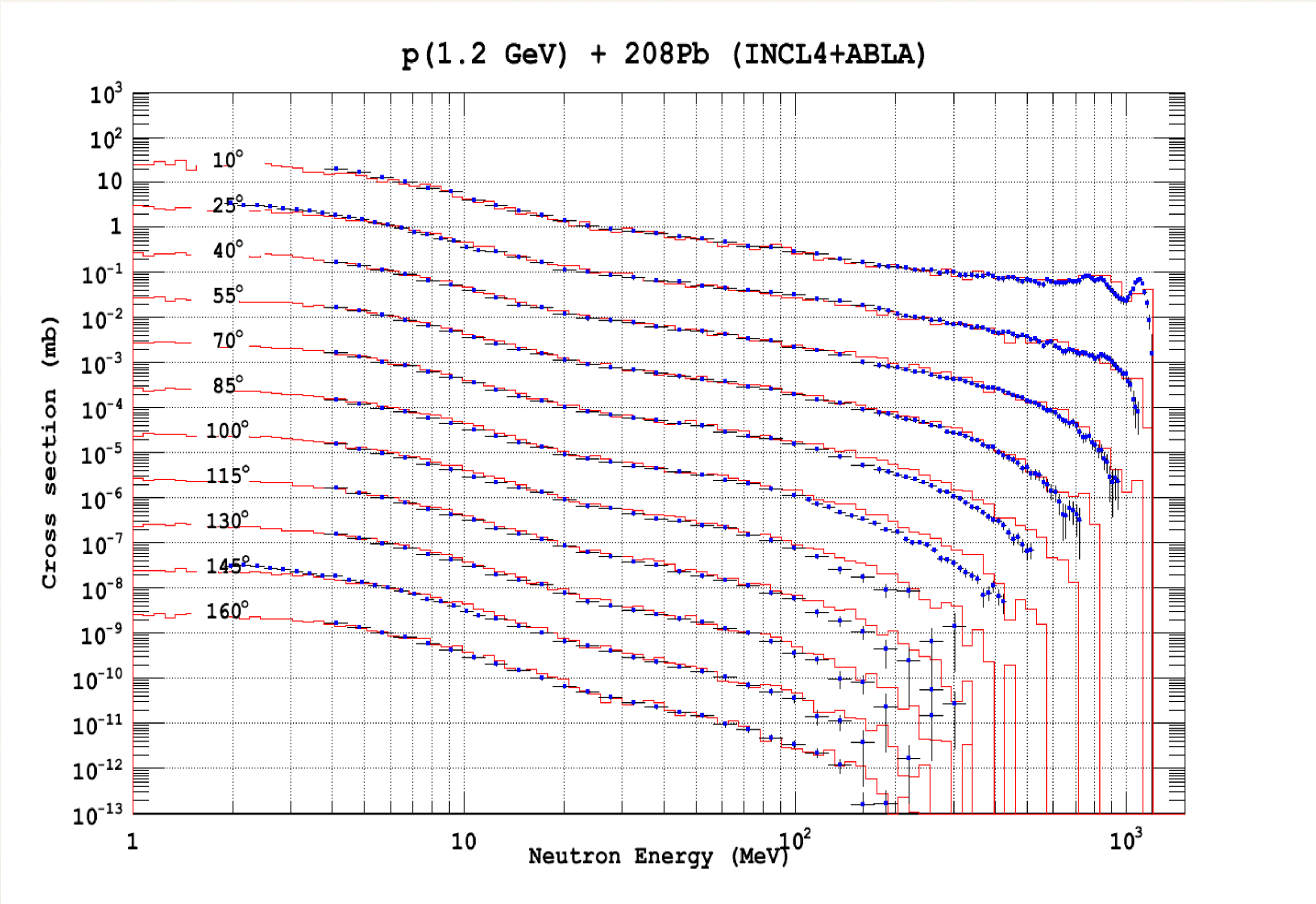


Ablation process

Physics List for Abrasion/ Ablation

```
G4HadronInelasticProcess* theIPGenericIon =        new G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() );
// Cross Section Data Set
G4TripathiCrossSection * TripathiCS= new G4TripathiCrossSection;
G4IonsShenCrossSection * ShenCS = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(ShenCS);
theIPGenericIon->AddDataSet(TripathiCS);
// Model
G4BinaryLightIonReaction * theGenIonBC= new G4BinaryLightIonReaction;
theGenIonBC->SetMinEnergy(0*MeV);
theGenIonBC->SetMaxEnergy(0.07*GeV);
theIPGenericIon->RegisterMe(theGenIonBC);
G4WilsonAbrasionModel* theGenIonAbrasion = new G4WilsonAbrasionModel();
theIPGenericIon->RegisterMe(theGenIonAbrasion);
//Apply Processes to Process Manager of GenericIon
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()-> GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Some different recent result



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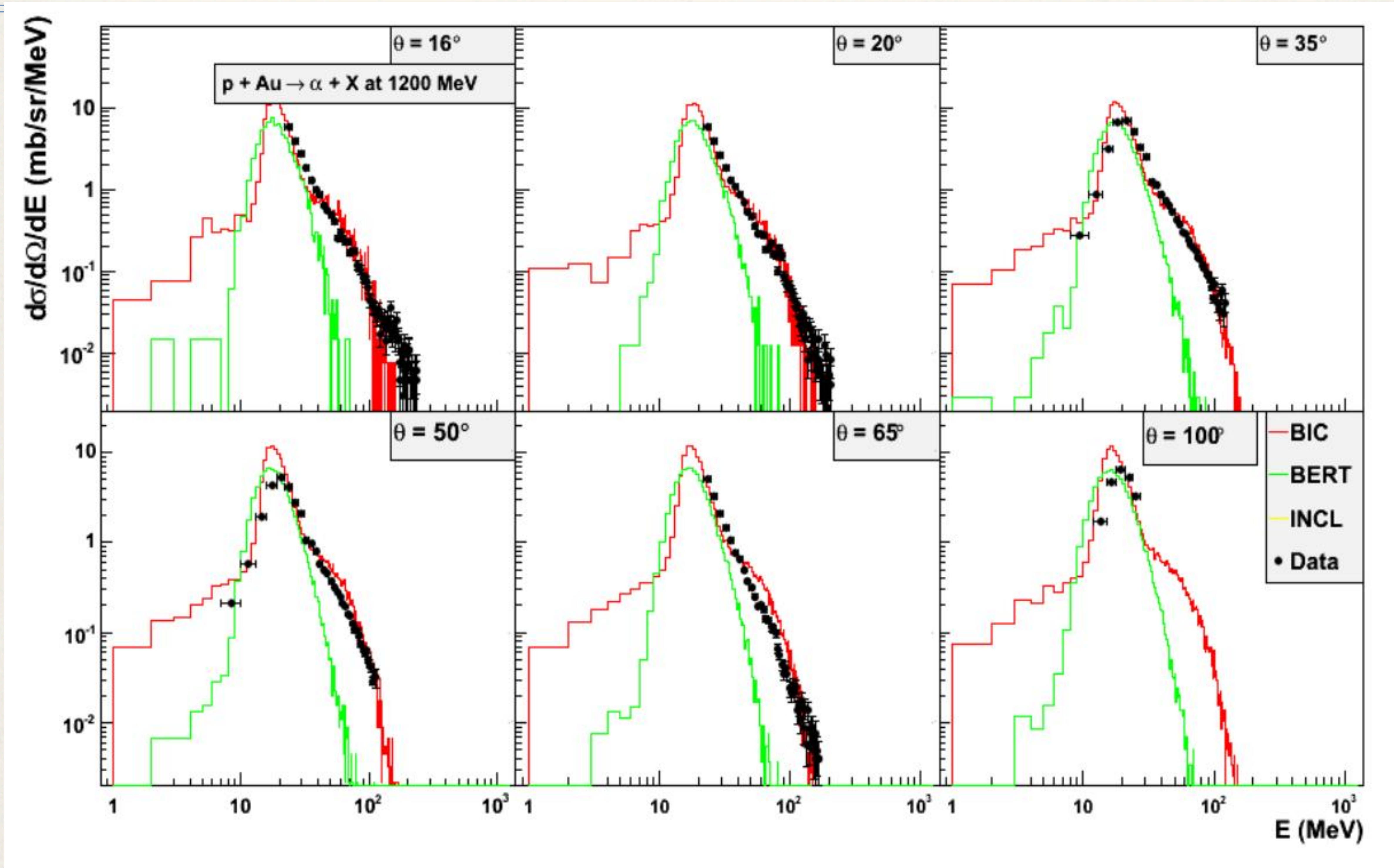
Some different recent result:prec + de-excitation



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Precompound model

- G4PreCompoundModel
  - for nucleon-nucleus interactions at low energy
  - 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, 3He, alpha
  - once equilibrium state is reached, four other models are invoked via G4ExcitationHandler to take care of nuclear evaporation and breakup
  - these models not currently callable by users
- The parameterized and cascade models all have nuclear de-excitation models embedded

Equilibrium models

- Fermi breakup
  - Light nuclei, (A,Z) < (9,17)
- Multifragmentation
  - Highly excited nuclei
- Evaporation
  - Emission of p,n, d, t, alpha;
  - or using GEM up to Mg
- Gamma emission
  - Both discrete and continous
- G4Precompound and the equilibrium models were significantly improved in 9.3

Using the Precompound

```
G4Processmanager * procMan = G4Neutron::Neutron()->GetProcessManager;
  // equilibrium decay
  G4ExcitationHandler*  theHandler = new G4ExcitationHandler;
  // preequilibrium
  G4PrecompoundModel* preModel = new G4PrecompoundModel(theHandler);

  G4NeutronInelasticProcess* nProc = new G4NeutronInelasticProcess;

  // Register model to process, process to particle
  nProc->RegisterMe(preModel);
  procMan->AddDiscreteProcess(nProc);
```

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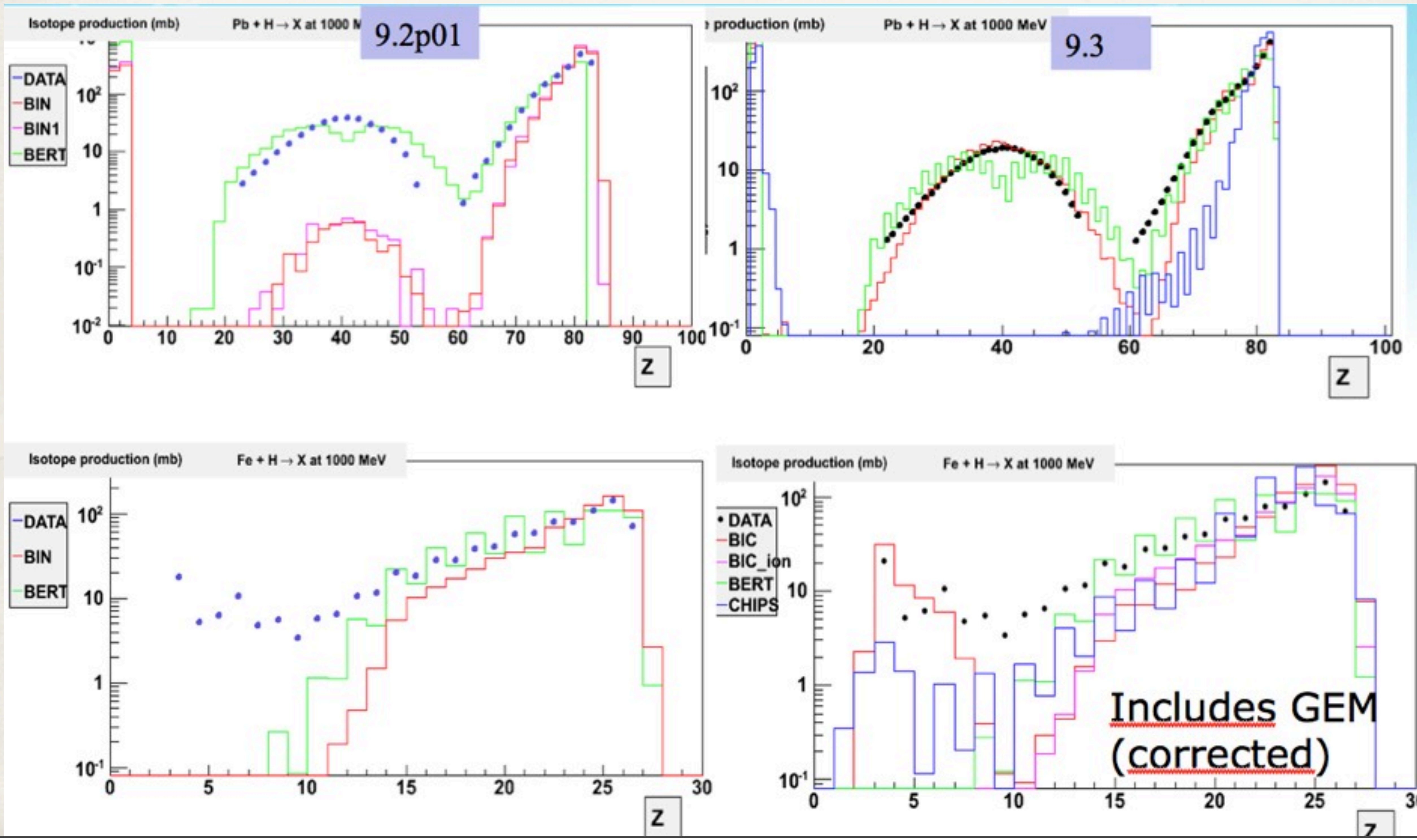
Precompound and de-excitation validation



Something on low energy neutrons physics

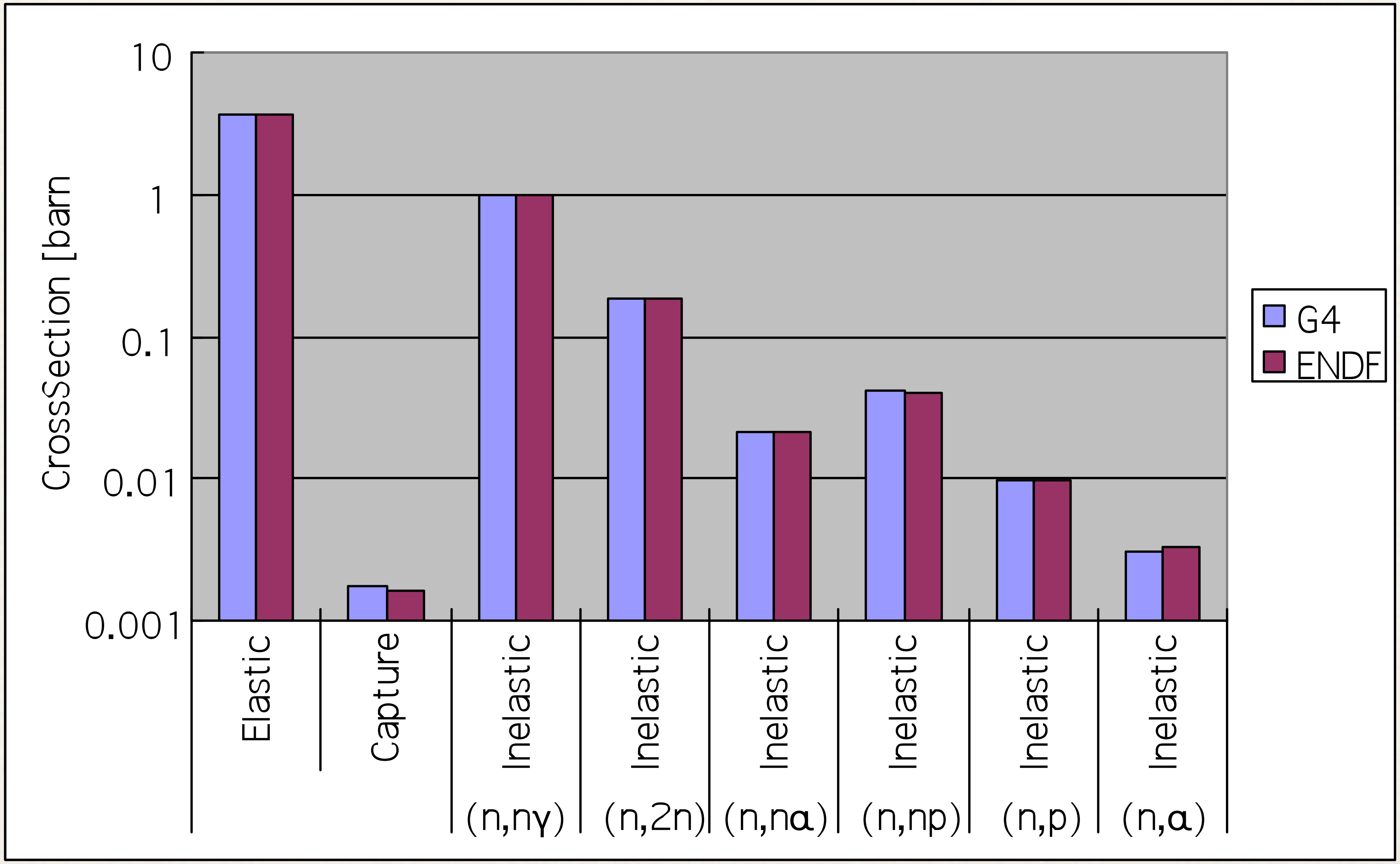
- High precision models and cross sections data set
  - G4NDL
  - Elastic (G4NeutronHPElastic)
  - Inelastic (G4NeutronHPInelastic)
  - Capture (G4NeutronHPCapture)
  - Fission (G4NeutronHPFission)
- Thermal scattering models (G4NeutronHPThermalScattering)
- G4NeutronHPorLEModels: when precise models are not available LEP is called

Thanks to Dennis Wrigth

G4NDL (G4 Neutron Data Library)

- Neutron data files for High precision models
- These data include both cross sections and final states
- These data derived by the following evaluated data libraries
  - Brond-2.1
  - CENDL2.2
  - EFF-3
  - ENDF/B
  - FENDL/E
  - JEF2.2
  - JENDL-FF
  - MENDL

Some verification: channel cross section



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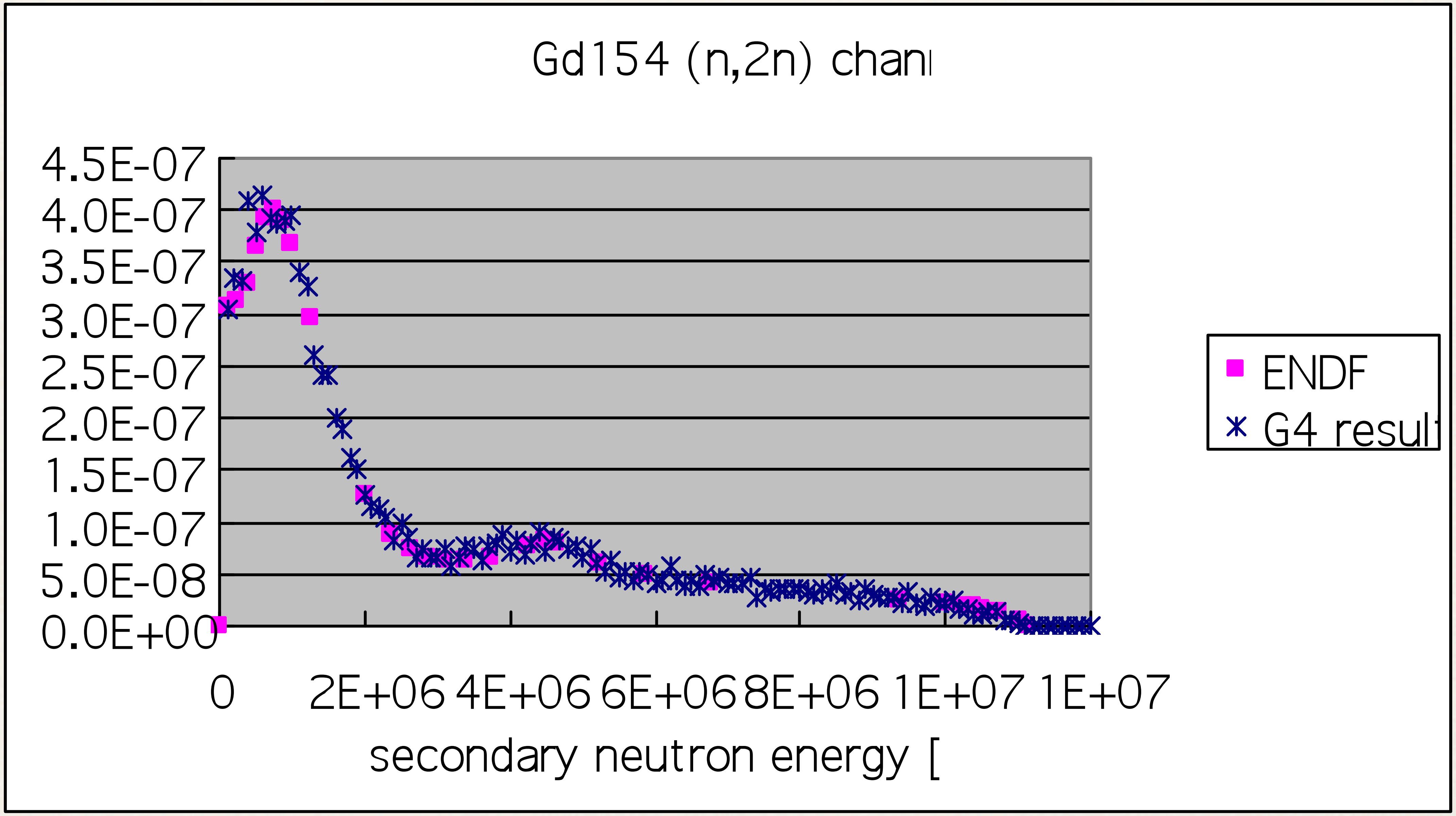
Some verification: secondary energy spectrum



Thermal neutron scattering

- 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 in the default NeutronHP models.

Thermal neutron scattering

- These files constitute a thermal sub-library
- Use the File 7 format of ENDF/B-VI
- Divides the thermal scattering into different parts:
  - Coherent and incoherent elastic; no energy change
  - Inelastic; loss or gain in the outgoing neutron energy
- The files and NJOY are required to prepare the scattering law $S(\alpha, \beta)$ and related quantities.

Physics lists for NeutronHP

```
/For example  Elastic scattering below 20 MeV
G4HadronElasticProcess*    theNeutronElasticProcess   = new
   G4HadronElasticProcess();
// Cross Section Data set
G4NeutronHPElasticData* theHPElasticData = new G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theHPElasticData );
// Model
G4NeutronHPElastic* theNeutronElasticModel = new G4NeutronHPElastic();
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel)
```

```
G4ProcessManager* pmanager = G4Neutron::Neutron()-> GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

Physics lists 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 );
```

Ionisation

- Ionisation and delta ray production (class **`G4IonParametrisedLossModel`**)
- The ICRU73 Stopping power are used up to 1 AGeV, if the ion/target combination is available

```
G4ionIonisation* ionIoni = new G4ionIonisation();
ionIoni -> SetEmModel(new G4IonParametrisedLossModel());
```