Hadronic Physics II

Geant4 School at IFIN-HH, Bucharest

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Outline

- Hadron Elastic Processes
  - cross sections
  - models
- Neutron physics
  - HP models
  - LEND models
- Ion-ion physics

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

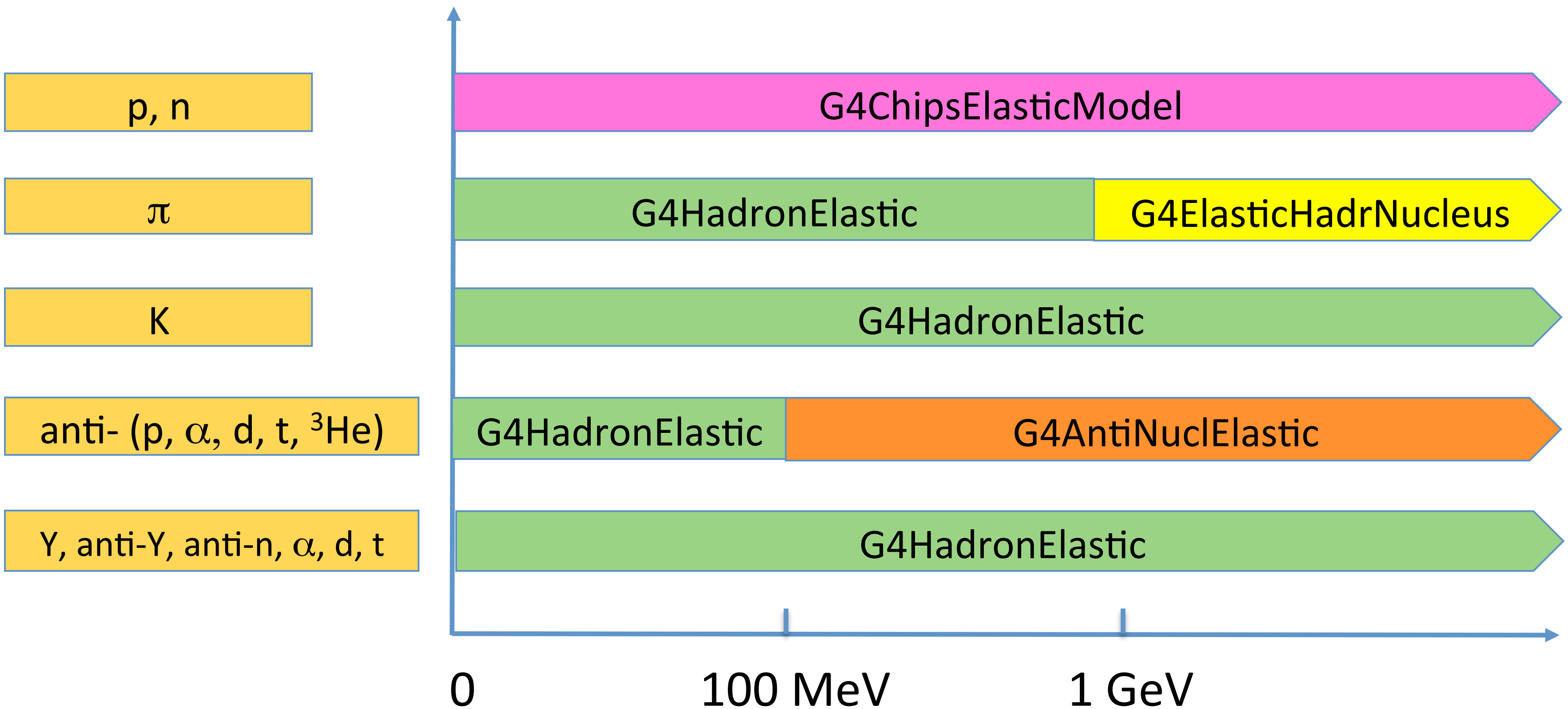
- G4HadronElasticDataSet (from Geant4/Gheisha)

- G4ComponentAntiNuclNuclearXS
  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach

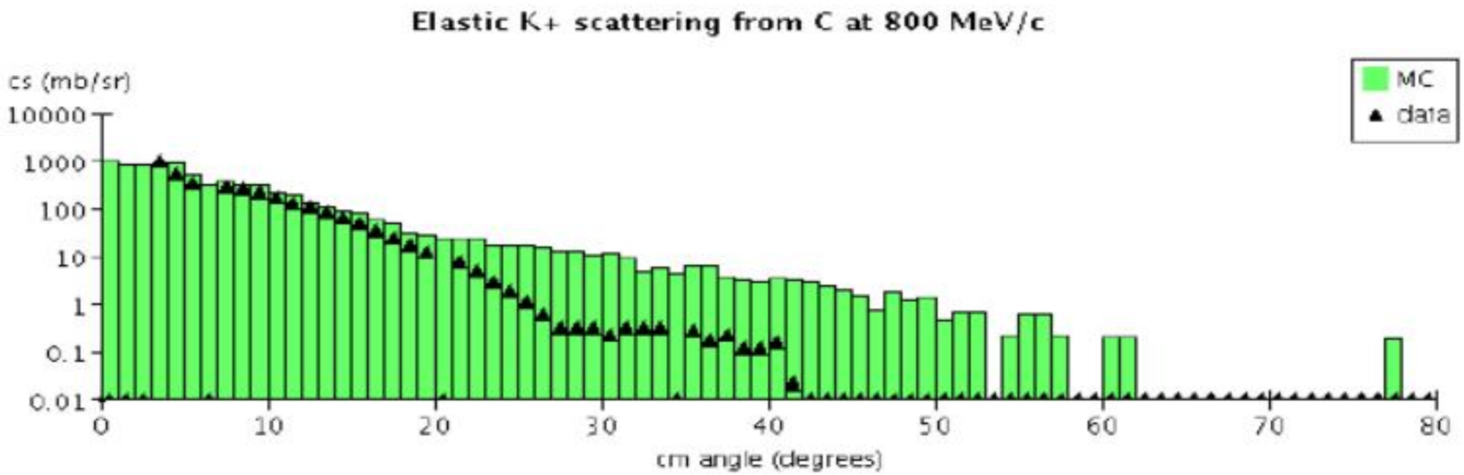
- G4BGGPionElasticXS
  - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above

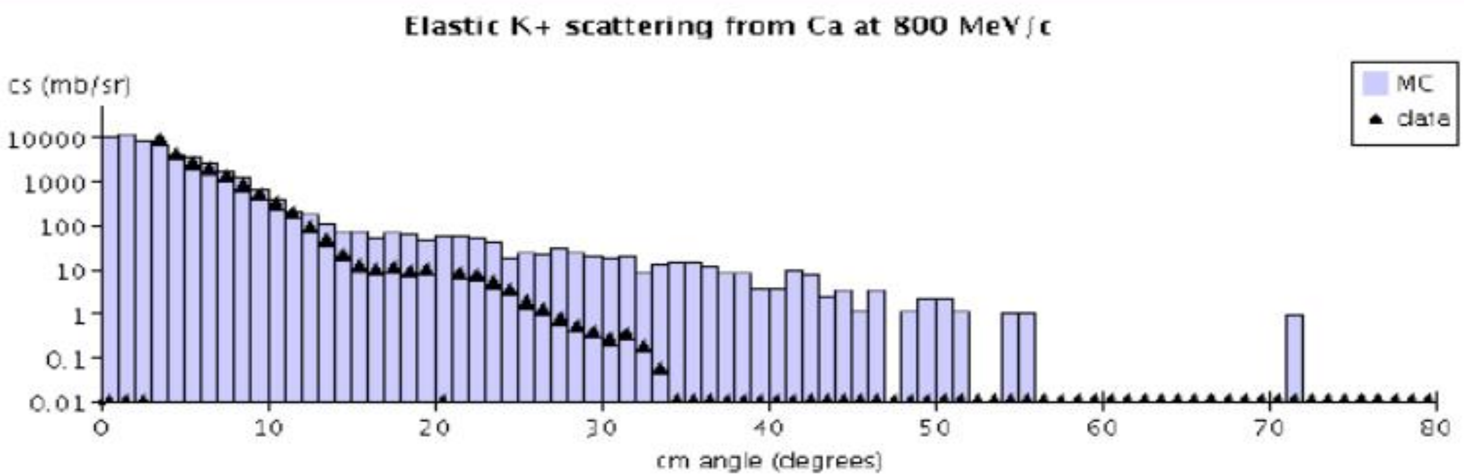
- G4ChipsNeutron(Proton)ElasticXS
  - elastic cross sections extracted from CHIPS framework

Hadronic Models Implementing G4HadronElasticProcess

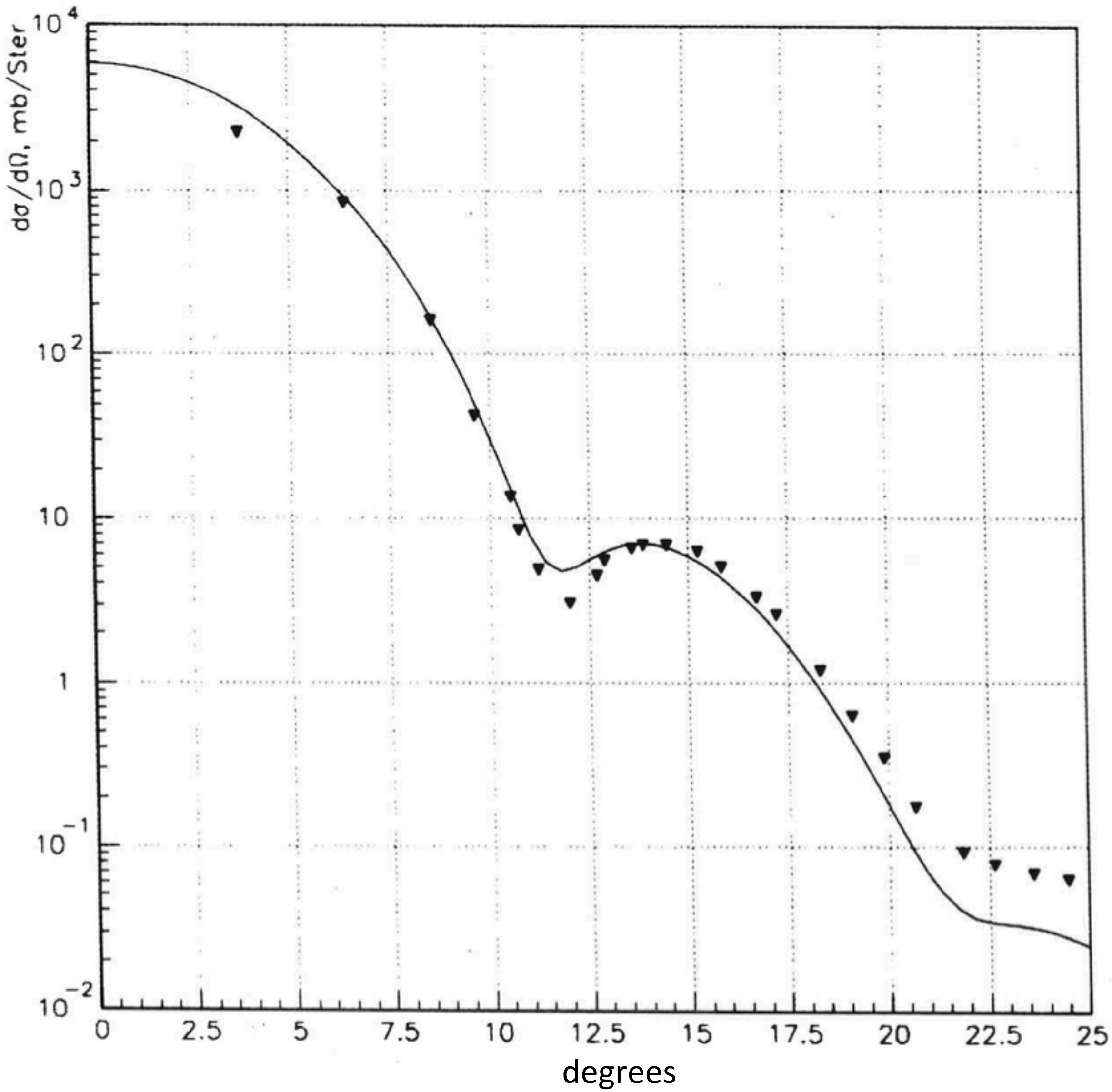


Elastic Scattering Validation (G4HadronElastic)





G4ElasticHadrNucleusHE (1 GeV p on C)



Low Energy Hadron Physics

- Below 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 Particles

- ParticleHP models provide elastic, inelastic, capture and fission for incident n, p, d, t, ^{3}He, α
  - mostly below 20 MeV for n
  - 0 < E < 200 MeV for charged
  - also depends on large database (ENDF)
  - alternative dbs ready: TENDL, IAEA medical, IBANDL
  - recently merged with NeutronHP

- Code currently available
  - good comparisons so far with MCNP

Geant4 Neutron Data Library (G4NDL)

- Contains the data files for the high precision neutron models
  - includes both cross sections and final states

- From Geant4 9.5 onward, G4NDL is based solely on the ENDF/B-VII database
  - G4NDL data is now taken only from ENDF/B-VII, but still has G4NDL format
  - use G4NDL 4.0 or later

- Prior to G4 9.5 G4NDL selected data from 9 different databases, each with its own format
  - Brond-2.1, CENDL2.2, EFF-3, ENDF/B-VI, FENDL/E2.0, JEF2.2, JENDL-FF, JENDL-3 and MENDL-2
  - G4NDL also had its own (undocumented) format

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
  - also interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
  - scattered particle and recoil nucleus generated as final state

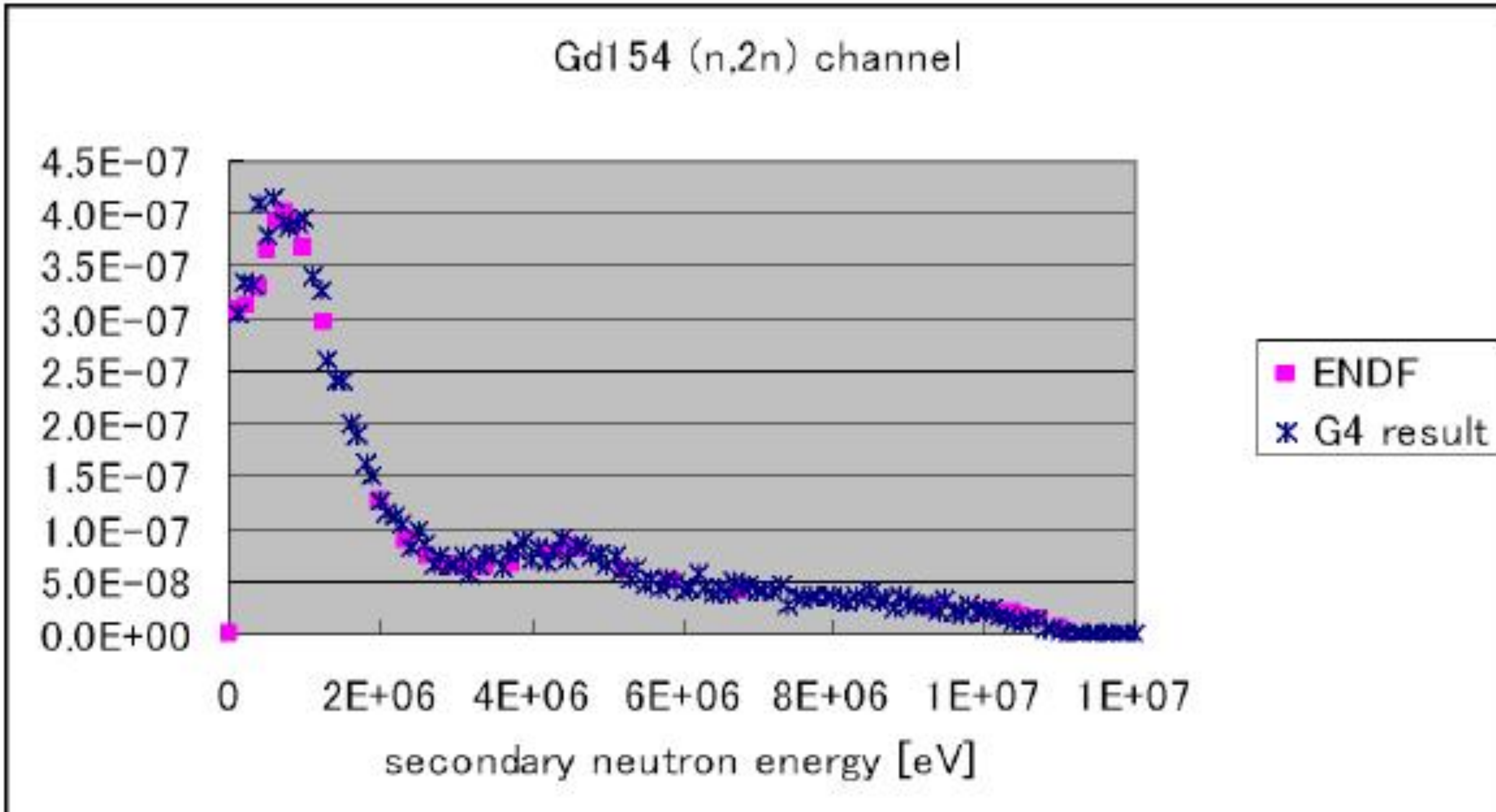
- Note that because look-up tables are based on binned data, there will always be a small energy non-conservation
  - true for inelastic, capture and fission processes as well

G4ParticleHPInelastic

- Currently supports many inelastic final states + n gamma (discrete and continuum)
  - 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)

Neutron Inelastic: ^{154}Gd (n,2n) Comparison to Data



Thermal Neutron Scattering from Chemically Bound Atoms

- At thermal energies, atomic motion, vibration, rotation of bound atoms affect neutron scattering cross sections and the angular distribution of secondary neutrons

- The energy loss (or gain) of such scattered neutrons may be different from those from interactions with unbound atoms
- Original HP models included only individual Maxwellian motion of target nucleus (free gas model)

- New behavior handled by model and cross section classes
  - G4HPThermalScatteringData, and
  - G4HPThermalScattering

LEND – the new Livermore Neutron Models

- An alternative to the HP models
  - better code design
  - faster
  - Livermore database not yet as extensive G4NDL
- Corresponding model for each model in HP
  - elastic, inelastic, capture, fission
- Invocation in physics list:
  - use model names G4LENDElastic, G4LENDInelastic, G4LENDCapture, G4LENDFission, and cross sections G4LENDElasticCrossSection, G4LENDInelasticCrossSection, G4LENDCaptureCrossSection, G4LENDFissionCrossSection
- Database to use: go to ftp://gdo-nuclear.ucllnl.org/pub/ and select G4LEND, then ENDF-B-VII.0.tar.gz

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 (to be discussed later)

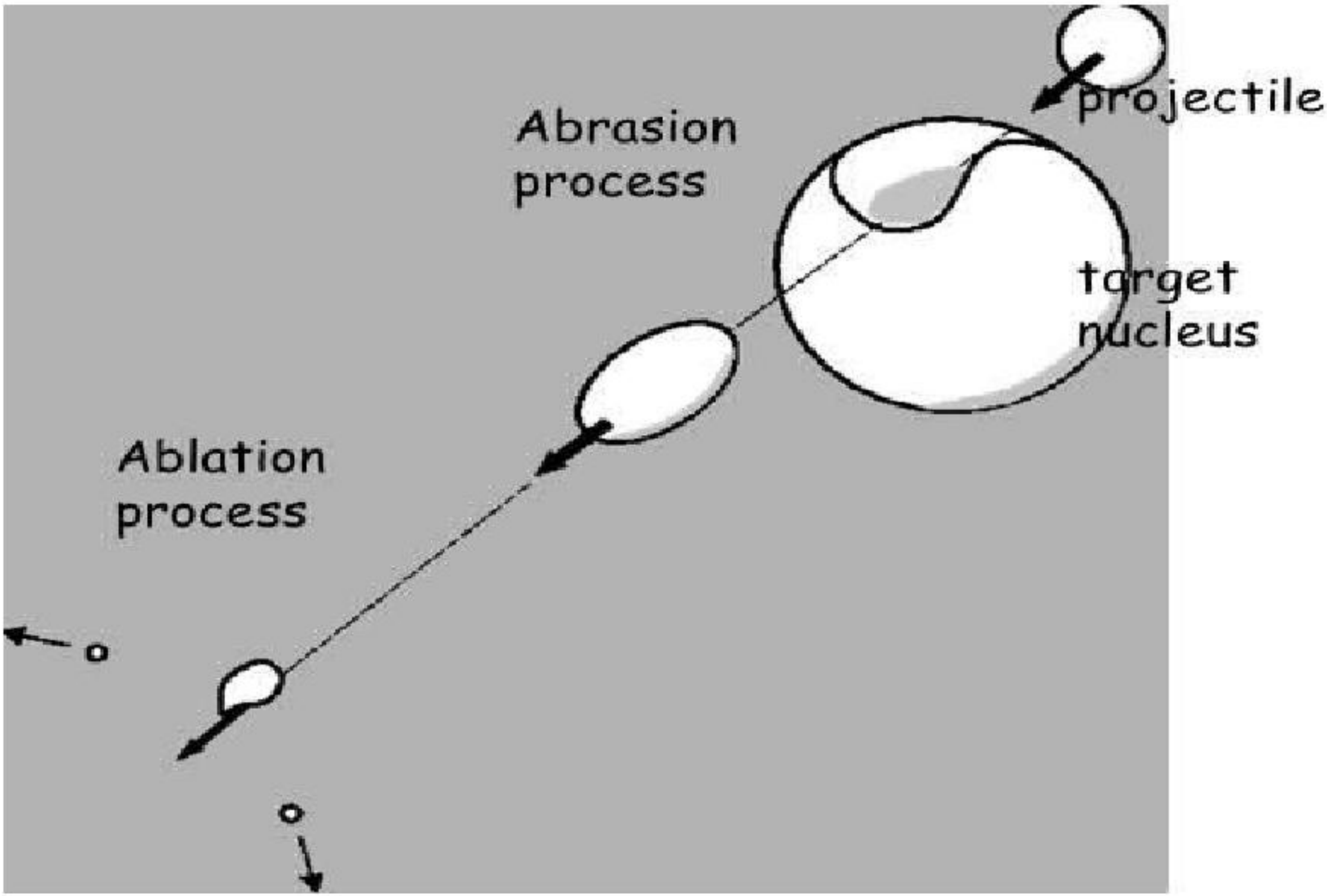
- The hadron-nuclear interaction part is identical, but the nucleus-nucleus part involves:
  - preparation of two 3D nuclei with Woods-Saxon or harmonic oscillator potentials
  - lighter nucleus is always assumed to be the projectile
  - nucleons in the projectile are entered with their positions and 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



G4EMDissociation Model

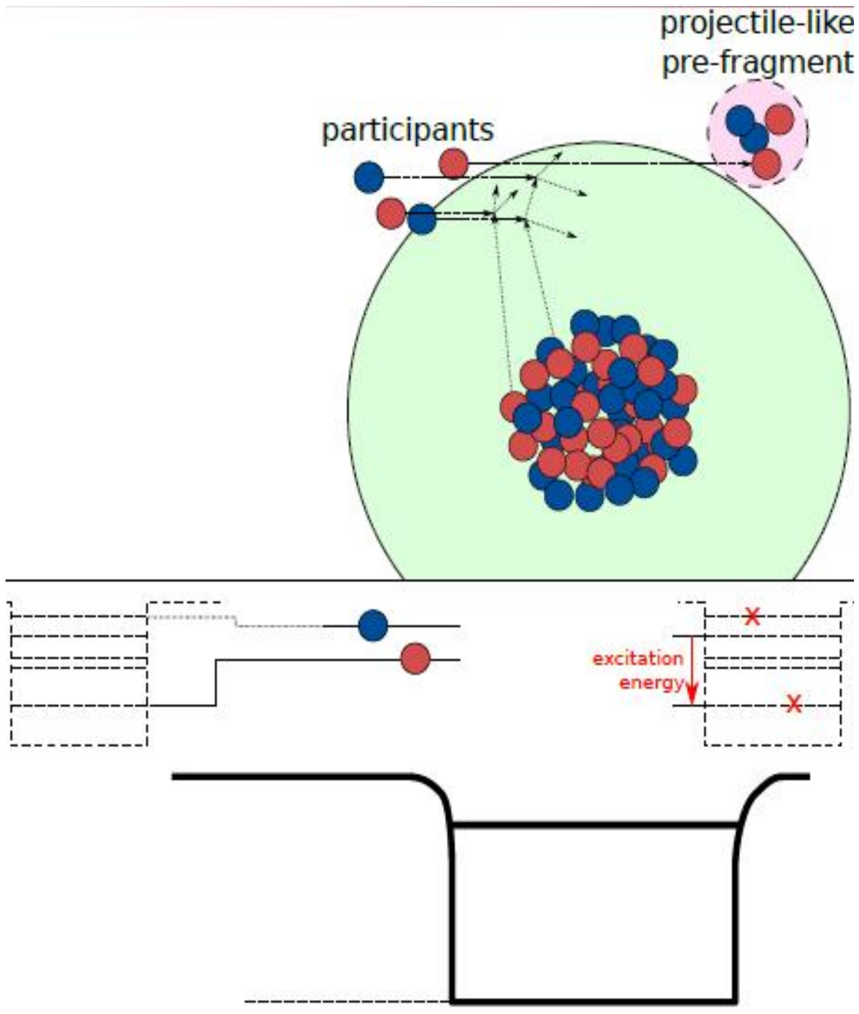
- Electromagnetic dissociation is the liberation of nucleons or nuclear fragments as a result of strong EM fields
  - as when two high-Z nuclei approach
  - exchange of virtual photons instead of nuclear force

- 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

- 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



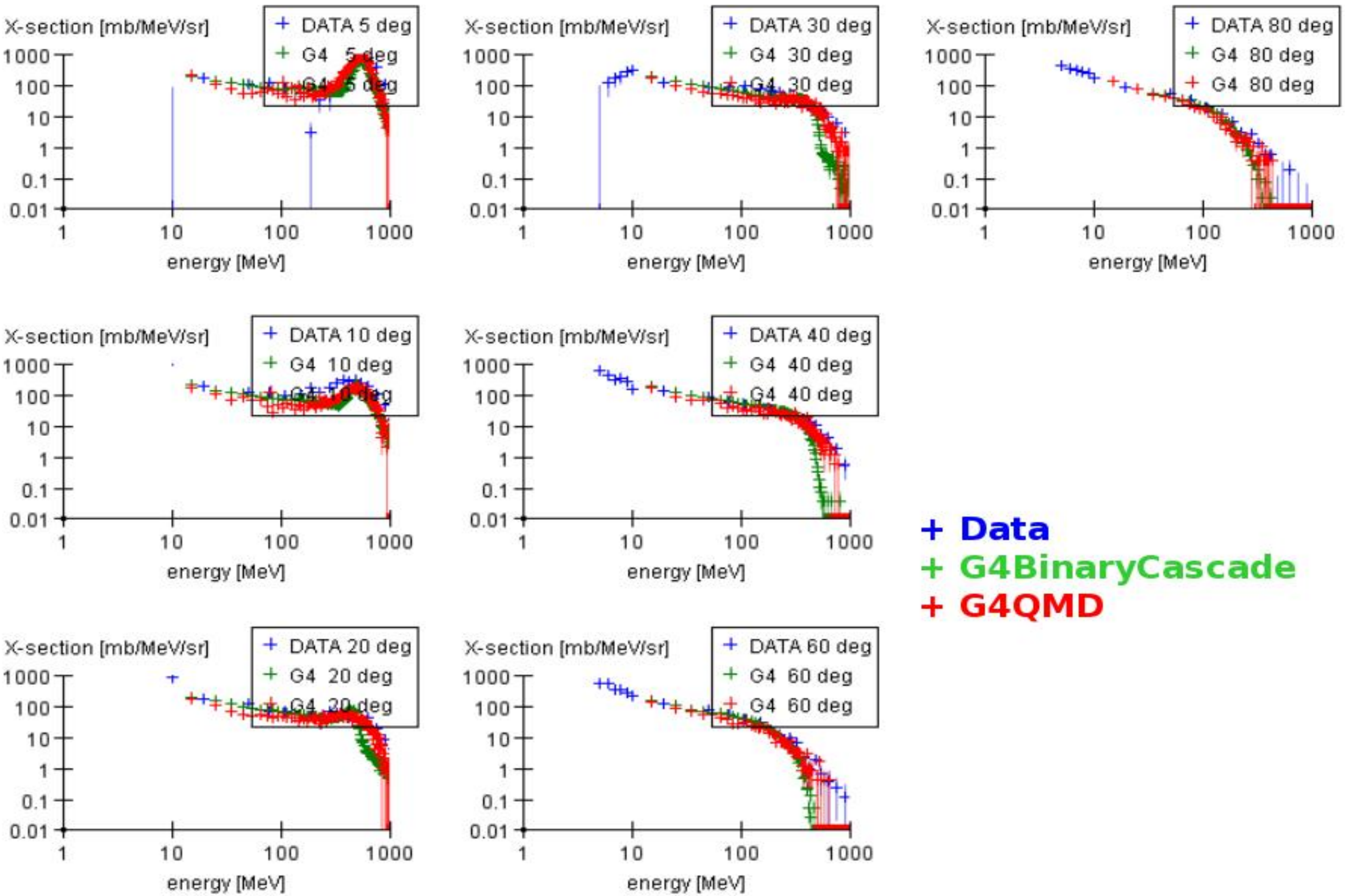
G4QMD Model

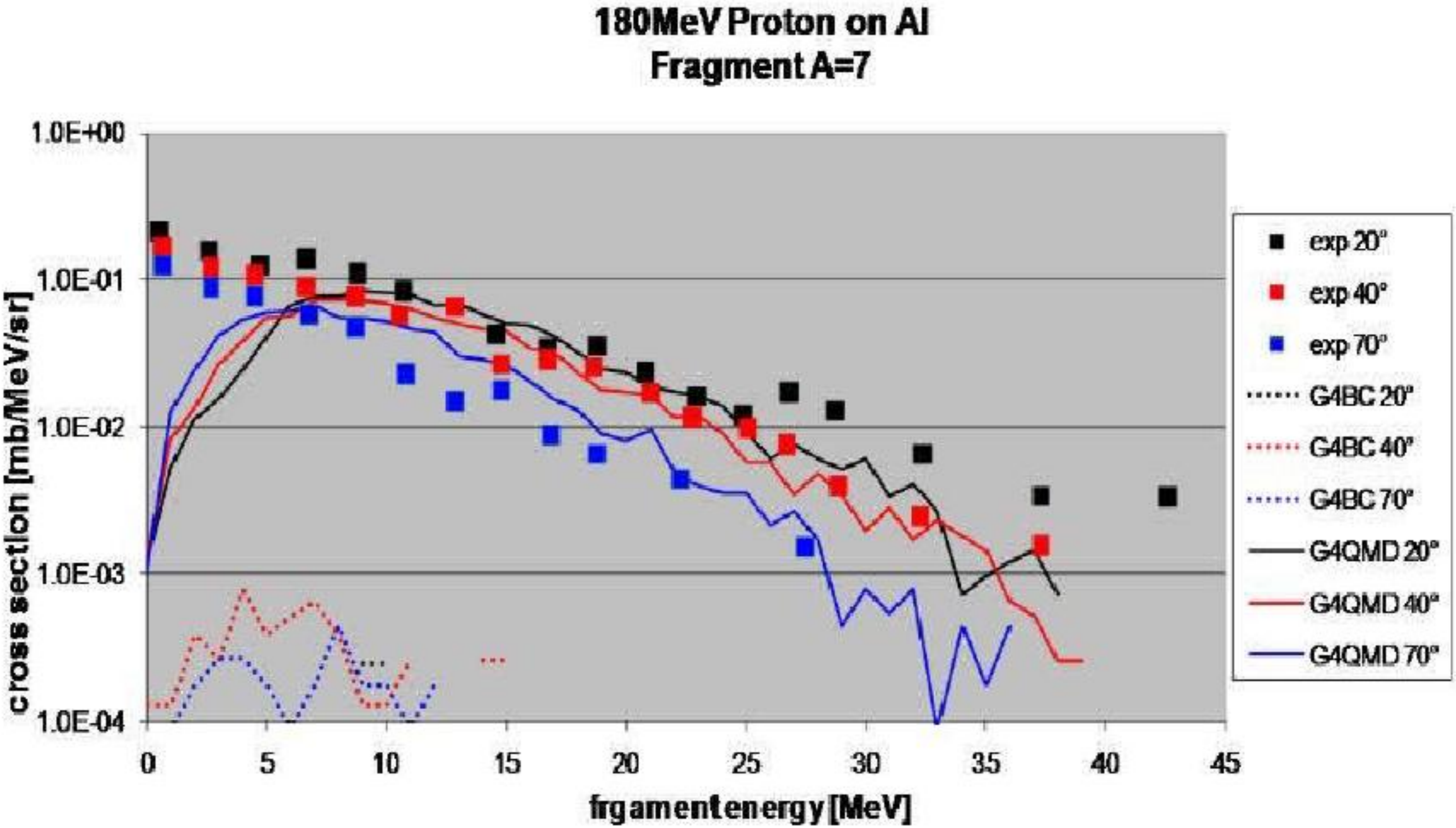
- BinaryLightIonReaction has some limitations
  - neglects participant-participant scattering
  - uses simple time-independent nuclear potential
  - imposes small A limitation for target or projectile
  - Binary cascade base model can only go to 5-10 GeV

- 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

Ar40 560MeV/n on Lead

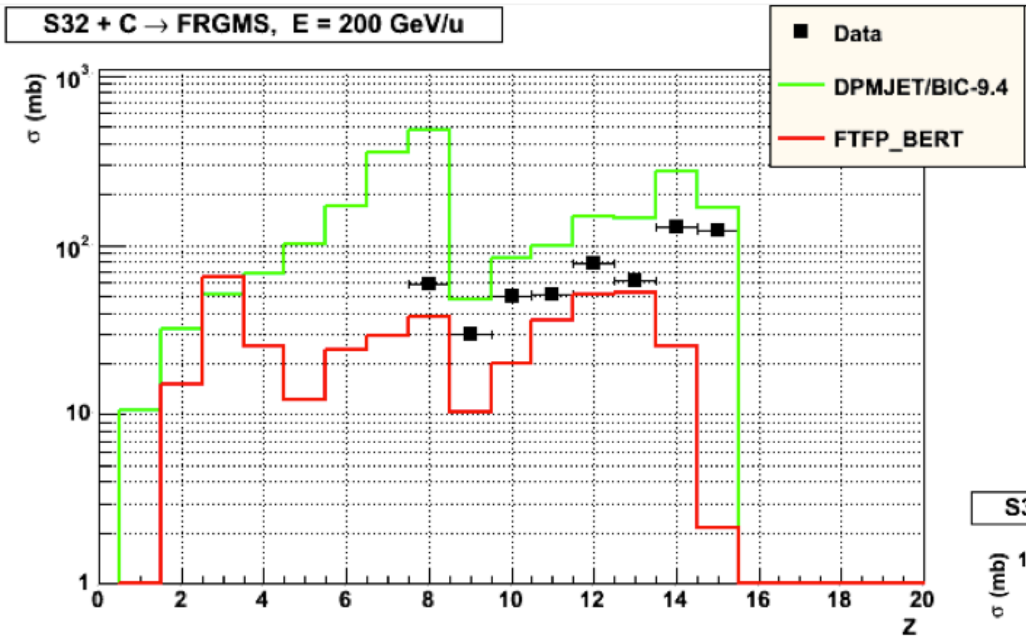


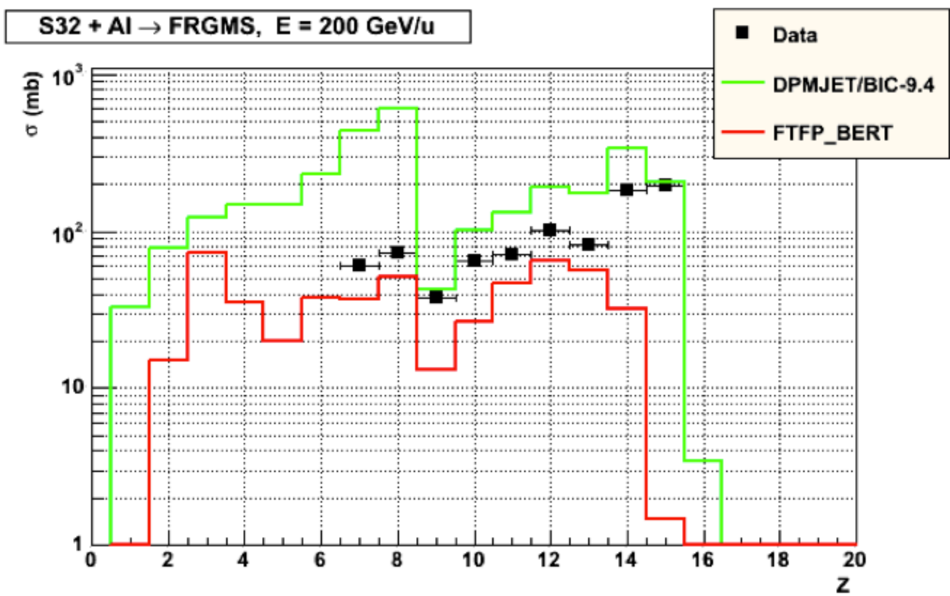


180MeV Proton on Al
Fragment A=7
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
cross section [mb/MeV/sr]
0
5
10
15
20
25
30
35
40
45
frgamentenergy [MeV]
exp 20°
exp 40°
exp 70°
G4BC 20°
G4BC 40°
G4BC 70°
G4QMD 20°
G4QMD 40°
G4QMD 70°

High Energy Nucleus-nucleus Models

- Most Geant4 nucleus-nucleus models so far have been low to medium energy (< 20 GeV/N)
  - until recently we used interface to DPMJET-II for higher energies but this came with restrictions and was difficult to maintain
- We began looking for a native Geant4 solution
  - Fritiof (FTF) is now being developed for this
  - for light to medium nuclei, as good or better than DPMJET


S32 + C → FRGMS, E = 200 GeV/u
Data
DPMJET/BIC-9.4
FTFP_BERT
σ (mb)
Z


S32 + Al → FRGMS, E = 200 GeV/u
Data
DPMJET/BIC-9.4
FTFP_BERT
σ (mb)
Z

Nucleus-nucleus Cross Sections

- Cross section data sets available from 10 MeV/N to 10 GeV/N
  - Tripathi, TripathiLight (for light nuclei)
  - Kox
  - Shen
  - Sihver

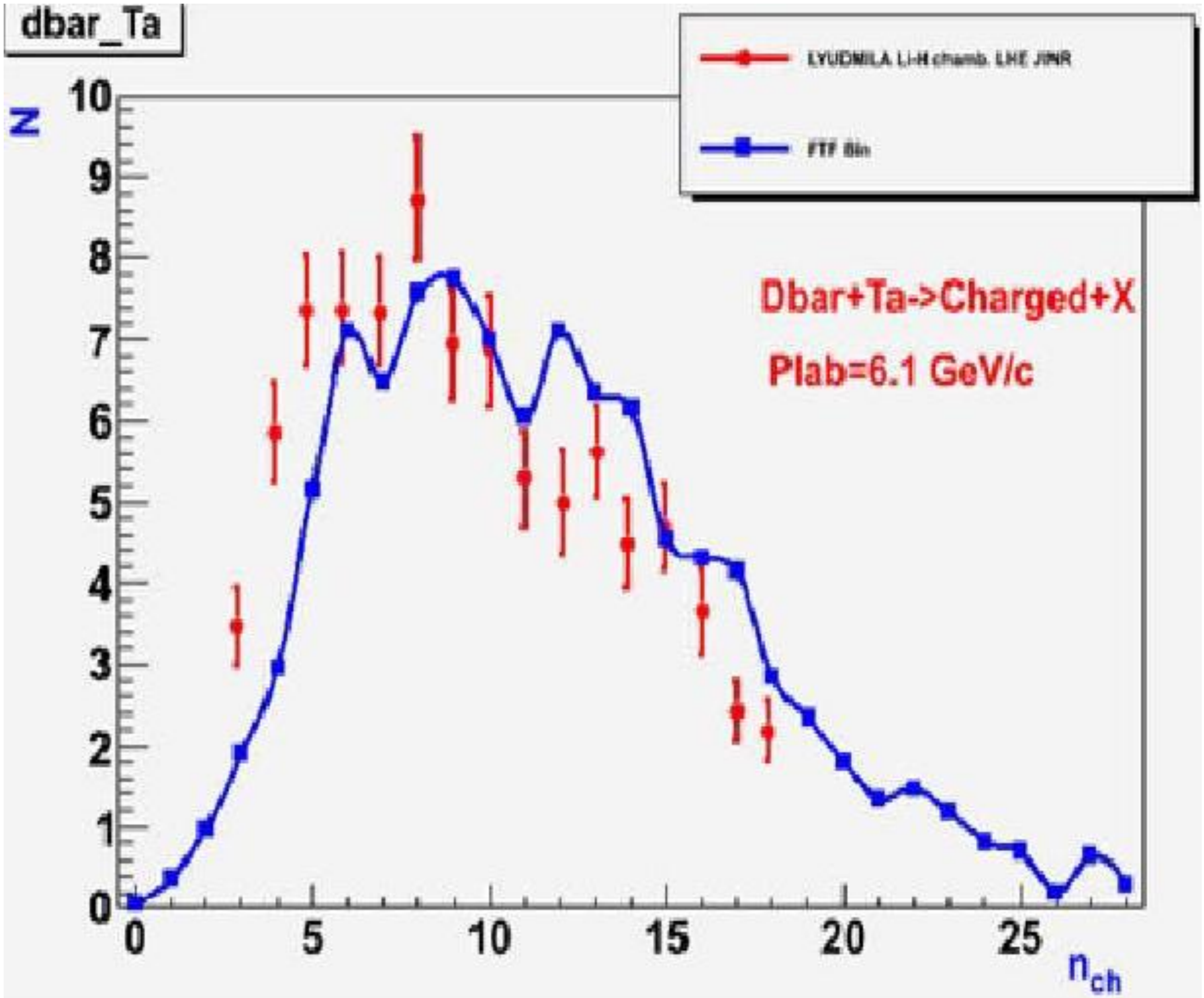
- These are empirical and parameterized cross section formulae with some theoretical insight
- G4GeneralSpaceNNCrossSection was prepared to assist users in selecting the appropriate cross section formula

Nucleus-nucleus Cross Sections

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

- G4ComponentAntiNuclNucleusXS
  - total, inelastic and elastic cross sections for anti-nucleon and anti-nucleus nucleus scattering

FTF Anti-deuteron Scattering



Summary

- Hadron elastic scattering
  - now several models which improve on the old Gheisha version
  - cross sections now usually based on Glauber approach

- Specialized high precision models (n, p, d, t, ^{3}He, α)
  - HP models which use G4NDL, now based entirely on ENDF/B-VII
  - alternative LEND (Livermore) models are faster but currently less extensive – use the ENDF.B-VII library

- 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
  - FTF model for high energies

Backup Slides

Including QMD in Your Physics List

- G4HadronInelasticProcess* ionInel =

```
        new G4HadronInelasticProcess("ionInelastic",
                                     G4GenericIon::G4GenericIon());
  // the cross sections
  G4TripathiCrossSection* tripCS = new G4TripathiCrossSection;
  G4IonsShenCrossSection* shenCS = new G4IonsShenCrossSection;
  ionInel->AddDataSet(shenCS);
  ionInel->AddDataSet(tripCS);
  // assign model to process
  G4QMDReaction* theQMD = new G4QMDReaction;
  ionInel->RegisterMe(theQMD);
  G4ProcessManager* pman = G4GenericIon::G4GenericIon()->
                              GetProcessManager();
  pman->AddDiscreteProcess(ionInel);
```

Including HP Particles in Your Physics List

- Elastic scattering

```
G4HadronElasticProcess* theNEP = new G4HadronElasticProcess;

// the cross sections
G4ParticleHPElasticData* theNEData =
                                        new G4ParticleHPElasticData;
theNEP->AddDataSet(theNEData);

// the model
G4ParticleHPElastic* theNEM = new G4ParticleHPElastic;
theNEP->RegisterMe(theNEM);
neutManager->AddDiscreteProcess(theNEP);
```