Geant4 Hadronics Overview

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Additional reading (1/2)

- Geant4 Collaboration, *Geant4—a simulation toolkit*, Nucl. Instr. and Meth. **A** 506 (2003) 250–303
- *Geant4 Physics Reference Manual*
- *Geant4 User's Guide For Application Developers*
- J.P. Wellisch, *Hadronic shower models in GEANT4—the frameworks*, Comput. Phys. Commun. 140 (2001) 65–75
- A. Heikkinen and N. Stepanov, *Bertini intra-nuclear cascade implementation in Geant4***,** ePrint nucl-th/0306008

Additional reading (2/2)

- V. Ivanchenko, *Geant4: physics potential for instrumentation in space and medicine*, Nucl. Instr. and Meth. **A** 525 (2004) 402–405
- V. Ivanchenko et. al., *The Geant4 Hadronic Verification Suite for the Cascade Energy Range***,** arXiv:physics/0306016

Outline

- Processes and hadronic physics
- Hadronic cross sections
- Parametrised models
- Theoretical models
- Model framework
- Physics lists
- Code examples
- Physics validation against experimental data

Hadronic physics challenge

- Even though there is an underlying theory (QCD), applying it is much more difficult than applying QED for EM physics
- We must deal with at least three energy regimes:
  - Chiral perturbation theory (< 100 MeV)
  - Resonance and cascade region (100 MeV – 20 GeV)
  - QCD strings (> 20 GeV)
- Within each regime there are several models:
  - Many of these are phenomenological

The Geant4 philosophy of hadronics (1/2)

- Provide a general model framework that allows implementation of processes and models at many levels
- Separate models and processes in framework:
  - Hadronic models and cross sections implement processes
- Provide processes containing:
  - Many possible models and cross sections
  - Default cross sections for each model

The Geant4 philosophy of hadronics (2/2)

- Provide several optional models and cross section sets in each region
- Let the user decide which physics is best:
  - Complex task is handled with physics lists
  - Educated guess physics lists are provided by use-case
- Validate new models against latest data:
  - Extensive and systematic validation program

Geant4 process

- A process uses cross sections to decide when and where an interaction will occur:
  - *GetPhysicalInteractionLength()*
- A process uses an interaction model to generate the final state:
  - *DoIt()*
- Three types of process:
  - *AtRest*
  - *AlongStep*
  - *PostStep*
- Each particle has its own process manager
- Each process has a set of models coordinated with energy range manager

Hadronic process

- At rest:
  – Stopped muon, pion, kaon, anti-proton
  – Radioactive decay
- Elastic:
  – Same process for all long-lived hadrons
- Inelastic:
  – Different process for each hadron
  – Photo-nuclear
  – Electro-nuclear
- Capture:
  – Pion- and kaon- in flight
- Fission

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 only a few numbers to parameterize cross section
  - Some represent large databases (data driven models)
- Cross Section Management:
  - *GetCrossSection()* sees last set loaded for energy range

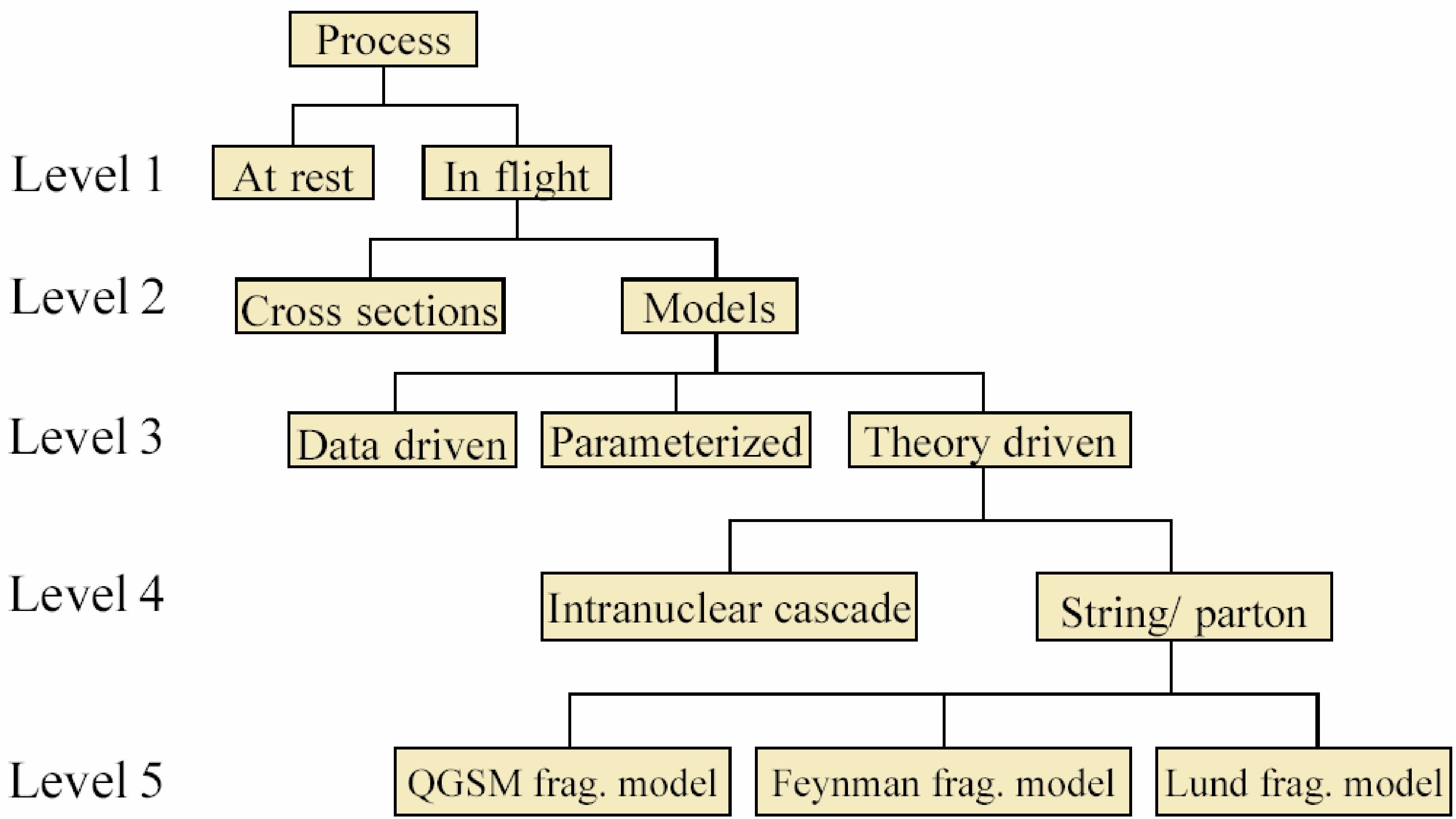
Alternative cross sections

- Low energy neutrons
  - G4NDL available as Geant4 distribution data files
  - Available with or without thermal cross sections
- Neutron and proton reaction cross sections
  - 20 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections
  - Good for E/A < 1 GeV
- Isotope production data
  - E < 100 MeV

Different types of hadronic shower models

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

Models in hadronic framework



Data driven models (1/2)

- Characterized by lots of data:
  - Cross section
  - Angular distribution
  - Multiplicity
- To get interaction length and final state, models simply interpolate data:
  - Usually linear interpolation of cross section, and Legendre polynomials
- Examples:
  - Coherent elastic scattering (pp, np, nn)
  - Radioactive decay
  - Neutrons (E < 20 MeV)

Data driven models (2/2)

- Transport of low energy neutrons in matter:
  - The energy coverage of these models is from thermal energies to 20 MeV
  - The modeling is based on the data formats of ENDF/B-VI, and all distributions of this standard data format are implemented
  - The data sets used are selected from data libraries that conform to these standard formats
  - The file system is used in order to allow granular access to, and flexibility in, the use of the cross-sections for different isotopes, and channels
  - Code in sub-directory: */source/processes/hadronic/models/neutron_hp*

Parametrisation driven models (1/2)

- Depends on both data and theory:
  - Enough data to parameterize cross sections, multiplicities, angular distributions
- Final states determined by theory, sampling:
  - Use conservation laws to get charge, energy, etc.
- Examples:
  - Fission
  - Capture
  - LEP, GEISHA based HEP models

Parametrisation driven models (2/2)

- Based on GHEISHA package of Geant3.21, two sets of models exist for inelastic scattering of particles in flight:
  - Low energy models:
    - E < 20 GeV
    - */hadronic/models/low_energy*
  - High energy models:
    - 20 GeV < E < O(TeV)
    - */hadronic/models/high_energy*
- Original approach to primary interaction, nuclear excitation, intra-nuclear cascade and evaporation is kept
- Fission, capture and coherent elastic scattering are also modeled through parametrised models

Theory driven models (1/2)

- Dominated by theory (QCD, strings, chiral perturbation theory)
- Data used mainly for normalization and validation
- Final states determined by sampling theoretical distributions
- Philosophy implies the usage physics lists, providing wanted collection of models, such as:
  - Parton string models at high energies, of intra-nuclear transport models at intermediate energies, and of statistical break-up models for de-excitation

Theory driven models (2/2)

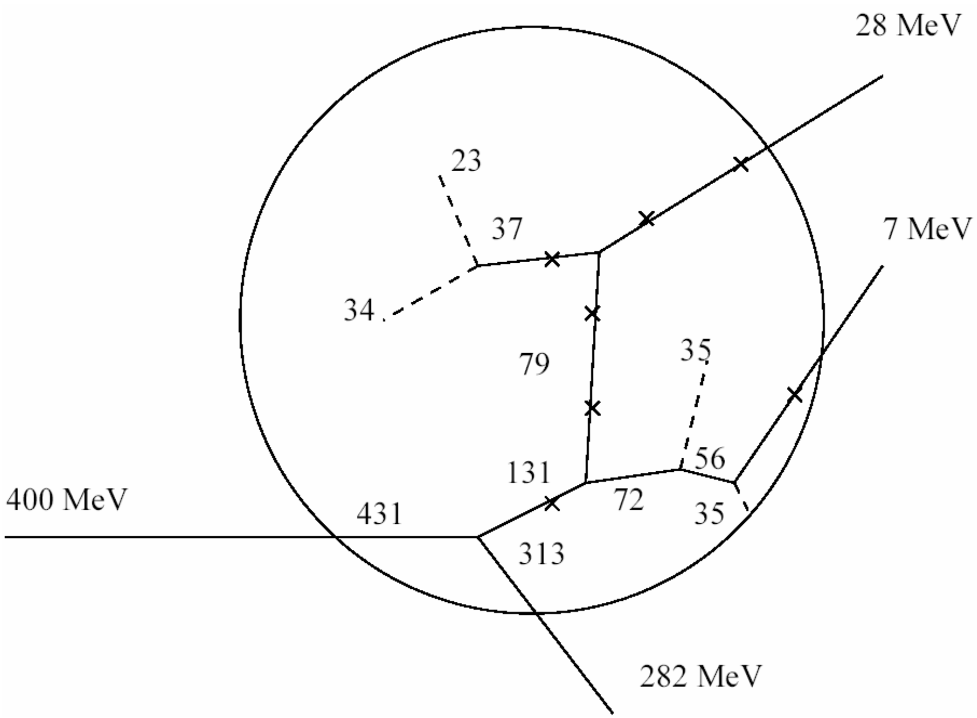
- Parton string:
  - Projectiles with E > 5 GeV
  - */hadronic/models/parton_string*
- Chiral invariant phase space, CHIPS:
  - All energies
  - Quark-level event generator for the fragmentation of hadronic systems into hadrons
  - Interactions between hadrons are treated as purely kinematic effects of quark exchange
  - Decay of excited hadronic systems is treated as the fusion of two quark-partons within the system
  - Includes nonrelativistic phase space of nucleons to explain evaporation
  - */hadronic/models/chiral_inv_phase_space*
- Nuclear de-excitation and breakup

Bertini intra-nuclear cascade (1/2)

- Collection of theory driven models with parametrisation features:
  - */hadronic/models/cascade*
- Intermediate energies ~100 keV – 10MeV
- Models included:
  - Bertini INC model with exitons
  - Pre-equilibrium model
  - Nucleus explosion model
  - Fission model
  - Evaporation model

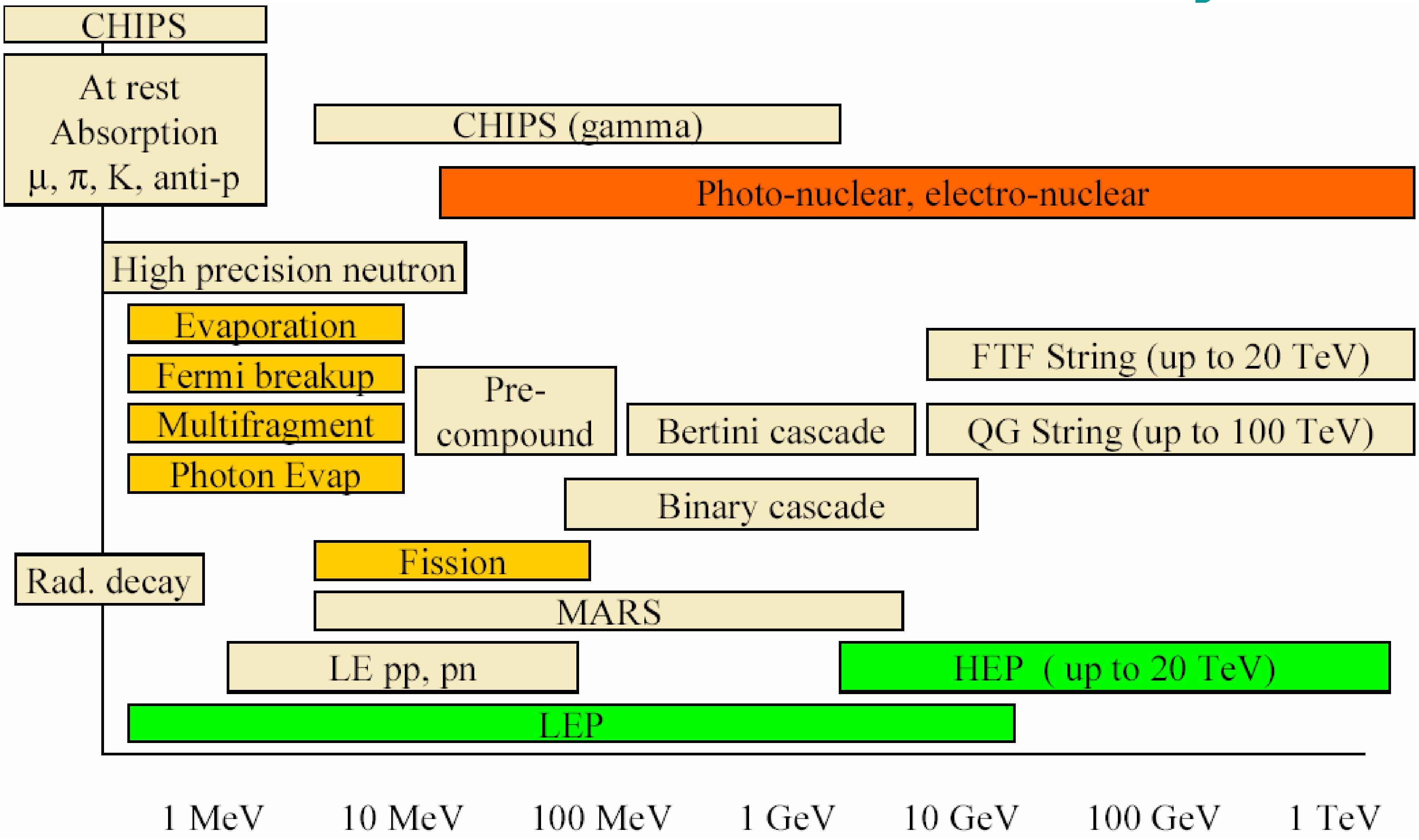
Bertini intra-nuclear cascade (2/2)

- For A>4 a nuclei model is composed of three concentric spheres
- Impulse distribution in each region follows Fermi distribution with zero temperature
- Particle treated p,n, pions, photon evaporation and nuclear isotope remnats
- Latest addition include incident kaons up to an energy of 15 GeV:
  - Final states, will be included for K+, K-, K0, K0bar, lambda, sigma+, sigma0, sigma-, xi0 and xi-



Schematic presentation of the intra-nuclear cascade. A hadron with 400 MeV energy is forming an INC history. Crosses present the Pauli exclusion principle in action.

Hadronic model inventory



Physics Lists – putting physics into your simulation

- User must implement a physics list:
  - Derive a class from *G4VUserPhysicsList*
  - Define the particles required
  - Register models and cross sections with processes
  - Register processes with particles
  - Set secondary production cuts
  - In main(), register your physics list with the Run Manager
- Care is required:
  - Multiple models, cross sections allowed per process
  - No single model covers all energies, or all particles
  - Choice of model is heavily dependent on physics studied

Physics lists by use case

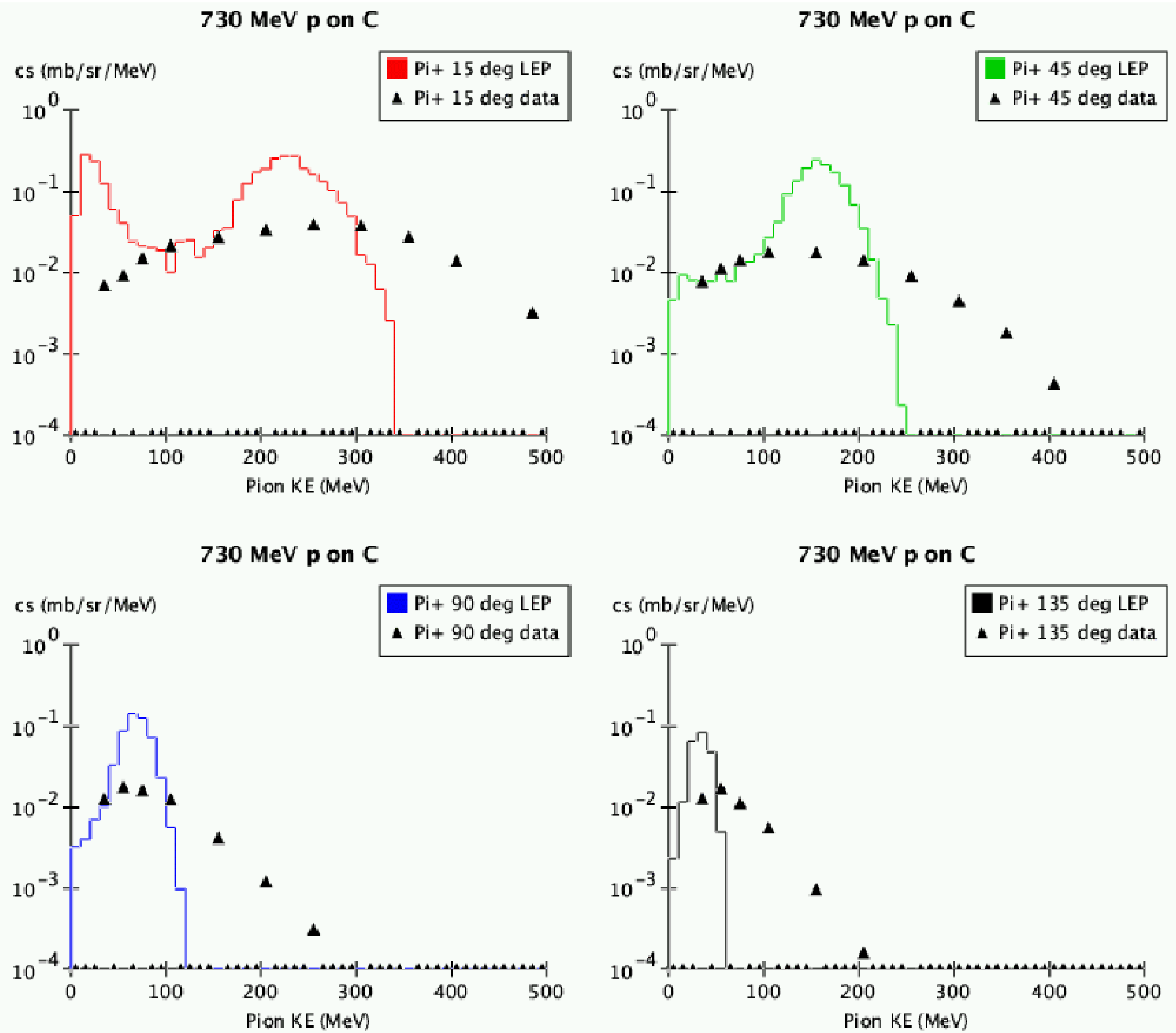
- Geant4 recommendation:
  - Use example physics lists
  - Go to Geant4 home page > Site Index > physics lists
- Many hadronic physics lists available including:
  - Low and high energy nucleon penetration shielding
  - Low energy dosimetric applications
  - Medical neutron applications
  - Low background experiments (underground)

Code Example (1/2)

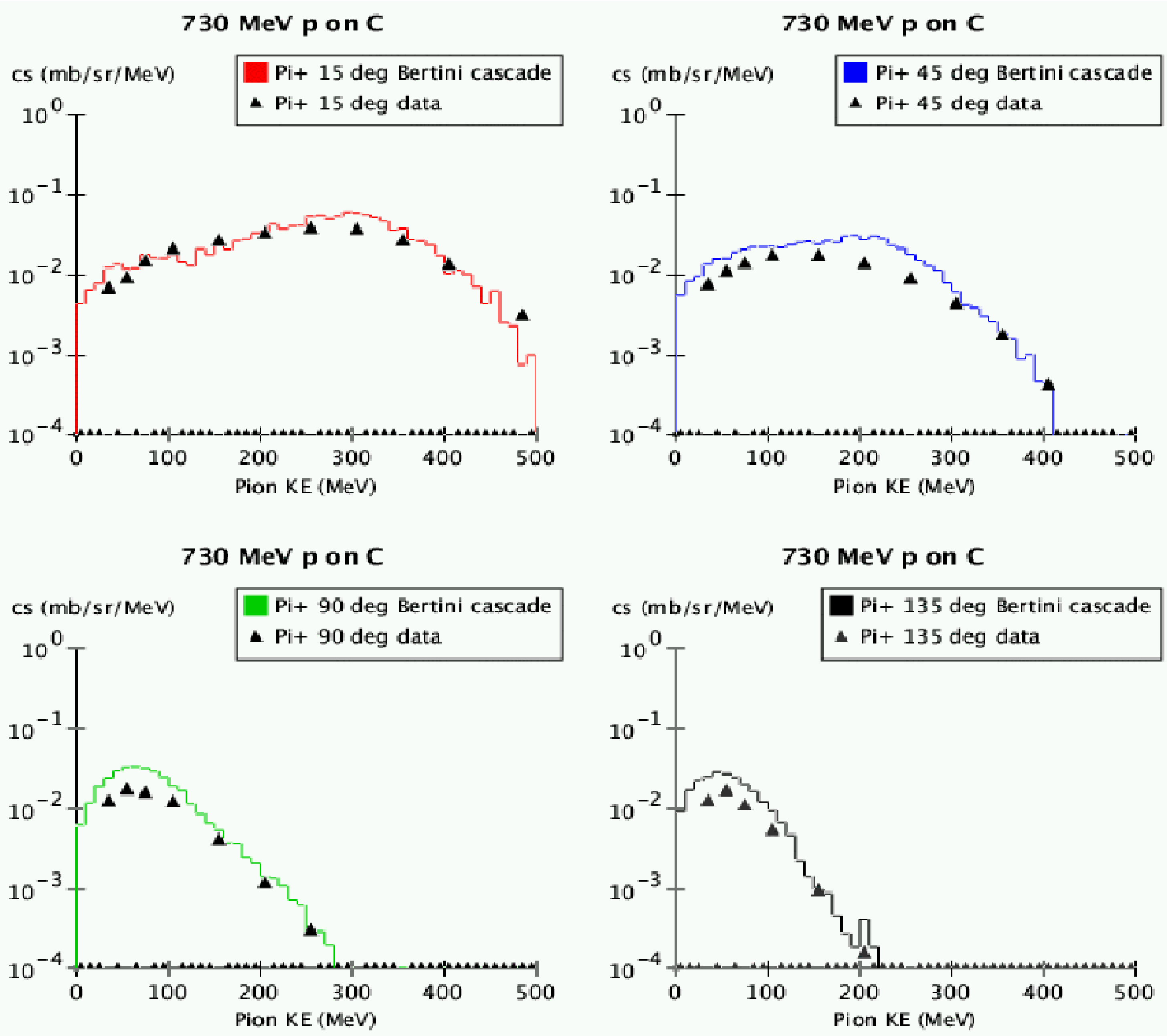
```
void MyPhysicsList::ConstructProton() {
   G4ParticleDefinition*    proton = G4Proton::ProtonDefinition();
   G4ProcessManager* protonProcessManager =
                                   proton->GetProcessManager();
   // Elastic scattering
   G4HadronElasticProcess* protonElasticProcess =
                                  new G4HadronElasticProcess();
   G4LElastic* protonElasticModel = new G4LElastic();

   protonElasticProcess->RegisterMe(protonElasticModel);

   protonProcessManager->AddDiscreteProcess(protonElasticProcess);
...
```

Code example (2/2)

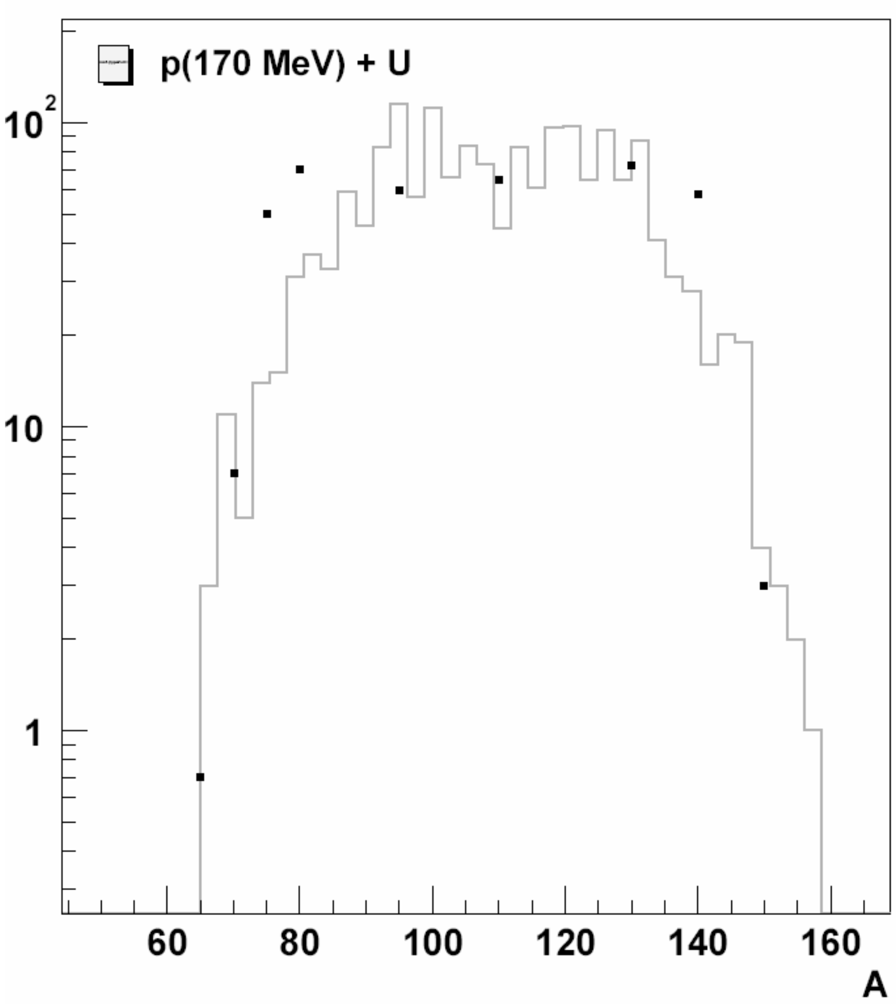
```
...
// Inelastic scattering
G4ProtonInelasticProcess* protonInelasticProcess =
                                  new G4ProtonInelasticProcess();

G4LEProtonInelastic* protonLowEnergyInelasticModel =
                                      new G4LEProtonInelastic();
protonLowEnergyInelasticModel->SetMaxEnergy(20.0*GeV);
protonInelasticProcess->RegisterMe(protonLowEnergyInelasticModel);

G4HEProtonInelastic*protonHighEnergyInelasticModel =
                                      new G4HEProtonInelastic();
protonHighEnergyInelasticModel->SetMinEnergy(20.0*GeV);
protonInelasticProcess->RegisterMe(protonHighEnergyInelasticModel);
}
```



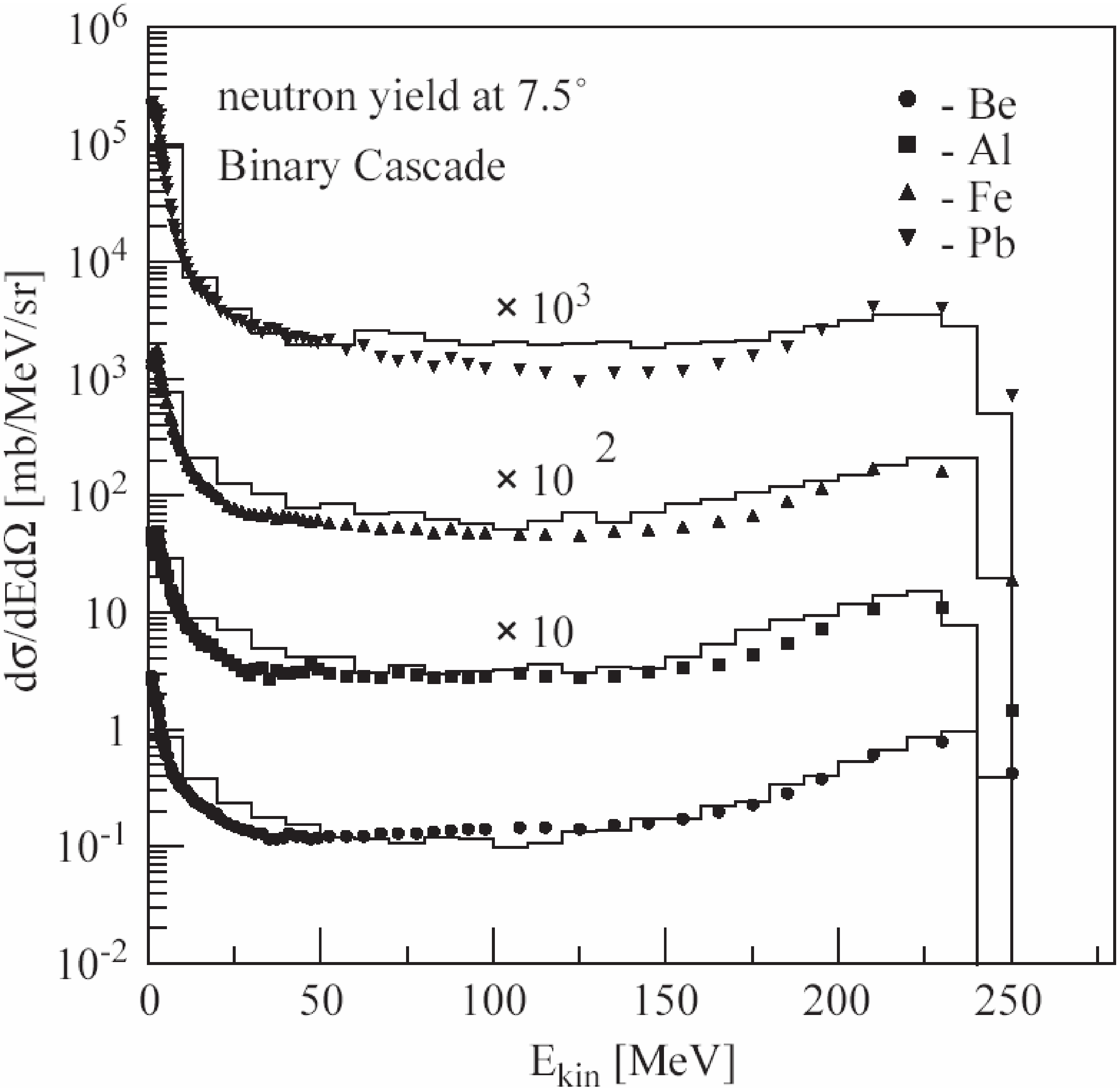
Gean3.21 based Geant4 LEP model pion production from 730 MeV proton on Carbon.



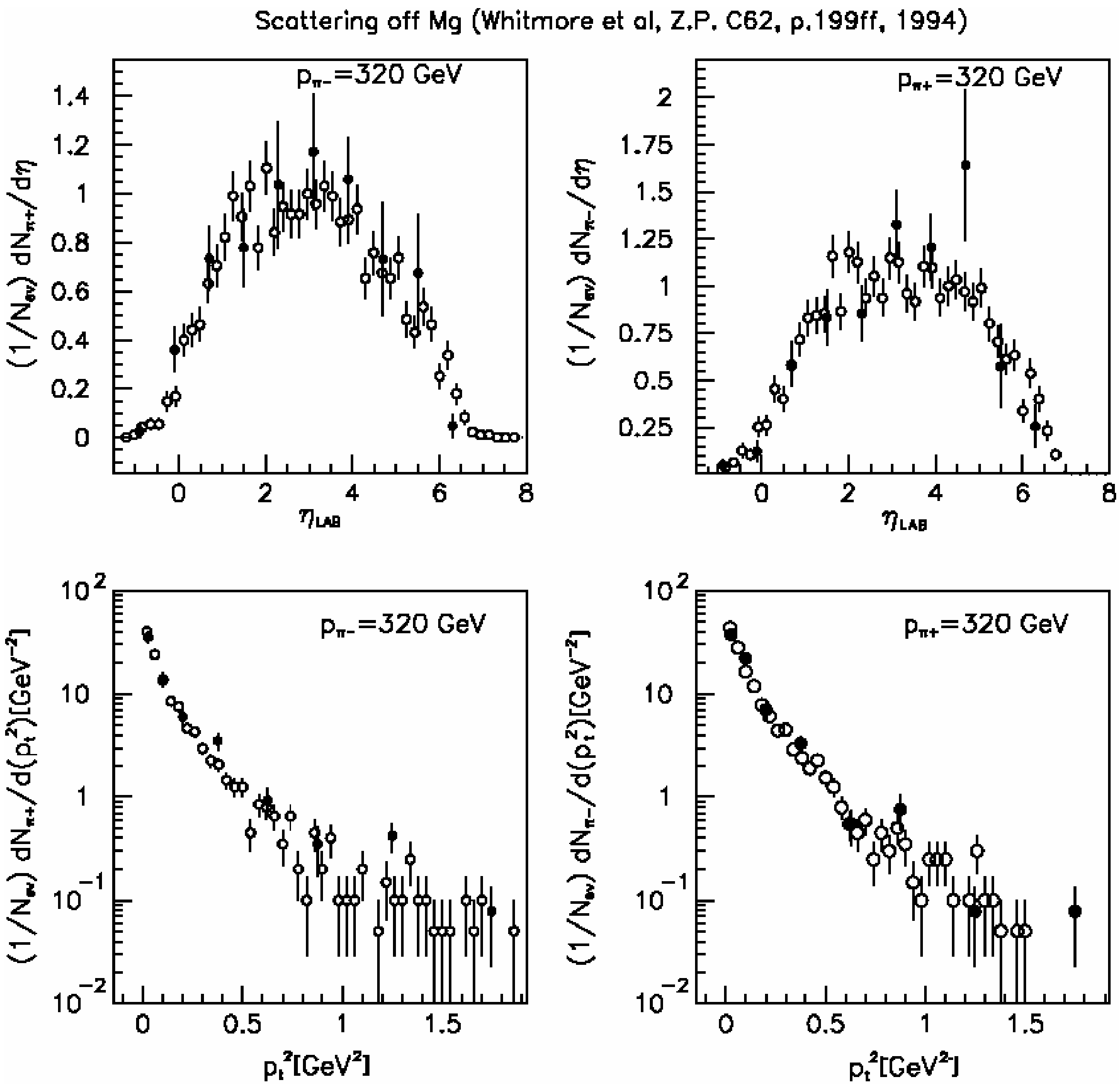
Bertini cascade model pion production from 730 MeV proton on Carbon.



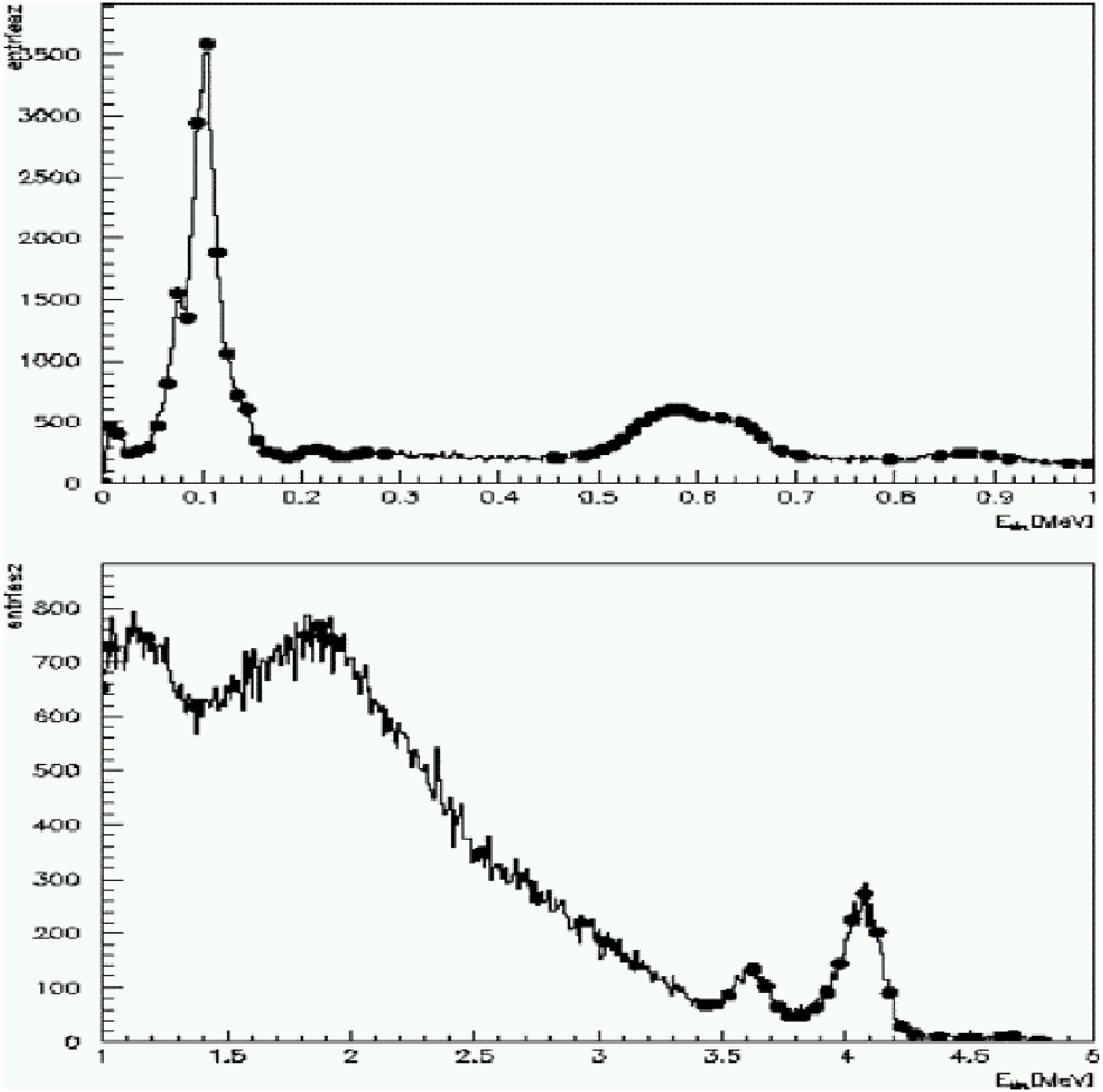
Bertini cascade model nuclei fragmet production from 170 MeV proton on Uranium.



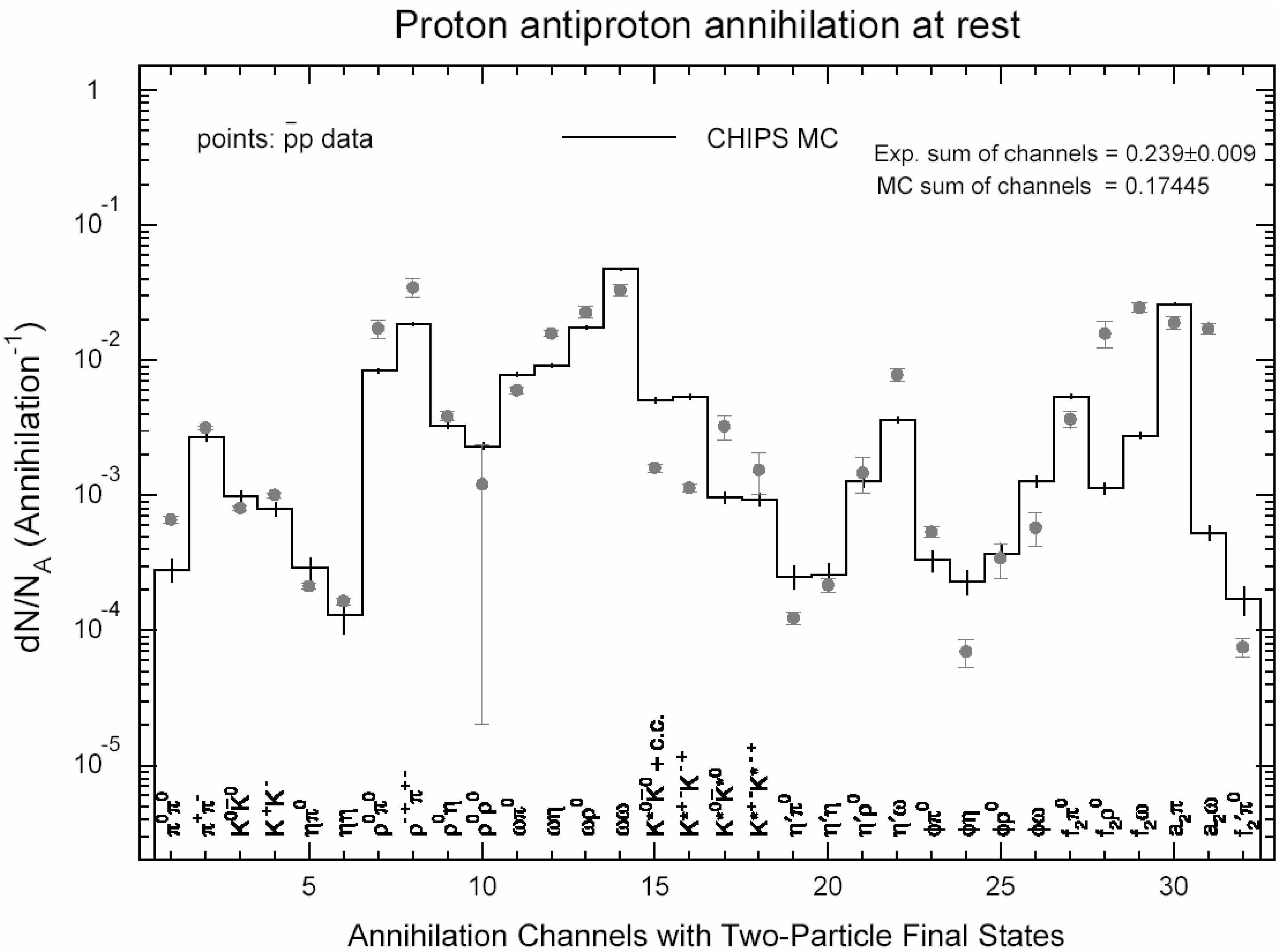
Double differential cross-section for neutrons produced by 256 MeV protons.



Comparison of differential pion yields for positive and negative pions in pion Magnesium reactions at 320 GeV lab momentum. The dots are data and the open circles are Monte Carlo predictions by G4QGSModel.



Geant4 simulation of gammas from 14 MeV neutron capture on uranium.


Proton antiproton annihilation at rest
points: p̄p data
CHIPS MC
Exp. sum of channels = 0.239±0.009
MC sum of channels = 0.17445
dN/N_A (Annihilation^-1)
1
10^-1
10^-2
10^-3
10^-4
10^-5
5
10
15
20
25
30
Annihilation Channels with Two-Particle Final States

Conclusion

- Geant4 provides a large number of hadronic physics models for use in simulation
- Cross sections, either calculated, or from databases, are available to be assigned to processes
- Interactions are implemented by models, which are then assigned to processes
- For hadrons there are many models to choose from, so physics lists are provided by use-case