RECENT DEVELOPMENTS FOR GEANT4 LOW-ENERGY HADRONIC PHYSICS

V. Ivanchenko *CERN & Tomsk State University, Russia*

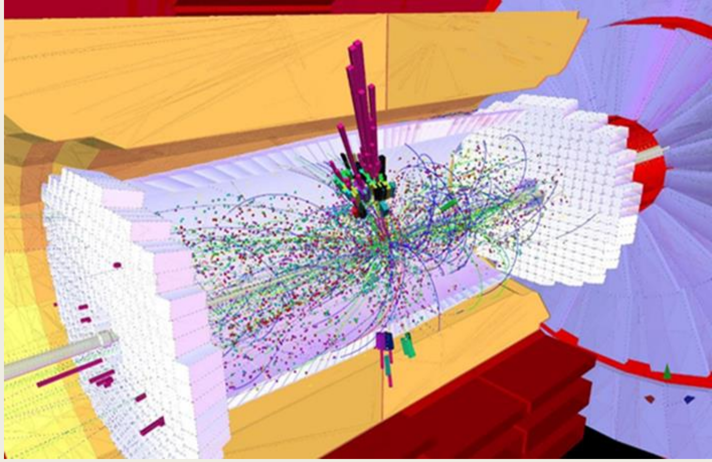
14th Geant4 Space User Workshop

Xylokastro 20400, Korinthia, Greece - October 20-23, 2019

Outline

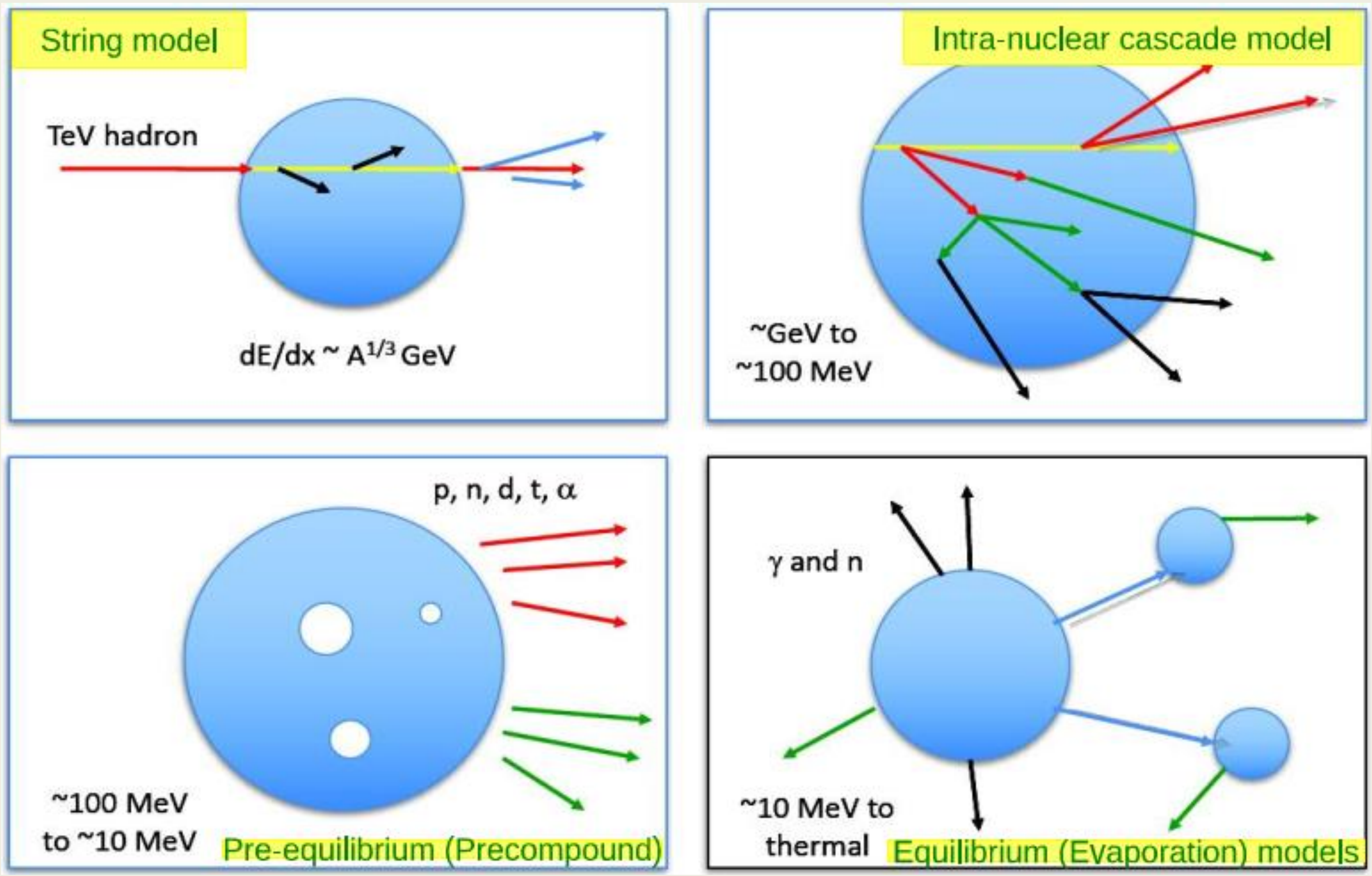
- Introduction
- Geant4 hadronic physics design
- High energy models in Geant4 10.6
- Low energy models in Geant4 10.6
- Selected validation results
- Hadronic Cross Section Updates
- Summary

Introduction



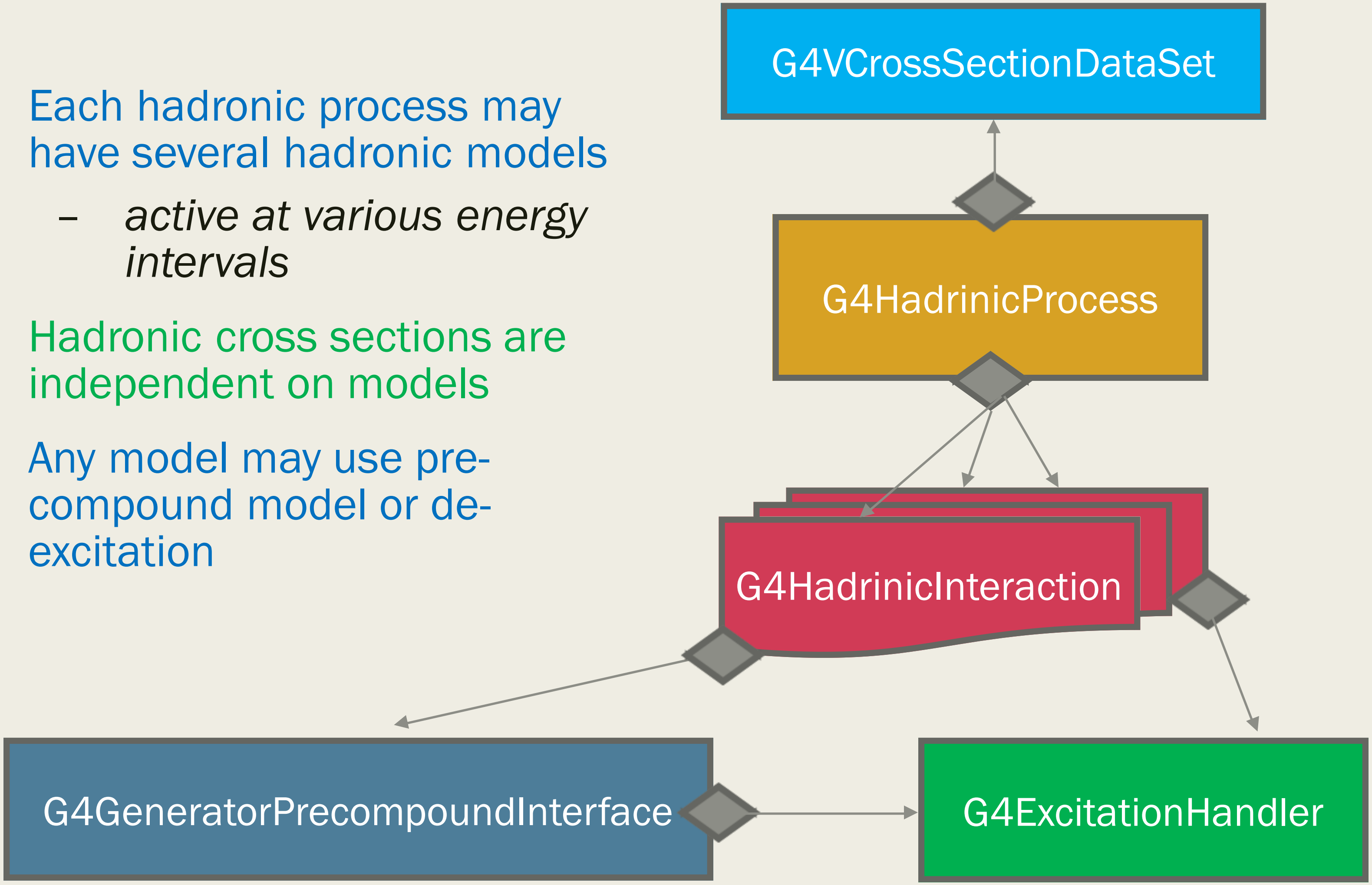
- Geant4 hadronic working group is focused first of all on simulation for experiments at LHC
  - *~100 B events are already simulated for LHC detectors*
- LHC results are sensitive to systematic uncertainty of Monte Carlo
- Low-energy component of hadronic shower affect results for
  - *Simulation of calorimeter responses*
  - *Simulation of background for tracking detectors*
- Requirements for low-energy hadronic models
  - *Provide correct energy deposition and fluctuation*
  - *4-momentum balance in each interaction*
  - *CPU and memory efficiency*

Hadron nucleus interaction

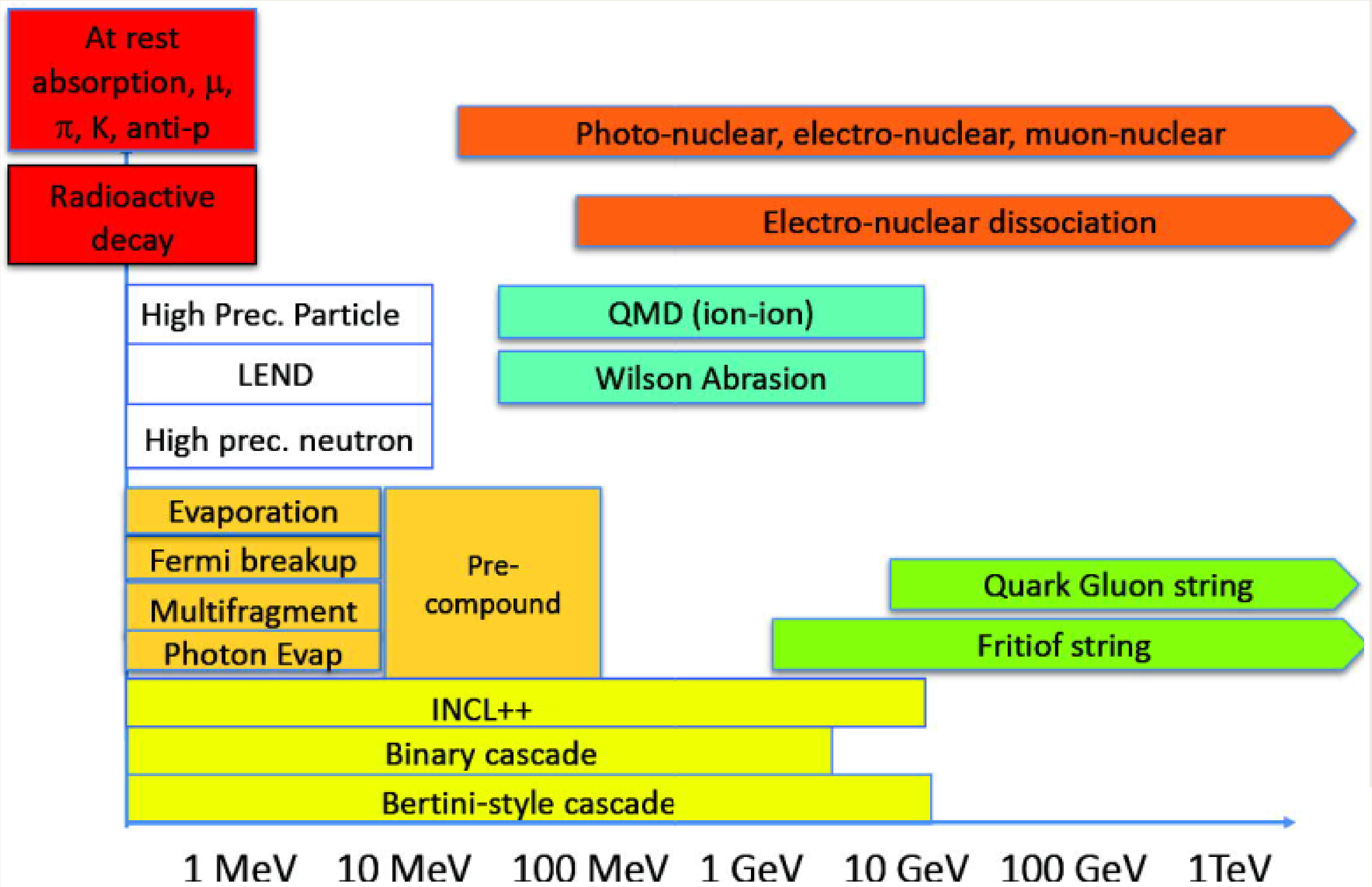


Geant4 hadronic physics design

- Each hadronic process may have several hadronic models
  - *active at various energy intervals*
- Hadronic cross sections are independent on models
- Any model may use pre-compound model or de-excitation



Geant4 hadronic models



General infrastructure update for 10.6

- Removed final state rotation both from elastic and inelastic processes
- Removed G4HadronicException and try/couch pattern from cross section sub-library and GetMeanFreePath() method, use only G4Exception
- Removed default GHEISHA cross sections
- Share cross section data between threads for XS and BGG classes
- Created new utility G4NuclearRadii with several parameterizations of nuclear radius
- Updated Starkov parameterizations for pion and kaon hadron-nucleon cross section
- Added G4PARTICLEXS2.1 dataset

High Energy Models in Geant4 10.6

String Models Developments

- Since 10.5 development versions of FTF and QGS are merged to the production release
  - *kept during 3 years separate to provide stability*
- FTF improved for
  - *thin target benchmarks*
  - *Interactions of light anti-ions*
  - *Introduced a coalescence model*
- QGS
  - *Improved thin target benchmarks*
  - *Provide narrower shower and increased visible energy*
- In 10.6 unified between Physics Lists transitions
  - *between FTFP and QGSP is 12-25 GeV*
  - *between cascade and FTFP is 3-6 GeV*

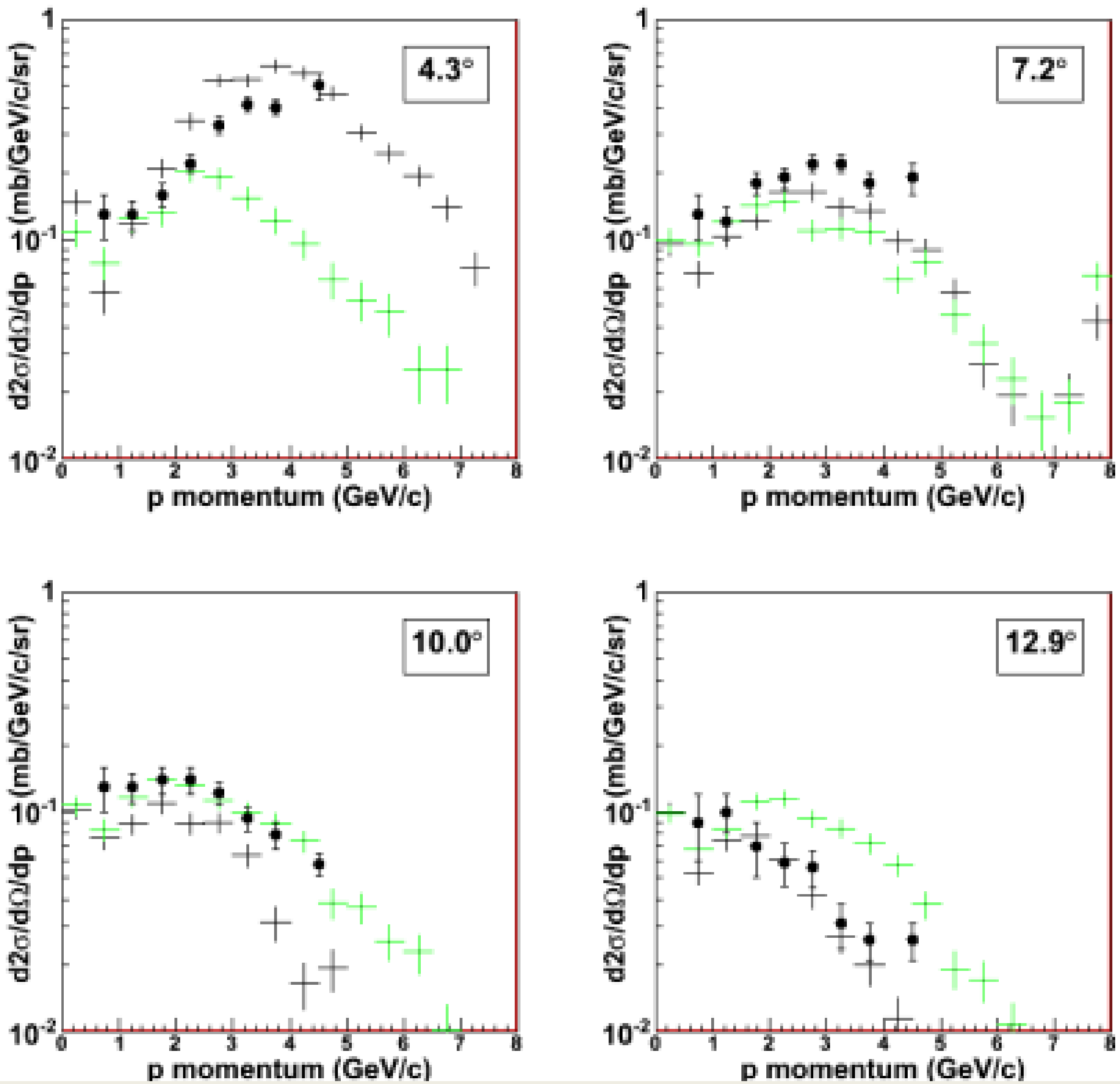
Cascade Models: Bertini

- Phase space generation
  - for final states with more than two bodies
  - old Bertini generator incorrect

- Tried Kopylov phase space generator
  - validation results inconclusive (better in some regimes, worse in others)
  - keep original generator for now

- New possibility
  - INCL++ uses a biased phase space generator (based on Raubold-Lynch method)
  - entire final state can be rotated by arbitrary angle
  - sample angle from exponential describing elastic p-p and pi-p scattering
  - adapt this to Bertini

Biased Phase Space p + C -> p + X @ 8 GeV/c



HARP data:
black dots

Original Bertini
generator :
green crosses

Biased phase space:
black crosses

Cascade models

- Main developments for INCLXX was for 10.5:
  - *Improved strangeness production*
  - *Provide the best description of d, t, He3, He4 production*
  - *New dataset INCL1.0*
- Only few bug fixes in the Binary cascade
  - *Transition energy with the Bertini cascade 1-1.5 GeV*

Low Energy Models in Geant4 10.6

Developments for pre-compound model and de-excitation module

- Established set of model parameters for PRECO and DEEX and user interface to these parameters
- Renewed internal data structure for nuclear levels
  - *G4ENDSFSTATEDATA, G4LEVELGAMMADATA, G4RADIOACTIVEDATA are coherent*
  - *New data format was introduced in Geant4 10.3*
  - *All components of PRECO and DEEX use this data and not hard-coded numbers*
- Provided long-lived isomer production
  - *Added floating level states*
  - *Long lived isomers may be tracked by Geant4*
- Provided correlated gamma emission for radioactive decay
  - *Is disabled by default but may be enabled by a flag*
- It was completed in general for Geant4 10.4
  - *However, some fixes and improvements are still added in 10.5 and 10.6*

Parameters for pre-compound/de-excitation

- G4DeexPrecoParameters scheme
  - *Printout of all important parameters values at initialisation*
  - *Modification of parameters allowed only at G4State_PreInit*
  - *New boolean parameters are added recently allowing disable DEEX or PRECO*
- How it can be used?
  - *G4DeexPrecoParameters* param=*
    G4NuclearLevelData::GetInstance()->GetParameters();
  - *param->StoreStoreICLevelData(true);*
  - *param->SetCorrelatedGamma(true);*
  - *param->SetInternalConversionFlag(true);*
  - *param->SetDeexChannelType(fGEM);*
  - *..........*
  - *param->Dump();*
- G4ExcitationHandler has public Set methods
  - *This interface is left in order to allow creation of custom handler*
  - *Normally parameters should be set via G4DeexPrecoParameters class*

G4FermiBreakUpVI model

- Old G4FermiBreakUp model was based on hard-coded data
  - *A pool of 112 states, Z < 9, A < 17*
  - *Precomputed probabilities of decay of each state from this pool into 2-, 3-, 4-body final state from this pool*
- New G4FermiBreakUpVI model fully based on data of G4GAMMALEVELDATA
  - *A pool of 260 states from data files and 399 reactions, Z < 9, A < 17 (10.4)*
  - *A pool of 380 states from data files and 991 reactions, Z < 9, A < 17 (10.5)*
    - Maximal excitation energy 20 MeV
  - *Only binary decay chains are considered*
    - A standard Coulomb barrier computation is used
  - *An extra set of 80 unphysical fragments not known from data in 10.5*
    - Including very exotic intermediate states like H_8 or He_2
    - Will be removed in 10.6 – decay of unphysical fragments will be delegated to Evaporation
  - *Probability of the first decay is computed on fly if initial excitation of the primary fragment is not equal to one of known levels*
  - *The second and others decay probabilities are precomputed*
  - *Final product is always a list of states from the main pool, which has no Fermi decay channel (may have gamma transition)*

De-excitation module: parameterisation of level density

- For long time a simplified level density parameterization was used: Ld = 0.1*A
- In literature several fits to nuclear level data are published
- For Geant4 10.5 a variant was chosen from A.Mengoni and Yu. Nakajima, JNST 31 (1994) 151
  - $Ld = \alpha \cdot A \cdot (1 + \beta / A^{1/3})$
  - It turned out, that in order to have reasonable results, the same parameterisation should be used in evaporation, fission, photon evaporation
  - There is a new option in G4DeexPrecoParameters Get/Set LevelDensityFlag
  - The new default Ld = 0.075*A

ParticleHP

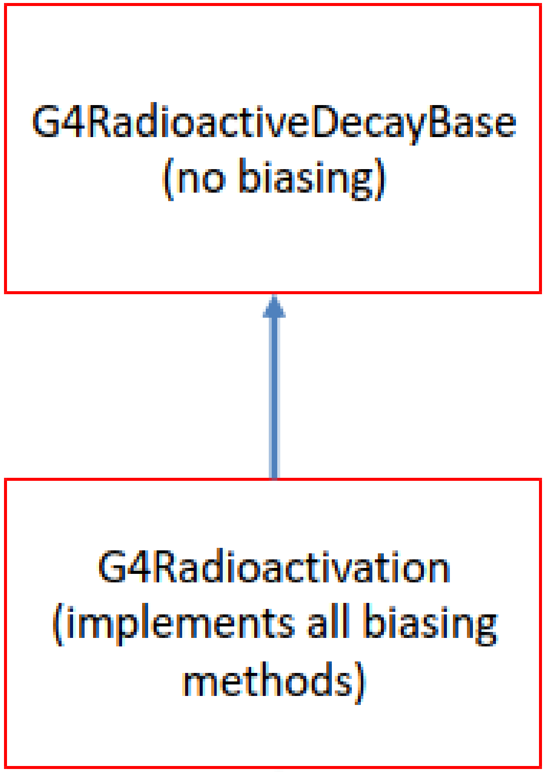
- By default tries to conserve energy/momentum event-by-event
  - works sometimes
  - in general no

- Current ParticleHP code often makes common sense modifications to get energy conservation, but this often destroys agreement with ENDF energy distributions
  - ENDF database rules deal only with distributions
  - violating these rules can cause unexpected results (like extra gammas) which make validation difficult
  - many environment variables exist to “fix up” ENDF

- Quick and dirty fix:
  - export G4NEUTRONHP_DO_NOT_ADJUST_FINAL_STATE=1
  - export G4PHP_DO_NOT_ADJUST_FINAL_STATE=1

Radioactive Decay Refactoring Completed

- Remove all radioactive decay biasing methods from G4RadioactiveDecay
  - better CPU performance for those not using biasing
  - cleaner code
  - new class name: G4RadioactiveDecayBase
  - rename as G4RadioactiveDecay for major release
- Put all biasing functionality in derived class
  - use for activation studies
  - new class name: G4Radioactivation



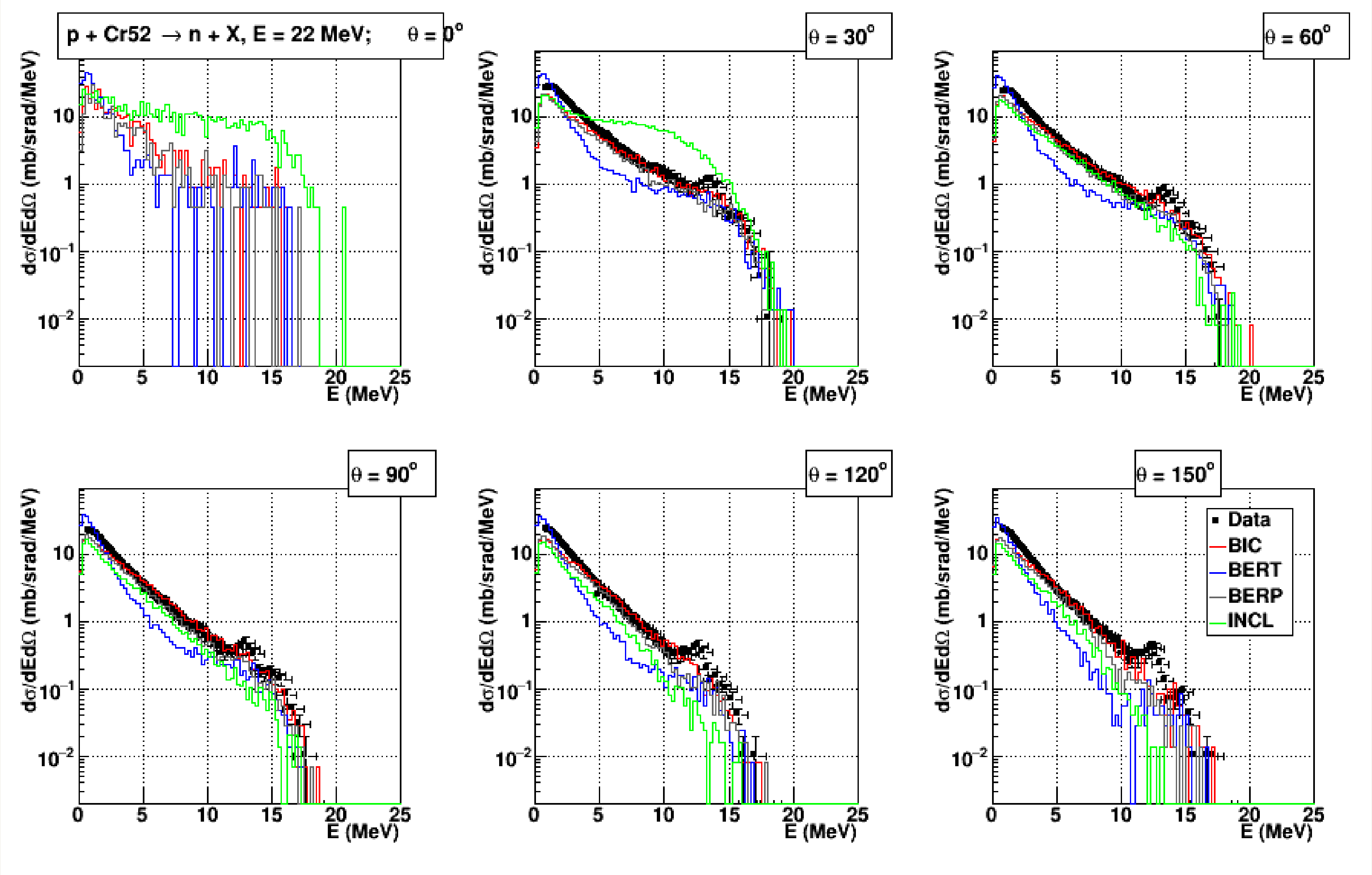
Radioactive Decay: Electron Capture

- N-shell capture added to G4ECDecay
  - machinery is there for all nuclides but currently data for only a few are included in RadioactiveDecay5.3
- Subshell capture ratios added
  - tables of PL2/PL1, PM2/PM1 and PN2/PN1 added to RadioactiveDecay5.3
  - based on bound electron radial wave amplitudes from Bambynek (1977)
  - partial probabilities of subshell capture calculated from above tables

Selected validation results

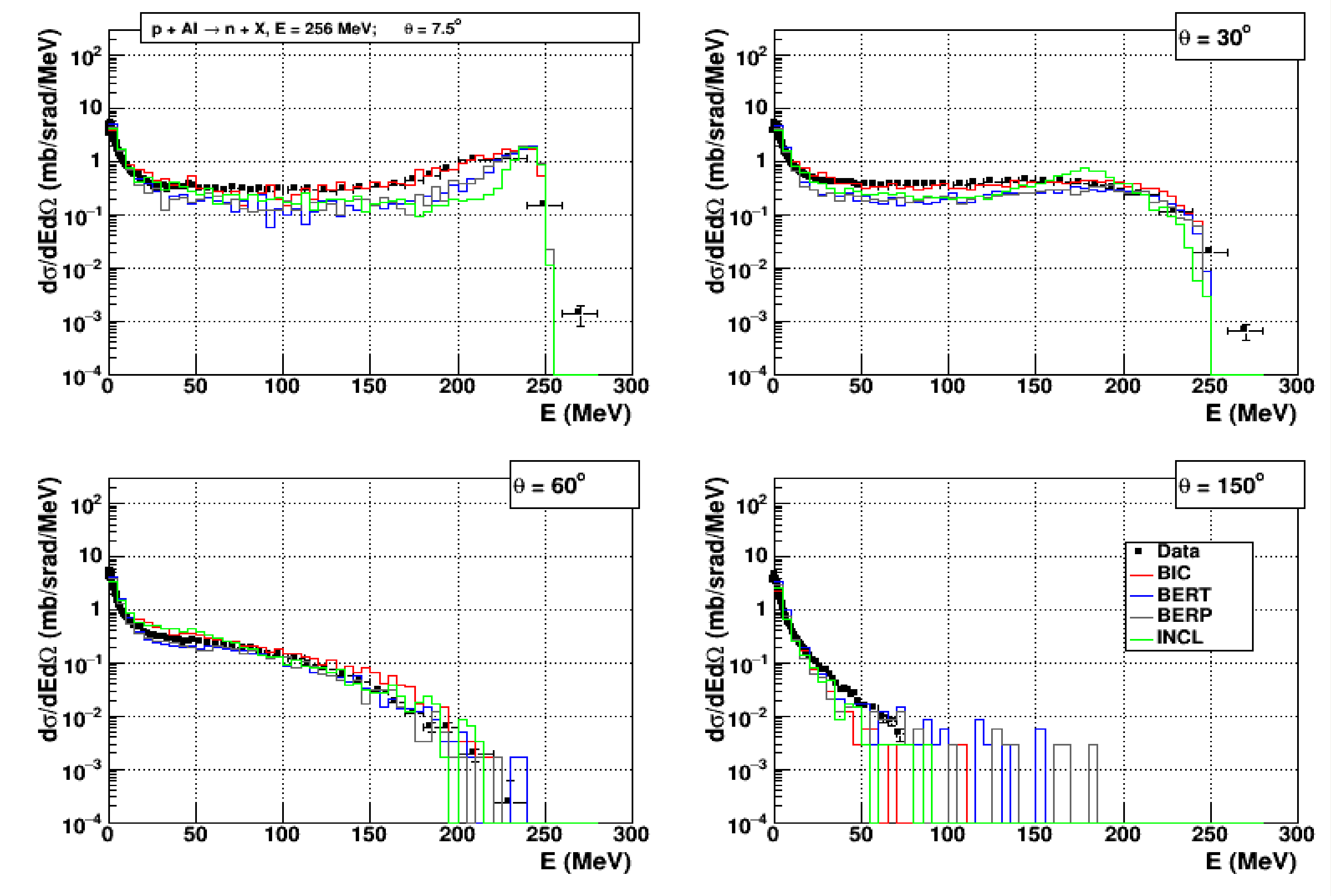
Double differential neutron production cross section for 22 MeV protons in ^{52}Cr target

N.S.Biryukov et al., Sov. J. Nucl. Phys. 31 (1980) 3



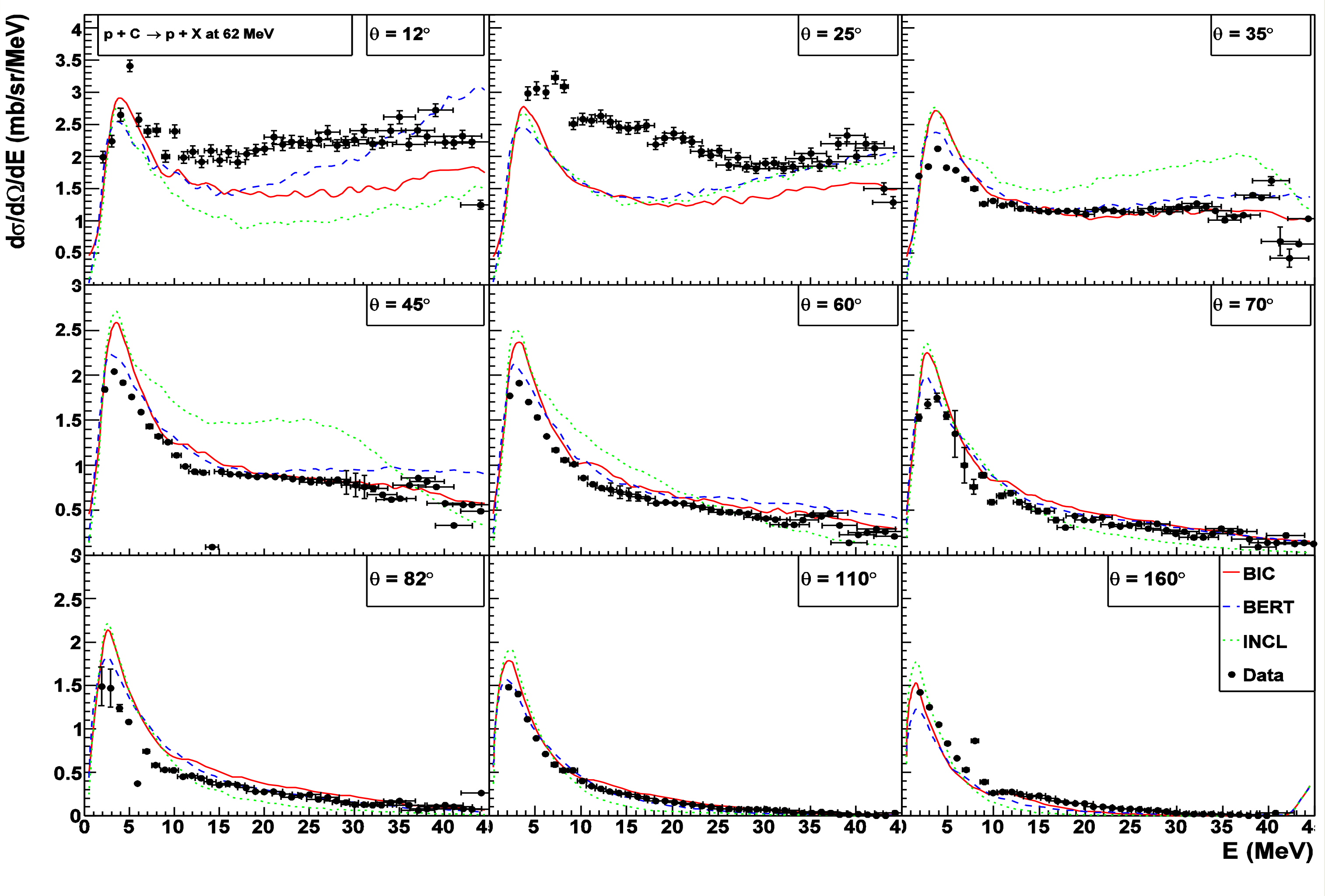
Double differential neutron production cross section for 256 MeV protons in Al target

M.M.Meier et al., Nucl. Sci. Engeneering 110 (1992) 289



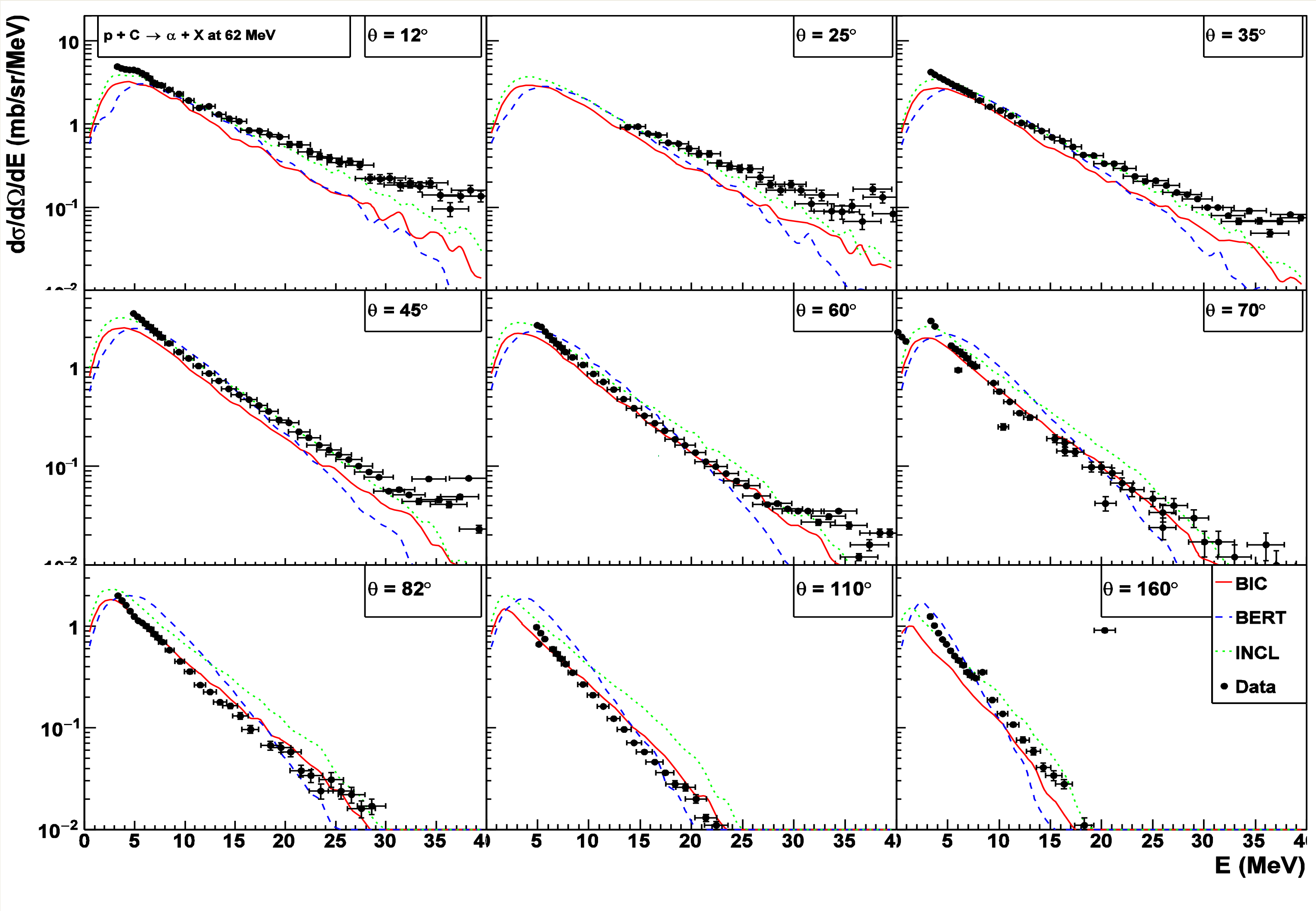
Double differential proton production cross section for 62 MeV protons in carbon target

F.E.Bertrand & R.W.Peelle, Phys. Rev. C 8 (1973) 1045



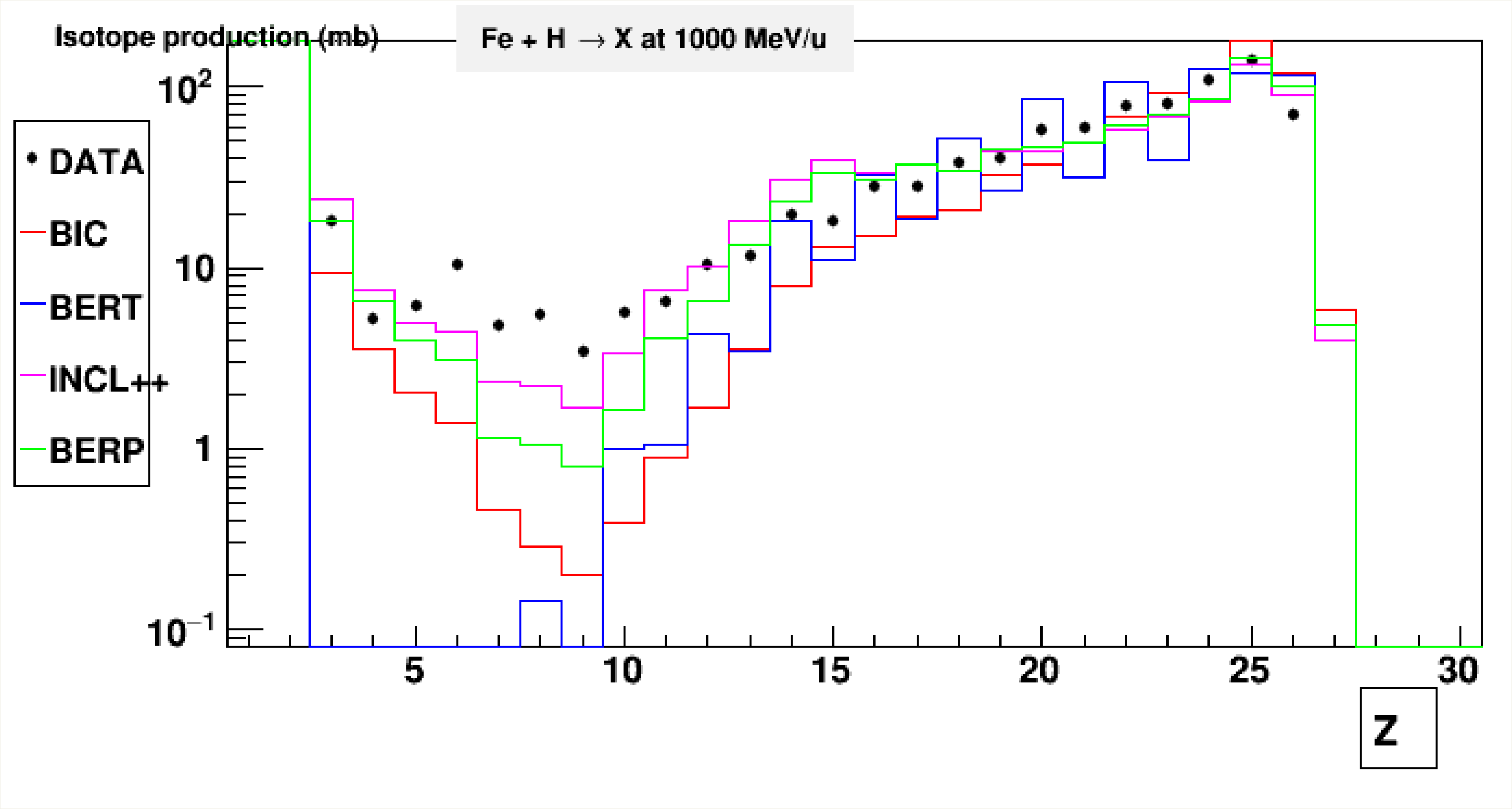
Double differential alpha production cross section for 62 MeV protons in carbon target

F.E.Bertrand & R.W.Peelle, Phys. Rev. C 8 (1973) 1045



Isotope production by 1 GeV protons in Fe target

C.Villagrasa et al., AIP Conference Proceeding 769 (2005) 842



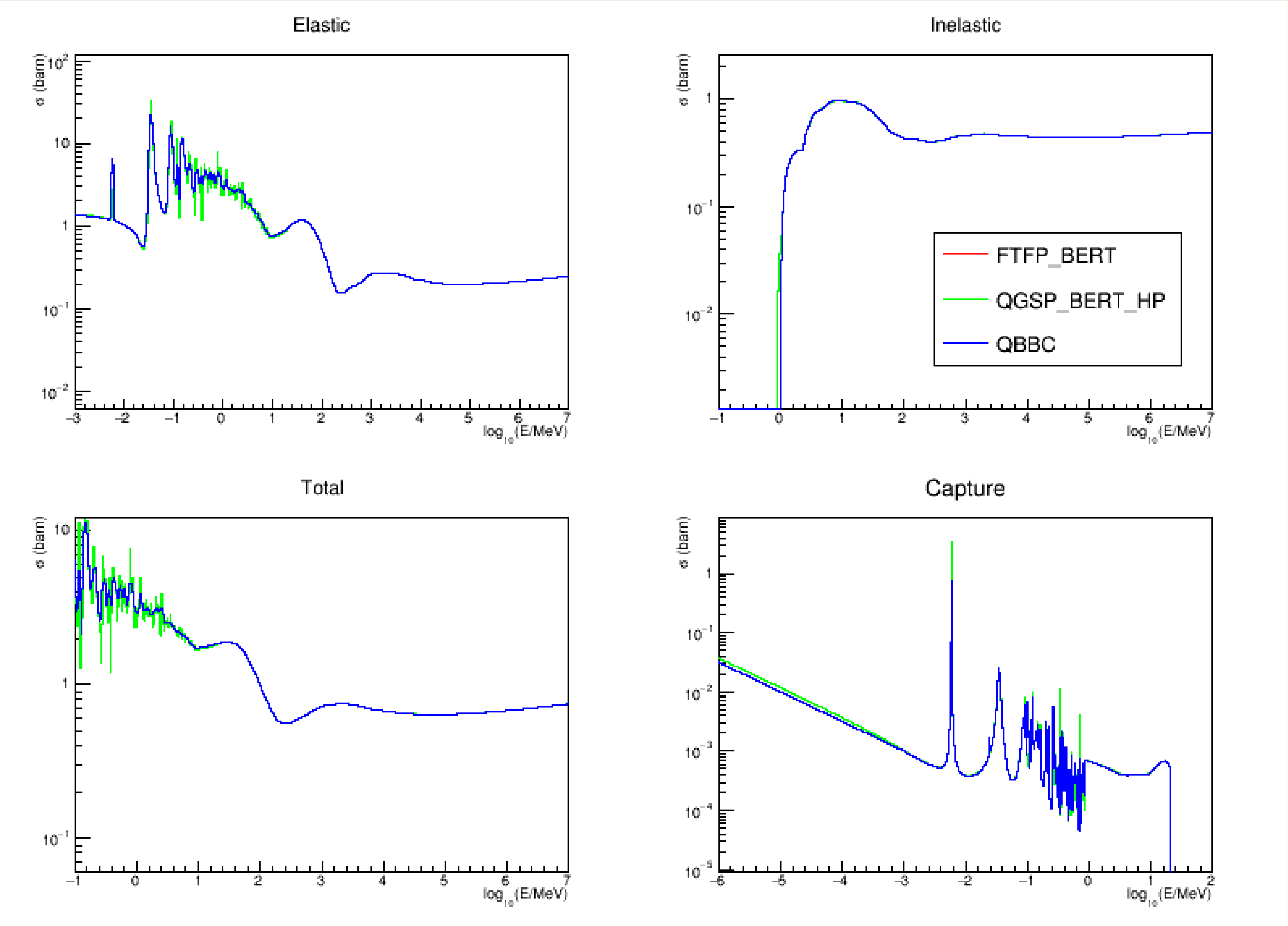
- At this and previous plots INCL++ demonstrates more accurate simulation for ion components
- The binary cascade predictions improves when multi-fragmentation sub-model is enabled

Hadronic Cross Section Updates

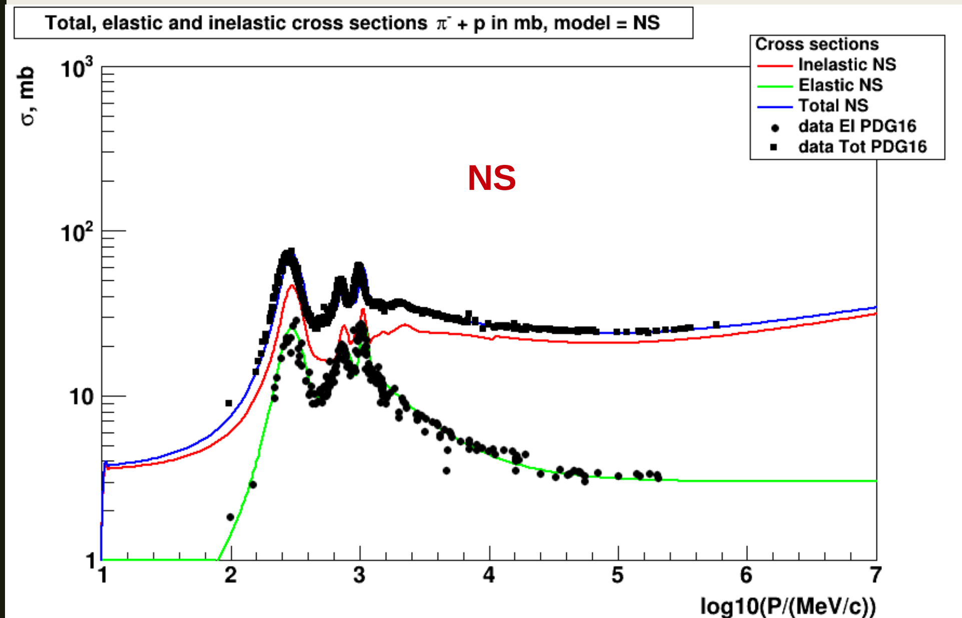
G4PARTICLEXS2.1

- Structure of the data set is change because of particle HP
  - *Separate directories for n, p, d, t, he3, he4 cross sections*
  - *Element x-sections from threshold to max hadronic energy (100 TeV)*
    - Physics data tables shared between threads extracted from ParticleHP
    - Glauber Gribov cross section above 20 GeV for p and n
    - Glauber Gribove cross sections above 20 MeV for , d, t, he3, he4
- Added extra isotope data for 11 more elements (was 17 before)
  - *Ne, Mg, S, Cl, K, Sc, Ti, Ga, Pd, In, Pt*
  - *Limit on isotope abundance is reduced to 0.001 (was 0.01)*
- Fixed discontinues in last bins
  - *Isotope data only for E < 20 MeV, above – element data*
- Fixed G4CrossSectionDataStore code
  - *Isotope selection*
  - *Integral approach*

Neutron x-sections in Aluminum

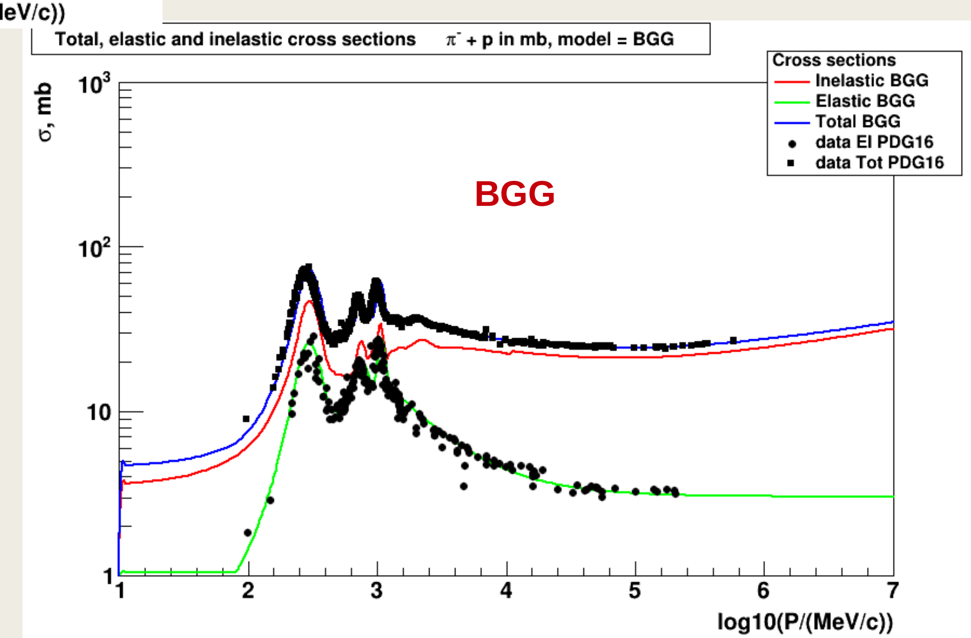


Hadron-nucleon cross sections: $\pi^- + p$

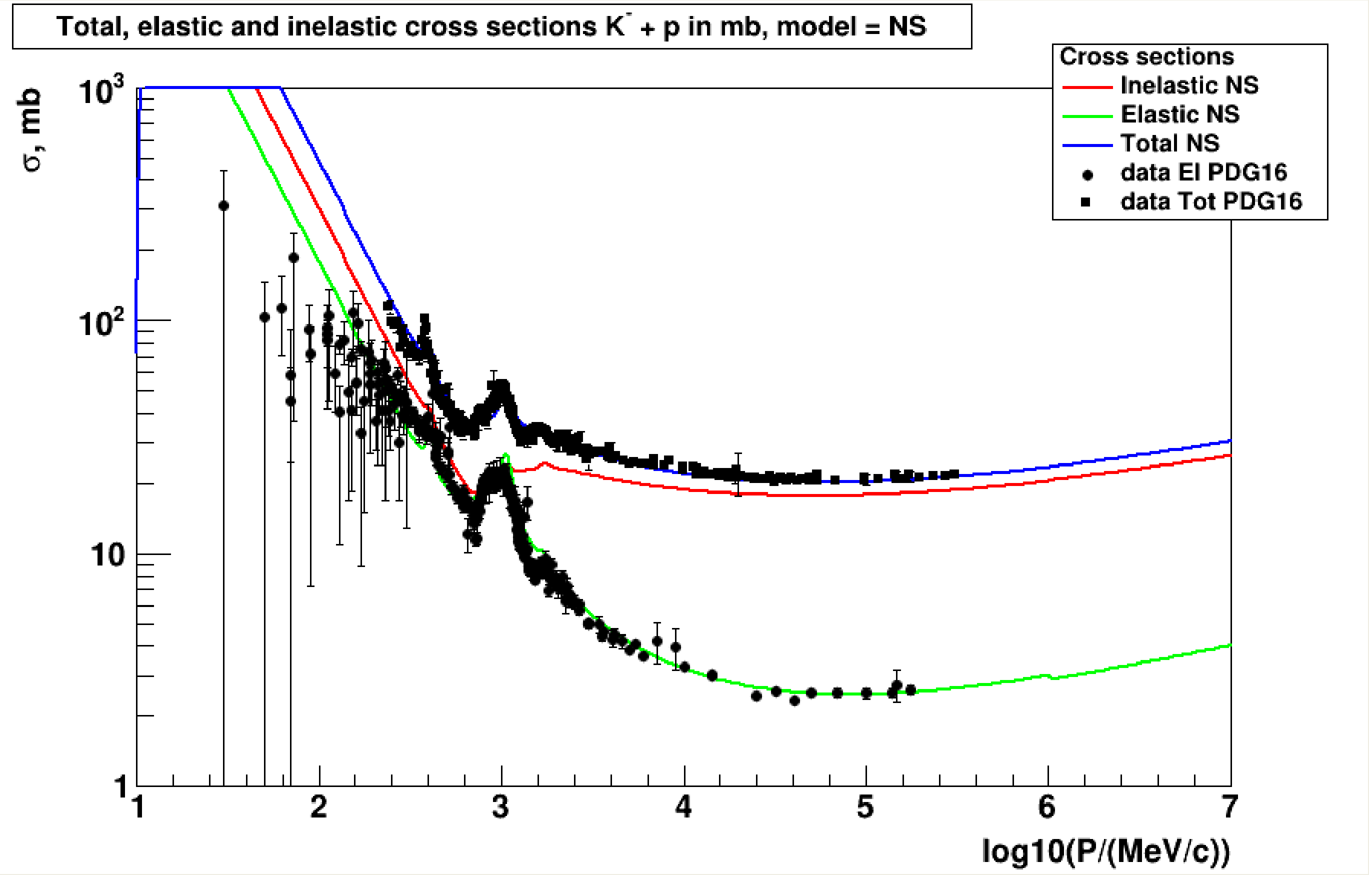


An example of improved cross section parameterization in G4HadronNucleonXsc class

NS and BGG:
Both total and elastic xs are good



K⁻ cross sections



- 1/v cross section shape at low energy confirmed by data
- Similar cross section shape for π^-
- Coulomb barrier for positively charged hadrons

Summary

- For Geant4 10.5 FTF and QGS development versions were integrated
- Substantial developments of low-energy models started in Geant4 10.3 and continued up to 10.6
- In Geant4 10.6 a significant efforts were put for unification of various Physics Lists
  - *Common transitions between string/cascade*
  - *Common data sets for nuclear properties*
  - *Glauber-Gribov cross sections in majority of Physics Lists*