Geant4 Hadronic Physics Developments

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Outline

- General matters
- Photo-nuclear and lepto-nuclear physics
- Ion-ion collisions
- Low energy data-driven models
- Particle stopping and capture
- Precompound and de-excitation models
- Radioactive decay
- Hadronic Physics Lists

Event Reproducibility in Geant4

- Results of two runs were not always identical when using the same random seed
  - also the case that you could not take the seed from the end of one run, start another run, and get the same answer as when only a single run of combined statistics was done
  - physics was OK, but this caused problems for debugging
  - a long-standing problem due to caching in hadronics

- This is now fixed for the most part in 9.6
  - only physics lists involving high precision neutrons (HP) are still a problem
  - work continues

Deprecated Hadronic Models

- LEP, HEP (Gheisha-style) models are deprecated
  - better models now available to cover all particles, all energies formerly handled by LHEP
  - after Geant4 10.0, physics lists using LEP, HEP models will not work – for underground physics applications, we recommend the Shielding list
- CHIPS (Chiral Invariant Phase Space) code deprecated
  - cross sections and other important pieces of code extracted into other models
  - physics lists using original CHIPS code will disappear
    - this includes some stopping and nuclear de-excitation code

Other General Matters

- Hadronic processes now trigger re-sampling of the interaction if energy/momentum non-conservation limits are exceeded
  - some models have tighter limits than others, but “catastrophic” non-conservation is now avoided
- html files containing process, model and cross section descriptions can now be output by invoking methods:
  - ProcessDescription()
  - ModelDescription()
  - CrossSectionDescription()
  - in near future these will be integrated for all processes/models/cross sections in a physics list

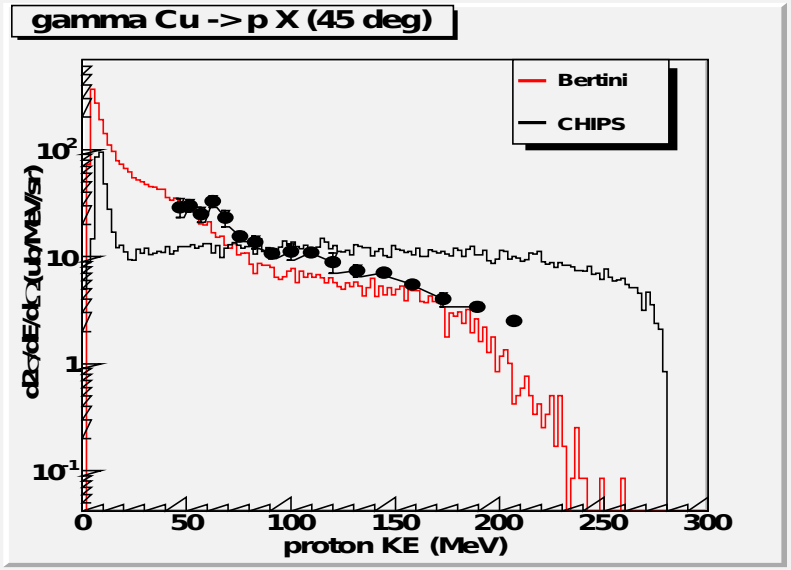
Photo- and Lepto-nuclear Models

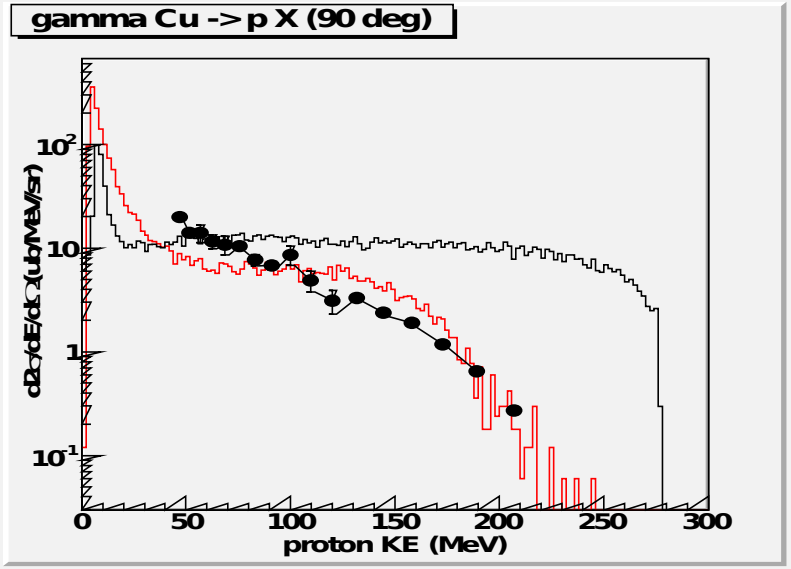
- Improved photo-nuclear process
  - gammas from ~10 MeV to 10 GeV now interact directly with nuclei using the Bertini-style cascade
  - above 10 GeV, the FTF string model is used, but first the gamma is converted to a pion

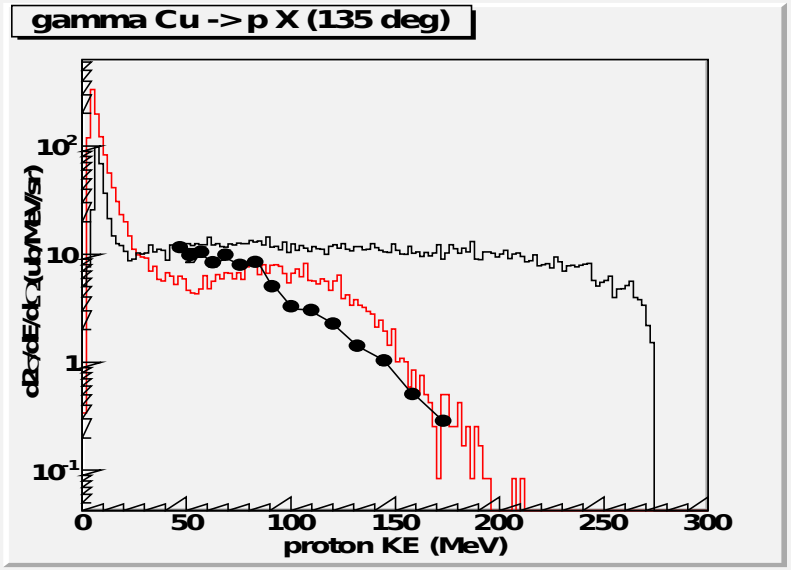
- Improved mu-nuclear model (G4MuonVDNuclearModel)
  - no longer need to replace virtual photon with 50% π+, 50% π-

- New electro-nuclear model (G4ElectroVDNuclearModel)
  - as in old model, uses CHIPS cross sections and virtual gamma generation

γ Cu -> p X


gamma Cu -> p X (45 deg)
Bertini
CHIPS
d2σ/dEdΩ (ub/MeV/sr)
proton KE (MeV)


gamma Cu -> p X (90 deg)
d2σ/dEdΩ (ub/MeV/sr)
proton KE (MeV)


gamma Cu -> p X (135 deg)
d2σ/dEdΩ (ub/MeV/sr)
proton KE (MeV)

Ion-Ion Collisions

- INCL++ v5.0 cascade model can now handle ion collisions up to 3 GeV (projectiles up to mass 12)
  - complete redesign in C++
  - Physics-wise equivalent to INCL4.6
  - keeps only the best physics from INCL4.6

- The FTF string model can now be used for all ions at energies from ~ 3 GeV to ~ TeV
    - although validation is still underway

- For the first time in Geant4, we can consider doing heavy ion collisions at all energies
  - QMD (or INCL++ or Binary cascade) coupled with FTF model
  - should now address all cosmic ray needs

Low Energy Data-driven Models

- Two high precision neutron models available (E < 20 MeV)
  - neutronHP
    - the old standard, but now more (8) data library options
    - data sources are no longer mixed
  - LEND
    - newer and faster model (data format) based on Livermore database (GIDI interface)
    - ENDL99 and ENDF-VII.0 have been converted to new data format and are distributed from LLNL website
    - so far, fewer isotopes than neutronHP, but will improve

- High precision charged particle models (p, d, α)
  - prototype for protons available, still being tested
  - α model expected sometime this year
  - will have same data sources as neutronHP

CIEMAT translated libraries for Geant4 (available at IAEA website)

The following ENDF-6 format libraries have been translated into the GEANT4 format:

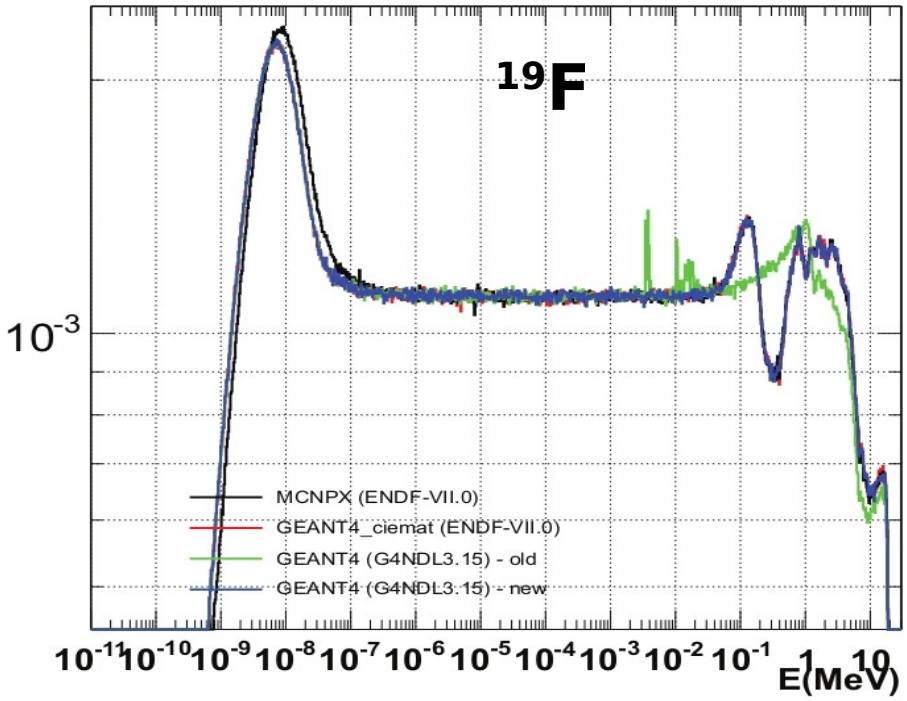
– ENDF-VII.0 (USA) – 389 isotopes (+ 3 natural abundances and 9 excited isomer states)
– ENDF-VI.8 (USA) – 317 isotopes
– JEFF-3.0 (EU) – 373 isotopes
– JEFF-3.1 (EU) – 334 isotopes
– JENDL-4.0 (Japan) – 400 isotopes
– JENDL-3.3 (Japan) – 332 isotopes
– BROND-2.2 (Russia) – 120 isotopes
– CENDL-3.1 (China) – 239 isotopes

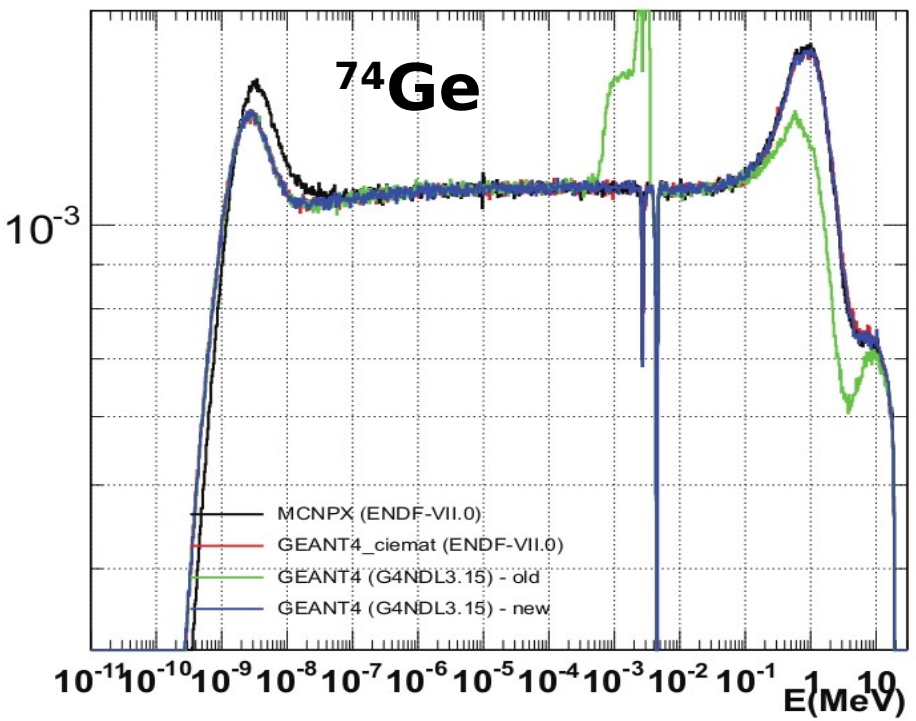
- G4NDL-3.14 (Geant4.9.4) – 181 isotopes

G4NDL-4.2 (Geant4.9.6 release) set was significantly extended (395 isotopes up from 181) and old isotopes data were renewed

High Precision Neutrons

Comparing Geant4HP and MCNPX



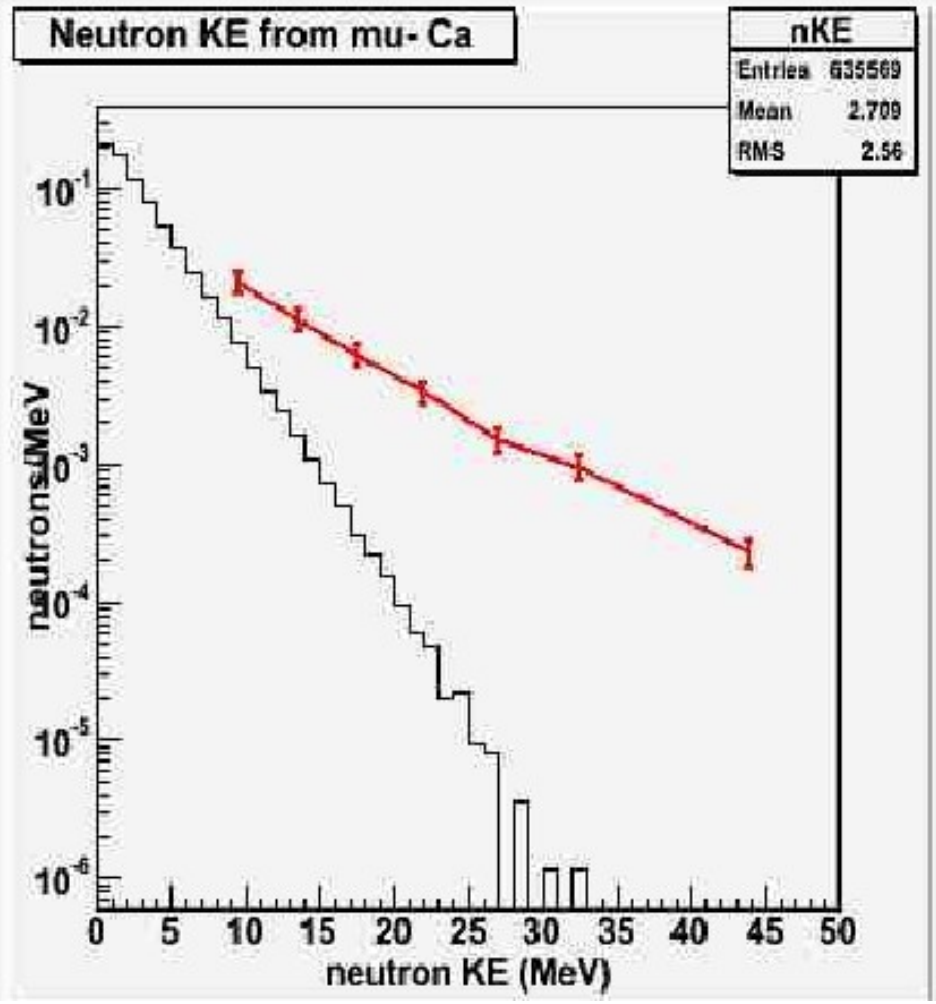


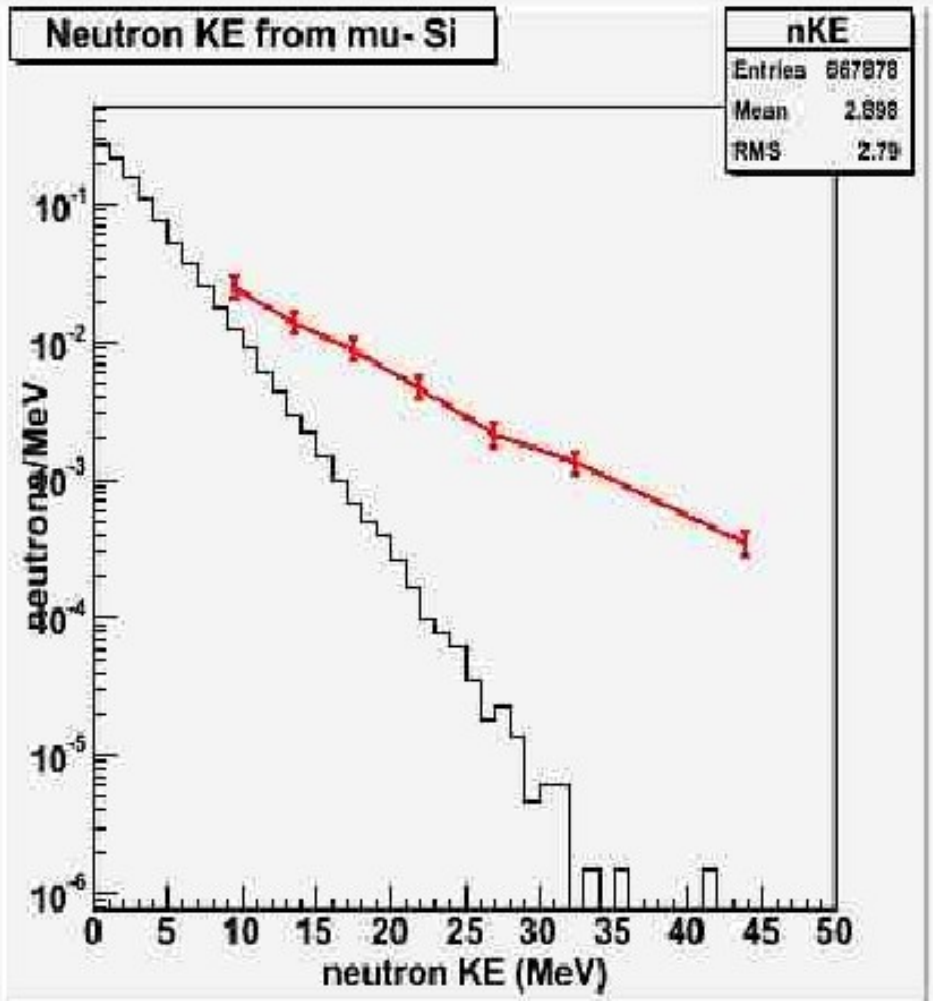
Particle Stopping and Capture

- New stopping models (to replace old CHIPS models)
  - G4PiMinusAbsorptionBertini
  - G4KaonMinusAbsorptionBertini
  - G4SigmaMinusAbsorptionBertini
  - G4AntiProtonAbsorptionFritiof

- Improved mu-stopping
  - current model is quite simple, with too-soft neutron spectrum
  - to be replaced with Bertini using both one and two nucleon muon absorption
  - expected by 1st half of this year

Neutron Energies from Muon Capture





Precompound and de-excitation

- Refinements of de-excitation models and code optimization (performed and underway)

- Introduction of production and transportation of long lived isomers
  - Needs corresponding changes in base hadronic classes
  - Needs update of photo-evaporation model including modifications needed for gamma decay angular correlations
  - Needs to use RadioactiveDecay (its CPU impact should be carefully considered)

- Correlated neutron gamma emission in fission (spontaneous-, neutron-induced- and photo-fission)

Radioactive Decay

- New data set required
  - RadioactiveDecay3.6 (available in download area)
  - 534 nuclear states now have precise beta decay spectrum shapes (classified as 1st, 2nd, or 3rd unique forbidden)
- Improved activation code
  - good agreement with proton activation data
  - can now output built-up radioactivity table
- Directional biasing of decay daughters
- Production and propagation of isomers/metastable nuclear states
  - coming 1st half of this year

Hadronic Physics Lists

Table I. Geant4 models for the simulation of hadron/ion inelastic interactions (Ivanchenko et al. 2008, Apostolakis et al. 2009b) from left to right: Model acronym, model name, applicability's energy range, and primary particles.

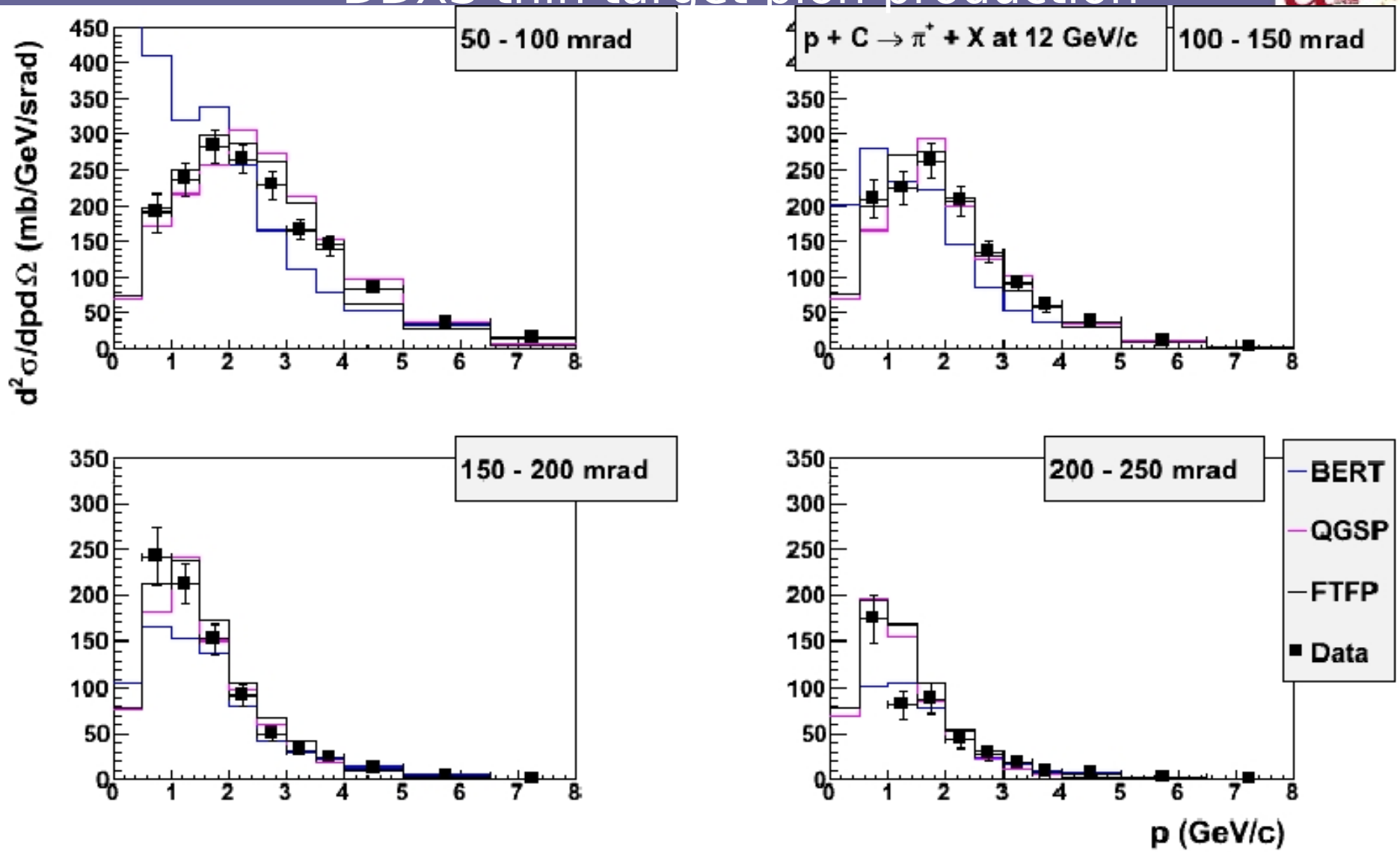
Model acronym	Model name	Energy ranges	Incoming particles applicabilities
LHEP	Low-High Energy Parameterized	0–100 TeV	All hadrons
PRECO	Pre-compound	0–100 MeV	Protons, neutrons
BERT	Bertini cascade	0–15 GeV	Protons, neutrons, pions, kaons, hyperons
BIC	Binary cascade	0–5 GeV	Protons, neutrons, pions
BIC_Ion	BinaryLightIon cascade	0–5 GeV/u	Ions
INCL	Intra-Nuclear Cascade Liege	150–3000 MeV	Protons, neutrons, pions, kaons, light ions
QGSP	Quark Gluon String + PRECO	10–10^5 GeV	Protons, neutrons, pions, kaons
FTFP	Fritiof + PRECO	3–10^5 GeV	Protons, neutrons, pions, kaons, hyperons
CHIPS	Chiral Invariant Phase Space	0–100 TeV	All hadrons
G4QMD	Quantum molecular dynamics	10–10^4 MeV/u	Protons, neutrons, ions
Abrasion	Abrasion-ablation model	10^2–10^4 MeV/u	Ions

Source :
Anton V. Ivantchenko, Vladimir N. Ivanchenko, Jose-Manuel Quesada Molina & Sebastien L. Incerti, " Geant4 hadronic physics for space radiation environment", International Journal of Radiation Biology, January–February 2012; 88(1–2): 171–175

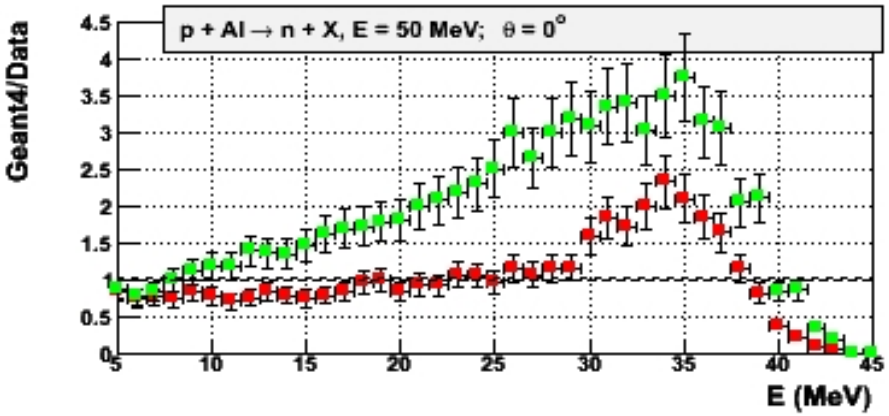
QBBC

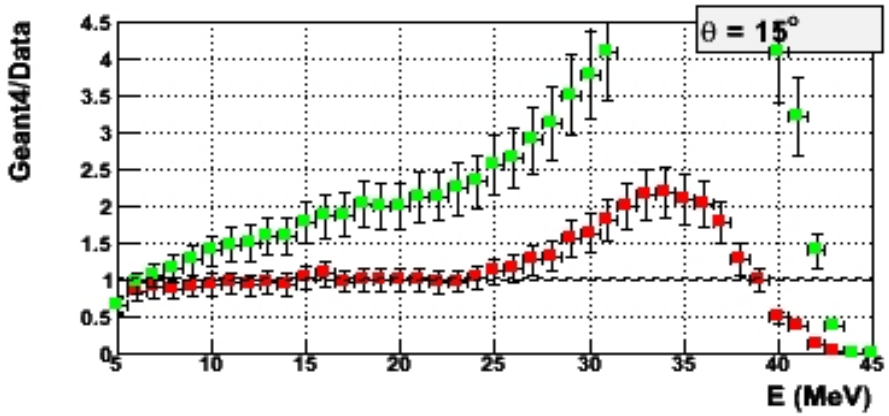
- Created for space applications, rad. biology, and rad. protection.
- Includes combinations of BIC, BIC-Ion, BERT, QGSP and FTFP
- Higher precision than the others for many hadron-ion and ion-ion interactions in a wide energy range

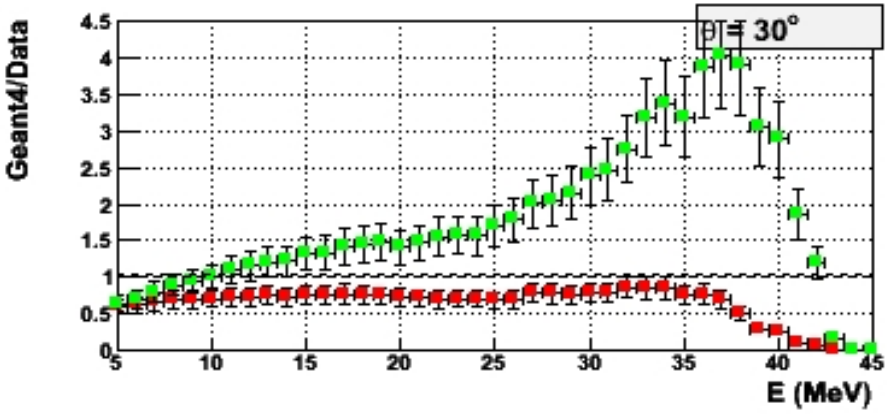
DDXS thin target pion production

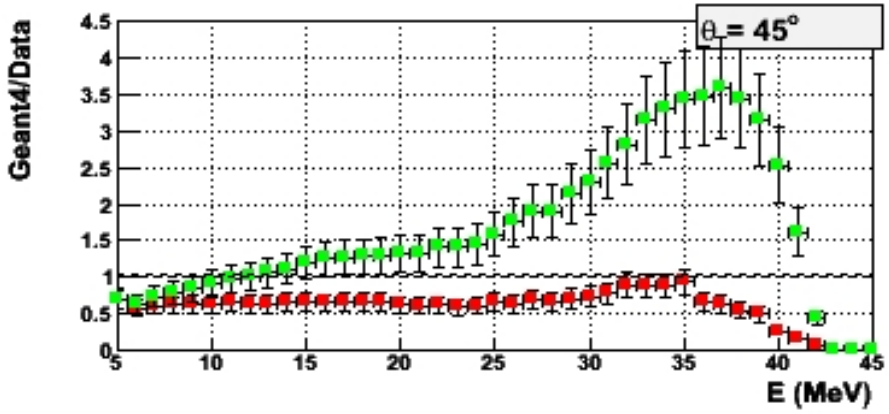


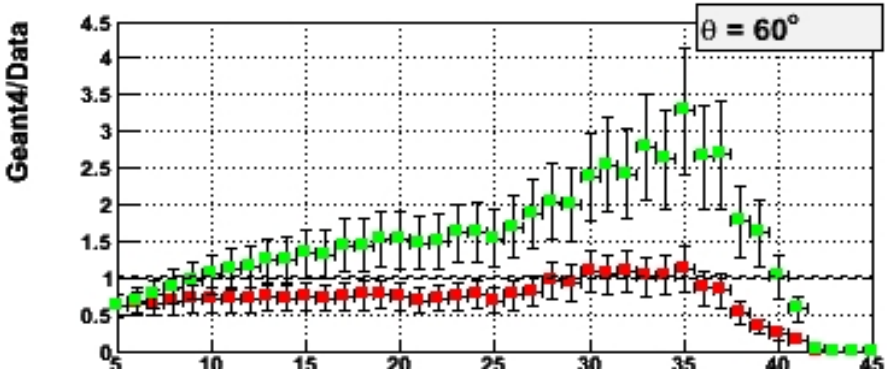
DDXS thin target neutron production

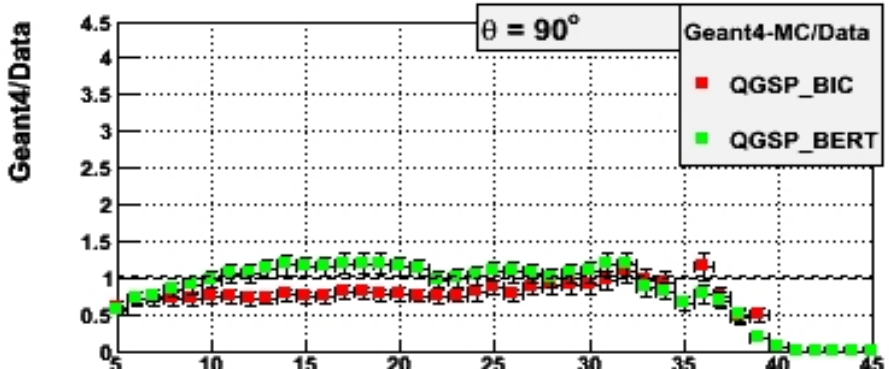




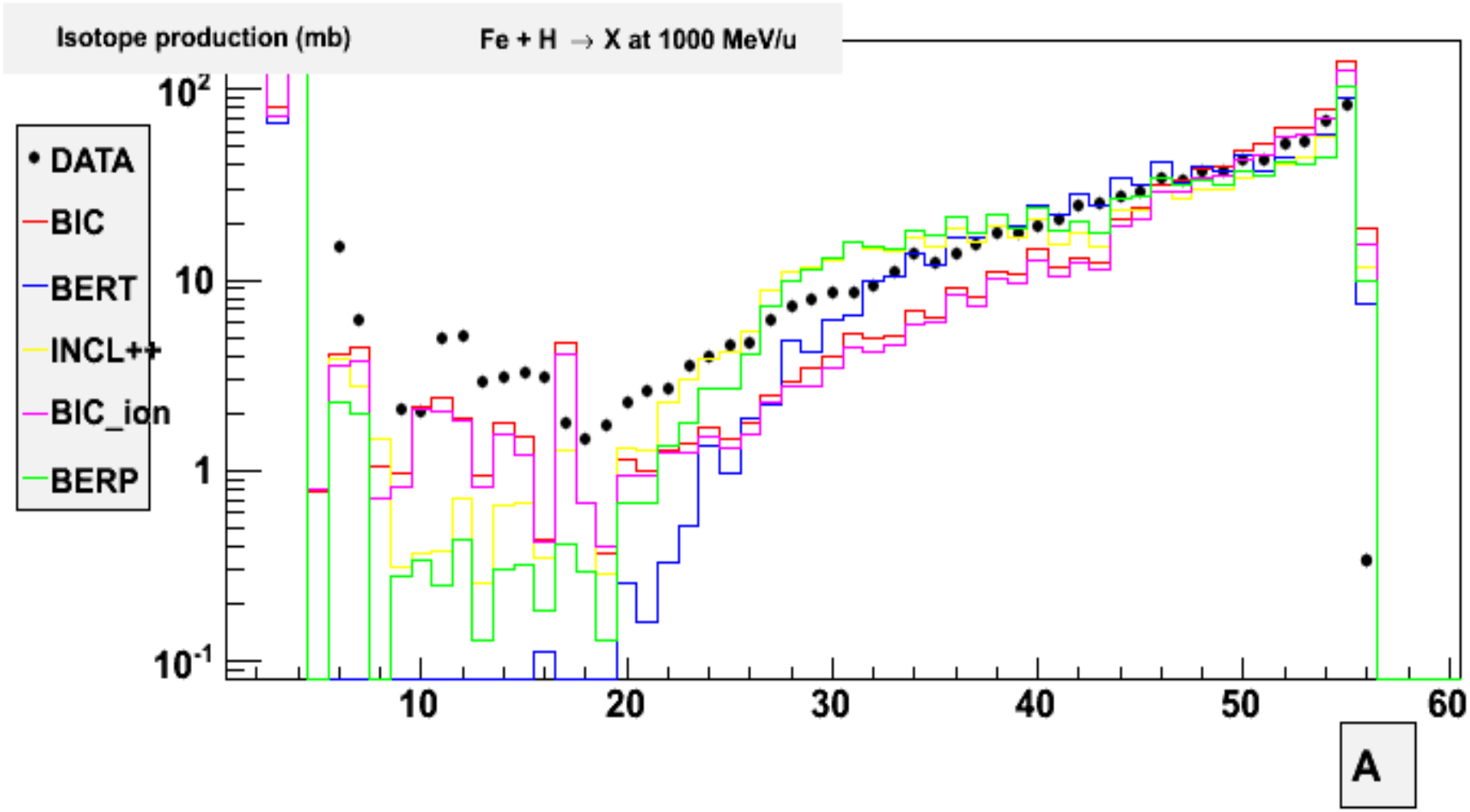








Isotopes production



Conclusions

- Geant4 hadronic models are able to describe nuclear interactions in a space radiation environment

- Geant4 provides good results for interactions of neutrons, protons, and pions with atomic nuclei in the energy interval 10 MeV–15 GeV .

- For ions there is good agreement with data in the energy interval 100 MeV/u–1.5 GeV/u.

- String, cascade, preequilibrium and de-excitation models are under continuous development.

Thanks for your attention